



UNITED NATIONS
UNIVERSITY

GEOHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
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Reports 2007
Number 8

GEOHERMAL MAPPING IN THE KRÝSUVÍK GEOHERMAL FIELD

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ABSTRACT

This report describes the results of a mapping exercise of surface geothermal manifestations and the main structures of the Hveradalir field in the Krýsuvík area, SW Iceland. The main aim of this project was to map the geothermal manifestations in order to find out if a correlation existed between geothermal, volcanic and tectonic features in this field.

The main manifestations mapped include fumaroles and steaming grounds, mud pits, hot, warm and cold springs, and hot and warm grounds delineated by 50°C isotherms and 15°C isotherms, respectively. The manifestations are seen to be controlled by NE–SW oriented faults. The lithology of the study area includes three lithological units. A hyaloclastite unit belonging to the youngest Sveifluháls hyaloclastite formation is by far the most voluminous unit and hosts all the geothermal manifestations. This hyaloclastite unit is from the last glacial period. Mappable lava patches of much younger age, either of late interstadial or very early Holocene age, are found exposed on top of the hyaloclastite. Of younger age still is a scoriaceous tephra and earth ejected from explosive craters of early Holocene age.

1. INTRODUCTION

Geothermal energy is an important energy source. Economic efficiency, reliability and environmental benefits are factors justifying a wide application of geothermal energy in many countries. Geological and geothermal mapping are amongst the first conventional research methods to evaluate a geothermal resource that can lead to utilization. Commonly, the siting of exploratory drill holes in geothermal fields has been based on geological mapping of geothermal manifestations and their relationship to geological structures.

The present project in geothermal mapping was carried out in one of the sub-fields of the extensive Krýsuvík high-temperature area in the central part of the Reykjanes peninsula, SW-Iceland. The Krýsuvík geothermal field is one of five main high-temperature fields on the Reykjanes peninsula in SW-Iceland. The others are Reykjanes, Svartsengi, Brennisteinsfjöll and the Hengill geothermal fields. The larger of these fields are split into several sub-fields. The Krýsuvík field, for instance,

includes the Sandfell, Trölladyngja, Köldunámur, Seltún, Hveradalir and Austurengjahver sub-fields. The present reports deals with a part of the Hveradalir sub-field.

The surface geothermal manifestations in the Hveradalir sub-field consist of hot ground where the bed rock has been intensely altered by acid surface leaching. In this hot ground, steam vents and mud pools are common as well as local solfataras. Fumaroles and hot ground are very often located along faults and fissures indicating that these near-vertical structures control the upflow of the geothermal fluid (Arnórsson et al., 1975a and b). According to a conceptual model of the development of volcanic centres in Iceland, the Krýsuvík field is in an early stage of evolution with no major shallow magma chamber (Arnórsson, 1987).

The Krýsuvík area has attracted the interest of researchers for many decades. A short summary report on the historical activity was presented by Ármannsson and Thórhallsson (1996). Sulphur was mined intermittently in the Krýsuvík geothermal field during the 18th and 19th centuries and exported to Europe for military purposes. During most of the 20th century, the local municipalities have been keen on utilizing the geothermal fields in the Krýsuvík area for electricity production, large scale domestic heating, and other purposes such as balneology, green housing, etc. So far, however, no large scale utilization has been realized. During 1945-1950 some 19 shallow exploration wells (KV-series) were drilled in the Krýsuvík field and some of them were used locally for various purposes. Three additional wells were drilled in 1960 (KR-series), two of them more than 1200 m deep. An additional well (KR-04) was drilled in 1964 within the present study field and used locally for the following decades, until it was replaced by a new well in 1995 (KR-09). Information from well KR-09 is used for the geothermal model presented in this report.

In relation to an extensive geothermal exploration effort in the early 1970s, four more slim exploration holes were drilled in the Krýsuvík area in 1971, wells KR-05 to KR-08 (Arnórsson et al., 1975a and b). The result of all this exploratory activity was rather negative, as all the deep exploration wells showed temperature reversal with increasing depth. The highest temperature measured was 262°C in well KR-06 in the Trölladyngja sub-field at 400-500 m depth. Some 19 geological maps in the scale 1:25.000 of the entire Reykjanes peninsula were published a few years later (Jónsson, 1978), with chief emphasis on the Holocene lavas. Arnórsson (1987) published a paper on the gas chemistry of the Krýsuvík geothermal fields, suggesting reservoir temperatures approaching 300°C.

The next serious exploratory phase began at the end of last century with an extensive resistivity survey and the drilling of well TR-01 and later TR-02 in the Trölladyngja sub-field, (Eysteinnsson, 2001; Fridleifsson et al., 2002; Mortensen et al., 2006). The highest bottom hole temperatures at 2.3 km depth are close to 320°C in both these wells, but both also show a temperature reversal below 700-800 m, which affects the production character severely. Further appraisal drilling is needed in the Trölladyngja sub-field. The current exploration and appraisal activity is funded by the Hitaveita Sudurnesja Ltd. Energy Company, which has a research permit for the entire Krýsuvík area. The survey included an extensive geothermal survey with detailed geological and geothermal mapping, TEM and MT resistivity surveys, a gravity survey, a geochemical survey and more exploration drilling including several 2-2.5 km deep wells. This may lead to utilization of some of the Krýsuvík sub-fields in the near future. The present mapping exercise is linked to this survey effort.

