GEOLOGIC MAPPING FOR GEOTHERMAL EXPLORATION, TRÖLLADYNGJA AREA, REYKJANES PENINSULA, SOUTH WEST ICELAND

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ABSTRACT

The need for author's practical training in geological exploration for geothermal evaluation has prompted this geologic mapping of the Trölladyngja high temperature geothermal field. Emphasis has been placed on mapping young volcanic rocks, tectonic structures, hydrology and hydrothermal manifestions which are important characteristics in any geothermal evaluation.

Field findings have been interpreted in terms of heat source, permeability, source of geothermal fluids and past surface activity. It is author's view that the geothermal resource in the Trölladyngja field is restricted to narrow zones controlled by dykes intruded during a limited period, and that successful tapping of this resource heavily depends on striking these dykes and defining the zones of dyke intrusion in space and time.

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1. INTRODUCTION

Geologic mapping in the Trölladyngja high temperature geothermal field has been conducted as part of the six month geothermal training programme organized by the United Nations University and the Iceland National Energy Authority (Orkustofnun). The field work, therefore, was intended to provide practical training in geologic mapping for field evaluation of a geothermal prospect. Emphasis has been placed on volcanic, tectonic and hydrothermal features which are important for understanding any geothermal system. Trölladyngja area is stuated in the Reykjanes Peninsula, South West Iceland. Its location is shown in Figure 1.

2. GENERAL GEOLOGY OF THE REYKJANES PENINSULA

Reykjanes Peninsula is covered by interglacial lava shields probably formed during the last interglacial period in the Upper Pleistocene, and Postglacial lava flows (Kjartasson, 1960 and Jónsson, 1978). Prominent geologic feature in the peninsula is the hyaloclastite ridges and tuyas formed by subglacial eruption of the Mid-Atlantic Ridge. The ridge assumes a ENE trend and is represented in the peninsula by four to five NE trending en echelon arrays of fissure swarms. A maximum of lava production and the presence of the high temperature geothermal fields suggest intrusive complexes near their centers, Figure 1. Also prominent in the peninsula is large number of subparallel NE trending faults evident in the hyaloclastite, interglacial and early Postglacial lava flows.

The peninsula is also the most active seismic zone in Iceland. Epicenters of recorded earthquakes are confined to a narrow linear zone less than 10 km wide and striking in a ENE direction (Tryggvasson, 1973 and Jakobsson et al.,1977). Within the earthquake zone a 2-5 km wide microearthquake zone has been identified and is interpreted as the American and European plate boundary (Klein et al., 1973, 1977). Only basalts have been erupted on the Reykjanes Peninsula and these basalts range from picrite lava through olivine tholeiite lava shields to tholeiite fissure lavas (Jakobsson et al.,1977). The picrite lava is associated with small lava shields formed in the earliest Postglacial period, while the olivine tholeiite forms large shields the youngest of which are early Postglacial period. The tholeiite lavas are associated with volcanic fissure eruptions which began during the later part of the Postglacial period and the latest episode occured about 1000 years ago (Orkustofnun, 1986).

3. PREVIOUS INVESTIGATIONS

Scientific investigations in the Trölladyngja area have been conducted by various researchers in the past, and several reports either of preliminary nature or dealing with specialised aspects of the geothermal resources are in existence. These investigations included, among others things, geology (Jónsson, 1978 and Muhagaze, 1984), geophysics (Orkustofnun, 1986), and geochemistry (Guðmundsson et al., 1971, Arnósson et al., 1975 and Orkustofnun, 1986). Reports of these investigations form the basis for the following precis:

3.1. Geology

Orkustofnun (1986) categorized lavas of Trölladyngja area into four volcanic episodes, viz: lava shields 8000-10000 years old erupted by the Hrútagja and Þráinsskjöldur volcanoes, and three fissure episodes with ages of 5000-7000, 2000, and 1000-1500 years old. Muhagaze (1984) classified seven lava eruption episodes by subdividing the youngest two of the Orkustofnun's (1986) episodes into five eruption episodes. He also found out under the microscope that the lavas in the area range in composition from picritic type through olivine tholeiites to tholeiites, and occur as holocrystallines or hypocrystallines with aphyric or porphyritic textures.

Stratigraphy reconstructed from a 843 m well no. 6 at the foot of the Trölladyngja Mountain shows a succession of alternating hyaloclastites and basalt lavas intruded by dolerite dykes. Highly altered hyaloclastite was encountered at 500-585 m depth (Orkustofnun, 1986). Drillhole geologic section along with alteration minerals and temperature profiles are shown on Figure 2.

3.2. Geophysics

Schlumberger resistivity soundings and head-on profilings (Orkustofnun, 1986) in the Trölladyngja area indicated a NE-SW elongated resistivity low (<5 ohm m) along the western roots of the Trölladyngja-Nupshliðarhals ridge from the Eldborg cone to Selsvellir. A NE-SW elongated low (<5 ohm m) is also indicated along the western roots of the Sveifluhals ridge from Köldunámur to Traðarfjöll. Fumaroles at Eldborg and Oddafell are located in the western resistivity low. The western low resistivity zone and the fumaroles are shown on Figure 9.

3.3. Geochemistry

Geochemical investigations of fumaroles in the Trölladyngja area were initiated since early 1970 (Sigurmundsson et al., 1971 and Arnórsson et al., 1975). Table 1 shows chemical analysis of gas and steam samples collected in 1983 from a fumarole just north of well no. 6 at the northern roots of the Trölladyngja and a boiling spring at Sog. Mercury concentration indicated a hotter and stronger up-flow at Trölladyngja than at Sog, and geothermometry also indicated higher deep fluid temperature at Trölladyngja than at Sog (Arnórsson and Gunnlaugsson, 1985, D'Amore and Panichi, 1980 and Nehring et al., 1981). However, the measured temperature in well no. 6 at 500 m was 260°C, Figure 2 (Orkustofnun, 1986).

4. PRESENT GEOLOGIC INVESTIGATIONS

Geologic investigations have involved mapping of rock units, and tectonic and geothermal features by field observation and supplemented where possible by aerial photography and microscopic rock analysis.

