Report 13, 1992

GEOLOGY AND GEOTHERMAL CONSIDERATIONS OF KRISUVIK VALLEY, REYKJANES PENINSULA, ICELAND

Juan R. Vargas Morales,
UNU Geothermal Training Programme,
Orkustofnun - National Energy Authority
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent Address:
Instituto Costarricense De Electricidad,
Departamento de Recursos Geotermicos,
Sabana Norte,
San José,
COSTA RICA C.A.

ABSTRACT

A geological and geothermal alteration mapping over about 20 km^2 in the Krisuvik valley, Reykjanes Peninsula, revealed an Upper Pleistocene succession of interglacial basalts overlain by pillow lava and hyaloclastites. The Postglacial volcanic rocks are characterized by hydrothermal and phreatic explosion debris, pyroclastic scorias, welded lavas and basaltic lava flows. Some areas show an intense geothermal alteration; a zeolite zone, lacking in deep wells, was found at the surface.

From the shape of the en echelon structural array on the Reykjanes Peninsula, a shear strain model is proposed. The trend of the seismic zone in the Reykjanes Peninsula (Az 80) leads to the formation of extensional fissures at 45° (Az 35), and to a maximum horizontal compressive axis perpendicular to them (Az 35). The maximum compression would produce a conjugate set of strike-slip faults on both sides at 30° with itself (Az 5 and 65). Normal to maximum compression minor jointing would also be expected. This model matches well with the surface geology in the Krisuvik area, where the main faults and fissure eruptions can be interpreted according to it. Also, almost all the focal mechanism solutions determined for the peninsula behave according to the trends predicted by the model, taking into account some local geological conditions.

A hydrogeological interpretation is proposed for the widespread thermal reversal in the geothermal reservoir, assuming an extended cold water percolation from lake Kleifarvatn, through fissures and two possible maars in the lake.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The Krisuvik geothermal area is located on the Reykjanes Peninsula, SW-Iceland (Figure 1). It covers a large area and can be divided into several sub-areas, such as the Krisuvik field, the Trolladyngja field and the Sandfell field. The purpose of this project was to carry out a surface geological survey in a valley which is located between the Sveifluhals hyaloclastite ridge and the Geitahlid-Kistufell table mountains. The valley has no name but in this report it is referred to as the Krisuvik valley, after the farm Krisuvik found there. The mapped part of the valley lies between lake Kleifarvatn and the mountain Arnarfell. It straddles the watershed of the Reykjanes Peninsula. Figure 1 shows the extent of the study area. The geological survey included searching for local stratigraphy, structural geology and the extent of the surface hydrothermal alteration. This information is later used for giving a hydrogeological interpretation of the geothermal system. Many Icelandic place names are used in the text, most of which can be found on the the geological map (Figure 5) and the map of the hydrothermal alteration (Figure 11).

The previous geological maps were made by Imsland (1973) and Jonsson (1978). Imsland mapped Sveifluhals, next to the mapped area, and separated several volcanostratigraphic units among the hyaloclastites. Jonsson prepared a more general map of the whole peninsula including the present study area. He differentiated between basalts, hyaloclastites and scorias. Noll (1967) studied the maar-craters around Graenavatn and their deposits. He showed that what was previously interpreted as tills and dead ice holes were actually explosion breccias, and craters.

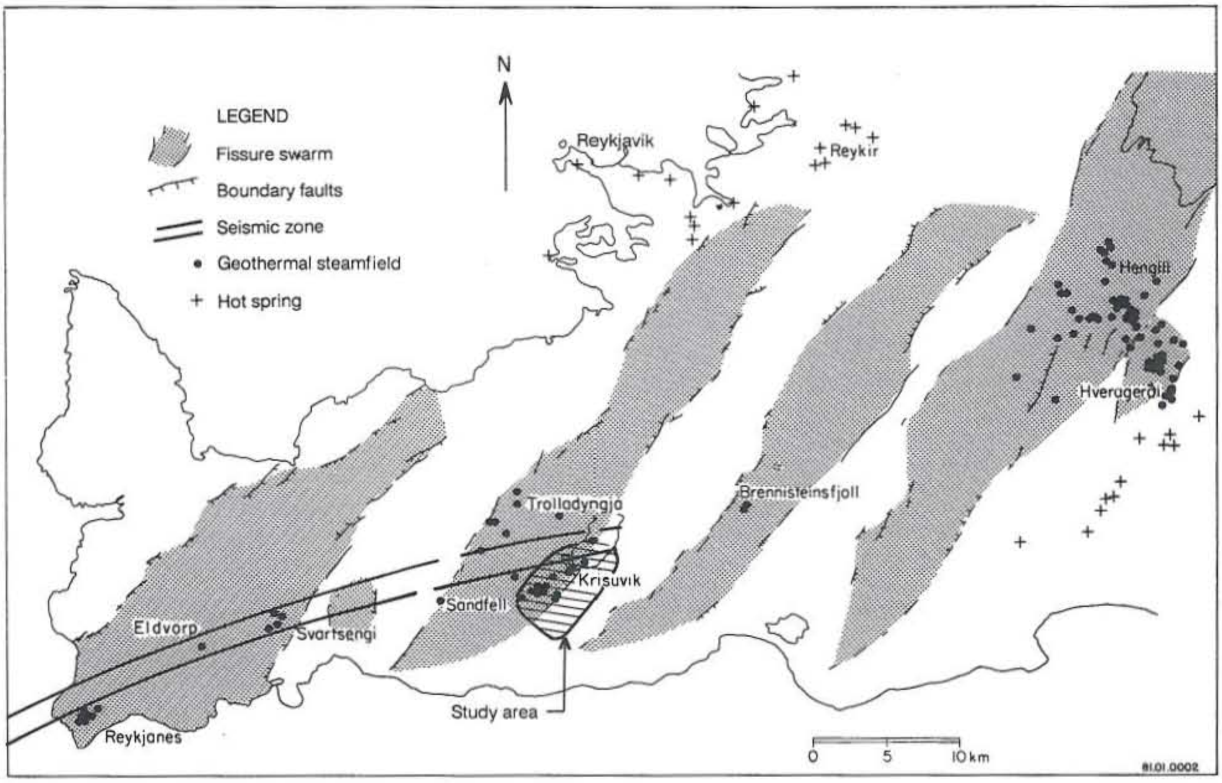

FIGURE 1: Volcanic systems and high-temperature areas of the Reykjanes Peninsula (Saemundsson and Fridleifsson, 1981)

2. GEOMORPHOLOGY AND TECTONICS OF REYKJANES PENINSULA

Iceland is a unique part of the active mid ocean ridge system, being subaerial. It is a matter of discussion what geodynamic process is responsible for the anomalously large extrusion rate of magma which has its maximum just south of central Iceland (Jakobsson, 1979). However, it must be closely linked to both the orientation change of the axial rift zone across Iceland and the existence of the submarine swell from Greenland to Scotland.

The Reykjanes Peninsula is elongated, orientated roughly N75°E. It forms an oblique segment of the constructive plate margin, constituting the transition between the submarine ridge to the southwest, and the Iceland block to the northeast (Figure 2).

The general relief of the Reykjanes Peninsula is of a dual character. A mountainous chain defines the zone of extrusion along its axis, from which an apron of lava flows has spread mainly to the north, forming an undulating plane. The mountain chain is composed of table mountains and parallel ridges striking approximately N40°E and arranged en echelon. They are made of hyaloclastites (tuffs and breccias) and were formed below the ice cover of the last glaciation (Upper Pleistocene). The hyaloclastite ridges have a very sharp transverse profile rising up to often more than 100 m above the surroundings. They are relatively narrow (up to 1-1.5 km) and long (up to 20 km). The broader part of the ridges usually coincides with their highest peaks and is situated near the middle. The lavas originate in shields and eruptive fissures interspersed with the ridges and striking parallel to them.

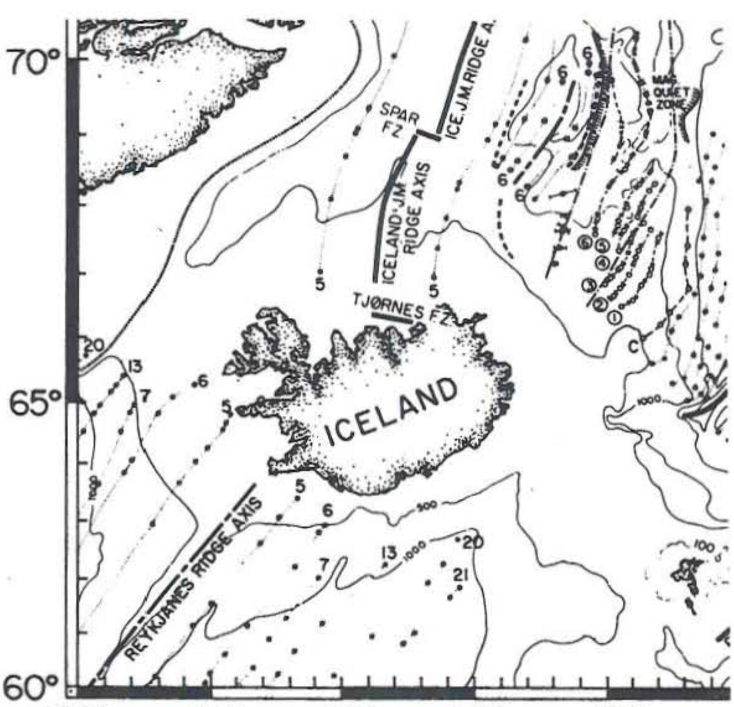

FIGURE 2: Iceland and the surrounding ocean area (after Talwani and Eldholm, 1977)

The hyaloclastite ridges and crater rows define a zone of maximum volcanic extrusion formed by the alignment of their broadest and highest segments. The trend of this topographic axis is the same as the trend of the peninsula (N75°E) and it constitutes its watershed; nevertheless, it is located in an asymmetrical southerly position in respect to the geometric middle line of the peninsula. The topographic axis in the western part of Reykjanes Peninsula is 8 km from the southern coast, but 13 km from the northern coast. The reason for this is that in this part of the peninsula, voluminous lava shields are located north of the water divide, and their lavas have spread northwards rather than to the south.

The general pattern of the hyaloclastite ridges and table mountains in the Reykjanes Peninsula as a whole shows a wedge shape with the tip towards Cap Reykjanes indicating that the volcanic production increases progressively eastwards along the peninsula.

Another morphological feature of the Reykjanes Peninsula is the formation of lakes, especially among the hyaloclastites and, in some places, in central, narrow valleys in the upper part of the ridges. Most of them have a clear origin by phreatic explosions with a very small magmatic component. However, Kleifarvatn, the biggest lake of the peninsula, was formed in a more complex structural situation as will be discussed later, in Section 3.3.2.

The shore line of the Reykjanes Peninsula doesn't show any fiord morphology. The local morphology has developed through constructive sub-, supra- and interglacial volcanism rather than by erosional forces. However, near the southern coast there are some ancient cliffs eroded by marine or glacial action. They were later left on shore as the lava plain grew beyond them towards the sea.

The structural geology of the Reykjanes Peninsula is characterized by the presence of fissure swarms trending NE-SW, whose curved ends have a sigmoidal shape. None of these fissure swarms pass through a well defined central volcano as is the general rule for the axial rift zone elsewhere in Iceland. However, high temperature geothermal areas occur at the intersection of the fissure swarms with the peninsula's main production axis of N75°E trend. The fissure swarms are characterized by very prominent linear features such as crater rows and their subglacial, ridge shaped equivalents, faults and open fissures.

The mapping area of Krisuvik lies in the southern part of the so called Krisuvik fissure swarm. Postglacial volcanic activity in this part of the swarm is restricted to explosion craters and minor scoria and lava emissions. Prominent fault scarps occur only in the northwestern part of the mapped area. Vigorous geothermal activity occurs in the western and central part of the mapped area.

3. GEOLOGY OF KRISUVIK VALLEY

3.1 Volcanology

The area of study is located in the neovolcanic axis in a zone of tholeiitic rock composition (Jakobsson, 1979). The volcanic activity is strongly influenced by glacial action. The presence or not of an overlying thick ice sheet conditioned the type of eruptions and the nature and mode of piling up of the volcanic products. Thus, the volcanic activity and the rocks produced can be classified into ice free volcanism and glacial time volcanism. The ice free volcanism, moreover, can be subdivided into inter- and postglacial volcanism. The glacial time volcanism can be divided into sub- and supraglacial volcanism.

Only basalts occur. There are several petrographic types, sufficiently different to allow distinction in the field.