2. GENERAL GEOLOGY AND GEOTHERMAL ASPECTS OF ICELAND

2.1 Geological setting

The Icelandic basalt plateau is situated at the junction of two large submarine physiographic structures, the Mid-Atlantic Ridge and the Greenland–Iceland–Faeroe Ridge (Figure 1). This plate boundary slowly diverges 1 cm per year in each direction, and is marked by a zone of seismic and volcanic activity. The construction of the Icelandic basalt plateau is considered to be the product of an

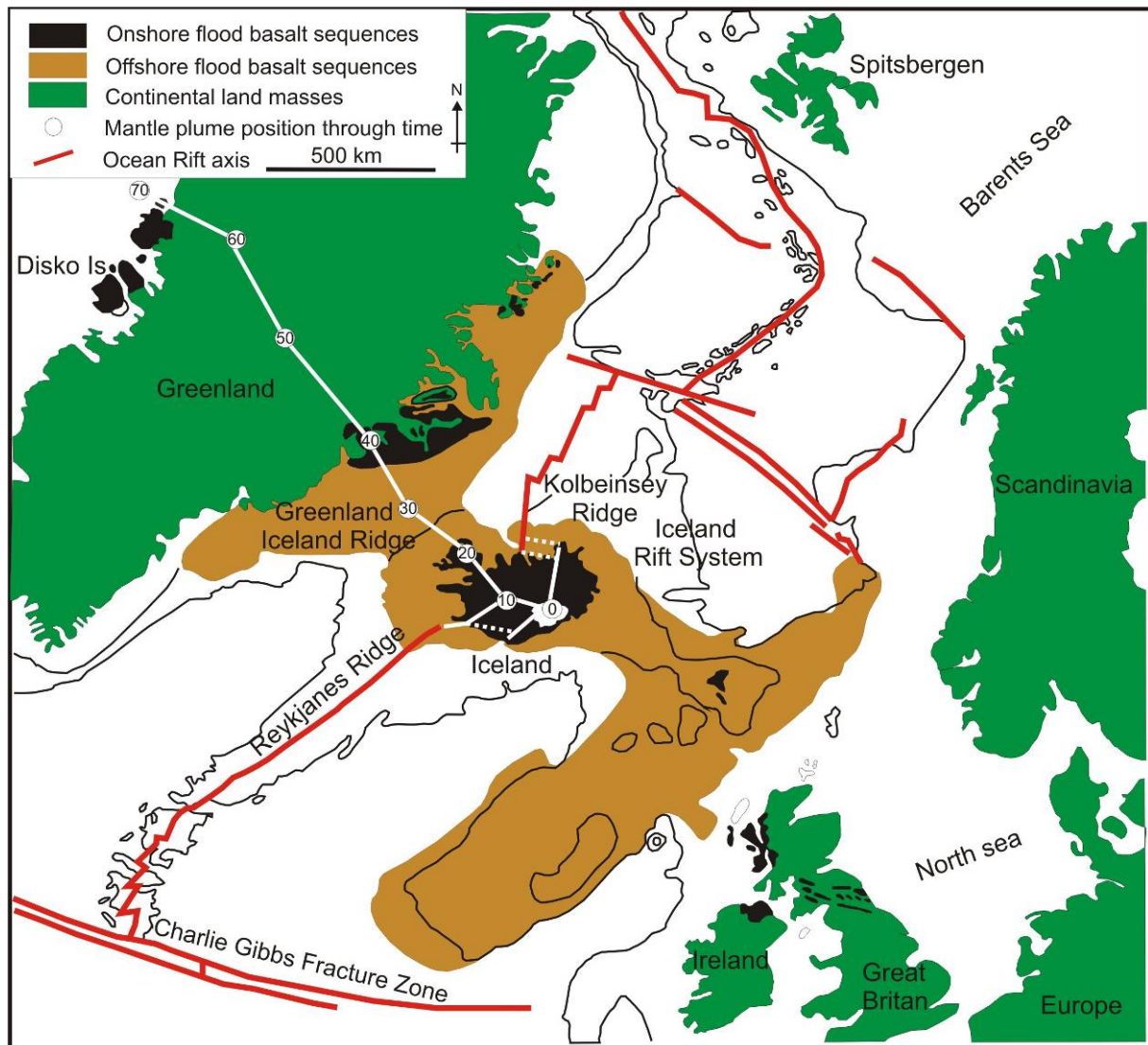


FIGURE 1: Iceland is an elevated plateau in the middle of the North Atlantic, situated at the junction between the Reykjanes Ridge and Kolbeinsey Ridge segments.
(Thórdarson and Larsen, 2007)

interaction between the spreading plate boundary and a mantle plume. This interaction leads to the dynamic uplift of the Icelandic plateau. The construction is thought to have begun about 24 million years ago, although the oldest rocks exposed on land in Iceland are only 14–16 million years old. (Thórdarson and Larsen, 2007, and references therein).