4.1. Geology

Dominant rock units in the Trölladyngja area are hyaloclastites and Postglacial lava flows with subordinate superficial deposits, Figure 3. These and minor intrusive bodies are described below:

4.1.1. Hyaloclastites

The most prominent geologic feature in the Trölladyngja area is the hyaloclastite ridges. Formation phases of the hyalocl-astites are well documented by, among others, Sæmundsson, 1967 and Jones, 1968. They were formed subglacially and are characterized by four consanguineous rock units; namely pillow lava, pillow breccia, tuff and lava. The pillow lava represents the initial effusive phase under deep meltwater and it tends to pile-up around the volcanic orifice. The pillow breccia phase then follows. It is a process essentially involving gravitational slumping on the flanks of the pillow lava. As eruption continues under shallow water condition an explosive phreatic activity becomes evident with the formtion of a bedded tuff. If the volcanic pile emerges above the meltwater level, subaqueous eruption changes to subaerial one and lava may be erupted, more commonly capping the volcanic pile, particularly on top of tuyas. In the Trölladyngja area ridges of hyaloclastite tuffs and associated minor pillow breccias are dominating subordinated by ridges of pillow lava, Figure 3. They are locally capped by basalt lavas, suggesting emergence above the confining glaciers. Further categorization of the hyaloclastite tuffs and associated lavas is as follows from the oldest to youngest:

Age subdivisions are tentative, based on morphologic and stratigraphic criteria. The hyaloclastite ridges lack the smooth morphology of old eroded ridges. Their ruggedness is taken as evidence of Weichselian (115000-10000 B.P) even late Weichselian age. Supporting evidence is that they are nowhere seen to be overlain by interglacial shield basalts (Sæmundsson, 1986, personal communication).

1. Trölladyngja porphyritic hyaloclastite tuff and associated pillow lava fragments represent the oldest subglacial extrusive rock in the area, probably 70000-40000 years old (Sæmundsson, 1986, personal communication). The hyaloclastite tuff has a yellowish brown tinge caused by 'palagonitization' a mechanism involving leaching and cementing of the glassy tuff, and oxidation of ferrous iron to ferric iron (Jakobsson, 1979). Both the tuff and the pillow lava fragments are characterized by a high proportion of 4-7 mm feldspar (plagioclase) phenocrysts. The hyaloclastite tuff is intercalated by basalt lava that indicates subaerial phase of a subglacial eruption, and was eventually covered by hyaloclastite tuff of a later subglacial eruption.

2. Fiflavallafjall porphyritic hyaloclastite tuff and breccia, like the rest of the hyaloclastite in the area, is probably 40000-12000 years old (Sæmundsson, 1986, personal communication). The tuff is yellowish brown and consists of sparsely distributed 4-6 mm feldspar phenocrysts, while associated pillow lava fragments contain occasional 2-3 mm feldspar phenocrysts.

3. Further subdivision of the hyaloclastite has been difficult due to similarity of both the tuffs and the pillow lava fragments in hand specimens. Microscopic analyses of the pillow lava fragments, however, indicate similarity of samples 14505-7 and 14511-17, (Table 2), both are olivine tholeiite, microporphyritic in texture and dominated by plagioclase and olivine. The microscopic analyses also indicate dissimilarity of samples 14503-5, 14505-7, 14506-10, 14509-14 and 14508-12 (Table 3, Figure 3 for sample locations). Based on these limited micro-

scopic findings and field mapping, the hyaloclastite has been subdivided into six units, Figure 3.

With the exception of the Trölladyngja hyaloclastite tuff which is the oldest, the rest of the hyaloclastites in the area which include those of Fiflavallafjall, Grænadyngja and Selsvallafjall ridges are believed to have been formed about 40000-12000 years ago (Sæmundsson, 1986, personal communication). These were followed by the Postglacial eruptions of lavas and scoria evident in the recent times.

4. Porphyritic pillow lava and hyaloclastite breccia overlies the hyaloclastite tuff northeast and southwest of the lake Djúpavatn, (Figure 3). The lava contains abundant 3-4 mm feldspar phenocrysts. Under the microscope it has a poikilitic texture with abundance of plagioclase and olivine indicating that it is olivine tholeiite type. The plagioclase also occurs as megaphenocrysts in the glassy matrix (Table 2, sample 14503-5). The unit southwest of lake Djúpavatn forms a narrow low ridge trending NW-SE. It is the only case suggestive of an eruptive fissure of that trend in the mapping area.

4.1.2. Dykes and sheets

Intruded into the hyaloclastite tuffs are aphyric basaltic dykes and sheets. Majority of the dykes are NE trending, parallel with the main tectonic direction of the area. Some are persistant in that direction for a few tens up to hundreds of meters. The NE trending dykes dip 80°-85° east. There are also N-S and NW trending dykes dipping 70°-80° east and northeast respectively. Sheets are irregular; and some of the dykes and sheets were feeders.

4.1.3. Gabbroic nodules

Gabbroic nodules occur northeast of the lake Djúpavatn, a location marked X on Figure 3. Here the nodules are associated with a porphyritic pillow breccia and are generally less than

8 cm in diameter. The nodules are porous and course, the mineral grain size being up to 5 mm. Hand specimen shows dominance of feldspar phenocrysts. Microscopic analysis also shows dominance of plagioclase in association with olivine, pyroxene and rare magnetite (Table 2, sample 14502-2). The nodules are believed to be cognate xenoliths formed freely floating at a shallow depth (Jakobsson, 1979).

4.1.4. Lava flows

Lava flows have been classified into seven volcanic episodes with some modifications of Muhagaze's (1984) and Orkustofnun's (1986) classifications. These lavas are shown on Figure 3, and are described starting with the oldest as follows:

1. Hrútagja lava is associated with Hrútagja lava shield. The lava is porphyritic (plagioclase phenocrysts) holocrystalline olivine tholeiite (Muhagaze, 1984).

2. Fiflavallafjall lava originates from a crater row north of Fiflavallafjall hyaloclastite ridge. The lava is tholeiite (Muhagaze, 1984).

3. Grænadyngja-Sog-Grænavatnseggjar lavas were erupted from crater rows of similar character north of Grænadyngja and west of Sog and Grænavatnseggjar. These lavas are hypocrystalline aphyric to microporphyritic tholeiite (Muhagaze, 1984), and underlies lavas of episodes 4, 6 and 7 to be mentioned later.

4. Eldborg lava was erupted from the Eldborg crater , and along a fissure at the northwestern foot of the Trölladyngja. This lava overlies that of episodes 2 and 3; and its occurrence in relation to lava episode 6 at Snókafell (outside the study area) suggests that the Eldborg lava is older than episode 6 (Einarsson, 1986, personal communication). The Eldborg lava is hypocrystalline tholeiite type (Muhagaze, 1984).