3.1.1 Sub- and supraglacial volcanism

During the last glaciation the ice thickness over Krisuvik has been calculated to be about 300 m (Arnorsson et al., 1975). Evidently though the ice thickness varied. Krisuvik is located at the limit between a zone with a predominance of supraglacial eruptions, to the east, with the consequent formation of table mountains, and a zone with a predominance of subglacial eruptions, to the west, with the consequent formation of hyaloclastite ridges. This difference in volcanism during glacial periods is due to the combined effect of shield volcanism under moderately thick ice and fissure volcanism under thick ice cover.

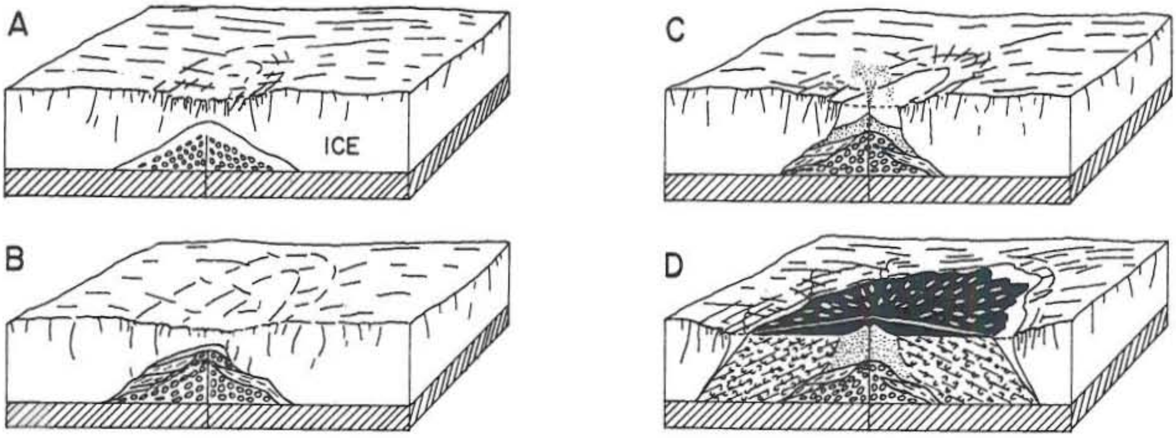

FIGURE 3: Growth of a subglacial monogenetic volcano. A: A pile of pillow lava forms in deep meltwater lake. B: Slumping on the flanks of the pillow lava pile produces pillow breccia. C: Hyaloclastite tuffs are erupted under shallow water. D: A lava cap progrades across its own delta of foreset bedded breccias (by Jones, 1970)

The formation of a single table mountain is illustrated in Figures 3 and 4. It can be summarized as follows. In the first stages of subglacial eruption, when effusion of lava occurs in rather deep meltwater or in a water chamber below the ice (Saemundsson, K., oral communication), a dome shaped structure of pillow lava is formed, which constitutes the core of the table mountain. In this report, this structure will be referred to as "pillow dome", and its associated lithological facies as "base pillow lavas". As the dome grows and gets unstable hillsides, slumping can take place with the consequent formation of pillow breccias forming slumping structures. When the pillow dome reaches depths of less than 200 m (Pullinger, 1991), explosive ejection of vitric ash and lapilli begins, covering the pillow dome. Slumping and gravitational collapse of further lava extrusions, are the causes for the formation of foreset bedded pillow breccias and tuffs, on top and flanks of the pillow dome. Pillow dykes, with lateral collapse to hyaloclastite tuffs and breccias, were frequently observed in the middle of hyaloclastic ridges. Baejarfell in the southern part of the mapped area is a good example of the internal structure of a table mountain. It shows a pillow dome at the northeastern slope, overlain by pillow breccias with slumping structures. Caves were observed in the internal part of the slumping structures. Above the pillow facies there are hyaloclastite tuffs. When the subglacial volcano reaches the water surface of the partially melted glacier, phreatic explosion activity changes to tranquil lava flows with the formation of an island sticking up above the surrounding glacier. Further lava eruptions form a lava shield with a central crater, preserved for example in Geitahlid. While the shield grows, spreading itself horizontally, it forms a foreset bedded breccia up to the level of the meltwater lake (Figure 4).

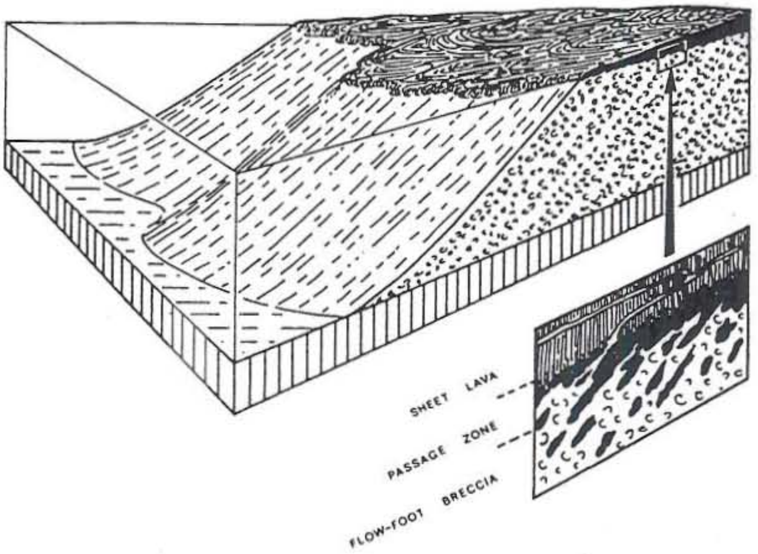

FIGURE 4: Structure of foreset bedded breccias (by Jones and Nelson, 1970)

The formation of the subglacial hyaloclastite ridges (like Sveifluhals) follows a similar development as the table mountains. However, the ridges represent a truncate stage in the development during the subglacial phase because the volume of extruded magma was not enough to reach the glacier's surface. Their lithologies show mainly facies of hyaloclastite tuffs and breccias lying over pillow facies. The top supraglacial lava usually is not present, except in cases where the eruption occurred within a thin ice sheet. Examples of this are eastnortheast trending ridges south of Kleifarvatn. An example of a pillow dome structure at the base of a hyaloclastite ridge, is a pillow outcrop in the middle of the internal valley at the top of Sveifluhals. In this valley, along which there are also explosion craters like Arnarvatn, there is an elongated central pillow mound northeast of Arnarvatn that probably constitutes the top of an elongated pillow dome in the core of unit 4 of Sveifluhals (Imsland, 1973).

The elongated shape of the hyaloclastite ridges, which may extend over tens of kilometers reflects the underlying eruptive fissures. Because of the quick solidification of the lava under the glacier, the transportation of the volcanic products is restricted to the immediate surroundings of the fissural vent, and the growth of the volcanic pile is carried out mainly upwards. This contrasts with the wide areas covered by the interglacial basaltic flows and their small thickness.

The above mentioned extrusion of the hyaloclastite ridges implies that they are the glacial time equivalents of the postglacial crater rows. It is reasonable to assume that they were formed during many events separated by hundreds or thousands of years. This mode of growing up of the volcanic pile defines an internal structure of the ridges as consisting of several on- or overlapping hyaloclastite units. The stratigraphic units may taper out rather abruptly. Therefore, it is possible to find in the field different units of different ages at what seems to be the same stratigraphic level.

The passage from the hyaloclastite ridge stage to the table mountain is a gradual one, depending upon the shape of the vent and the volume of extruded lava. The table mountains east of Krisuvik valley were evidently erupted from central vents. They might have begun as fissures, however, and the hypothetical early stage pillow dome of Figure 3 should be accordingly modified to a strong elongation, parallel to the regional fissure trend of Reykjanes Peninsula.

3.1.2 Inter- and Post-glacial volcanism

The volcanic activity during the ice free periods in Krisuvik is represented by subaerial volcanic products and morphological landscape features like explosion craters or lava flows. Among the volcanic products the most common are lava flows, pyroclastic scorias, welded lavas and scorias, and explosion breccias. Hypabyssal volcanic dykes occur in Sveifluhals.

Lava flows

Lava flows in the mapped area are quite abundant. There are three postglacial lavas that have flowed from the table mountain cluster in the east down into the valley (see geological map). Many scattered outcrops of glacially eroded lavas that may be interglacial occur also. These merge with the largest interglacial lava outcrop in the southern part of the area. According to the Icelandic geological map, their age is Upper Pleistocene (Saemundsson and Einarsson, 1980).

The postglacial lava flows are easily recognizable by morphology because of their fresh surface features. Both aa and pahoehoe type lavas occur. In aerial photographs, the aa lavas show curved flow structures indicating the direction of movement. The surface being uneven favours the preservation of soil and tephra layers in depressions. The northernmost lava flow reached the waters of Kleifarvatn.

In contrast to the reduced extension of the postglacial lava flows in Krisuvik valley, Mohalsadalur valley, next to Krisuvik in the west, is almost completely filled up by postglacial lavas. These show a great variety of cooling and flow structures and a number of crater rows.

Pyroclastic scorias and welded lavas

The lava extrusions during ice free times are represented, besides lava flows, by hawaiian activity eruptions, piling up volcanic products around the vents. Their main volcanic products are lapilli, scorias, welded scorias, welded lavas and reomorphic lava flows. There is a continual transition from the first member of the list to the last one. The differences are related to the eruption's thermodynamic factors, such as ratio lava/gas or water, extruded volume, viscosity and even the vent's shape and local topography.

The scoriaceous lapilli and bombs usually form layered beds in the area that do not form well defined cones. Some of them have been overrun by ice (Imsland, 1973) and they would easily have been flattened. The two major lapilli outcrops are exploited for road material. One is located west of Gestsstadavatn, and the other at the road opposite Stora-Lambafell. The fresh scorias usually show colourful reddish surfaces.

If the temperature and thickness of the ejected pile of scoriaceous lapilli and bombs are sufficient to weld the still hot pyroclasts, then these will become welded scorias. If the temperature and weight of the pile are even higher so as to permit the mass to flow, it will become a welded lava or a rheomorphic lava flow, depending much on the site's topography.

Many occurrences of welded lavas are found on the eastern slopes of Sveifluhals (Imsland, 1973; Jonsson, 1978) coating the hyaloclastite. Apparently the magma extrusion along the hyaloclastite ridge during ice free times has been mainly in the mode of lava fountains as is seen from the spray of scoria on hill tops higher than the vents.

In the bottom of the valley there are many scattered outcrops of welded lava. They usually indicate the nearness of craters; although many of them are only relics, eroded by glacier action. The most recent examples of welded lava flows are at Graenavatn. In Graenavatn the welded lava at the crater's edge in the east is 2 m thick. It shows a welded central zone between two transitional scoriaceous layers.

Explosion debris
The volcanic activity during ice free times also includes the formation of a large number of explosion craters. These are particularly abundant in Krisuvik valley. Most of the craters have been formed in hydrothermal explosions with insignificant if any extrusion of magma. This can be inferred from the lack of juvenile material and the low rims around the craters. Some of them, like Graenavatn, however, developed a late hawaiian activity. Nevertheless, the erupted materials are predominantly explosion debris; formed by the cracking up of wall rocks from the conduit. The debris covers a large area next to Graenavatn, Gestsstadavatn and many smaller explosion craters near them. The hydrothermal explosions apparently were caused by the contact of ascending magma with a geothermal aquifer at a relatively shallow depth (Noll, 1967). According to Cas and Wright (1988) the geographical distribution of hydrothermal and phreatomagmatic craters is determined essentially by hydrological factors.

Frequently, the craters show straight contours or elongation (for example Gestsstadavatn and Djupavatn), indicating a structural control. Explosion crater rows are also frequent. For example, Engjahver is the southernmost of a row of small craters aligned to define a N-S trending fissure.

3.1.3 Sediments

Besides the widespread subglacial and subaerial volcanics in Krisuvik valley, there occur also sedimentary formations of glacial, aeolian, lacustrine and fluvial origin. The various types and distribution will be described later in Section 3.2.7.

3.2 Stratigraphy

The local stratigraphy in Krisuvik valley is dominated by the piling up of subglacial hyaloclastites, intercalated with subaerial lava flows and pyroclastic facies, as described in Section 3.1. According to Saemundsson and Einarsson (1980) the age of Sveifluhals hyaloclastic ridge and the hyaloclastites in Krisuvik valley is expected to be Upper Pleistocene, most of them having been formed during the last glaciation. The same can be said for Geitahlid and the other table mountains southeast of Krisuvik valley. The southern basaltic flows reaching the sea show spread glacial striations. They are expected to be of Upper Pleistocene age, representing the last interglacial period. In this survey small intercalations of subaerial lavas were found among the hyaloclastite piles, both in Sveifluhals and in the bottom of the valley. Regarding their reduced extension, they can be considered to belong to short ice free periods, caused by size fluctuations of the glacier. This phenomenon has been found in other parts of Iceland (Saemundsson, K., oral communication).