In Iceland, geothermal areas are divided into two main groups, i.e. high- and low-temperature areas. The high-temperature areas are found only within the area of active volcanism within the rift zones, characterized by active volcanoes and fissure swarms. They are localized features mostly confined to a central volcano or volcanic complexes. The temperature in the high-temperature areas is above 200°C at 1 km depth. The uppermost 1000 m of the rift zone are made up of highly porous and permeable basaltic lava successions and hyaloclastites. Due to an abundance of cold groundwater, low temperature gradients characterize the uppermost kilometre within the rift zone outside the localized high temperature areas. The low-temperature areas flank the rift zones, and involve geothermal systems with temperatures lower than 150°C at 1 km depth; they are located within the Pleistocene and Tertiary rocks. The low-temperature areas derive their heat from a hot crust, through active and localised convection in near-vertical fractures. Away from the fractures the bedrock is less permeable and heat transfer is dominated by conduction (Flóvenz and Saemundsson, 1993 & references therein).

2.2 Tectonics and regions of active volcanism

Iceland is on the junction of two mid-oceanic ridges, the Reykjanes Ridge (RR) in the south and the Kolbeinsey Ridge (KR) in the north (Figure 2). The South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone comprise an oceanic ridge discontinuity with high seismicity, strike-slip faulting and normal faulting (Gudmundsson, 2007).

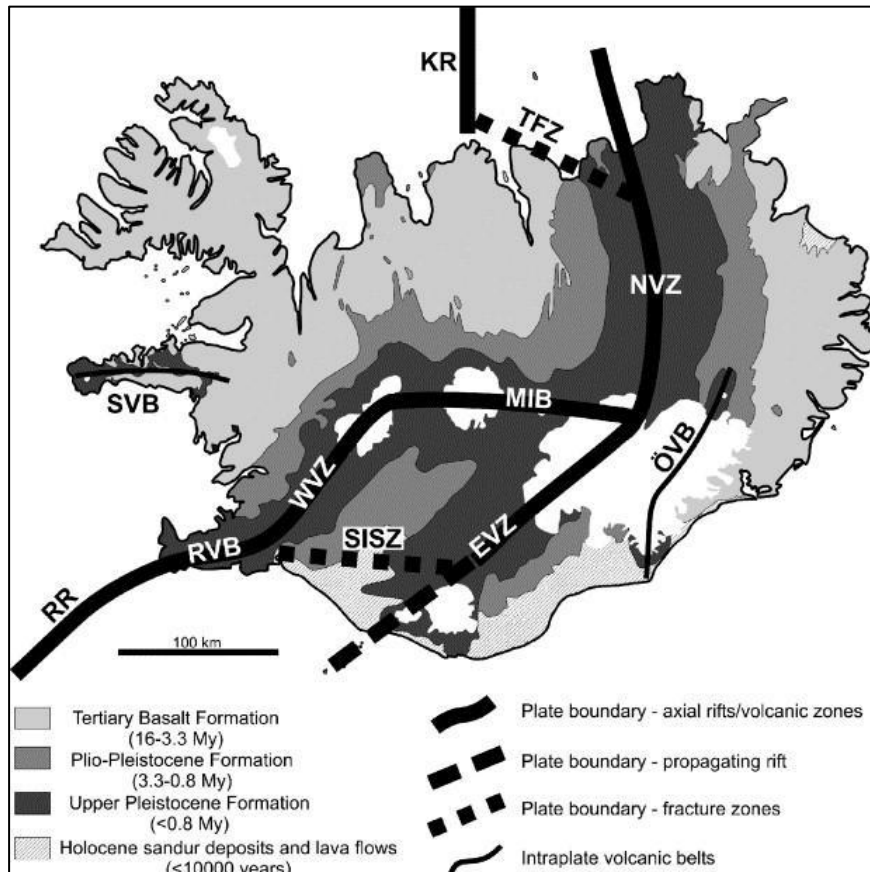


FIGURE 2: The principal elements of the geology in Iceland (Thórdarson and Larsen, 2007)

The active volcanism in Iceland is the result of a spreading plate boundary and the existence of the mantle plume. The surface expressions of this interaction are the neovolcanic zones, a discrete 15–50 km wide belt of active faulting and volcanism. Of those, the most prominent belt is the axial volcanic zone, the loci of active spreading and plate growth that follows the plate boundary across Iceland (Figure 2). There are also two active intraplate volcanic belts of mildly alkalic magmatism in Iceland: the Öraefi volcanic belt situated to the east of the current plate margins, which may represent an embryonic rift, and the Snæfellsnes volcanic belt in West Iceland, an oblique rift

zone activated about 2 My ago, which is currently propagating to the east-southeast (Thórdarson and Larsen, 2007 and references therein).

