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GEOTHERMAL MAPPING IN WESTERN ÖLKELDUHÁLS FIELD, HENGILL AREA, SW-ICELAND

Kiflom Gebrehiwot
Ministry of Energy and Mines
Department of Mines, Geological Survey
P.O.Box 272, Asmara
ERITREA
kflmgt@yahoo.com

ABSTRACT

This paper presents the results of mapping the main structures and surface geothermal manifestations in Western Ölkelduháls area, SW- Iceland which is a part of the active Hengill geothermal and volcanic system. The main objective of this study was to map the manifestations and investigate the relationship between the geothermal manifestations, the tectonic and volcanic structures and rock types.

Geothermal activity is widely distributed in the mapped area, the main manifestations being fumaroles and steam vents; boiling mud pots and water pools; hot, warm and cold springs; hot, warm and steaming grounds. The manifestations occur at elevations between 230 and 430 m above sea level and are mainly fault or fracture controlled. The main structures that control these manifestations trend NE-SW and N-S. Northwest oriented faults and fractures also occur. Hyaloclastites, pillow lavas and lava flows predominate the lithological units in the area. These rocks have been exposed to variable degrees of alteration due to reactions with hydrothermal fluid. Two types of hydrothermal alteration are distinguished on the map, slightly altered rocks, and extensively altered rocks characterized by widespread clay alterations, either extinct or grading from active to cold.

1. INTRODUCTION

The Mid-Atlantic ridge, a constructive plate margin appears above sea-level in Iceland, one of few countries in the world attaining an increase in its surface area due to the creation of new lithosphere by sea floor spreading. The newly created lithosphere occurring at the plate boundaries is characterized by high heat flow due to volcanic activity and extensional tectonics. This heat flow is a result of magmatic intrusions and from the Earth's hot interior, with hot water brought up close to the surface along fracture zones to shallower levels by deep convective circulation. It is then concentrated into shallow reservoirs or discharged as hot springs. These reservoirs are the main targets for drilling, the hot water and/or steam being piped to the surface where it is used directly, or high pressure-steam separated to drive turbines for power generation. Technology enables it to be utilised to generate electricity and provide domestic and industrial heat. Geothermal energy has proven to be reliable, economic, environmentally friendly and renewable.

The first step to achieve the goal of utilizing a geothermal resource is geological exploration. It involves mapping any hot springs or other surface thermal features and the identifying of favourable geological structures. The results can be used to recommend where production wells be drilled with the highest probability of tapping the geothermal resource. Integrated with different exploration disciplines, it can also locate resources including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses and highly pressurized hot fluids. Geological exploration is, therefore, a very important tool in the early stages of geothermal prospecting.

This study presents the results of mapping the main structures and surface geothermal manifestations including shallow temperature surveys in Western Ölkelduháls area, SW-Iceland which is a part of the active Hengill geothermal and volcanic system. Clay alterations, slight surface alterations and terrace have also been mapped. The different types of clay and crystalline minerals occurring around the manifestations are also identified using X-ray diffraction (Appendix I).

In the Hengill area, the currently active spreading plate boundary is represented by the Hengill volcanic system, a north-northeast striking swarm of normal faults and fissures containing the Hengill central volcano. The large Hengill geothermal system which contains the study area is one of the biggest geothermal fields in Iceland. This field being an extensive high- temperature area containing several economically promising geothermal prospects has been the focus of attention for many decades. Reconnaissance geological mapping was carried out in the mid sixties in this area and was later remapped giving emphasis to the geothermal manifestations and hydrothermal alterations (Saemundsson 1967; 1995a, 1995b; Saemundsson and Fridleifsson, 1992). Resistivity surveys that identified the most conductive zones at depth, an aeromagnetic survey and a gravity survey were also carried out (Björnsson et al., 1986). Apart from that, surface exploration and TEM-resistivity soundings in 1986, and in 1991 and 1992, respectively, were carried out in the Ölkelduháls geothermal area (Árnason et al., 1987; Árnason, 1993).

2. GEOMORPHOLOGY

The volcanic succession in the mapped area is composed of two rock types, hyaloclastite and lava series. The former is dominant and is formed in subglacial eruptions while lava series form during subaerial eruptions. The landscape is characterized by ridges and table mountains which built up beneath glaciers of the last and second last glacial period, and lavas running during post-glacial time. In addition, carved erosional valleys both of fluvial and glacial origins and terraces with flat tops have also been dominant in the area.

The mountainous geothermal area is dominated by hyaloclastites. When a basaltic magma beneath a glacial cover comes in contact with ice or water it will explode but later solidifies into hyaloclastite in a heap above the orifice, or create pillow lava, instead of normal flows. The magma which was intruded subglacially below the ice sheet was moulded against the walls of the ice into almost the present shape of series of hyaloclastite ridges. If the eruption comes to an end at this stage then the result is a hyaloclastite hill which will only be visible after the melting of the ice cover. When the accumulation of the erupted material has reached above the water level the eruption will continue sub-aerially. At this final stage normal lava flows are poured out and the pile of hyaloclastite will be capped with one or more basalt sheets forming table mountains. The height of the hyaloclastite mountains formed through this process has been used to determine the thickness of the Pleistocene ice sheet (Saemundsson, 1979).

In Hengill as in most parts of the country, glaciation has played a strong role in shaping the area. Glaciers are effective agents of landscape change. The gradual movement of ice down a valley causes abrasion and plucking of the underlying rock. Although it appears solid, the bottom of a glacier flows like a liquid because the ice turns plastic under pressure. As it flows, the glacier can scour out bedrock, carving a trough and moving rocks and gravel great distances. Repeated glacial advances and retreats can transform previously flat areas to the carved valleys we see today. Stream and ice erosion are most pronounced in the areas where fluvial and glacial activity were prominent.

3. GEOLOGIC AND TECTONIC SETTING

3.1 Iceland

Iceland straddles the Mid-Atlantic Ridge, a divergent plate boundary between the European and American plates evidenced in a zone of active rifting and volcanism. Its surface is almost entirely made up of volcanic rocks with basalts being 80-85% of the volcanic pile, and acid and intermediate rocks 10%. The amount of sediments of volcanic origin is 5-10% in a typical Tertiary lava pile, but may locally be higher in Quaternary rocks (Saemundsson, 1979). The rifting followed by continuous volcanic eruptions along the divergent plates forms new crust pre dominantly of basaltic composition as the older rocks in the east and west of the country spread away from each other at a rate of 2 cm/year. Hence, Quaternary formations are found along the margins of the rift zone while Tertiary basalts predominate away from the rift zone to the east and west (Figure 1).

The volcanic rift zone, a zone of active rifting and volcanism, is characterized by well developed extensional structures such as tension fractures, normal faults and grabens and rocks younger than 0.8 million years old. It runs mainly NE-SW in southern Iceland with a more northerly trend in N-Iceland (Figure 1) (Pálmason and Saemundsson, 1974).

The active geothermal areas in Iceland are distinguished as low-temperature areas and high-temperature areas (Bödvarsson and Pálmason, 1961). The low-temperature areas are located outside the volcanic rift zone and have reservoir temperatures lower than 150°C at 1 km depth. High-temperature fields, on the other hand, are confined to the active rift zone and characterized by reservoir temperatures of more than 200°C at a depth of 1 km (Figure 1).

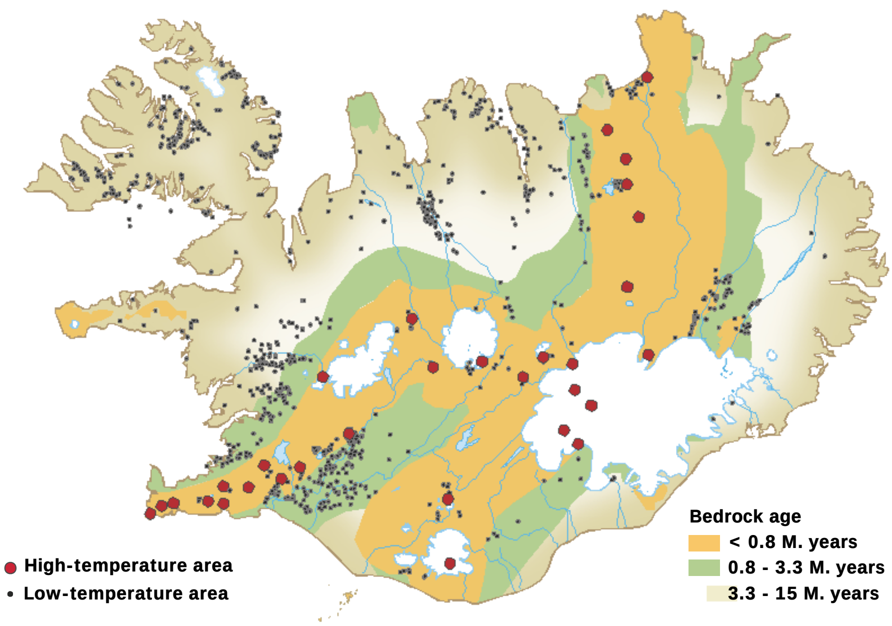

FIGURE 1: Geological and geothermal map of Iceland (Orkustofnun database)

3.2 Hengill

The Hengill area is almost entirely built up of volcanic rocks. Subglacially formed hyaloclastites together with pillow basalts constitute the main rock types in the area. Second in extent are Pleistocene and Postglacial lava flows (Saemundsson, 1967).

