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GEOLOGICAL AND GEOTHERMAL MAPPING AT NUPAFJALL AND SVARTSENGI, REYKJANES PENINSULA, SW-ICELAND

Carlos R. Pullinger,
UNU Geothermal Training Programme,
Orkustofnun - National Energy Authority,
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent address:
Comisión Ejecutiva Hidroeléctrica del Rio Lempa (CEL),
Departamento de Exploración,
Km.11½ Carretera al Puerto La Libertad,
Santa Tecla,
Departamento de La Libertad,
EL SALVADOR

ABSTRACT

Geological mapping was done in the Nupafjall area south of Hveragerdi, SW-Iceland. The area is found at the eastern margin of the Reykjanes oblique spreading zone where it runs into the South Iceland seismic zone, of transform character, to the east, and into the Hengill spreading zone, of spreading character, to the northeast. Therefore tectonic activity is high. In the field work a special emphasis was put on the relationships between volcanism and tectonics. The volcanic stratigraphy reveals a lowest succession of lavas and foreset breccias which originated outside the map area. This is followed upwards by a relatively thin succession of simple lava flows also of distant origin, that are found to be more abundant north of the map area. Above these, thick piles of subglacially erupted hyaloclastites that have a local origin are found. The topmost units are late glacial and post-glacial lavas, again erupted outside the map area, within the spreading zone to the northwest. Faults and fractures belonging to N-S, NE-SW and NW-SE directions were found in the older rock units. Large throws were identified generally in N-S trending faults, and two N-S trending graben structures were found in the map area. An analysis on some of the borehole sites in the Olfus region is made, with respect to geologic structures of the region, and their characteristics discussed in light of the geologic information collected in the field.

The second part of the report consists of the mapping of the geology, faults and surface hydrothermal alteration of an area around the Svartsengi geothermal field. Special emphasis was put on the relationship of surface alteration and geologic structures. Several areas of intense surface hydrothermal alteration were identified to the south and east of the present geothermal field. These areas apparently are directly connected to either faults or fracture zones. Detailed geologic mapping identified several eruptive sites that had been previously incompletely mapped. The contacts of various post-glacial lava flows were more accurately drawn, and a new interpretation of the geology of Svartsengisfell revealed that it is a monogenetic structure akin to a table mountain and not a hyaloclastite ridge. Faults and fractures were identified and it was established that N-S and NE-SW trends dominate the tectonics of the area. Large displacements were found to occur on faults of both systems. The location of the Svartsengi power plant's well field is discussed with respect to the structural geology.

The fault patterns of both areas were found to be very similar and perhaps have common origins. The NE-SW faults in both areas are probably related to magma tectonics. They form, if magma is mobilized, during rifting episodes occuring in Nupafjall on the Hengill-Hromundartindur fissure swarm and in Svartsengi on the Grindavik fissure swarm. The N-S faults, on the other hand, are probably related to transform faulting where magma movement is not involved. This interpretation is in good accord with the N-S faults occurring on or close to a microseismic zone at 1-5 km depth, that has been defined for the western part of the Reykjanes peninsula.

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1. INTRODUCTION

1.1 Scope of work

This report is the result of the author's six months' training received in Iceland as part of the UNU Geothermal Training Programme at Orkustofnun - National Energy Authority, Reykjavik, through a fellowship awarded by the United Nations University and the Government of Iceland.

The geothermal training programme began with five weeks of a series of lectures involving all the different aspects of geothermal energy research. This was followed by six weeks of field work in an active tectonic field and in eroded volcanic strata. Two weeks were spent in field excursions through most of Iceland's low- and high-temperature geothermal fields, the purpose of these field excursions being the direct study of the geologic setting, the exploration methods used and different possibilities of geothermal utilization of the fields visited. Finally, two weeks were spent in the mapping of hydrothermal alteration in an active geothermal field. The rest of the time was used to do laboratory work and in the elaboration of this report.

Geologic exploration is one of the initial and most important steps for the exploration and identification of geothermal prospects and continues to be necessary throughout the development and exploitation of a geothermal field. The purpose of the author's training was to gain experience in geologic mapping with special emphasis on the relationships between volcanic, tectonic and geothermal activity, through the mapping of two field areas.

The first area, Nupafjall, south of Hveragerdi, is found in an active volcanic and tectonic field. Here, the study emphasized the mapping of the different geologic units and structures and their relationship to volcanism and the geothermal activity of the area. The second area mapped is in the Svartsengi geothermal field. Here, more attention was given to the mapping of surface hydrothermal alteration and its relationship to geologic structures.

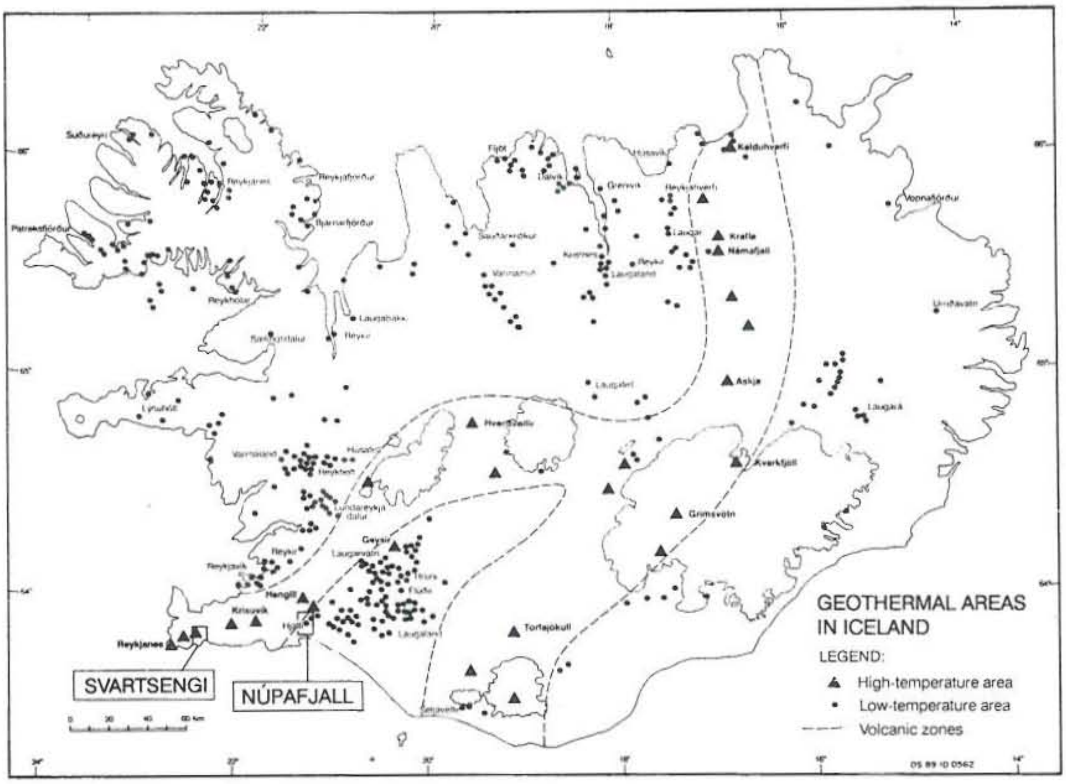

FIGURE 1: Geothermal areas in Iceland and location of study areas

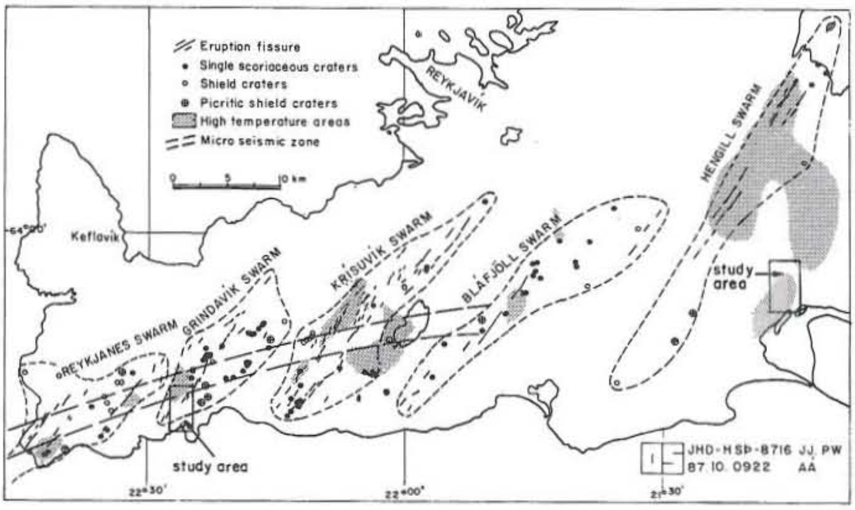

FIGURE 2: Map of Reykjanes peninsula showing location of study areas

In the author's country of origin, El Salvador, exploration and developmental projects are in progress in four high-temperature geothermal fields and ambitious plans exist to increase electricity by 225 MW, the majority from geothermal resources, in the upcoming ten years. Therefore, the training and experience gained through the geologic exploration training course will be used to help achieve some of the goals set by the company in charge of geothermal development, Comisión Ejecutiva Hidroeléctrica del Rio Lempa (CEL).

1.2 Location of study areas

Both study areas are on the Reykjanes peninsula which is an oblique spreading zone. Nupafjall is at its eastern extremity. It is an area of active tectonism on the border of the active spreading zone. The other area, Svartsengi lies in the western part of the peninsula where both tectonism and volcanism are active.

The Nupafjall area is approximately 21 km^2 in size and is found on the cliffs south of the town of Hveragerdi, 45 km east of Reykjavik (Figure 1). The boundaries of the map area are delineated to the north by the old road that connects Hveragerdi and Reykjavik, to the west by the Skalafell lava shield, to the south by the Thoroddstadir farm and to the east by the road that connects Hveragerdi and the community of Thorlakshofn.

Nupafjall is near the southwestern limits of the Hveragerdi high-temperature geothermal field and extinct central volcano. The geology of the area is characterized by glacial hyaloclastite ridges, interglacial lavas and lava flows of Holocene age. The tectonic structures are directly related to both the spreading of the active rift zone and to the transform faulting of the South-Iceland seismic zone.

The Svartsengi area includes the Svartsengi high-temperature geothermal field on the Reykjanes peninsula, approximately 50 km southwest of Reykjavik (Figure 2), and covers an area of about 14 km^2. The geology of the area is characterized by Holocene lava flows and hyaloclastite ridges formed during periods of glaciation. The active rift zone intersects the area and dominates the tectonics.

2. PREVIOUS WORK

Scientific investigations have been conducted in both the Nupafjall and Svartsengi areas. Researchers have studied general and specific aspects concerning the characteristics of the geothermal fields. In the case of Nupafjall area, the research has been directed to the Hveragerdi, Hengill and Bakki geothermal systems. In the Svartsengi area extensive studies in all aspects of geothermal science have been carried out, some of them still in progress. A brief summary follows.

2.1 Nupafjall area

The field area lies on the outer limits of both the Hengill-Hveragerdi and Bakki geothermal systems, so not much work has been carried out specifically in Nupafjall. Einarsson (1951) presented a section through Nupafjall in his geological description of the Hengill area. Saemundsson (1967), in his study of the Hengill geothermal system, mapped the area north of Hveragerdi and is currently mapping an area to the west and north, which includes the Nupafjall area (Saemundsson and Fridleifsson, 1991, work in progress). The regional geology of SW-Iceland which includes Nupafjall, was compiled and put into a 1:250,000 map by Saemundsson and Einarsson (1980). Arnason et al. (1987) mapped the eastern margin of the Hengill volcanic system and discuss in detail the history of volcanic activity of the area. Fridleifsson (1990) produced several geologic cross-sections with information obtained from boreholes in the Olfus region.

A regional geophysical survey that includes the area of study, was carried out by Bjornsson et al. (1986), and further geophysical studies in the Bakki geothermal system have been done by Georgsson (1989), and Onacha (1990). The geochemistry of the wells in the Bakki geothermal field was studied by Kristmannsdottir et al. (1990). Temperature and geology logs of the boreholes in the Olfus region were done by researchers from Orkustofnun and are available in their files. These are the investigations that are made reference to in this report, but many others exist that discuss the Hengill, Hveragerdi and Bakki geothermal systems.

2.2 Svartsengi area

The Svartsengi geothermal system has been thoroughly studied in every field of geothermal energy, so giving a summary of all the research previously done would be exhausting and of no value to the reader, with respect to the study included in this report. A brief summary only is given of the investigations that are mentioned in the text.

Kuthan (1943) was probably one of the first researchers to do a regional study of the geology of the Reykjanes peninsula, mapping the general geology of Svartsengi in the process. Jonsson (1978) was the next to map the geology of the Reykjanes peninsula, with a very detailed account of his findings recorded in the text of his report; unfortunately the map of the Svartsengi area does not include several things mentioned in the text, giving the impression that he misinterprets a few aspects of the geology. Sigurdsson (1985) mapped an area in the west of the Reykjanes peninsula including Svartsengi. He recognizes that N-S trending faults are related to the microseismic zone at depths greater than 2 km. Johannesson (1989) made a map of the Reykjanes peninsula, placing special emphasis on historical lava flows and on the relationship of N-S faulting to the microseismic zone. A special map of the surroundings of Grindavik is rather incomplete with many crater rows omitted although previously recognized. Finally Franzson (1990) outlined the areas of superficial hydrothermal alteration and structural lineations. In this same report he studies the borehole geology and alteration of the wells in Svartsengi and generates important information concerning the geology of the Svartsengi reservoir. Bjornsson and Steingrimsson (1991) studied temperature and pressure measurements in the wells and propose a widely accepted conceptual model of the Svartsengi geothermal system.

