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GEOLOGICAL AND GEOTHERMAL MAPPING IN THE TRÖLLADYNGJA FIELD, SW-ICELAND

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ABSTRACT

The Trölladyngja field in the Krýsuvík area is a part of five high-temperature geothermal fields in the Reykjanes Peninsula in southwest Iceland. The area has undergone extensive research for exploitation of geothermal resources. Findings of this report contribute to the current investigations of the study area and also accomplish the author´s training in Geological Exploration studies at the UNU-GTP, in Iceland 2012. Geological and geothermal mapping of the study area was conducted and both maps are presented. There are three main lithological units: pillow lavas, hyaloclastite tuffs formed during sub-glacial eruptions in the last glacial period (Weichsel), and Holocene lavas during post-glacial eruptions that cover a substantial part of the study area. Normal faults trending N20°-40°E are dense on the hyaloclastite ridges and are covered by the Holocene lava in the valleys. Several fissures and dykes occur in a similar trend to the faults. Geothermal mapping of surface manifestations revealed that most previously active sites have been cooling and the remains of extinct altered clay or hot grounds were mapped. Fumaroles are the only active manifestations that occur linearly along the NE-SW trending faults and fissures, indicating up-flow zones that are controlled by these structures. A geothermal conceptual model is presented from which possible drilling targets for production and/or exploration wells are inferred.

1. INTRODUCTION

1.1 The study area

Krýsuvík is one of five main high-temperature geothermal fields in the Reykjanes Peninsula, southwest Iceland, and is also referred to as the Trölladyngja-Krýsuvík field. The others are Reykjanes, Svartsengi, Brennisteinsfjöll and the Hengill geothermal fields. The fields are divided into sub-fields. The present study was conducted in Trölladyngja area which is a sub-field of the main geothermal field. Trölladyngja is located 40 km southwest of Reykjavik, the capital of Iceland (Figure 1). It is accessible by an 8 km unsealed road from the main highway between Hafnarfjördur and Keflavík. The study area comprises hyaloclastite mountain ridges reaching up to 400 m above sea level and flat areas partly covered by young basaltic lavas and sediments.

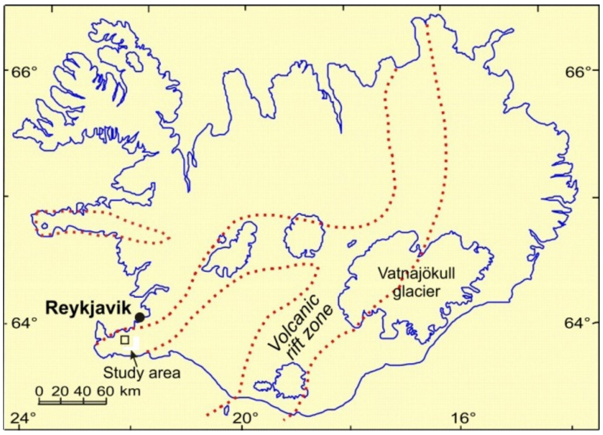

FIGURE 1: Locality map of study area

This study is a part of the six months training at the United Nations University Geothermal Training Programme (UNU-GTP) in Iceland. The objective of the training was to acquire practical experience in geological and geothermal exploration. Geological mapping is the first and foremost important step in exploring for geothermal resources. Understanding the geology and tectonics of an area usually leads to successful geothermal exploration and development. Geothermal features are also mapped during geological mapping and surface geological and geothermal maps are produced. These surface data and sub-surface data from boreholes/drill holes including geophysical data are used to create a conceptual geothermal model of the area. Drill holes are sited using the conceptual geothermal model be it shallow geothermal gradient wells, deeper exploration wells or production wells.

1.2 Methodology

Geological and geothermal mapping was carried out to identify different lithological units, structures, active geothermal areas and extinct volcanic craters to establish relationships between the tectonic setting and the geothermal activity of the area. Data gathered were used to produce both geological and geothermal maps. Sub-surface data from well logs were used to correlate with the surface data to create a conceptual geothermal model from which exploratory drilling sites were identified. The mapping exercise took place from mid-July to the end of August 2012, excluding weekends and extra days, with a supervisor. A total of 15 days were spent in the field. The following instruments and tools were used to conduct the field work:

1) A Garmin GPS 72 was used for tracking faults, volcanic craters, lithological boundaries and geothermally altered areas. Where the terrain would not allow for tracking, points were taken and later joined at the office. GPS points were taken of sample locations and geothermal manifestations.
2) Topographic and aerial photo maps were used for the traverses and digitizing of all geological and geothermal features in ArcMap.
3) A Thermal-couple set was used to take temperature readings of fumaroles and hot grounds. A 60 m tape was used for a soil temperature survey and a spade for digging up pits to investigate the ash layers.
4) A geological hammer, compass, hand lens and digital camera were also used, including a field note book and small sampling bags for taking samples during the mapping exercise.

The GPS data was downloaded using MapSource and later converted to ArcMap shapefiles and processed in ArcMap 10. All geological and geothermal data were digitized in ArcMap from which both maps were produced. Several pits were dug at various locations to identify volcanic ash, charcoal and soil. Volcanic ash and charcoal can be used for dating the age and origin of the ash. This study is called tephrochronology.

1.3 Previous work

The Krýsuvík field was explored as early as 1755 which is the first record of drilling of shallow wells (~3 m). More shallow wells were drilled from 1941-1953 but there was no progress made towards geothermal energy utilization. Geothermal exploration resumed in the Krýsuvík farm area in the 1960s with the drilling of four exploration wells. Two of the wells were drilled to more than 1200 m depth and the other two were shallow wells drilled to 300 m. Results from all the wells were not promising but all of them passed a temperature maximum of 200-225°C at 300-400 m depth, showing decreasing temperatures at deeper levels (Flóvenz et al., 1986).

After a decade of no work, a systematic approach to geothermal exploration in the Trölladyngja-Krýsuvík area was initiated in 1970 by Orkustofnun. This was a research project that included detailed geological, geophysical and geochemical surveys. Four new exploration wells (KR-05 – KR-08) were drilled, one (KR-06) in Trölladyngja and the rest in other areas in Krýsuvík. The results of these surveys were published by Orkustofnun (Arnórsson et al., 1975a and b; Jónsson, 1978). Jónsson mapped the volcanic craters, the hyaloclastite ridges and sorted out the Holocene lavas in the region. An updated regional geological map was produced later by Saemundsson and Einarsson (1980). Results of the four wells were again disappointing as they all displayed an inverse thermal gradient passing a temperature maximum at 500 m. Well KR-06 was the hottest, with a maximum temperature of 260°C at 400-500 m and decreasing to 225°C at deeper levels (Arnórsson et al., 1975b).

Flóvenz et al. (1986) conducted further geothermal investigation at Trölladyngja, adding to the geothermal knowledge of the area. Further research continued in the area with eight additional wells being drilled in the Trölladyngja area between 1998 and 2006. The wells are TD-1 – TD-6, TR-01 and TR-02 (Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006; and Hafstad et al., 2001). TR-01 and TR-02 were deep wells reaching more than 2000 m depth; the others were shallow water wells, TD-1 to TD-6. Several former UNU-GTP Fellows have published surface geology and geothermal survey reports of the area (e.g., Al-Dukhain, 2008; and Mbogoni, 2008) as part of their training.

2. GEOLOGICAL AND GEOTHERMAL ASPECTS OF ICELAND

2.1 Geological setting

Iceland, an island basalt plateau, is one of a few places in the world where a mid-oceanic ridge is observed above sea level. It was formed as a result of an interaction between spreading plate boundaries, the North American plate and the Eurasian plate, and a hot spot fed by a deep mantle plume beneath it (Saemundsson, 1979).

The Mid-Atlantic Ridge (MAR) dissects the island from southwest to northeast over a distance of more than 400 km. The active tectonic movement on the ridge progressively diverges towards the east and west at a rate of 2 cm per year. As a result of this tectonic activity, active volcanism occurs followed by earthquakes along the neo-volcanic zones from Reykjanes Ridge in the southwest through to the Kolbeinsey Ridge in the north. The main fault structures and volcanic zones and belts that lie within these zones are called volcanic rift zones, which are characterised by intense volcanic, seismic and high-temperature geothermal activity (Gudmundsson and Jacoby, 2007; Thórdarson and Larsen, 2007).

The geological formations of Iceland, with the oldest rocks ranging back to 16 m.y., are divided into four stratigraphic groups or series based on climatic evidence from inter-lava sediment or volcanic breccias and palaeomagnetic reversal patterns supported by absolute age data (Figure 2). These are from oldest to youngest: Tertiary, 16-3.1 m.y. (Miocene-Pliocene); Plio-Pleistocene, 3.1-0.78 m.y. (includes Matuyama and Gauss epochs); Upper Pleistocene, 0.78-0.11 m.y. (Brunhes magnetic epoch); and Postglacial, 11,000-present (Saemundsson, 1979).

The volcanic pile exposed in Iceland is predominantly of basaltic composition (80-85%) and is classified into three main lava types, recognisable in the field. They are: compound flows of olivine tholeiite, simple flows of tholeiite with little or no olivine, and porphyritic flows in plagioclase and/or pyroxene.

