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STRUCTURAL MAPPING AND SUBSURFACE GEOLOGY COMPARED TO THERMAL GRADIENT AND THE GEOTHERMAL SYSTEM IN MÖDRUVELLIR, SW ICELAND

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ABSTRACT

The Mödruvellir geothermal field is a low-temperature geothermal resource located in southwest Iceland. Exploration in this region started in 1978 by drilling shallow gradient wells and using them for temperature measurements. At present there are two production wells and 22 gradient wells in the area. This study is based on an investigation of the surface geology, analyses of gradient well data and subsurface geology. Stratigraphical units in this area belong to the sequences of Late Tertiary to early Quaternary and approximately 480 m of basalt with intercalations of hyaloclastites are exposed in this area. Several faults and fractures were plotted on geological map. These faults have two main trends, NE-SW and ENE-WSW, some were observed and measured in the field while others were deduced from examination of aerial photographs. The geothermal gradient method was applied to locate a geothermal anomaly and a thermal map showing temperatures at 50 m depth in the gradient wells revealed two anomalies that are related to a local structural pattern in this area. Five different temperature zones were revealed on the local geothermal gradient map, the highest temperature zone on the map was within the highest gradient zone. Subsurface geology in this area was based on an analysis of drill cutting samples of two vertical wells, and the main rock types that comprise the subsurface geology of the studied wells were basaltic lavas and minor hyaloclastites. Correlation between subsurface lithological unites showed that displacement of these units are related to the normal dip of topography in this area. Based on this study the first conceptual model for the Mödruvellir low-temperature geothermal system is proposed.

1. INTRODUCTION

Geothermal energy constitutes one of the most important natural resources in Iceland and has been extensively harnessed, particularly for house heating, but also for greenhouses, farming, power generation and various industries (Gudmundsson and Pálmason, 1987; Arnórsson, 1991). Bödvarsson (1961) classified geothermal areas in Iceland as either high- or low-temperature areas. The high temperature areas are located within the active volcanic zones of Iceland but geothermal activity of low

FIGURE 1: Location of study area

temperature, which is defined by reservoir temperatures ranging from just above ambient to about 150°C, is widely distributed in Quaternary and Tertiary formations (Arnórsson, 1995a). In the Hvalfjördur area in SW Iceland, several low-temperature fields have been located, one of which is in Mödruvellir to the northeast of Mt. Esja (Figure 1). There are two production wells and 22 gradient wells in this area. This study combines detailed field data on the faults and dykes, an interpretation of a geothermal gradient map and borehole geology of wells MV-19 and MV-24 in the Mödruvellir low-temperature field. This paper is submitted as a requirement for the partial fulfilment and attainment of a six-month postgraduate course on geothermal geology at the United Nation University Geothermal Training Programme (UNU-GTP) in the period between May and October 2015.

1.1 Previous work

The first comprehensive study of the geology of the area was done by Fridleifsson (1973). This research included the petrology and structural geology of Mt. Esja in SW Iceland (Figure 1), and a regional geological map of the area on the scale 1: 25,000 was republished by Orkustofnun after mapping by Fridleifsson (1973). There are no surface manifestations of geothermal activity in the region. However, drilling resulted in the discovery of an 80°C hot geothermal reservoir in Hvalfjördur. The anomaly is N-S elongated suggesting that the hot aquifer is related to a fractured zone in this area. The anomaly was defined on the basis of 60 m deep boreholes. Kristinsson, (2009) studied the stratigraphy, tectonics and alteration of the Hvalfjördur central volcano, and divided this central volcano into three major units. The oldest one is the western part of the volcano made of tholeiite lavas and some rhyolite, and this part is crosscut with dykes and mainly cone sheets. A middle unit is more complex with thick basalt lavas, hyaloclastites and rhyolite lavas. The youngest unit is the caldera filling with 150 to 200 m thick sediments, hyaloclastites and some lava. Other studies have also been completed about the surrounding study area. Kristjánsson et al., (1980) worked on the stratigraphy and paleomagnetism of Esja, Eyrarfjall and Akrafjall mountains, SW Iceland. Weisenberger and Selbekk (2007) studied multi-stage zeolite facies mineralization in the Hvalfjördur area. Tibaldi et al., (2008) investigated strike-slip fault tectonics and the emplacement of sheet laccolith systems in Thverfell area. The last effort in the exploration of the geothermal resource in this area was the drilling of two deep wells, MV-19 in 2011 and MV-24 in 2014.

1.2 Location of study area and accessibility

The Mödruvellir area is located about 40 km NE of Iceland's capital Reykjavik, sitting behind the Esja Mountain. The area is accessed by road from Reykjavik as shown in Figure 1.

2. GEOLOGICAL SETTING

2.1 Iceland

Iceland is located in the North Atlantic Ocean at 63°23´N to 66°30´N. It is believed to have been built from the interaction of a mantle plume with the north Atlantic divergent plate boundary (Schilling, 1973; Gudmundsson, 2000; Jacoby and Gudmundsson, 2007). The mid Atlantic ridge defines the constructive plate boundary between the American and Eurasian plates and from magnetic anomalies to the north and south of Iceland, the spreading rate has been estimated as 2 cm/year. This region is known as the Icelandic basalt plateau, which rises more than 3000 m above the surrounding ocean floor and covers about 350,000 km^2 of which 103,000 km^2 is above sea level (Thórdarson and Höskuldsson, 2002). The stratigraphical succession of Iceland spans three geological periods, that of late Tertiary (Miocene and Pliocene), the Quaternary or Pleistocene and the Holocene (Figure 2).

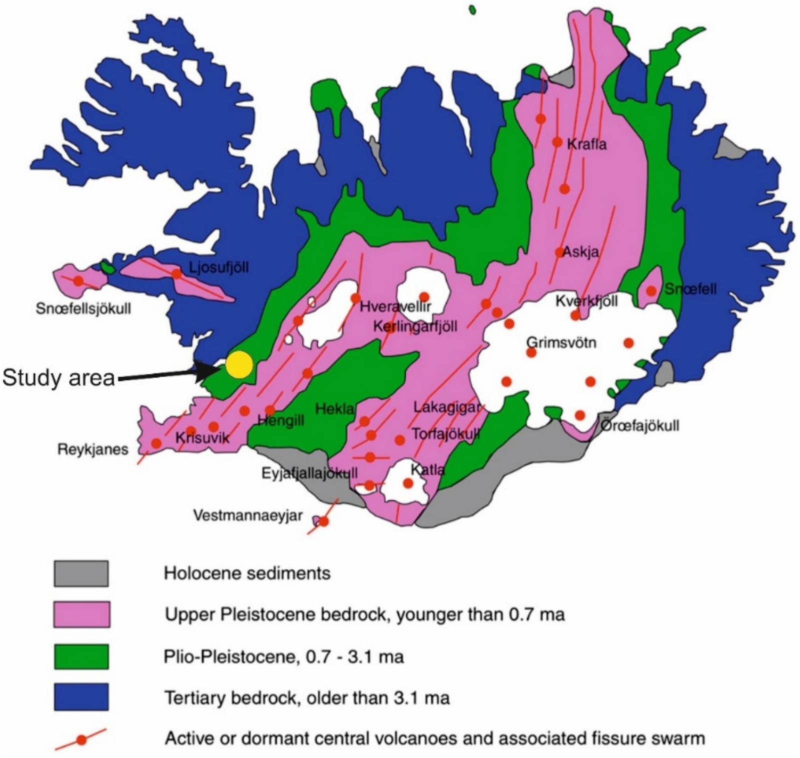

FIGURE 2: Bedrocks of Iceland and distribution of central volcanic systems (Thórdarson and Höskuldsson, 2002)

Geothermal areas in Iceland are divided into two main groups, high-temperature and low-temperature areas. The high temperature areas are found only within the area of active volcanism within the rift zones and are usually ascribed to intrusive activity at high levels within the upper crust (Flóvenz and Saemundsson, 1993). Geothermal activity of low-temperature type, which is defined by reservoir temperature ranging from just above ambient to about 150 °C, is widely distributed in Quaternary and Tertiary formations west of the belts of active volcanism and rifting in Iceland. They are located on the American plate east of these belts, (Arnórsson, 1995b).

2.2 Geology of study area

The study area Mödruvellir is in the Hvalfjördur region. Hvalfjördur belongs to a sequence of late Tertiary to early Quaternary flood basalts with a minor interlayer of hyaloclastites and rhyolites (Figure 3). Rock formations from the Hvalfjördur central volcano can be seen on both sides of the fjord. They are from the Gauss magnetic polarity epoch (3.1-2.4 Ma), and represent the time from Mammoth paleomagnetic event to the Gauss/Matuyama boundary, about 600-700,000 years. The local dip of the lava pile in the area is 5-10°C at the coast.

The Hvalfjördur central volcano can be divided into three major units (Kristinsson, 2009). The oldest one is the western part of the volcano made of tholeiite lavas and some rhyolite. In this part the alteration is high, with chlorite/epidote facies on the coast. This western part is crosscut with dykes, mainly cone sheets with NE-SW strike and a 25-40° dip.

The middle unit is more complex, with thick basalt lavas, hyaloclastites and rhyolite lavas. Rocks in this unit dip over 20° in some parts to the south but mainly dip to the southeast. Alteration is less prominent, quartz/laumontite, at the coast. There are basaltic intrusions (dolerite) and three diamictite and/or hyaloclastite units within the middle part. The middle part represents the caldera of the central volcano. The calderas are two, the western rim of the larger one is defined at the Hrafnabjörg intrusion

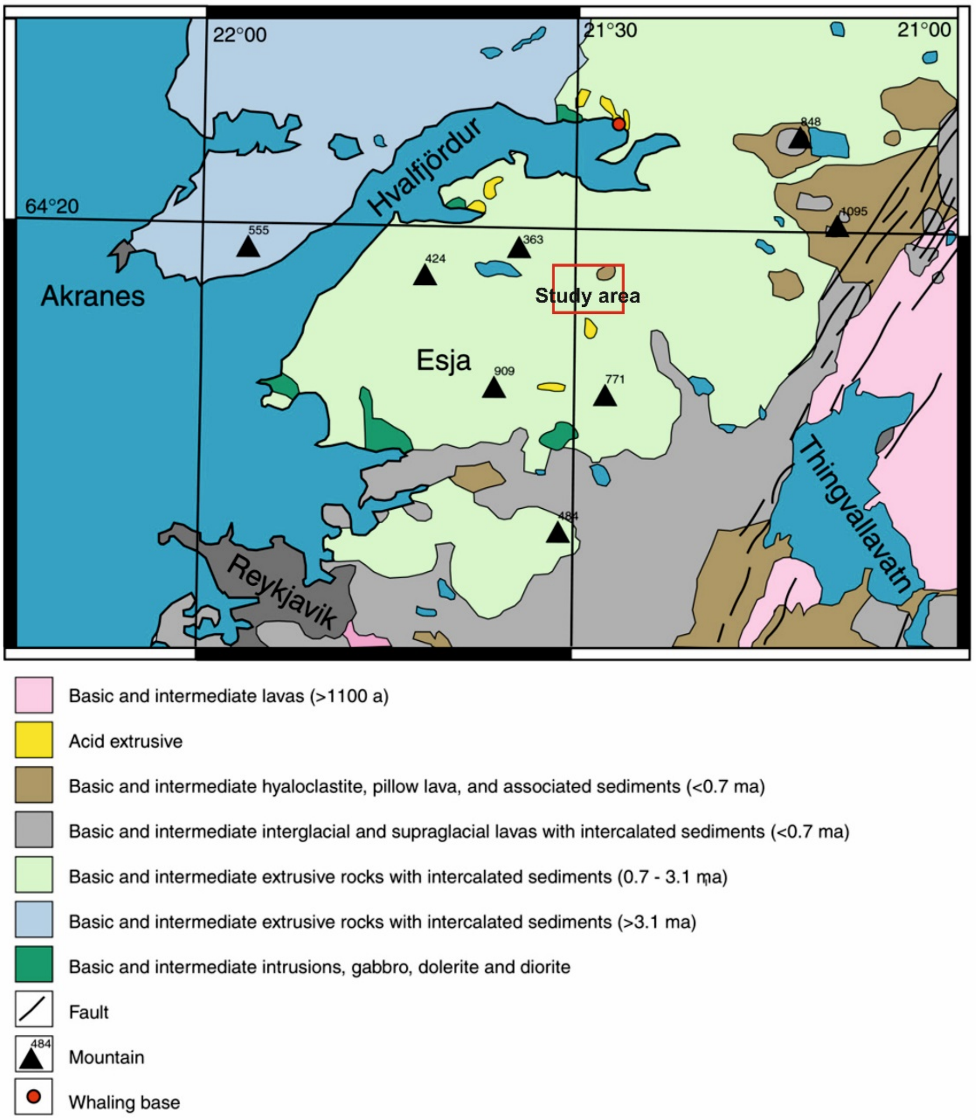

FIGURE 3: Geology map of Hvalfjördur area (Weisenberger, 2005)

and the eastern rim near Bláskeggsá. The smaller caldera is within the other, the western rim is the same but the brittle structures and tilting of the strata up of Stapi mark the eastern rim. The youngest unit is the caldera filling with 150-200 m thick sediments, hyaloclastites and some lavas (Kristinsson, 2009).