5. Móhálsadalur lava has been erupted from crater rows at Móhálsadalur eastern part of the study area. The lava overlies lavas of episodes 1 and 2, and underlies that of episode 7; and it does not come into contact with lava of episode 3. The Móhálsadalur lava is aphyric tholeiite.

6. Melhóll (Afstapahraun) lava has originated from Melhóll crater southwest of the Trölladyngja area, and flowed northwards. The lava is tholeiite type.

7. Mávahliðar lava is associated with craters west of Mávahliðar hyaloclastite ridge at northeast limit of the study area. The lava overlies lavas of episodes 2 and 3. It is tholeiite type.

4.1.5. Superficial deposits

Superficials cover small and patchy areas,Figure 3, and consist of silts, sands and soils. The silts and sands are derived essentially from the hyaloclastite tuffs. At places soils have been formed ; and at places brown and grey pumiceous loose tuffs, and black and grey pumiceous ashes occur as bands within the brown soils. Some of these ashes have been used as a tool for dating lava flows in the area.

The occurrence of a well bedded clayey silt and sand formation (10-20 m thick) at Sog is interpreted as lacustrine sediments deposited in a glacial lake probably during the last glaciation. It is suggested that geothermal activity that existed then, had sustained a shallow lake into which sediments were deposited. Higher groundwater table sustained by the lake meant that hydrothermal manifestations were in the form of hot springs that deposited aragonite and calcite observed in viens in the area.

4.1.6. Dating of lava flows

Jónsson (1978), using historical records, carbon dating, tephrochronology of known ash layers, and relation to lava flows of known ages reconstructed the Postglacial volcanic history of the Reykjanes Peninsula; and his dating forms the basis for the present dating of the Trölladyngja area but with some modification according to latest stratigraphic knowledge of the area (Einarsson, 1986, personal communication). For example, Torfajökull ash layer, (the layer of settlement) erupted in the year 900, occurs above the scoriceous tephra from the Eldborg and Traðarfjöll craters but is separated from it by a thin red ash. The ages of the Eldborg and Traðarfjöll lavas have been estimated from this relationship. Stratigraphically relating ages of the Eldborg and the Traðarfjöll, ages of other lava flows were estimated as shown on Figure 3. Ambiguity, however, exits. Stratigraphic evidence puts lava flow episode 5 younger than that of episode 2 and older than that of episode 7; and no contact exists between lava episode 5 and lava flows 4 and 6. Therefore, the position of lava flow episode 5 in the stratigraphy shown on Figure 3 is rather arbitrary and subject to age uncertainty.

4.2. Tectonics

4.2.1. Faults and fissures

Figure 4 shows tectonic features of the Trölladyngja area. A NE trending fault system is recognized making the axial rifting of the so called Mid-Atlantic Ridge. The main tectonic feature of the axial rifting is the graben structures evident in the hyaloclastite ridges where throws up-to 6 m are indicated and fault movements are continuing. Contemporary with rift faulting are the NE trending fissures both eruptive and non-eruptive, and they cluster into a swarm. Crests of the hyaloclastite ridges define Upper Pleistocene eruptive fissures. Their trend coincides with that of the present fissures despite of the east or west shifts.

4.2.2. Fractures

Fracture measurements were made at six localities (Figure 5). Measurement layout consisted of two 50 meter long profiles kept approximately perpendicular to each other in N-S and E-W directions. Using a compass and a measuring tape, distribution and orietations of the fractures more than 5 m long and near vertical were recorded. The data obtained were plotted as rose diagrams giving a visual representation of frequencies and preferred orietations of the measured fractures, (Figure 5). The longer the arrow the higher is the frequency of the preferred fracture orientation.

Two major fracture systems are evident in the area. One swings from 25 to 35 degrees and the other from 95 to 115 degrees but strongest between 95 and 105 degrees (Figure 5). The 25-35 degrees fracture system is interpreted as extension feature formed in the same way as the normal faults, by the extension stresses associated with the rifting and dyke injection in the axial zone. Jefferis, R.G. and Voight, B.(1981) working in the Reykjavik-Hvalfjördur area also recognized two fracture systems: a northeast and a broad east-west, trending 10-30 degrees and 70-130 degrees respectively. By examining secondary minerals in vug and fractures they determined the area's thermal history which indicates that the NE system were formed while the area was within the axial zone of active volcanism and drifting. They also concluded that some of the E-W trending fractures opened at this time but many formed later after the area had begun to cool and drift from the active zone. One would expect, therefore, that similar tectonic events occur in the Trölladyngja area. The E-W trending fracture system in the study area is thus associated partly with drifting stresses and partly with thermal stresses.

The NE trending fractures are persistantly straight, generally less than 5 cm wide and infilled. But those near major active faults are up-to 50 cm wide, and at places those up-to 0.5 cm are indurated. The E-W trending fractures are generally thin and open, some are curved and segmentary, and sometimes they are younger than the NE trending ones.

4.3. Hydrothermal manifestations

Surface hydrothermal manifestations in the Trölladyngja area are fumaroles and altered ground typical of acid enviroment. Classification into high, medium and low (slight) alteration intensities have been employed, Figure 6. Intensity here is a measure of how completely a rock has been changed into clay. A rock completety changed into clay is hihgly altered, that containing some clay is medium altered, and that containing traces or no clay is slightly (low) altered. Locally most extensively and highly altered ground, about 0.3 sq. km, is found at Sog where hydrothermal activity had been extremely vigorous in the past. X-ray Diffraction analses showed that highly altered earth is composed of smectite, kaolinite and gypsum for fossil ground, and smectite for steaming ground. Medium altered earth contained some smectite and zeolite; whereas no clay minerals were detected, as expected, in the slightly altered rock.