The Hengill volcanic area is commonly separated into three volcanic systems, the youngest and most active one is Hengill itself centred in the west, located within the axial rift zone. The second youngest is the Hrómundartindur system, further to the east and much smaller in distribution. The third one, the Hveragerdi system, is furthest to the east. It is now extinct, and was considerably eroded in Pleistocene time (Figure 2). The oldest rocks, about 0.8 my old from the Matuyama epoch, are located in the lowlands southeast of Hveragerði town, and the youngest are the Holocene lava flows from the fissure swarm cutting Hengill volcano in the west. The Hrómundartindur system also includes an early Holocene lava flow from the Tjarnarhnúkur volcanic cone, extending into the author's field area in western Ölkelduháls.

From borehole data, two types of intrusive rocks are identified, fine-grained basalt and fine-grained andesitic to rhyolitic intrusions, indicating that they are dykes and/or sills. An age of about 0.4 million years is proposed for the Hengill central volcano which puts a lower age limit on the geothermal system (Franzson et al., 2005).

Tectonically, Hengill is the easternmost of a series of four closely spaced basaltic fissure systems that cut diagonally across the Reykjanes Peninsula. It is traversed by a graben about 10 km broad which runs NE-SW parallel to the hyaloclastite ridges. This graben is part of a greater structure which accompanies the Reykjanes-Langjökull volcanic zone. The western part of the Hengill area is split up by numerous subparallel normal faults. These constitute a 5 km broad inner graben of most intense

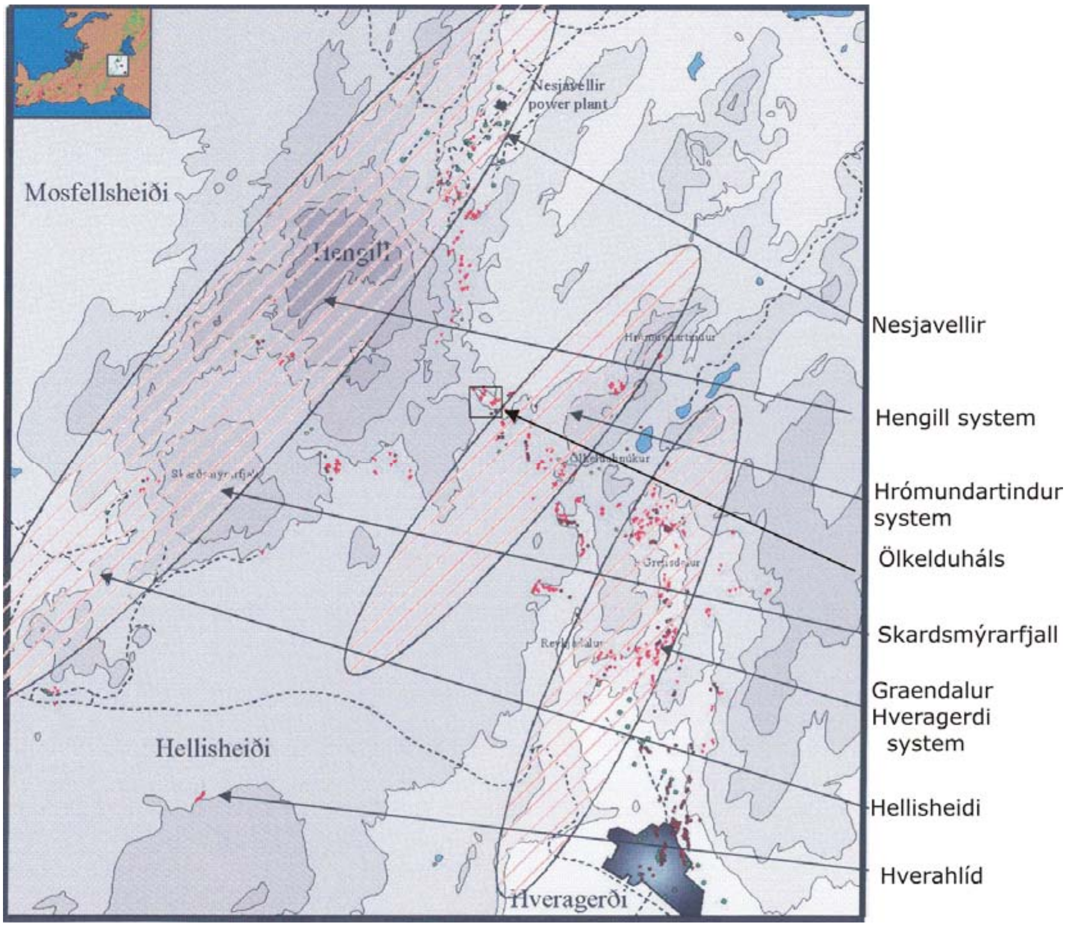

FIGURE 2: Location map of the Hengill volcanic system and the study area

faulting and fissure volcanism. During post glacial time six fissure eruptions occurred within this graben, four south and two north of the mountain (Árnason et al., 1967). Faults and major fractures strike mostly NE-SW and are conspicuous in the east and west marking the boundaries of the fault and fissure zones of the volcano (Figure 2). Postglacial volcanism includes three fissure eruptions of ages 9000, 5000 and 2000 years. The two younger NE-SW volcanic fissures are believed to provide some of the main geothermal upflow channels of the system (Franzson et al., 2005).

4. SEISMICITY

Shield volcanoes and earthquakes do occur on constructive plate boundaries. In SW-Iceland it is expressed by a rather complex pattern of three tectonically active zones. The Reykjanes peninsula, a direct landward continuation of the submarine Reykjanes ridge, the southwestern volcanic zone, one of the two parallel volcanic zone in the southern part of Iceland and the south Icelandic seismic zone in an E-W trending belt of destructive earthquakes that extends across the lowlands in South Iceland. The three active zones join in some kind of a triple point near 64°N and 21°W; (Foulger and Einarsson, 1980). As a result, earthquake activity is distributed over the whole of the high-temperature geothermal area and some areas peripheral to it. It exhibits continuous microearthquake activity correlated with surface geothermal activity. A seismological study carried out in this area concluded the seismicity in the area could be divided into two parts, infrequent and intense episodes of crustal movement due to the stress release along the plate boundary and secondly, continuous small magnitude earthquakes mostly associated with the extinct Graendalur (Hveragerdi) central volcano (Foulger, 1988). Recently, two earthquakes of magnitude 6.6 occurred in the South Iceland Seismic Zone which were associated with right lateral horizontal slips on two parallel 15-20 km long N-S striking faults spaced 15 km apart (Björnsson et al., 2001), resulting in large hydrological changes in geothermal fields in the area, creating an overflow in some of the boreholes while lowering the water table in others.

5. RESISTIVITY SURVEY

A resistivity survey was conducted in the Hengill and Ölkelduháls areas. The resistivity survey conducted over the Hengill area showed a low-resistivity anomaly associated with the geothermal area. It is assumed to be related to a highly conductive layer which is interpreted as being caused by high porosity, high temperature and ionic conduction in highly thermally altered rocks. Figure 3 shows the resistivity at sea level below the Hengill area. Below the low resistivity higher