The basalt is affected by low-temperature zeolite facies alteration, caused by the burial of the lava succession and a higher heat flow influenced by the Hvalfjördur central volcano. The high alteration represents the garnet-epidote field. The coast from Hálshólar at the Hvammsvík peninsula is altered with chlorite and laumontite. The northern coast from Saurbær to Hrafnabjörg has the same alteration except from a local epidote-granat zone near Ferstikla (Kristinsson, 2009).

The low-temperature zeolite facies in the basaltic lavas in Thyrill and Midfell at the western and eastern sides of the volcano represents the mesolite-scolecite zeolite zone (Walker, 1960). That indicates that nearly 1 km has been eroded off the lava pile.

The Esja mountain (Figure 1) is located between the western rift zone and Tertiary basalts NW of the rift. This transitional zone incorporates a succession of basaltic lava flows and hyaloclastites (Fridleifsson, 1973), known as the Plio-Pleistocene formation on the geological map of Iceland by Jóhannesson and Saemundsson (1998). These lava units, totalling a thickness of 1300 m and comprising the core of the Esja, were erupted 2.8, 2.0 and 1.7 Ma ago (Thórdarsson and Höskuldsson, 2002) from the Thverfell, Midsandur and Stardalur magmatic complexes (Villemin et al, 1994). When the volcanic activity ceased, the Esja was dissected by glacial erosion, which exposed the inner structure of three magmatic complexes (mainly doleritic intrusions).

The latest and most detailed map of the Esja (Fridleifsson, 1973) depicts a doleritic body surrounded by lavas and hyaloclastites. These lavas and hyaloclastites succession is associated with the Thverfell and Stardalur complexes and is locally intruded by inclined sheets, some of which were already mapped by Fridleifsson (1973). The structure features of the area were first described by Fridleifsson (1973) and later in more detail by Villemin et al, (1994). Both reported NE to NNE striking normal faults and dykes and Villemin et al, (1994) reported the occurrence of transcurrent faults in the area but noted their minor importance relative to normal faults.

The succession of volcanic rocks becomes generally older to the northwest, away from the NNE- striking Thingvellir central graben (Saemundsson, 1992) (Figure 3). The lake Thingvallavatn lies in the recent graben system, with historic subaerial basaltic products surrounded by table mountains comprising hyaloclastites and pillow-lavas that were formed under subglacial conditions (Saemundsson, 1992). The bedrock of Esja Mountain and of the southern and north eastern Hvalfjördur area rocks are of Plio-Pleistocene age (0.7-3.1 Ma). The Plio-Pleistocene sequence is formed of alternating successions of lava flows, hyaloclastite and glacial deposits (Saemundsson and Einarsson, 1980; Saemundsson, 1992).

Fridleifsson (1973) descripted the stratigraphy and chronology succession in Esja. He divided the rocks into 26 units, some of these units are located in the research area.

2.3 Eruption history

Volcanism was active in the Esja region for just over one million years and during this time span, at least ten glaciations occurred in the region (Fridleifsson, 1973). The stratigraphy succession is therefore, characterised by a sequence of lava flows intersected with thick subglacial hyaloclastite units. Two central volcanos were active in the Esja region; the Kjalarnes volcano for about 0.6 million years which was succeeded after a short interval by the Stardalur volcano, which remained active for about 0.3 million years. Flood basalt volcanism was concomitant with the central volcanism and most of the olivine tholeiites are considered to have been erupted in fissures and shield volcanoes unrelated to the central volcanoes (Fridleifsson, 1973).

3. GEOLOGICAL AND GEOTHERMAL MAPPING

Mapping of geothermal manifestations, structures and hydrothermal alteration is an essential part of any geothermal survey. Geological mapping helps to define many important parameters which control the flow of hydrothermal fluids, such as rock types, alteration, strike and dip of rock formations and the location of faults, fractures and dykes (Saemundsson and Einarsson, 1980). Surface activity in low-temperature geothermal areas in Iceland is distinctly different from that of the high temperature areas. Sometimes low-temperature activity in an area is represented by a single, isolated thermal spring, although clusters of springs forming a field or an area are also a common feature, Arnórsson (1995b). During this research the published geology map of the study area (scale 1:25,000, Hjartarson and Kristinsson, 2007) and aerial photographs were used to study the geology.

The research area has no surface manifestations and geothermal exploration was carried out by measuring temperatures in shallow drill holes (gradient wells), which have been drilled in this area. Geothermal mapping, including mapping of the main structures like faults, fractures and dykes, was carried out in the Mödruvellir area.

3.1 Stratigraphical units

The study area is about 4 km long and 3 km wide and includes the superficial deposits on the flats and lava flows, and hyaloclastite formations in two flanks (Figure 4). Stratigraphical units in this area belong to the sequences of Late Tertiary to early Quaternary and exposed in this area are approximately 480 m of basalt with intercalations of hyaloclastites. The volcanic succession dips towards the southeast.

Stratigraphic units in this area are divided into four major units, these units are described below (Fridleifsson, 1973):

Unit mf8: Olivine tholeiite lavas: Fine grained olivine tholeiite lavas spread over the region. The unit thickness in this area is about 100 m and most of the lavas here are of olivine tholeiite.

Unit mf9: Tholeiite lavas: The olivine tholeiites of unit mf8 are capped by a few tholeiite lavas, which, because of their higher resistance to erosion, form escarpments. In this region the thickness of unit mf9 is about 60 - 100 m.

Unit mf10: Basaltic hyaloclastite, 50 to 100 m thick. During the glaciation that followed the extrusion of lava unites mf8 and mf9, the volcanism was most active in this region and gave rise to a rugged hyaloclastite mountain. In this area the unit consist of tuffaceous hyaloclastite and breccia.

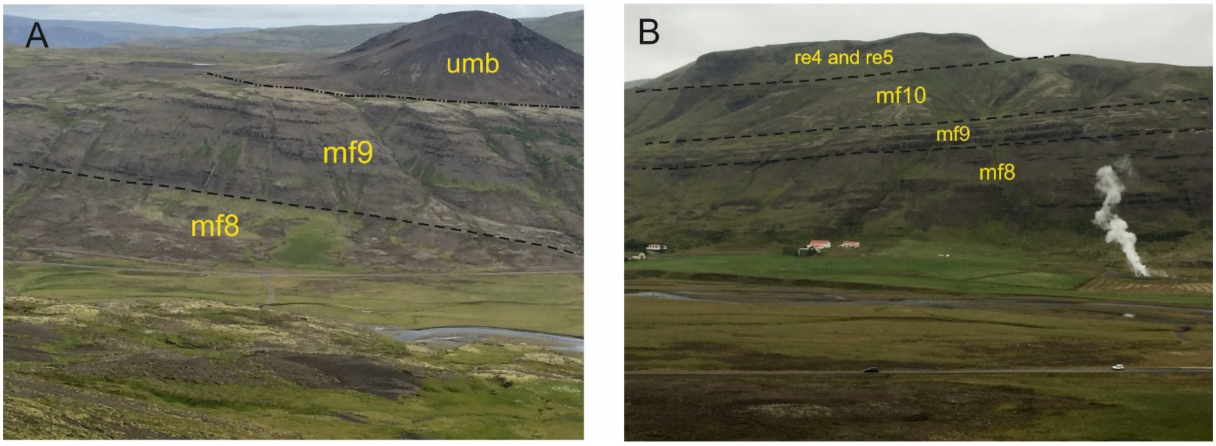

FIGURE 4: Sequences of lava flow and hyaloclastite unite in Mödruvellir geothermal area.
A: North eastern flank, B: South western flank

Unit ref4: Tholeite lava: this unit has a small outcrop in the upper part of the south western flank of the study area. The thickness of this unit is about 50 m.

Other minor units are shown on the geology map. The central part of the study area is covered by superficial sediments (unit lj). This unit consists of sedimentary rocks like clay, silt, sand and gravel that were transported by streams and deposited on the flats. Sandfell Mountain in the north eastern part of the study area is made of hyaloclastite (unit umb) and was deposited on top of the eroded surface, forming an unconformity. This unit is formed of younger hyaloclastite and was formed by feeder dykes that cut the oldest units and reached Sandfell Mountain (Figure 5A and 5C).

There are several scoria layers at the boundaries between lava flows, containing numerous vesicles and many type of zeolites (Figure 5B). Soil horizons and sedimentary layers are often deposited in scoria parts.

