UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme
Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2017
Number 18

# BOREHOLE GEOLOGY OF WELL THG-15 AT THEISTAREYKIR GEOTHERMAL FIELD, NE-ICELAND

**Adonias Mkangala**
Tanzania Geothermal Development Company (TGDC)
P.O. Box 14801,
Dar es Salaam
TANZANIA
*addonias.cn@gmail.com*

## ABSTRACT

Well ThG-15 is located within the Theistareykir geothermal field in NE-Iceland. It is a directional production well drilled to a total depth of 2260 m. 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 16 m down to 1992 m to determine the lithology, mineral alteration and the occurrence of intrusive rocks in well ThG-15. The stratigraphy of well ThG-15 is characterised by lava flows, which are intercalated by reworked sedimentary tuffs in the upper 114 m, hyaloclastites (basaltic breccia, tuff, glassy basalt) from 114 to 920 m and fine- to medium-grained crystalline basalt below 920 m. The hydrothermal alteration minerals in well ThG-15 are wairakite, zeolite, smectite, mixed-layer clay, quartz, pyrite, calcite, chlorite, epidote, prehnite, actinolite and wollastonite. Alteration zones have been established based on appearance and temperature dependency of alteration minerals in well ThG-15. These zones are zeolite-smectite zone (58-210 m), mixed-layer clay zone (210-445 m), chlorite zone (445-610 m), chlorite-epidote zone (610-978 m) and epidote-actinolite zone (978-1992 m). The most permeable zones in the well based on circulation losses and temperature logs were encountered at 1455-1475, 1800-1830 m and at 2090 m depth. Measured temperature after three months of well heating-up indicates that the geothermal system follows the boiling point curve in the upper 1000 m. Alteration temperature correlates with the measured temperatures at this depth, but well ThG-15 experiences cooling below 1000 m, possibly due to cold-water inflow from the feed zone/fractures in the deepest section of the well.

## 1. INTRODUCTION

Theistareykir is a high-temperature geothermal field in NE-Iceland. The geothermal activity has been estimated to cover an area of 11 km$^2$ (Gíslason et al., 1984). The first geothermal exploration in the area was carried out from 1972-1974 and a major geothermal assessment was made in 1981-1984 (Gíslason et al., 1984; Ármannsson et al., 1986; Darling and Ármannsson, 1989). However, Theistareykir has been known for centuries for hosting the main sulphur deposit in Iceland that provided the Danish king with the raw material for gunpowder (Ármannsson et al., 1986). The first deep exploration well was drilled in 2002 and as of 2008, five more exploration wells were completed including three inclined wells (Gautason et al., 2010). During 2016-2017 the field was further developed by Landsvirkjun – National Power Company, and eight production wells were drilled. Concurrently a 90 MWe geothermal power plant is in construction and the plan is to commence production of 45 MWe by December 2017 and reach full capacity of 90 MWe by April 2018.

Well ThG-15 is a directional production well. The well-head is located on well pad B together with wellheads of wells ThG-9 and ThG-11. Well pad B is located approximately 0.6 km north of Baejarfjall. Drilling of ThG-15 began on 29th January 2017 and drilling was completed to a depth of 2260 m by 16th of March 2017. After drilling, a multi-rate injection test was carried out, which resulted in an injection index of 3.9 (L/s)/bar (Sigurgeirsson et al., 2017a). This study was in particular focused on borehole geology to establish the stratigraphy, hydrothermal alteration minerals, intrusions and lithological boundaries, locate feed zone and finally assess the permeability and geothermal system history of well ThG-15 within the Theistareykir geothermal field.

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

## 2. GEOLOGIC SETTING

### 2.1 Geology of Iceland

Iceland lies on the Mid-Atlantic Ridge, which is the boundary between the North America and Eurasian tectonic plates which are moving apart at a rate of about 1 cm in each direction per year (Saemundsson, 1979). Iceland is thought to have formed as a result of an interaction between a spreading plate boundary and a mantle plume (Wolfe et al., 1997). The landmass is considered to have started building up about 24 m.y. ago (Saemundsson, 1978) although, the oldest rocks exposed on surface are dated as 14-16 m.y. old. (McDougall et al., 1984; Hardarson et al., 1997). The geology of Iceland consists of multiple volcanic systems resulting from the superposition of the spreading plate boundary over the mantle plume (Saemundsson, 1979; Hardarson et al., 1997). The most prominent structural belt is the axial volcanic zone with active faulting and fissure swarms that follow the plate boundary from Reykjanes in the southwest to Öxarfjördur in the northeast (Figure 1).

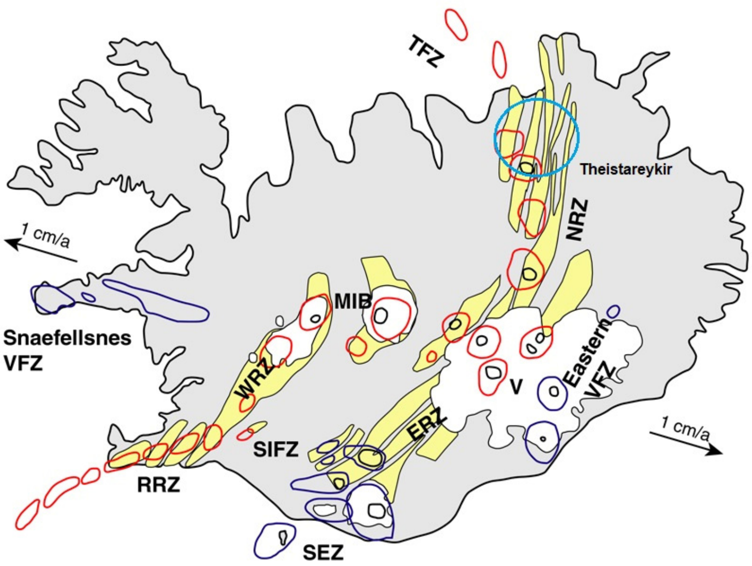


FIGURE 1: Volcano-tectonic map of Iceland. Fissure swarms drawn in yellow. Volcanic centres and calderas are outlined with red and black lines, respectively. The central volcanic areas of the volcanic flank zones (volcanic off-rift zones) are outlined with blue lines; simplified after Trönnes (2002). VFZ: Volcanic Flank Zone; RRZ: Reykjanes Rift Zone; WRZ: Western Rift Zone; ERZ: Eastern Rift Zone; NRZ: Northern Rift Zone; MIB: Mid-Icelandic Belt; SIFZ: South Icelandic Fracture Zone; TFZ: Tjörnes Fracture Zone; SEZ: South Eastern Zone; V: Vatnajökull

Surface geology is largely composed of igneous rocks of which 80-85% are basaltic in composition and about 10% acidic and intermediate rocks (e.g. Saemundsson, 1979). Sediments of volcanic origin constitute 5-10% in a typical Tertiary lava pile. There is no clear evidence of the occurrence of classical metamorphic rocks (Saemundsson, 1979; Jakobsson et al., 2008; Jóhannesson and Saemundsson, 1999). Saemundsson (1992) classified the geology of Iceland into four stratigraphic units which are distinguished by different landforms; Postglacial: last 9,000 to 13,000 a, Upper Pleistocene: back to 0.7 Ma, Plio-Pleistocene: 0.7-3.1 Ma and Tertiary: older than 3.1 Ma.

## 2.2 Geological setting of Theistareykir area

Theistareykir geothermal field in NE-Iceland lies in one of the fissure swarms forming the North Volcanic Zone (NVZ), which consists of five north-northeast striking left stepping *en echelon* volcanic systems. The major structural feature in Theistareykir is the fissure swarm, which is 7-8 km wide trending E-W and 70-80 km long trending in a N-S direction (Figure 2). The fissure swarm extends from