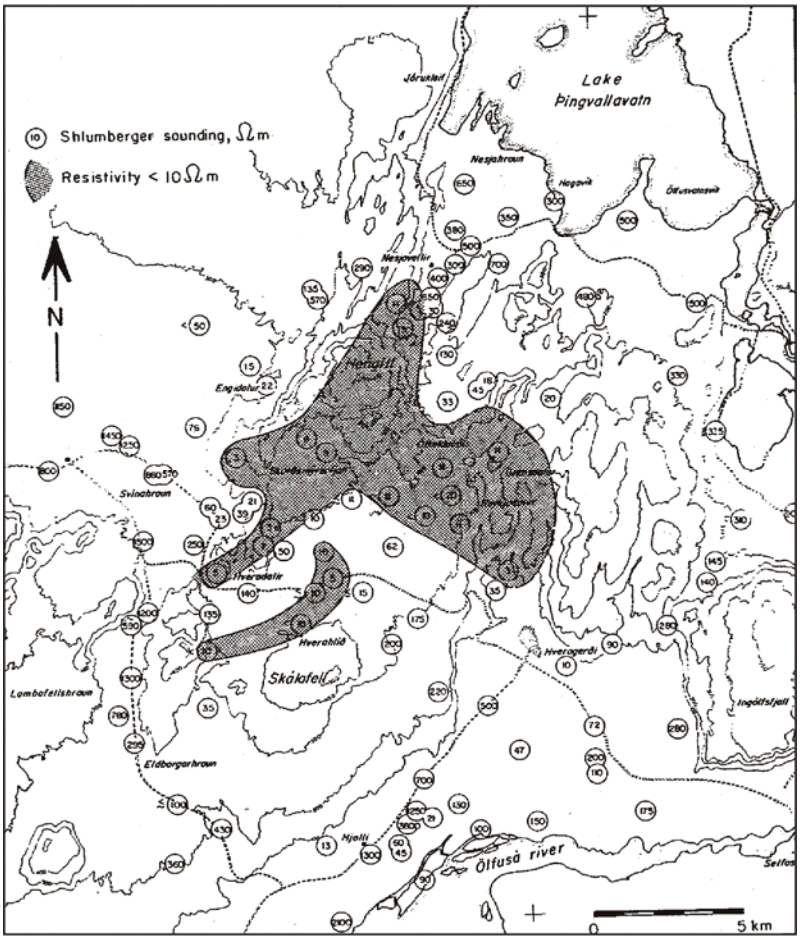

FIGURE 3: Resistivity at sea level in Hengill (Björnsson et al., 1986)

resistivity was seen. Nearly all surface geothermal manifestations in the Hengill area are within the boundaries of the low-resistivity anomaly at sea level (Björnsson et al., 1986; Árnason et al., 1987).

The TEM resistivity survey conducted in Ölkelduháls area revealed an extensive low-resistivity layer delineating the geothermal system with a pronounced increase in resistivity below the low-resisitivity layer. The increase was interpreted to reflect transition in dominant alteration minerals from low-temperature clays (smectite and mixed layer clays) to the higher temperature chlorite (Árnason, 1993).

6. GEOLOGICAL EXPLORATION

Geological mapping and petrographic studies help to define many important parameters which control the flow of groundwater such as rock types, compaction, alteration and vesicle filling, strike and dip of rock formations and the location of faults, fractures and dykes cutting it (Saemundsson and Fridleifsson, 1980). In addition, conducting geological exploration, mapping of geothermal manifestations, structures, and hydrothermal alterations is an essential part of any geothermal survey prior to exploration drilling. It is relatively inexpensive compared to geophysical methods and provides essential basic information on the nature of the geothermal system in concern.

6.1 Geology

The main lithological units that comprise the study area are hyaloclastites, hyalotuffs, compound lava flows and foreset breccias of the late glacial Bitra formation; pillow lava and hyaloclastite of the late Pleistocene Hengill formation; a part of the Ölkelduhnúkur hyaloclastite ridge of similar age as Hengill, and an early postglacial lava called Tjarnahnúkshraun (Saemundsson, 1995a) (Figure 4). In addition terraces, rock slides, and river gravels are distinguished on the geological map.

6.1.1 The Bitra formation

It is the dominant rock formation covering most of the mapped field area. Texturally, it is a densely plagioclased porphyritic basaltic lava and hyaloclastite formation. The formation is thought to have erupted at a very late glacial age (finiglacial), when the icesheet was thinning. During the final stage of its eruption, a huge lava shield volcano developed as the eruption became subaerial, partly upon drainage of the fluvial surroundings. At the beginning of the Bitra formation, the eruption was subglacial, forming pillow basalts, hyaloclastite breccias and hyaloclastite tuffs under shallow water conditions, and compound lava flows with foreset breccias, which are the results of subaerial lava flowing into water. The Bitra formation mostly fills the valley between the hyaloclastite ridges of Hengill and the Ölkelduhnúkur formations. Subsurface information from drillhole data from well ÖJ-1 in the Öldelduháls field revealed the thickness of the Bitra formation to be 124 m (Steingrímsson et al., 1997). One of the largest craters of the Bitra formation volcanic fissure is exposed outside the map area in the west.

6.1.2 The Hengill formation

The Hengill formation within the mapped area is comprised of basaltic hyaloclastite and pillow lava. It is glomero porphyritic in texture and forms the northwest ridges of the mapped area. This unit, exposed in the northwest is predominantly composed of pillow basalt within the field area. It is probably the oldest unit in the mapped area.

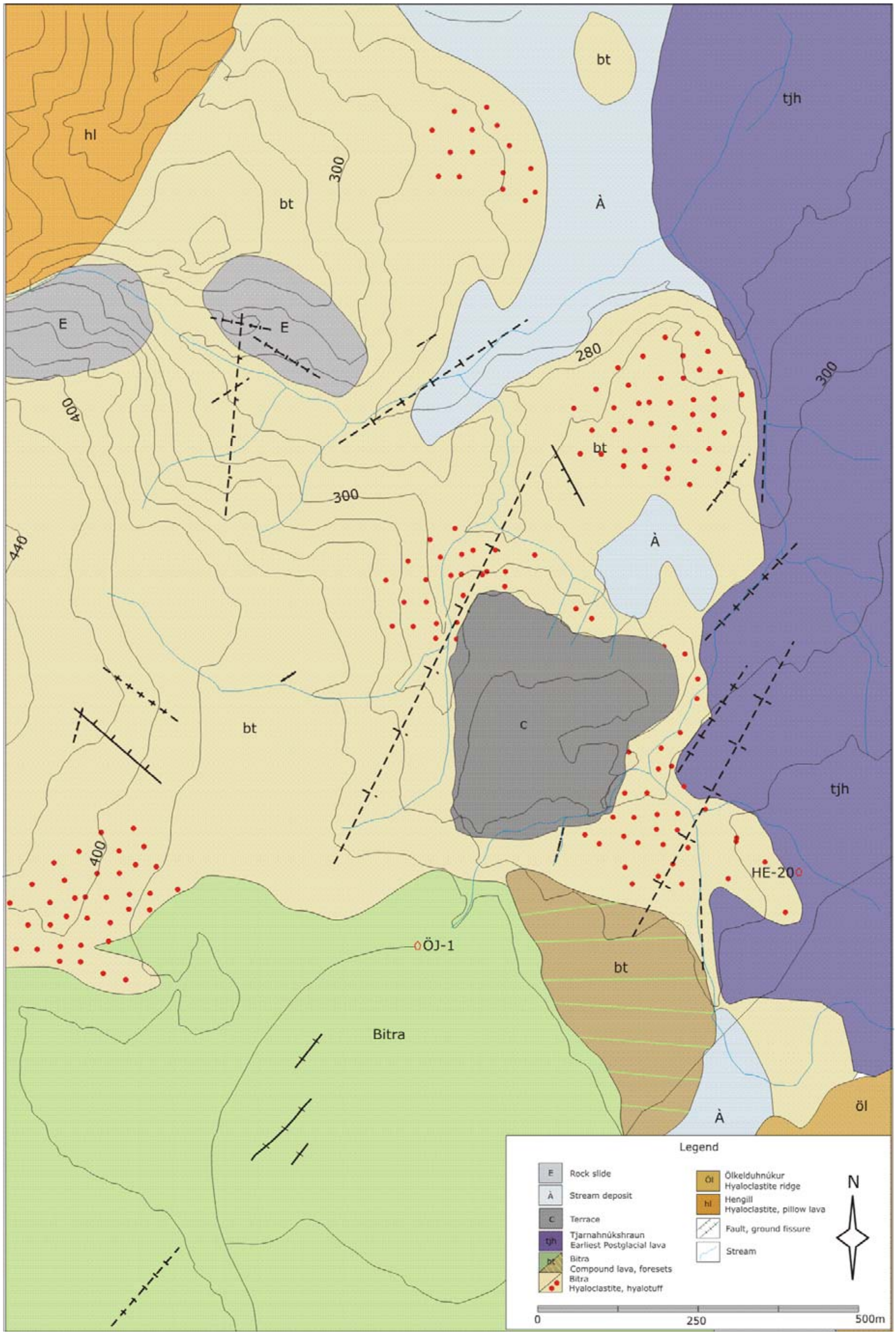

FIGURE 4: Geological map of the study area (after Saemundsson, 1995a)

6.1.3 Ölkelduhnúkur formation

Hyaloclastite tuff is the dominant rock type in the Ölkelduhnúkur formation, but in part it is also composed of pillow basalts. It formed in a subglacial eruption and is reported to be older than the Hengill formation (Saemundsson, 1995a). Texturally, it is very sparsely plagioclase phyric and occurs in the southeastern corner of the mapped area (Figure 4).