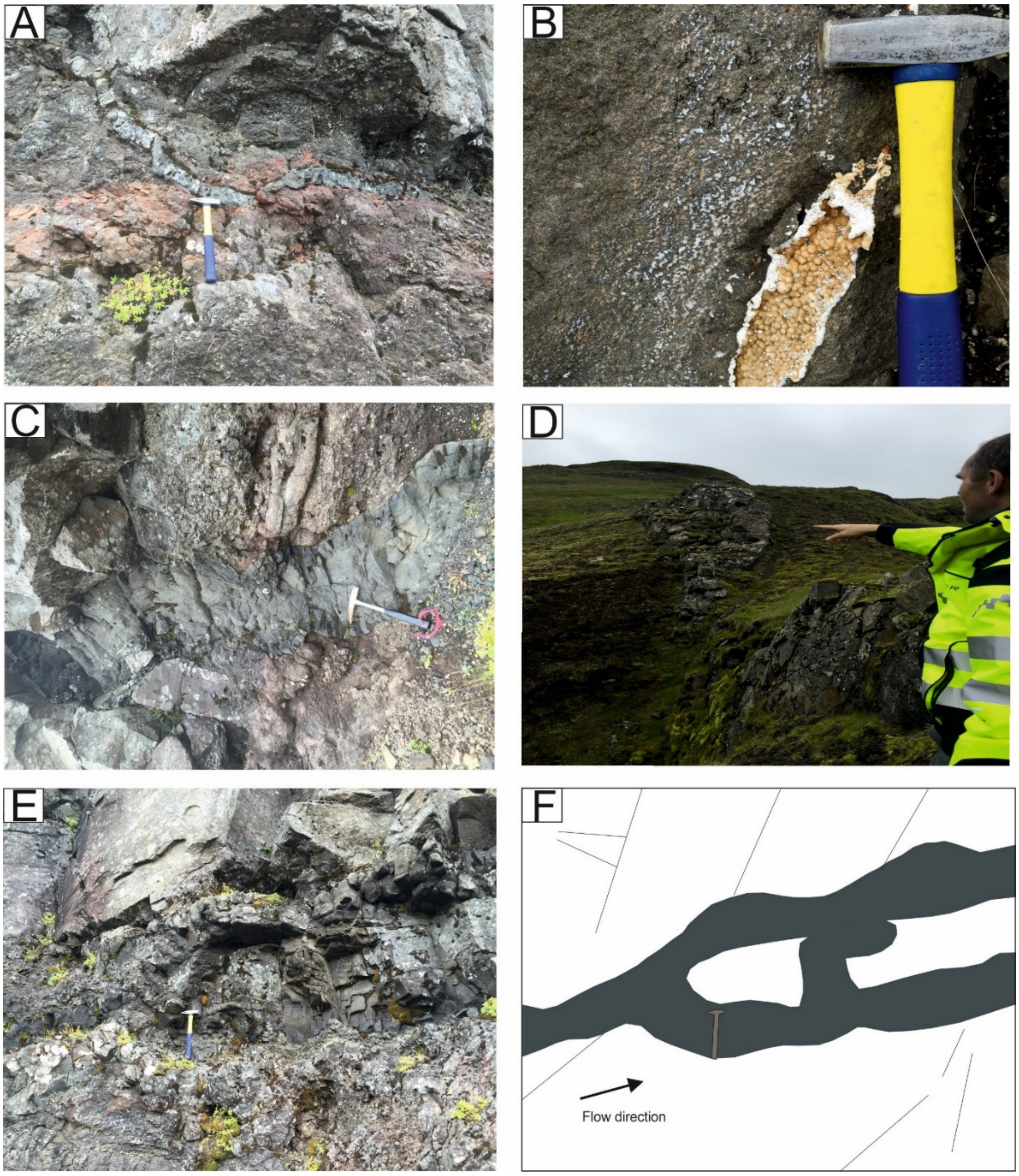

FIGURE 5: Field observations, A: scoria between lava flows, B: Zeolites in vesicle part of lava flow, C: Vesicular dyke, D: Big dyke in the south eastern part of the area, E and F: Photograph and interpretation illustrating the strike of the veins and direction of a thin sheet

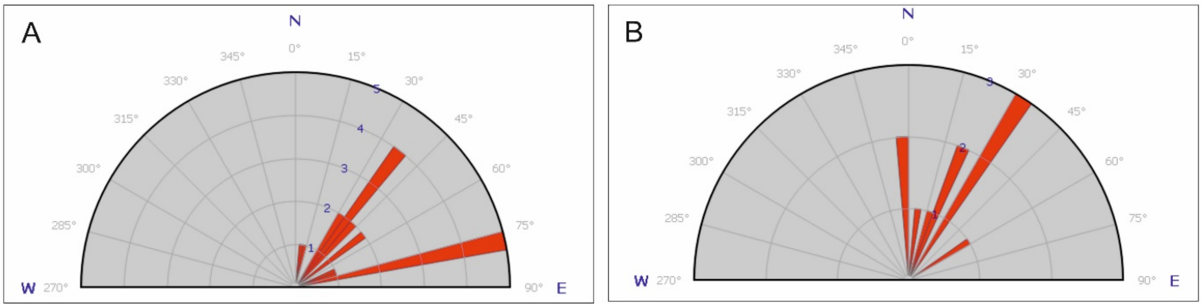

FIGURE 6: The main strike of faults (A) and strike of dykes (B) in the study area

Most of the dykes that were measured in the field have a NE-SW trend (Figure 6) and some of them were plotted on the geological map (Figure 7).

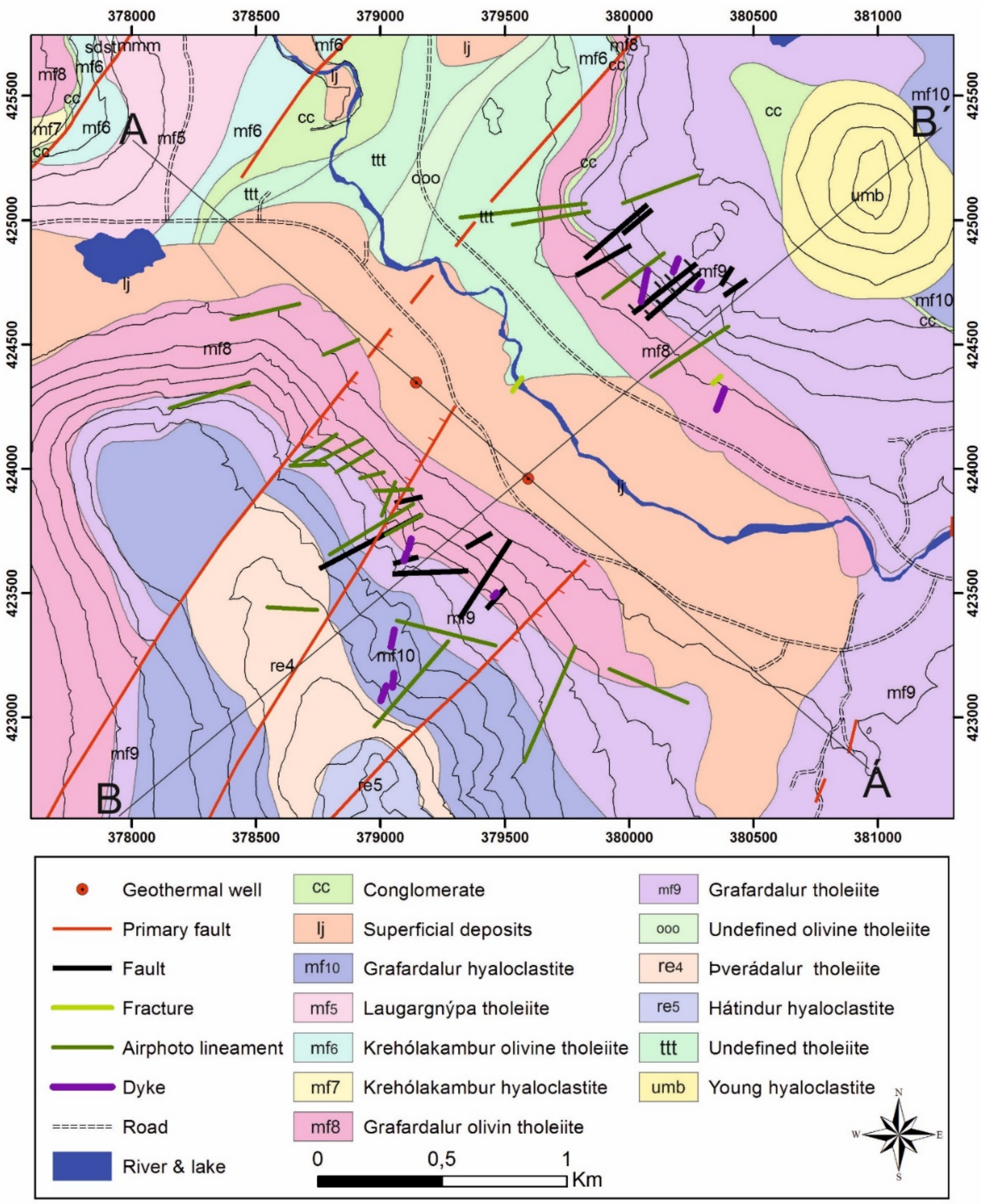

FIGURE 7: Geology map of the study area (modified from Fridleifsson, 1973; Hjartarson and Kristinsson, 2007). Cross sections A-A´ and B-B´ are shown in Figure 15 and Figure 16, respectively

3.2 Structural mapping

Mapping of faults and fractures is important in geothermal prospecting, as such structures may control the flow of hydrothermal fluids. Analysis of structural mapping included plotting faults and lineaments on a geological map and trend distribution on rose diagrams.

Mödruvellir area is characterized by several faults and fractures, most of them having a NE-SW trend. Three NW-SE faults occur parallel to each other and are already marked on the 1:25,000 scale geology map. Some of the faults that have been mapped in the study area were observed in the field, and others were deduced from examination of aerial photographs. Geological features are typically large and applications therefore require small scale imagery to cover the extent of the element of interest. Aerial photos can be used in some areas. During the field study, 18 faults and fractures were mapped with GPS in the field. In addition, 22 lineaments were derived from aerial photos and plotted on a geology map. Most of these faults and fractures have a general NE-SW trend and some have ENE-WSW trends (Figure 6) that appear to crosscut the NE-SW faults, (Figure 7).

Based on analysis of aerial photos, there are some lineaments that have WNW-ESE trends, and were not seen during the field study. These lineaments are located in the southern part of the study area.

4. GRADIENT WELLS

Drilling of gradient wells is a method used in exploration of both high and low-temperature geothermal areas. In Iceland many low-temperature geothermal systems have been discovered with this method where there were no surface manifestations. The temperature gradient in Iceland is mainly dependent on four factors: (1) the regional heat flow through the crust, (2) hydrothermal activity, (3) the permeability of the rock and (4) residual heat in extinct volcanic centres (Flóvenz and Saemundsson, 1993). In high temperature areas in Iceland, the gradient method is not used as an early step in subsurface exploration, except where resistivity surveys alone indicate a resource. More often, deep exploratory boreholes are drilled to follow up surface exploration if the results of the various methods correlate tolerably well, (Saemundsson, 2007). In the low-temperature areas, the method is used to outline the areal extent of an anomaly. It is important to avoid disturbances from the internal flow inside the well. In fracture controlled low-temperature fields, shallow wells give the best results (Saemundsson, 2007). Beside these, a heat flow map of Iceland has newly been released (Figure 8) and around 1000 wells have been used to construct the map (Hjartarson et al, 2015).

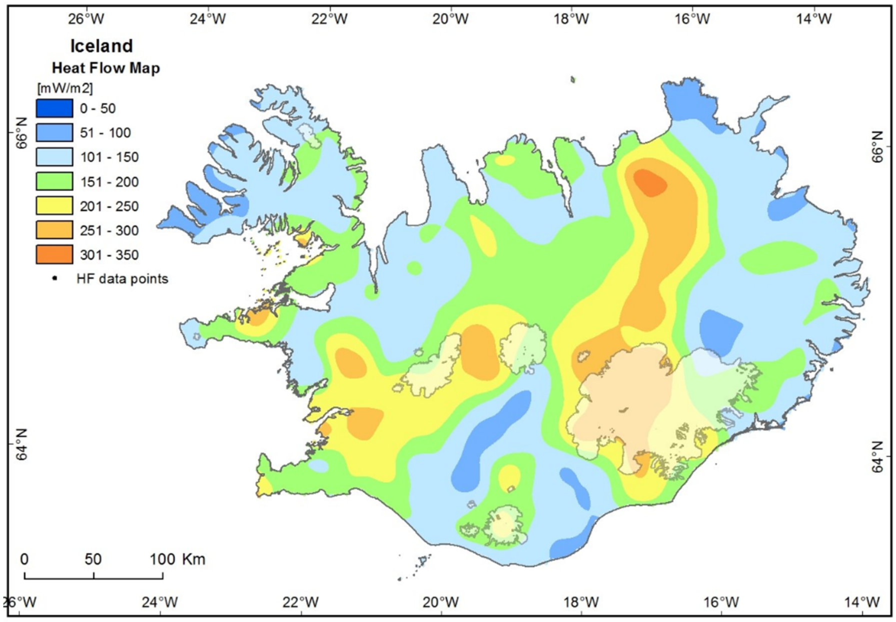

FIGURE 8: Heat flow map of Iceland (Hjartarson, et al., 2015)

As the basalt becomes buried the pores close due to lithostatic pressure and in formations of secondary minerals below 500 to 1000 m depth in uneroded lava pile, the

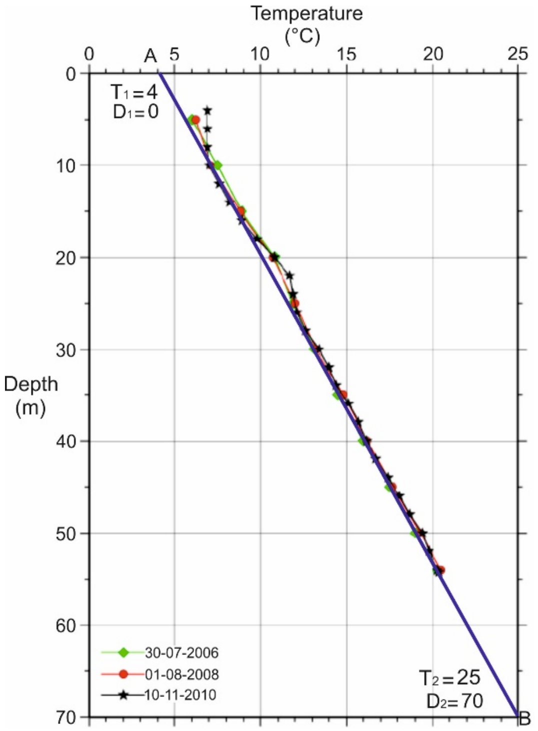

FIGURE 9: Temperature versus depth in well MV-14

heat is mainly transported by conduction. In the lowlands and valleys of Iceland outside the volcanic rift zone, 1000 to 1500 m of the original lava pile has been eroded, leaving thermal conduction as the most important heat transport mechanism (Flóvenz and Saemundsson, 1993).