Fumaroles and warm grounds are the only active manifestations in the Trölladyngja area. They are located at the western margins of the fossil highly altered grounds. Worth noting, the active manifestations occur in the western part of the area and north of the so called microearthquake zone, Figure 6. The latter observation is speculative because the boundaries of the microearthquake zone are inaccurately defined. Fumaroles at Eldborg are controlled by an active fissure that had probably been reactivated during the Eldborg eruption. Those at Sog are associated with dykes. Fossil hydrothermal mineralization in the area include aragonite and calcite at Sog; and silica sinter at Hverinn eini and a spot southeast of it. Aragonite and calcite deposition indicates that hydrothermal activity in the past were in the form of hot springs of probably carbonate character. As groundwater level fell, ascending steam condensates superseded them and caused the extensive kaolinite and smectite clay alteration seen today. Silica sinter also indicates that hot springs of neutral alkali chloride water existed in the past. Present day fumaroles deposit sulphur, a product of oxidized hydrogen sulphide gas being emmitted along with the steam. Worth noting on Figure 6 is that alteration is centered at Sog where hydrothermal activity had been most intensive and fades away towards the north, south and west, and narrows eastwards towards Krisuvik. This suggests that Trölladyngja may as well be a separate geothermal field.

4.4. Explosivity of volcanic craters

Explosivity is a measure of energetic ejection of pyroclastic material. By estimating the amount of scoria produced by, and the size of, craters, high, medium and low explosivities were recognized. High and medium explosivity craters are shown on Table 3; and the remaining craters are considered of low explosivity. Explosivity should be distinguished from explosivity index which is the percentage of pyroclastic material among the total products of a volcanic eruption. All high and medium explosivity craters are located within the hydrothermally altered zone, (Figure 6), and more so around Sog and Grænavatnseggjar area. Probably explosivity is caused by physical interaction between the rising magmas and hydrothermal fluids, boiling off into the volcanic vents as a result of pressure release.

4.5. Hydrogeology

Precipitation in the Trölladyngja area is high (1500-2000 mm, Orkustofnun, 1986), and all water percolates deep into the bedrock through faults, open fissures and fractures as well as through porous lava flows. Some of the precipitation would percolate deeper into the geothermal system and bulk of it flows laterally along faults and permeable horizons before it discharges at Straumsvik and Vatnsleysuvik north of the area (Orkustofnun, 1986 and Einarsson, 1986 personal communication). Anisotropy is apparent with higher permeability along faults than across them.

Relatively low permeability, with associated low infiltration rate, in the hydrothermally altered hyaloclastite ridges builds up a high groundwater table. Where the water table is intersected by a gully, slump or sometimes a fault springs or seepages occur.

These springs and seepages sustain small stream runoff that eventually disappears into the lava flows at the foot of the hyaloclastite ridges. Using the springs, seepages and lakes as markers of the groundwater table at various elevations, groundwater contours have been drawn as shown on Figure 6.

4.6. History of volcanic activity

Probably until late Upper Pleistocene the Trölladyngja area was marked by a gently undulated topography of the Plio-Pleistocene inter- and sub-glacial rocks, a few tens of meters above the present sea level. The present prominent topography of the area progressively began to form about 70000-40000 years ago when the Trölladyngja Mountain hyaloclastites were erupted. The basalt lava intercalation within the Trölladyngja hyaloclastite indicates that more than one eruption occured during this episode. This eruption episode was confined to a fissure zone about 2 km long; the volcanic pile rising, at its peak, to more than 400 m above the present sea level(Figure 7). Alteration mapping apparently has not associated this episode with the surface hydrothermal activity.

About 40000-12000 years ago a relatively major eruption episode occured forming the Grænadyngja-Selsvallafjall and Fiflavall-afjall ridges (the main hyaloclastite) as well as the Hrútafell, Oddafell and Lambafell pillow lava ridges(Figure 8). Also here, the lava intercalation indicates that more than one eruption occured during this episode. This was associated with extensive hydrothermal activity with main activity at Sog where it sustained a glacial lake. One might even speculate that implacement of the Trölladyngja high temperature geothermal system occured at this time.

The faulting style in the hyaloclastites was probably established during this time, which itself followed pre-existing tectonic structures of the axial volcanic zone. The fault planes dip towards SE or NW giving the typical graben and step faulting structures, whose maximum displacements change in space and time.

Postglacial eruptions then followed, which began about 12000 years ago. They are characterized by volcanic eruptions of lava shield, crater and fissure lava flows, and scoria. These lavas are geochronologically classified as shown on Figure 3. At places these Postglacial eruptions intruded the geothermal system with evident explosivity (Figure 6); and at places reactivated, or were accompanied by, surface hydrothermal activity.
It is probably during the Postglacial period that sufficient silt/clay material has formed into depressions between the altered hyaloclastite ridges to sustain the lakes seen today in the area.

5. DISCUSSION

Objective of a geologic mapping of any geothermal prospect is to evaluate the prospect in terms of its heat source, permeability and hydrology. In the Trölladyngja area, therefore, heat indicators such as young volcanics, altered ground and fumaroles were mapped. Faults and fractures which may indicate secondary permeability that has been found most important in most geothermal systems were also mapped. The positive role of groundwater in geothermal resources is undisputable. It transports heat energy from the reservoir to the geothermal well or earth's surface. Therefore such hydrologic features as cold springs and seepages were mapped, and existing hydrologic data were sighted with a view of determining the source of geothermal fluids, areas of recharge and discharge, depth to water table, etc. Geothermal evaluation of the Trölladyngja high temperature geothermal field as well as mapping limitations are discussed as follows:

5.1. Heat source

Like any other high temperature geothermal field in Iceland, the Trölladyngja field is located in an hihgly active volcanic zone where young volcanic rocks predominate. Here rocks as young as about 1000 years old occur. They have been erupted by narrow fissures which most likely are connected to narrow feeder dykes and sheets. Therefore, a high temperature gradient is evident in the area. However, these narrow dykes and sheets would inevitably cool rapidly implying limited resource and questionable longevity of the prospect unless rate of dyke or sheet injection is kept high. Kaolinite clays, silica sinter and sulphur indicate high subsurface temperature of geothermal fluids. Possibly a deeper heat source plays a role. Seismic studies indicate a depth of about 4-5 km to layer 3, which is to a large part intrusive and at a high temperature underneath active rift zone (Pálmason 1971, Flóvenz 1985). It is likely that intrusive bodies (magma chambers ?) rise to still higher crustal levels and help sustain geothermal systems over long periods of time. Zones of preferred dyke injections may shift to and fro across these and are of a more transient character.

5.2. Permeability

Trölladyngja area is highly faulted and fractured as clearly demonstrated by well developed systems of faults and fractures. In the hyaloclastites, faults and fractures are not associated with hydrothermal activity. This may suggest that at near surface the faults are sealed off by hydrothermal deposition, but are likely to be permeable at depth. Past and present association between dykes and up-flow of hydrothermal fluids can be observed at Sog where exposed dykes are bounded by altered zones. Therefore. dykes and sheets provide the most important permeability in the area. This has been confirmed in well no. 6 (Orkustofnun, 1986).