3. NUPAFJALL AREA

3.1 Surface geology

The geology of the Nupafjall area has been divided into nine separate units characterized by pillow lava, hyaloclastites, inter-glacial and post-glacial lava flows, and superficial deposits consisting of moraine, marine and fluviatile sediments. The main units and their subdivisions are described below (Figure 3).

3.1.1 Unit 1 - oldest hyaloclastite

This unit forms the basement for the field area, but is only found in one small outcrop in the southern part of the map. It consists of a vitric tuff breccia of basaltic composition. Extensive palagonitization of the glassy matrix has occurred producing a characteristic rusty brown color. Due to the lack of outcrops of this unit it becomes hard to define the upper limits of it, but we can assume that the outcrops found at the base of the Thurarhnukur cliffs (approximately 50 m a.s.l.) had a local origin and were close to the top of the unit since it is mainly composed of vitric tuff breccia, indicating proximity to the surface of the glacier.

3.1.2 Unit 2 - compound lavas and their basal foresets

This unit is found forming the cliffs along most of the map area, except. At the north end of the study area only a small outcrop of it is found, the rest being buried by scree and post-glacial lavas. Field work done by Saemundsson and Fridleifsson (1991, work in progress) identifies this unit to the north of the map area. It can be divided into four subunits genetically related to each other, all (Jones and Nelson, 1970) composed of aphyric olivine tholeiite.

At the base of the unit we find olivine tholeiite pillow lava, para-pillow lava and pillow breccia, grading up to a tuff breccia with distinct large foreset bedding structures. A transition zone between tuff breccia and subaerial shield lavas is found covering the foreset bedded breccia, and is mainly composed of pillow lava fragments and vitric tuff; its thickness ranges from 2-10 m. Overlying the transition zone we find olivine tholeiite compound lava flows (Table 1), with thicknesses in the range of 5-60 m.

Jones and Nelson (1970) describe the process that gives rise to this sequence of rocks as lava flowing from air into water. As the lava sheet makes contact with the water it begins to break up by rapid cooling and steam explosions into basalt glass fragments. This eventually forms a horizontal transition zone, characterized by pillow breccia and glass fragments, that identifies the water level at time of emplacement. The transition zone diverges from the sheet lava and becomes more inclined passing down to the breccia, with dips in the range of 30-45° from horizontal. The pillow lavas at the base of the unit were probably formed by the rapid effusion of lava, forming a flow of pillow lava that did not break up into hyaloclastite (Figure 4).

The entire unit was probably formed during an interglacial period when the sea level had transgressed inland and was found 90-100 m higher than the present. A series of lava flows reached sea level and began to form the foreset breccia. As the breccia reached the water level, continuous lava flows advanced forming a lava sheet on top. The process is similar to the formation of a pro-grading river delta, which advances into the sea. In some places the topography, at time of effusion, can be observed where thicker lava zones are found, indicating ponding of the lava flows. The direction of the dips of the foresets indicates in what directions the lavas were flowing. In the cliffs at Thurarhnukur one can observe two different directions of foreset dips, one to the southwest and the other to the northeast. These two directions indicate that there, a lava tongue advanced into the sea.

TABLE 1: Microscopic analysis results of rock samples

Sample no.	Unit	Rock type	Texture	Minerals present	Remarks
þ-651	Pillow from foresets, compound lava	Olivine tholeiite	Glassy	Plagioclase, pyroxenes, olivine, very minor oxides and glass	Chlorite and clay minerals found in vugs and associated veins
þ-652	Compound lava	Olivine tholeiite	Ophitic	Plagioclase, pyroxenes, olivine and oxides	Chlorite and clay minerals occur in spaces between grains; calcite in vugs
þ-15360	Skalafell shield lava	Olivine basalt	Ophitic	Olivine, pyroxenes plagioclase, oxides and minor glass	
þ-15361	Thurarhnukur hyaloclastite	Tholeiite	Ophitic	Olivine, pyroxenes plagioclase, and oxides	Very crystalline palagonitization of glass
þ-15362	Kviar lava	Tholeiite	Ophitic	Pyroxenes, plagioclase minor olivine, oxides	Calcite and clay minerals occur as alteration minerals in vugs
þ-15363	Lava flow 'D'	Porphyritic basalt	Porphyritic	Pyroxenes, plagioclase minor olivine, minor glass and oxides	Aphyric in hand specimen
þ-15364	Kviar lava	Tholeiite	Ophitic	Minor olivine, pyroxenes, plagioclase and oxides	Clay minerals occur as alteration minerals mineral zonation
þ-15365	Lava flow 'A'	Porphyritic basalt	Porphyritic	Oxides, plagioclase, pyroxenes and minor glass	Very large phenocrysts of plagioclase mineral zonation
þ-15366	Thurarhnukur hyaloclastite	Tholeiite	Ophitic	Pyroxenes, oxides plagioclase, glass, minor olivine	Palagonitization of the glass
þ-15367	Compound lava flow	Olivine tholeiite	Ophitic	Pyroxenes, oxides, plagioclase, olivine and minor glass	Calcite and clay minerals occur as alteration minerals in vugs agglomeration of crystals
þ-15368	Nupafjall hyaloclastite	Olivine tholeiite	Ophitic	Pyroxenes, oxides, plagioclase, olivine	Very crystalline and vesicular
þ-15369	Lava flow 'B/C'	Porphyritic basalt	Porphyritic	Pyroxenes, minor olivine, plagioclase, oxides	Sparsely plagioclase porphyritic in hand specimen
þ-15370	Thurarhnukur hyaloclastite	Tholeiite	Ophitic	Glass, minor olivine, pyroxenes, oxides, plagioclase	Extensively palagonitized

FIGURE 3: Geology of the Nupafjall area

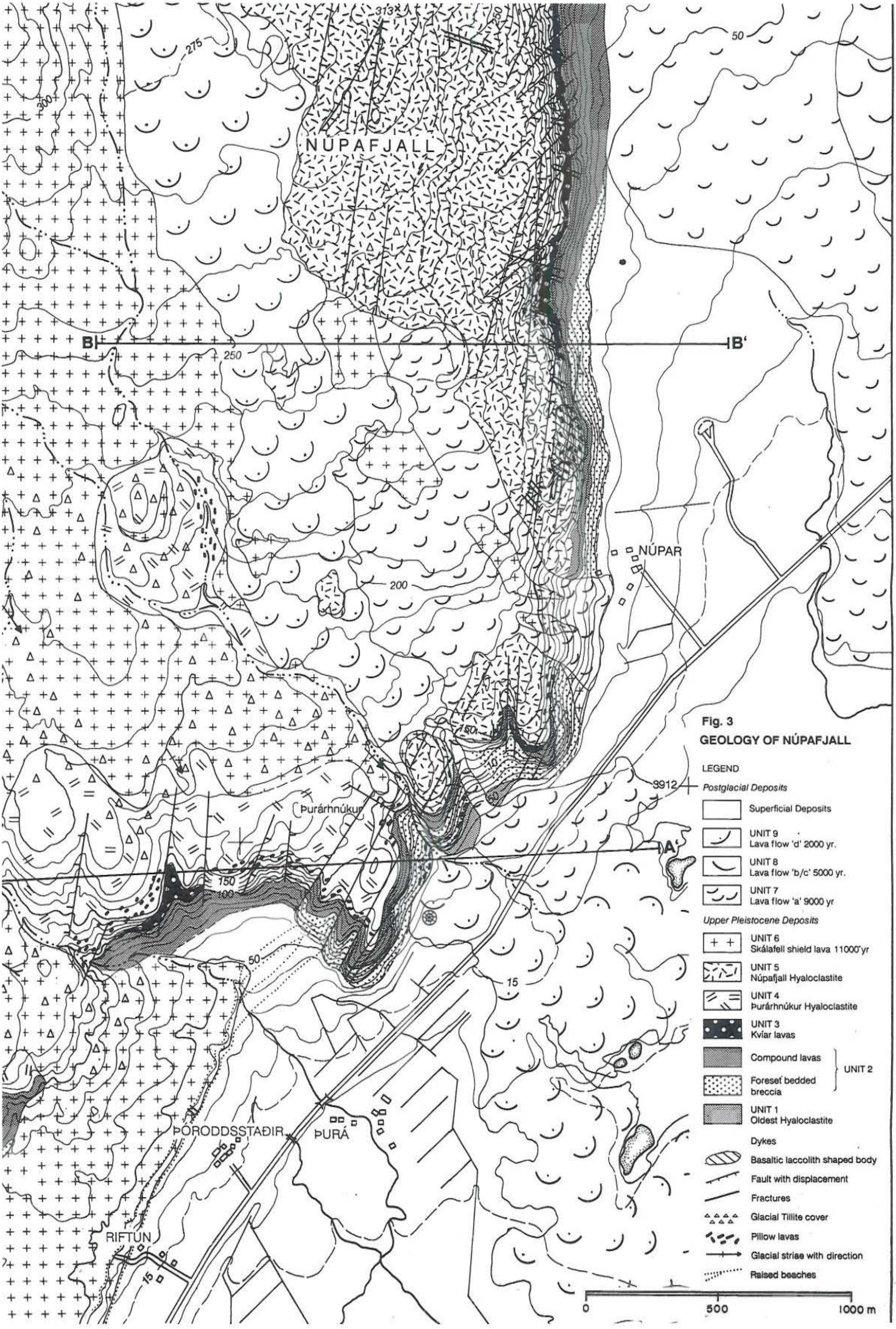

Fig. 3
GEOLOGY OF NÚPAFJALL

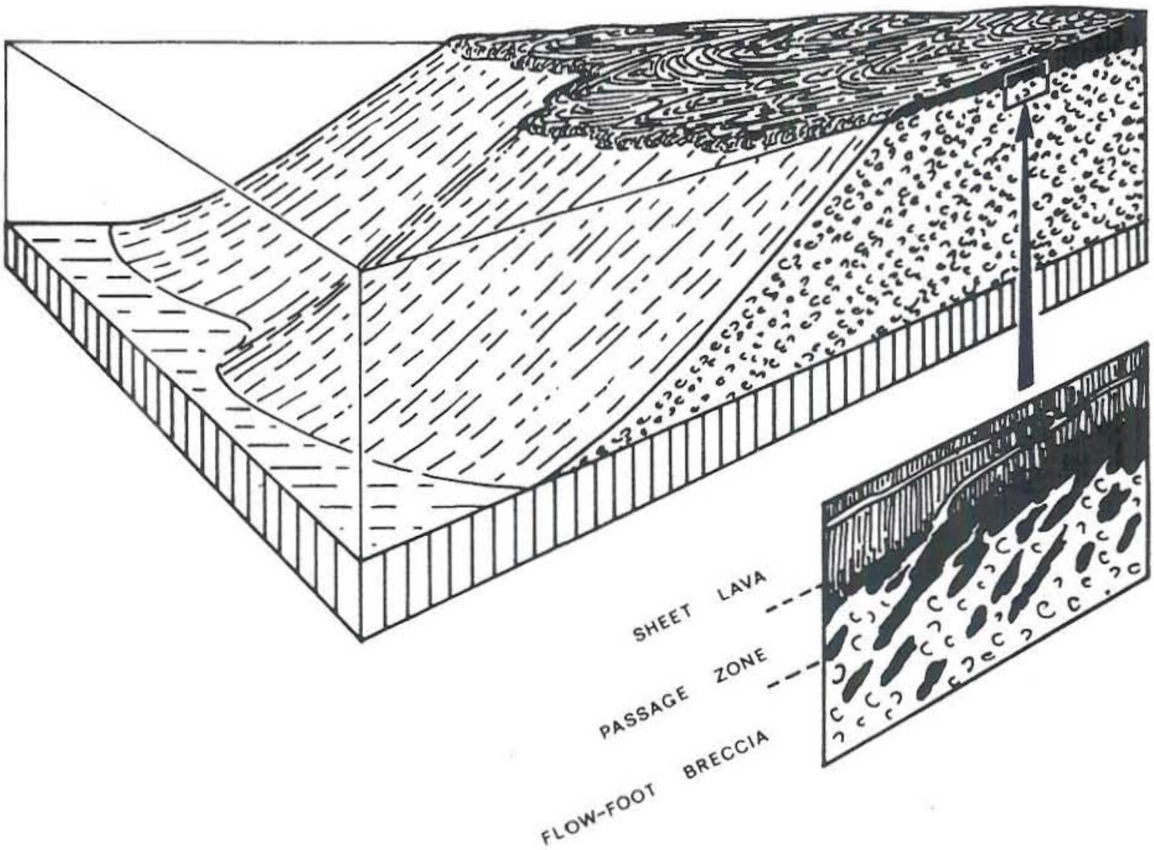

FIGURE 4: Form and structure of foreset bedded breccias (Jones and Nelson, 1970)

Later glaciation has caused some extensive erosion of the unit. In some outcrops the whole sheet lava subunit of thicknesses up to 60 m is missing. The upper contact of the unit is defined by a layer of fluviatile, tuffaceous sediments overlain locally by glacial till, its thickness varying from 5-10 m.