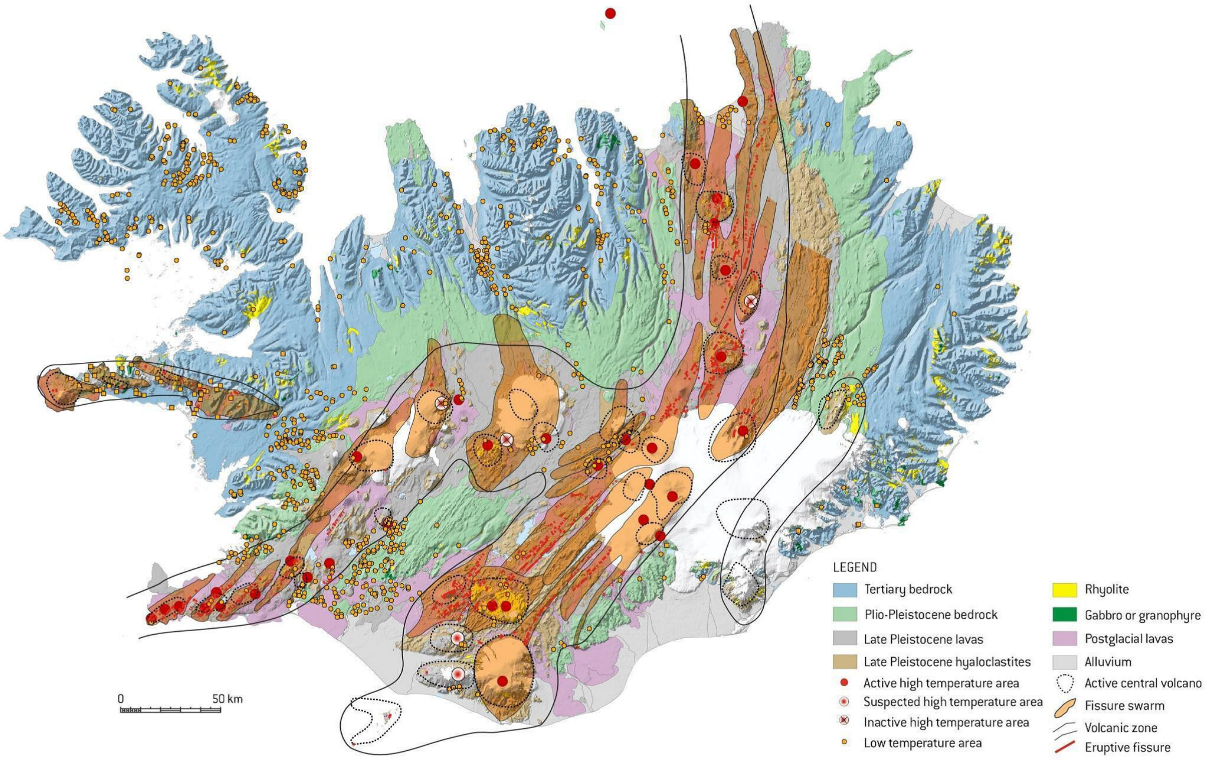

FIGURE 2: Geological map of Iceland (Jóhannesson and Saemundsson, 1999) showing the main formations, the volcanic zone (MAR) and the geothermal areas

Olivine tholeiite often produces pahoehoe lava flows, while olivine poor tholeiite produces aa lava fields. Acidic and intermediate rocks constitute 10%, and sediments of volcanic origin are about 5-10% in a typical Tertiary lava pile. The Tertiary lava pile is the oldest bedrock in Iceland (Saemundsson, 1979).

2.2 Geothermal activity

Geothermal activity is abundant in Iceland due to its location on the mid-Atlantic spreading ridge. Hot springs occur almost everywhere (Figure 2) as a result of high heat flow within the earth's crust. About 1000 geothermal localities are found in the country with hot springs known in a few places on the sea floor surrounding the island (Fridleifsson, 1979).

Geothermal activity is classified into high and low-temperature fields. High-temperature fields have temperatures greater than 200°C at 1 km depth. Their heat sources are cooling intrusions or the magma body. High-temperature fields are confined within the active zones of rifting and volcanism (Figure 2). Hot water (and steam) from high-temperature fields is suitable for electricity generation or co-generation such as a binary plant. Low-temperature fields, on the other hand, have temperatures of less than 150°C at 1 km (Bödvarsson, 1961). They occur within Plio-Pleistocene and Tertiary volcanics outside the volcanic zones. The heat sources in low-temperature fields are from crustal heat being conducted and convected upwards along structures (faults and dykes). Hot water from low-temperature fields is suitable for direct use.

3. GEOTHERMAL RESEARCH HISTORY OF TRÖLLADYNGJA

The Trölladyngja high-temperature field is located within the Krýsuvík area within one of five fissure swarms that form the active volcanic zone of the Reykjanes Peninsula. These fissure swarms are surface expressions of dyke swarms, which inland develop into central volcanoes, and constitute the continuation of the Mid-Atlantic Ridge across Iceland. They form en echelon arrays that may be dextral or sinistral, the controlling factor being the direction of maximum tensional stress which is parallel to the direction of spreading (Jakobsson et al., 1978). Exploited high-temperature fields in the Reykjanes Peninsula are the Reykjanes and Svartsengi fields to the southwest and Hengill to the northeast of the Trölladyngja field in the Krýsuvík fissure swarm (Figure 3). The Krýsuvík area is currently licenced by a research permit to the Icelandic power company, HS Orka hf.

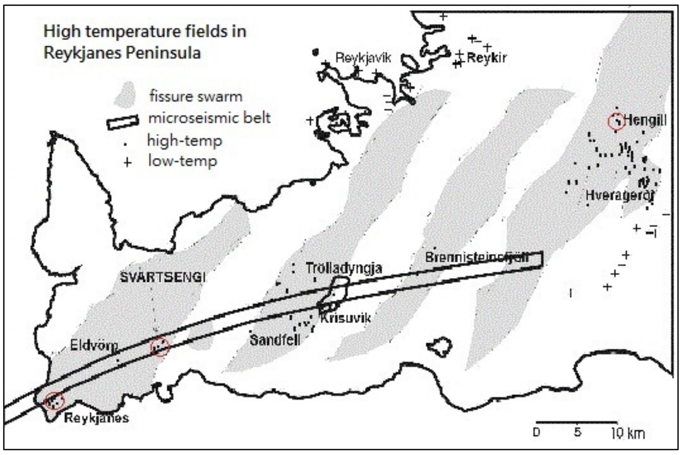

FIGURE 3: High-temperature geothermal fields on the Reykjanes Peninsula (Franzson, 2012)

3.1 Geothermal exploration

The geothermal exploration history of the Trölladyngja-Krýsuvík area was briefly discussed in Section 1.3. Numerous studies were conducted in the area because of its extensive surface geothermal manifestations and convenient location with respect to the capital area. A systematic exploration of the area, initiated in 1970, produced relatively detailed geological, geophysical and geochemical data and some understanding of the geothermal system of the area. At present, in relation to the research permit held by HS Orka hf, the entire Krýsuvík area is being re-mapped by my supervisors, G.Ó. Fridleifsson and K. Saemundsson, who intend to produce both a detailed geothermal map, and a detailed geological map.

The geochemical study of exploration wells KR-05 – KR-08 in the 1970s displayed an inverse thermal gradient passing a temperature maximum at 500 m, as shown in Figure 4. No conclusive evidence was found of the up-flow zones from depth. The highest temperature was obtained in well KR-06 which indicated 260°C at 400-500 m, decreasing to 225°C at deeper levels. The inverse temperature gradients of the wells were explained, based on two hypotheses. The first hypothesis assumed that there were separate up-flow zones not yet localised by the wells and a mushroom shaped body of hot water was at the top of these zones. The second hypothesis assumed gradual cooling of the hydrothermal reservoir from above and below by relatively fresh water which was supposed to be replacing water which was originally more saline (Arnórsson et al., 1975a and b; and Flóvenz et al., 1986).

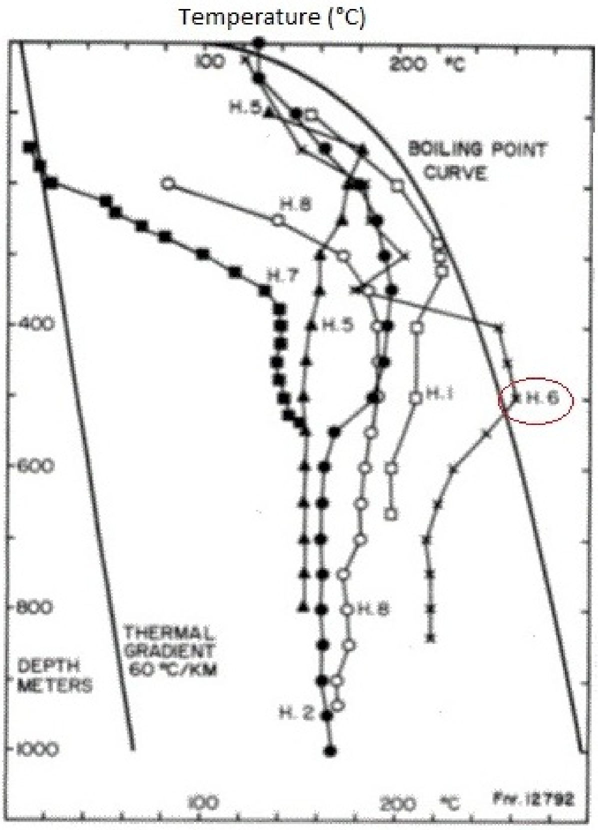

FIGURE 4: Temperature profiles of wells in the Trölladyngja-Krýsuvík high-temperature field including well KR-06 (H6) (Arnórsson et al., 1975)

Drilling of the first deep exploration wells, TR-01 (2307 m) and TR-02 (2280 m) took place in 1999 and 2005. The alteration in TR-01 is intense in the entire well approaching 100°C (heulandite and stilbite) at 50 m, 180°C (quartz) at 120 m and greater than 200°C (wairakite) at 600 m depth. Epidote (>230°C) first occurs at 690 m depth, and actinolite (>280°C) was first found close to 2000 m depth. The bottom temperature reached 320°C. An intrusion (dolerite/gabbro) was analysed from 2,240-2,307 m. It was noted that thin intrusions cool quicker than larger and coarser grained intrusions; hence, large intrusions are heat sources for high-temperature areas, which could be the case for this bottom intrusion in TR-01 (Fridleifsson et al., 2002).

The high-temperature alteration minerals in TR-02 occur at shallower depth than in TR-01. Quartz formed at 180°C occurs at 52 m and again at 92 m. Wairakite (200°C) was found at 304 m and epidote, formed at temperature >230°C, was found at 562 m depth. The temperature at the bottom of well TR-02 was 325°C (Mortensen et al., 2006). A comparison between secondary mineral temperatures and measured and evaluated formation temperatures at present is shown for both wells in Figures 5 and 6.