It seems necessary to think about the glaciations as a time of fluctuations in the thickness and extension of the ice. Therefore, it is not possible to delimit a sharp boundary between glacial and ice free periods. These considerations are also applied to the table mountains southeast of Krisuvik valley, since they show different topographic levels of the flat tops. One hyaloclastite ridge, trending eastnortheast, appears to be in a higher topographic and stratigraphical position than the next table mountain to the east, as the ridge reaches on to it with its northeastern extremity.

The geological map is shown in Figure 5. The mapping was carried out by comparing the different lithologies found and, in a second step, grouping them into textural petrographic groups. Thus, a petrographic group includes rocks genetically different, like hyaloclastite breccias and lavas. The petrographic groups may consist of several eruptive units of different ages which are described in stratigraphic order. The selected names have a textural designation. Other units have a genetic grouping. The use of formational names is avoided.

3.2.1 Highly porphyritic hyaloclastites

This group occurs as three small outcrops near Tindholl, probably constituting a single unit. The petrographic texture is characterized by a high porphyritic index. Phenocrysts are usually more than 20%, reaching 40% in some samples. Euhedral plagioclase is almost the only phenocryst. It is frequently zoned. This is even seen in macroscopy when the samples are somewhat weathered.

The outcrops show pillow cores with structures grading laterally into hyaloclastite tuffs and breccias, that originated from the pillow dykes' growth. The contact with the overlying aphyric unit is sharp. These highly porphyritic hyaloclastites are correlated to "unit 1" of Imsland (1973).

3.2.2 Aphyric hyaloclastites and lavas

This group occurs mainly in the central part of the valley. At least three units constitute the group. The lowest is best exposed in and around the two Lambafells, a second occurs in Baejarfell and Arnarfell and a third around the southwestern end of Kleifarvatn. The group is composed of pillow lavas, hyaloclastite tuffs and breccias, dykes, and lava flows.

The petrographic texture is usually aphyric, but hypidiomorphic plagioclase phenocrysts can range in some samples up to 5%. The main part of the group around the Lambafells is strongly altered. A diffused geothermal alteration to zeolites was found in the subglacial facies in Baejarfell and Arnarfell, which is not visible macroscopically.

1) Around the two Lambafells lava flows which are typically flowbanded and dense form erosional remnants on top of a pedestal of hyaloclastite. At the top of Stora Lambafell and Austurengjahaed the lavas are again covered by hyaloclastite. The largest coherent lava outcrop underlies Austurengjahaed. Spread outcrops occur in the southern part of the area north and south of Stori Nyibaer. The connection with Austurengjahaed is obscured by explosion debris. The upper contact of the Lambafell-unit with the overlying porphyritic groups to the east is not sharp. A distinction was made at the limit of 5% of phenocrysts.

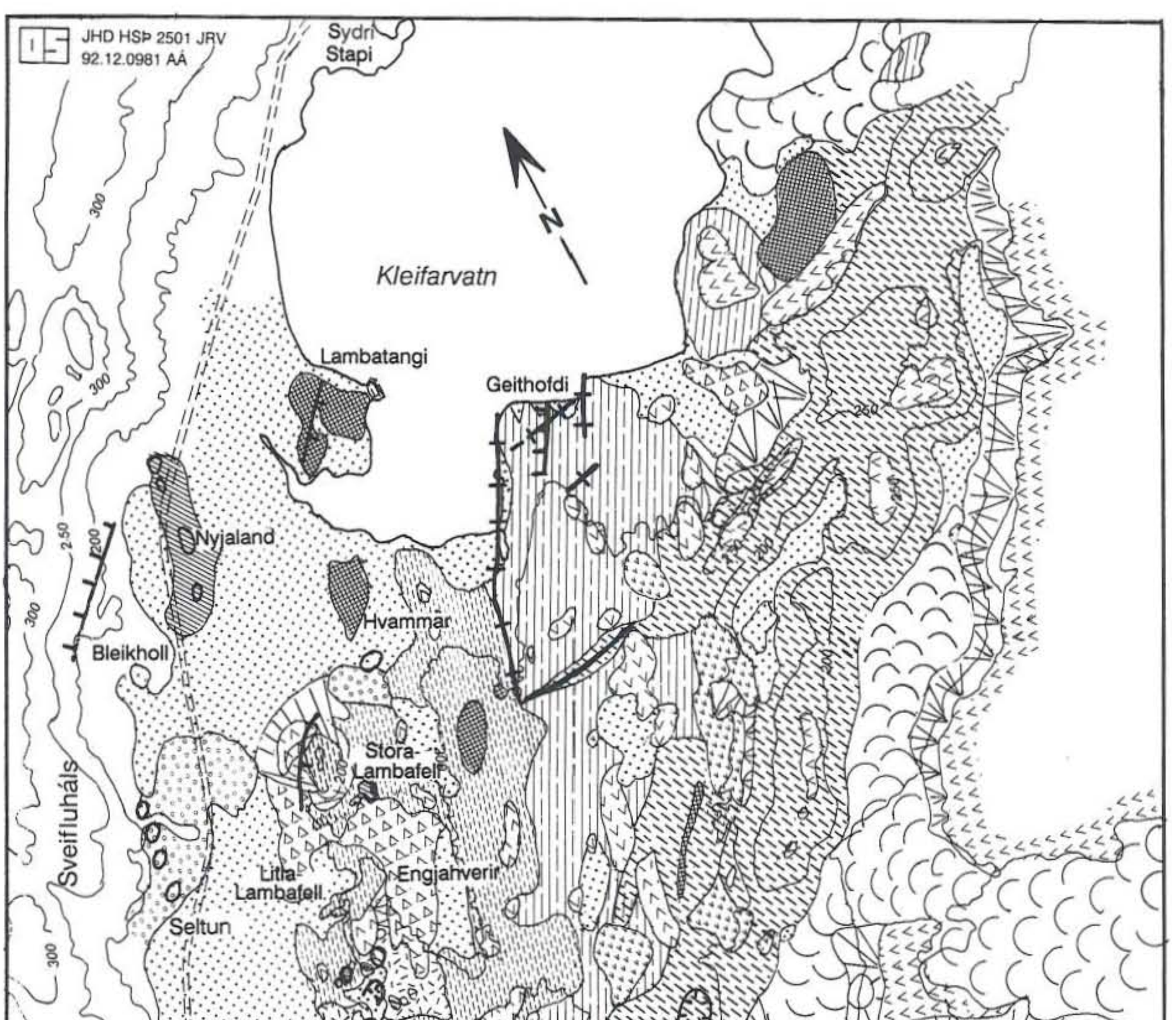

FIGURE 5: The geological map of Krisuvik valley (legend is shown on the next page)

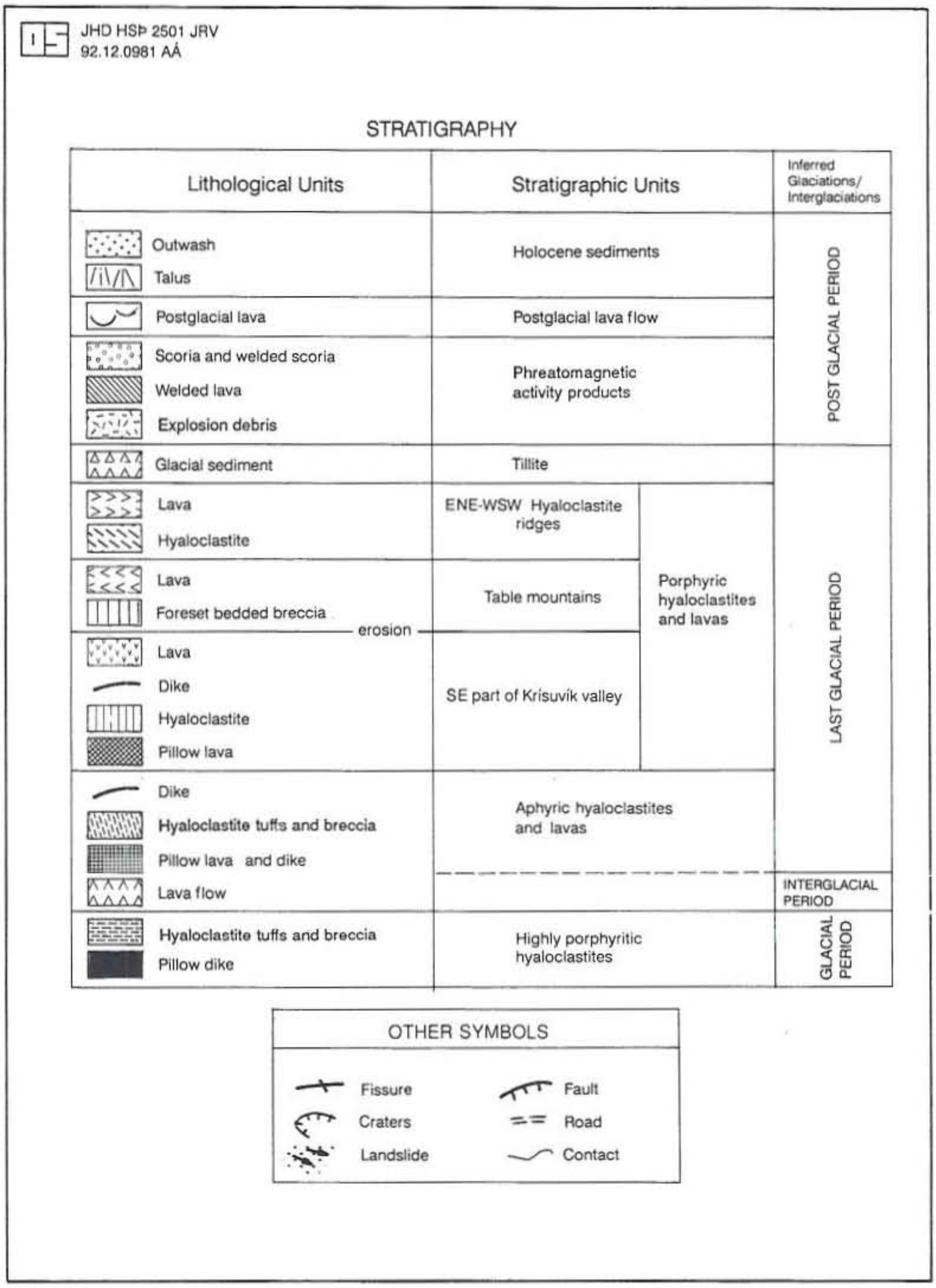

FIGURE 5: Legend for the geological map

2) Baejarfell and Arnarfell may be of much younger age, overlying the lavas south of Stori Nyibaer. There pillow lavas form the core of the hills. Hyaloclastite tuffs and breccias are associated with the pillow domes or more frequently form tens of meters thick layers around them. In both units, hypabyssal volcanic dykes of the same composition intruding the unit were also found. The best example of such dykes is in Baejarfell, where a 2 m thick vertical dyke trends northeast, parallel to Sveifluhals.

3) The third unit occurs as three separate mounds of pillow lava. The largest forms Lambatangi. Another is south of Lambatangi at the same topographic level. The third is

at a higher elevation in the hills south of Hvammar. All are relatively fresh as compared to the adjacent and underlying unit which composes the two Lambafells.

3.2.3 Porphyritic hyaloclastites and lavas

This group occurs mainly in the southeastern part of the valley, at a greater topographic elevation than the aphyric group. The rocks comprise pillow lavas, hyaloclastite tuffs and breccias, dykes and lava flows.

The petrographic texture is porphyritic with phenocrysts ranging between 5 and 15%, usually being about 10%. The most common phenocryst is plagioglase, but pyroxene (about 2%) and olivine (about 1%) occur also in some of the units. The olivine bearing rocks are typical of the table mountains.

The porphyritic group can be subdivided into three main units:

1) The lowest unit forms a broad, shieldlike area of hyaloclastites and lavas extending from Geithofdi southwestwards. The lavas are much eroded and only remnants are left on top of the hyaloclastites. The eruption centre of the unit is not preserved, but would be expected where the lavas attain the greatest elevation, about 2-3 km south of Kleifarvatn. The lavas are seen to drape the slopes of the underlying hyaloclastite down to Kleifarvatn in the north and down to Bleiksmyri in the south.