5.3. Hydrothermal activity

Precipitation and permeability in the area are high. Despite of this, active surface hydrothermal activity is insignificant and confined to a narrow zone. This may be indicative of a restricted nature of the geothermal resources in the area in terms of areal extent and output; or the plentyful groundwater suppresses activity of an otherwise extensive and vigorous geothermal system. The former view is the most probable.

5.4. East-west trends

Alteration zones are east-west elongated indicative of structural control. But there are little surface structural features that could explain this alteration trend. It appears, therefore, that there are deep structures that control the up-flow of geothermal fluids. Are these deep structures associated with the seismic zone? Or are the inferred NW trending fractures (Figure 4) surface traces of the deep structures? Present mapping is not able to answer these questions.

5.5. Hyaloclastite mapping

The non-porphyritic hyaloclastite tuffs and associated pillow lava fragments show a remarkable similarity. Therefore, their classification requires detailed mapping effort and microscopic rock analysis. The present mapping of them was based on limited microscopic work which makes their classification here uncertain.

6. CONCLUSIONS

6.1 Narrow intrusive dykes and sheets are the heat source at shallow depth, but are subject to rapid cooling. Unless their rate of injection is high, this heat source is unreliable. Deeper heat source may be associated with magma bodies intruded to shallow depth.

6.2 Two general fracture systems are present in the Trölladyngja area. The systems trend northeast and east-west. The NE system is an extension feature and the E-W system is associated with drifting and thermal stresses.

6.3 Surface hydrothermal activity is fissure controlled at Eldborg and Oddafell, and dyke controlled at Sog.

6.4 Hydrothermal alteration zones are approximately NW-SE trending, strongly suggesting structural control.

6.5 Fossil mineral deposits indicate that in the past hydrothermal activity was in the form of hot springs in the area.

6.6 Craters with high to medium explosivity occur within the alteration zones. It appears that there is a physical interaction between the rising magmas and the hydrothermal fluids, boiling off into the volcanic vents as a result of pressure release.

6.7 Fracture permeability is important in the area especially at the margins of intruded dykes and sheets; and success of geothermal wells will depend on striking these dykes and sheets.

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Table 1: Chemical analysis of gas and steam from the Trölladyngja field (after Orkustofnun, 1986).

		Trölladyngja	Sog
	CO	89,24	89,03
Volume	H_2S	1,35	1,21
%	H_2	4,30	0,30
gas	O_2	0,49	0,63
	CH_2	0,18	0,33
	N_2	4,35	8,31
	Ar	0,10	0,20
dpm/l			
in gas	Rn	13646	16508
mg/kg	CO_2	13214	7064
in steam	H_2S	16	117
ng/kg	Hg	2500	850

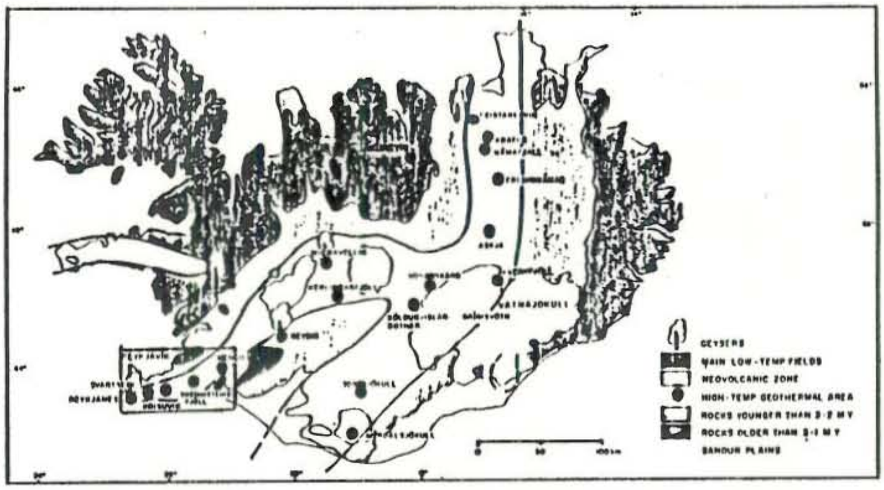
Table 2: Microscope analyses of pillow lavas associated with hyaloclastite tuffs in the Trölladyngja area

Sample no.	Rock type	Texture	Minerals present	Remarks
14508-12	Tholeiite	Porphyritic *Porphyritic	Plagioclase Rare quartz Rare ortho-pyroxene Clays Palagonite	Mega plagioclase phenocrysts and laths within glass matrix
14509-14	Tholeiite	Aphyric *Vitric	Calcite Clays Plagioclase Palagonite	Few plagioclase laths as microphenocrysts but abundant within matrix
14511-17	Olivine tholeiite	Aphyric *Porphyritic	Plagioclase laths Olivine Rare quartz Some clay Magnetite Veined iron oxide	Olivine microphenocrysts altered and remain with pseudomorphs of iron oxide Glass matrix
14503-5	Olivine tholeiite	Porphyritic *Poikilitic	Plagioclase Olivine Iron oxide Rare pyroxene	Olivine crystals enclosed by plagioclase also as mega phenocrysts in glass matrix
14505-7	Olivine tholeiite	Aphyric *Porphyritic	Plagioclase Calcite Olivine Iron oxide	Few plagioclase laths as microphenocrysts but abundant within matrix Olivine within plagioclase laths (ophitic texture)
14506-10	Olivine tholeiite	Aphyric *Porphyritic	Plagioclase laths Olivine Magnetite Iron oxide	Abundant olivine surrounded by plagioclase showing poikilitic texture
14502-2	Gabbro	Porphyritic	Plagioclase Pyroxene Rare olivine and magnetite	Abundant plagioclase phenocrysts

* microscooic texture

Table 3: Crater explosivity in the Trölladyngja Area

Crater no.	Length m	Width m	Depth m	Magnitude
1	120	90	sediment	high
2	140	110	10-15	high
3	30	30	5	medium
4	70	65	15-20	high
5	35	30	10-15	medium
6	55	20	5-10	medium
7	50	30	10	medium
8	45	30	15	medium
9	100	80	15-20	high
10a	160	120	15-20	high
b	120	100	15-20	high
11a	60	45	5-10	medium
b	90	50	20	high
12	30	30	10	medium/high
13	60	35	sediment	medium
14	30	30	sediment	medium
15	25	20	10-15	high
16	pile of scoria			high
17	100	70	20	high
18	100	100	15-20	high
19	90	50	10-15	medium
20	60	35	10	medium
21	175	175	cone	high