6.1.4 Tjarnahnúkshraun lava

This unit is composed of lava flow and occurs in the eastern part of the map area (Figure 4). The lava is densely plagioclase porphyritic, but also contains olivine and pyroxene phenocrysts. The lava is the product of the early Holocene Tjarnahnúkur fissure eruption, originating from the prominent Tjarnahnúkur crater, just outside the map in the east (Saemundsson 1995a).

6.1.5 Terraces

At the end of the glacial periods, during extensive melting upon warming, temporary lakes formed in mountainous areas, dammed up by glaciers, and fed and drained by glacial rivers. Large amounts of erosional debris, ranging in grain size from gravel to silt, can accumulate on the bottom of such lakes. Upon further glacial retreats these lakes may drain rapidly and leave flat terraces behind. A lake terrace formed in this way occurs within the central part of the mapped field area (Figure 4).

6.1.6 Rockslides

Rockslides are another erosional feature shown on the geological map in the field area, caused by rock avalanches of steep unstable slopes in Postglacial times. Two such occur in the western part of the field area, partly covering some of the geothermal manifestations. These slides are interpreted to have been triggered by earthquakes which are common in the study area.

6.1.7 Stream deposits

River gravels and other stream deposits occur on the valley floors in the north, central and southern parts of the field area, shown on the geological map.

6.2 Structures

Mapping of volcano-tectonic features, such as volcanic fissures, craters and crater rows, faults, and fractures, are extremely important in geothermal prospecting, as such structures may control the flow of hydrothermal fluids, and possibly form pathways for hot fluids reaching the surface (geothermal manifestations). Within the mapped field area, faults and fractures are the main structural elements of concern, as the young volcanic edifices discussed above are located outside it. The presence of faults and fractures may often be blurred by erosional products like screes and gravels, as well as by soil, and in the case of the present field, only a few faults and fractures have been mapped. The eruption of the young Bitra formation partly obscured most of the structural elements. One of the author’s tasks was to re-evaluate the structural features within the field area, partly by studying aerial photographs for structural lineaments.

Mapping the distribution of hydrothermal manifestations, prominent lineaments or directional trends, suggests structural control of the manifestations mapped. The result of the hydrothermal mapping, discussed in later sections, shows several prominent trends that can be interpreted as suggestive of structural control of some of the geothermal manifestations. The main trend is predominantly oriented NE-SW, but N-S and NW-SE oriented faults and fractures also occur in the mapped area. Alignment of manifestations, extinct clay alterations, combined with the temperature isolines, especially the 15°C isoline, proved useful in interpreting the potential topographical and structural control in the area.

Open fractures of variable orientations proved to be fairly common in the area. These fractures occur in the different formations, either controlling the manifestations, or as cracks in the rocks without any sign of geothermal activity, sometimes partly covered by erosional material. Two open fractures controlling geothermal manifestations are noteworthy in the northern and northwestern part of the area having orientations northeast and northwest, respectively. The fracture in the northwest part occurs within a rockslide and extends for about 50 m. This northwesterly oriented fracture contains a series of steaming fumaroles along the open fracture and its margins (Figure 5). The other fracture contains aligned hot springs and extends for about 20 m. The other sets of fractures are those with no geothermal activity located elsewhere in the field area. Three parallel fractures, 70, 140 and 60 m in length, are exposed as minor depressions in the soil covered Bitra lava, or open fissures in the southern part of the field. The general trend of these fractures is NE-SW, following the main tectonic trend in the Hengill area, and in this case is evidence of a clear tectonic movement in postglacial time. NW-SE trending normal faults are observed at two locations in the mapped area. A third fault, oriented N-S, was added to the existing map in the north-western part of the field.

FIGURE 5: Open fractures controlling fumaroles northwest of the mapped area

7. GEOTHERMAL MAPPING

Geothermal mapping, including mapping of the main structures, surface geothermal manifestations and variable degrees of alteration together with shallow temperature surveys, was carried out in the Western Ölkelduháls area. While mapping, the different boundaries of the geothermal manifestations were delineated by tracking using GPS in the field. The recorded data then was transferred and processed using the ARCINFO and CorelDraw softwares. The different geothermal manifestations and alterations were mapped; structures either observed in the field or interpreted from aerial photographs, preferred orientations of geothermal manifestations and extinct clay alterations. In addition, a shallow temperature survey within the mapped area was carried out to identify the hot, warm and steaming grounds. A rod, tipped with a thermometer, is pushed down to a depth of ~0.3 m into surface soil to record the temperature distribution around hot springs. Surveys of this type can provide important structural information (Flóvenz, 1985). Such a survey was conducted in all areas within the mapped field, where there was some indication of geothermal manifestation, and in places proved very valuable in identifying or suggesting a structural control on the manifestations studied. The 15 and 50°C isolines are used to differentiate between warm grounds and hot grounds, respectively. The geothermal map is presented in Figure 6.

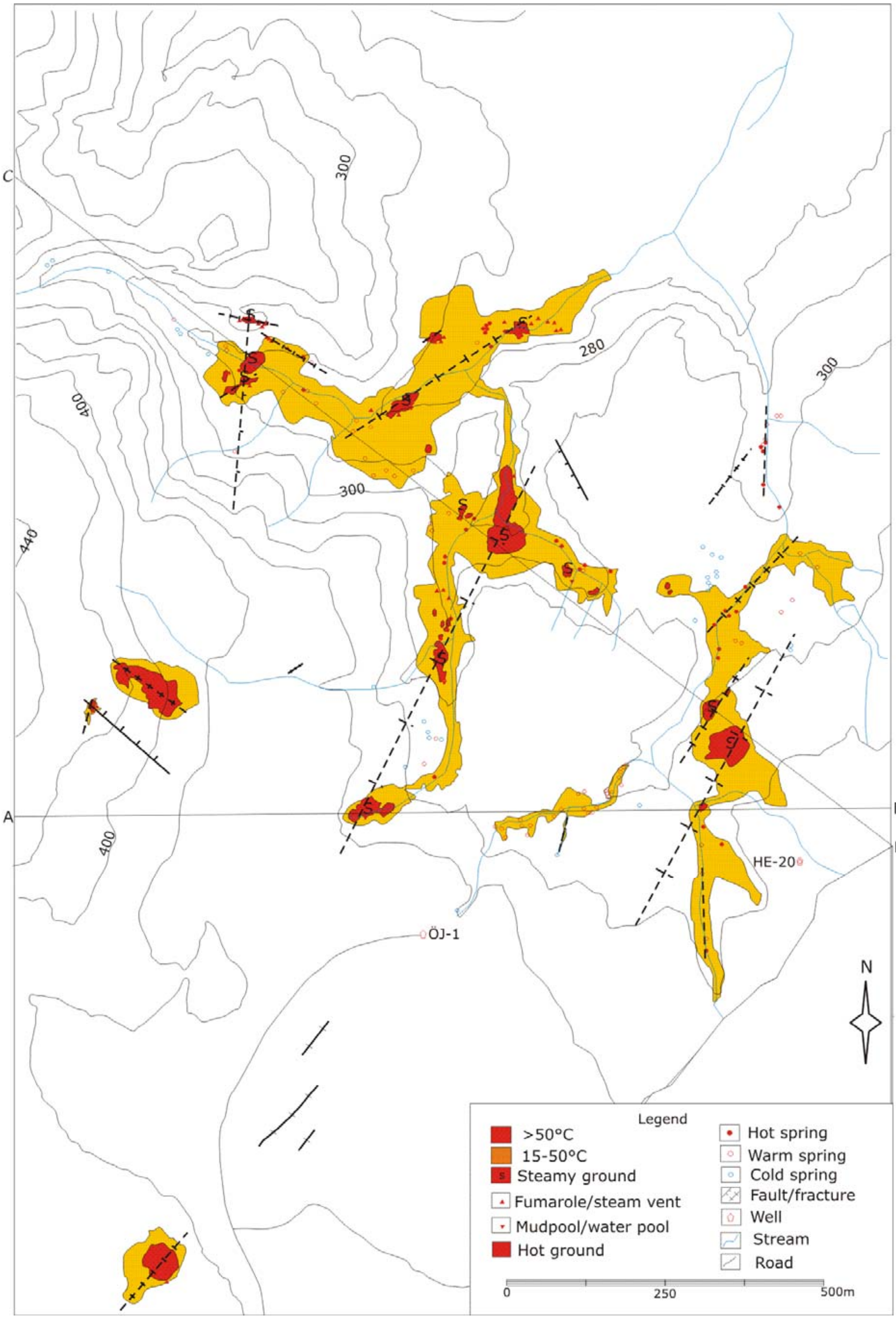

FIGURE 6: Geothermal map of the study area

7.1 Geothermal manifestations

Geothermal manifestations are outlets of hydrothermal systems which indicate high heat flow. Fumaroles, boiling mud pots and water pools, hot and warm springs, and hot, warm and steaming grounds are the main types of manifestations, widely distributed within the mapped area. The field area is at elevations between 230 and 440 m above sea level, involving flat grounds, steep slopes i.e. flat ground within the Bitra formation, steep slopes and V-shaped valleys at its margin with adjacent formations. In addition, a clear pattern in the type of manifestation was observed and related to the landform. Steaming grounds deficient in water are more characteristic at high elevation and in steep slopes while the mud pools, boiling hot springs and runoff springs are concentrated within the low ground. Some of the mapped manifestations show clear alignments suggesting fault or fracture controls. Others, on the other hand, are topographically controlled resulting from the lateral dissipation of steam in the permeable Bitra pillow unit. Usually, the manifestations are surrounded by clays of different composition and some crystalline minerals such as travertine. Vegetation changes have been noticed where geothermal manifestations occur in areas covered by vegetation.