There are no surface manifestations in the Mödruvellir area, so the gradient method was applied to locate geothermal anomalies, and the drilling of shallow gradient wells revealed geothermal activity. Today there are 22 gradient wells in the area, and Table 1 shows the characteristics of the wells. In this study, two geothermal anomalies were defined on the basis of temperature at 50 m depth and the thermal gradient in wells.

The regional geothermal gradient must also be known as a baseline for recognizing thermal anomalies (Saemundsson, 2007). It is well established that temperature increases with depth, indicating that heat is generated at depth and transferred through rock and sediment layers to the surface (Forrest et al., 2007). Thermal gradients were calculated for all gradient wells based on the gradient equation. Figure 9 presents an example for this calculation, and shows temperature versus depth for well MV-14. A-B is a straight line which cuts the maximum points of temperature versus depth points. The gradient well logs are presented in Appendix I.

TABLE 1: Characteristics of the gradient wells in Mödruvellir area

Well	**Coordinate system**		**Temperature at 50 m depth**	**Gradient °C/ km**	**Depth (m)**
	x	**y**			
MV-6	379666	423651	14	205	75
MV-7	379848	423502	14	183	73
MV-8	379541	423856	18	265	58
MV-9	379266	424200	18	272	59
MV-10	379400	424036	17	245	59
MV-11	379187	424364	19	300	60
MV-12	378908	424435	15	190	59
MV-13	379208	424325	19	297	60
MV-14	379147	424388	19	300	54
MV-15	379051	424372	19	282	71
MV-16	379274	424393	19	275	70
MV-18	379251	424502	19	290	70
MV-20	379492	423944	17	257	69
MV-21	379388	423832	17	256	71
MV-22	379646	423781	16	230	70
MV-23	379639	423958	16	265	90
EJ-5	379792	424149	13	160	51
KM-3	379571	424698	16	210	51
KM-4	379624	424674	16	236	45
KM-5	379343	424884	12	160	64

Gradient equation:

$$G = \frac{\Delta T}{\Delta Z} = \frac{T2 - T1}{D2 - D1}$$

In Figure 9: T1= 4°C; T2= 25°C and D1= 0 m; D2= 70 m

Gradient equation yields:

$$G = \frac{25-4}{70-0} = 0.3\text{°C/m}$$
$$= 300\text{°C/km}$$

The thermal gradient was calculated for 22 gradient wells by using this equation. Figure 10 shows the temperature gradient map in this area. There are five different temperature zones on the map, the highest temperature gradient is >270°C/km and the lowest is <180°C/km. This map can be considered a portrayal of the subsurface temperature distribution.

In Figure 11, a map shows the temperature at 50 m in the gradient wells. There are two temperature anomalies in this area, the main anomaly is clearly related to fractures trending NE-SW and another has a WNW-ESE trend, suggesting that the hot water flow is related to both the fractured zones.

Figure 12 illustrates a comparison between the thermal and gradient maps. It shows that the highest temperature zone on the thermal map is within the highest gradient zone. Based on Figure 12 the main temperature anomaly is located between two major faults in this area.

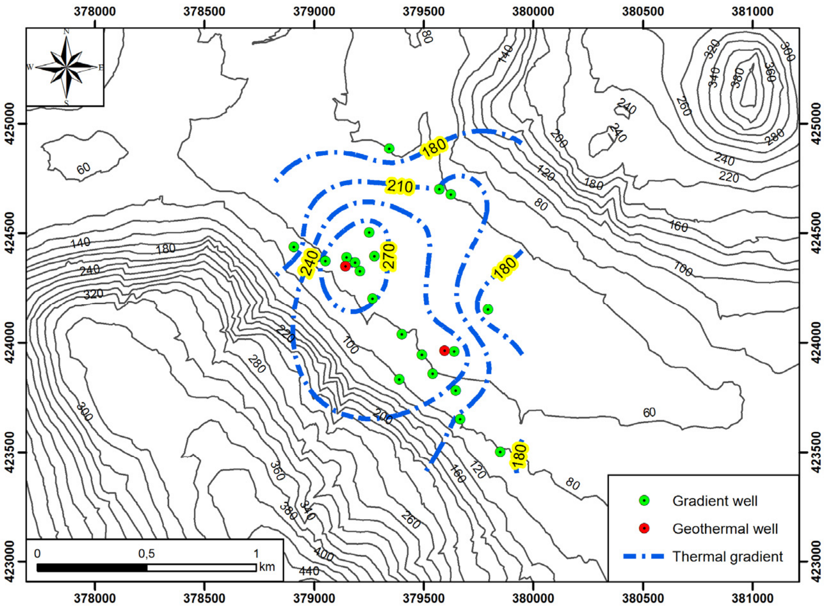

FIGURE 10: Thermal gradient map of the Mödruvellir geothermal area

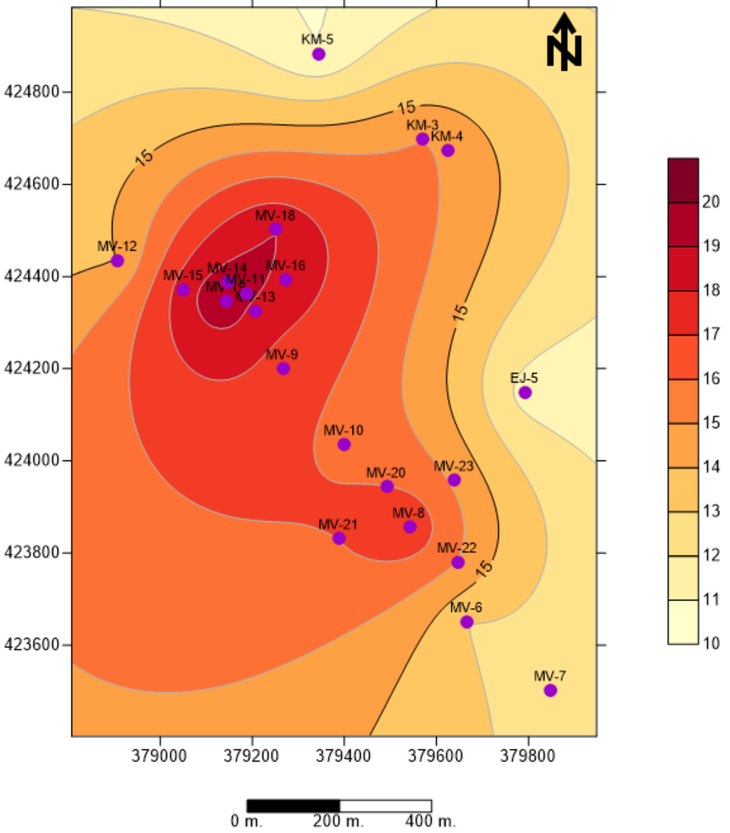

FIGURE 11: Temperature map at 50 m depth in the gradient wells

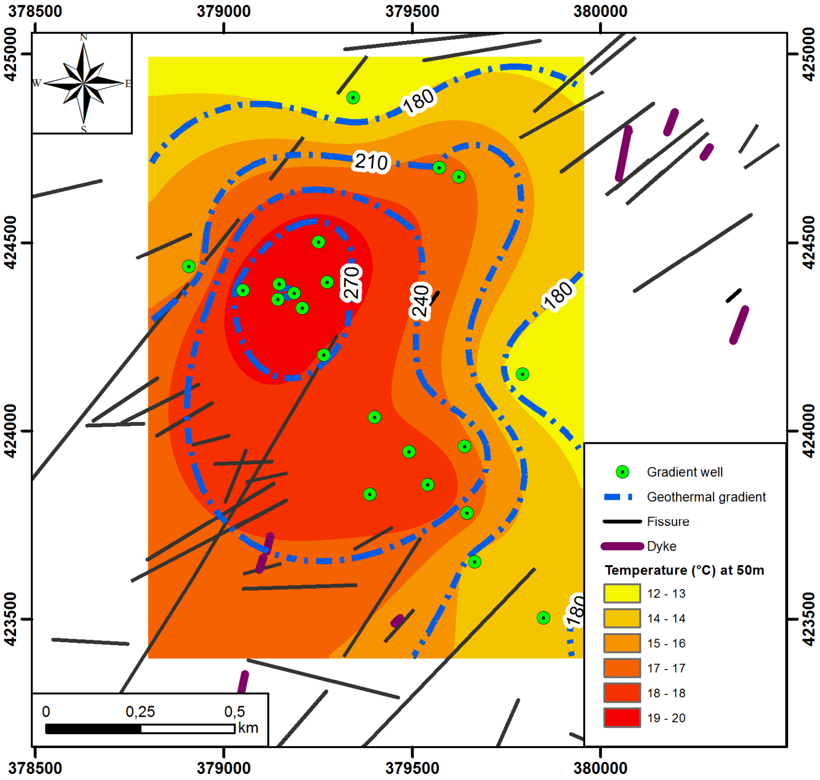

FIGURE 12: Comparison between thermal map and gradient map in Mödruvellir area

5. SUBSURFACE GEOLOGY

After the surface mapping of a geothermal system, further exploration and evaluation of the geothermal system is mainly based on information gained from wells. This development has led geologists to measure various parameters directly from boreholes and get in-depth information about the geothermal system.

Subsurface geology in this area is based on an analysis of drill cutting samples from two vertical wells, MV-19 (820 m) and MV-24 (1704 m). The sample cuttings were analysed using a binocular microscope. Rock cuttings had been collected at 2 m intervals and a total of 1200 samples of drill cuttings for both wells were analysed in this study. The analysis consisted of identifying lithological units, secondary minerals, vein fillings, oxidation and subsurface structures like fractures and veins (Figure 13 and Figure 14). Studies of drill cuttings have provided important information on the subsurface stratigraphy and rock units. Based on these studies five distinct volcanic units were defined in the study wells.

5.1 Subsurface stratigraphy

The main rock types that comprise the subsurface geology of the studied wells are basaltic lava and minor hyaloclastites.

The crystalline basalt formations have been differentiated based on their composition being tholeiite, olivine tholeiite and olivine basalt.