2) The next unit comprises a number of table mountains. The lowest occur near the southeastern shore of Kleifarvatn. They are small and preserved as entities. The eruption foci must underlie them although craters are not preserved. The larger ones form the southeastern margin of the mapped area and, apart from Geitahlid, were all formed by spreading of lava and foresets from eruption centers, east of the mapped area (Kistufell). All the table mountains are capped by lavas and three foreset/lava transition levels are evident. Geitahlid and Kistufell (outside the mapped area) have craters preserved.

3) The youngest subunit comprises ENE-WSW trending hyaloclastite ridges. The highest have a basalt cover and scoria craters occur at lower levels in the extreme southwest. The ridges are seen to overlie the lower table mountains to the northeast, but their relationship with the higher ones (Kistufell) was not checked. Evidently the ice was only about 100 m thick southeast of Kleifarvatn at the time of formation of these ridges. The scoria craters that developed on them in the southwest would indicate subaerial conditions.

3.2.4 Tillites

Tillites and outwash occur in spread outcrops, especially covering the slopes of table mountains. An outcrop on the south slope of Geitahlid comprises sandstones and conglomerates. The sandstone facies which is bedded is more frequently found on the slopes of the table mountains, but the conglomerates are more common at the mountains' foot or in the low ground where they are exposed in stream beds. In general, they are semicompacted, dipping generally parallel to the slope.

The sandstones are generally coarse grained. The conglomerates have rounded pebbles and boulders embedded in a coarse sandy matrix.

The tillites and outwash material mark the end of the last glaciation, when the suspended sediments were deposited as the glacier melted. Nevertheless, the possibility cannot be excluded that some of them could be older.

3.2.5 Hydrothermal and phreatomagmatic to hawaiian activity products

This group comprises several eruptive episodes of late glacial to Postglacial age. The group overlies directly all previously described volcanic rock units. There are several eroded craters which may have formed at a late stage of the last glacial period. Because of the fresh morphology of others they are assigned to the Holocene (Postglacial). The high explosivity indicated by the prevalent scoria, spatter and spatter lava probably was due to some ingression of water (Cas and Wright, 1988).

The oldest, late glacial outcrops occur on the slopes and immediately east of Sveifluhals. Well defined crater rows occur at Nyjaland and west of Bleikholl. Their trend is NNE-SSW. The craters have emitted scoria and spatter which grade into welded spatter lava. Lava from the crater row near Bleikholl has spread across the valley to the foot of Stora Lambafell.

The youngest Postglacial eruptions occurred in a NE-SW trending zone which extends from Kleifarvatn for almost 4 km to Baejarfell. The zone includes a large number of explosion craters varying in size from a few meters up to 300 m in diameter. The craters are largest and most numerous in the southwest. There a blanket of explosion debris covers a large area around them. The explosion debris consists of allochtonous material of clay to boulder size. Some craters have produced late phase strombolian deposits of scoria, spatter and (spatter) lava, among them Gestsstadavatn and Graenavatn. Others of the kind were found south of Litla Lambafell, east of Stora Lambafell and at Hvammar 500 m south of Kleifarvatn.

The explosion debris consists of angular blocks (in a granulometric sense) enclosed in a finer matrix, poorly sorted and non-stratified. The blocks are polygenetic. All the different petrographic rock types of the prior stratigraphic units are found. In Tindholl crater, there were found some blocks of hyaloclastite tuff and breccia. The matrix contains glassy lapilli, considered to have been formed by the cracking up of the hyaloclastite tuffs and breccias during the explosion. The presence of juvenile glassy lapilli in the matrix is considered to be minimal. The spatter signed by Noll (1967) in the inner slope of Gestsstadavatn was not found, as no digging was done. He found it present in every deep cut that he dug in the inner wall of the crater.

The smallest craters, among them Engjahver, were formed by shallow hydrothermal explosions along a fissure trending N5°E. The larger craters probably also were the result of hydrothermal explosions when geothermal water boiled up through fissures or volcanic vents. This phenomenon is well known in geothermal fields (Muffler et al., 1971).

3.2.6 Postglacial lava flows

This groups consists of three basaltic lava flows in the southeastern part of the mapped area. Two of them flowed into the area down from the table mountain cluster. One reached Kleifarvatn. By means of tephrochronology, K. Saemundsson (oral communication) dated it as approximately 2000 years old. Another lava, farther south, that fanned out on the floor of a closed depression was dated by Saemundsson to be about 1000 years old (historical age), because it is overlain by an ash layer from 1226 A.D., but lacks the so called "settlement" ryolitic layer (from about 900 A.D.). Those two postglacial basalts are porphyritic in plagioclase and some olivine. A third flow that was extruded from Stora-Eldborg is porphyritic in olivine, other phenocrysts being scarce. It forms a small shield at the foot of Geitahlid. Its age is about 4000 years (Saemundsson, K., oral communication). The thickness of the lavas in general is small on the slopes but they may be quite thick in the low ground.

3.2.7 Holocene sediments

The largest outcrops of this group occur on the floor of the Krisuvik valley. The sediments are composed of a variety of clays, silts, sands, gravels and boulders of different origins such as aeolian, lacustrine, talus and fluvial.

The glacial sediments consist of tillites, frequently deposited on the slopes of the table mountains but also on lower ground as they are exposed sometimes in the stream beds. Spread blocks of a moraine are found over the Upper-Pleistocene interglacial basaltic flows, in the south part of the area. Striations are frequently found on the underlaying lava. The relatively small quantity of glacial sediments found in Krisuvik is probably due to the big extension of the glacier. The main glacial sedimentation areas were probably situated far offshore. The local morphology is influenced more by the constructive volcanism than by the destructive glacial erosion. The clearest traces of glacial erosion are found in the hills south of Kleifarvatn where a basalt cover has been eroded down to discontinuous knobs. Glacial valleys are absent.

Typical fluvial alluvium with cross bedding was not found in the mapped area, except as scree and at the lake's shore, outside the area. Streams from Sveifluhals have deposited clay rich alluvium in the valley between Kleifarvatn and Graenavatn. The area is boggy and well vegetated. There are examples of lakes being invaded by vegetation.

Sediments have accumulated in small closed basins, mostly in lacustrine environments, sometimes filling up explosion craters. Old lake deposits once formed in a basin northwest of Engjahver. The lake has been drained subsequently and streams cut into the deposits expose up to 10 m of bedded clay.

A niche in the eastern slope of Sveifluhals around Badstofa hot springs is interpreted as a slump scar. The debris has reached low ground and contributed to filling up craters forming the extension of Gestsstadavatn to the north.

Aeolian sediments in the area consist of fine laminated sandy soils, a few meters thick, continuous in the plains but as remnants among the hills. In Iceland the formation of loessial soil is very rapid. About 15 km west of Mount Hekla there is a loessial soil thickening of 4 m in the last 6000 years, which has been increased by deflation of the areas around (Thorarinsson, 1979). In Krisuvik it is frequent to find small relics of loessial soil being eroded by the wind. The rate of soil erosion is high in Iceland. It is estimated that at least 50% of the area vegetated at the beginning of settlement has since been deprived of its soil cover by wind and water (Thorarinsson, 1979).

3.3 Structural geology

The aim of this subchapter is to define a structural model for the interpretation of Krisuvik geothermal field. Krisuvik lies in a NE-SW elongated valley on the neovolcanic axis of the

Reykjanes Peninsula, within the plate boundary zone. It is at the boundary between a segment dominated by table mountains, to the east, and a segment dominated by hyaloclastite ridges, to the west. The most prominent morphotectonic features in the area, visible even from satellite images, are to the southeast the Geitahlid and Kistufell table mountains, to the northwest the Sveifluhals hyaloclastite ridge, and Kleifarvatn in the valley.

The most significant structural element in the Krisuvik area is a NE-SW orientated fissure swarm, which controls the major part of the volcanic features and constitutes the regional structural frame for the study area.

3.3.1 Krisuvik and Brennisteinsfjoll fissure swarms

The Krisuvik fissure swarm is one of the large en echelon structural units of Reykjanes Peninsula. It extends from Ellidavatn (close to Reykjavik) in the northeast, to the south shore. To the southeast it borders on the Geitahlid and Kistufell table mountains, which separate it from the adjacent Brennisteinsfjoll fissure swarm.

The northeastern end of the fissure swarm, in the Ellidavatn surroundings, is emplaced in Upper Pleistocene interglacial lava formations. It shows a greater density of fractures than the rest of the swarm which is emplaced in younger formations. For that reason it is possible that the Ellidavatn area shows older structural styles.

The rest of the fissure swarm, emplaced mainly in glacial and postglacial formations, comprises the following morphotectonic units from west to east: Vesturhals, Mohalsadalur, Sveifluhals, Kleifarvatn and Krisuvik valley, and Geitahlid and Kistufell table mountains.

Vesturhals is a hyaloclastite ridge parallel to Sveifluhals. Its northeastern half owns some spurs showing a second NNE-SSW volcanic trend of minor dimensions. Like Sveifluhals, it also has explosion crater lakes. The lakes partly show straight-lined shores, indicating that their explosive origin was structurally controlled. This ridge also exhibits a high geothermal alteration and hot springs related to the geothermal system in the study area.

Mohalsadalur valley, between Vesturhals and Sveifluhals, is almost completely covered by Postglacial lava flows. It has many Postglacial craters and eruptive fissures.

The Krisuvik valley is characterized by NE-SW trending eruptive fissures and faults. Crater rows and fissures trending just east of north occur also (Bleikholl, Nyjaland, Engjahver).

Geitahlid and Kistufell table mountains form the southeastern limit of the fissure swarm. They act like a horst structure between the Krisuvik and Brennisteinsfjoll fissure swarms, which can be considered as complex graben structures, on a regional scale. The horst role of the table mountains is suggested by the geological map in the scale 1:250,000 (Saemundsson and Einarsson, 1980), showing the highest vents aligned above the normal fault limiting the Brennisteinsfjoll fissure swarm. The table mountains would form the main recharge of Kleifarvatn.

It is possible that the eastnortheasterly trending ridges south of Kleifarvatn belong to the Brennisteinsfjoll fissure swarm. Their trend is conformable with the curving (sigmoidal shape) observed at its extremity and other fissure swarms on the peninsula.

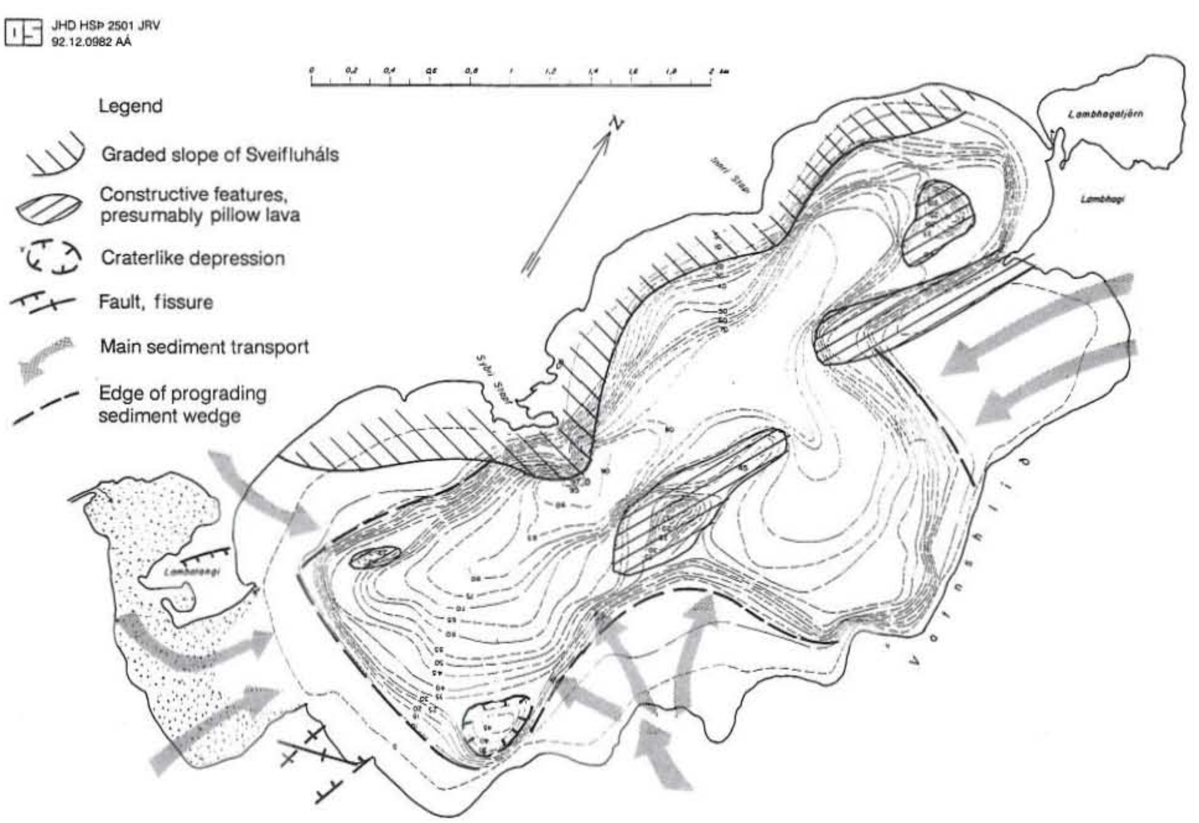

FIGURE 6: Bathymetry of Lake Kleifarvatn and its interpretation

3.3.2 Kleifarvatn

Kleifarvatn is the only large lake of Reykjanes Peninsula. It occupies the central part of Krisuvik valley. Even if the geology of the lake was not the aim of this survey, it is important for any hydrogeological or geothermal consideration to try to establish the role played by such a big mass of water in the hydrogeology and its relation to the structural geology of the area.