7.1.1 Fumaroles and steam vents

Fumaroles and steam vents are geothermal manifestations which discharge steam from a hydrothermal system boiling at depth. Usually it emits steam and gases of different compositions such as water vapour, carbon dioxide and hydrogen sulphide. The name solfatara is given to fumaroles that emit sulphurous gases and are usually surrounded by sulphur (Figure 7). Solfataras are observed at two places in the mapped field, in the northwest part and in the eastern part. Hydrogen sulphide (H_2S), one of the typical gases issuing from fumaroles, readily oxidizes to sulphuric acid and native sulphur. This accounts for the presence of sulphur around some of the fumaroles. Fumaroles in the study area occur along cracks or in clusters on the surfaces of different rock types. In the field area 72 fumaroles and steam vents with a few solfataras were mapped. The fumaroles occur at elevations between 250 and 430 m above sea level and range in temperature from 55 to 99.7°C.

FIGURE 7: Solfatara in the Ölkelduháls field

7.1.2 Mud pots and water pools

Numerous boiling mud pots and water pools occur in the mapped area. A mud pot is formed in high-temperature geothermal fields deficient in water, and exclusively occurs in heavily altered ground. At least part of the near surface water is rain water, and seasonal variation commonly affects geothermal manifestations of this type, leading to variable viscosity of the mud pools from season to season. The water content in some of the mud pools observed was relatively high, leading to a more watery appearance than slurry. If the geothermal area gets a recharge through fractures or is occurring at an elevation close to the water table of the area, either water pools or hot springs develop instead of mud pots depending on the amount of recharge to the system.

As the boiling mud is often spouted over the edges of some of the most active mud pits, a sort of “mud volcano” builds up around them, sometimes reaching a height of 1 m. Most of the mud is of white to greyish colour, but sometimes stained with reddish or pink spots. In some of the mud pots dark oily looking fluid is observed floating on the surface of the mud indicating the presence of pyrite in the system. In the area 25 mud pots were mapped occurring at an elevation range between 260 and 360 m above sea level with a temperature range between 73 and 99.8°C.

7.1.3 Springs

Hot, warm and cold springs comprise one of the dominant geothermal manifestations that occur in the area. Spring imply zones of subsurface flow and heating in thermal areas. The springs are classified in three categories, i.e. hot springs having temperature above 50°C, warm springs with temperature between 15 and 50°C and cold springs below 15°C. Cold groundwater temperatures in the Ölkelduháls area seem to be close to 6°C, which is unusually high for Iceland, indicating some geothermal heating in most of the Ölkelduháls area. The general groundwater temperature in Iceland is below 4°C (Hjartarson and Sigurdsson, 1993). The hot springs and warm springs have variable temperature and occur at elevations between 220 and 360 m. Travertine or calcite deposits commonly occur around those springs which relate to runoff water (Figure 8). At some of the hot springs bubbling gases are observed, while others are truly boiling at the boiling point temperature. In the area 49 hot springs and 62 warm springs were mapped. Cold springs are widely distributed within the map area at different elevations ranging from 240 to 370 m above sea level. The temperature of the springs is in the range 6.3-15°C. In some cases these springs are the sources or are parts of streams with an estimated flow rate of 3-5 l/s. Cold springs are useful in delineating the water table within the field area, as their main source is groundwater. Bubbling carbonated cold springs are also observed, especially in the eastern part of the mapped area. The word ölkelda in Icelandic means bubbling mineral spring, cold, warm or hot. Accordingly the word Ölkelduháls, indicates the hill with many ölkelda, and indicates a gas rich field. CO_2 is the dominant gas type.

FIGURE 8: Calcite around a hot spring

7.1.4 Hot and warm grounds

Hot and warm grounds are indicators of variable degrees of geothermal activity underground. These are common manifestations in the mapped area and were mapped by measuring shallow ground temperature. In some cases steam is observed under moist air conditions in some of the hot grounds. The temperature of the hot grounds reaches as high as 99.2°C. Hot ground is the result of underground thermal conduction. During this process hot vapours rise near the surface but are not actually discharged. As the vapour, reaches close to the surface it condenses and drains away without being released to the atmosphere, raising the temperature of the ground. Warm ground on the other hand represents a lower level of geothermal activity. Warm ground occurs in most of the valleys in the mapped area and ranges in temperatures from 15 to 50°C (Figure 6). Sometimes warm ground can be identified by vegetation changes on the ground.

7.1.5 Steaming ground

Steaming grounds are hot grounds that exhibit different geothermal manifestations with a discharge of steam, occurring all over the mapped area and containing all the above discussed manifestations with temperatures ranging from 50 to 99.8°C, at different elevations both in the valleys and at higher altitudes (Figure 6).

7.2 Hydrothermal alteration

The presence of widely distributed geothermal manifestations in the whole of the mapped area suggests the presence of a widespread hydrothermal system beneath. As a result most of the rock types at depth have been exposed to a variable degree of alteration upon reaction with geothermal fluids and steam during the lifetime of this hydrothermal activity. The extent of alteration is affected by many parameters, like the rock type, permeability, temperature, duration, pressure and fluid composition, while the degree of alteration chiefly depends on the temperature. Extensive alteration occurs in zones of high permeability and porosity while the extent of alteration is usually more limited in rocks of low permeability and porosity. In this section both surface alteration observed during mapping and subsurface alteration from drill hole data of a well ÖJ-1 will be described. The surface alteration map is shown in Figure 9.

7.2.1 Surface alteration

Two types of alterations were recognized at the surface during mapping, slight alteration and clay alteration. These types of alterations were classified based on the intensity of alteration the rock types experienced. Slight alteration covers a wide area while the clay alterations are restricted to around the active geothermal areas and where there has been geothermal activity.

Slight alteration
As the hydrothermal activity is widespread in the mapped area, a considerable part of the rocks in the field area is slightly altered or visibly affected by some thermal alteration. This is recognized by the development of secondary minerals in the rocks. When slightly altered the hyaloclastites become darker than their reddish brown weathering and palagonitized original colour, mostly due to the development of smectites. Light coloured low-temperature minerals, conspicuous of slight alteration, include calcite, aragonite and opaline silica scales. Comparing the geological map and the alteration map (Figures 4 and 9) we can see that slight alteration follows the lithological contact of the Bitra formation, especially in the eastern part with the Tjarnahnúkshraun lava, implying this alteration to be related to the Bitra formation and could be of Finiglacial age.

Clay alteration
The other surface alteration observed is termed clay alteration. The clay alteration is related to either the currently active hydrothermal activity on the surface or to similar activity in the past (extinct clay alteration). The rock formation gives the minimum age of the past activity, e.g. all extinct clay alteration within the Bitra formation is definitely younger than some 15,000 years; all soil alteration could be considerably younger and definitely of Holocene age, and so forth. In some soil sections only the base of the soil is hydrothermally altered while the upper part is covered by unaltered soil, possible to date by tephrachronological studies or C^{14} if needed.