3. INTRODUCTION TO THE KRÝSUVÍK AREA

The Krýsuvík high-temperature area is about 40 km² and located in the centre of the Reykjanes peninsula (Figure 3). This area is characterized by extensive post-glacial lava fields, steep-sided mountains and ridges of pillow lavas, pillow breccias, and hyaloclastites. The latter formations are of upper Quaternary age, in all likelihood from the last glaciation, formed during volcanic eruptions in melt water chambers within the glacial ice sheets. All the rocks are of basaltic composition. Topographically, the Krýsuvík field (Hveradalir, Seltún and Köldunámur) are characterized by two major northeast-southwest striking hyaloclastite ridges.

Numerous volcanic eruptions have occurred on the peninsula in historical times, the last one in the 13th century including several in the vicinity of Krýsuvík high-temperature area (Jónsson, 1978). The high content of dissolved solids in the thermal water in the Krýsuvík area, in comparison with other

drilled high-temperature fields in Iceland (outside the Reykjanes Peninsula), is believed to result from a slight mixing of sea water with fresh groundwater within the Krýsuvík hydrothermal systems.

The faults of the fault swarm that dissects the Krýsuvík area are much denser in the hyaloclastite ridges than in the lava-covered valley in-between. This is explained by the longer exposure of the glacial formation to the tectonic activity than within the young Holocene lavas. Several explosion craters (maar) can be found

within the Krýsuvík field close to Hveradalir but not elsewhere. Some magma and scoria has been ejected to the surface during the eruption of some of these craters. It is considered that this activity results from the crystallization of shallow magma batches (Arnórsson et al., 1975a).

The Krýsuvík fault swarm crosses the plate boundary at an angle of 30 to 40 degrees (Klein et al., 1977). Geophysical data have determined that the currently active plate boundary is a zone approximately 2-5 km wide with an average strike of 076 degrees. Most of the seismicity on the peninsula occurs within this zone and has predominantly strike-slip focal mechanisms. Near the surface, left lateral shear is accommodated along north north-northeast-striking right-lateral strike-slip faults in a style of deformation referred to as bookshelf faulting. Focal mechanisms are predominantly right-lateral strike slip. Geothermal areas lie along a WNW–ESE trend extending from the west side of Núpshlíðarháls to the southern end of Kleifarvatn (Clifton et al., 2003).

4. GEOTHERMAL MAPPING

4.1 Methodology and geothermal map

The recognition and geothermal mapping of geothermal manifestations is important for estimating geothermal potential for utilization. In the present mapping project, extensive use was made of a portable GPS positioning instrument and a thermometer stick to locate and delineate the thermal manifestations exposed within the bedrock or loose surface deposits and soils. The local points and tracks of cold and warm springs, mud pots, fumaroles, solfataras and tectonic structures were all recorded by GPS. The received data were downloaded into the computer and then edited using the *Map Source* and *Corel Draw* programs, and exported into ArcGis and edited for final processing combined with a topographical map (scale 1:3,500). Aerial photographs were also used for interpretation of the field data.

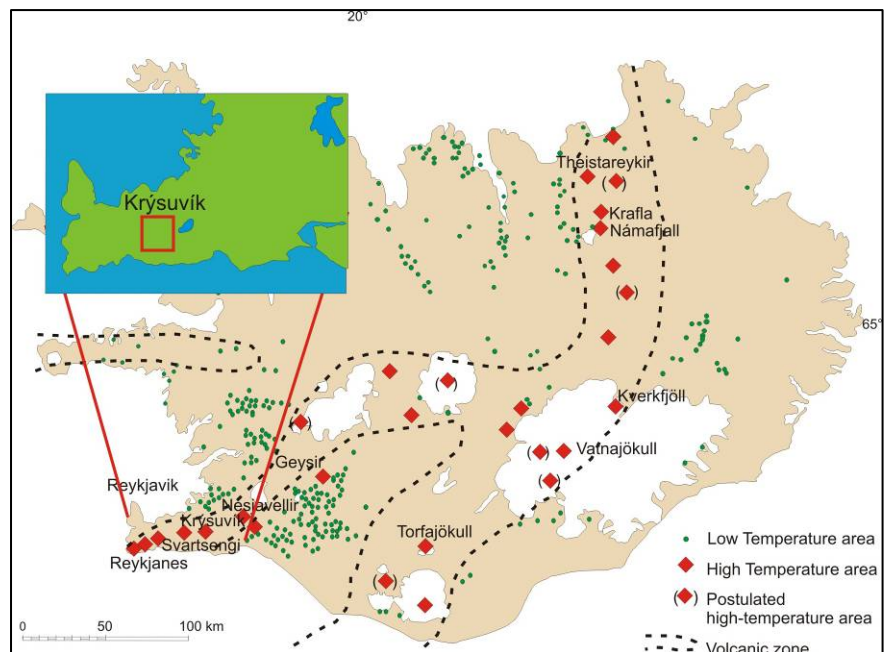


FIGURE 3: Geothermal areas in Iceland; the five high-temperature areas in production are the Reykjanes, Svartsengi, Nesjavellir, Krafla and Námafjall fields (map from Ármannsson et al., 2000)