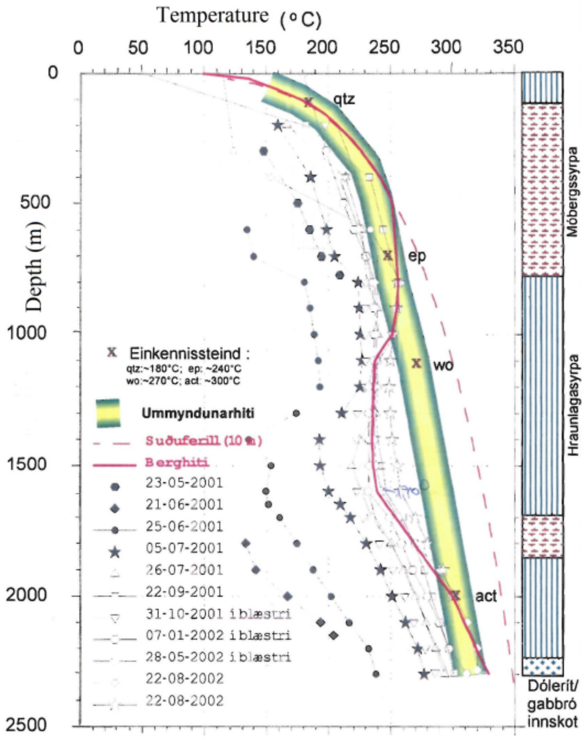

FIGURE 5: Temperature profile of well TR-01 showing mineral (yellow-green), measured (solid red line) temperatures and boiling point curve (dashed red line) (Fridleifsson et al., 2002)

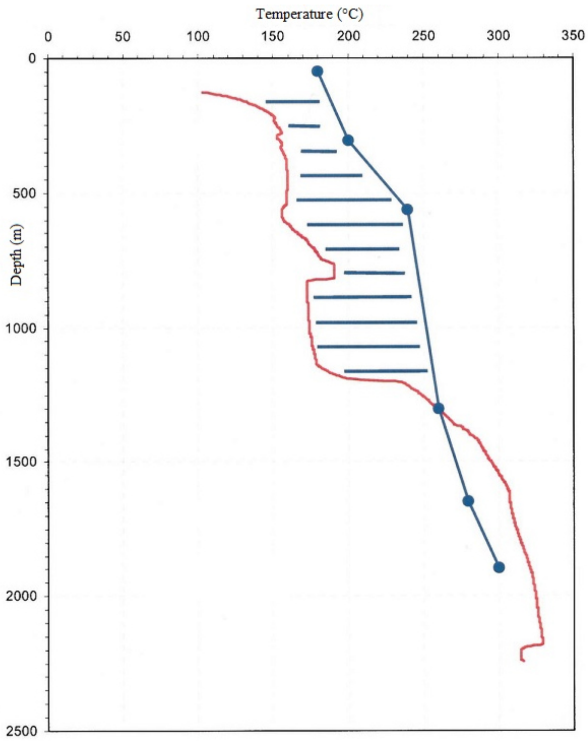

FIGURE 6: Temperature profile of well TR-02 showing mineral (blue) and measured (red) temperatures (Mortensen et al., 2006)

3.2 Geophysical studies

Several resistivity surveys were conducted in the Trölladyngja-Krýsuvík area in the past. A recent survey was carried out in 2007-2008, in relation to the current research permit, that involved twelve additional NW-SE profiles of MT and TEM soundings. The interpretation of the survey was based on a joint inversion of TEM and MT data by Hersir et al. (2010). The resistivity cross-section map of profile SA8 (Figure 7), which runs through wells TR-01 and TR-02, provides the following explanations:

- Surface to 100 m a.s.l. shows a slight to moderately resistive layer (≥ 30 Ωm) related to clay alteration that was observed at the surface near well TR-02 in the Sog Valley.

- The conductive layer (≤ 10 Ωm) at different depths b.s.l. represents the smectite-zeolite layer which corresponds to alteration mineral temperatures observed in wells (heulandite, and stilbite < 100°C in well TR-01 and wairakite at 200°C in well TR-02).
- Slight to moderately resistive layer (≥ 30 Ωm) at 1,400 m b.s.l., but at different depth ranges in wells, represents chlorite-epidote alteration.
- Bottom resistive layer (≥ 70 Ωm) represents somewhat denser and possibly a less altered rock formation of an intrusive nature like those intersected at the bottom of both wells. This layer is within the epidote-actinolite zone.

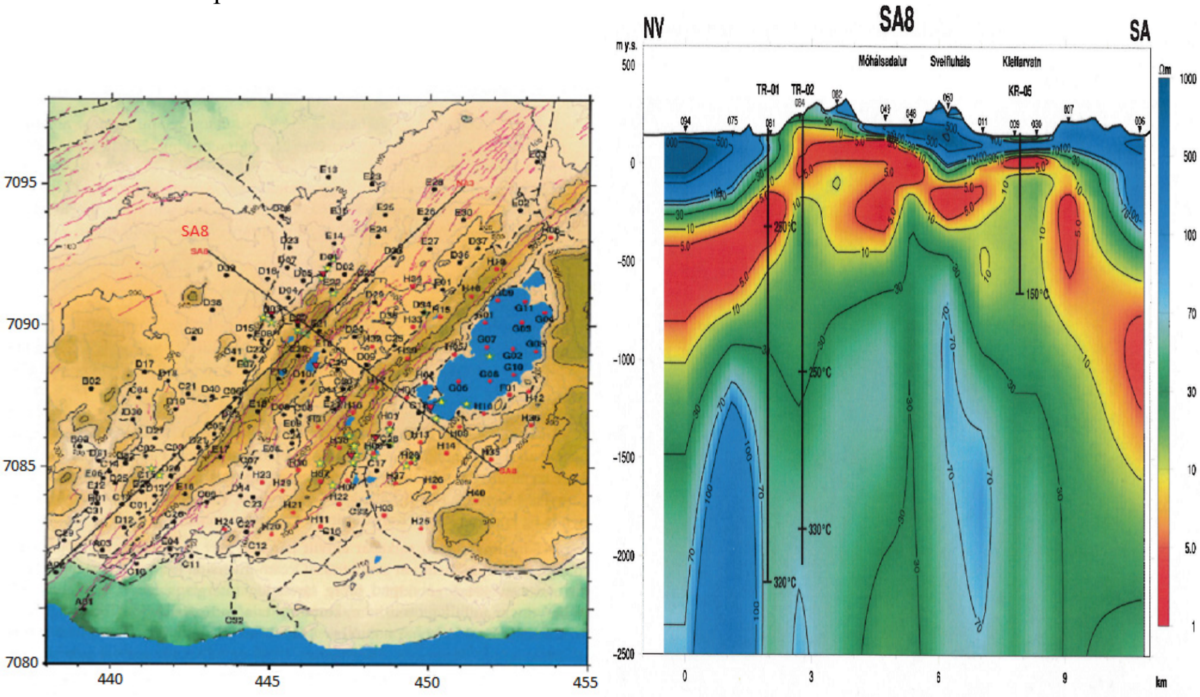

FIGURE 7: (left) Location of MT and TEM survey (profile SA8); and (right) NW-SE cross-section of profile SA8 (Hersir et al., 2010)

Resistivity surveys provide information which is used in conceptual geothermal modelling of a field and aid in siting exploration and production wells. The TEM-MT data gathered during 2007 and 2008 were later interpreted through a 3D MT inversion (Hersir et al., 2011).

4. GEOLOGICAL MAPPING

The Trölladyngja area comprises rock formations that were formed during sub-glacial and postglacial volcanic eruptions. The most prominent geological features are the NE-SW trending hyaloclastite ridges that protrude through the postglacial lava fields at 200-400 m above sea level (a.s.l.). They are steep-sided and are several kilometres long and about a kilometre wide. The hyaloclastite ridges were formed on eruptive fissures under ice during the last glacial period (Weichsel). The postglacial activity in the area consisted of fissure eruptions that produced the Holocene lavas (Jónsson, 1978). Figure 8 is a typical diagram which describes a sub-glacial eruption.

The generally accepted geological time scale with respect to volcanic activity in the area is as follows (e.g. EPICA Community Members, 2004):

Holocene	~ 0-11,700 years (warm period)
Last glaciation (Weichsel)	~ 11,700-110,000 years (cold period)
Last interglacial period (Eemian)	~ 110,000-130,000 years (warm period)

Second last glaciation (Saale)	~ 130,000-200,000 years (cold period)
Second last intergl. period (Holstein)	~ 200,000-240,000 years (warm period)
Third last glaciation (Mindel)	~ 240,000-300,000 years (cold period)
Third last interglacial period	~ 300,000-340,000 years (warm period)

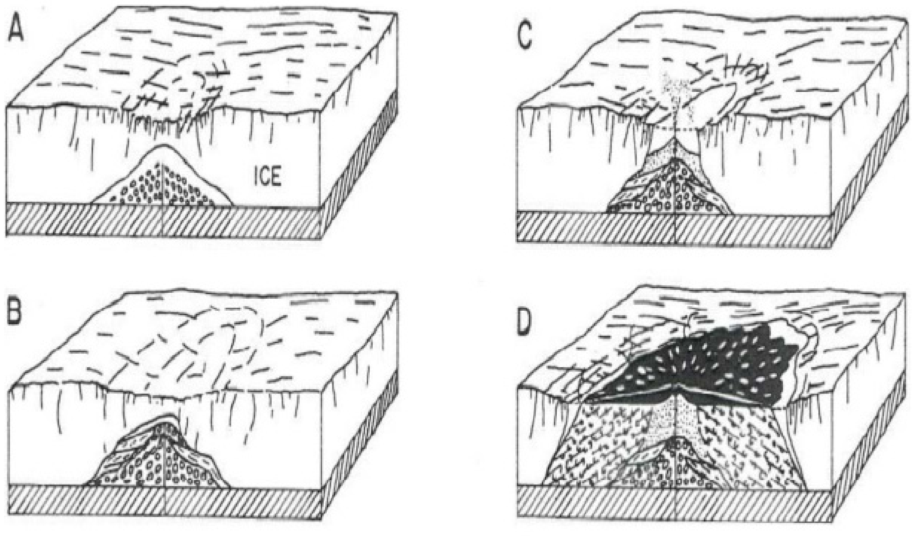

FIGURE 8: Growth of a sub-glacial, monogenetic volcano (Jones, 1969; Saemundsson 1979) A: A pile of pillow lava forms in a deep melt water lake. B: Slumping on the flanks of the pillow lava pile produces pillow breccia. C: Hyaloclastite tuffs are erupted under shallow water conditions. D: A lava cap progrades across its own delta of foreset bedded breccias.