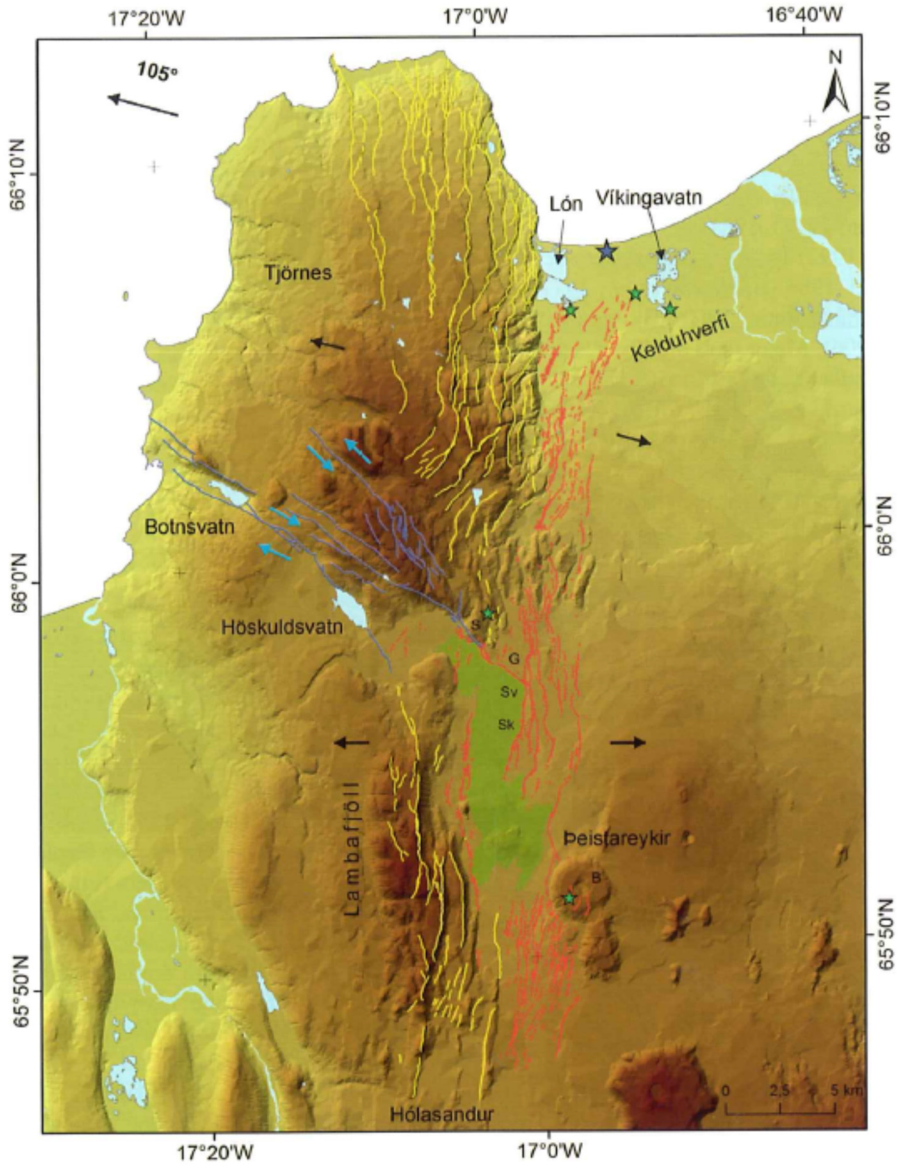


FIGURE 2: Structural map of Theistareykir volcanic system showing normal faults (yellow), fissure swarm (red) and strike-slip faults within the Húsavík-Flatey fault system (blue). Black arrows denote the localized spreading direction and light-blue arrows indicate fault movement in the HFFS. The green shaded area in the centre of the map represents the Theistareykir lava flow (modified from Magnúsdóttir and Brandsdóttir, 2011)

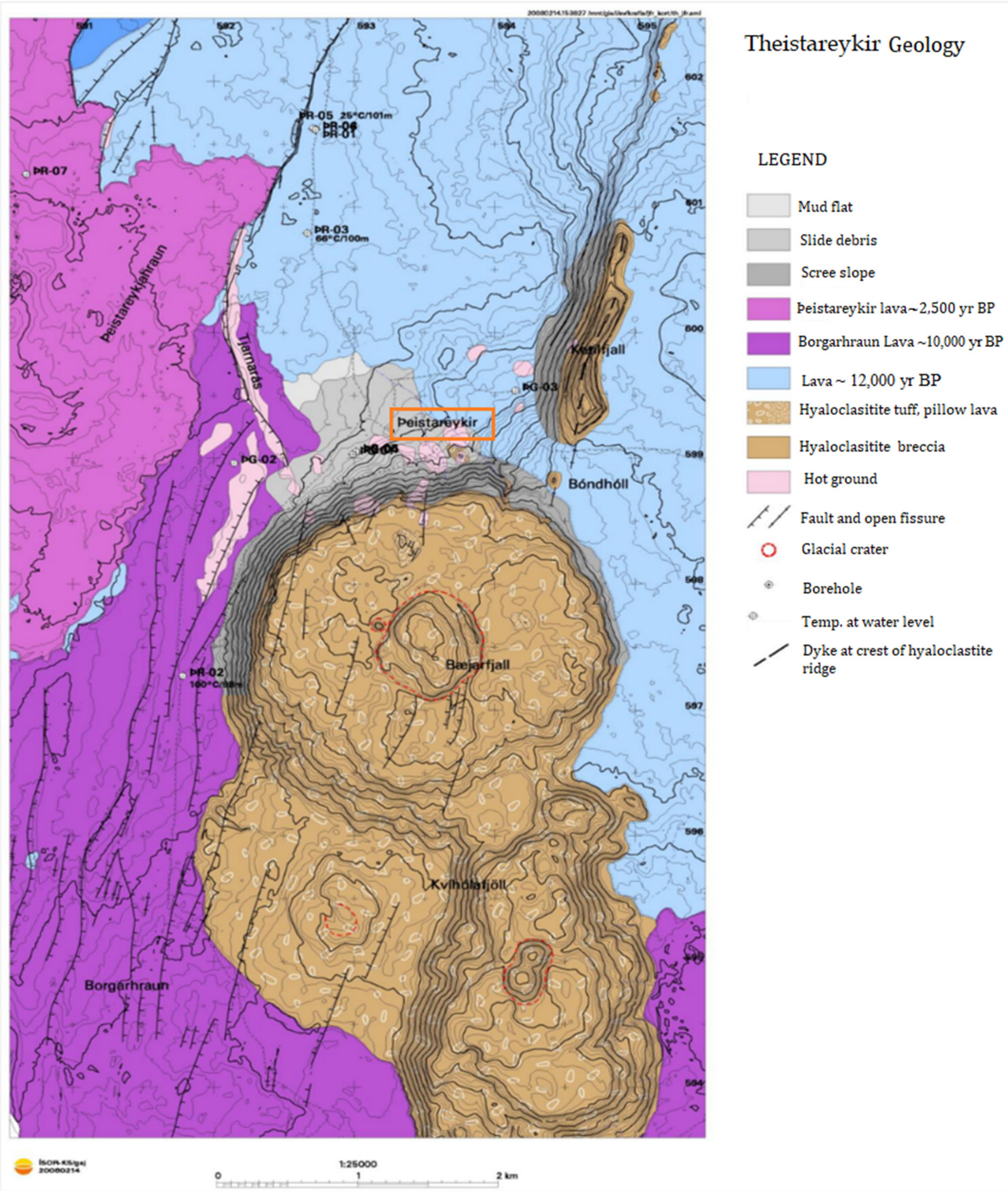


FIGURE 3: Geological map of Theistareykir (Saemundsson, 2007)

the Hólasandur region through Theistareykir, the eastern Tjörnes peninsula and the western Kelduhverfi into the Öxarfjördur bay. The fissure system intersects the N-W strike-slip Húsavík-Flatey fault system (HFFS) to the north. The overall strike of the Theistareykir system on land and offshore is approximately N27°E (Magnúsdóttir and Brandsdóttir, 2011). Forming the northwestern boundary of NVZ, the Theistareykir fissure swarm consists of large normal faults with displacement of 200-300 m along its western rim, in the Lambafjöll and Tjörnes mountains (Magnúsdóttir and Brandsdóttir, 2011). Figure 3 shows the geological map of the Theistareykir area (Saemundsson, 2007)

## 3. PREVIOUS SURFACE EXPLORATION

Surface exploration in the Theistareykir geothermal field commenced in the 1970s and detailed exploration projects continued to the mid 1980s (Gíslason et al., 1984). The first deep exploration well was drilled in 2002 and five other wells were drilled from 2003 to 2008 (Gautason et al., 2010). Previous surface studies undertaken in the area include among others geological mapping, resistivity surveying and geochemistry measurements.

### 3.1 Geological mapping

The surface geological map of Theistareykir (Figure 3) shows the main geological units seen on surface. The area is mostly covered by lava flows which pre- and post-date the latest glaciation period. The lava flows seem to be from a shield volcano (Saemundsson, 2007). The oldest hyaloclastite formations are exposed in the west at Lambafjöll and in the vicinity of the geothermal activity at Ketilfjall. Baejarfjall and Kvíhólafjöll are younger table-mountains formed by eruptions on short fissures or single volcanic vents during glaciation.

The highlands between the hyaloclastite mounds and ridges are covered by basaltic lava-flows dated ~10,000-12,000 years before present. Theistareykjahraun is the youngest lava flow and is considered to be about 2,500 years old (Saemundsson, 2007). The lava flows have partially buried the sub-glacial table mountains and ridges so their roots are concealed.

### 3.2 Geophysical surveys

Geophysical studies undertaken in Theistareykir include Transient Electromagnetic measurements (TEM) carried out in 2004-2006 and MagnetoTelluric (MT) measurements in 2009 (Karlsdóttir et al., 2006; Karlsdóttir and Vilhjálmsson, 2011). Kahwa (2015) reported Theistareykir resistivity results after processing nine TEM and seven MT soundings measured by ÍSOR in 2009-2011.