Measurements of temperature at 15 cm depth in the soil around hot and warm geothermal manifestations were carried out to delineate the 15°C and 50°C isotherms. Isotherms of 50°C indicate areas of high geothermal activity and isotherms of 15°C indicate larger areas of geothermal activity surrounding the hotter manifestations or cooling fields elsewhere. Figure 4 shows the geothermal map of the project area.

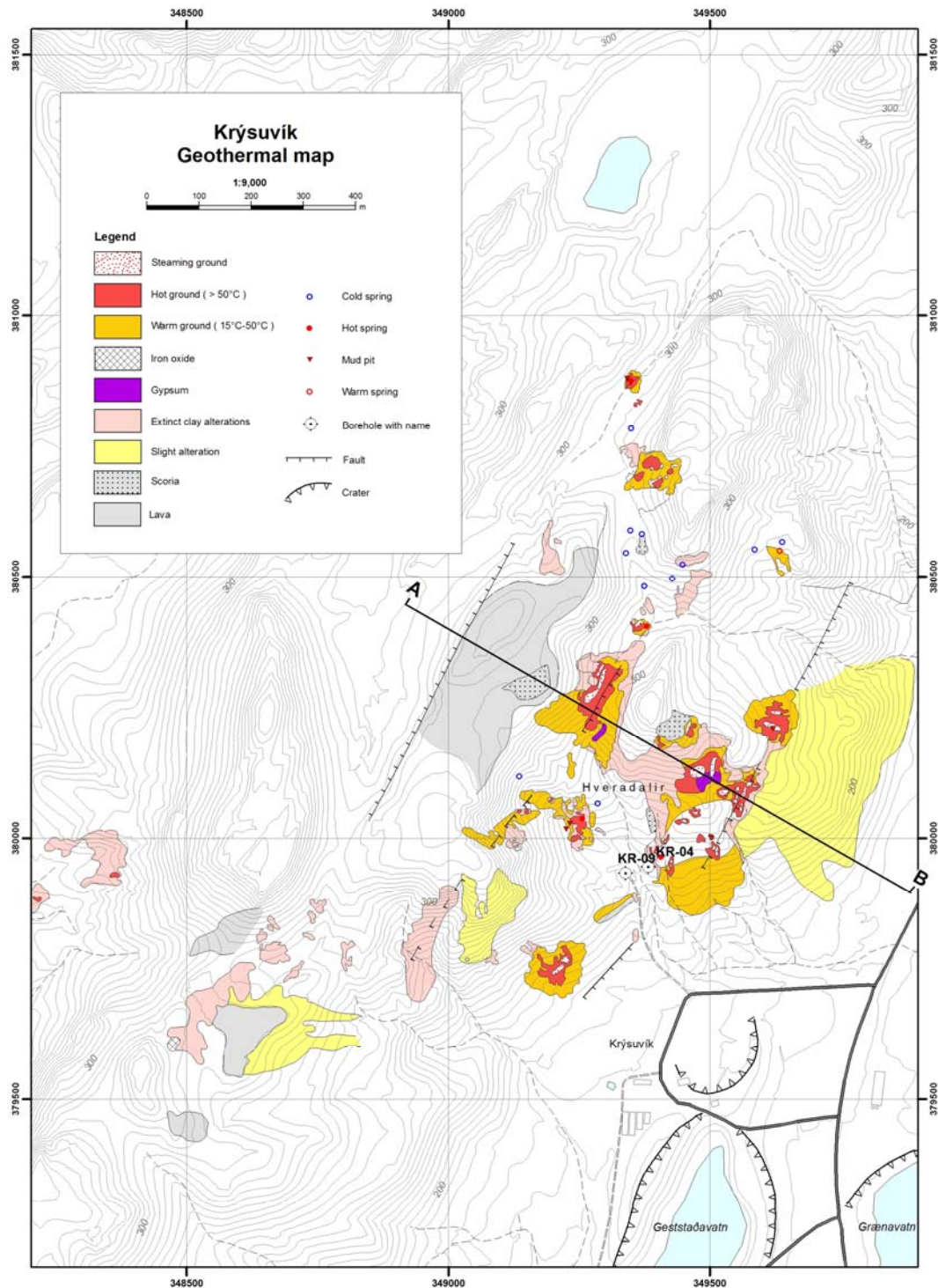


FIGURE 4: Geothermal map of Hveradalir field in the Krýsuvík area; explosive craters are seen in the southeast corner, outside the mapped geothermal field

4.2 Surface hydrothermal activity

4.2.1 Mud pits

Descending springs are typical for geothermal manifestations. Very often such water-bearing horizons have no hydraulic contact with the geothermal reservoir, but represent steam-heated surface waters. The steam normally contains high concentrations of acidifying gases (sulphur and carbon dioxide), which result in a drop in pH of the surface waters to values down to 3 or even less. The acid leaching results in intensively altered rocks, enriched in silica and alumina, characteristically light coloured kaolinite clays, and red stained iron oxide enriched clays or solid deposits.