Field work was concentrated on Trölladyngja and the area to the north and west of it. The southeast part of the area was mapped by Al-Dukhain (2008). The geological map of the study area is presented in Figure 9 followed by a NW-SE cross-section of it in Figure 10. The temperature in KR-06 shows substantial cooling of the geothermal system down to 800 m at depth in relatively recent times, based on the occurrence of laumontite (< 180°C). The relatively recent heating is possibly related to dyke injection of the Holocene activity.

4.1 Main rock types

4.1.1 Volcanics

Hyaloclastite, the dominant rock formation in the study area, is made up of pillow lavas, breccias and tuffs.

Pillow lava or pillow basalt is fine grained and has a glassy rind and inter-pillow matrix. It can be aphyric, sparse or rich in feldspar phenocrysts. The pillow lavas have their characteristic pillow shapes and radial jointing structures. The pillow size is generally from ~ 20 cm to a few tens of cm across a few metres of length. They occur as massive outcrops or as large or small clasts within the tuffs and breccias. The pillow lavas break up from weathering and form scree deposits on the slopes of the ridges. Pillow basalts form where water pressure is significantly high enough to prevent mixing of magma and water, thus allowing quenching of the magma upon contact with water and the formation of the distinctive pillow-shapes. Hot lava breaks away from a pillow and forms another pillow. Pillow lava forms during the first eruptive phase in a sub-glacial eruption and commonly represents the basal unit of sub-glacial mountains (Jones, 1969; and Saemundsson, 1979). In the study area, the lower hills and ridges consist almost solely of pillow lava.

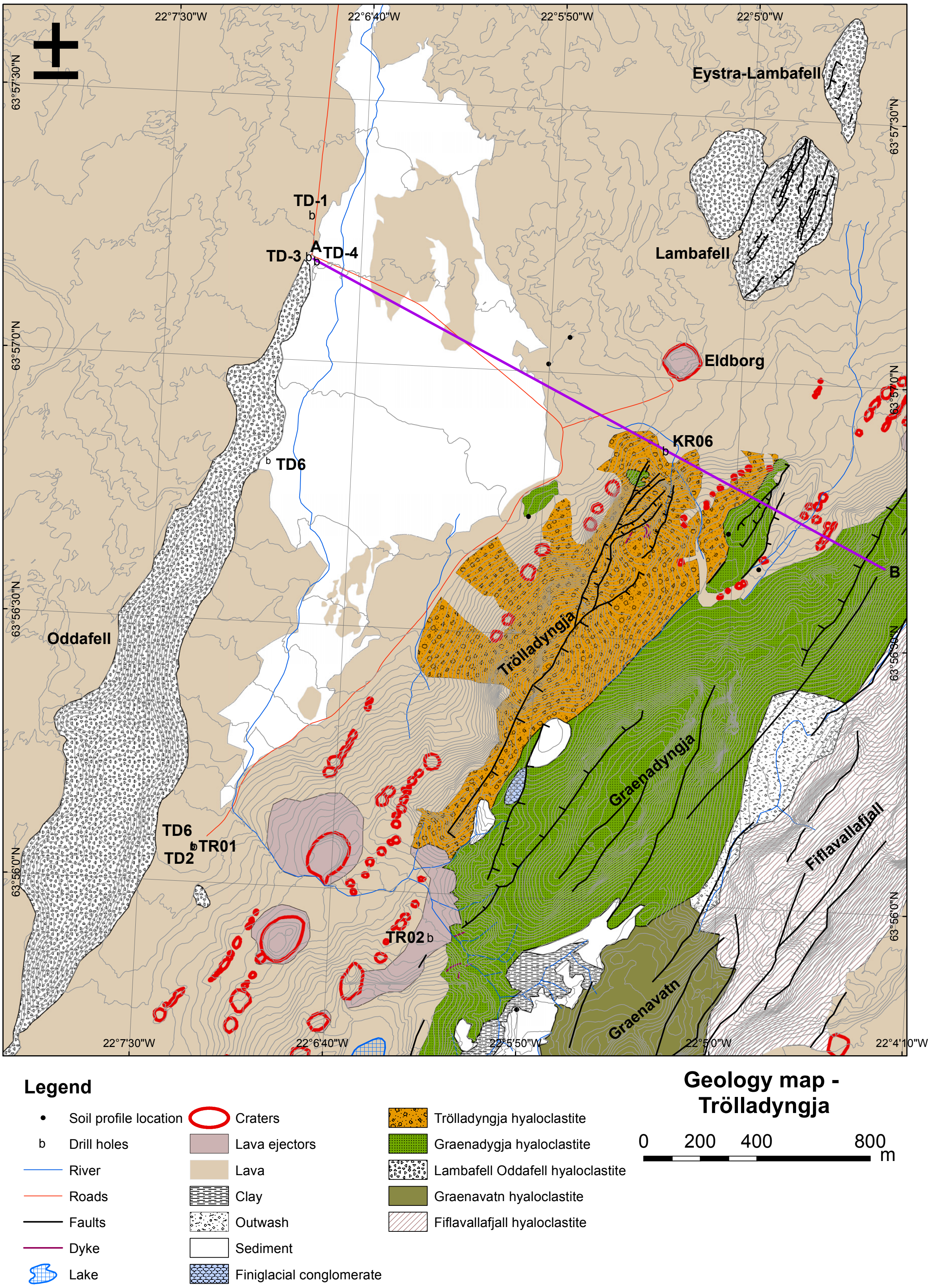

FIGURE 9: Geological map of Trölladyngja

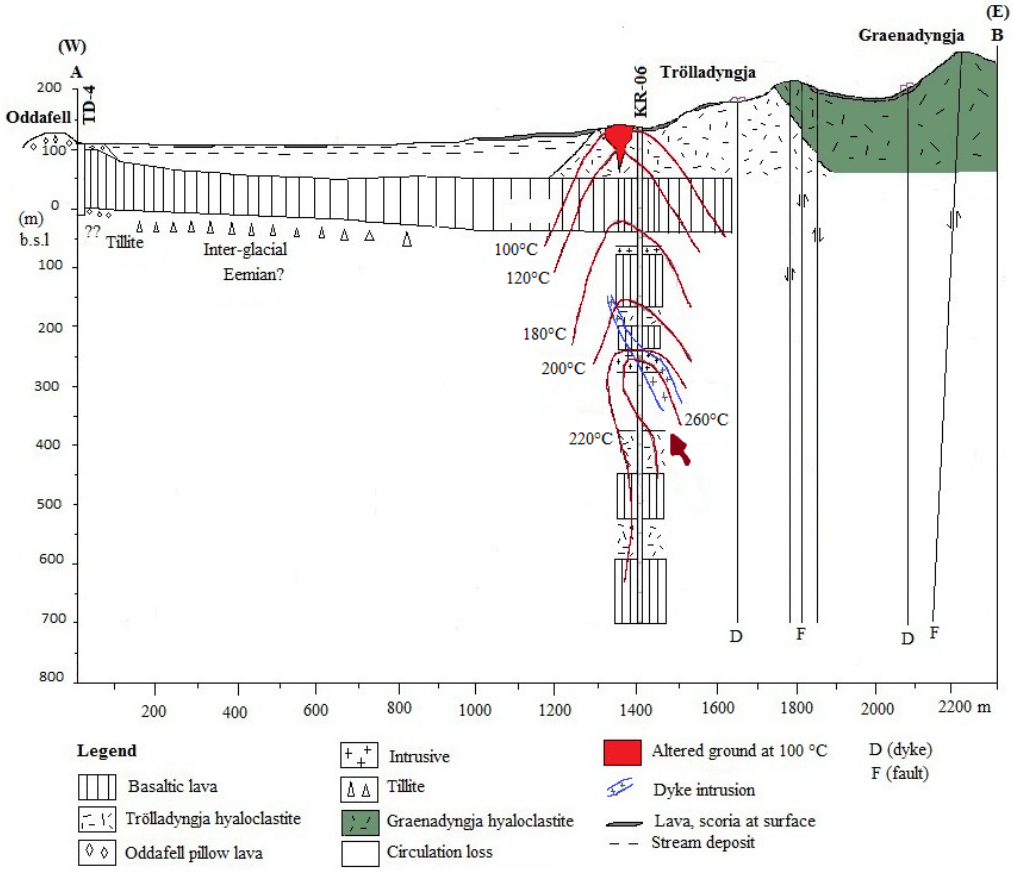

FIGURE 10: Geological cross-section AB, from end of Oddafell through TD-4 and KR-06 and Graenadyngja

The *breccias* are mostly unsorted, glass-rich fragmental rock that contains clasts (made from fragments of pillows and recognised by the glass coating on the surfaces and the vesicle patterns) intermittently with tuffs. The pillow clasts are embedded in a matrix of volcanic glass tuff. The breccias were formed by slumping on the flanks of the pillow lava pile, as described in Figure 8; thus, pillow fragments are the main constituents of the breccias.

The *tuffs* are very conspicuous brown to orange in outcrops that are palagonitized to a varying degree giving them their colour (Figure 11). They consist mainly of sand-sized fragments of clear basalt glass with rinds of palagonite. The tuff is either water-sorted or not water-sorted; the former are fine grained and stratified. They are found on the ridges and their flanks, most prominent on Trölladyngja with the stratified part found mainly higher up on the ridge. The tuff is dominant from the base to higher up the mountains, as observed on Trölladyngja and Graenadyngja. As the eruption lasts, a growing pile of volcanic material eventually reaches shallow water and the eruption changes in character to an explosive phreatic eruption style, producing mainly well bedded fine grained hyaloclastite tuffs. The upper stratified tuff facies formed from explosive phreatic eruptions in shallow water and then emerged from the water, while a lower coarser grained and poorly stratified section was formed sub-aqueously at less efficient explosive activity (Saemundsson, 1979; Jakobsson and Gudmundsson, 2008).

The lower hills, namely Oddafell, Lambafell and Eystra-Lambafell, were formed under ice thick enough to prevent disintegration of the pillows under low continuing pressure, as was the case with the higher mountains (Saemundsson, 1979). The pillow lavas on these hills are fine grained, greyish and mostly aphyric but are sometimes sparsely porphyritic. Oddafell was formed on a fissure but did not erupt at the surface since it was formed in deep water under a glacial cap where water pressure was high (Fridleifsson and Saemundsson, pers. com). Lambafell and the lower hill to the west on Lambafell were formed during a similar sub-glacial eruption in the same manner as Oddafell.