Figure 4 shows a TEM-MT cross section north of Baejarfall down to 5,000 m below sea level (b.s.l.) and reveals the low-resistivity cap at shallow depth and the underlying high-resistivity core (>100 Ωm).

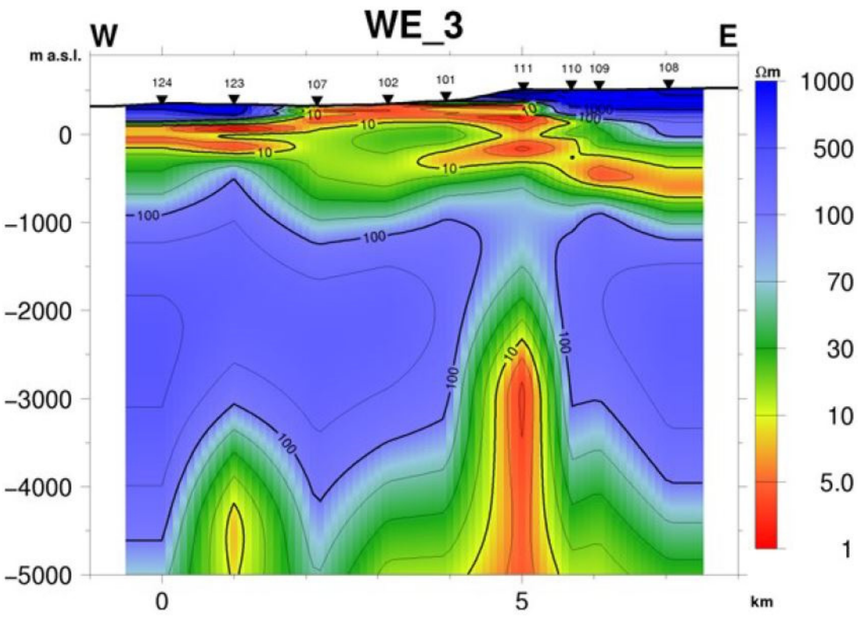


FIGURE 4: Resistivity profile WE_3 based on 1D joint inversion of TEM and MT data down to 5,000 m b.s.l. (Kahwa, 2015)

The resistivity core extends from 800 m b.s.l. down to 4,000 m b.s.l. and correlates with the chlorite-epidote alteration zone (Kahwa, 2015). Below the resistivity core there is a peak in the relatively conductive layer, which might indicate the heat source for the geothermal field.

### 3.3 Geochemistry

The first few steam samples analysed from Theistareykir field date from about 1950 (Icelandic Drilling Co., 1951). Grönvold and Karlsdóttir (1975) and Gíslason et al. (1984) have reported that a comprehensive geochemical study was conducted in the 1970s and 1980s. Gíslason et al. (1984) collected 34 samples from fumaroles and estimated reservoir temperatures based on gas geothermometry with results ranging from 230 to 315°C.

## 4. SUBSURFACE GEOLOGY OF WELL ThG-15

### 4.1 Drilling of well ThG-15

Well ThG-15 was drilled from well pad B located about 0.6 km north of Baejarfjall (Figure 5). The geographical coordinates of well ThG-15 are 593445.2 east, 599590.5 north and it stands at an elevation of 349.2 m above sea level (m a.s.l.). Coordinates are in the ISNET93 system.

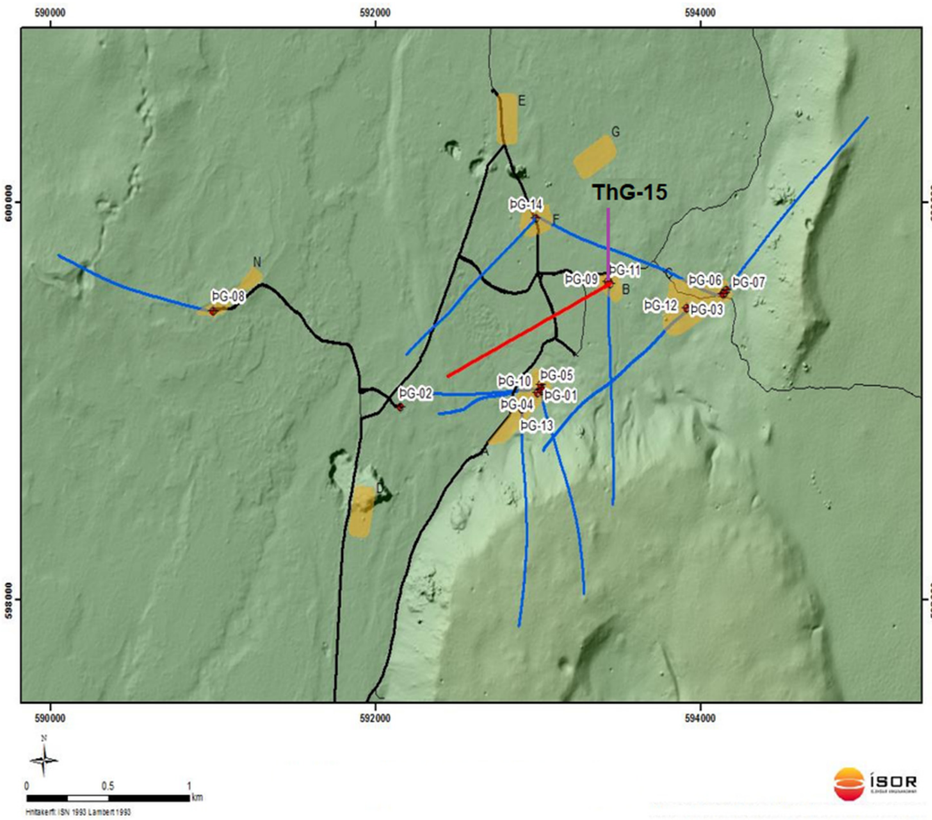


FIGURE 5: Location of well ThG-15, the planned well path (red line) (Sigurgeirsson et al., 2017b)

The Icelandic Drilling Company (Jardboranir) undertook the drilling of well ThG-15 for Landsvirkjun, using the drill rig Ódinn. Drill cutting inspections, geophysical logging and geothermal consultancy services were conducted by ÍSOR - Iceland GeoSurvey (Sigurgeirsson et al., 2017b). The well was directionally drilled towards southwest, with the target of intersecting permeability zones related to fractures and volcanic fissures northwest of Mt. Baejarfjall (Khodayar et al., 2016; Mortensen, 2012).

### 4.2 Drilling progress of well ThG-15

Well ThG-15 was drilled in four consecutive phases, pre-drilling for surface casing, drilling for anchor casing, drilling for production casing and drilling of the production section where a perforated liner was installed. Pre-drilling (Phase 0) commenced on 29th of January 2017 and reached a casing depth of 100 m on 1st of February. The 18⅝" surface casing was set at a depth of 97.6 m. Drilling of phase 1 progressed from 7th of February and reached a depth of 300 m after two days, whereby the 13⅜" anchor casing was set at 295.2 m depth. Phase 2 started on the 9th of February and was drilled to 920 m in five days. The 9⅝" production casing was run downhole to 917.1 m. Finally, drilling of phase 3 (production part) started on 18th of February and reached a depth of 2260 m on 16th of March 2017. However, during this phase the drill rig was not in operation for 10 days due to technical disorders (Sigurgeirsson et al., 2017a).

## 5. ANALYTICAL METHODS

Rock cutting samples were collected by the Ódinn drilling crew at an interval of 2 m during the drilling of well ThG-15. Binocular microscopic analyses of drill cuttings, thin section petrography and X-ray diffraction analyses of samples were undertaken at the ÍSOR main office in Reykjavík. Rock cuttings from 16 m down to 1992 m depth were analysed by using a binocular microscope to determine the lithology, mineral alterations and identification of intrusive rocks of well ThG-15. Petrographic analysis was limited to 10 thin sections. The aim of the thin section study was to confirm rock type(s), texture, and alteration minerals not observed by the binocular microscope, but also the identification of depositional sequences of secondary minerals. XRD analysis for clay minerals identification in rock samples were carried out on 28 samples collected from different depths.

## 6. RESULTS

### 6.1 Stratigraphy of well ThG-15

The stratigraphy of well ThG-15 was constructed based on binocular microscope and petrographic studies of the cuttings from 16 m down to 1992 m. The well is composed of lava flows which are intercalated by scoria layers and sedimentary tuffs, a hyaloclastite formation composed of basaltic breccia, tuff and glassy basalt units and fine-grained crystalline basalt, which is intersected by an intrusion consisting of a medium- coarse-grained crystalline basalt. The alteration minerals observed in the cuttings are wairakite, zeolite, clay minerals, quartz, pyrite, calcite, epidote, prehnite, actinolite and wollastonite. A brief description of the lithological units of well ThG-15 is outlined below and presented in Figure 6.