The volcanic zone and the high temperature geothermal areas in Iceland

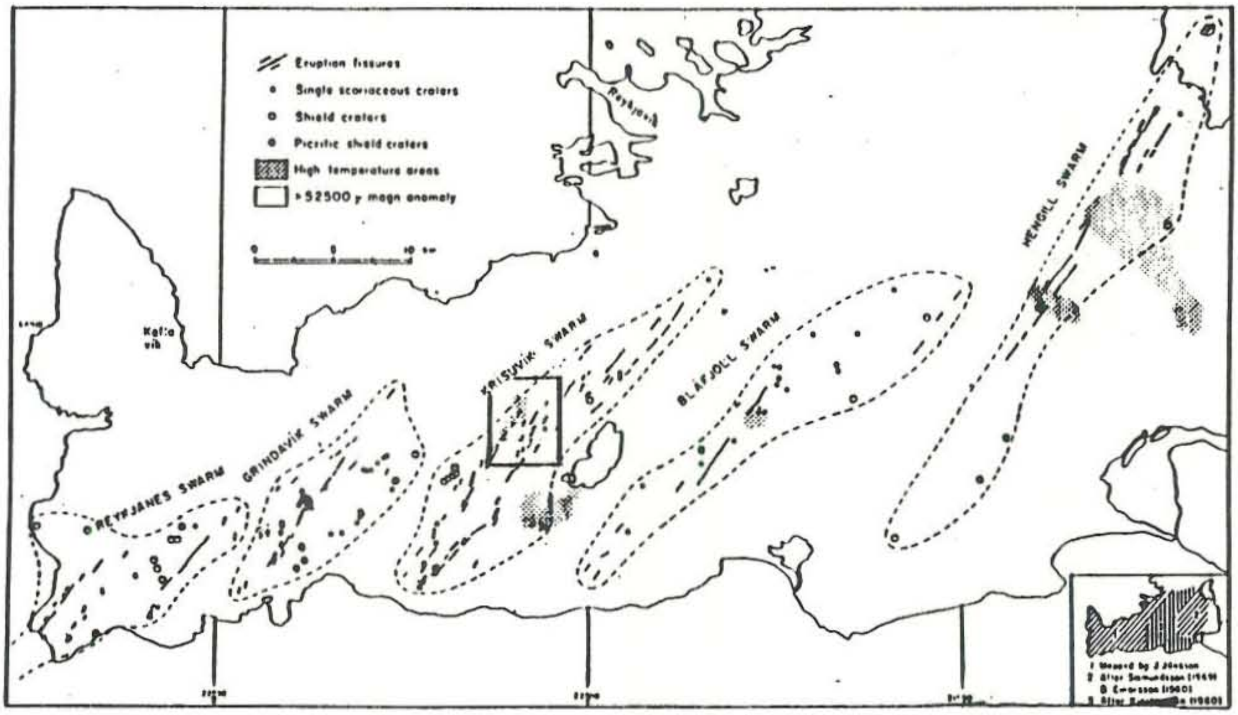


Figure 1: The active volcanic zone of the Reykjanes Peninsula, SW-Iceland (after Jakobsson et al., 1978).

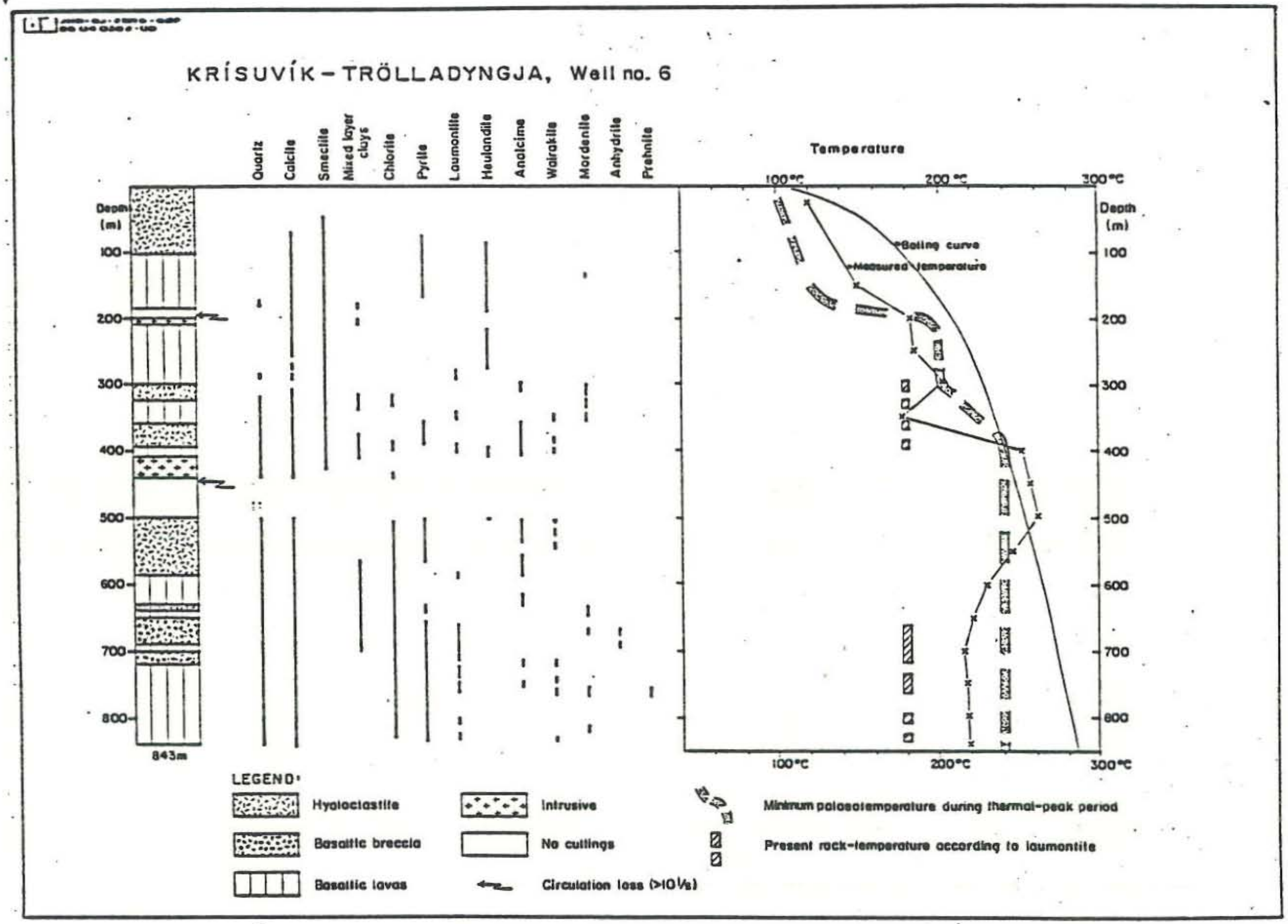


Figure 2: Well no. 6, simplified stratigraphic section, distribution of alteration minerals and temperature profiles (after Orkustofnun, 1986).