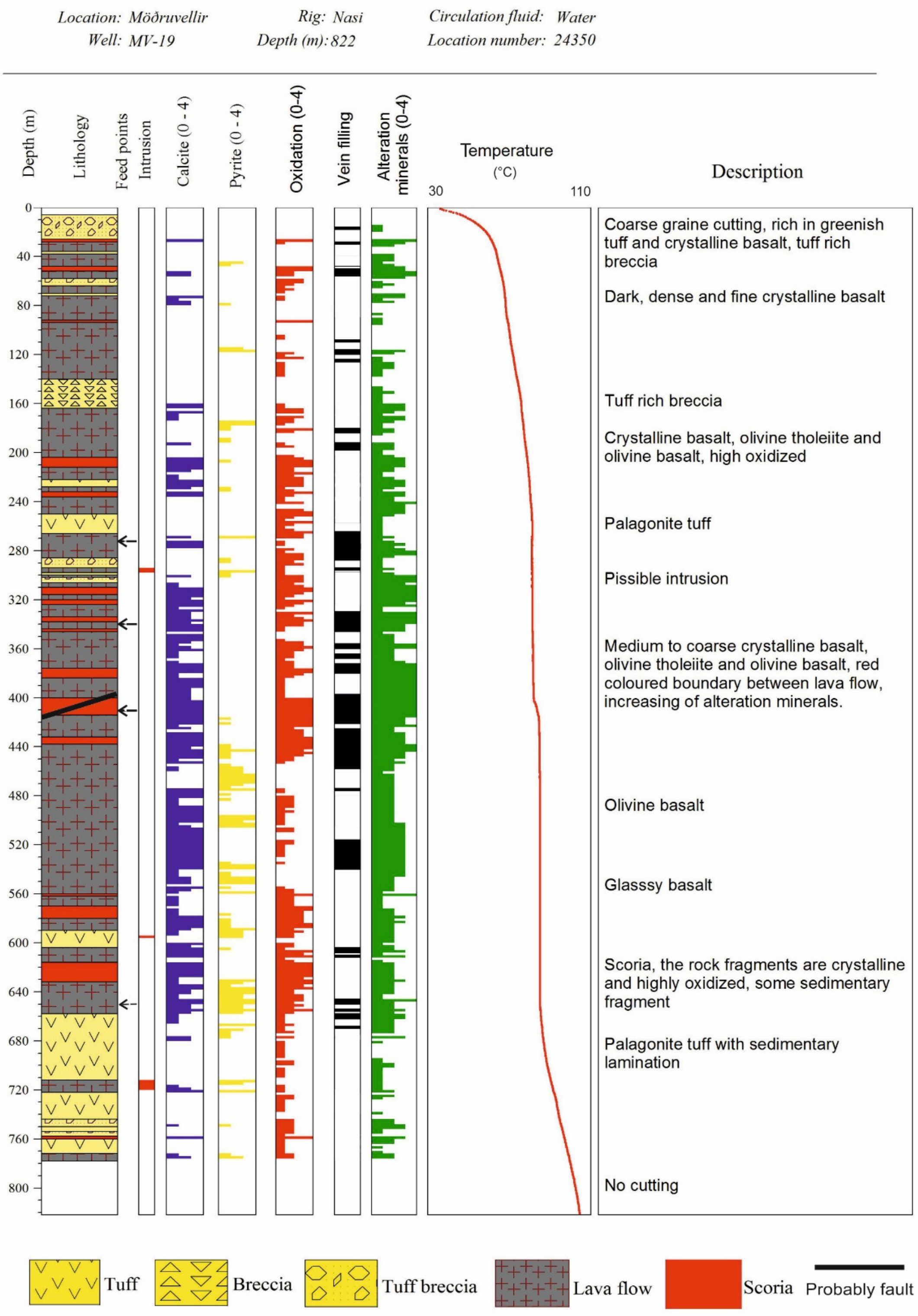

FIGURE 13: Lithology, selected alteration minerals and temperature log of MV-19

Lithological units in well MV-19 are comparable with the mf4, mf5, mf6, mf7, and mf8 units. In well MV-24 the lithological units are similar to unites mf1 (tholeiite), mf4 (hyaloclastite), mf5, mf6, mf7, mf8. These units are tholeiite lavas, basaltic hyaloclastites, olivine tholeiite lavas and olivine basalt lavas. Lithological logs from well MV-19 and MV-24 are presented in Figure 13 and Figure 14, respectively. Based on these studies, the different lithological units are described below.

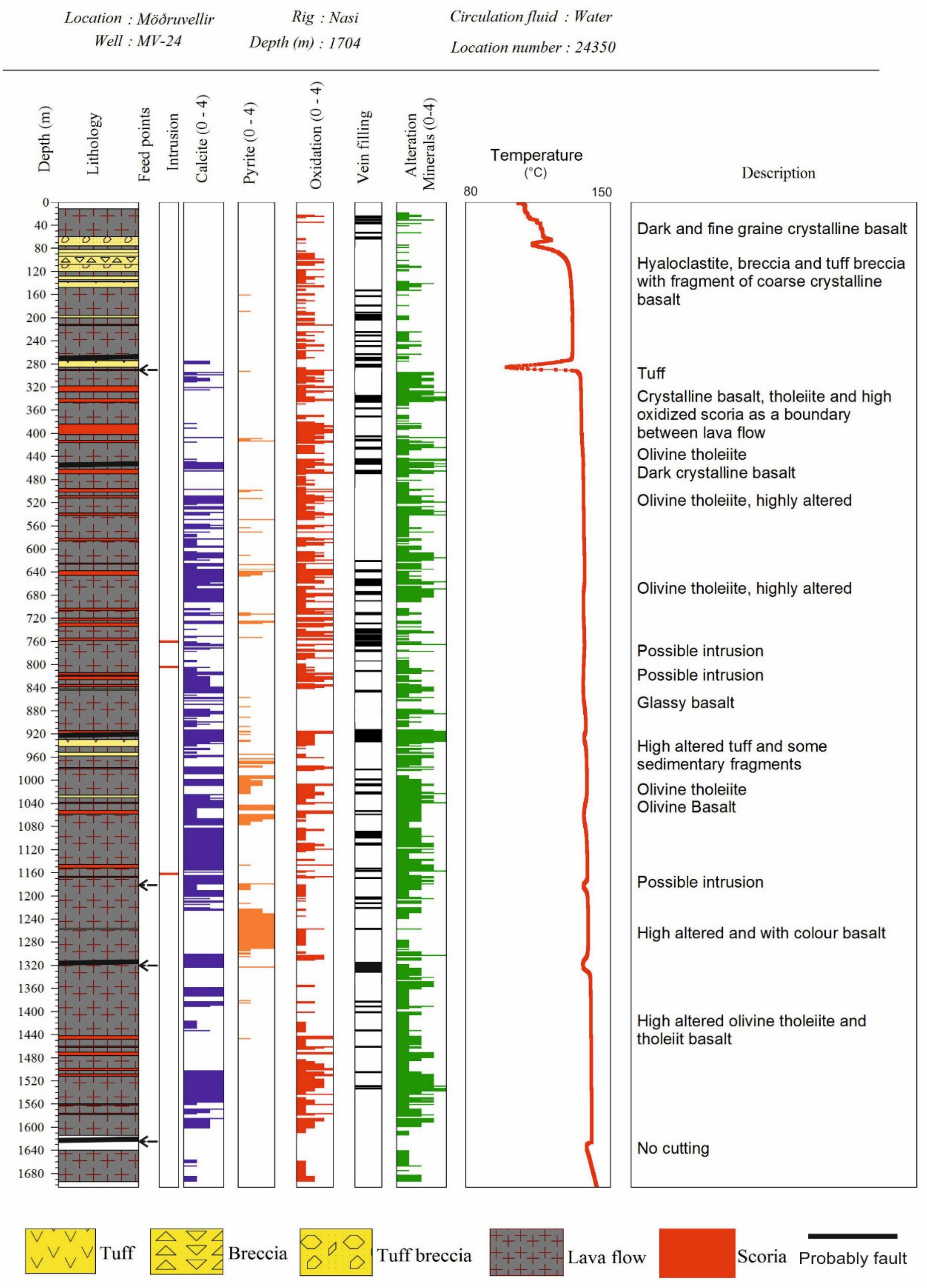

FIGURE 14: Lithology, selected alteration minerals and temperature log of MV-24

Tuff:
Mostly reworked tuff, greenish and red colour, fine to medium grained, mixed with fragments of crystalline basalt and secondary minerals are scarce. Tuff was found from 222 to 228 m, 250 to 266 m, 590 to 604 m, 660 to 744 m, 760 to 772 m depth in well MV-19, and 82 to 88 m, 128 to 134 m, 142 to 148 m, 196 to 200 m, 274 to 286 m, 930 to 942 m, 952 to 958 m, 1026 to 1030 m, in well MW-24. Tuffs occur as brown colour palagonite tuff in the lower part of well MV-19, which were formed in a lacustrine

environment but this sedimentary interval is not present in well MV-24. The tuff in the lower intervals of well MV-24 is highly altered to clays.

Tuff breccia and breccia:
Various type of tuff mixed with pieces of fine to medium grained crystalline basalt in certain intervals. These hyaloclastite units were noted between 6 to 26 m, 36 to 38 m, 58 to 64 m, 70 to 72 m, 286 to 294 m, 302 to 306 m, 744 to 750 m, 754 to 758 m, 140 to 164 m in well MV-19, and 60 to 76 m, 94 to 120 m in well MV-24. In these intervals the amount of secondary minerals is relatively small but zeolites can be seen.

Lava flow:
The majority of the units in both wells consist of lava flows. There is a range in composition from tholeiite to olivine basalt; fine to medium grained and oxidized basalt, moderately altered in well MV-19 and strongly altered in lower part of well MV-24. There are boundaries between these lava flows. Alteration minerals in vesicular part are zeolites and calcite. Pyrite is also formed in many intervals of the crystalline basalt. The lava flows are sometimes partly glassy.

Scoria:
Highly oxidized, red in colour, very porous and the amount of alteration minerals increases in the scoria parts. Scoria sits at boundaries between lava flows. There are 16 scoria boundaries in well MV-19 and 32 scoria boundaries between lava flows in well MV-24.

5.2 Feed points and permeability

Feed point locations have been estimated by using the temperature log and they are shown in Figure 13 and Figure 14. The main source of permeability in the wells is related to lithological boundaries and fractures.

5.3 Intrusions

Table 2 shows a list of possible intrusive rocks in well MV-19 and MV-24. These intrusive rocks are characterized by fresh appearance, coarse graining and dark basalt, and an increase in alteration in the surrounding formations.

TABLE 2: intrusive rocks determined from drill cutting from well MV-19 and MV-24

Well	Depth interval (m)	Type
MV-19	292-298	Possible intrusion
MV-19	596-598	Possible intrusion
MV-19	712-722	Possible intrusion
MV-24	758-762	Possible intrusion
MV-24	802-806	Possible intrusion
MV-24	1160-1166	Possible intrusion

5.4 Alteration minerals

Alteration minerals in these wells are zeolites, calcite, and to a lesser extent quartz. Zeolites form the majority of alteration minerals in this study. Zeolites are formed during alteration and precipitation in vugs and vesicles. Zeolites are often classified by shape into three main categories, fibrous, tabular and granular and some of them are variable in shape. Most of the zeolites in both wells have fibrous and tabular shapes. Zeolites in this study include mesolite, thomsonite, stilbite and scolecite. Epidote is found