*16-114 m: Lava flow.* Lava flows are intercalated by reworked-sedimentary tuffs. The formation is moderately altered, not much oxidized and porous with plagioclase phenocrysts. The groundmass is rich in olivine, whereas fine-grained zeolite, pyrite, calcite and greenish clay appear in pores within the depth interval from 104 to 114 m.

*114-290 m: Hyaloclastite.* This unit is composed of light coloured basaltic breccia. Pyrite is common in this unit and becomes abundant between 166 and 170 m. Basaltic tuff is completely altered from 200 to 228 m depth.

*290-440 m. Fine-grained and glassy basalt.* This unit consists of highly altered, dark grey to blackish basalt with green glass fragments. The unit is rich in pyrite and the vesicles and voids are filled with crystalline clay minerals.

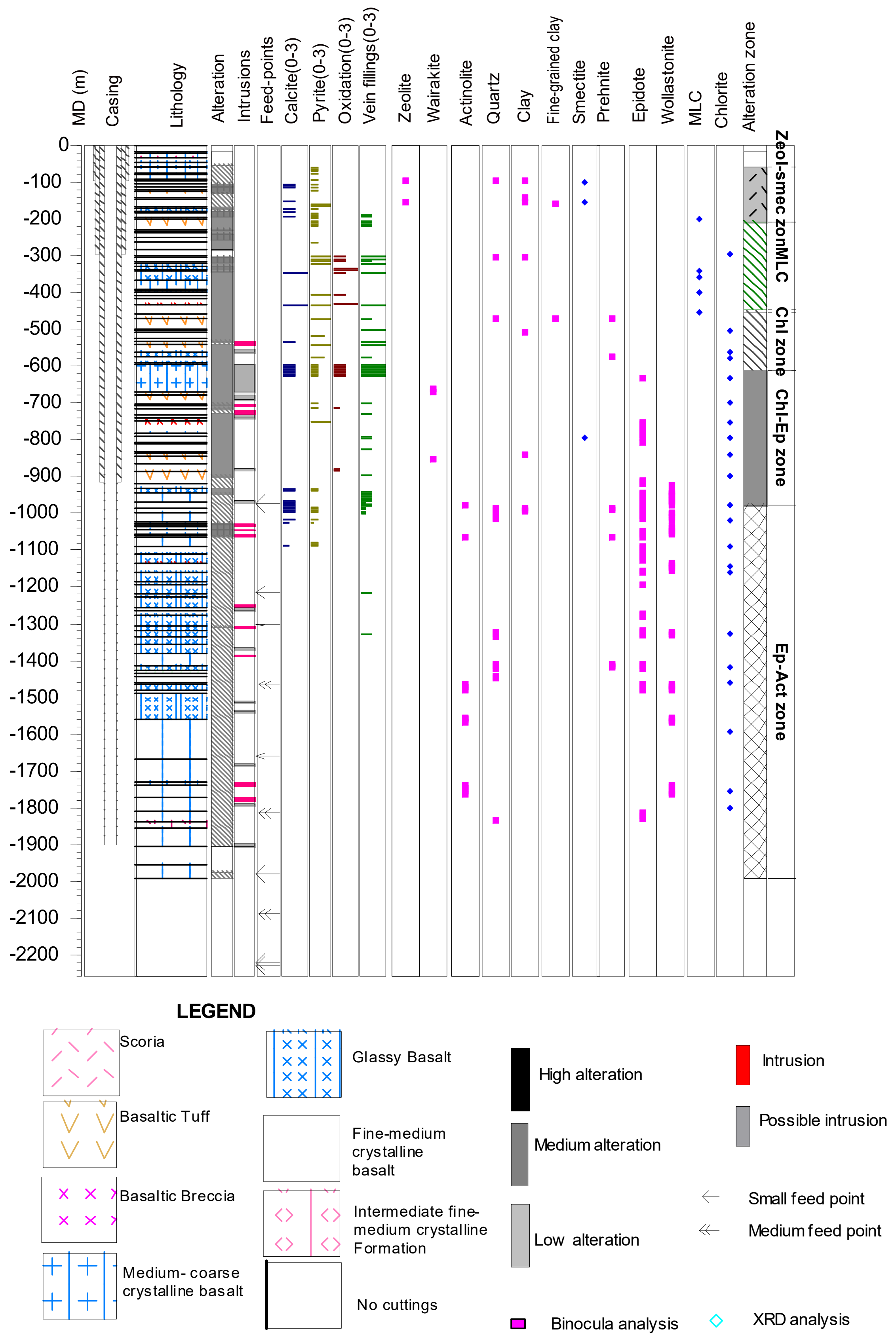


FIGURE 6: Lithology, alteration minerals and alteration zones of ThG-15

*440-600 m. Hyaloclastite tuff.* Mixed fragments of white grey basaltic tuff and breccia, strongly altered. The voids are filled with crystalline clay and quartz, pyrite and calcite.

*600-665 m. Medium- to coarse-grained basalt.* Thick unit that consists of dark green to black medium- to coarse-grained basalt (intrusion). Quartz, calcite and pyrite occur as vein fillings. Epidote occurs at 632 m and wairakite was noted at 660 m depth.

*665-920 m. Hyaloclastite.* The formation is composed of basaltic breccia, tuff and medium- to coarse-grained basalt. The tuff is highly altered and the pores are filled with crystalline clay, calcite and quartz. Feldspar phenocrysts and secondary pyrite crystals are common. A possible fine-grained basaltic intrusion was observed from 680 to 692 m depth. Wairakite was observed at 668 and 850 m. Epidote is abundant. At 914 m about 50% of the fragments hold epidote crystals.

*920-1100 m: Fine- to medium-grained basalt.* This formation is made of mixed fragments from crystalline and glassy basalt, brownish, grey and greenish in colour. It is very dense and non-vesicular. Epidote is abundant. Prehnite, wollastonite and actinolite are common. Calcite and pyrite are present in moderate amounts and disappear at the base of this unit.

*1100-1560 m: Glassy basalt.* Fine-grained and cryptocrystalline basalt. Light grey and brownish in colour. Plagioclase phenocrysts are common. Epidote is abundant from 1278 to 1306 m and 1466 to 1488 m. Mixed greenish and whitish fragments of possible acidic/silicic tuff were noted from 1428 to 1436 m. This unit may be related to the peak in the gamma log observed at about 1450 m.

*1560-1992 m: Fine-grained basalt.* Light-coloured grey to greenish fine-grained and cryptocrystalline basalt with sparse plagioclase porphyritic texture. Actinolite and wollastonite are common. From 1838 to 1854 m the formation is intersected by fine- to medium-grained rocks of intermediate composition which correlate with the anomaly observed in the natural gamma log at about 1825 m. No cuttings were recovered from 1904 to 1954 m and below 1992 m due to total loss of circulation.

## 6.2 Intrusive rocks

Cuttings analyses of well ThG-15 with the aid of a binocular microscope reveal many intrusions and possible intrusions intersected during drilling (Figure 6). Most of the intrusions are dark-grey or light-brown in colour**.** Medium- to coarse-grained intrusive rocks occur between 600 and 655 m, while fine- to medium-grained intrusions were noted from 900 down to 1992 m.

## 6.3 Wire-line logging

The geophysical borehole measurements undertaken in well ThG-15 consisted of a XY caliper log, resistivity log, neutron-neutron (N-N) response (back scattering of thermal neutrons) and natural gamma ($\gamma$). Figure 7 shows the responses of the geophysical logs in relation to the lithology of the well. From 917 down to 1200 m there are no clear anomalies in both the natural gamma radiation log and the neutron-neutron log. The resistivity is generally low and variable in this interval and the formation is composed of basaltic tuff, breccia, glassy basalt and fine-to medium-grained crystalline basalt.

Resistivity increases from 1208 to 1258 m indicating an increase in alteration. High anomalies are observed in the neutron-neutron log from 1240 to 1250 m and from 1250 to 1270 m, indicating responses of basaltic intrusions. This observation fits with the cutting analysis, which identified dense, dark grey coloured, fine-grained basalt intrusions at 1250 and from 1256 to 1266 m.