The most active part of the geothermal field contains completely altered rocks, replaced by clays and residual minerals or mineraloids of different composition, some rich in Fe or Ti. In distribution, the extinct clay alteration mostly occurs around the presently active systems (Figure 6), while in places it is observed covered by more recent soils, indicating former geothermal activity in Holocene - or earlier times (e.g. Figure 10). XRD analysis of differently coloured clays from these areas has revealed that the composition of the clays is mostly smectitic with some indication of traces of

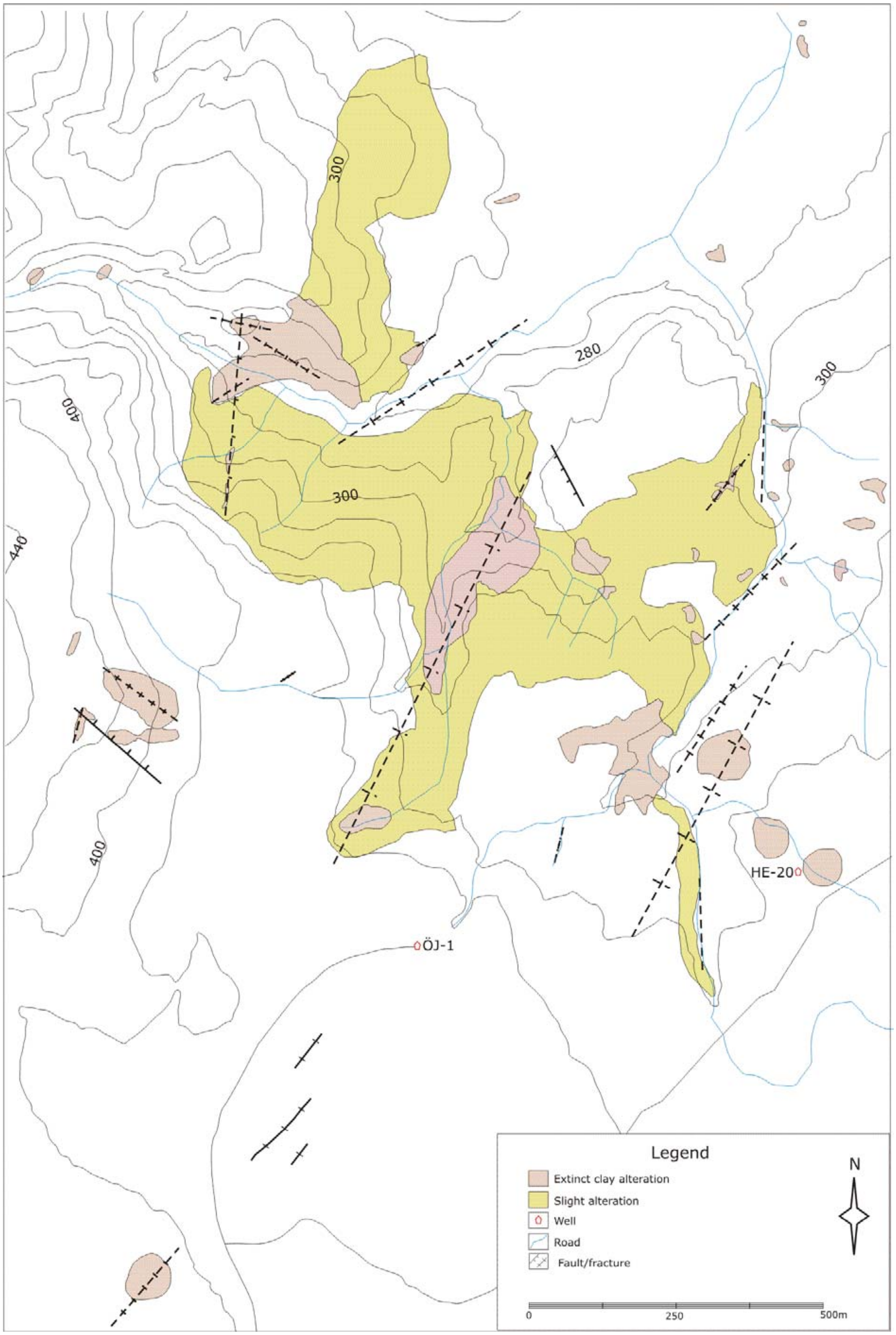

FIGURE 9: Areas with slight alteration and extinct clay alteration

FIGURE 10: Extinct clay alteration

kaolinite (Table 1). The analysis of the crystalline minerals on the other hand showed the most dominant minerals to be gypsum and opal (Table 2).

TABLE 1: XRD results of clay samples

Sample	Untreated	Glycolated	Heated	Result
221	7.5	7.5	-	Traces of kaolinite
358	13.5	17.2	-	Traces of smectite
359A	16.19	17.81		Traces of smectite
359B	-	-	-	No clay
420	7.5	7.5	-	Traces of kaolinite
357A	-	-	-	No clay
357B	-	-	-	No clay
314A	14.33	17.33		Smectite
314B	14.33	17.33		Smectite

TABLE 2: XRD results of mineral precipitates

Sample	Result
356A	Gypsum, anhydrite
356B	Opal, gypsum
356C	Opal, gypsum
420A	Opal, sulphur
420B	Opal, gypsum, sulphur
420C	Opal
420D	Mg-silicates
420E	Non crystalline iron compounds
420F	Mg-silicates
421	Opal, calcite, aragonite

7.3 Subsurface geology and alteration

7.3.1 Subsurface geology

Reykjavik Energy drilled one well (ÖJ-1) in the Ölkelduháls area in 1994. It is located in the eastern part of the mapped area and at the western margin of a volcanic fissure zone which is a part of the Hrómundartindur volcanic site (Steingrímsson et al., 1997). This well is 1035 m deep.

Hyaloclastite tuff, pillow basalts, lavas and breccias with a thin tillite bed make up the stratigraphy of the well. The lithology is divided into 13 units out of which 9 are composed of hyaloclastites and only one unit of lavas. The lithological log below 820 m depth is somewhat uncertain due to total circulation loss, and thus mostly interpreted from the geophysical logs. The drilling revealed 22 feed points at different depths, the main feeders being at depths of 825, 950, 957 and 1010 m (Figure 11). These aquifers are categorized into three systems. A cold groundwater system, about 7°C dominates the top 50 m of the well followed by a 30°C warm groundwater system extending to a depth of 150 m. The third system is the geothermal reservoir system dominated by a water temperature of around 200°C.

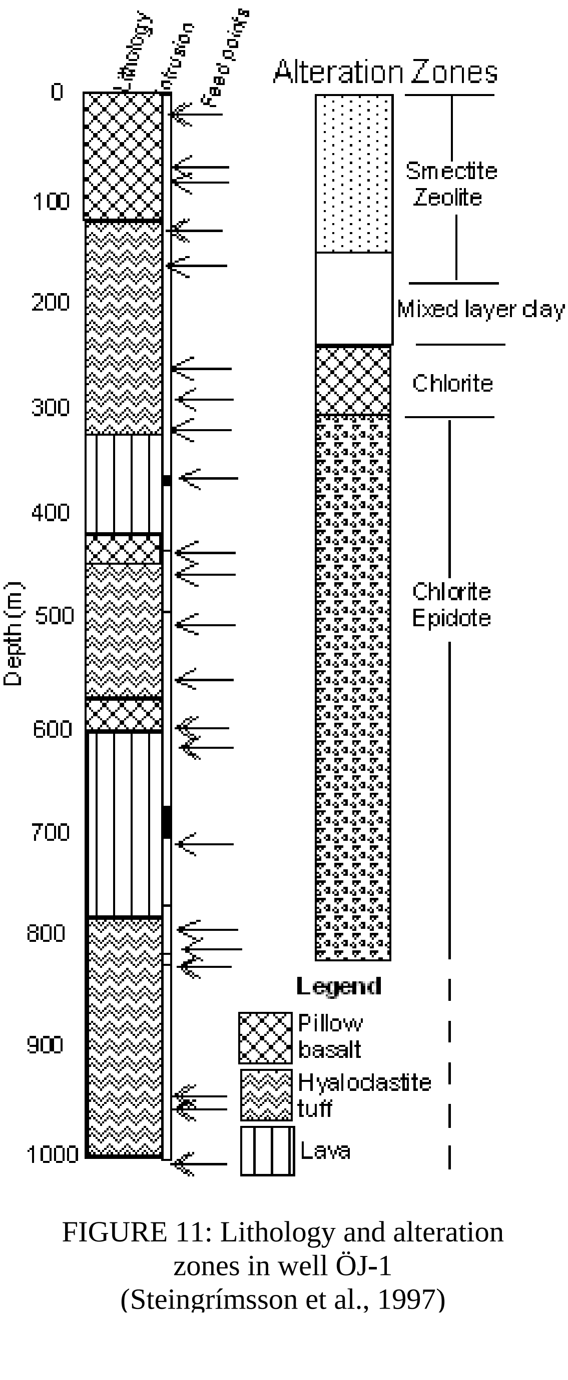

FIGURE 11: Lithology and alteration zones in well ÖJ-1 (Steingrímsson et al., 1997)

The first 124 m of the well are mostly composed of pillow basalts with an intercalation of two layers of basaltic lavas above 50 m depth and four layers of tuffs at different levels of depth. All this interval contains plagioclase porphyritic rocks and was interpreted as part of the Bitra formation (Steingrímsson et al., 1997). Underlying the Bitra formation is a 3 m thick grey sedimentary layer interpreted as tillite. A hyaloclastite unit and pillow basalt intercalated with two layers of basaltic lava extend down to 212 m depth. The layer is sparsely feldsparphyric and was interpreted as belonging to the Ölkelduhnúkur formation. The tillite bed occurs between the two units, indicating a time gap between their depositions, and is observed altered indicating the geothermal activity in the area to be younger than the tillite (Steingrímsson et al., 1997). Below 212 m depth hyaloclastite tuffs and pillow basalt intercalated with lavas are the dominant lithological units. In addition to this, a few thin intrusive dykes were observed or interpreted from the drill cuttings (Figure 11).