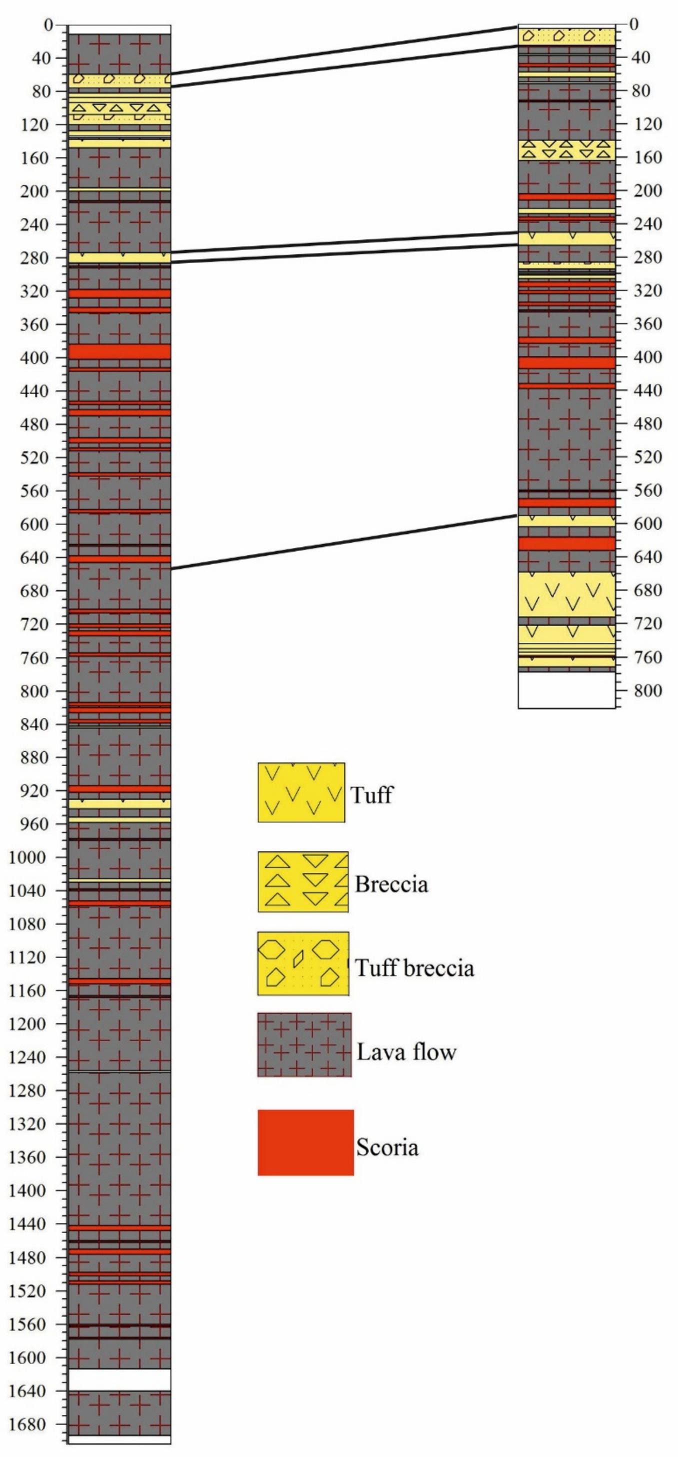

FIGURE 15: Stratigraphic correlation between wells MV-19 and MV-24 in Mödruvellir area

in the lower part of well MV-24, from 1400 m depth to the bottom. This epidote is deformed without any crystal shape and is not related to the low-temperature geothermal system but probably to some older geothermal system. In order to identify the alteration minerals and types of clay minerals, thirteen samples were prepared for XRD analysis. Each sample was prepared and analysed in three conditions: untreated, glycolated and heated. The peaks recorded from the analysis were interpreted, and the XRD analysis showed the presence of different type of zeolites and smectite that indicate a temperature in the range 50 - 200°C. Some examples of the XRD analysis are shown in Appendix II.

5.5 Subsurface correlation

Correlation between wells MV-19 and MV-24 is difficult because there are no clear marker horizons or key beds in these wells. For the subsurface correlation some tuff layered units that have sedimentary layers and lamination were used. In addition, the type of lava flow composition between these layers helped. Correlation between subsurface lithological units is shown in Figure 15. It seems that the displacement of units is related to the normal dip of topography in the area (Figure 4 and Figure 16).

6. CONCEPTUAL MODEL

In order to interpret the subsurface geology and examine the geothermal system in Mödruvellir, two cross sections A-A´ and B-B´ on the geological map (Figure 7) were used. A conceptual model for the low-temperature geothermal system is based on an analysis of the geological information and is shown in Figures 16 and 17. Geology cross sections across these wells show the correlation of the lithological units at the surface and subsurface. Based on the interpretation of the data collected from the studied wells and thermal gradient map, two upflow zones were found in the area. The NE-SW, ENE-WSW faults and fractures act as upflow zones and the main upflow zone is close to well MV-19. This anomaly is restricted between two major faults in the area, which have opposite dips and form a mini graben. It seems that the intersection of these faults has an important role in the formation of the temperature anomaly. Another temperature anomaly is close to well MV-24. Geothermal gradient in

Figure (16) shows a lower temperature for this anomaly and based on Figure (12) this anomaly occurs above fractures and fault that have ENE-WSW trend.

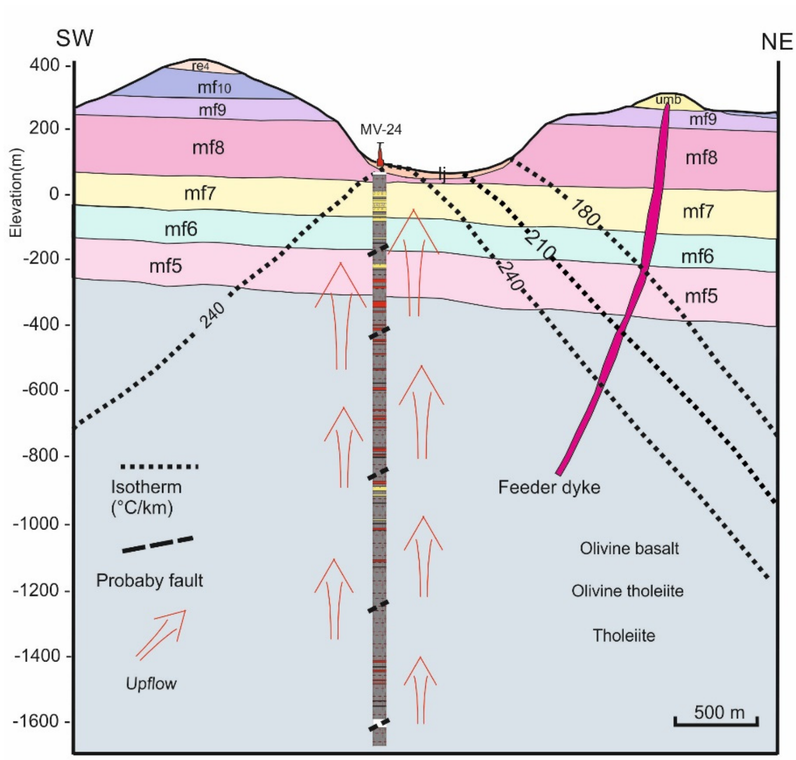

FIGURE 16: Geological cross section and conceptual model along A-A´ shown in Figure 6

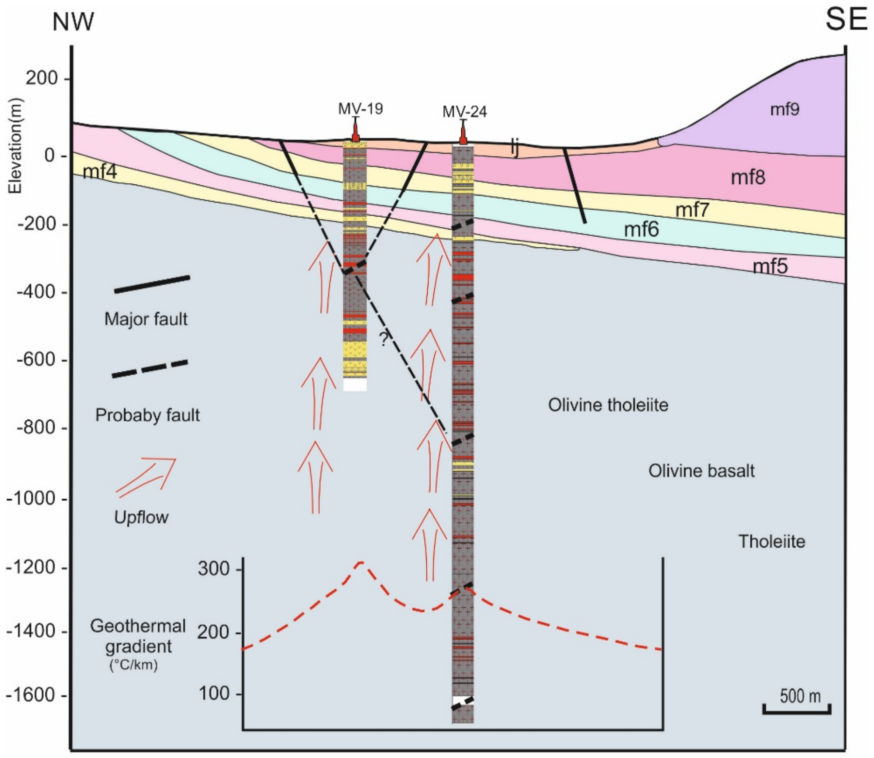

FIGURE 17: Geological cross section and conceptual model along B-B´ shown in Figure 6

7. CONCLUSION

The main conclusions drawn from this work are as follows:

- Geology structures that control the flow of the fluids upwards, have three main directions, NE-SW, WSW-ENE and WNW-ESE.
- The mini graben in the area that was formed between two major faults with different dips, has an important role in increasing the permeability in the north western part of the study area.
- Based on the analysis of the temperature map, there are two temperature anomalies in this area that are related to fracture zones.
- The highest temperature zone in the temperature map is within the zone with the highest geothermal gradient.
- The lithostratigraphy of wells MV-19 and MV-24 is similar and is composed of different lithological units: Crystalline basalt, tuff, tuff breccia, and scoria.
- Secondary minerals in these wells are zeolites, calcite and to some extent quartz.
- Oxidation in this area is very high and there are 16 scoria boundaries between lava flows in well MV-19 and 32 scoria boundary in well MV-24.
- Based on a conceptual model in this area, the best place for future drilling is in the north western part of the study area, close to well MV-19.

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REFERENCES

Arnórsson, S., 1991: Geochemistry and geothermal resources in Iceland. In: D´Amore, F. (co-ordinator), *Applications of geochemistry in geothermal reservoir development.* UNITAR/UNDP publication, Rome, 145-196.

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

Arnórsson, S., 1995b: Geothermal systems in Iceland: Structure and conceptual models – II. Low-temperature areas. *Geothermics, 24*, 603-629.

Bödvarsson, G., 1961: Physical characteristics of natural heat resources in Iceland. *Jökull, 11,* 29-38.

Forrest, J., Marcucci, E. and Scott, P., 2007: Geothermal gradients and subsurface temperature in the northern Gulf of Mexico. *GCAGS Transactions, 55*, 233-248.

Flóvenz, Ó.G. and Saemundsson, K., 1993: Heat flow and geothermal processes in Iceland. *Tectonophysics, 225*, 123-138.

Fridleifsson, I.B., 1973: *Petrology and structure of the Esja Quaternary volcanic region SW Iceland*. Oxford University, PhD dissertation, 208 pp.

Gudmundsson, A., 2000: Dynamics of volcanic systems in Iceland: Example of tectonism and volcanism at juxtaposed hot spot and mid-ocean ridge systems. *Annual Review of Earth and Planetary Sci., 28*, 107-140.

Gudmundsson, J.S. and Pálmason, G., 1987: The geothermal industry in Iceland. *Geothermics, 16*, 567-573.

Hjartarson, Á. 2015: Heat flow in Iceland. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 4 pp.

Hjartarson, Á. and Kristinsson, S.G., 2007: *Kjalarnes – Botnsdalur. Bedrock map 1:25,000 and descriptions of strata*. ÍSOR – Iceland GeoSurvey, ÍSOR-2007/064 (in Icelandic).

Jacoby, W. and Gudmundsson, M.T., 2007: Hotspot Iceland: An introduction. *J. Geodynamics, 43*, 1-5.

Jóhannesson, H. and Saemundsson, K., 1998: *Geological map of Iceland 1:500,000. Tectonics* (2nd ed.). Icelandic Institute of Natural History, Reykjavík, Iceland.

Kristjánsson, L., Fridleifsson, I.B. and Watkins, N.D., 1980: Stratigraphy and paleomagnetism of Esja, Eyrarfjall and Akrafjall Mountains, SW-Iceland. *J. Geophys., 47*, 31-42.