From 1300 to 1500 m there are no anomalies in both the resistivity and the neutron logs. However, below 1350 m resistivity increases consistently with an increase in the neutron response. A peak

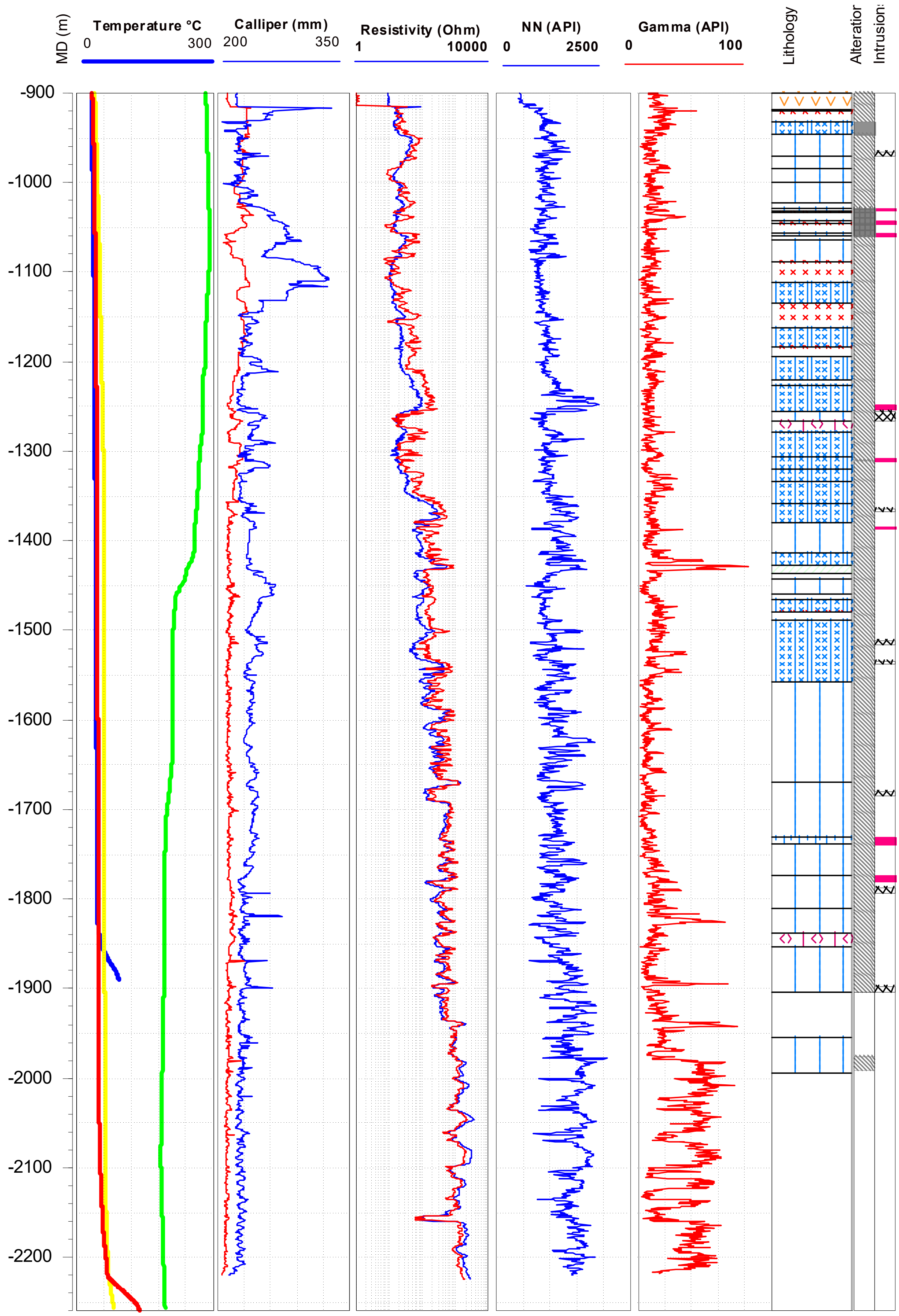


FIGURE 7: Lithology, temperature profiles and geophysical logs of well ThG-15

suggesting the presence of acidic formation is observed in the gamma log at 1450 m. This anomaly correlates with the possible intermediate to silicic tuff formation observed in cuttings from 1428 to 1436 m. From 1500 to 1668 m the resistivity and neutron responses are consistent, representing alternating dense and less dense strata of a few metres thickness.

From 1668 to 1674 m the low gamma radiation and increased resistivity together with a high neutron response indicates a basaltic intrusion. There are no significant anomalies revealed in the resistivity from 1700 to 1900 m, but the log depicts alternating dense and less dense rock layers. The neutron-neutron log portrays the same pattern as the resistivity log in that interval. From 1838 to 1900 m the natural gamma log shows anomalies indicating intermediate to silicic rock formations. The anomalies are not thought to be associated with intrusions as there are no corresponding responses from the resistivity and neutron-neutron logs. At the deepest part of the well from 1980 to 2220 m, the natural gamma log and the neutron-neutron log show increased responses. Resistivity is also relatively high in a similar depth interval. The anomalies in the natural gamma ray log along with anomalies in the neutron-neutron log and resistivity log suggest that the formation is composed of intrusions, most probably of intermediate and silicic composition.

### 6.4 Hydrothermal alterations

Hydrothermal alteration refers to the change in mineralogy, texture, porosity and permeability of rocks when interacting with hot fluids. Basically, hydrothermal alteration constitutes two main components; the replacement of primary minerals in the rocks by alteration and dissolution, and the precipitation of secondary minerals into voids/pores in the rock or as replacement product (Franzson et al., 2008).

In well ThG-15 the primary minerals are olivine, plagioclase, pyroxene, and opaque minerals. These minerals are altered to secondary minerals under certain conditions, particularly in geothermal environments where there is high permeability, elevated temperatures and intense fluid activity.

Olivine is very susceptible to alteration. It is distinguished in thin sections by its high birefringence, distinctive irregular fracture pattern and lack of cleavage. In well ThG-15, olivine is partly altered to clay at 440 m. Plagioclase is the most abundant primary rock mineral in well ThG-15 and occurs as phenocryst and in fine matrix. It is easily identified by its low relief and conspicuous polysynthetic twinnings under a petrographic microscope. Plagioclase is relatively resistant to alteration but starts to alter to clay minerals and, in accordance with increasing temperature, to zeolite, albite, calcite, wairakite, chlorite and epidote. Clinopyroxene is the main pyroxene mineral identified in well ThG-15. In a 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. Fresh clinopyroxene was identified in a thin section at 630 m. Opaques are more resistant to alteration and may be only partially altered to titanite and pyrite.

#### 6.4.1 Alteration minerals in well ThG-15

*Zeolites:* These are hydrous alkali and alkaline-earth aluminium silicates forming in rock cavities during hydrothermal fluid interaction with volcanic glass and plagioclase. Zeolites are classified in three main groups based on their shapes; fibrous/acicular, tabular/prismatic, and granular (Kristmannsdóttir, 1979). In well ThG-15, zeolites were observed at 70, 100 and 154 m depth.

*Quartz:* Secondary quartz forms at temperatures above 180°C (Franzson, 1998). In a binocular microscope, euhedral quartz is distinguished from zeolites by its hexagonal shape and conchoidal fracture. In a thin section, quartz has a low refractive index, a lack of cleavage. In well ThG-15, the first appearance of quartz was noted at 186 m depth.

*Calcite:* Calcite was first noted in cuttings between 58 and 60 m and disappeared below 1100 m depth. It is easily identified in cuttings by the use of hydrochloric acid and in a thin section calcite exhibits clear cleavage and high birefringence.

*Pyrite:* Sulphide mineral that forms when iron-bearing minerals interact with hydrothermal fluids. Pyrite is distinguished by its yellowish cubic crystals, dark coloured in a thin section under crossed nicols. In well ThG-15, pyrite was first noted in cuttings at 60 m depth and it appears throughout the upper 1100 m. The presence of pyrite in a geothermal system indicates good permeability.

*Wairakite:* It is a zeolite mineral that forms at temperatures greater than 200°C (Kristmannsdóttir, 1979). It appears transparent with very low birefringence and is easily recognized by its box-like structures in thin section. In well ThG-15, wairakite was identified in cuttings at 210-310, 630, 660 and 668 m.

*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-15 prehnite was observed at 482 m depth.

*Epidote:* Is an abundant secondary mineral in well ThG-15. Epidote forms at temperatures above 230°C and occurs in vesicles and fractures (Saemundsson and Gunnlaugsson, 2002). In cuttings, epidote crystals are identified by their distinctive yellow to green colouration and strong pleochroism of green and yellow in thin section. Epidote occurs sporadically from 414 to 780 m. The amount of epidote in cuttings increases from 810 to 884 m and becomes abundant below 914 m depth.

*Wollastonite:* Wollastonite 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-15, wollastonite was first identified in cuttings at 924 m and it becomes common below 1002 m.

*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 980 m depth while XRD analysis points out actinolite at 1000, 1144, 1460, 1592 and 1800 m.

*Clay minerals:* These are phyllosilicates that form by the alteration of primary silicate minerals such as plagioclase, pyroxene, olivine and pyroxene. Clay minerals were analysed using a petrographic microscope and XRD analysis. Table 1 indicates 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 100 and 154 m.

*Mixed-layer clay (MLC):* This forms multiple clays filling fractures and voids. XRD and petrographic analyses of the cuttings from well ThG-15 identified mixed-layer clays at 356, 400, 440 and 450 m.

*Chlorite:* Chlorite is a clay mineral that forms at temperature above 230°C (Kristmannsdóttir, 1979). In well ThG-15, chlorite occurs in a wide depth range. It was first identified by XRD analysis at 504 m and occurs throughout down to 1800 m depth.