Trölladyngja and Graenadyngja ridges are mostly composed of hyaloclastite tuff with lenses of intermingled pillow breccia in places. The Trölladyngja hyaloclastite ridge is characteristically composed of dense feldspar phenocrysts, giving it a porphyritic texture easily distinguishable from the aphyric Graenadyngja. Graenadyngja is observed to be banking against Trölladyngja on the northern end of Trölladyngja. Two outcrops of Graenadyngja type rock were mapped on the northern and western sides of Trölladyngja. These may have been more extensive, but erosion has left only these remnants. These observations show clearly that Graenadyngja is younger than Trölladyngja.

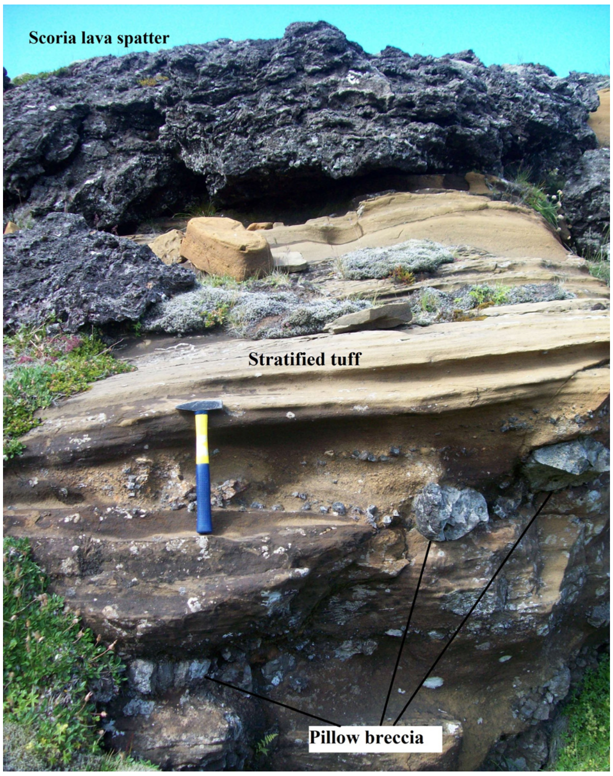

FIGURE 11: Stratified hyaloclastite tuff consisting of varying sizes of pillow breccia and scoria, covered by lava spatter at the northern end of Trölladyngja

The *lavas* in the flat areas and valleys comprise both aa and pahoehoe types. They are fine-grained with a porous glassy scoreaceous surface and are sparsely feldsparphyric. The aa lava appears stringy and rough while the pahoehoe is flat and smooth. The aa variety predominates, whereas pahoehoe was seen locally, forming smooth lava rivers downslope from some of the craters in the northeast and western parts of the map (Figure 9).

The ejecta near the craters consist of scoria, spatter and explosion debris. The *scoria* is distinctly reddish pink, brown and black. It is of very light weight, loose and scattered around and near the crater rims. The scoria formed where lava lumps thrown up from the craters cooled before reaching the ground. The *spatter* was formed from lava fountains where the lava was still hot when it fell to the ground. It is recognizable from the flattened out spatter lumps. The colour is reddish brown and black. The spatter lava grades locally to welded spatter around the craters. Such welding was found to occur at a distance of 120 m from the craters west of Sog Valley and also at the northern end of Trölladyngja. The *explosion debris* consists of blocks and small rocks that have been ejected by explosive activity. These are lava and fragments from the conduit that have been thrown high up and are deposited around the crater. They are mainly found at a 100 m diameter crater west of Sog Valley. Lava pipes observed on the northern end of Trölladyngja show the flow direction from nearby craters and extend down to the flat areas, as shown in Figure 12.

FIGURE 12: Lava pipe on the northern end of Trölladyngja showing flow direction

4.1.2 Stream deposits

The *stream deposit* consists of debris washed down through a gully from the Sog Valley to the east of the map sheet. It consists of material from the hyaloclastite ridges surrounding the Sog Valley, including sediments that were deposited between them. Due to rapid erosion of the Sog Valley, a large amount of clayey sediment was transported onto the 2000 year old lava, forming an extensive outwash plain between Oddafell and Trölladyngja. Stream deposits are referred to as fluvial outwash by Al-Dukhain (2008) and Mbogoni (2008), who mapped the eastern part of the map area. A much older sedimentary deposit of approximately 10 m by 30 m is seen to the north of well TR-02, at the southern end of Trölladyngja. Very thin (0.5-1 cm) layers of fine grey clayey material are observed at the base of the outcrop. The layers thicken upwards with an increase in grain size. The top of the outcrop is covered with unconsolidated material which originated from the hyaloclastite mountains. The sedimentation of fine grained material from the mountains most likely took place under water in late glacial time, aided by geothermal activity, as the sedimentary material is also altered.

Holocene *screes* on the mountain slopes consist of loose material from the hyaloclastite ridges (tuff, breccia and pillow lava). The pillow lava is particularly apt to break up due to weathering. The depression between Trölladyngja and Graenadyngja consists of material from both mountains.

4.1.3 Soil and volcanic ash layers

The soil of the area consists mainly of wind-blown volcanic dust, brown in colour. The thicknesses vary. In sheltered positions, it may be several meters at low grounds within the hyaloclastite ridges. Thin layers of grey and black volcanic ash occur within the soil. The lavas are typically moss covered. Soil on the 2000 year old lava is absent or very thin.

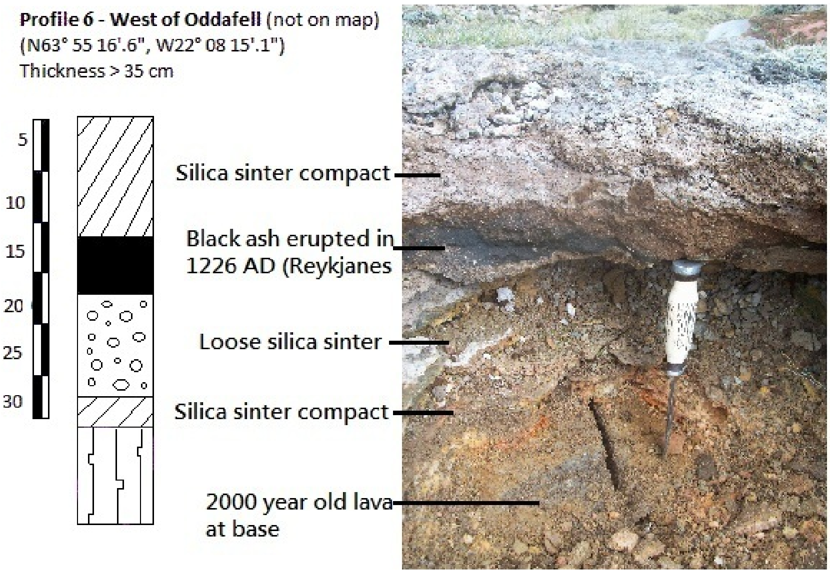

FIGURE 13: Profile of extinct geyser site south of Oddafell showing the different layers identified

Several pits were dug up to inspect the soil and ash layers in the area. The locations are indicated in Figure 9. Five soil profiles are attached in Appendix I, two of which are located outside of the map. An old sinter site, observed 200-300 m south of Oddafell, is shown in Figure 13 as an example. The Holocene lava around the old sinter site appears to be broken up, unlike the lava in the surrounding area. The sinter was formed during geyser activity, which apparently followed the 2000 year old lava eruption. Geyser activity was then repeated in historic time after the 1226 AD ash layer was deposited. The sinter deposit is an indication of deep reservoir water reaching the surface.

Volcanic ash from distant volcanoes is also found in the soil sections, like ash layers from Katla, Hekla, and Reykjanes, which erupted in 1226 AD. A light coloured ash was deposited at about 870 AD at the time of the settlement of Iceland. The ash layers are extensively used in Iceland to date postglacial lava flows (Sigurgeirsson and Saemundsson, 2010).

4.2 Tectonics

The tectonic features in the area are characterised by the occurrence of faults and fissures that have a general NE-SW trend. They are controlled by the regional tectonic setting of the Reykjanes Peninsula.

4.2.1 Faults

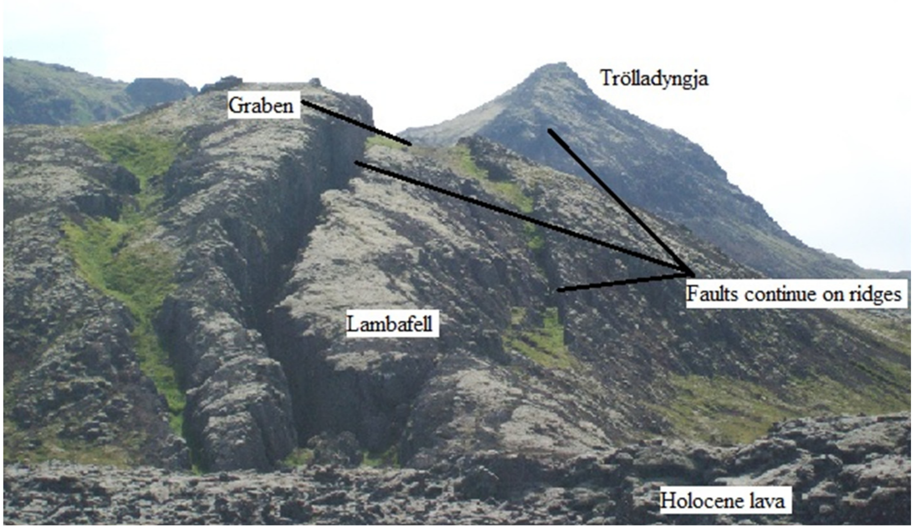

FIGURE 14: A photograph showing continuity of normal faults from Trölladyngja to Lambafell

Numerous NE-SW trending normal faults occur in the area. The faults on the northern end of Trölladyngja continue to Lambafell and Eystra-Lambafell (Figure 14). They are clearly seen in the field and on aerial photos and were mapped in detail. Fumaroles occur between Trölla-dyngja, Eldborg and Lambafell, indicating continuity of faults that are buried by the 2000 year old lava. Fault fissures of 3-30 meters deep occur on Lambafell, forming a small graben. The throws of some of the faults range from 1-6 meters either to the east or west.