Kristinsson, S.G., 2009: *The Hvalfjördur central volcano, stratigraphy, tectonics and alteration*. University of Iceland. MSc thesis (in Icelandic), 93 pp.

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

Saemundsson, K., 2007: Geology and gradient wells. *Presented at "Short Course II on Surface Exploration for Geothermal Resources", organized by UNU-GTP and KenGen, Lake Naivasha, Kenya,* 11 pp.

Saemundsson, K. and Einarsson, S., 1980: *Geological map of Iceland, sheet 3, SW-Iceland* (2nd ed.). Museum of Natural History and the Iceland Geodetic Survey, Reykjavík, Iceland.

Schilling, J.G., 1973: Iceland mantle plume: geochemical study of Reykjanes Ridge. *Nature, 242*, 565-571.

Tibaldi, A., Vezzoli, L., Pasquare, F.A. and Rust, D., 2008: Strike-slip fault tectonics and the emplacement of sheetelaccolith systems: The Thverfell case study (SW Iceland). *J. Structural Geology, 30*, 274-290.

Thórdarson, T. and Höskuldsson, A., 2002: *Iceland (Classic Geology in Europe 3).* Terra Publishing, Reykjavík, 200 pp.

Weisenberger, T. and Selbekk, R.S., 2007: Multi-stage zeolite facies mineralization in the Hvalfjördur area, Iceland. *Int. J. Earth Sci (Geol Rundsch), 98,* 985-999.

Weisenberger, T., 2005: Zeolite facies mineralisation in the Hvalfjördur area, Iceland. Freiburg: Albert Ludwigs Universitat Freiburg, Diploma thesis, 142 pp.

Walker, G.P.L., 1960: Zeolite zones and dyke distribution in relation to the structure of the basalts of eastern Iceland. *J. Geol., 68,* 515-528.

Villemin, T., Bergerat, F., Angelier, J. and Lacasse, C., 1994: Brittle deformation and fracture patterns on oceanic rift shoulders: The Esja peninsula, SW Iceland. *Journal of Structural Geology, 16*, 1641-1654.