### 6.4.2 Alteration mineral zonation of well ThG-15

Hydrothermal mineral alteration in active Icelandic geothermal systems has been described in zones with respect to temperature (Figure 8). The sequence of alteration minerals that fill voids and those which replace primary minerals depends on the temperature of the geothermal system (Franzson et al., 2008). For Icelandic geothermal systems, low-temperature zeolites and amorphous silica form below 100°C, chalcedony below 180°C, quartz above 180°C, wairakite above 200°C, epidote above 240°C and garnet and amphiboles above 280°C (Kristmannsdóttir, 1979; Saemundsson and Gunnlaugsson, 2002; Franzson, 1998). Clay minerals like smectite, crystallize below 200°C, mixed-layer clays at 200-230°C and chlorite above 230°C (Kristmannsdóttir, 1977).

Alteration mineral zones in well ThG-15 were defined by considering the appearance of alteration minerals in the well and their dependency temperatures based on the binocular, petrographic and XRD analyses of the cuttings (Table 1).

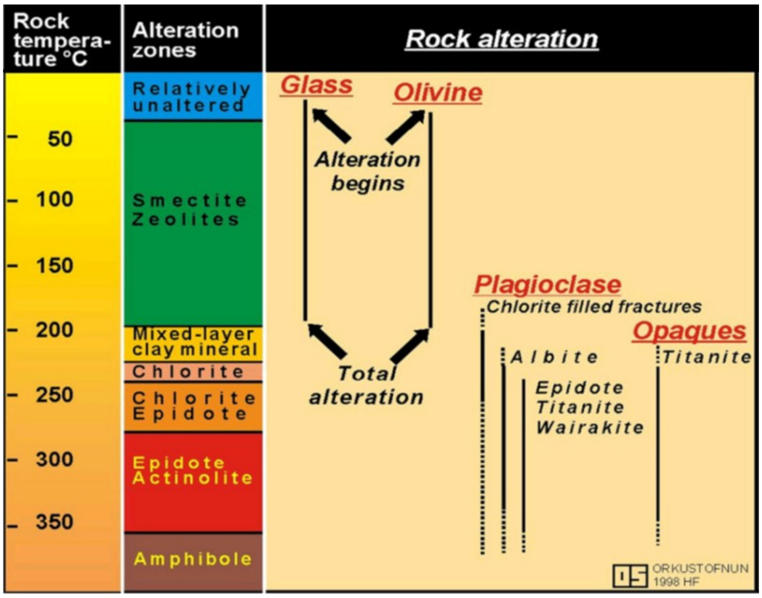


FIGURE 8. Mineral alteration vs. temperature diagram (Franzson, 1998)

TABLE 1: 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) | Type of clay |
|---|---|---|---|---|---|---|
| 1 | 100 | 15.2 | 16.3 | 10.3 | 0 | Smectite, zeolite |
| 2 | 154 | 15.2 | 15.5 | _ | 9.1 | Smectite , zeolite |
| 3 | 200 | 15.2 | 17.2 | 10 | 7.2 | Unstable chlorite, MLC |
| 4 | 250 | 14.8 | 17 | 10 | 7.2 | Unstable chlorite, vermiculite |
| 5 | 298 | 14.8 | 17 | 10 | 7.2 | Chlorite |
| 6 | 356 | 15.5 | 14.9 | 13.2 | 7.3 | Mixed layer clays (MLC) |
| 7 | 400 | 14.5 | 14.5 | 14.5 | 7.2 | Mixed layer clays |
| 8 | 450 | 14.7 | 14.7 | 13 | 7.2 | Mixed layer clays |
| 9 | 504 | 14.8 | 14.8 | 14.8 | 7.2 | Chlorite |
| 10 | 580 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 11 | 632 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 12 | 640 | 14.7 | 17 | 10 | 7.2 | Chlorite |
| 13 | 700 | 14.5 | 14.5 | 10.3 | 7.2 | Chlorite, illite |
| 14 | 750 | 14.7 | 14.7 | 10.4 | 7.2 | Unstable chlorite |
| 15 | 798 | 14.7 | 14.7 | 9.9 | 7.2 | Unstable chlorite, smectite |
| 16 | 840 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 17 | 900 | 14.8 | 14.8 | 14 | 7.2 | Unstable chlorite |
| 18 | 976 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 19 | 1000 | 15.3 | 17.2 | 8.6 | 7.2 | Smectite, actinolite |
| 20 | 1020 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 21 | 1086 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 22 | 1144 | 14.6 | 14.6 | 8.6 | 7.2 | Chlorite, actinolite |
| 23 | 1328 | 14.5 | 14.5 | 14.5 | 7.2 | Chlorite |
| 24 | 1420 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 25 | 1460 | 14.6 | 14.6 | 8.6 | 7.2 | Unstable chlorite, actinolite |
| 26 | 1592 | 14.4 | 14.4 | 8.5 | 7.1 | Unstable chlorite, actinolite |
| 27 | 1756 | 14.7 | 14.7 | 14.7 | 7.2 | Chlorite |
| 28 | 1800 | 14.4 | 14.4 | 8.5 | 7.1 | Unstable chlorite, actinolite |

*Unaltered zone (16-58 m*): This is the top zone which includes relatively fresh rocks which do not indicate any evidence of hydrothermal alteration.

*Zeolite-smectite zone (58-210 m):* This zone is marked by the appearance of zeolite and smectite, which were identified by XRD analysis at 100 and 154 m. Secondary calcite, pyrite and quartz are present in this zone.

*Mixed-layer clay zone (210-445 m):* This zone is characterised by mixed-layer clays forming in voids and fractures at 356, 400, 440 and 445 m.

*Chlorite zone (445-610 m):* This zone is defined by the appearance of chlorite at 504, 580 and 640 m. Prehnite was observed in this zone at 482 m.

*Chlorite-epidote zone (610-978 m):* It is defined by the appearance of epidote and chlorite. Wollastonite appears in this zone at 924.

*Epidote-actinolite zone (978-1992 m):* This zone is defined by the appearance of epidote and actinolite. Chlorite is also common in this zone. In cuttings, actinolite appears at 980 m while in the XRD analysis it was observed at 1000, 1144, 1460, 1592 and 1800 m depth.

### 6.5 Thin section petrography

Petrographic analysis of the cuttings from well ThG-15 involved 10 samples collected at different depth intervals from 98 to 1582 m (Table 2). Thin sections were analysed using an Olympus petrographic microscope at ÍSOR head office in Reykjavik. The objective of the examination 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 plagioclase, clinopyroxene, olivine and opaque minerals. Plagioclase is the most abundant primary mineral in well ThG-15 (Table 2). It occurs both in

TABLE 2. Results of the thin section petrography

| Depth (m) | Rock type | Primary minerals | Secondary minerals | Comments |
|---|---|---|---|---|
| 98 | Fine-grained basaltic tuff | Pl, OP | Cal, Py and zeolite | Highly altered tuff |
| 212 | Basaltic tuff | Pl, OP | Py, Qz | Highly altered tuff |
| 440 | Fine-grained basalt | Pl, Ol | Py, Cal, clay | The rock is highly altered |
| 630 | Medium-grained basalt breccia | Pl, Ol, Cpx | Wrk, clay, Qz, Cal | Plagioclase highly altered |
| 762 | Fine- to medium-grained basalt | Qz, Pl | Clay | Fine-grained basalt fragments |
| 902 | Fine-grained crystalline basalt | Pl, Ol | Cal, clay, | The rock is highly altered |
| 1002 | Fine- to medium-grained basalt | Pl, OP | Qz, Wo | Porphyritic texture |
| 1120 | Glassy basalt | Pl | Qz, Ep, Act | Probably a pillow lava |
| 1338 | Glassy basalt | Pl, Ol, OP | Cal, Act | Dense and non-porous |
| 1582 | Fine- to medium-grained basalt | Pl | Epidote, calcite, actinolite | Dense and non-porous |
| Qz: quartz; Pl: plagioclase; Ol: olivine; Cpx: clinopyroxene; Chl: chlorite; OP: opaque minerals, Act: actinolite, Cal: calcite, Ep: epidote, Py: pyrite, Qz: quartz, Wo: wollastonite, Wrk: wairakite | | | | |