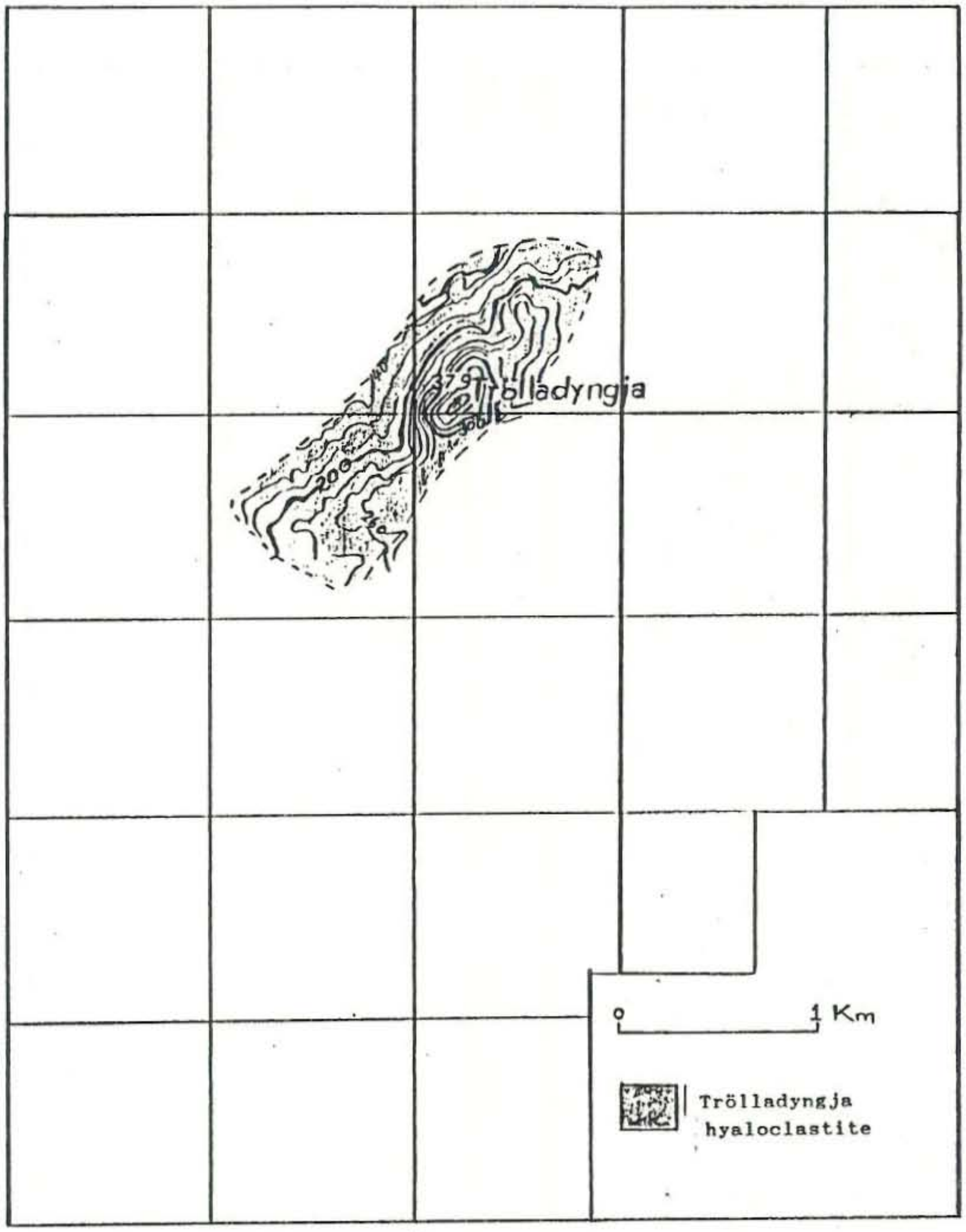


Figure 7: Prominent hyaloclastite ridge 70000-40000 year ago, Trölladyngja area.