4.2.2 Dykes

A few dykes were mapped on the northern end of Trölladyngja and in the creek in Sog Valley near well TR-02. They generally trend NE-SW, having the same trend as the faults and fissures represented on the surface by hyaloclastite ridges and the crater rows. The apparent strike of the observed dykes was 50-65°NE and they dip steeply to the southeast (65-84°SE). Their thickness ranges from 30-60 cm at both locations. The basaltic dykes observed in Sog Valley are aphyric. A few millimetre thick calcite veins were noted in those dykes. The dykes on Trölladyngja, however, are feldspar porphyritic. They are columnar jointed and do not necessarily trend NE-SW, except for one where the apparent strike is 48°NE and the dip is 84°SE. The chilled margins between the dykes and the hyaloclastites are black in colour, characteristic of trachytic basaltic glass.

5. GEOTHERMAL MAPPING

5.1 Geothermal manifestations

The geothermal manifestations in the area are fumaroles and hot and altered grounds left behind by previous fumarolic activity. No hot springs were found; the only cold spring at the time of mapping was located to the southeast in Sog Valley. A number of fumaroles in a 4 by 15 m area occur ~100 m south of drill hole TR-02. The vent areas consist of coloured (white, red, green, yellow, brownish orange) precipitates that are referred to as sulphate salts or hot spring salts. These sulphate salts are pickeringite and have a bitter taste. They usually dissolve easily during rainy periods. The highest temperature obtained for this area is at boiling temperature (99°C). An active fumarole, also at boiling temperature, is located ~150 m east of TR-02 in Sog Valley (Figure 15). It is 4 m wide and forms a light brownish clayey mound of sulphate salts (white, yellow, reddish-orange). It is steaming hot and emits sulphuric gas. A couple of fumaroles on Lambafell emit steam through greenish altered pillow basalts that are oxidised on the surface. The temperatures of these two fumaroles are 60 and 93°C, respectively.

Several fumaroles occur in the lava fields between well KR-06 and Eldborg, and between Eldborg and Lambafell. The highest temperatures for these areas are 69°C and 86°C, respectively. Previous

FIGURE 15: An active fumarole in Sog Valley showing clayey mound and pickeringite (coloured sulphate salts)

fumarolic active areas with temperatures almost at the boiling point are altered to clay, represented by various colours such as green, yellow, white, pinkish purple, etc., with visible steam vents. A 10 m by 30 m fumarolic area is found on Oddafell and much smaller areas on Lambafell and the northern end of Trölladyngja near well KR-06. Their temperatures are 99, 87 and 102.4°C, respectively. The vegetation, especially moss grass on hot ground and near fumaroles, is quite different from those on non-active grounds. The moss grass is light yellowish-green and can easily be identified. It was noted that there was an increase in the amount of steam emitted from the fumaroles after it rained. Hence, the previously active areas are lacking water and cannot produce steam even though the ground is hot.

The geothermal manifestations are structurally controlled, as can be noted by the fumaroles in the lava field between Trölladyngja and Lambafell. The faults from Trölladyngja continue to Lambafell and on to Eystra-Lambafell, as observed in the field as shown in Figure 16. The fumaroles are more likely located on faults that are covered by the lava.

5.2 Surface alteration

Alteration of a rock is a result of chemical changes in its mineral composition. The original rock is partly or completely altered when one or more minerals have altered to a new mineral or completely new minerals have formed due to the effects of hydrothermal fluids (heat and water). The alteration types are usually identified according to the intensity of the alteration, ranging from very weak to very intense alteration. A rock that is completely changed to clay is referred to as being most intensely altered. A distinction is made between palagonitization of hyaloclastites and true hydrothermal alteration.

Hydrothermal rock alteration in the map area is of two main types: (i) an old and extinct alteration, related to hydrothermal activity of Pleistocene age, and (ii) young alteration of Holocene age, at or near the present-day surface. Rocks showing the former alteration type have been exposed due to erosion and include some minerals which were formed at higher pressure and temperature than can thrive at the surface. The latter type has been active from early Holocene time, and only a fraction of it is still active. In places, early Holocene alteration may be covered by soil, and the former hydrothermal activity can thus be dated by using C^{14} age dating of peat, and/or by tephrochronological studies of ash layers, as discussed in Section 4.1.3.

All hyaloclastites in the area have undergone cold alteration called palagonitization, formed at ambient weathering temperatures, and aided by rainwater that percolates through the rocks. The main component of hyaloclastites, basaltic glass, is very unstable in water and, therefore, alters forming distinct coloured rinds on every glass grain (e.g. pillow rims, hyaloclastite particles, fractures, vesicle walls) exposed to fluids. The intensity of the palagonitization colours may dependent on the temperature. The lighter coloured palagonite is formed at lower ambient temperatures, whereas the rare dark reddish palagonite is possibly formed at higher temperatures in the vicinity of fumarolic activity (Stroncik and Schmincke, 2002). The following alterations were observed in the field and are represented in Figure 16:

Intense alteration of Pleistocene age is represented by greenish grey altered hyaloclastites (Figure 17). The basaltic glass in the hyaloclastites has altered to smectitic clays at around 100-200°C, greatly changing the original rock. Trölladyngja has, in places (at the southern end), undergone such intense

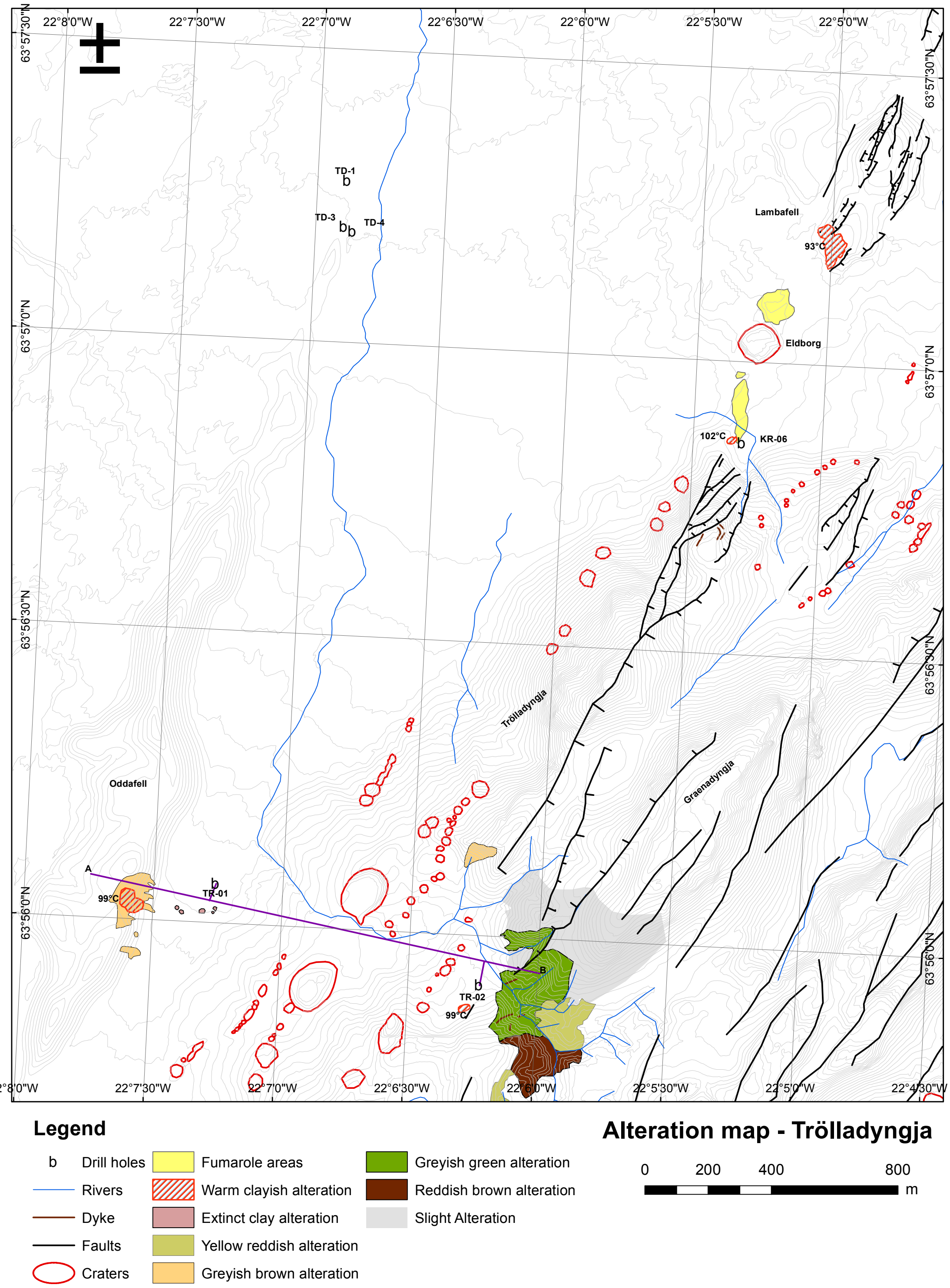

FIGURE 16: Geothermal map of Trölladyngja

alteration, as well as Graenadyngja on the south side. Intense alteration of Holocene age also occurs in the area, represented by extinct clayey altered spots on Lambafell, Oddafell and near well KR-06 (Figure 18). Pillow lavas on Lambafell and Oddafell, near extinct spots, are greenish grey.