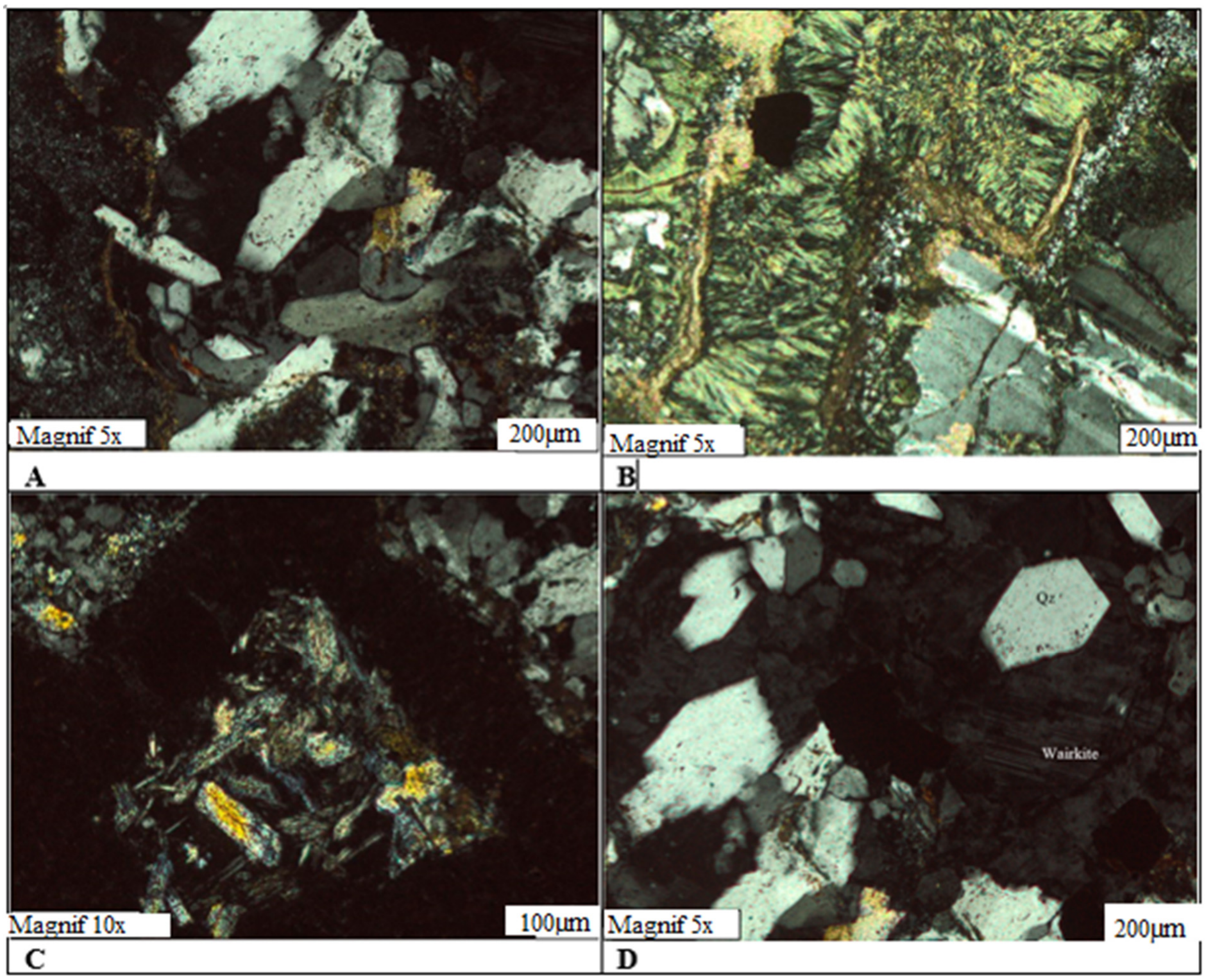


FIGURE 9: Thin-section microphotographs showing alteration minerals;
A: Quartz crystals in vesicle at 440 m; B: Clay and epidote filling void at 630 m;
C: Wollastonite and epidote at 1002 m; D: Quartz and wairakite at 440 m

groundmass as well as phenocrysts in fine- to medium-grained crystalline basaltic rocks. Secondary minerals identified in thin sections are quartz, wairakite, calcite, epidote, wollastonite and actinolite. Figure 9 shows microphotographs of secondary alteration minerals observed at 440, 630 and 1002 m depth.

## 7. FEED ZONES

Feed zones (aquifers) are horizons that are sufficiently permeable to yield significant quantities of water to wells and springs. Aquifer simply implies 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 governs the movement of ground water. The pores, voids and interstices 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 target 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).

Feed zones in well ThG-15 were noticed due to circulation losses and temperature logs during drilling (Figure 9). All the feed zones are considered small to moderate in relation to their sizes (Sigurgeirsson et al., 2017a). Small feed zones which are constrained by lithological boundaries were observed between 950 and 1000 m, 1200 and 1230 m, and at 1300 m depth. The most permeable feed zones in the well, evidenced by high circulation losses and a decline in the temperature profile, were encountered at 1455-1475, 1800-1830 and at 2090 m depth (Sigurgeirsson et al., 2017a).

## 8. DISCUSSION

The stratigraphy of well ThG-15 is characterized by lava flows, intercalated with scoria and reworked tuff in the upper 114 m. The lava flow is underlined by hyaloclastite units (breccia, tuff and glassy basalt,) down to 920 m. From 920 to 1992 m the formation is mainly glassy and fine- to medium-grained crystalline basalt. The hyaloclastite formation is cut by a thick unit of medium- to coarse-grained basaltic intrusive rocks between 600 and 655 m and many other intrusions and possible intrusions intersect the fine-grained crystalline basalt below 920 m. However, the geophysical logs (natural gamma and the neutron- neutron log) show increased responses at the deepest part of the well from 1980 to 2220 m, suggesting that the formation is composed of intrusions most likely of intermediate and silicic composition.

In comparison with the two wells (ThG-9 and ThG-11) drilled on the same well pad, the lithology of well ThG-15 corresponds with their lithological units in the upper 900 m. Similar succession of lava flows and hyaloclastite rocks appear in the three wells and several intrusive rocks intersected indicate similarities (Poux et al., 2017). Wells ThG-9, ThG-11 and ThG-15 do not show good correlation below 900 m. The hyaloclastites dominate from 900 to 2200 m in ThG-9 and ThG-11 while ThG-15 is composed of glassy and fine- to medium-grained basalt in that interval. The observed lithological differences in these intervals could be due to the different orientations of the wells, since ThG-9 is vertical, ThG-11 trends south and ThG-15 southwest and as the depth increases the lateral distance between them increases (Sigurgeirsson et al., 2017a).

Hydrothermal alteration minerals of well ThG-15 have been studied and provide significant insight regarding the temperature, permeability and thermal evolution of the geothermal system. The occurrence of temperature dependent alteration minerals such as zeolite, quartz, epidote, chlorite, prehnite, wollastonite and actinolite allow the establishment of a temperature curve for comparison with the measured temperature logs of the well (Figure 10).

Measured temperature logs indicate that the geothermal system follows the boiling point curve (BPC) in the upper 1000 m. Alteration temperatures seem to be in good correlation with the temperature profile, suggesting that the geothermal system is in equilibrium at shallow depth. However, a temperature reversal occurs below 1000 m. The decline in measured temperature reflects a cooling of the geothermal system in the lower section, possibly due to influx of cold water through highly permeable zones and/or fractures intersected in the lower section of the well.

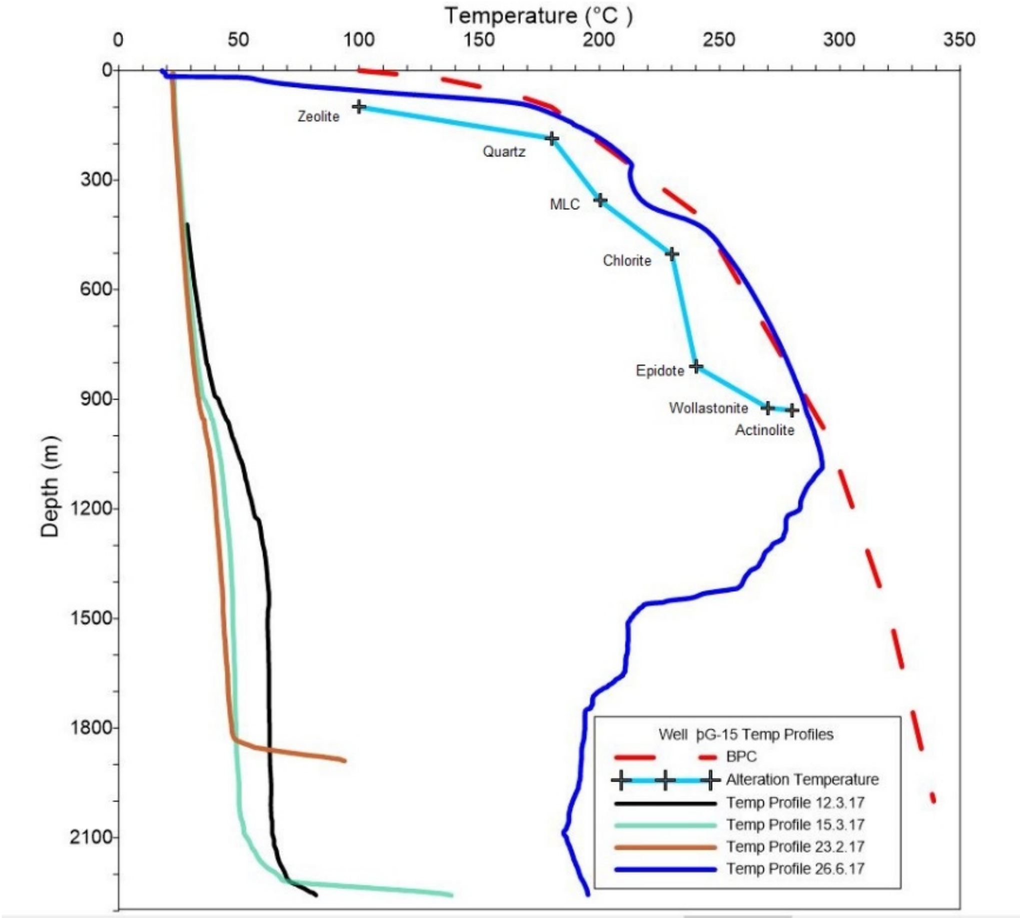


FIGURE 10: Temperature profile, boiling point curve and alteration temperature of well ThG-15