The origin of the lake can be explained by the combination of three geological circumstances, a morphological one, a structural one, and a volcanic one. First of all, Kleifarvatn occupies a low in the Krisuvik valley. It is elongated, trending NE-SW, as does the valley. The Upper Pleistocene formations of Sveifluhals hyaloclastite ridge, on one side, and Kistufell table mountain, on the other side, conditioned the formation of the valley in between. This morphovolcanic genesis does not fully explain the contours of the lake and its bottom topography.

The bathymetry is shown in Figure 6 with an interpretation of alignments, shoals and elliptical shapes. Also shown are faults found in the surroundings. Several features of the bottom morphology of the lake can be directly related to volcanic rocks close to the shore of the lake. Thus, Sydri Stapi is a fan of hyaloclastite that has spread to the southeast from Sveifluhals. A NE-SW elongated hill on the lake bottom northeast of Lambatangi (in the southwest) is probably yet another segment of the pillow lava of the Lambatangi unit. The hyaloclastite/pillow lava ridge of Lambhagi (in the northeast) probably continues southwestwards in the middle of the lake as a segmented ridge at least as far as opposite Sydri Stapi. The flat shoals in the lake extending from the shores out to 10 to 15 m depth are most likely of sedimentary origin, formed of outwash carried into the lake by streams. This is clearly the case around the southwestern end of the lake where quite extensive stream deposits reach down to the lake. Another fan (pre lava) spreads out in the southeast, and yet another fills an embayment south of Lambhagi.

Normal faults no doubt occur in the lake as they do in its surroundings. In view of the small throws it is doubtful if they have any effect upon the morphology of the lake bottom. In the area southeast of the lake where the oldest rocks occur, subvertical normal faults exist with a maximum vertical displacement of 1.5 m. A small graben passes through Lambatangi with throws up to 3 m. Geological maps (Jonsson, 1978) show a prominent fault running west of Geithofdi into the lake. The evidence for this fault is weak, primarily morphological, and the size of throw could not be determined. Displacement of a few tens of meters is supposed. No evidence is seen for it on the lake bottom (Figure 6). Kleifarvatn's deepest point, an elongated depression, occurs next to a steep cliff. This might be a small graben comparable to the one in Lambatangi.

The third factor that was speculated on to explain the bottom morphology of Kleifarvatn was maar volcanism. The bottom contours show elliptical depressions elongated and aligned along the deepest part of the lake. The morphology is suggestive especially the northeasternmost depression with a conical hill in the center, but in lack of other evidence the matter cannot be decided. Maaars of this size (with a long axis up to 1.5 km) are common in other parts of the world (for example Laguna Hule in Costa Rica). Cas and Wright (1988) mention that maar craters range in diameter from a few hundred meters to about 3 km. Djupavatn, a likely explosion crater in the Vesturhals, is 750 m long.

3.3.3 The en echelon structural array

The arrangement of the main structural features of the Reykjanes Peninsula has been described by many authors as an en echelon arrangement. However, the shape of the plate boundary, the direction of movement and the microseismicity do not entirely fit with the en echelon model. The two most common structural interpretations for the Reykjanes Peninsula concern the seismicity and the fault pattern.

The maximum microearthquake occurrence, aligned in a zone trending near E-W, has been seen as a deep, left-lateral, transform fault boundary between the oceanic plates (Einarsson and Bjornsson, 1979), even though there is no surficial geological evidence for it. Three examples can be taken to emphasize this: The San Andreas fault, the Polochic-Motagua fault (Guatemala) and the Tjornes Fracture Zone (N-Iceland) are all strike-slip fault boundaries between plates, however, they control the main structural features of the surficial geology.

The fissure swarms on the Reykjanes Peninsula are commonly interpreted as rift zones interconnected by transform faults at upper crustal level. However, there is no surficial evidence for transform faults, and the geometrical disposition of the fissure swarms is such that they merge and sometimes overlap with each other.

In this chapter it will be shown how an en echelon model can integrate the surficial geology and the microseismicity data to interpret the structural geology of Krisuvik. Although it is necessary to make some general considerations for the whole Reykjanes Peninsula, the application of the model to the rest of the peninsula would need much additional research.

The en echelon extensional arrangment in geology is found at scales ranging from microns to tens of kilometers. Basically, it has been defined as "planar features, such as tension gashes, arranged parallel with each other, but oblique to the boundaries of the zone in which they occur" (Hills, 1963). Large dykes have been found intruding in an en echelon manner over distances of more than a kilometer in other parts of the world (Atkinson, 1987).

The en echelon array is related to the extensional strain produced when shear stresses push in opposite directions to each other over a rock block. Hills (1963), based on experimental observations, describes it as follows: "Tensional fractures first form at right angles to the direction of greatest elongation in the deformed zone; these fractures make an angle of 45° with the direction along which the relative displacement occurs, but if the experiment is continued, they open out into gashes, and finally may make an angle of as much as 60° with the direction of relative displacement; this is brought about by the rotation of those portions lying between the first formed fractures; however the continued movement of blocks after tension gashes are first formed causes these to be dragged into an S-shape". He also mentions the appearance of a conjugate couple of shearing planes, one set of them making an angle of 15° with the direction of relative displacement.

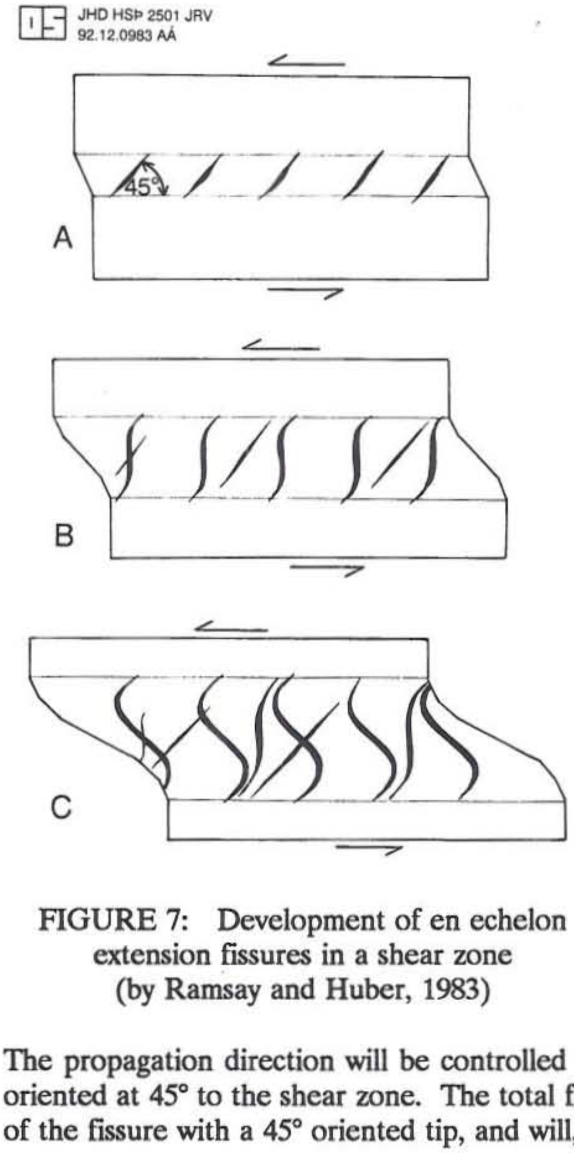

FIGURE 7: Development of en echelon extension fissures in a shear zone (by Ramsay and Huber, 1983)

The following summary of the evolution of extensional fissures in a model of simple shear strain is by Ramsay and Huber (1983), and is illustrated in Figure 7. The orientation of the first strain ellipse long axis is at 45° to the shear direction. The orientation of any incremental strain ellipse developed at any stage during the deformation history is also identically oriented because the geometric increments are the same. If an extension fissure system was to form during the initial shear displacement, then the fissures would be oriented perpendicular to the first maximum incremental extension, that is at 45° (complement = 135°) to the shear zone displacement. They would form a parallel en-echelon array (Figure 7A).

Once formed, the fissures become carried along by subsequent displacements taking place in the shear zone, so that their initial formation angle of 45° becomes increased. Therefore, the first formed fissures rotate; nevertheless, it is important to emphasize that this rotation is not around an axis, but it is the geometrical result of the parallel displacement of an infinitesimal number of planes. As the shear zone widens and the deformation front moves outwards, the fissure tips will propagate into the shear zone walls. The propagation direction will be controlled by the incremental strains and will, therefore, be oriented at 45° to the shear zone. The total fissure geometry now links the rotated central part of the fissure with a 45° oriented tip, and will, therefore, exhibit a sigmoidal shape (Figure 7B).

If the shear displacement at the zone centre becomes very large, it is possible that the central part of each sigmoidal feature will be rather badly oriented to allow the stretching that is necessary along the direction of maximum incremental extension. At this stage new cross-cutting fissures may initiate at 45° to the shear zone walls, the older system becoming effectively dead as the new extension system develops (Figure 7C).

The assumptions for applying an en echelon model in the Reykjanes Peninsula are the following: The plate boundary is not a left-lateral, strike-slip fault plane, but a lithospheric belt subjected to a left-lateral shear strain. This is consistent with the observed absence of a surficial fault trace. The en echelon arrangement of hyaloclastite ridges and fissure swarms are controlled by this shear strain, caused by the plates' movement. Perhaps the cause for not having a strike-slip fault plane is the geometry of the neovolcanic axis (orientated Az 80 in the general Krisuvik area), making an angle of 20° with the spreading direction (Az 100). This implies that there is a component of the plates' movement tending to separate any fault plane that could form along the volcanic axis.

3.3.4 Stress state analysis

Figure 8 displays the expected stress state for the Krisuvik area according to an en echelon model with simple shear strain. Rather than taking the spreading direction as the base data for the stress orientation in the area, we will use the trend of the seismic zone which is approximately Az 80.

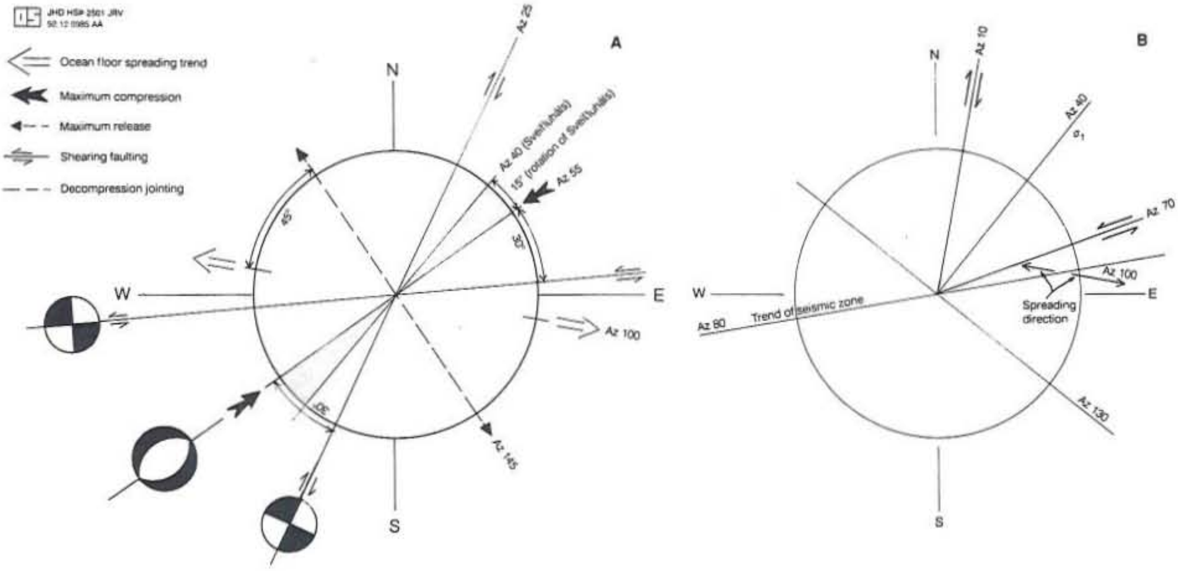

FIGURE 8: Stress state analysis. A) The test of a model taking the spreading direction as a base data for the stress orientation in the area. The fit with the actual structural trends in the area is poor. Maximum conpression is orientated at 55° and conjugate couple of strike-slip faults at Az 25 and Az 85. B) A better fit is obtained taking the trend of the seismic zone (Figure 1) as the base tectonic element. It has a trend of Az 80 in the Krisuvik area. This would produce a maximum compression trend of Az 35 and a strike-slip couple at Az 5 and Az 65

The opposite plate's movement on both sides of Reykjanes Peninsula causes a shear stress along the peninsula. This brings about an extensional en echelon arrangement. The maximum release direction is then orientated at 45° (Az 125) to the seismic shear zone direction. This maximum release would cause the formation of en echelon extensional fissures perpendicular to it (Az 35).