Depending on the supply of surface water, the mud pits range from being very muddy to almost clean hot springs. In the Krýsuvík area, mud pits (Figure 5) contain blue clay. Blue clay in geothermal systems is saturated with pyrite, because with low entrance of oxygen into the system, pyrite cannot be oxidized to limonite. More than 7 mud pits were studied within the mapped area, at elevations from 234 to 302 m above sea level, and with temperatures between 85 and 96°C.



FIGURE 5: Mud pits in the Krýsuvík area

The springs are classified into three categories: hot springs, with temperatures higher than 50°C; warm springs, from 15 to 50°C and cold springs, below 15°C. The groundwater temperatures in Iceland, however, are much lower, ranging from 2-3°C in the north, up to 4-5°C in the south. Accordingly, all proper springs in Iceland, hotter than 5°C or so, represent heated groundwater. Evidently, groundwater temperatures in the world vary depending on latitudes and local conditions. Therefore, the minimum temperature of warm springs depends on local conditions. Mapping of cold springs is important in geothermal explorations, as they are potential sources for drilling fluid.

1. *Hot spring* areas show the highest geothermal activity. The hot springs are the most visible manifestations and some groups of hot springs overlie a geothermal system and can be used to locate drilling sites (Wohletz and Heiken, 1992).

The hot springs are heated groundwaters of surface origin, augmented by rising steam, originally in a superheated state, rising from an underlying heat source through deep cracks in the crust. In Iceland, superheated steam is rarely found on the surface, due to an abundant supply of surface water. The majority of steam vents show temperatures very close to the boiling point of water at surface pressure (1 atm). The steam rises from a boiling reservoir at some depth below the surface, from where it may rise adiabatically towards the surface, and condense to some extent, depending on the environment, until it mixes with ground- or surface waters. In Iceland, magmatic or hydrothermal steam has but a slight chance of finding a path of dry ground up to the surface, and most of it is drenched in the ground- and/or surface water. In Icelandic hot springs the groundwater body is large enough to condense practically all magmatic vapour before it reaches the surface.

In the Krýsuvík area, hot springs (Figure 6) at different temperatures occur in one locality and have formed water pools in depressions caused by intense geothermal alteration and erosion.

The hot springs in the Krýsuvík area are colourless to grey-brown muddy waters as a result of suspended clay.

The hot springs measured have temperatures of 94-96°C and occur at elevations from 228 to 302 m. In the mapped area, 6 warm spring and 4 hot spring zones were studied. The hot springs and mud pits only temporarily have a fixed position, and are spread over a large area within the hottest hydrothermal manifestations (Figure 6).



FIGURE 6: Hot spring area in Krýsuvík

2. *Warm springs* also occur in the area of hot springs. In the mapped field, warm springs were studied at elevations of 269-278 m a.s.l. The temperature of these springs is 34-37°C. They are usually run-off surface water that seeped through surface deposits above the thermal manifestations.
3. Proper *cold springs* do not exist in the studied field. However, apparent cold springs were observed at 257-310 m.a.s.l. These ranged in temperature from 6 to 16°C, and represent heated cold springs, which themselves result from an elevation or false groundwater table, temporarily created during heavy rain falls to produce groundwater flowing out of fractures in the bedrocks, or through rock slides or other surficial deposits. When rainfall ceases, the flowrate of these springs is reduced and some of them disappear completely during dry seasons. The characteristics of these slightly heated cold springs in the study area are a brown-green boggy moss and colourless water.

The lack of cold springs and a good groundwater resource in the Krýsuvík fields (known from former exploration drilling) affects all drilling activity. The only useable source of water for drilling activity is nearby Lake Kleifarvatn.

4. *Fumaroles*, which emit mixtures of steam and other gases, are fed by conduits that pass through the water table before reaching the surface. Hydrogen sulphide (H₂S), one of the typical gases released from fumaroles, readily oxidizes to sulphuric acid and native sulphur. Fumaroles may occur along tiny cracks or along fissures and on the surfaces of lava flows and thick deposits of pyroclastic flows. They may persist for decades or centuries if they are above a constant heat source or disappear within weeks to months if they occur at the top of a fresh volcanic deposit that quickly cools. In the study area the fumaroles occur along cracks or in clusters on the surface. In the field area more than 26 steam zones were mapped (steam zones, like hot springs, are found in groups). The fumaroles occur at elevations from 206 to 330 m a.s.l. and range in temperature from 94 to 100°C.