## 9. CONCLUSION

Based on the results of the borehole study of well ThG-15, the following can be concluded:

- The stratigraphy of well ThG-15 is composed of lava flows, a hyaloclastite formation (breccia, tuff and glassy basalt) and fine-to medium grained crystalline basalt. In the deepest part, where no cuttings were recovered, the formation seems to be composed of intrusive rocks most likely of intermediate and silicic composition.

- Six alteration zones of well ThG-15 were identified, based on hydrothermal mineral deposition sequences. These zones are: unaltered zone (16-58 m), zeolite-smectite zone (58-210 m), mixed-layer clay zone (210 to 445), chlorite zone (445-610 m), chlorite-epidote zone (610-978 m) and epidote-actinolite zone (978-1992 m).

- Well ThG-15 has moderate permeability. The major permeable feed zones located at 1455-1475, 1800-1830 and at 2090 m are associated with circulation losses and measured temperature logs during drilling.

- Well ThG-15 has high temperature above 1000 m. Alteration temperatures show good correlation with the measured temperature suggesting that the geothermal system is in equilibrium, but it experiences cooling below 1000 m, probably due to inflow of cold water from the feed zones/fractures in the lower section of the well.

**ACKNOWLEDGEMENTS**

I would like to acknowledge the United Nation University Geothermal Training Programme (UNU-GTP) Director, Mr. Lúdvík S. Georgsson and his Deputy, Mr. Ingimar G. Haraldsson for the opportunity to participate in the 6-month geothermal training in Iceland. I extend my thanks to Ms. Thórhildur Ísberg, Ms. Málfrídur Ómarsdóttir and Mr. Markús A.G. Wilde for their services during the training.

I thank my supervisors, Dr. Tobias B. Weisenberger, Ms. Helga Margrét Helgadóttir and Ms. Sylvia Rakel Gudjónsdóttir for their guidance and critical discussion on various aspects of this project. Ms. Anette K. Mortensen and Mr. Sigurdur Sveinn Jónsson are thanked for their technical assistance during laboratory analysis. I appreciate the knowledge sharing from all lecturers during the training.

Many thanks go to the Government of United Republic of Tanzania and particularly my employer TGDC for granting me the chance to attend this training programme.

Special thanks go to my family and friends for their endurance, encouragement and prayers during my stay in Iceland. God bless you abundantly.

**REFERENCES**

Ármannsson, H., Gíslason, G. and Torfason, H., 1986: Surface exploration of the Theistareykir high-temperature geothermal area, Iceland, with special reference to the application of geochemical methods. *Appl. Geochem., 1*, 47-64.

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

Darling, W.G., and Ármannsson, H., 1989: Stable isotope aspects of fluid flow in the Krafla, Námafjall and Theistareykir geothermal systems of northeast Iceland. *Chem. Geol., 76,* 197-213.

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

Franzson, H., Zierenberg, R., and Schiffman, P., 2008: Chemical transport in geothermal systems in Iceland. Evidence from hydrothermal alteration, *J. Volcanol. Geotherm. Res., 173*, 217-229.

Gautason, B., Gudmundsson, Á., Hjartarson, H., Blischke, A., Mortensen, A.K., Ingimarsdóttir, A., Gunnarsson, H.S., Sigurgeirsson, M.Á., Árnadóttir, S., and Egilson, Th., 2010: Exploration drilling in the Theistareykir high-temperature field, NE-Iceland: Stratigraphy, alteration and its relationship to temperature structure. *Proceedings of the World Geothermal Congress 2010*, *Bali, Indonesia*, 5 pp.

Gíslason, G., Johnsen, G.V., Ármannsson, H., Torfason, H., and Árnason, K., 1984: *Theistareykir. Surface exploration of the high-temperature geothermal area*. Orkustofnun, Reykjavík, report OS84089/JHD16 (in Icelandic), 134 pp.

Grönvold, K. and Karlsdóttir, R., 1975: *Theistareykir. An interim report on the surface exploration of the geothermal area* (In Icelandic). Orkustofnun JHD-7501, 37 pp.

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

Icelandic Drilling Co., 1951: *Chemical analyses in hot springs and warm springs*. Icelandic Drilling Co., Reykjavík, report, 88 pp.

Jakobsson, S.P., Jónasson, K., and Sigurdsson, I.A., 2008: The three igneous rock series of Iceland. *Jökull, 58,* 117-138.

Jóhannesson H., and Saemundsson, K., 1999: Geological map 1:1.000.000, Icelandic Institute of Natural History.

Kahwa, E., 2015. Geophysical exploration of high temperature geothermal areas using resistivity methods. Case study: Theistareykir area, NE-Iceland. *Proceedings of the World Geothermal Congress 2015 Melbourne, Australia*, 11 pp.

Karlsdóttir, R., Eysteinsson, H., Magnússon, I.Th., Árnason, K, and Kaldal, I., 2006: *TEM soundings at Theistareykir and Gjástykki 2004-2006* (in Icelandic). ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2006/028, 88 pp.

Karlsdóttir, R., and Vilhjálmsson, A.M., 2011: *MT and TEM measurements at Theistareykir in 2009.* ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2011/002 (in Icelandic), 62 pp.

Khodayar, M., Kristinsson, S.G., and Karlsdóttir, R., 2016: *Structural drilling targets from platforms A, B, and F at Theistareykir. Northern Rift Zone and Tjörnes Fracture Zone*. ÍSOR – Iceland GeoSurvey, Reykjavík, report, ÍSOR-2016/030, 24 pp.

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

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

Magnúsdóttir. S., and Brandsdóttir, B., 2011: Tectonics of the Theistareykir fissure swarm. *Jökull, 61,* 65-80.

McDougall, I., Kristjánsson, L., and Saemundsson, K., 1984: Magnetostratigraphy and geochronology of northwest Iceland. *J. Geophys. Res., 89(B8),* 7029-7060.

Mortensen, A.K., 2012: *Theistareykir. Recommendations on locations of drillholes in the Theistareykir geothermal field.* ÍSOR - Iceland GeoSurvey, Reykjavík, report ÍSOR-2012/043 (in Icelandic), 36 pp.

Poux, B., Haraldsdóttir, S.H., Tryggvason, H., Gunnarsson, B.S., and Vilhjálmsson S., 2017: *Theistareykir - Well ThG-15. Phase 2: Drilling for production casing down to 920 m.* ÍSOR - Iceland GeoSurvey, report, ÍSOR-2017/015 (in Icelandic), 88 pp.

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

Saemundsson, K., 1978: Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. *Geol. J., Sp. issue, 10,* 415-432.

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

Saaemundsson, K., 1992: Geology of the Thingvallavatn area. *Oikos, 64,* 40-68.

Saemundsson K., 2007: Geology of the Theistareykir area. ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-07270 (report in Icelandic), 23 pp.

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

Sigurgeirsson, M.Á., Ásgeirsdóttir, R.S., Tryggvason, H.H., and Stefánsson, H.Ö., 2017b: *Theistareykir - Well ThG-15. Phases 0 and 1: Drilling for surface casing down to 100 m and anchor casing down to 300 m*. ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2017/014 (in Icelandic), 83 pp.

Sigurgeirsson, M.Á., Gudjónsdóttir, S.R., Ásgeirsdóttir, R.S., Tryggvason, H.H., Egilson, Th., Gudmundsdóttir, V., Gunnarsson, B.S., Vilhjálmsson, S., Ingimarsson, H., Pétursson, F., and Ingólfsson, H., 2017a: *Theistareykir - Well ThG-15. Phase 3: Drilling for a 7" perforated liner down to 2260 m* ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2017/036 (in Icelandic), 162 pp.

Trönnes, R. G., 2002: *Geology and geodynamics of Iceland*. Nordic Volcanological Institute, University of Iceland, 1–19.

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