3.1.3 Unit 3 - Kviar lavas

The lower contact is defined by a layer of fluviatile sediments and glacial till approximately 5-10 m thick. The upper contact is defined by a layer of glacial till of up to 5 m in thickness. The unit is found in two small outcrops in the southern cliffs and continuously on the cliffs north of the Nupar farms. The lavas are the southern continuation of a lava-group called Kviar lavas by Saemundsson and Fridleifsson (1991, work in progress). According to them these lavas are of considerable thickness west of Hveragerdi.

The unit is composed of a basal parabreccia (Jones, 1970) and overlying it are a series of up to four tholeiitic simple lava flows with characteristic fluidal structures (Table 1). Some of the lavas are slightly plagioclase porphyritic. The total exposed thickness of the unit is approximately 30 m, but because of erosion by later glacial events, the original thickness of the unit is unknown. By studying the different glacial events that have happened in the area, we relate this unit to an interglacial period some 300,000 years ago (Saemundsson and Fridleifsson, 1991, work in progress). The first lava flows probably flowed into standing water in the south area of the map and gave rise to the parabreccias that are found underlying the lava flows.

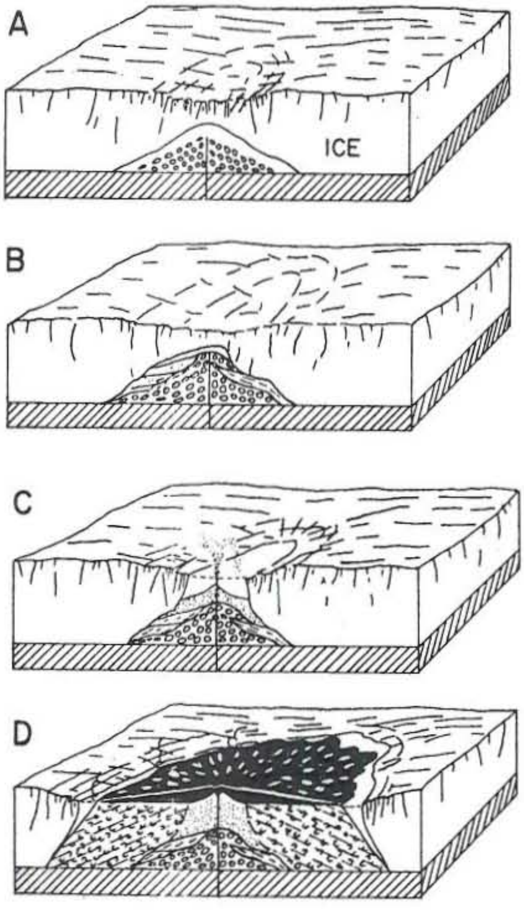

FIGURE 5: Growth of a glacial monogenetic volcano (Jones, 1970)

3.1.4 Unit 4 - Thurarhnukur hyaloclastite

This unit forms the top of the cliffs to the south and is composed of tuffs, very fine grained thick glassy crusts and aphyric tholeiitic orthobreccias and para-pillow lava (Table 1), formed in subglacial eruptions probably during the Saalian glacial period (Saemundsson and Fridleifsson, 1991, work in progress).

The pillow lava is formed in the first stages of eruption when effusion of lava occurs in rather deep meltwater. As the pillow lava mound grows and reaches depths of less than 200 m, explosive ejection of vitric ash begins, covering the pillow lava mound. Slumping and gravitational collapse are the causes for the formation of pillow breccia and tuff breccia. The absence of a lava shield covering the hyaloclastites is evidence that the volcanic activity never reached the surface of the glacier and was entrapped by ice and meltwater (Figure 5).

The exposed thickness of the unit is approximately 90 m, but because of glacial erosion the original thickness of the unit is unknown.

3.1.5 Unit 5 - Nupafjall hyaloclastite

This unit caps off the cliffs of the northern part of the map area, generally overlying a glacial till layer found in the upper contact of unit 3 (described in section 3.1.3). It is sometimes overlain by the most recent post-glacial and inter-glacial lava flows. Its thickness is approximately 120 m.

The Nupafjall hyaloclastite is composed of aphyric, medium grained para-pillow lava, ortho- and parabreccia, tuff breccia, feeder dykes, small sills and a large laccolith shaped intrusive body of basaltic composition (Table 1). Most of the unit was probably formed during the late Saalian glaciation in a similar fashion as unit 4 was formed, but its olivine tholeiitic composition and the intrusive bodies help to differentiate between the two units.

All the intrusives seem to be genetically and compositionally related to each other. A thin basaltic sheet is found at the base of the unit. At one location a laccolith shaped intrusion occurs which is characterized by a vesicular, olivine rich basalt. The dykes and sills are not more than 0.5 m wide and have a glassy texture at the contacts with the host rock, gradually becoming more crystalline towards the center. Evidence was found that suggests that the dykes serve as feeder dykes to the upper parts of the Nupafjall unit. Such evidence is found in one dyke that, as it approaches the upper parts of the unit, begins to change into a breccia until it finally becomes part of the tuff breccia. The high level of vesicularity found in the intrusive body suggests a shallow level of emplacement. Basaltic plugs are found on the surface of the Nupafjall unit. These plugs have a similar texture and composition as the dykes, also suggesting that they are intrusions related to the basaltic dykes. The basaltic dykes are seen at least in one locality to extend upwards from the basal sheet.

From the evidence collected in the field we can assume a sequence of events that led to the emplacement of the Nupafjall hyaloclastite. First, subglacial eruptions began to deposit para-pillow lavas and as the eruptions progressed hyaloclastite tuffs began to form, slumping and gravitational collapse formed tuff breccias, orthobreccia and parabreccia. Sometime after this the emplacement of a large basaltic body at the base of the unit began, forming the laccolith shaped intrusive. Also at a large stage during growth of the mound the basal sheet was intruded. It seems to have fed the dykes through E-W fractures (probably formed due to the updoming of the area by the basal intrusive sheet). The dykes then continue to feed the top of the unit with tuff and, in some cases, form lava plugs on the surface.

3.1.6 Unit 6 - Skalafell shield lavas

This unit is composed of an olivine-plagioclase porphyritic basaltic lava (Table 1) belonging to the Skalafell lava shield. The crater of this lava shield is at 450 m altitude some 5 km west of Nupafjall. The compound lava flows are mostly found on the western limits of the map area, but some small outcrops were found behind the Nupar farms, where the lava flowed over the cliff down to the level of the farms. Behind Thoroddsstadir farm, the base of the Skalafell lava consists of pillow lava and breccia, indicating foreset breccias. The transition occurs at around 40 m above the present sea level.

The age of the lava flow has been estimated to be about 11,000 years old. This age relates to the Allerod interstadial interglacial. Glacial striae and polished surfaces are found on the surface of the lava flows. These and glacial sediments covering part of the lavas were formed by the Younger Dryas glacial advance.

3.1.7 Unit 7 - lava flow 'A'

This unit is composed by lava flow 'A' (Einarsson, 1951) of plagioclase porphyritic basaltic composition (Table 1). The plagioclase phenocrysts range up to 15 mm in size. The lava flows are found in the valley between the Nupafjall unit and the Skalafell lava and flowed into the lowlands along the gullies to the south and immediate west of the Nupar farms. It is also found on the north part of the map area. The lava flow has been dated by ^{14}C (Jonsson, 1983) as being approximately 9,000 years old.

3.1.8 Unit 8 - lava flow 'B/C'

Lava flow 'B/C' (Einarsson, 1951) is characteristically a sparsely plagioclase porphyritic basalt lava flow (Table 1), the plagioclase crystals generally being 2-3 mm in size. The lava flow is found on the north of the map area and flows into the lowlands, partially covering units 6 and 7. This lava flow has been dated by ^{14}C (Jonsson, 1983) giving an age of approximately 5,000 years. Einarsson (1951) suggested that these were two flows which he called 'B' and 'C'. New evidence indicates that 'B' and 'C' are flow units belonging to the same volcanic episode (Saemundsson, 1991, personal communication).

3.1.9 Unit 9 - lava flow 'D'

This unit again defined by Einarsson (1951) is the youngest post-glacial lava flow in the area, dated by ^{14}C (Jonsson, 1983) as being about 2,000 years old. It is a sparsely plagioclase porphyritic basalt with plagioclase phenocrysts of 1-3 mm in size (Table 1). The lava flow is found partially covering the older lavas, and flows into the lowlands through a gully south of the Nupar farms, where it fans out. It has the same origin as units 7 and 8, in crater rows on the active rift 7-8 km west of the map area.

3.1.10 Superficial deposits

Superficial deposits cover the major part of the lowlands and stream beds. These consist of fluviatile sediments found on the stream beds and eroded from the hyaloclastite and lava units. In some places soils have formed where the topography is smooth and the sediments accumulate and at other places clays and silts have formed by the ponding of drainage water. Moraines of up to 5 m in thickness, deposited by the last glaciation approximately 10,000 years ago, are found covering large areas of the western part of the field area. These deposits consist of an unsorted mix of fine clays, silts, sands and gravels with a distinct grey color. Along some of the cliffs in the south, the moraine has cut small channels through the older rock units. Scree slopes are found along the base of cliffs. They reach highest below the laccolithic intrusion of unit 5.

On the lowlands in the east part of the map the sediments consist of fluviatile sands and silts from the drainage system of Olfusa river. These are underlain by marine sediments which consist of shales, silts and gravels. The marine and fluviatile sediments have thicknesses of up to 90 m in the area, but taper out towards the north and west (Saemundsson, 1991, personal communication). In the south part of the map area a series of raised beaches have been formed by the last transgression of the ocean into the land, approximately 10,000 years ago. The highest beach is found at about 50 m altitude. Peat deposits, that had been mined in earlier years, are found in the lowlands.

3.2 Structural geology

Approximately 300 readings of trends and dips were taken from fractures, fissures and faults and plotted as rose diagrams and bar charts to illustrate the main tectonic directions of the Nupafjall area. Figures 6 and 7 show the trends and dips of four locations.

Three general systems are identified, these are: N-S, NE-SW and E-W trending fracture systems. The N-S fracture system ranges in values from 0 to 20 degrees east of north and is found throughout most of the area, but less frequently in the north. The NE-SW fracture system ranges in values of 30 to 50 degrees east of north and is also identified along most of the area. The E-W fracture system ranges in values of 60 to 90 degrees east of north. This fracture system is usually found along the edges of cliffs in the south of the area and is related to the basaltic dykes found along the Nupafjall hyaloclastite (described in section 3.1.5). The dips of all three systems are in the range of 75-90° to the east, with a few exceptions that have dips to the west, related to antithetic faults and graben systems.

Faults with displacements greater than 1 m are few and are only found in the south cliffs, where a series of faults form a graben with a displacement of about 30 m, trending north. On the cliffs west of Nupar a series of four step faults displace blocks up to 20 m to the east. In the northwest part of the map is found a graben trending north with displacements of 35 m (Figure 8).