A new well (HE-20) is currently being drilled in the map area and is expected to give additional information on the subsurface geology of the area. It had been drilled down to 280 m depth at the time of preparation of this report. The lithological logging showed the first 60 m of the well to be composed of plagioclase porphyritic hyaloclastites and breccia which is interpreted as the Bitra formation. Below that basaltic lava predominates until at ~165 m where three layers of acidic intrusives occur. These intrusives are underlain by basaltic lavas, breccias and tuffs.

7.3.1 Subsurface alteration

Lithological logging of well ÖJ-1 revealed important information on the change in hydrothermal alteration with increasing depth. Drill cuttings, thin section and XRD were used for the identification of the alteration minerals (Steingrímsson et al., 1997). The hydrothermal alteration reflected the formation temperatures, showing a smectite-zeolite system dominates the uppermost 200 m, followed by mixed-layer clays, and then a chlorite zone below 200 m depth, and finally by an chlorite-epidote zone below 300 m depth (Figure 11). The chlorite-epidote zone reflects a minimum temperature of about 240°C, which is considerably higher than the present day temperature within the well. Application of geothermometers on the well fluid suggested equilibrium temperatures around 210-250°C which is somewhat higher than the current temperatures (Figure 12). Older investigations on the composition of steam from fumaroles in the area also suggested that 300°C reservoir temperature should be expected, which is about 100°C hotter than the current temperatures in well ÖJ-1. The discrepancy was interpreted such that the well is extracting liquid from a fracture containing boiled and degassed liquid which is re-entering the Ölkelduháls geothermal system (Steingrímsson et al., 1997).

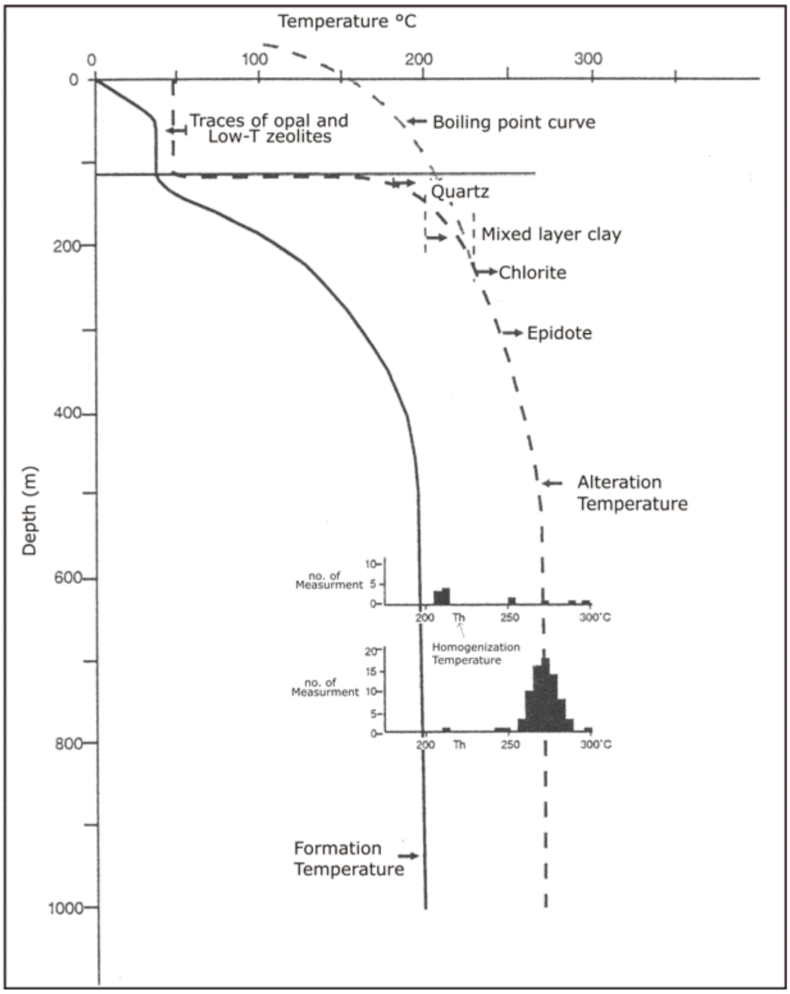

FIGURE 12: Alteration temperature, fluid inclusion and formation temperature (Steingrímsson et al., 1997)

8. HYDOTHERMAL MODEL

In order to visualize the underground conditions in the mapped area a hydrothermal model along lines A-B and C-D is proposed based on the results of the surface mapping and borehole data interpretation (Figures 6 and 11). The two sections have been used to show the widely distributed geothermal manifestations and to include the subsurface data from wells ÖJ-1 and HE-20 (Figures 13 and 14). The temperature distribution through the alteration zones is based on the drillholes. In addition, lithology from the two wells has been correlated. Well ÖJ-1 showed four zones of hydrothermal alteration with increasing depth with the smectite-zeolite system dominating the uppermost 200 m, followed by mixed-layer clays, and then a chlorite zone below 200 m depth, and finally by a chlorite-epidote zone below 300 m depth. The appearance of epidote at a depth of about 300 m implies a

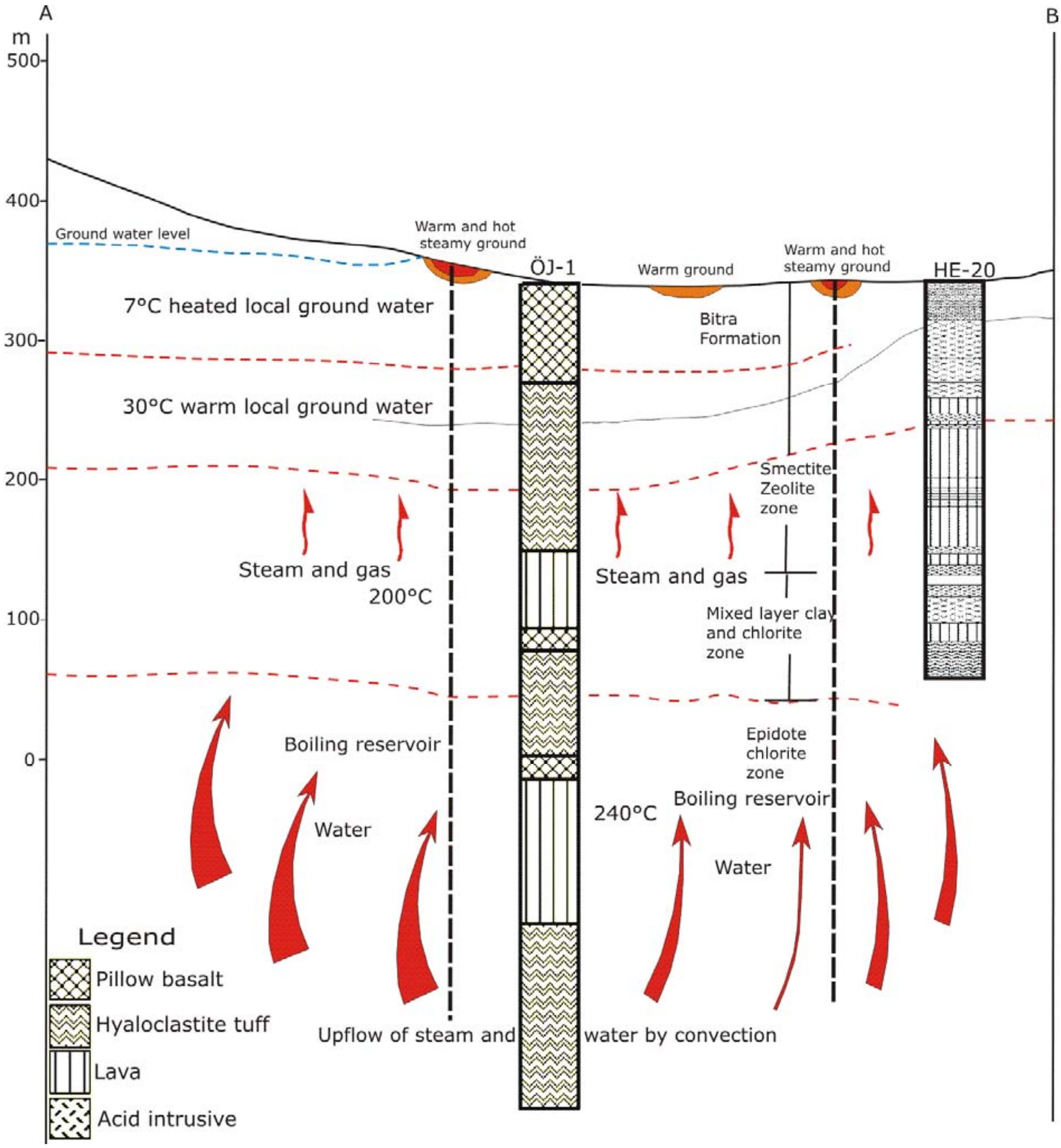

FIGURE 13: Hydrothermal model of the mapped area with the drillholes along line A-B (vertical scale twice the horizontal scale), location shown in Figure 6