The maximum compression axis would be orientated perpendicular to it (Az 35), and it would cause the formation of a conjugate couple of strike-slip faults, each set being orientated at 30° to each side of the maximum compressive axis (at Az 5 and 65, respectively). Finally, the formation of a set of decompression jointing normal to the maximum compression axis (Az 125°) could be expected. This is because the compression is not constant through time. After release by an earthquake, the previously compressed rocks can respond by the formation of decompression jointing.

The NE-SW trend would also develop in a stress state where the maximum compressive axis was vertical. If so, we would have to assume variations in the maximum compression from vertical to horizontal NE-SW.

The sigmoidal shape of the fissure swarms in the Reykjanes Peninsula indicates that their central segments have already had some internal rotation. According to the model one might then expect to find some anticlockwise rotation of linear features, such as faults and hyaloclastite ridges from the direction predicted by the shear zone direction.

3.3.5 Comparison with surface geology

The previously outlined model matches quiet well with the main structural features of Krisuvik and some other structures of Reykjanes Peninsula. The main structural trend in Krisuvik is given by the strike of Sveifluhals (Az 40) and numerous faults and eruptive fissures trending NE-SW (averaging Az 40). It represents the fissure swarm's orientation in the area (see Figure 9).

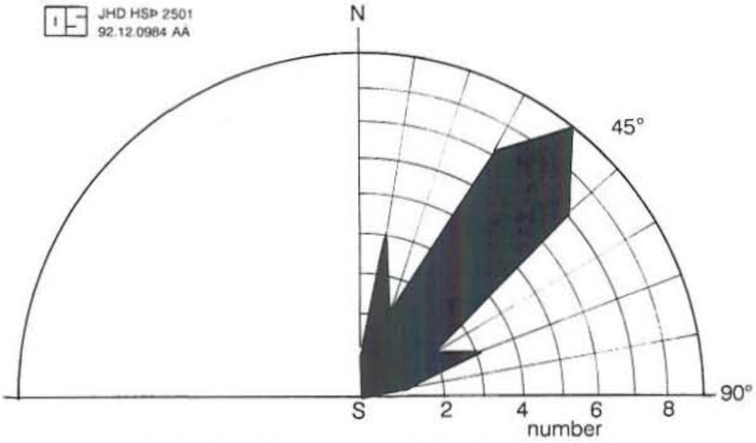

FIGURE 9: Fissure trends in the Krisuvik area

The expected right-lateral strike slip faulting trend at Az 5 is represented by a number of crater rows and lines of hot springs such as Gestsstadavatn, crater rows near Bleikholl and Nyjaland and the Engjahver hot springs.

The conjugate strike slip set at Az 65 is also well developed. Some minor faults cutting Sveifluhals and east of Geithofdi follow that trend and it occurs also among the young hyaloclastite ridges south of Kleifarvatn.

The young extensional fissures, averaging Az 35, perhaps best fit the model. They are common in Sveifluhals both as faults with throws of sometimes over 10 m and as fissures open by a few tens of centimeters. Faults with this trend occur in Stora Lambafell and Lambatangi (same fault zone) and similarly small faults and open fissures trending NE-SW were observed southwest and east of Geithofdi. Young crater rows in the Krisuvik valley also have this trend, such as the one near Tindholl. The main hydrothermal alteration zone (see hydrothermal alteration map) has this trend.

Finally the minor faults cutting perpendicularly across Sveifluhals can be correlated to the expected decompressional jointing normal to the ridge.

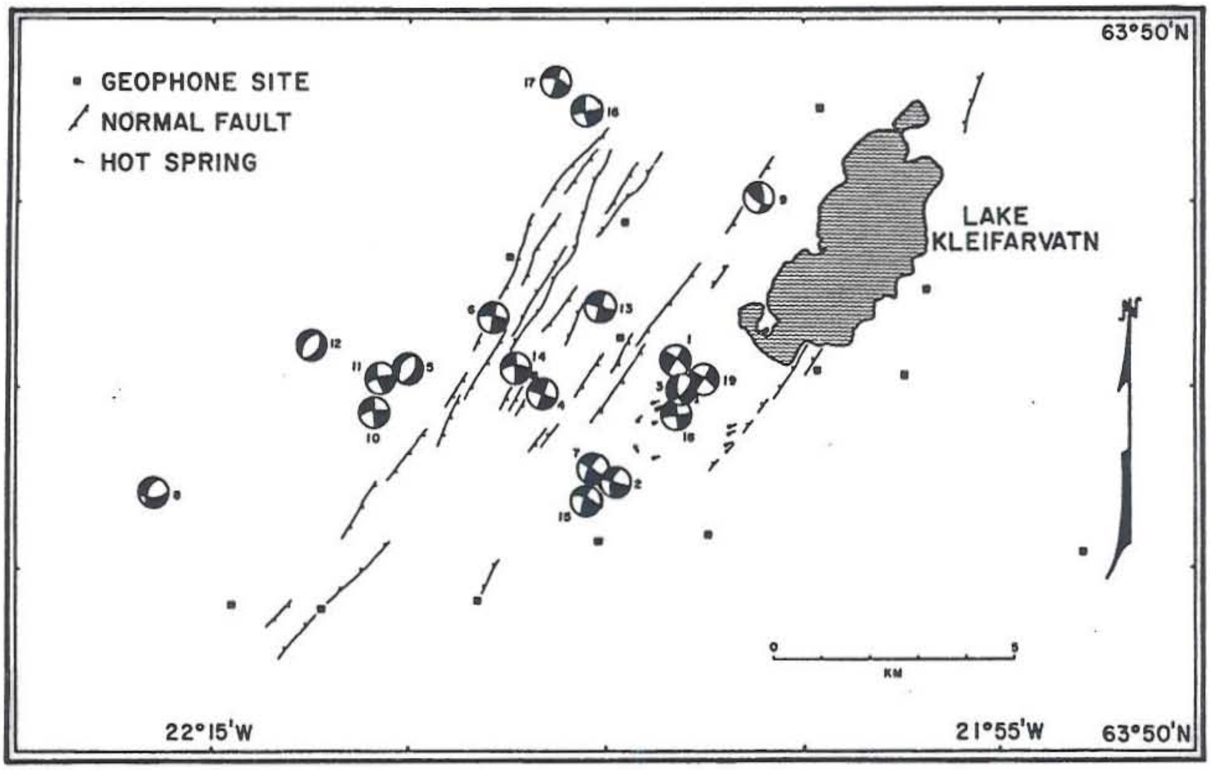

FIGURE 10: Upper hemisphere focal mechanism solutions of 19 earthquakes in Krisuvik shown at their epicenters' location; compressions are in black and dilations in white; the numbers refer to Table 1 (by Klein et al., 1973)

3.3.6 Microseismicity of Krisuvik

The microseismicity of Krisuvik has been studied by Klein et al. (1973). Their focal mechanism solutions are presented in Figure 10, however, they are here reinterpreted according to the shear strain model. Their correlation to the model and selected fault planes are given in Table 1.

The stress state analysis presented in Figure 8 leads to the focal mechanism solutions also shown in Figure 10. The fitting of the focal mechanism solutions given by Klein et al. and those expected by the model is also good.

Events 2-15-7, which occurred near Gestsstadavatn correlate to the model's Az 5 set (Figure 8). The same applies to events 13-17-4-6, which are all right-lateral, and fit to the same model's Az 5 set.

Events 12-5-3 and 8 are all of graben (extensional) character and match with the model's Az 35 set. Their graben feature can be explained by Krisuvik area as an extensional zone (graben), where the Az 35 set acts as ascent of magma. Event 8, of graben character, fits very well with the model's Az 35 extensional set.

Events 10-11-14-16-18 are all left-lateral and fit very well with the model's Az 65 set. The events 10-11 follow subvertical fault planes.

Event 9, of reversed character, is perpendicular to the maximum compression axis expected by the model.

TABLE 1: Match between focal mechanism solutions and the shear stress model and selected fault planes

Event no.	Depth (km)	Model's fault set	Fault character
2	4.1	Az 5	right-lateral
15	3.3	Az 5	right-lateral
7	3.9	Az 5	right-lateral
13	6.9	Az 5	right-lateral
17	3.6	Az 5	right-lateral
4	4.6	Az 5	right-lateral
6	4.4	Az 5	right-lateral
12	5.3	Az 35	graben
5	4.7	Az 35	graben
3	4.2	Az 35	graben
8	2.5	Az 35	graben
10	3.1	Az 65	left-lateral
11	3.9	Az 65	left-lateral
14	5.3	Az 65	left-lateral
16	3.5	Az 65	left-lateral
18	3.4	Az 65	left-lateral
9	3.1	Az 130	reversed
1	5.2	Az 130	right-lateral
19	6.3	Az 130	right-lateral

Events 1 and 19, located near Seltun hot springs, fit in strike with the jointing normal to the ridge. They are aligned suggesting a right-lateral fault. However, this behaviour is anomalous and would not be expected from the model.

The slightly anticlockwise deviations of some of the focal mechanism solutions, compared to the expected ones by the model, can be explained regarding the existence of previous planes of weakness in the crust. These weak planes are the former fault planes after they have had some rotation. If the rotation is not very big the seismic movement can take place along one of these previous planes.

4. GEOTHERMAL CONSIDERATIONS

The Krisuvik geothermal area, according to the literature, includes both Krisuvik and a wide area to the west and northwest, including Mohalsadalur valley and Vesturhals. It can be divided into at least 3 sub-areas, the Krisuvik field, the Trolladyngja field and the Sandvik field. Three of six deep wells drilled in the area are located in Krisuvik valley, which is the aim of this survey. The other three are found in Mohalsadalur valley and Vesturhals. The following considerations refer only to Krisuvik valley, although it is necessary to make some comparisons with Mohalsadalur.

4.1 Surface manifestations

The surface manifestations of the geothermal system under Krisuvik comprise highly altered clayey zones, a general geothermal alteration of the area, thin filled veins, boiling springs, warm springs, warm soils, hydrothermal explosion craters and mineralized waters (Graenavatn means "green lake", because of hydrothermal fluids emitted into the lake). The craters are disposed in rows; in particular, a crater row aligned together with geothermal alteration can be correlated to fissures striking at Az 5-10 and 35-40.

The hydrothermal alteration map (Figure 11) was prepared mainly from a field survey and with the help of photointerpretation. It shows the distribution and intensity of the surface hydrothermal alteration. The hydrothermal alteration mineralogy was not studied.