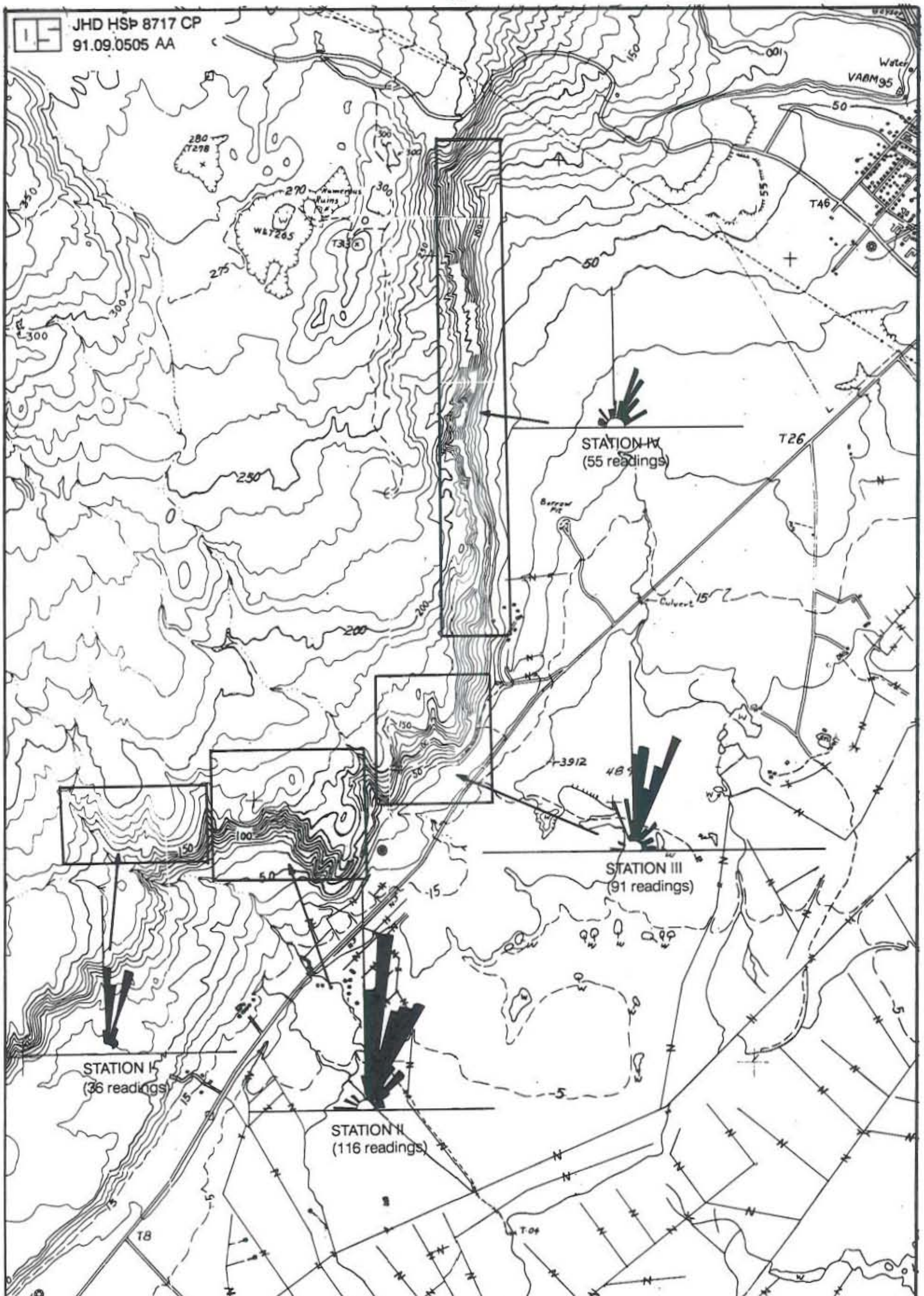

FIGURE 6: Location and trends for structural stations I-IV

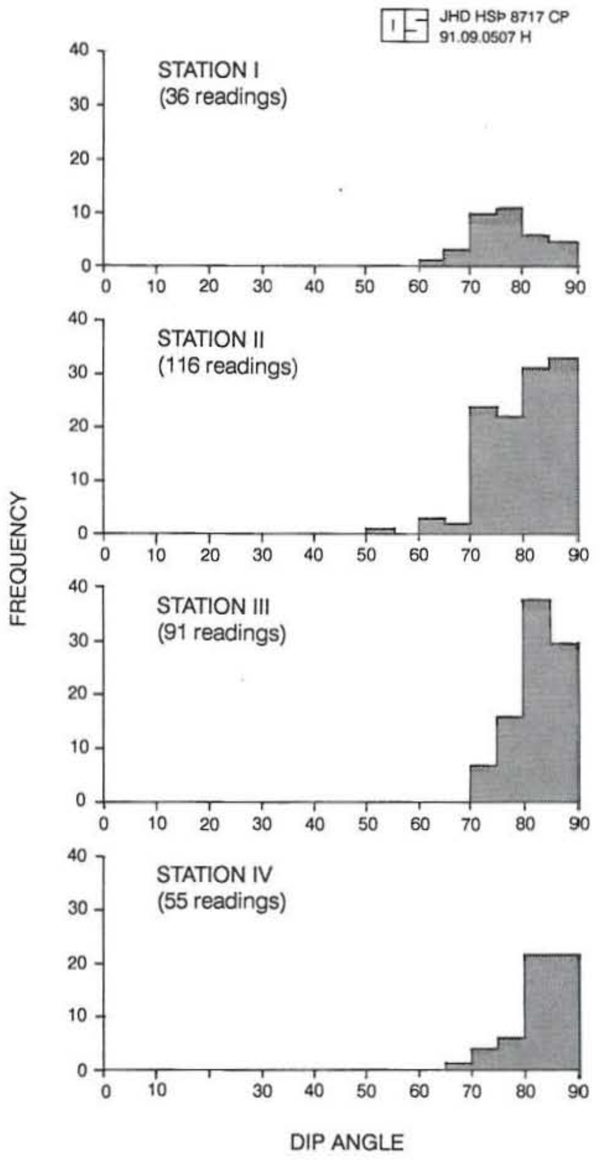

FIGURE 7: Dips for structural stations I-IV

Fractures and fissures are the most abundant structural features in the Nupafjall area and are usually found everywhere where post-glacial lavas have not buried them. These fractures follow all three trends described above and range in size from small fractures to large open fissures with openings of up to 3 m.

Nupafjall is located close to the Hengill triple junction where the Reykjanes peninsula plate boundary splits into the Western Volcanic Zone and the South Iceland Seismic Zone (Einarsson, 1991). The tectonics of the Hengill fissure swarm are characteristic of normal faulting, trending NE-SW, in response to a minimum compressive stress oriented NW-SE. The NE-SW fracture system that is observed in the Nupafjall area apparently is a reflection of the tectonics in the Hengill fissure swarm. The N-S fracture system, on the other hand, seems to reflect the conditions of the South Iceland Seismic Zone, which is marked by a 10-15 km wide, E-trending epicentral belt (Einarsson, 1991). This seismic zone is characterized by an overall left-lateral transform motion, producing N-S striking faults. Field evidence suggests that both N-S and NE-SW fracture systems are contemporaneous. The E-W fracture system can be related to drifting stresses and strike-slip faulting caused by the South Iceland Seismic Zone, although in some cases such as in the south cliffs, where the E-W fractures are found on the edges of the cliffs, it could be related to gravitational collapse caused by wave erosion during the last sea transgression approximately 10,000 years ago.

The basaltic dykes found in the Nupafjall hyaloclastite usually intrude through fractures of the E-W system, which could have originated by extensional stresses produced by the doming up of the area caused by the sill intruded at the base of the unit during a late phase of its growth.

3.3 Hydrogeology

Precipitation in the Nupafjall hills is high (over 2,000 mm), and most of the water infiltrates into the lower layers through the permeable lavas, faults and fissures. Surface runoff occurs in areas covered by hyaloclastite tuffs. As the water percolates, some of it travels along fractures and permeable layers and discharges at several cold water springs found along the north and south

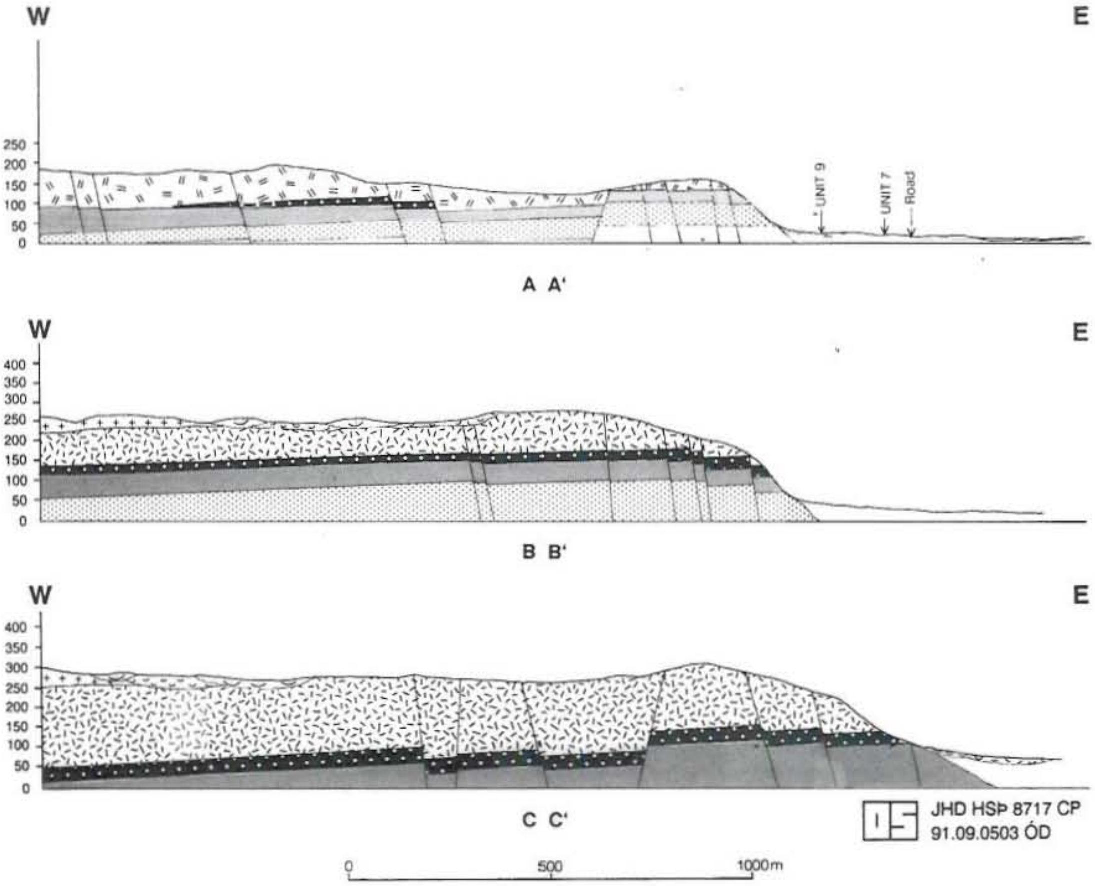

FIGURE 8: Cross-sections A-A^1, B-B^1 and C-C^1

cliffs of the area. The springs are usually found at elevations between 100-125 m a.s.l. at contacts between permeable layers above, usually associated with fractures, and impermeable layers below. The basaltic dykes associated to unit 5 do not seem to contribute to the flow of cold water due to their very low permeability. Some of the water that percolates at the surface reaches deeper levels, where it is heated by the local heat flow and then probably flows south into the lowlands, contributing to the Bakki and Hveragerdi hydrothermal systems.

Figure 9 shows the location of most of the cold water springs, hot springs and boreholes drilled in the area. As we can observe from the map most of the cold water springs are found on the cliffs at elevations around 100 m a.s.l. and are probably related to perched aquifers that are dependent on the precipitation that occurs in the Nupafjall hills. The hot springs are found located in three broad groups in the lowlands to the south and east of Nupar. The three groups seem to follow a distinct N-S lineation, probably indicating open northerly trending fracture zones through which the hydrothermal waters can rise and reach the surface.

Several wells have been drilled in the Nupar farms and some exploration boreholes were drilled next to cliffs north and south of Nupar. The depths of these boreholes range from 20 to 500 m. Small cold aquifers have been intercepted at depths above 100 m, but production of geothermal water is only obtained from borehole NU-5, with a depth of 499 m. It produces 3 l/s of 75°C water. All the other wells are shallower and do not produce any geothermal waters. This is probably because they are too shallow to intercept any permeable fractures or because the hydrothermal system is found at deeper levels. The geothermal wells in the south of the map area are located on the extension of the main graben zone of Thurarhnukur.

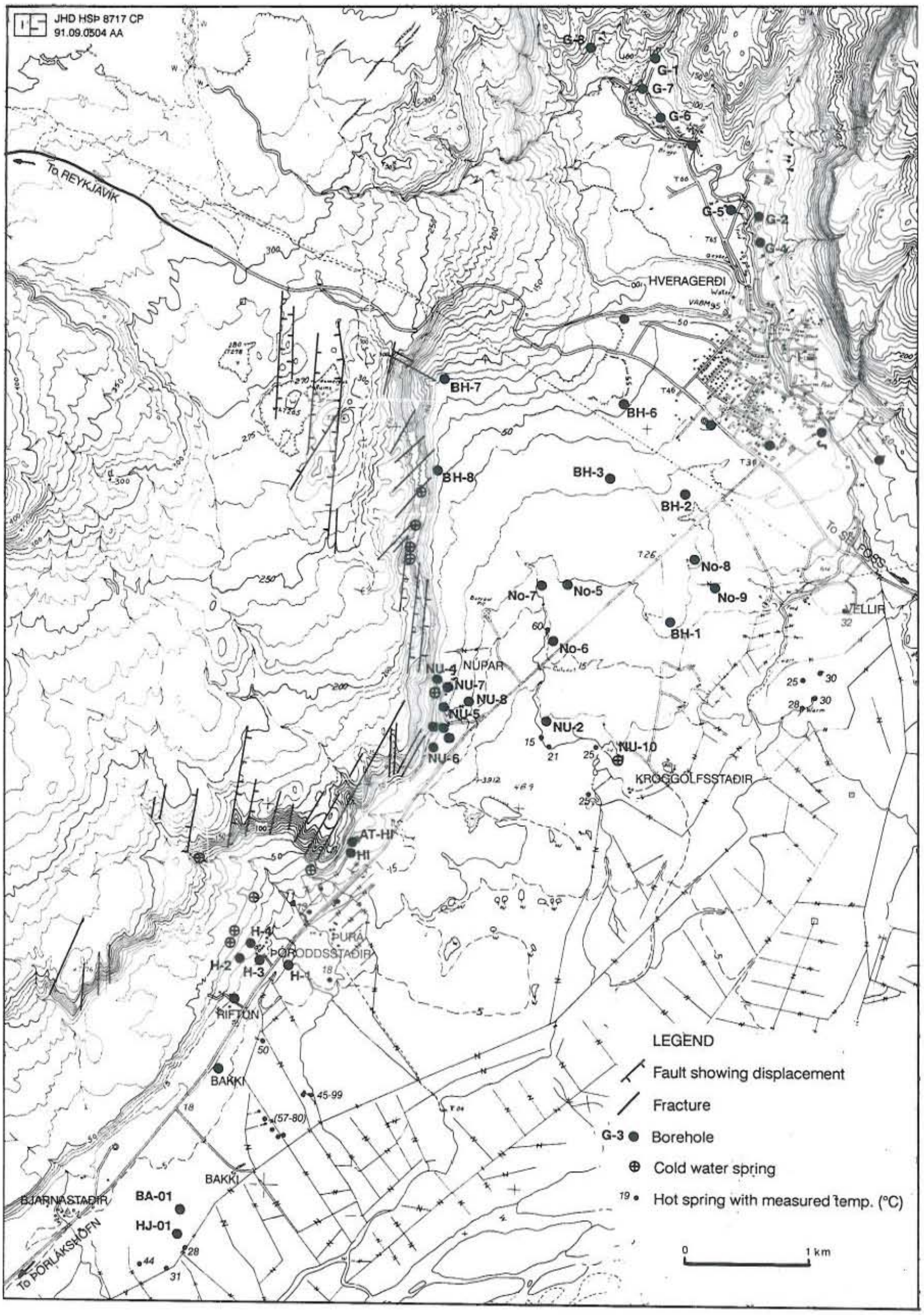

FIGURE 9: Nupafjall area, location of boreholes, springs and important structures

3.4 History of volcanic activity

The oldest hyaloclastite unit that forms the basement of the stratigraphic sequence in the Nupafjall area was probably deposited during a glaciation period. During the following interglacial period, the sea level had risen to about 90 m above the present elevation. At this time olivine tholeiitic lavas were erupted and flowed towards the shoreline where they formed the foreset bedded breccias at the base of a large lava shield. The direction of the large foresets indicates that the effussion center for these lavas was somewhere to the west or northwest of the map area - perhaps close to the present rift axis.