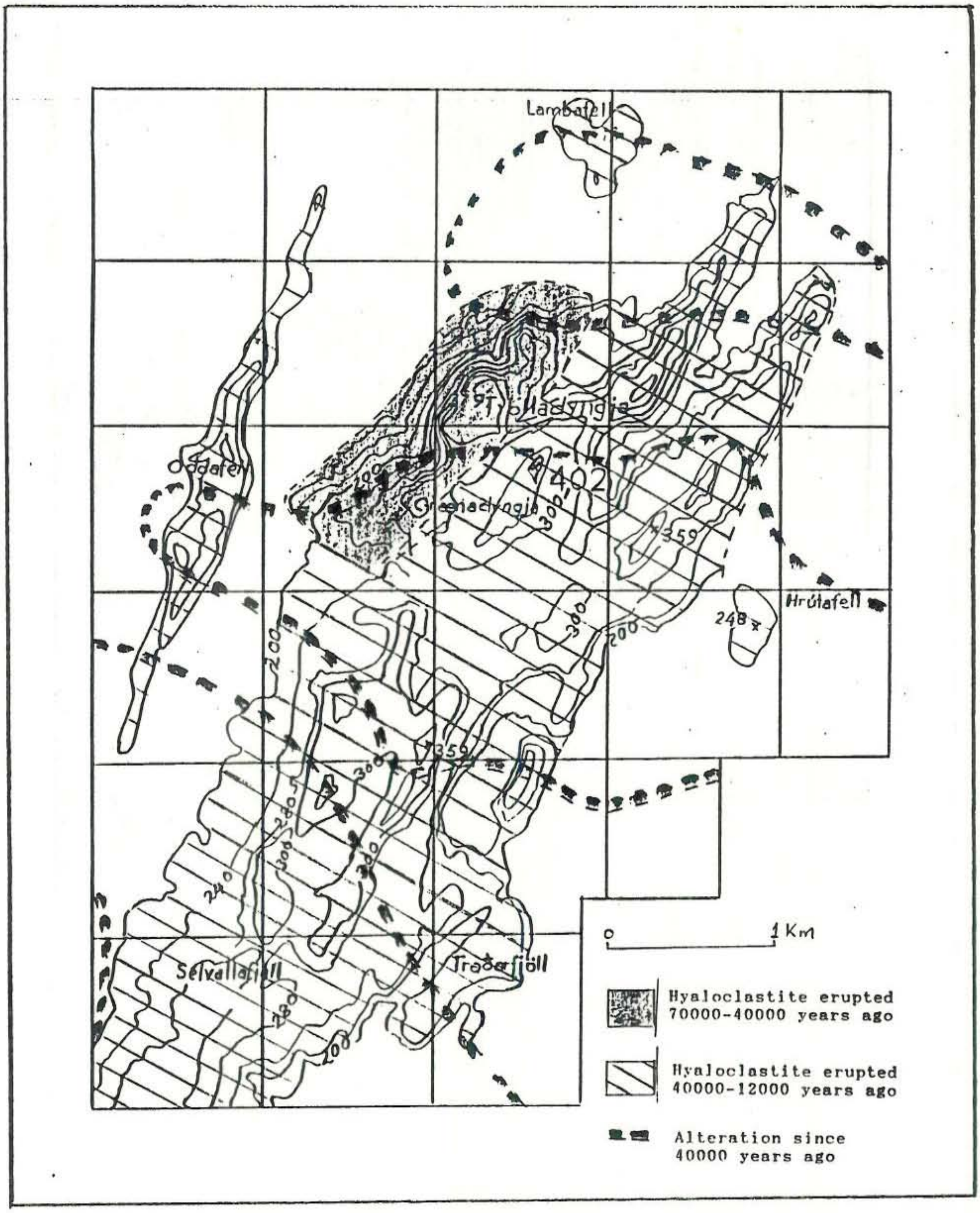


Figure 8: Prominent hyaloclastite ridges 70000-12000 years ago, Trölladyngja area.

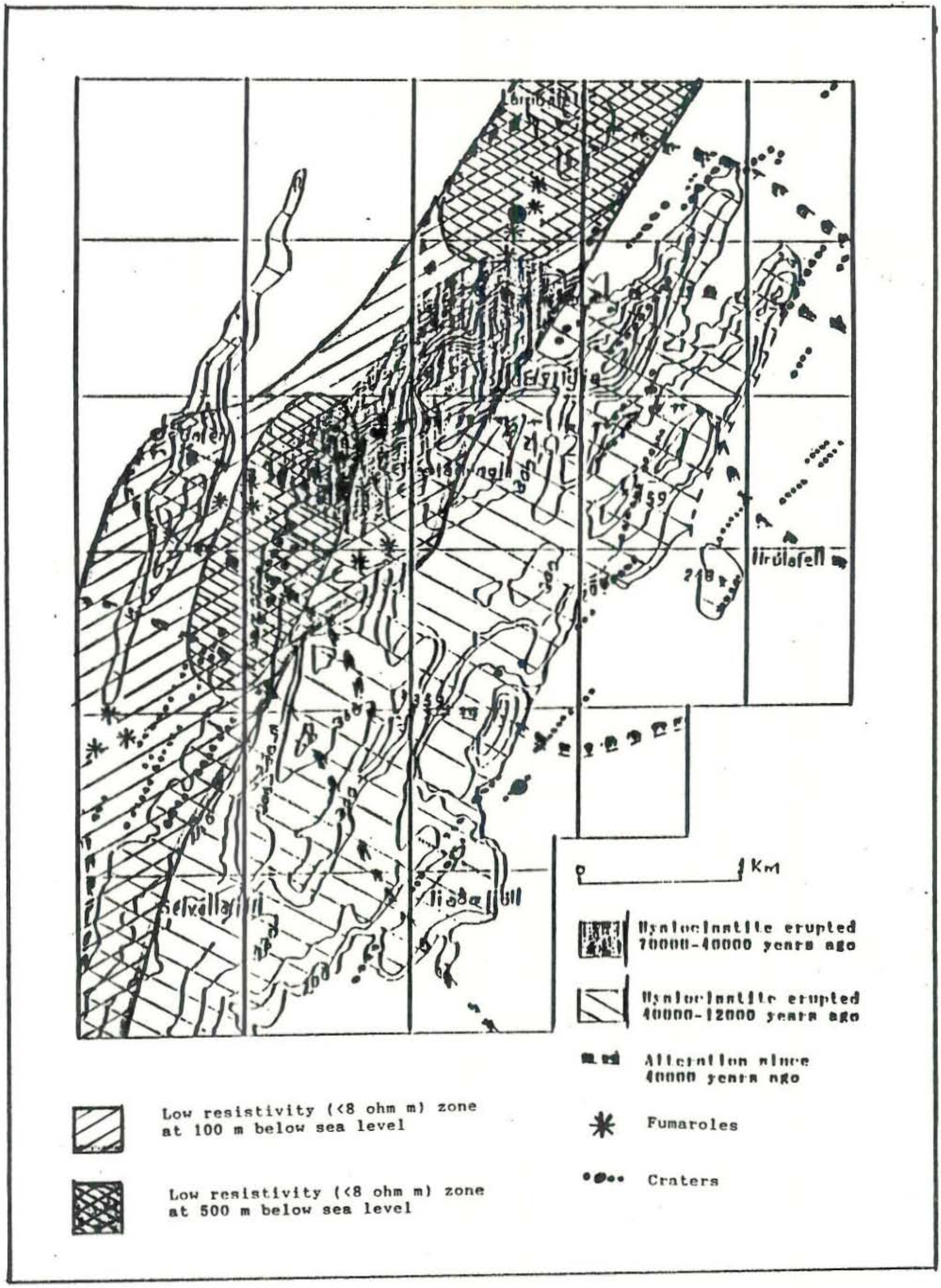


Figure 9: Low resistivity zone in relation to active hydrothermal manifestations and Postglacial volcanism.