Three hydrothermal alteration grades were distinguished in the mapping:

> **First alteration grade:** This is recognizable by yellowish hydrothermal alteration colours; the occurrence of filled veins is common (about 1 per 30 m). It mainly affects the hyaloclastites, but also slightly affects lavas (carbonatization). A widespread profuse zeolitization was found in Baejarfell and Arnarfell, in pillow basalts and pillow breccias, visible only in microscopy. Arnorsson et al. (1975) mentioned that the alteration in the Krisuvik area is anomalous as compared with the most common patterns in Iceland. They reported that a typical zeolite zone is lacking. Also the chlorite zone appears at a depth of only about 100 m in well 5, which is unusually shallow. Therefore, it looks like the profuse zeolitization found in Baejarfell can be interpreted as the zeolite zone lacking in the wells. The alteration zonation in Krisuvik is otherwise anomalously high.
>
> **Second alteration grade:** This is characterized by a widespread hydrothermal alteration, recognizable in the field by yellow and brown colours affecting more than 50% of the rock volume. It also affects the lava facies and its phenocrysts. The occurrence of geothermal mineralized veins is high (about 1 per 1 m).
>
> **Third alteration grade:** This is the maximum geothermal alteration recognizable in the field. It is characterized by a 100% alteration of the rock. Grey, red, brown, yellow and white colours are conspicuous. Carbonates, sulfur, pyrite, quartz, opal and gypsum were found. The occurrence of geothermal veins is very common (about 5 per 1 m). In Sveifluhals, behind the Krisuvik farm, the third grade alteration has brought about a small landslide (see geological map).

Around the areas of geothermal alteration the formations show a slightly yellowish colour that could be due to weathering or palagonitization. The occurrence of thin geothermal mineralized veins is scarce (about 1 per 100 m).

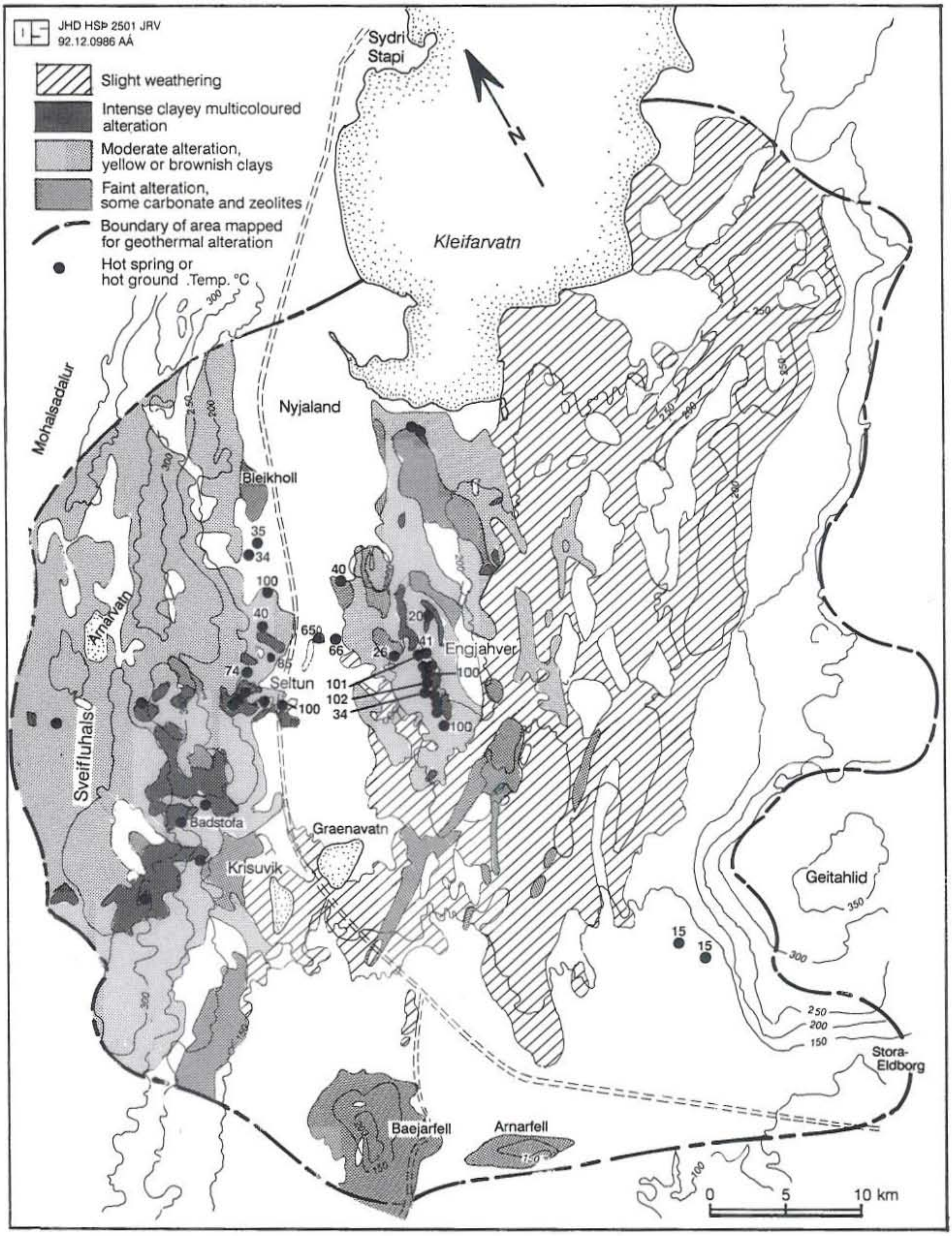

FIGURE 11: Hydrothermal alteration map of Krisuvik valley

4.2 Geophysical prospections

The geophysical prospections that have been carried out in the Krisuvik area comprise various methods, the most important being temperature logs and resistivity surveys (Schlumberger configuration).

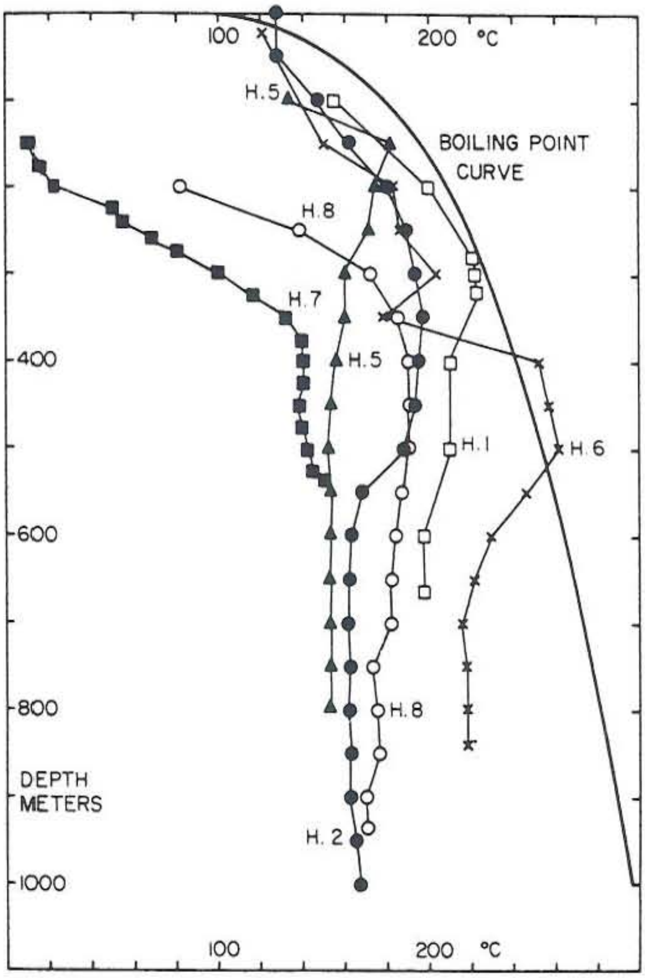

FIGURE 12: Temperature logs of deep wells in Krisuvik (by Arnorsson et al., 1975)

Temperature logs

The temperature logs in deep wells are shown in Figure 12 (Arnorsson et al., 1975). The main feature for all the wells is a deep convective gradient. Five of the six wells display a thermal reversal. Arnorsson et al. noted that the inverse gradient cannot be a localized phenomenon because the wells are spread over a large area. Relatively cold water floats on top of wells 7 and 8, separated by a very high conductive gradient from the geothermal system (with convective gradient below). According to Arnorsson et al. (1975) the inversed gradient indicates an insignificant vertical flow of water in this layer.

Resistivity

In the eighties an extensive resistivity survey was carried out in the Krisuvik geothermal area (Flovenz et al, 1986; Georgsson, 1987) in addition to older surveys. It shows widespread low-resistivity layers (< 8 Ωm) in the uppermost 500 m as seen in Figure 13 which displays a resistivity map at 300 m below sea level (Georgsson, 1987). The low-resistivity layers are correlated with geothermal activity in permeable near-horizontal layers of hyaloclastite breccias, below which denser and cooler basaltic lavas dominate, manifested in increasing resistivity with depth (10-80 Ωm). Inside the low-resistivity zone, several small areas of extra low resistivity are found (3-5 Ωm), which may represent upflow zones.

4.3 Hydrogeological considerations

The main hydrological characteristic of Krisuvik high temperature reservoir is its good permeability, demonstrated by the convective gradients along hundreds of meters of thickness down to the bottom of all the wells.

The thermal reversals are explained by local upflows along narrow faults or fractured dykes and their horizontal spread. All wells located near surficial manifestations display thermal reversal. Well 7, at Lake Djupavatn, which is not close to surficial manifestations, doesn't show thermal reversal. Similarly, well 8 located relatively far from surficial manifestations, shows only a slight thermal reversal.

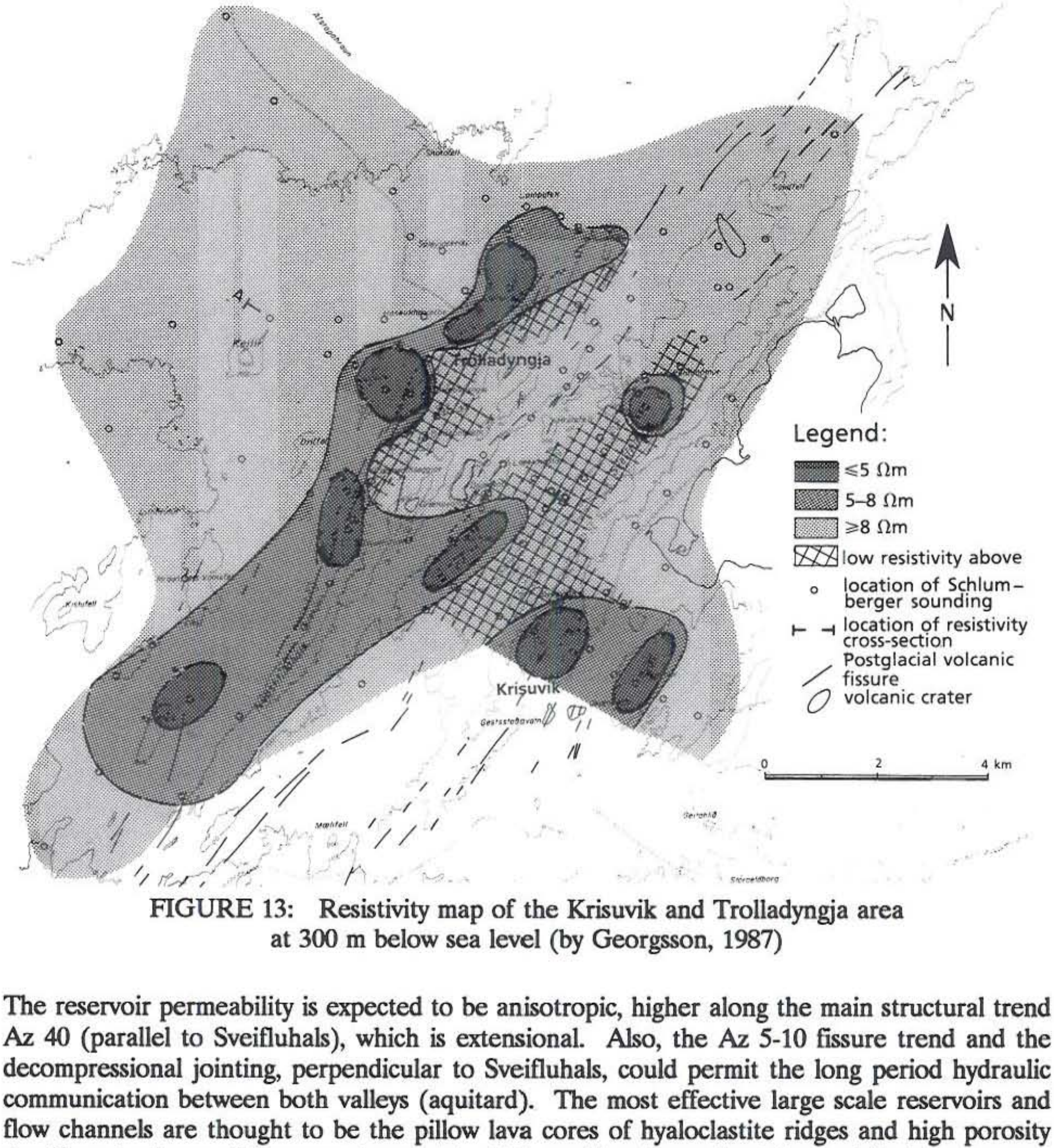

FIGURE 13: Resistivity map of the Krisuvik and Trolladyngja area at 300 m below sea level (by Georgsson, 1987)

The reservoir permeability is expected to be anisotropic, higher along the main structural trend Az 40 (parallel to Sveifluhals), which is extensional. Also, the Az 5-10 fissure trend and the decompressional jointing, perpendicular to Sveifluhals, could permit the long period hydraulic communication between both valleys (aquitard). The most effective large scale reservoirs and flow channels are thought to be the pillow lava cores of hyaloclastite ridges and high porosity stratiform horizons of fragmental material which are likewise cut by dykes and faults.