A period of little or no volcanic activity followed, in which erosion was characteristic. This period is represented by a layer, 5-10 m thick, of fluviatile sediments deposited on top of the compound lavas. The sediments are composed of fine to medium subrounded fragments of breccia and lava, indicating a proximal origin.

Next a glaciation period occurred. During this period there exists no evidence of volcanic activity within the map area, but hyaloclastites are found north of Hveragerdi, between the olivine tholeiite compound lavas and the Kviar basalts and thus belonging to this time frame (Saemundsson and Fridleifsson, 1991, work in progress). In the Nupafjall area the only evidence found is a layer, 1-5 m thick, of glacial till deposited on top of the compound lavas. Erosion of the compound lavas is typical of this glaciation, sometimes eroding up to 60 m of material.

During a new interglacial period, a series of simple basaltic lava flows (Kviar lavas) were erupted, probably from the Hveragerdi central volcano (Saemundsson and Fridleisson, 1991, work in progress). These flows are found mainly northwest of Hveragerdi covering an extensive area, but in the Nupafjall area only four flows are found in the cliffs north of the Nupar farms, and only three flows in some small outcrops in the cliffs at Thurarhnukur.

Sometime after the Kviar lavas were deposited a period of glaciation eroded large parts of the Kviar lavas and deposited a layer of up to 10 m of fluviatile sediments and glacial till on top of them. No volcanic activity is evident in the Nupafjall area during this glaciation, but north and east of Hveragerdi, Saemundsson and Fridleifsson (1991, work in progress) identify hyaloclastite units that would belong to this period. The heavy denudation of the Kviar lavas is suggestive of a prolonged period of erosion, extending through a glaciation cycle. It is assumed that a glaciation cycle consists of a period of approximately 100,000 years of glaciation and an interglacial period lasting about 10,000 years (Imbrie and Imbrie, 1979).

The next units to form after the break in the volcanic accumulation are the hyaloclastites of Thurarhnukur and Nupafjall. It is not clear from the field evidence which one is older. Both were probably formed during the Saalian glaciation period (120,000-200,000 years ago). At this time volcanic activity had shifted westward from the Hveragerdi central volcano to the Nupafjall area southwest of Hveragerdi, and its continuation towards N into the Hromundartindur system northeast of Hveragerdi (Arnason et al., 1987).

During the next glacial cycle (Eemian interglacial and Weichselian glaciation) the Nupafjall area was again under erosion with no volcanic accumulation occurring until towards the very end of the Weichselian, when the Skalafell lava shield formed. It is believed that this shield was formed during the Allerod interglacial, 11,000-12,000 years ago (Saemundsson and Fridleisson, 1991, work in progress), sometime after the glacial retreat and while the sea level was approximately 50 m above the present. Its center of emission is the Trolladalur crater west of the map area.

The Younger Dryas glacial advance occurred approximately 10,000 years ago and eroded parts of the lava shield, depositing thick layers (up to 5 m) of glacial moraine in parts of the Nupafjall area. No volcanic activity is evident during this glaciation in the area. Finally during post-glacial times (0-10,000 years), three lava flows, ^{14}C dated at 9,000, 5,000 and 2,000 years, have been erupted from crater rows in the present rift axis, and flowed into the western part of the map area and into the lowlands.

A tentative correlation of the stratigraphy of the Nupafjall area with the glacial-interglacial chronology is shown in Figure 10. It takes notice of the volcanic stratigraphy of the Hveragerdi area, mapped by Saemundsson and Fridleifsson (1991, work in progress).

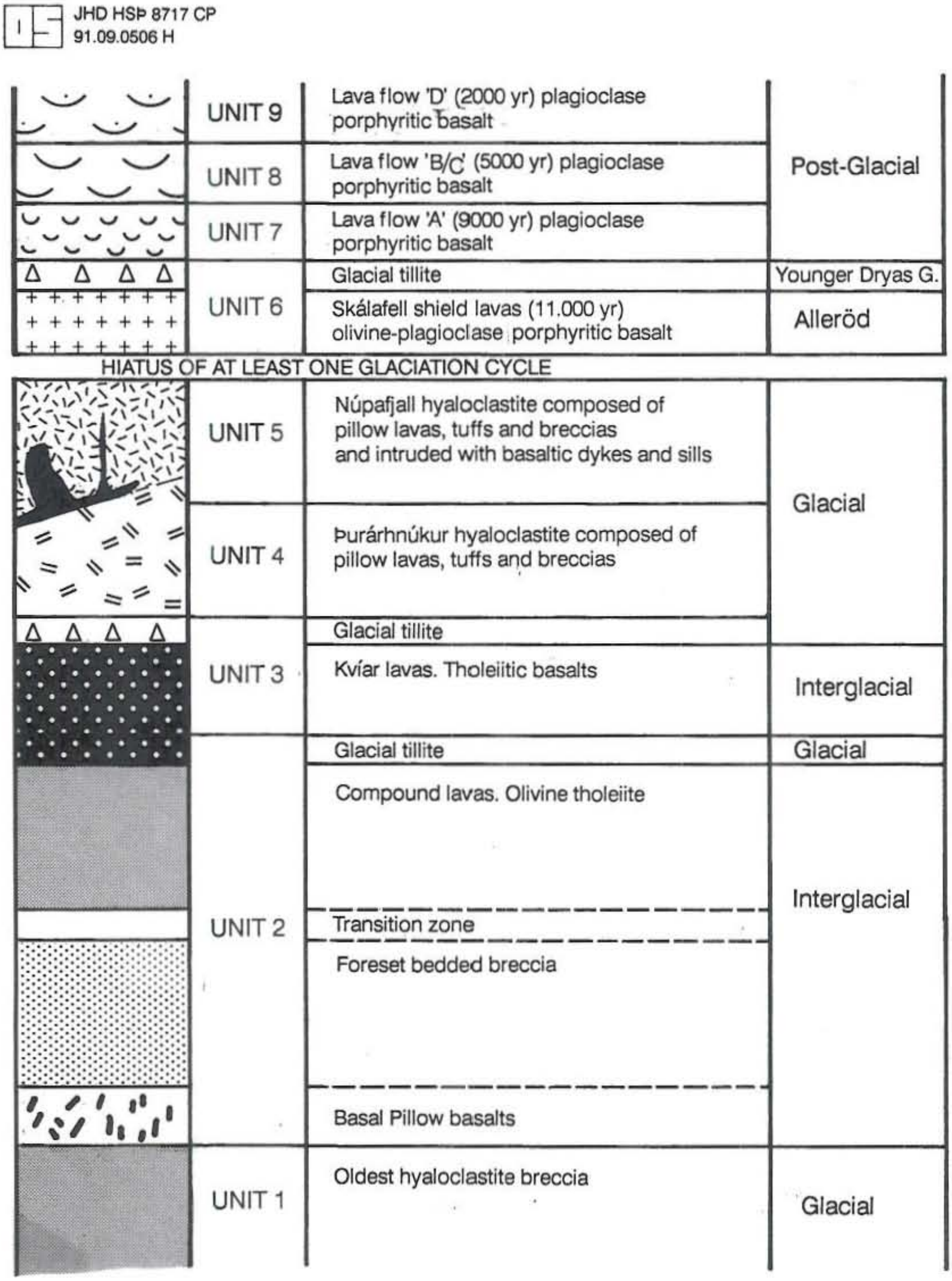

FIGURE 10: General stratigraphic section of Nupafjall

3.5 Discussion of borehole sites

Part of the work done in the Nupafjall area was to study the location of boreholes that have been drilled in the area with respect to the geologic and tectonic information obtained from the mapping. Table 2 shows general characteritics of some boreholes in the Nupar - Bakki area; their locations are found in Figure 10. Temperature logs of selected boreholes are found in Appendix A.

Boreholes BH-7 and BH-8 are two shallow research boreholes, drilled for the purpose of determining the groundwater level. They also give information about geothermal gradients below the shallow cold water aquifer. They are located next to the cliffs north of the Nupar farms. The geology of both boreholes consists of a top layer of soil overlying a sequence of basaltic lavas, sands and gravels and hyaloclastites at the base. Borehole BH-7 shows a temperature gradient of 0.17°C/m below a depth of 30 m, and BH-8 has a gradient of 0.37°C/m below 20 m. Both wells have a higher temperature gradient than the regional temperature gradient of 0.1°C/m, indicating the probable existence of geothermal waters at some depth, that are increasing the local temperature gradient. The higher temperature gradient observed in borehole BH-8 can be explained by the fracture zones found in the vicinity of its location. This increases the permeability of the rocks, thereby increasing the flow of geothermal waters.

TABLE 2: Borehole characteristics

Borehole no.	Depth (m)	Maximum temperature (°C)	Approximate production (l/s)
BH-7	52	9.3	
BH-8	34	10.5	3
NU-4	62	21.0	
NU-5	60		
NU-6	82	20.0	
NU-7	499	100.0	2-3 of >40°C
NU-8	345	104.0	
ÞA-1	325	77.0	50 of 10°C
ÞS-1	1734	125.0	20 of >100°C
ÞS-2	45		
ÞS-3	116	7-10.0	70-80
ÞS-4	33	7-10.0	70-80
RT-1	349	>48.0	
BA-01	886	135.0	40 of >100°C
HJ-01	605	119.0	35 of >100°C
EB-01	1025	120.0	10 of >100°C

Several shallow wells were drilled within the Nupar farms, with the intention of finding a shallow tepid aquifer. Of these wells NU-4, NU-5 and two shallow wells south of the farms found a shallow aquifer of 15-20°C. As a result of this, borehole NU-6 was drilled down to 82 m, producing water of about this temperature from a depth of about 70 m.

Two deeper production wells were also drilled, boreholes NU-7 and NU-8. NU-7 is a production well found behind the farm, producing 2-3 l/s of 75°C water. NU-8 was also meant to be a production well but drilling was stopped at 345 m before reaching the desired target. It is apparent from the temperature measurements that both wells are fed by an aquifer of 70-95°C water at about 250-300 m.

Well ÞA-1, located in the Thura farm, yields about 50 l/s of 10°C from a shallow aquifer (above 100 m). Below this it has a temperature gradient of about 0.23°C/m, which is indicative of geothermal waters below, but has no apparent aquifers at these depths. In order to find greater permeability caused by fracturing, the well would have to be deepened to at least 500 m.

The other wells in Table 2, at Riftun, Thoroddsstadir, Eystri-Bakki and Bakki, are located within the Bakki low temperature geothermal field, identified by resistivity soundings as an area of 5-10 Ωm (Georgsson, 1989), and of different water chemistry from the waters at the Hveragerdi geothermal system (Kristmannsdottir et al., 1990). The reservoir from which the wells produce appears to be related to permeable strata or fractures at depths between 200-800 m.

Well RT-1, at Riftun was first drilled down to 160 m in 1969, but a year later was deepened to 340 m, where it found a maximum temperature of 48°C. Later temperature measurements discovered that the temperature had dropped to about 20°C. It was found that the reason for this drop in temperature was that cold groundwater from a shallow aquifer (40-70 m) was flowing down into the well and cooling the lower aquifer (Saemundsson, 1991, personal communication). Presently the well has been plugged with cement, thereby preventing any further cooling of the aquifer. The location of this well is in line with NE-SW trending fractures found in the cliffs to the north and appears to be a good site, for any future drilling. So as to prevent this from occurring in any future wells the shallow cold groundwater aquifer should be cased off.

At the Thoroddsstadir farm four wells have been drilled, of which ÞS-2, ÞS-3 and Þ-4 are shallow wells. Of these, wells ÞS-3 and ÞS-4 (116 m and 33 m deep), are located next to the cliffs formed by the Skalafell lava shield and intersect cold water aquifers within the foreset bedded breccia at their base. They produce 70-80 l/s of 7-10°C water. Well ÞS-1 is a 1734 m deep well producing about 20 l/s of 100-125°C water.

The well at Eystri-Bakki (EB-01) identifies one 90-105°C aquifer between 300-450 m and another 90-110°C aquifer between 600-700 m. The location of the well is too distant (350 m) from the main NE fracture zone, evident at Thurarhnukur, to be directly affected by it, but there are probably fractures trending N-S, evident on the cliffs to the east of Thurarhnukur, that do affect the permeability of the well.

Two wells have been drilled in the Bakki area; BA-01 was drilled in 1977 and HJ-01 in 1984. The water from the wells is used for heating the community of Thorlakshofn, 11 km southwest of Bakki. It appears that both wells are fed by an aquifer of 115-120°C water at 300-450 m depth, but at lower depths a number of smaller aquifers of lower temperature yield about 20% of the full discharge (Georgsson, 1990), bringing the temperature down to 100-110°C. Georgsson (1990) states that this cold water inflow can be explained by a "fracture or fracture system in a direct connection to the reservoir, feeding the bottom aquifer in the well".