temperature of 240°C and above, which further indicates a hot boiling reservoir below this depth. In addition, the three systems of aquifers revealed from drilling of this well i.e. the cold groundwater system, about 7°C which could be explained as heated groundwater dominating the top 50 m of the well; 30°C warm groundwater system extending to the depth of 150 m, and the third system which is the geothermal reservoir system dominated by water temperatures ~200°C, are incorporated into the model to show the temperature build-up in the system (Figure 13). The temperature distribution in well HE-20 has also been analysed from the mineralogical assemblage. The appearance of quartz and wairakite at ~110 and 186 m depth implies a temperature of 180 and 200-300°C, respectively which could be correlated with the previous well. The zone below the depth where the quartz was detected relates to the steam- and gas-dominated zone, having temperatures close to 200°C.

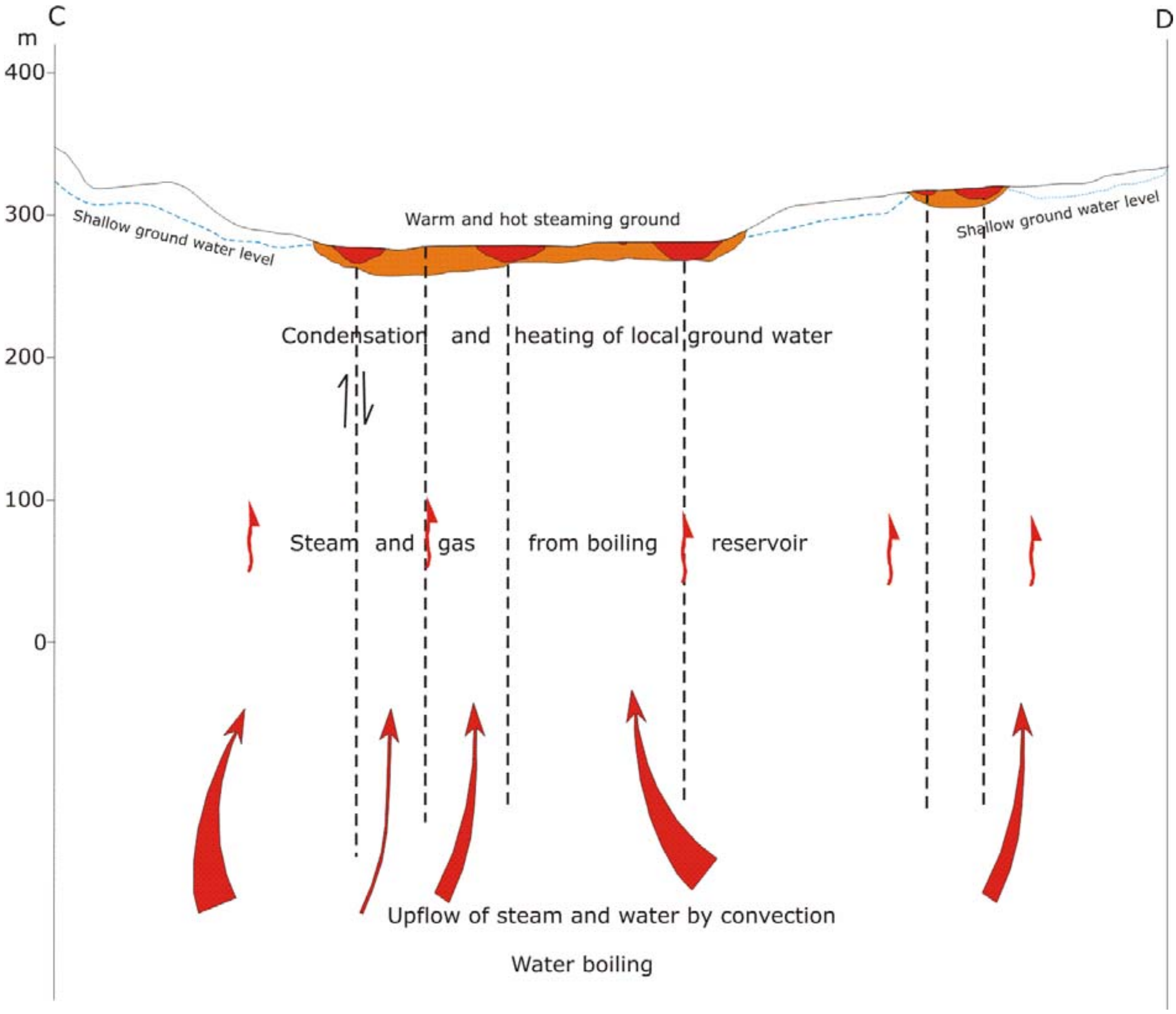

FIGURE 14: Hydrothermal model of western Ölkelduháls field along line C-D (vertical scale twice the horizontal scale), location shown in Figure 6

The possible sources for the recharge of the system are meteoric water percolating directly to the ground in flat and low grounds or sipping in through fractures after flowing from the highlands to join Lake Thingvallavatn located north of the mapped area. This water that descends down to great depths through either primary or secondary permeability is heated up as it reaches the reservoir. Steam and gas boiled off from the hot reservoir is brought up close to the surface along fracture zones to shallower levels to mix with local groundwater. It is then discharged at the surface as geothermal manifestations. While ascending to the surface the fluid decreases in temperature creating mineralogy of different composition and formation temperature by reacting with the surrounding rock types.

9. CONCLUSIONS

Detailed geothermal mapping has been carried out in the western Ölkelduháls geothermal field. The work comprises mapping the geothermal manifestations, surface alterations, the structural elements dissecting the area and shallow soil temperature surveys. The field is characterized by widespread geothermal manifestations having variable temperatures, and variable degrees of alteration controlled by structural elements such as faults and fractures. A geothermal map at a scale of 1:2000 has been produced. The following conclusions are drawn from the field work:

1. The lithology of Ölkelduháls is composed of hyaloclastites, pillow lavas, lava flows and foresets breccias of different formations that are formed in subglacial and subaerial environments.
2. Fumaroles and steam vents; boiling mud pots and water pools; hot and warm springs; hot, warm and steaming grounds are the main manifestations widely distributed in the mapped area and occur at different elevations.
3. The alignment of geothermal manifestations and clay alterations and the orientation of temperature isolines in preferred directions are taken to indicate some of the manifestations to be structurally controlled.
4. The major structural trends that seem to control the geothermal manifestations are oriented NE-SW although there are N-S and NW-SE oriented fractures and faults.
5. Hydrothermal alteration mainly controlled by permeability, temperature and rock type has affected the area in different degrees. Rocks are either slightly altered or completely transformed to clay. Two types of alterations were distinguished during surface mapping, slight alteration and clay alterations.
6. The slight alteration is related to the Bitra formation and could be of Finiglacial age.

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APPENDIX I: Preparation of samples for analysis

a) Clay mineral analysis:

1. Into a clean test tube place a small amount of clay. Fill the tube to approximately two-thirds full with distilled water. Place the tube in a mechanical shaker for 2 - 3 hours.
2. Pipette a few millilitres from each tube and place approximately 5 drops on a labelled glass plate, not making the film thick and let them dry at room temperature overnight.
3. Run the samples in the range 2 - 14° for a time of about 13 minutes on the XRD machine.
4. After running the samples air dried place them at a desiccator containing glycol ($C_2H_6O_2$) solution. Store it at room temperature for at least 24 hours.
5. Run the glycolated samples in the same way in the XRD machine.
6. After the glycolated samples are analysed the samples are put into an oven and heated at 500 - 550°C for one hour. When the samples have cooled, the samples are analysed through he same process on the XRD machine.

b) XRD mineral analysis

1. Crush the samples to a grain size of 5 - 10 Å. Acetone is usually added to prevent loss of sample while powdering.
2. Smear the sample on a glass plate and let the acetone dry.
3. Run the sample from 4 - 60° on the XRD machine.