4.2.3 Hot and warm grounds

Hot grounds ($T > 50^{\circ}\text{C}$) are common manifestations within the study area. Warm ground is characterized by uncovered layered ochre surfaces and can include pickeringite, halotrichyte, brochantite, amorphous silica and calcite. The bedrock is completely altered to yellow-brown, ochre, white, grey-blue, violet, and dark-red clayish material.

Warm ground ($T=15-50^{\circ}\text{C}$) represent a lower level of geothermal activity and also surround isolated spots and heated soil in cooling areas. They can occur in both bare and vegetated areas. In the bare ground, they are found with whitish or cream-white colouration on the surface and with wet smooth clayey surfaces.

4.2.4 Surface alteration

Hydrothermal fluids have various effects on the rocks they pass through: existing minerals can be removed, new minerals can be deposited in fractures and pores in the rocks, or the existing minerals can be replaced by other minerals in processes of hydrothermal alteration. All of these processes may occur together. The new minerals that are formed, whether by deposition in cavities or by replacement, are called secondary minerals. At the surface two kinds of alteration were recognized during mapping, i.e. slight alteration and extensive clay alteration. These vary in grade from very slight to complete rock alteration.

Slight alteration is determined by the presence of secondary minerals in the rocks, characterized by red-brown and yellow-brown bedrocks or soils, and light coloured minerals like opaline silica scales, calcite (Figure 7) and zeolites.



FIGURE 7: Hyaloclastite with calcite veins

Clay alteration is characterized by completely altered bedrock. Light coloured clay at the thermal areas basically relates to kaolinite clay, whereas red clay relates to oxidized pyrite which produces iron oxides (limonite). Blue clay mostly owes its colour to tiny grains of pyrite.

Within the clay fields of the mapped area, large deposits of gypsum were found (Figure 8). The gypsum is formed at the expense of native sulphur which has oxidised, hydrated and added calcium upon cooling and weathering of the solfataras.

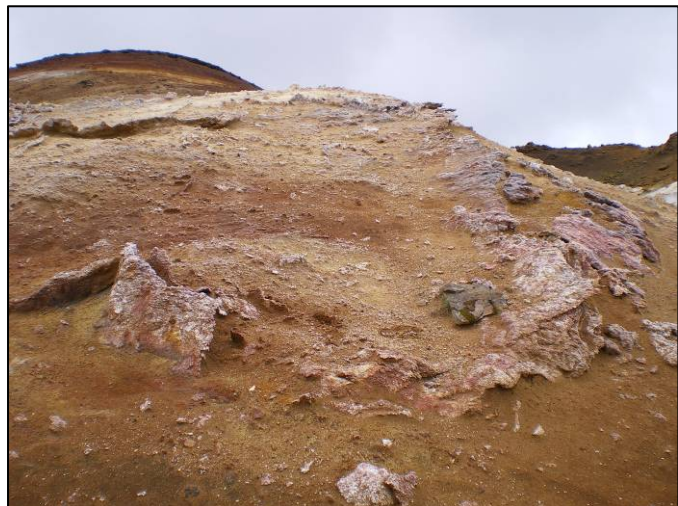


FIGURE 8: Gypsum in the geothermal field

4.3 Geology

The lithology in the study area comprises three main rock types: hyaloclastite, lavas and scoria. The hyaloclastite is by far the most abundant rock type in the study field and hosts all the surface manifestations. The hyaloclastite is a part of the late glacial Sveifluháls hyaloclastite formation (Imslund, 1973), one of the main rock units in the area trending NE-SW, forming a ridge extending over 10 km. This hyaloclastite was formed subglacially during a fissure eruption in late glacial time.

Somewhat later, during the last glaciation period, possibly during so-called interstadial or ice-free periods within the last glacial era, a subaerial fissure eruption created welded spatter lavas, which form

a mapable unit within the field area. This lava is severely eroded but from its distribution in the field, it seems likely that the volcanic fissure may have been very close to the exposed lava patches, trending NE-SW along extensively altered ground and a fault. The extinct hydrothermal alteration was clearly active in early Holocene time, but is, in places, covered by thick soil formation.



FIGURE 9: Fault with a NE-SW orientation in the Krýsuvík area

The youngest volcanic rock in the field is a scoriaceous tephra layer of early Holocene age, presumably ejected from the explosive craters just southeast of the study field. Gabbro xenoliths are found in the scoriaceous ejecta, similar to those known to be from the explosive craters.

Four faults with NE-SW orientation were mapped, see Figures 4 and 9. One of them shows a downthrow to the west along which an extinct geothermal field was mapped. The other three faults have downthrows to the east, and the most active geothermal fields are located along these faults.