A mixed-layer alteration was noted in the Sog Valley near well TR-02 by Al-Dukhain (2008), where hyaloclastite has undergone smectite-chlorite alteration. A similar alteration type was observed southeast of well TR-02 on Graenadyngja where a dyke has cut through the hyaloclastites (pillow basalt), showing greenish chloritic clay (probably smectite or mixed-layer clay) and including well-formed

FIGURE 17: Intense alteration on southern end of Trölladyngja

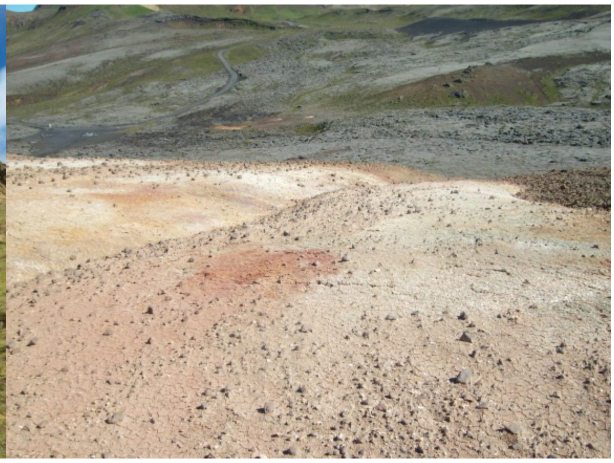

FIGURE 18: Intense alteration of pillow lava to clay by extinct fumarolic activity on Oddafell

quartz crystals in pores. The formation temperature for mixed-layer clays occurs at 200-240°C. The secondary mineral distribution in drillhole TR-02 (Section 3.1) can be compared to this observation, where quartz (formed at or above 180°C) occurs at 50 m depth in the drillhole, while epidote, formed at T>230°C, first occurred at 562 m. The clay minerals need to be identified by the X-ray diffraction method (XRD), which was not undertaken during the present study.

Medium intensity alteration is represented by reddish to orange brown coloured hyaloclastites that have undergone hydrothermal alteration whose intensity is just below the highly intense alteration. This type of alteration is where the volcanic glass is partly altered to smectitic clays and where amorphous silica, calcite (or aragonite) and low-temperature zeolites may have been deposited in veins and vesicles. This type of alteration surrounds the intensively altered Pleistocene alteration sites, but is also found elsewhere in the Krýsuvík field (Fridleifsson, pers. com.), though it is not so common in the present mapped area.

Weak-or low-intensity alteration is characterised by less altered hyaloclastites that have infillings of zeolites and calcite. Thin section observation by Al-Dukain (2008) showed partial alteration of basaltic glass to brown palagonite and some smectite. Hyaloclastites that have undergone low or slight alteration are usually darker coloured than the reddish brown palagonites. This alteration type was observed on the west side of Graenadyngja.

5.3 Lineaments

Steeply dipping NE-SW trending normal faults occur in the area cutting through the hyaloclastite ridges. The faults are seen in the ridges but not in the lava fields. However, the faults seem to continue from Trölladyngja below the lava fields across to Lambafell and Eystra-Lambafell. Geothermal manifestations follow this lineament on the surface, apparently structurally controlled by the faults underneath, and possibly along a feeder dyke to the Eldborg crater.

Three volcanic fissure swarms trending in the same manner as the faults, were noted in the area by mapping the Holocene volcanic crater rows. All the fissure eruptions took place during rifting episodes in the Trölladyngja fissure swarm during Post-glacial times, the earliest taking place 5000-7000 years while the latest about 2000 years ago (Flóvenz et al., 1986). Within the fissure swarms, at depth, volcanic dykes are evidently emplaced, and possibly also more widespread intrusions, as well (sills or laccoliths). Mapping of such young volcanic features is, therefore, important in relation to geothermal mapping of active manifestations, and normally these young features are included on a geothermal map, as well as all faults and fractures.

6. GEOTHERMAL MODEL AND DISCUSSION

The general scheme of alteration minerals in Iceland is grouped according to mineral assemblages and rock temperature relationships. Minor differences may occur due to the varying composition of basaltic rocks. Smectites, zeolites, calcite, pyrite and quartz form at rock temperatures below 200°C followed by the transformation of smectites into mixed-layer clay minerals and swelling chlorites in a temperature range of 200-230°C. Chlorite, epidote and prehnite form at slightly higher temperature, and actinolite (>280°C) forms at temperatures approaching 300°C (Kristmannsdóttir, 1979).

Two NW-SE cross-sections were chosen to display surface and sub-surface features. The former is shown in Figure 10, extending from Oddafell to well KR-06 and Trölladyngja on the north side. The latter is shown in a simplified geothermal model (Figure 19), extending from the active fumarole field at Oddafell through well TR-01 across to well TR-02, just south of the Trölladyngja ridge. The geothermal manifestations at both ends are at boiling temperatures and occur along a fault in the southeast and on a fissure in the northwest. The lithology in both wells includes basaltic hyaloclastites, basaltic lavas and intrusives that were formed during the last several glacial and inter-glacial periods

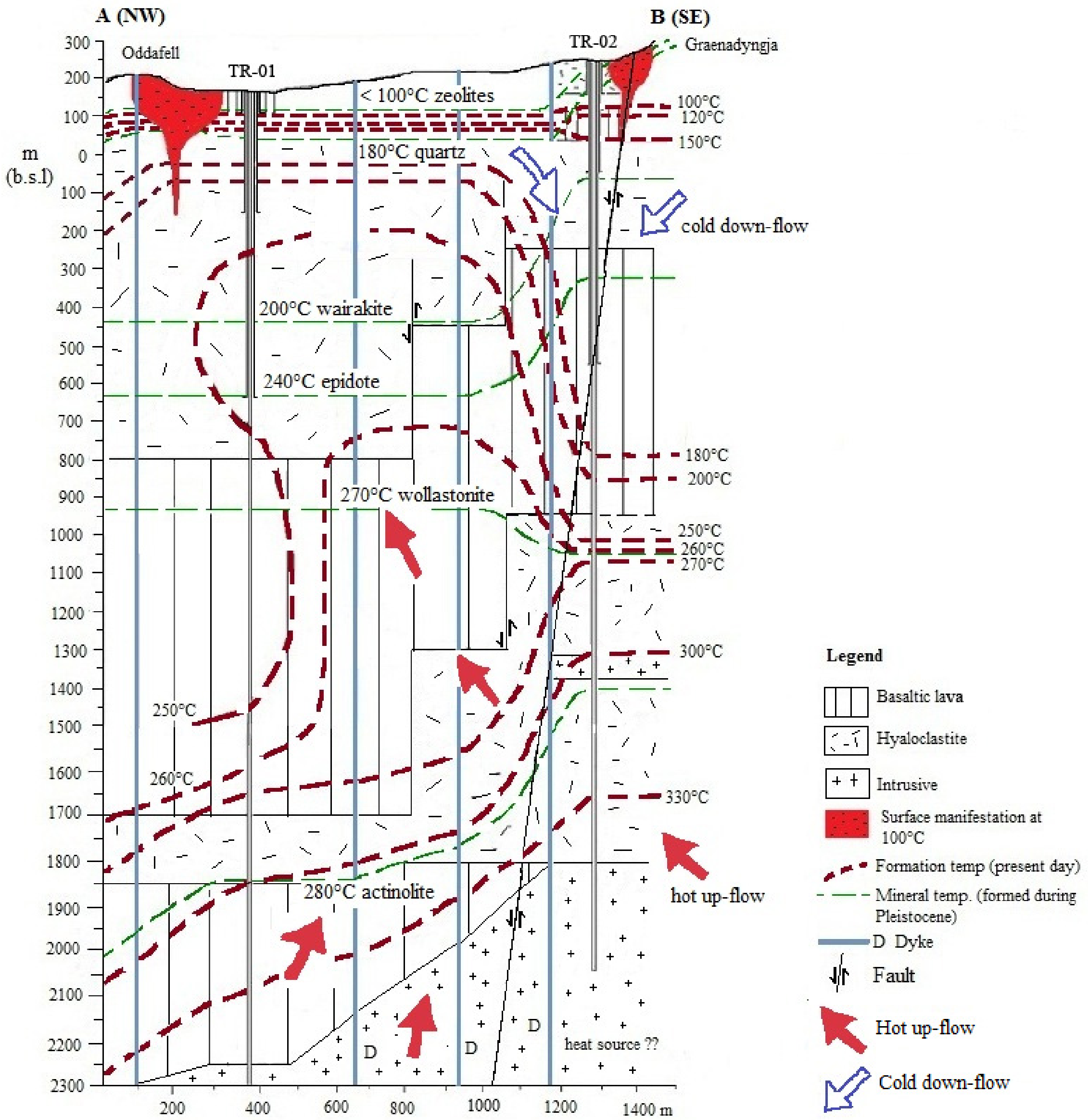

FIGURE 19: Conceptual model of the geothermal activity in the Trölladyngja area (cross-section NW-SE through wells TR-01 and TR-02, indicated by profile A-B in Figure 16)

(Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006). The number of intrusives increases with increasing depth. An intrusive body (dolerite/gabbro) is located below 2000 m and extends to the bottom in both wells, and may possibly be a part of the same intrusive body. Three volcanic fissures, mapped in detail, are shown between the wells with Oddafell (which is fissure-fed itself) in the NW, characterized by vertical dykes in the model (Figure 19). Several large phreatic craters occur at the surface on the southeast side of the cross-section in the mapped area. These large and localized craters may possibly have formed due to interaction with the underlying geothermal system. Magmatic intrusions are the heat sources of geothermal systems, and the larger they are the better as small intrusions cool faster than large ones.

The alteration mineral temperatures obtained from analyses of the drill cuttings (Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006) are inserted into the model in Figure 19, and correlated between the two wells. low-temperature smectite-zeolites appear at the upper levels, quartz (180°C) at 50 m and wairakite (at 200°C) appearing at 300-400 m. Epidote (240°C) is found below 500-600 m while wollastonite, formed at temperatures approaching 270°C, is found below 1,300 m. Actinolite, formed at temperature above 280°C, appears deeper still at 1,580 m in well TR-02 and at 2,000 m in well TR-01. The present-day reservoir temperatures, interpreted from measured temperature logs taken after the drillholes recovered from drilling, can then be compared with the alteration mineral temperatures in both drillholes. The result is quite striking, showing firstly that the alteration grade (mineral temperatures) rises to the southeast, and secondly, that dramatic cooling has taken place in the field close to well TR-02. Up-flow of hot geothermal fluids is shown by red arrows, while cooling down-flow is shown by blue arrows in Figure 19.