APPENDIX I: Gradient well logs in Mödruvellir geothermal field

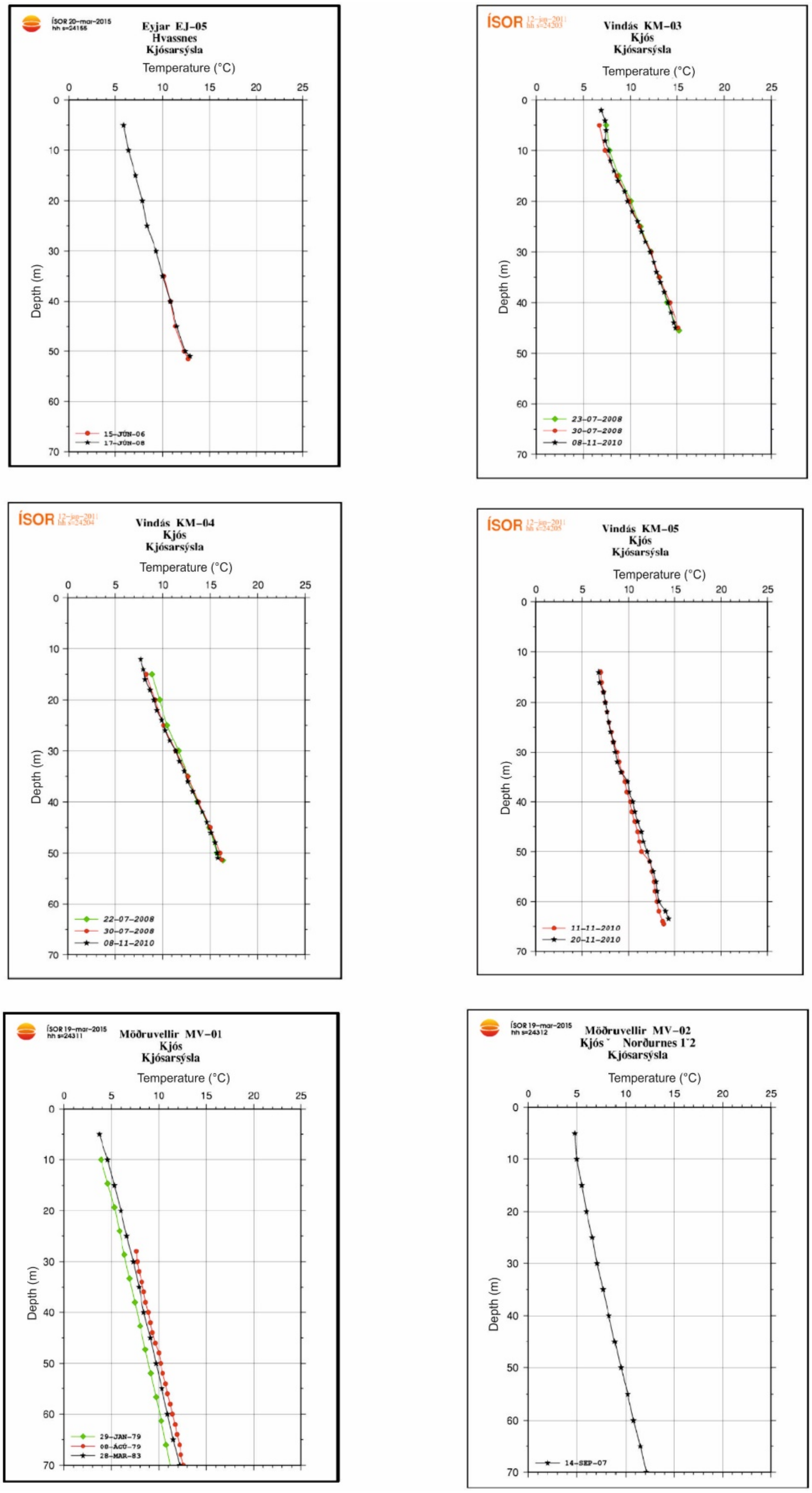

FIGURE 1: Temperature versus depth in wells EJ05, KM3, KM4, KM5, MV01 and MV02

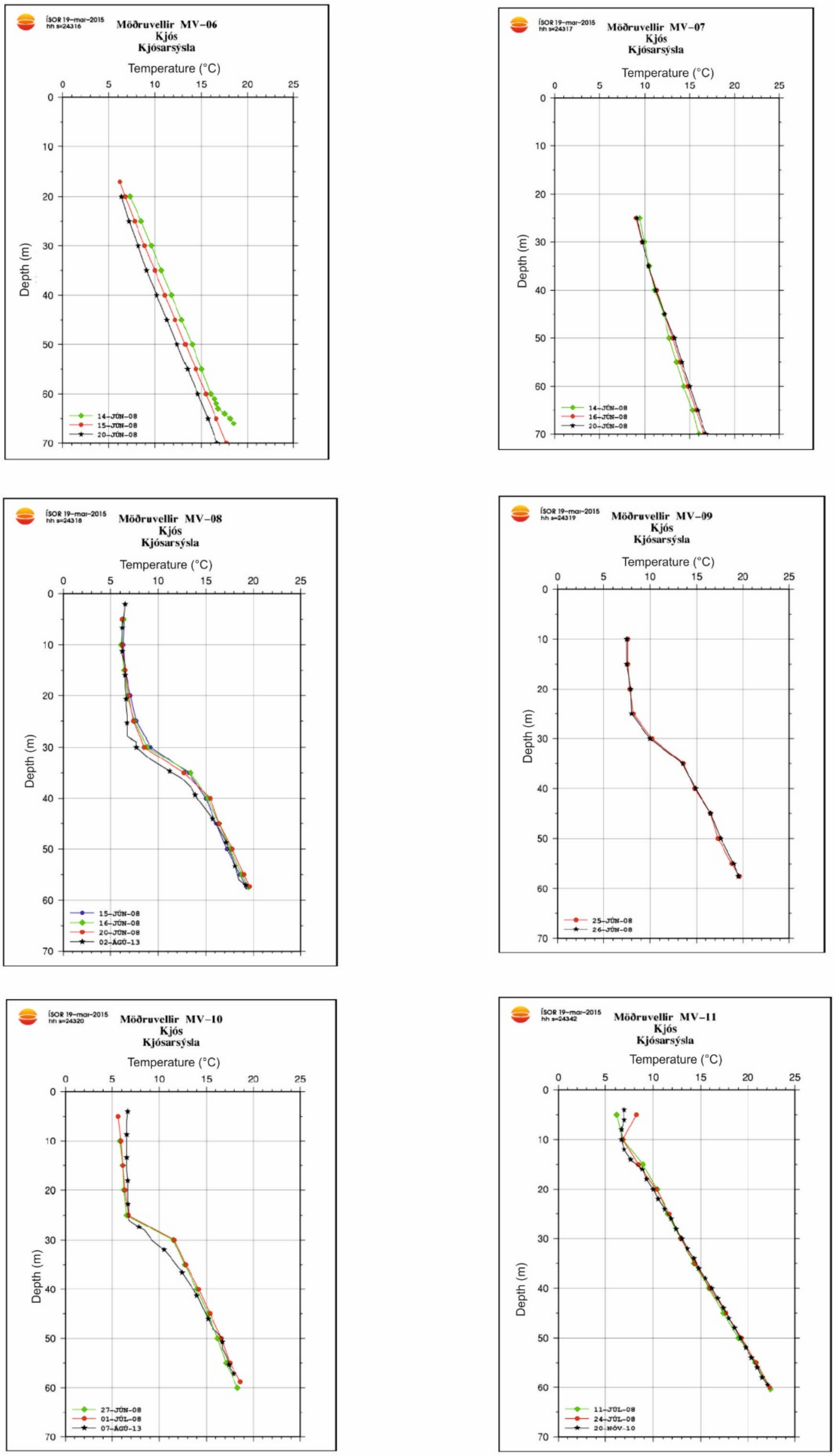

FIGURE 2: Temperature versus depth in wells MV06, MV07, MV08, MV09 and MV10

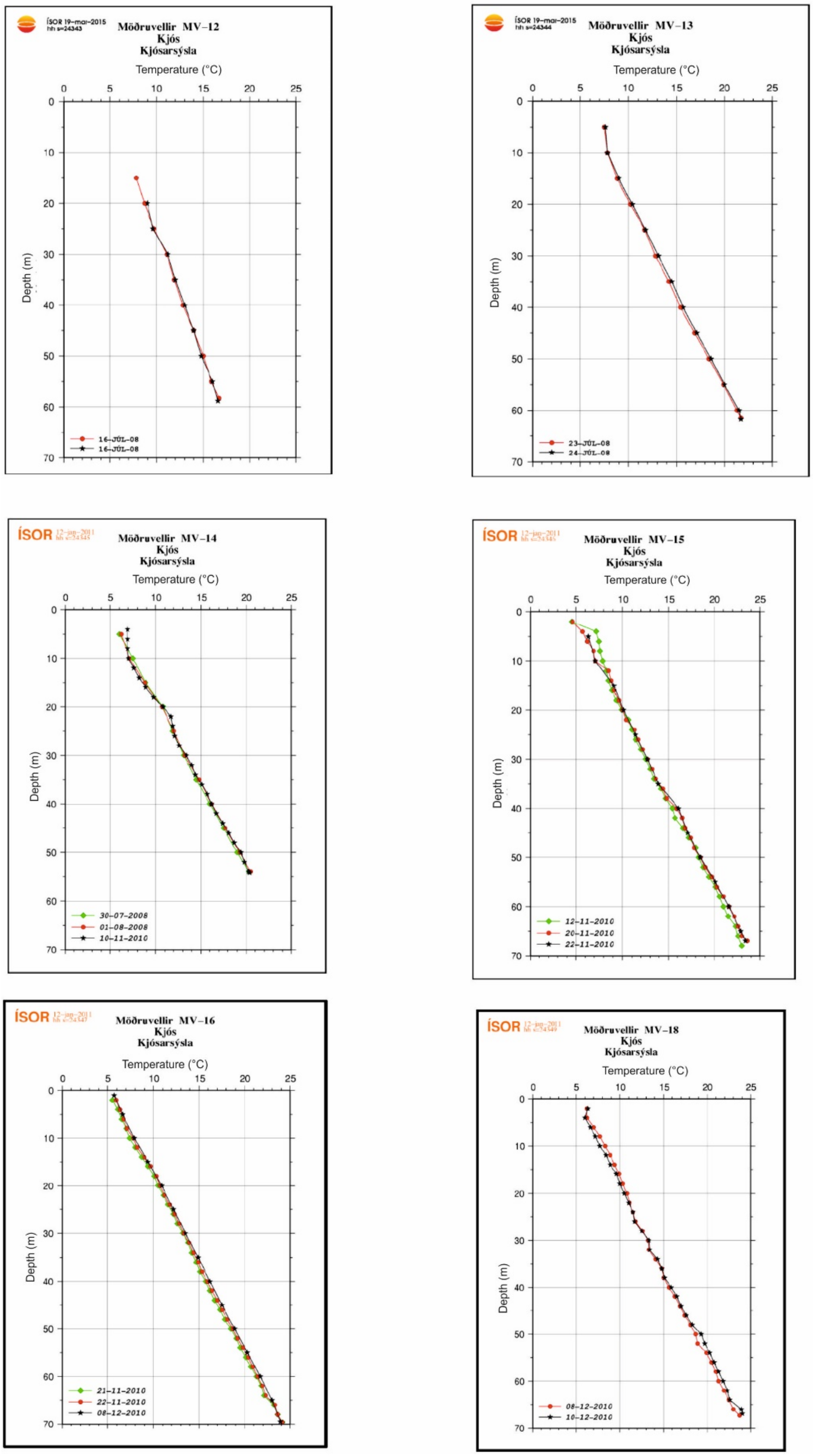

FIGURE 3: Temperature versus depth in wells MV12, MV13, MV14, MV15 and MV16

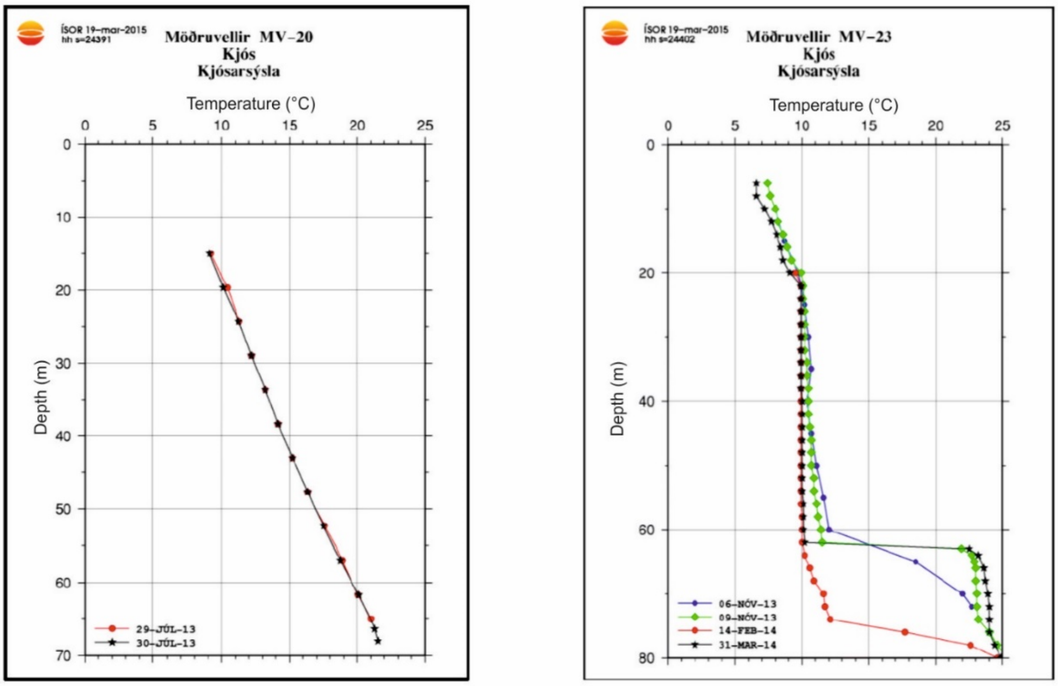

FIGURE 4: Temperature versus depth in wells MV20 and MV23

APPENDIX II: The XRD measurements for clay minerals and zeolites in wells MV-19 and MV-24

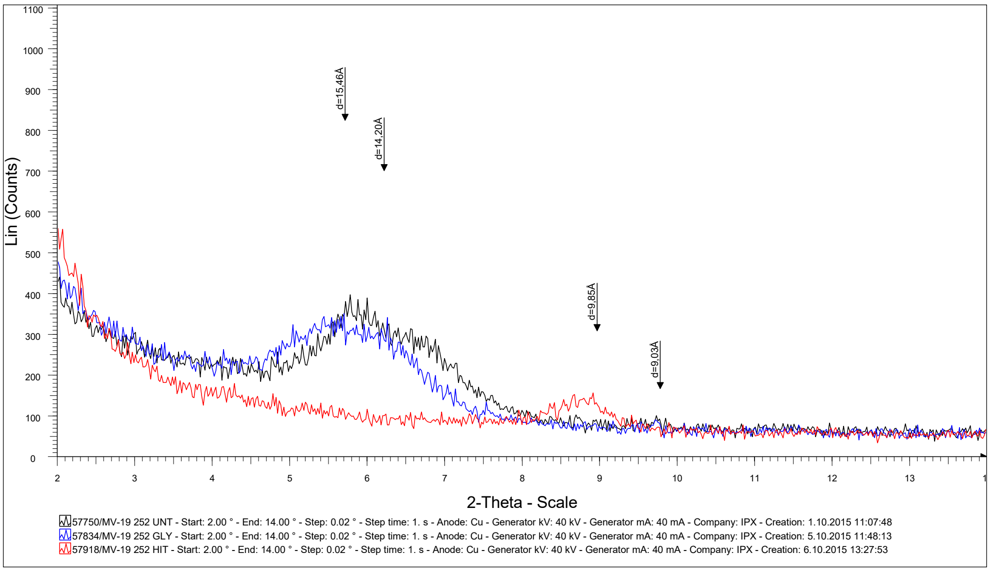

FIGURE 1: Well MV-19, XRD analysis from 252 m

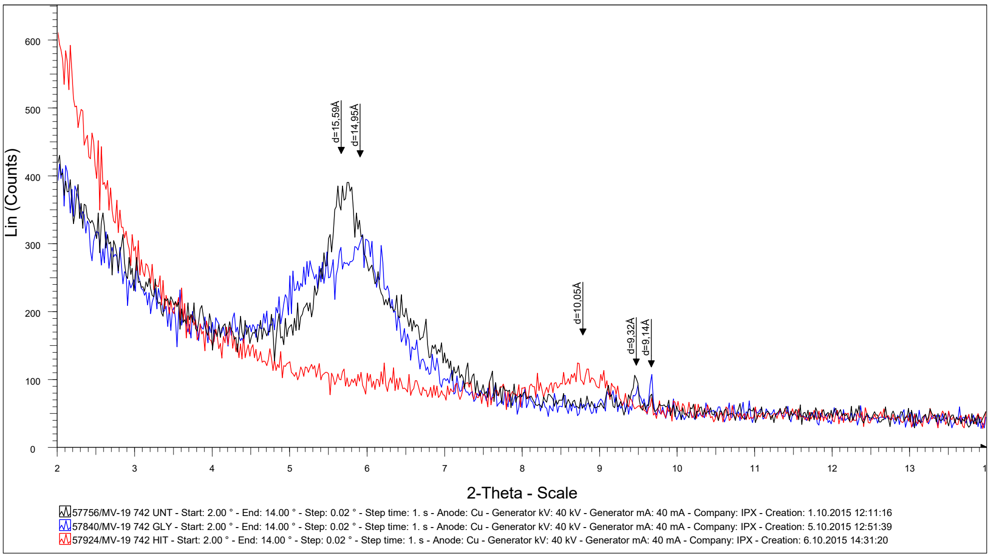

FIGURE 2: Well MV-19, XRD analysis from 742 m

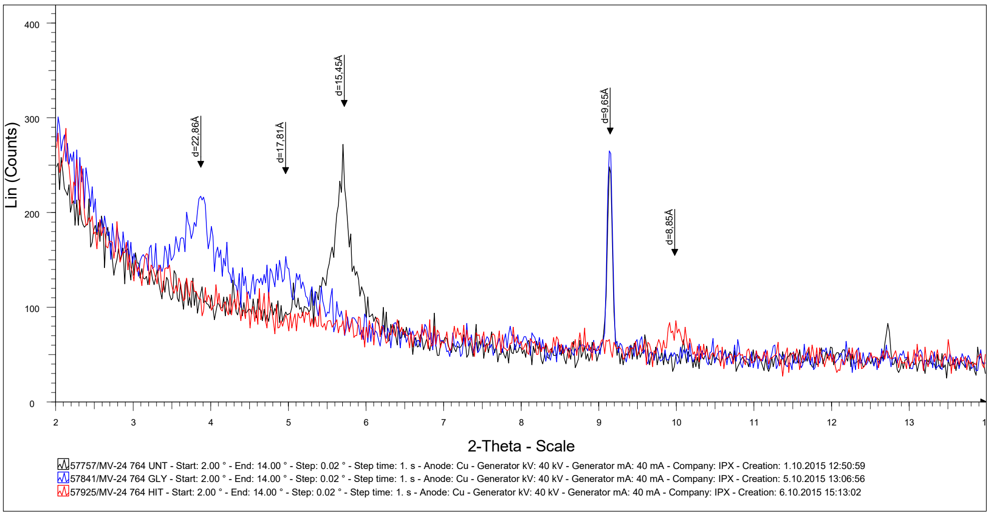

FIGURE 3: Well MV-24, XRD analysis from 764 m

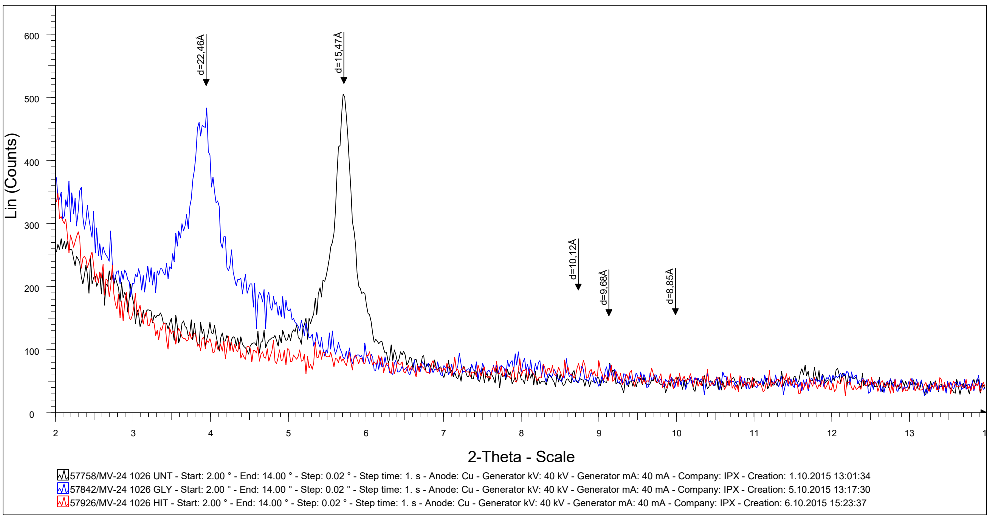

FIGURE 4: Well MV-24, XRD analysis from 1026 m