4.4 Geothermal model

For displaying of the geothermal model, a NW-SE cross-section across the most active geothermal fields is shown in Figure 10. The model assumes a boiling reservoir at some depth below the surface with the active geothermal surface manifestations. From the geothermal model, the geothermal system seems to be more active in the east than in the west. This is shown by the existence of extinct

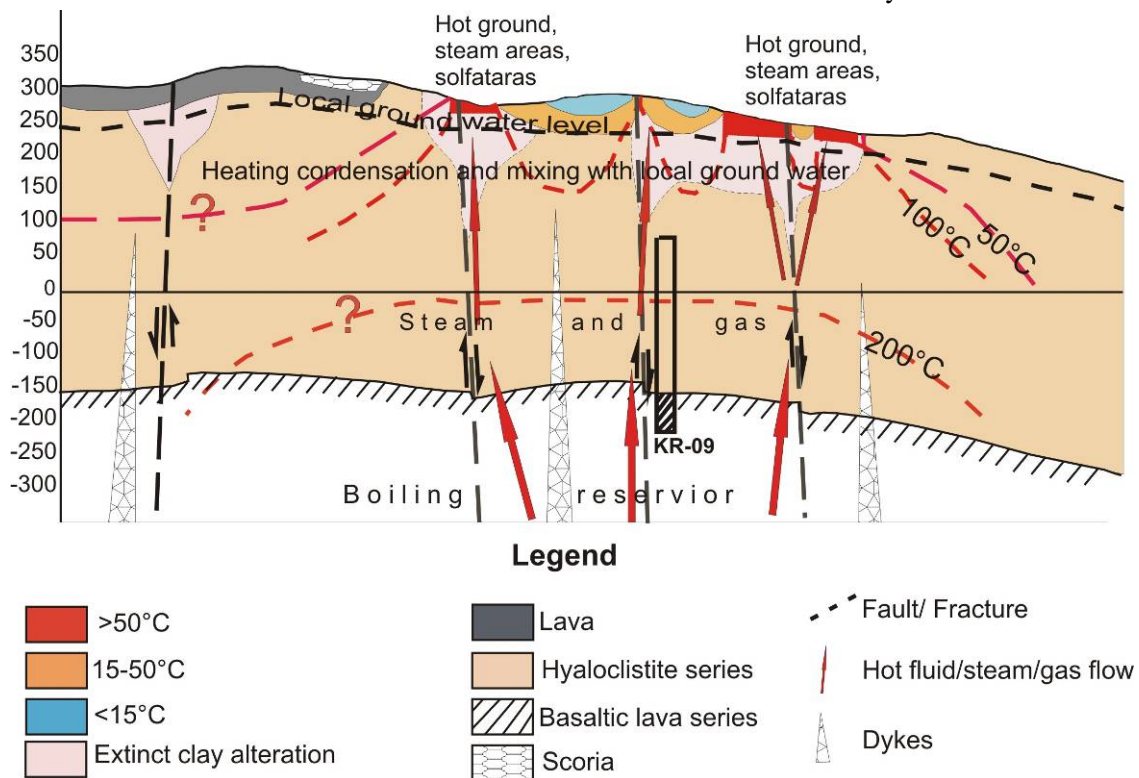


FIGURE 10: Geothermal model of the Hveradalir field in the Krýsuvík area

clays in the west. This implies that the system is cooling down in the west because of deposition of secondary minerals in fractures and pores which reduces permeability, sealing off the conduits of geothermal fluids. Heat is transferred from hot rock into groundwater descending through faults and fractures.

In the model, the craters have been associated with more recent eruptions that are thought to have resulted in emplacement of magmatic dykes at depth. The magmatic intrusions are thought to be the source of heat for the geothermal system. The most active geothermal activity is in the eastern part of the area (Figure 4), near or in line with the explosion craters which are thought located above a cooling young intrusion body of some shape and size.

Included in the model is information on the subsurface data from well KR-09 (Figure 10), both lithological and on the likely subsurface temperature distribution.

5. CONCLUSIONS

In the studied area, hot springs, mud pits and fumaroles have no fixed position but meander within areas of fumaroles.

- Tectonic structures in the area seem to have a significant influence on the distribution of the geothermal manifestations, since faults and fractures work as channels where hydrothermal fluid finds its way towards the surface. The most active geothermal areas are above and along faults with downthrow towards east.
- Noteworthy is the observation that the fault showing downthrow to the west involves an extinct surface manifestation, which may indicate migration of the reservoir.
- This field may also have been connected to the eruptive fissure emanating from the late glacial lava flow on the surface.

ACKNOWLEDGEMENTS

My sincere thanks go to the United Nations University Geothermal Training Programme and the Icelandic Government for funding my training. Special gratitude to Dr. Ingvar Birgir Fridleifsson and Mr. Lúdvík S. Georgsson for their assistance given throughout the course. Thanks to Thórhildur Ísberg and Dorthe H. Holm for their help and moral support. Skúli Víkingsson and Gudrún Sigríður Jónsdóttir are acknowledged for their help in the preparation of maps using the Arcinfo GIS software. All lecturers and the staff of Orkustofnun and ISOR are greatly acknowledged for sharing their knowledge in the field of geothermics. Thanks to the Institute of Volcanology and Seismology FEB RAS for nominating me to participate in this programme.

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