It is apparent from the geologic structures that two fracture systems are playing an important role in the permeability of the Bakki geothermal system: a N-S fracture system and a NE-SW fracture system. Both fracture systems are found in the cliffs to the east of Thoroddsstadir and Thurarhnukur. The NE-SW fracture system consists of fractures dipping 75-82°SE and up to 1 km in length. The N-S fracture system has dips on the average of 80°E, with a few exceptions dipping due west. Both fracture systems might either exist combined or independently of each other, but it is clearly evident that they do increase the permeability of the field and help to transport geothermal fluids to shallow depths.

4. SVARTSENGI AREA

4.1 Introduction

The Svartsengi area is located in the Reykjanes peninsula, approximately 50 km southwest of Reykjavik and covers the Svartsengi geothermal field, the lava fields surrounding it, and the pillow lava piles of Hagafell, Lagafell and Thorbjarnarfell and the table mountain of Svartsengisfell (Figure 1).

The Svartsengi geothermal field is a high temperature geothermal field producing 100 $MW_{thermal}$ and 8 $MW_{electric}$ for the communities in the Reykjanes peninsula. The geothermal field has a very high degree of faulting caused by an active fissure swarm cutting across the field, but surface manifestations are few and surface alteration is of rather small extent.

Previous work done in the area consists of geologic mapping by Kuthan (1943), Jon Jonsson (1978), Freysteinn Sigurdsson (1985) and Haukur Johannesson (1989); Hjalti Franzson (1990), mapped the surface alteration and structural lineations of the geothermal field. The purpose of this work is to confirm all the previous work done by mapping the geology, surface alteration and geologic structures and to try to establish a relationship between the structures and surface alteration.

4.2 Surface geology

The geology of the Svartsengi field previously mapped by Jonsson (1978), Sigurdsson (1985), and Johannesson (1989) was mapped again and a few discrepancies were found with all previous works. It has been divided into different geologic units including pillow lava piles, a table mountain, lava flows and crater rows. A description of the units is given below. Reference is made to Jonsson's (1978) descriptions where the units are correspondent, but the description is more extensive where there exist differences (Figure 11).

4.2.1 Thorbjarnarfell - Lagafell

Thorbjarnarfell (elevation 231 m), is located to the south of the Svartsengi geothermal power plant. It is almost circular in outline were it not for the eroded NW- side of the mountain. It stands out as the highest mountain in the area, and also due to a pronounced graben structure cutting through it. The faults of this graben form a labyrinth of deep fissures at the summit with vertical walls of up to 40 m. The rocks are composed of olivine-plagioclase porphyritic pillow lava covered in places by a thin veneer of breccia up to 10 m thick. Very minor amounts of palagonitized tuffs occur. From a plateau-like surface at 150-160 m altitude there rises a 231 m high cone of 1.5 km diameter. Sunk into it is a crater, 300-400 m in diameter open towards north. The summit and crater have been partially destroyed by faults. The crater, like the rest of the mountain, is found altogether in the pillow lava. Neither lava nor large thicknesses of tuffs were observed on the rims of it. Steep cliffs are found on the northwest side of Thorbjarnarfell. These are probably erosional, formed by gravitational slumping and aided by faulting. Opal crusts are found in fractures and in the vugs of the pillow lava throughout most of Thorbjarnarfell, however only sporadically on the summit and its southern part. High intensity alteration is found in the north slopes of the mountain, apparently related to the faults forming the graben. Judging by the elevation of Thorbjarnarfell and by the absence of either lavas or larger amounts of breccias and tuffs, it can be deduced that the glacial ice sheet must have been approximately 450-500 m thick, which is thicker than previously thought for this part of the Reykjanes peninsula.

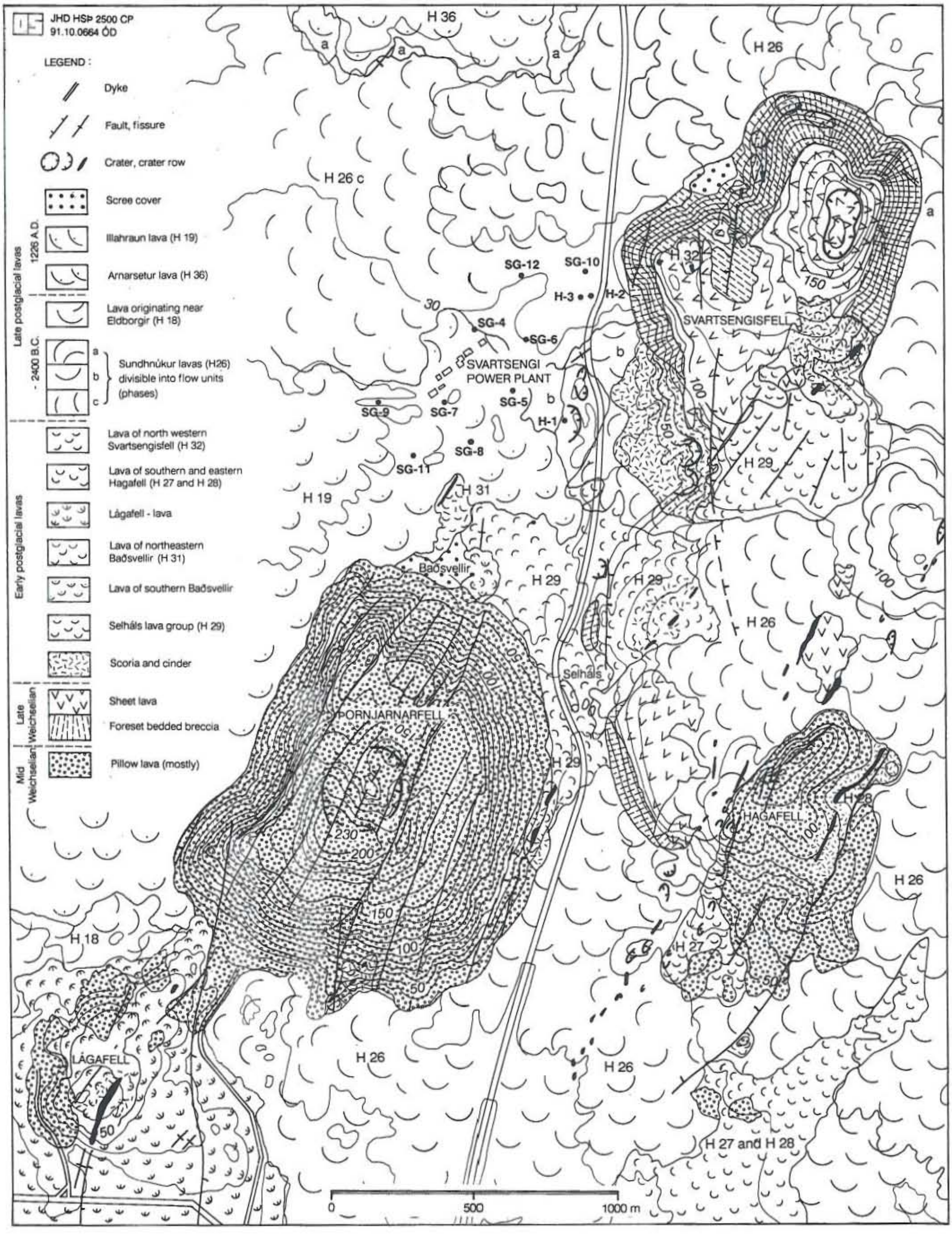

FIGURE 11: Geology of Svartsengi

Lagafell (71 m) is a small pillow lava mound of similar composition to Thorbjarnarfell, located to the southwest of it. It is covered by a postglacial lava and scoria, described in a later section. Jonsson (1978) maps Lagafell as being hyaloclastite capped by a coarse grained interglacial basalt. In reality only a few outcrops of pillow lava are present, the rest being covered by a post-glacial lava.

Both Thorbjarnarfell and Lagafell were erupted during a glaciation period, when the ice had advanced south beyond this area. The eruptive activity probably began as a fissure eruption and then concentrated in Thorbjarnarfell, but never reached the surface of the meltwater lake.

4.2.2 Hagafell

The Hagafell ridge (143 m), is located east of the main road to Grindavik. It is composed of olivine-plagioclase porphyritic pillow lava and a cover of approximately 5-10 m of breccia of similar composition. The olivine and plagioclase phenocrysts are as large as 1mm and 3mm respectively. Several N-S trending fractures and open fissures are found on the crest of the ridge, and on the east side, a large fault with displacement of approximately 5-10 m to the west has a NE-SW trend. Jonsson (1978) mentions that the cliffs on the north side of Hagafell were formed by a large fault, but no clear evidence exists to support this idea. Another possibility of how the cliff was formed was by the action of glacial erosion, which in the area flowed south, encountering Hagafell as an obstruction and eroding its NW- side. Evidence contrary to a fault origin of the cliff is the fact that lava of the Svartsengisfell table mountain never advanced over the Hagafell pillow lava east of the presumed fault. Three small mounds of pillow lava with similar composition as the Hagafell pillow lava are found to the south of it. These are not indicated on any of the geological maps except partly on a 1:100,000 map by Kuthan (1943). Hydrothermal alteration is found only in the southern slopes of Hagafell and consists of aragonite and clay deposits. The cliff that forms the northwest side of Hagafell is a cross-section through a pillow lava mound, where well-shaped pillows can be observed. Three crater rows are located on the east and west side of the mountain. These have produced both lava and scoria which partially cover the pillow lava. They are described in a later section.

Hagafell was probably formed in a similar fashion to Thorbjarnarfell and their similarity in compositions seems to indicate that they were formed within the same time period.

4.2.3 Svartsengisfell

The Svartsengisfell table mountain (197 m), is found to the east of the Svartsengi power plant and consists of plagioclase porphyritic pillow lava, foreset breccia, dykes and sheet lavas. A crater consisting of two contiguous pits is preserved at the summit of Svartsengisfell. Younger aphyric lavas were erupted from crater rows cutting across Svartsengisfell in early postglacial time. These are described in later sections. Faults of N-S and NE-SW trends are found on the west and south slopes of Svartsengisfell and low to high intensity hydrothermal alteration is found, apparently related to the larger faults. The flat-topped hills southeast of Selhals are composed of foreset breccias capped by sheet lavas forming part of the Svartsengisfell table mountain. No faults or fractures are evident there and hydrothermal alteration is limited to small opal crusts within the breccias. The foreset breccias crop out in low cliffs and in many outliers surrounded by younger lava, west and north of Hagafell. The transition zone between foresets and sheet lava is highest in the north of Hagafell, but becomes gradually lower towards the south.

Svartsengisfell was most probably formed in a late stage of the last glaciation, when the ice cover was much thinner than when Thorbjarnarfell and Hagafell were formed, the ice surface sloping towards the south. Nothing is seen of an initial mound of pillow lava formed in an underwater eruption. Nor are tuffs formed as the eruption reached the surface of the meltwater lake. Only visible are foreset bedded breccias formed after the mound grew beyond the surface, and lavas on top of them. When lava began to emerge, it flowed south, forming foreset breccias as it advanced (Figures 4 and 5). The slope east of Selhals appears to be the southwest edge of the unit and a small outcrop below Sundhnukur to the east of the map area identifies that limit to the east. It is apparent from the morphology of the mountain that ice from the glaciers was much thicker on the north end and was pressed against its slopes. The ice became thinner towards the south, making it possible for the lavas to flow mainly towards the south. In the final stages of the eruptive cycle of Svartsengisfell, some small dykes were extruded radiating outwards from the northeast side of the crater.

4.2.4 Older crater rows and lavas

The postglacial volcanic activity within the map area occurred on several crater rows which fall into two age groups. The older group involves eight individual eruptive sites and crater rows which have produced lavas and, in some cases, quite large quantities of scoria. The crater rows all appear to be very old judging from the thickness of soil on them and their state of weathering, in particular disintegration by frost action. The lavas produced by these crater rows are usually covered by 40-50 cm of soil, on top of which lies an ash layer deposited in the year 1226 A.D.

Crater row and lava of Lagafell:
In the crest of Lagafell and down its south slope is found an eruptive fissure that has produced some scoria and lava which covers most of the pillow lava that constitutes the bulk of the hill. The lava is aphyric basalt. It has flowed downslope to the south, east and west of Lagafell. Jonsson (1978) describes the lava south of Lagafell as a shield lava, belonging to unit D-6 (from the Sandfellshaed lava shield), but due to the flow directions and slopes found on the lava this seems to be incorrect at least for that part closest to Lagafell. Jonsson (1978) maps the top of Lagafell as being covered by interglacial lava. In the text volume (p. 31), Jonsson states that Lagafell has a crater and some lava and scoria at the top showing no sign of glacial erosion. However, he considers the lava as belonging to the same eruption as the pillow lava of Lagafell. In fact, the lava and scoria are the ones produced by the eruptive fissure mentioned above. It occurred much later than the eruption of the pillow lava and is very different from it in hand specimen inspection.

Crater rows and lavas between Svartsengisfell and Thorbjarnarfell (H-29):
Under this heading are grouped together lava flows, cinders and scoria that occur in a NE-SW trending zone extending from Svartsengisfell to Thorbjarnarfell. Jonsson (1978), failed to indicate this on his map apart from the northeasternmost occurrence which he marks as H-29, although some are mentioned in the text volume.