The main conclusions based on the model are listed below:

- The thermal reversal observed in well TR-01 (indicated by a thick red line) is similar to that in well KR-06 (Figure 4). By interpreting the temperature profiles between wells TR-01 and TR-02, the temperature inversion in well TR-01 appears to be related to some cooling from the southwest.
- Geothermal manifestations are distributed linearly along the NE-SW normal faults and fissures and indicate up-flow zones controlled by these structures. The alteration and related temperatures at shallow depths, however, indicate fossil temperature that is related to Pleistocene hydrothermal activity and, therefore, is not representative of the present-day reservoir conditions except at great depths.
- The southeast part of the system has suffered dramatic cooling in relatively recent time, for unknown reasons. It may possibly have been caused by interaction between the hydrothermal system at upper levels (above 1,200 m depth) and the magma leading to the eruption of the large scoria craters at the surface 2000 years ago just west of well TR-02. However, other explanations are also possible. It is clear that the vividly active Pleistocene hydrothermal activity, now exposed in the Sog valley and surrounding area, has long since cooled down at the surface, the extent downwards being unknown. Possibly the clear cooling in well TR-02 may be indicative of widespread cooling to the east of the well in the uppermost 1 km or so.
- In order to connect and correlate the simplified lithological profiles between wells TR-01 and TR-02 as presented in the existing well reports (Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006), one or two very large faults need to be assumed, as shown in the model in Figure 19. However, such huge faults are not likely to exist at this site, and more detailed work on the lithological correlation is needed (Fridleifsson, pers. comm.).

7. CONCLUSIONS

The Trölladyngja field within the Krýsuvík geothermal area is a sub-field within one of the five high-temperature geothermal areas on the Reykjanes Peninsula (Reykjanes, Svartsengi, Krýsuvík, Brennisteinsfjöll, Hengill), in southwest Iceland. The low grounds in the study area are mostly covered by Holocene lava flows, while Trölladyngja and the nearby Graenadyngja are prominent hyaloclastite ridges, formed by sub-glacial eruptions during the last glaciation (Weichsel).

The tectonic features of the area are characterised by the occurrence of normal faults that trend N20-40°E. Several fissures and dykes have a similar trend and all are related to the regional tectonic setting of the Reykjanes Peninsula. The geothermal manifestations are distributed linearly along the faults indicating up-flow zones controlled by these structures.

The geothermal system in the eastern part of the area has cooled substantially from the surface down to more than 1 km depth in the field surrounding well TR-02. The extent of this cooling is not known. An extinct geyser site with sinter deposits is located 200-300 m to the south of well TR-01. Sinter activity was episodic in historic times. Combining information on the interpreted up-flows, down-flows and cooling, with the surface manifestations, may suggest a potential drilling target by drilling a directional well from well TR-01 towards the sinter site in the south.

In the north, close to well KR-06, potential drilling targets exist along the fumarole field which is tectonically controlled by a fault and fracture zone, involving young basaltic dykes as well.

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APPENDIX I: Five soil profiles from the Trölladyngja area

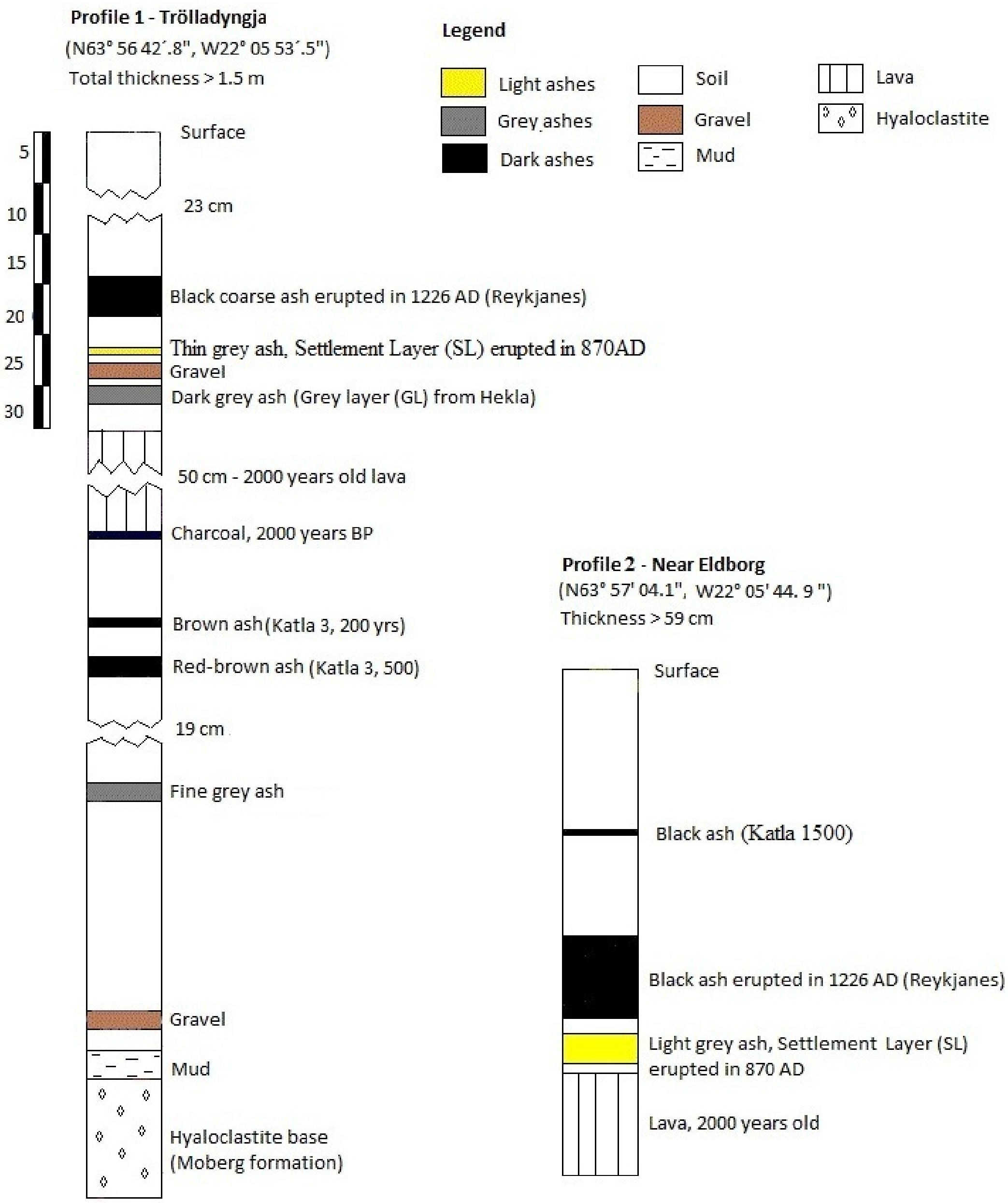

FIGURE 1: Soil profiles 1 and 2

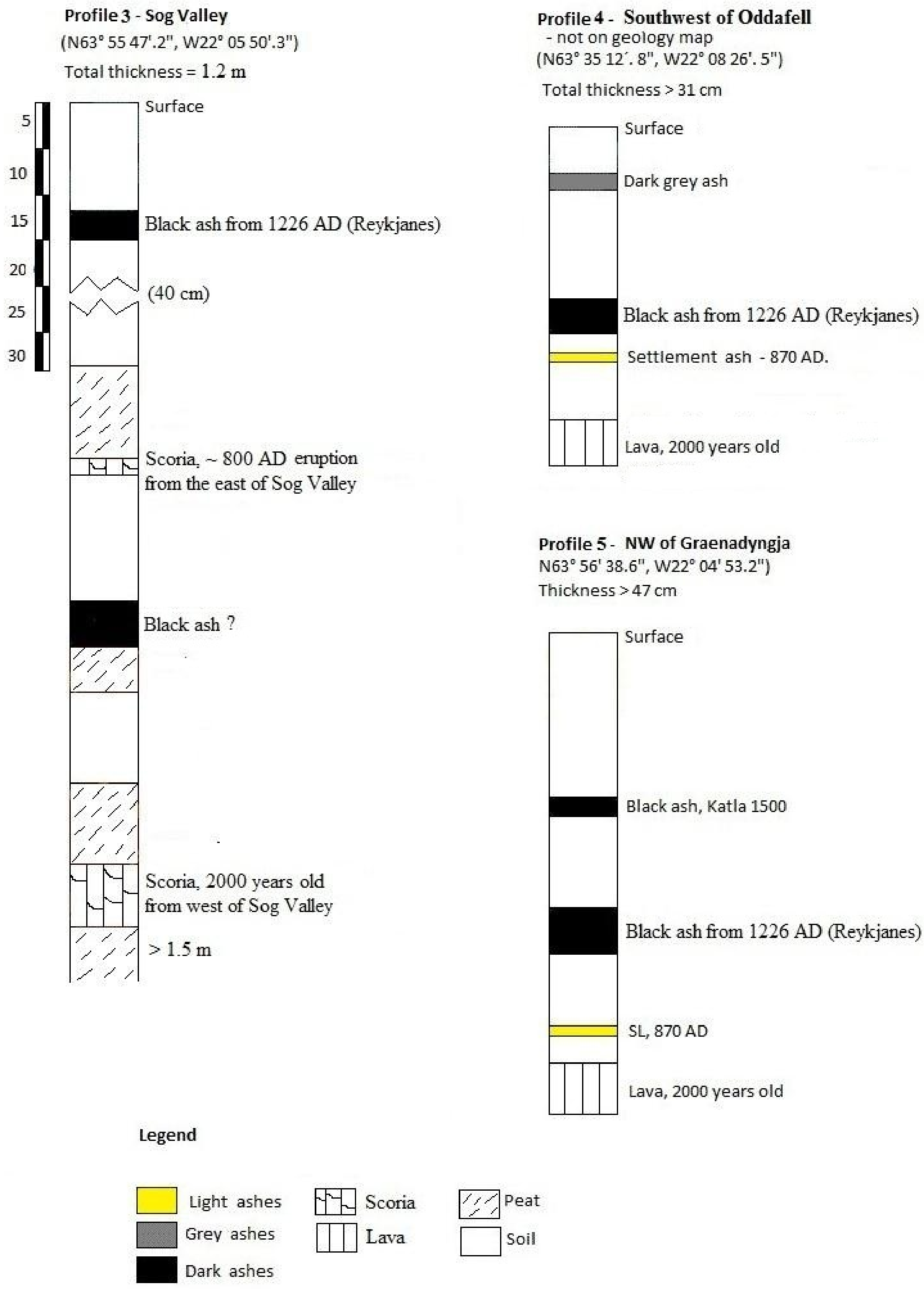

FIGURE 2: Soil profiles 3, 4 and 5