Fridleifsson (1979) pointed out that isotope studies indicate that hydrological circulation in high temperature areas is much more localized than that of low temperature areas. Local precipitation seeps deep into the bedrock along open fissures in the active fault swarms. The water is heated up by contact with the hot rock. The ascending hot water may flash to steam at a depth of 1 km or less and the dissolved gases are released. When the steam mixes with local groundwater the carbon dioxide may give rise to carbonate springs but the hydrogen sulphide is oxidized to sulphur or sulphate and the resulting water is acid. This is the reason for the intense alteration of the surface rocks.

In Krisuvik the location of upflow zones has not been identified, but from the geothermally altered areas and the low resistivity anomalies they seem to be associated with the hyaloclastite ridges. These overlie extensional deep fissures and dykes, which are followed upwards by pillow lava (good permeability), and hyaloclastite.

The valleys are expected to be underlain by alternating subglacial hyaloclastites and subaerial basalts, as is evident from the lithological borehole logs. This alternation can condition the emplacement of layered aquifers in the valleys, partially connected vertically by faults.

The above described structural frame suggests the following hydrogeological model. The hyaloclastic ridges (fractured hypabyssal dykes at depth) constitute the main vertical channels for the upflow of geothermal water. The upflow can laterally feed aquifers emplaced in the interstratified hyaloclastites and lava flows. Their permeability will depend on their primary permeability and fracturing (in lavas) or their geothermal alteration (in hyaloclastites). This gives rise to a succession of permeable and impermeable formations, very convenient for geothermal exploitation.

The hydrothermal alteration mineralogy in Krisuvik shows a cooling of the drilled reservoir and an unusually shallow depth of the mineralogical facies. It doesn't seem logical to attribute it to a cooling (old age) of the heat source because Krisuvik is located in the neovolcanic belt in the middle of the plate boundary and the surface geology indicates young volcanism. The cooling of the geothermal system as regards Krisuvik valley might be attributed to the formation of the widespread explosion craters, which would have drained the upper part of the geothermal reservoir by explosive boiling. The same phenomenon has been proposed for Krafla in Iceland (Saemundsson, K., oral communication). The explosion craters caused the simultaneous formation of an explosion breccia (highly permeable) in an underground cone, whose explosion depth could theoretically be roughly estimated assuming an angle of 60° (from rock mechanics theory).

Flovenz et al. (1986) and Georgsson (1987) have in a similar way suggested that the upper geothermal system is fed by an upflow of hot geothermal fluids from deeper levels in restricted zones, probably associated with volcanic and tectonic fissures. Thus, the Krisuvik high-temperature area can be divided into several small, near-independent fields. Volcanic activity has been confined to few main eruptive periods in Postglacial times and long term periodic activity has been observed in hydrothermal manifestations. This may indicate that local magma intrusions associated with these eruptive events are the deep level heat sources for the geothermal system. Thus, the fields are revived periodically but undergo a slow cooling process between events.

If the maars hypothesis hinted at for Kleifarvatn is invalid the hydrogeological role of the lake is considered to be mainly of recharge, favouring the vertical percolation of cold surface waters into the ground, thus, affecting laterally the shallowest geothermal aquifers. Open faults occur in the lake's surroundings, and very likely on the lake bottom. Joints and fractures are also abundant in the lake's surroundings. Even if the presence of big graben fault displacements was not demonstrated, the water only needs open fissures (secondary permeability) to percolate.

Regarding the lake, it must be added that hot springs are reported on the bottom in its southwestern part (Jonsson, 1978). This indicates that the geothermal aquifer in this area has an upflow, more or less in line with the the zone of hot springs and alteration extending from Graenavatn to the shore of the lake, near well no. 5. On the other hand, the lake has an underground discharge to the northeast, demonstrated by a surficial current in that direction (Saemundsson, K., oral communication).

The water chemistry described by Arnorsson et al. (1975) shows that the geothermal water is relatively high in salinity. The fissure swarm is expected to extend a few kilometers towards the sea and a slight input of sea water along the fissure swarm might enter the geothermal system.

The main recommendation for the evaluation of Krisuvik geothermal area is the same as presented by Arnorsson et al. (1975). It is necessary to drill a 2 km deep well to reach the bottom of the convective reservoir and penetrate any deeper geothermal system, below the influence of the cold percolation.

5. CONCLUSIONS

The Reykjanes Peninsula is aligned N75°E and forms a segment of the neovolcanic axis. This trend is obliquely intersected by volcanic structures and fissure swarms trending N40°E. They form an en echelon structural array, with development of sigmoidal shapes. This structural characteristic can be explained assuming that the plate boundary along the Reykjanes Peninsula is a crustal belt subjected to a left-lateral shear strain by the opposite plate's movement, in contrast to a left-lateral transcurrent fault assumption.

The mapped area south of Kleifarvatn forms part of the Krisuvik fissure swarm, one of the main volcanotectonic units on the Reykjanes Peninsula. An adjacent swarm to the east (Brennisteinsfjoll) extends into the eastern part of the mapped area with an array of hyaloclastite ridges.

In Krisuvik the surface rocks consist of a succession of Upper Pleistocene pillow lava basalts and hyaloclastites. In Postglacial time hydrothermal and phreatic explosion craters erupted and also welded lavas and scoria cones formed. Basaltic flows reached down into the Krisuvik valley from eruption fissures of the Brennisteinsfjoll swarm in the east.

The plate boundary which trends N80°E in the Krisuvik area according to seismic data (Klein et al. 1977) leads to the formation of extensional fissures at 45° with it (Az 35), and to a maximum horizontal compressive axis perpendicular to them at Az 35 or vertical. The maximum compression at Az 35 would produce a conjugate set of strike-slip faults at both sides at 30° with itself (Az 5 and 65). Normal to maximum compression minor jointing would be expected. From the sigmoidal shape of the main regional structures in the Reykjanes Peninsula, an anticlockwise rotation of the older alignments is also expected, according to the model. This model matches quite well with the surficial geology in the Krisuvik area, whose main faults and fissural eruptions can be interpreted according to it. Also, almost all the focal mechanism solutions determined by microseismicity behave according to the trends predicted by the model.

The geothermal field, located in the Krisuvik fissure swarm, is characterized by a thick zone of convective thermal gradient, showing a thermal maximum in the top of this convective layer. This is here interpreted by assuming a hot lateral flow in the top of the geothermal system. The lateral flow would be related to the vicinity of local upflow zones near the wells showing the thermal reversal.

The geothermal reservoir displays a lower temperature than expected from its geothermal mineralogy. Also, the mineral zonation indicates unusually shallow depths, even lacking the first zeolite zone, which is typical in the Icelandic geothermal fields. The zeolite zone was found at the surface in Baejarfell and Arnarfell.

The cooling of the geothermal reservoir can be related to the occurrence of hydrothermal and phreatic explosions common in the area. The hydrothermal explosions would require boiling at shallow depth. This is compatible with the high temperature mineralogy. Arnorsson et al. (1975) proposed the presence of a thick ice cap to permit such shallow high intensity geothermal alteration. The same assumption can be extended to the occurrence of hydrothermal explosions. After the thick glacier melted, the underground geothermal system became unstable because of the lithostatic pressure decrease. It responded to the change by means of the widespread occurrence of steam explosions. The Krisuvik valley is the weakest area, between the higher table mountains and the ridges, which did not suffer the lithostatic pressure decrease to the same degree.

ACKNOWLEDGEMENTS

Thanks go to my advisor Kristjan Saemundsson and to all other staff members of Orkustofnun who helped during completion of this work, to the United Nations University, and to Instituto Costarricense de Electricidad.

The original manuscript was thoroughly revised by the advisor (K.S.).

REFERENCES

Arnorsson, S., Bjornsson, A., Gislason, G., and Gudmundsson, G., 1975: Systematic exploration of the Krisuvik high- temperature area, Reykjanes Peninsula, Iceland. Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, Proceedings, 853-864.

Atkinson, B.K. (Ed.), 1987: Fracture mechanics of rock. Academic Press, Great Britain, 534 pp.

Cas, R.A.F., and Wright, J.V., 1988: Volcanic successions - modern and ancient. The Oxford University Press, Oxford, 528 pp.

Einarsson, P., and Bjornsson, S., 1979: Earthquakes in Iceland. Jokull, 29, 37-43.

Flovenz, O.G., Fridleifsson, G.O., Johnsen, G.V., Kristmannsdottir, H., Georgsson, L.S., Einarsson, S., Thorhallsson, S., and Jonsson, S.L., 1986: Vatnsleysa - Trolladyngja; geothermal investigations. Orkustofnun, report OS-86032/JHD-10B, 39-92.

Fridleifsson, I.B., 1979: Geothermal activity in Iceland. Jokull, 29, 47-56.

Georgsson, L.S., 1987: Application of resistivity sounding in the exploration of high-temperature geothermal areas in Iceland with examples from the Trolladyngja-Krisuvik area, SW-Iceland. Paper presented at Exploration '87, Toronto, Canada, Technical Program Abstracts, 52.

Hills, E.S., 1963: Elements of structural geology. Jarrold and Sons, Norwich, 483 pp.

Imsland, P., 1973: About the geology of Sveifluhals. University of Iceland, B.Sc.thesis, (report in Icelandic), 87 pp.

Jakobsson, S., 1979: Outline of the petrology of Iceland. Jokull, 29, 57-73.

Jones, J., 1970: Intraglacial volcanoes of the Laugarvatn region, southwest Iceland, II. Journal of Geology, 78, 127-140.

Jones, J., and Nelson, P., 1970: The flow of basalt lava into water - its structural expression and stratigraphic significance. Geol. Mag., 107-1, 13-19.

Jonsson, J., 1978: Geological map of Reykjanes Peninsula. Orkustofnun, report OS-JHD7831 (in Icelandic), 334 pp + maps.

Klein, F., Einarsson, P., and Wyss, M., 1973: Microearthquakes on the Mid-Atlantic plate boundary on the Reykjanes Peninsula in Iceland. J. Geophys. Res., 23, 5084-5099.

Klein, F.W., Einarsson, P., and Wyss, M., 1977: The Reykjanes Peninsula, Iceland, earthquake swarm of Sept. 1972 and its tectonic significance. J. Geophys. Res., 82, 865-888.

Kristjansson, L., 1979: The shelf area around Iceland. Jokull, 29, 3-6.

Muffler, L.J.P., White, D.E., and Truesdell, A.H., 1971: Hydrothermal explosion craters in Yellowstone National Park. Bull. Geol. Soc. Am., 82, 723-740.

Noll, H., 1967: Maare und maar-ahnliche explosionscrater in Island. Sonderveroffentlichungen des

Geologischen Institutes der Universitat Koln, Koln, 117 pp.

Pullinger, C., 1991: Geological and geothermal mapping at Nupafjall and Svartsengi, Reykjanes Peninsula, SW-Iceland. UNU G.T.P., Iceland, report 11, 45 pp.

Ramsay, J.G., and Huber, M.I., 1983: The techniques of modern structural geology - Volume 1: Strain analysis. Academic Press, London, 307 pp.

Saemundsson, K., and Einarsson, S., 1980: Geological map of Iceland (1:250 000), sheet 3, SW-Iceland, second edition. Museum of Natural History and the Iceland Geodetic Survey, Reykjavik.

Saemundsson, K., and Fridleifsson, I.B., 1980: Application of geology in geothermal research in Iceland. Natturufraedingurinn, 50 (3-4) (in Icelandic), 157-188.

Talwani, M., and Eldholm, O., 1977: Evolution of the Norwegian-Greenland Sea. Geol. Soc. Am. Bull., 88, 969-999.

Thorarinsson, S., 1979: Tephrochronology and its application in Iceland. Jokull, 29, 33-36.