On the south slope of the Svartsengisfell table mountain one finds scoria mounds that Jonsson (1978) defines as unit H-29 as one eruptive site producing aphyric lava and scoria. Further eruptive sites were identified during the recent field work, to the northeast of the one described by Jonsson (1978). Lava fountaining has sprayed spatter-lava on the south slope of Svartsengisfell up above the craters. Approximately 1 km to the southwest of these, three scoria mounds are identified that seem to be the remnants of craters that produced scoria and aphyric lava that flowed to the south and west.

On the south and east slopes of Thorbjarnarfell, two sets of eruptive sites are identified. The row of craters on the east slope have produced scoria and some aphyric lava, which flowed east, covering the Selhals area in between Thorbjarnarfell and Svartsengisfell. Of the previous maps only Franzson (1990), shows this crater row. The crater row on the south slope has produced some scoria and spatter lava that began to flow downslope from three different places aligned in a NE-SW direction. A younger lava (H-26) covers the ground to the south where the lava from the old craters should have spread out.

On the north slope of Thorbjarnarfell there exists a small hill of aphyric lava that has previously been mapped as hyaloclastite. The shape of the small hill suggests a crater that has been partially destroyed, but there are no scoriaceous deposits that would support this idea. It is difficult to relate this small hill of lava to any of the lava flows found in the area.

Scoria deposits on western slope of Svartsengisfell:
East of the road to Grindavik there exist on the slopes of Svartsengisfell thick deposits of cinder and welded scoria. The outcrop is shown on Jonsson's map (1978). However, it is stated in the text that accompanies his map that the scoria underlies the rocks of Svartsengisfell. This is incorrect. Pillow lava from Svartsengisfell can be seen to underlie the scoria in cinder pits at the foot of the mountain and cinder and scoria are also flund covering the upper edge of Svartsengisfell, east of the pits. Franzson (1990) identifies two N-S trending crater rows.

Saemundsson (1991, personal communication) believes that only one or two craters, located in the south of the outcrops, produced the scoria and related deposits of which the southern one acted as a main vent. He thinks that the scoria was blown northwards by the wind, giving the impression of being a crater row. Layers of welded scoria surround the main crater, whereas loose cinders were deposited farther away to the north. There appears to be a distinctive sorting in grain size away from the crater, and slope-parallel bedding becomes pronounced as well. Surge deposits and palagonitized tuffs suggest that part of the eruptive activity of the crater was phreatomagmatic. The deposits suggest that the eruption evolved from explosive to increasingly more lava fountaining. The explosivity probably was due to ingression of water into the conduit as is suggested by the layers of glassy tuffs interbedded with the cinders and scoria. As the conduit became more and more sealed, the eruption changed to lava fountaining forming welded spatter around the crater, particularly evident on the hillside south of it. No lava has been identified.

Approximately 400 m further SW there are similar scoria deposits at the foot of the Svartsengisfell table mountain. A small quarry has been operated, but the work was given up probably because of the half-welded state of the scoria. North of the pit there is a circular hollow open to the west. It might be a crater, but no lava has been identified.

Spatter on NW slope of Svartsengisfell (H-32):
The north and west slopes of Svartsengisfell contain a row of seven separate eruptive sites, small in size, the largest covering an area of only a few square meters. They are roughly aligned in a NE-SW direction and have produced scoria and apparently only a minor amount of lava. Jonsson (1978) refers to one of these eruptive sites as unit H-32. Franzson (1990) identified one more eruptive site. Two eruptive sites shown on Franzson's (1990) map in the west of Svartsengisfell south of those just mentioned could not be confirmed. The row of eruptive sites can be identified relatively easily because the scoria is aphyric and darker in color compared to the plagioclase porphyritic lighter colored surrounding rocks of Svartsengisfell. The scoria and lava are only remnants that are heavily broken up by frost weathering and much covered by scree.

Crater row north of Selhals (H-30):
Next to the main road to Grindavik, on the east side, two craters form a northerly trending crater row. This trend diverts from the normal trend in the area and can only be explained by a N-S trending eruptive fissure. The craters produced small amounts of scoria. Remnants of two craters can be observed. Lava erupted by the crater row has not been identified apart from a sheet exposed in the western wall of the northermost cinder quarry, east of the road. There the lava overlies the cinder and is separated from it by some 0.5 m of scree material and soil. A lava flow shown on Jonsson's (1978), map as flowing from these craters towards the northwest is much younger, i.e. part of H-26.

Crater row and lava north of Badsvellir (H-31):
Jonsson (1978) refers to this unit as H-31. The eruptive site trends in a NNE-SSW direction and has produced both scoria and a flow of aphyric lava that is exposed to the east of the crater row. The lava is omitted on all previous maps. The area to the west and north is covered by the younger Illahraun lava (H-19, described in a later section) which obscures the original extent of H-31. The amount of scoria would suggest that a sizeable lava flow was erupted.

Crater row and lavas in SW of Hagafell (H-27):
Hagafell contains two sets of crater rows that Jonsson (1978) identifies as units H-27 and H-28. One, H-27 is located in the southwest end of Hagafell. It consists of six different craters that have produced scoria and lava covering a small area surrounding the pillow lava mounds. A small, closed depression near the crater was apparently filled up by this lava and then emptied out, probably through an open fissure at its bottom, leaving lava levees around the rims of the depression.

An outlier of old lava occurs just northwest of the Grindavik harbour between the H-26 and a picrite lava marked D-8 in Jonssons map (1978). It is shown in Jonsson's (1978), map but has no designation. It almost certainly was erupted by the H-27 volcanic fissure.

Crater row in NE of Hagafell (H-28) and related lavas (H-24 and H-25):
The crater row that Jonsson (1978) describes as unit H-28 is located in the northeast of Hagafell and consists of a row of eruptive sites along a fault with NE-SW trend. It produced aphyric scoria, which is partly welded to spatter lava. A lava flow from this fissure eruption has not been identified with certainty, though it is likely that old lavas south of Hagafell not identified by previous mapping apart from small windows, belong to H-27 and H-28 crater rows.

South of Hagafell Jonsson (1978) shows two small window of older aphyric lava (H-24 and H-25), within the Sundhnukur lava (described in the following section). It is clear from the recent field work done that these windows of older lava are quite large, extending south to Grindavik and including the whole of Hopsnes peninsula. Being of the same character it is likely that both are the same lava flow, and that its origin was the H-28 volcanic fissure or its extension to the NE.

4.2.5 Younger crater rows and lavas

The group of "young lavas" includes four units erupted in two episodes, the older approximately 2400 years ago and the younger only about 750 years ago.

Sundhnukur crater row and lava flows (H-26):
The Sundhnukur crater row extends from a few hundred meters southwest of Hagafell, northeast along Hagafell and to the northeast of Svartsengisfell. It consists of many craters that have

produced scoria and lava that cover large areas in the north and south of the map.

North of the Svartsengi power plant three distinct flow units have been identified as flow units a, b and c. Flow unit a is recognized by Jonsson (1978) as unit H-27, but soil profiles dug in different localities identify approximately the same thicknesses of soil (4-5 cm) between the lava surfaces and an ash layer erupted in the year 1226 A.D. (Johannesson and Einarsson, 1988 a) on all three flow units. This indicates that not much time elapsed between eruptive events. Jonsson (1978) has had the Sundhnukur lava dated by ^{14}C as being approximately 2,400 years old. The Sundhnukur lava covers a much smaller area east and northeast of Grindavik than is shown on Jonsson's (1978) map. Fault movement within the Sundhnukur lava was observed only in one of the H-27 windows north of the Svartsengi power plant (Jonsson, 1978), and south of Hagafell, also shown in Jonsson (1978).

Older Eldvorp lava (H-18):
This unit is found to the west of Lagafell and is identified by Jonsson (1978) as unit H-18. The lava has its origin near the Eldvorp crater row, west of the map area (Jonsson, 1978). By looking at soil profiles dug on top of the lava, it is evident that it is older than the ash layer of the year 1226 A.D. The soil thickness between the surface of the lava and the ash happens to be the same (4-5 cm) as found for the Sundhnukur lava, suggesting that both are of about the same age.

Arnarsetur lava (H-36):
This lava which is a rough surfaced aa flow is only found in the northern limit of the map area, Jonsson (1978) identifies it as unit H-36 and thinks that it was erupted in historical time. Einarsson and Johannesson (1989), found indeed that the lava was erupted shortly after deposition of the 1226 A.D. ash.

Illahraun lava (H-19):
Jonsson (1978) defines this lava as unit H-19 in his report. It was erupted from a short NE-SW trending crater row approximately 2 km west of the Svartsengi power plant. Johannesson and Einarsson (1988 b), place the date of eruption around the time of the ash layer of the year 1226 A.D. By correlating to events described in Iceland's historical annals, they conclude that this ash layer which had been previously mapped and studied was deposited in the year 1226 A.D. (Johannesson and Einarsson, 1988 a). The Svartsengi power plant and most of the boreholes are located on this lava flow. No faults have been found to occur within the 1226 A.D. lavas.

4.3 Structural geology

Previous studies identify faults and fissures in varying degrees of detail. Kuthan (1943) only maps the major faults and general trends of the Reykjanes peninsula. Jonsson (1978) has mapped several important faults and fissures, but does not include all of them in his map. Sigurdsson (1985) did an exhaustive study of the structural geology of the Reykjanes peninsula, but does not include much detail of the Svartsengi area. Johannesson (1989) identifies the majority of faults and fissures, but does not include the direction and size of displacements. Franzson (1990) did an important analysis of structural lineations in Svartsengi, but also failed to identify direction and size of displacements.

Several faults and fissures have been identified (Figure 11). The faults are generally normal faults with throws of about 5-10 m, but extremes of up to 40 m are observed in the graben cutting through the Thorbjarnarfell mountain. Two fault systems are identified, the first one striking NE-

SW (30-40°), and a second striking N-S (0-20°) (Sigurdsson,1985). The faults belonging to the first system form the grabens found in the Thorbjarnarfell mountain and several smaller grabens in Svartsengisfell and north of the community of Grindavik. The dips are generally near-vertical.

The second fault system trending N-S is found less frequently than the NE-SW system, but the faults are characteristically long and continuous (approximately 1 km), and have throws of about 5-15 m. The dips are generally close to vertical as far as can be judged.

Both fault systems apparently are contemporaneous, although there are a few places where the N-S striking faults intersect the NE-SW faults, suggesting the possibility that N-S striking faults are younger. The origin of both fault systems is found in the spreading of the Mid-Atlantic rift which has minimum compressive stresses oriented horizontally on a WNW-ESE direction, therefore fissures open up against this minimum stress, striking in a NE-SW direction (Einarsson and Bjornsson, 1979). Sigurdsson (1985) relates the N-S trending faults directly to a narrow seismic zone identified in seismic studies done by Klein et al. (1973, 1977), suggesting that the N-S trending faults are a result of left lateral stresses in the microseismic zone (at depths below 2 km), caused by the oblique opening along the Reykjanes segment of the Mid-Atlantic Ridge. This action produces deformation of the stress fields and eventually would form N-S and NW-SE trending faults.

No surface evidence is found for the NNW-SSE faults mentioned by Franzson (1990), but it is entirely possible that these faults exist at depth within the microseismic zone (Figure 2), without having a representation at the surface. Fractures without displacement trending NW-SE are frequent. They seem ubiquitous in the Reykjanes area (Torfason et al., 1983 and Kifua, 1986), and may relate to the main trend (NE-SW), as a conjugate set.

The faults with the largest displacements (10 to 40 m), were identified in the pillow lava of Thorbjarnarfell, Lagafell and in Hagafell, which are the oldest units outcropping in Svartsengi. Faults with displacements in the range of 5-10 m were observed in the sheet lava of Svartsengisfell. The lavas from the oldest crater rows contain a few open fissures and faults of smaller displacements (3-5 m). Only a few open fissures (<1 m wide) were identified in the 2,400 year old lavas, but Jonsson (1978) mentions more fissures outside of the map area. No faults were observed in the lavas of 1226 A.D.

It is noteworthy that the main part of the wellfield of Svartsengi falls west of the graben structure of Thorbjarnarfell and west of the area of most intense surface alteration.

4.4 Surface hydrothermal alteration

Figure 12 shows the areas of surface alteration and active manifestations; the alteration zones have been classified into high, medium and low intensity alteration zones. High intensity alteration is found where extensive formation of clays occur; medium intensity alteration is characteristic of extensive deposition of silica, in the form of opal crusts, and/or aragonite, and low intensity alteration is characteristic of slight deposition of silica, also in the form of opal crusts. Active manifestations are characterized by hot soils and steaming ground.

Highly altered earth seems to be characteristic of fossil fumaroles, where the rock is altered to clays, usually smectite and kaolinite, by low pH geothermal fluids. Medium and low intensity alteration zones are characteristic of deposition of opal and /or aragonite and a distinction is made between the two zones by the amount of deposition of either mineral. Aragonite deposition

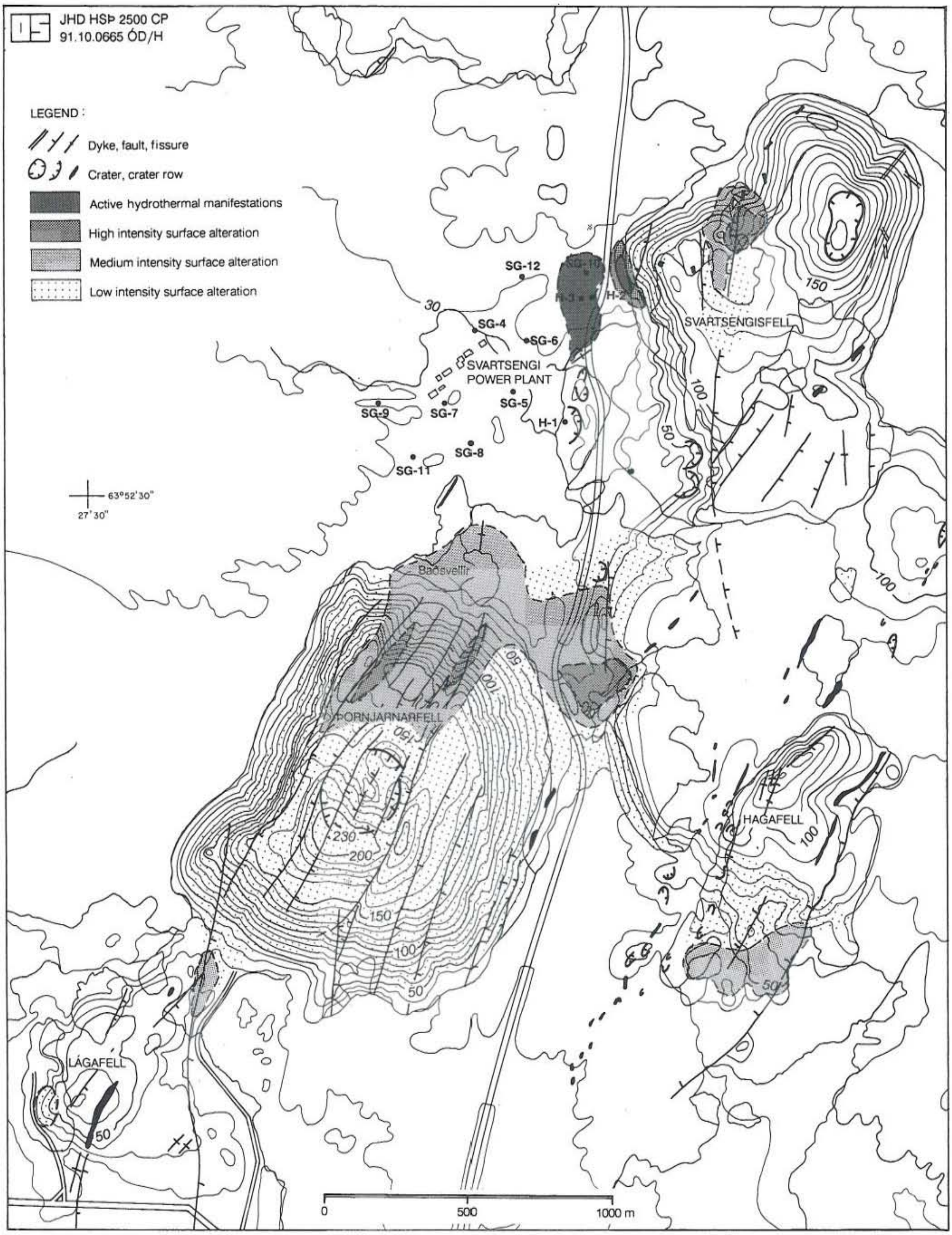

FIGURE 12: Surface hydrothermal alteration in Svartsengi

indicates that hydrothermal activity in the past was in the form of hot springs, probably of carbonate character. The deposition of opal also indicates hot springs and flow of water of a neutral alkali chloride composition (Kifua, 1987).

The low and medium intensity alteration zones were probably active during late glacial times, when the ridges of Svartsengisfell and Thorbjarnarfell were covered by water. At this time there probably existed a transient geothermal system caused by the heat in the pillow and hyaloclastite mounds superimposed on the regional geothermal system (Saemundsson, 1991, personal communication). Fluids travelled through fracture systems and the permeable parts of the pillow mounds, depositing opal and aragonite. In some places like Selhals, the fluids reached the surface, probably through fractures, forming hot springs that deposit either silica if the composition of the waters is alkaline, or aragonite if the water is of carbonate character.

As is mentioned before, the areas classified as highly altered seem to be indicative of fossil fumaroles, which were probably active in early post-glacial times when water levels were somewhat higher than the present. At Selhals the alteration is partly older than the H-29 lava. These zones are directly related to faults and fractures and an example can be seen in the north slopes of the Thorbjarnarfell mountain where the faults forming the large graben have high intensity alteration along the base of the mountain.

The present active geothermal manifestations occur as hot soils and steaming ground in an area surrounding wells no. 2, 3 and 10. Soil temperature measurements were taken in different locations of the active manifestations, giving temperatures in the range of 30-100°C at 0.5 m depth. There seem to be two 'hot spots', one on the east side of the main road to Grindavik, where the temperatures are found to be between 77-99°C, and the other spot next to well No. 10, where temperatures at 0.1 m depth are found to be in the range of 95-100°C. This area was active before exploitation of the geothermal field began, but dissappeared as it began to be exploited. Now a larger area is active again, increasing in size with time. The resurgence of the manifestations has been related to the drawdown experienced in the geothermal reservoir, which has in turn produced a steam cap around wells no. 2, 3 and 10 at about 200 m depth (Bjornsson and Steingrímsson, 1991). If the right geologic conditions exist so that pressure continues to build in the steam cap, a possibility exists that it will overcome the overlying lithostatic pressure and produce a phreatic explosion similar to those experienced in the Kawerau geothermal field in New Zealand (Cas and Wright, 1988).

4.5 Discussion

The objective of geologic mapping in a geothermal area is to evaluate its prospects for production in terms of heat source, dimensions and physical characteristics of the reservoir. In the Svartsengi area, mapping of the geology, geothermal manifestations and tectonic features has previously been done, the dimensions and physical characteristics of the reservoir have also been thoroughly studied and a good conceptual model of the geothermal field is continuously improved with new information obtained. The recent exercise in detailed mapping of the Svartsengi geothermal area has improved the geological map and has outlined the surface geothermal alteration, further improving the understanding of the geothermal system.

The mapping of the geology and tectonic features identified the geologic units present in the field and defined their contacts. Faults and fissures were identified and direction and size of displacements were noted. Eruptive sites and lavas of two age groups were identified and described. The age gap indicated by the two age groups of postglacial volcanics is supporting evidence for alternating periods of rifting and transform faulting reflected by dominant NE-SW faulting and by subordinate N-S faulting.

The alteration of the surface rocks indicates the extent of the geothermal field, identifying the outer limits and present active zone. The extent of the alteration demonstrates that the geothermal field was much more active and larger in size in the past. A zone of former fumarolic activity lies south and east of the present wellfield. It is bordered on the south by a zone of opal and aragonite deposits indicating an off flow during times of high groundwater stand (Franzson, 1990). The alteration also seems to be directly related to the tectonics, where faults and fissures probably serve as channels through which the geothermal fluids rise to the surface.

It is evident that the highest density of eruptive sites occurs within a narrow zone, approximately 1.8 km wide. Within this zone, there exists a restricted area of high intensity alteration 2 km (NE-SW), by 0.8 km (NW-SE). Other areas with both a high degree of alteration and significant eruptive activity are found approximately 3-7 km to the west and southwest (Eldborgir). The high degree of eruptive activity might be a corollary of high intensity of intrusions found at depth between 800-1600 m (Franzson, 1990) and might also suggest that the heat source for the geothermal system could be related to the intrusives.

Freysteinn Sigurdsson (1986) indicates that, at shallow depths, high permeability zones are related to tectonic and/or geomorphological depressions that have been filled with scoriaceous lavas and dissected with fissure swarms. At deeper levels Franzson (1990) suggests that aquifers are connected to the boundaries of accumulative units, meaning the scoriaceous parts at the top and bottom of lava flows, in the upper 800-900 m of the geothermal field, and that at depths down to 1700 m the aquifers generally relate to intrusive rocks. Bjornsson and Steingrimsson (1991) say that fluid flow in the reservoir is primarily related to a fracture network, but that most of the fluid mass and heat is stored within the rock matrix.

It is clear from what the above mentioned authors say, that the Svartsengi geothermal reservoir contains a high degree of primary and secondary permeability and as long as wells are drilled to a certain depth within the fissure zone, they will encounter geothermal fluids.

5. CONCLUSIONS

The geologic mapping done in the Nupafjall area revealed a long history of volcanic activity extending back to perhaps 400,000 years. It is very probable that the volcanic activity was related to the Hveragerdi central volcano and a fissure swarm in its vicinity. Several glaciation cycles were identified by using the stratigraphic relationships and from this, a general chronostratigraphic sequence was created. A high temperature geothermal system, probably related to the Hveragerdi central volcano, was active up until the Thurarhnukur hyaloclastite was formed (100,000-200,000 years ago), depositing calcite, chlorite and clay minerals in the cavities found in the pillow lava fragments and shield lava from unit 2. The next unit deposited was the Kviar lavas and these only contain calcite and clay minerals deposited in the vugs of the lava, suggesting that between the time of deposition of units 2 and 3, the geothermal system decreased in activity and size, leaving the Nupafjall area in the outer limits of the geothermal field.

The present geothermal systems in the area are the Hveragerdi high-temperature geothermal system and the Bakki low-temperature geothermal system. Both have an influence in the geothermal activity in the Nupar area, and help to produce waters with maximum temperatures up to 135°C that are used for space heating of individual farms and in fish-farming in the Olfus region.

The field work done in the Svartsengi area revealed an area of intense surface alteration, characteristic of fossil fumaroles, extending beyond the present well-field. This area suggests that the geothermal field was larger in the past and also indicates a direct connection between fractures and surface alteration.

The Svartsengisfell mountain was identified as a table mountain, correcting previous interpretations of it being a hyaloclastite ridge. Thorbjarnarfell is suggestive of a thick ice sheet covering the Reykjanes peninsula, since it is only composed of pillow lava and very minor breccia. The high intensity of eruptive activity in the Svartsengi area suggests the possibility that the heat source for the geothermal reservoir is located, at depth, to the southeast of the well-field, related to the concentration of crater rows around Selhals.

The tectonics of the Nupafjall area is characterized by faults and fractures with 3 different trends: N-S, NE-SW and NW-SE. The first two systems apparently are contemporaneous, while the third system might occur as a conjugate set to the main trends. Displacements were observed generally in N-S faults with a few NE-SW faults also having large (>1 m) displacements. The Svartsengi area is also characterized by tectonics similar to the Nupafjall area, except for NW-SE faults, which were not identified in the surface geologic mapping. Displacements were observed in both NE-SW and N-S fracture systems, with maximums of up to 40 m found in Thorbjarnarfell. With some exceptions caused by local features, there appear to be two fault systems active in the Reykjanes peninsula, one a N-S (0-20°) and, the second one, a NE-SW (30-40°) that are contemporaneous. The NE-SW fault system seems to be indicative of the spreading of the Mid-Atlantic ridge, reflected by the Hengill-Hromundartindur fissure swarm in the Nupafjall area, and the Grindavik fissure swarm in the Svartsengi area. The N-S fault system in the Nupafjall area can be explained by the left-lateral transform motion of the South Iceland Seismic Zone, which produces N-S striking faults. The same system in the Svartsengi area has been explained by Sigurdsson (1985) as being related to a micro-seismic zone (1-5 km depth) caused by the oblique trend of the plate boundary along the Reykjanes segment of the Mid-Atlantic ridge.
It is apparent that the NE-SW faults in the Reykjanes peninsula are related to magma tectonics, forming as magma is mobilized during rifting periods, in the various fissure swarms. The same does not apply for the N-S faults, which are connected to tectonic activity occuring in the South Iceland Seismic Zone and in the micro-seismic zone in the west Reykjanes peninsula at times when magma is not available.

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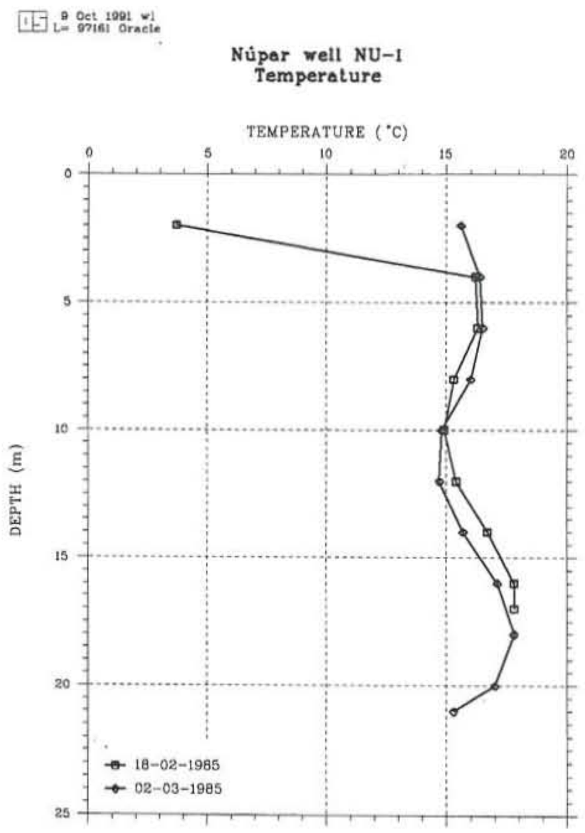
APPENDIX A:

Temperature logs of boreholes at Nupar and Bakki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Núpar well NU-1
Temperature
TEMPERATURE (°C)
DEPTH (m)
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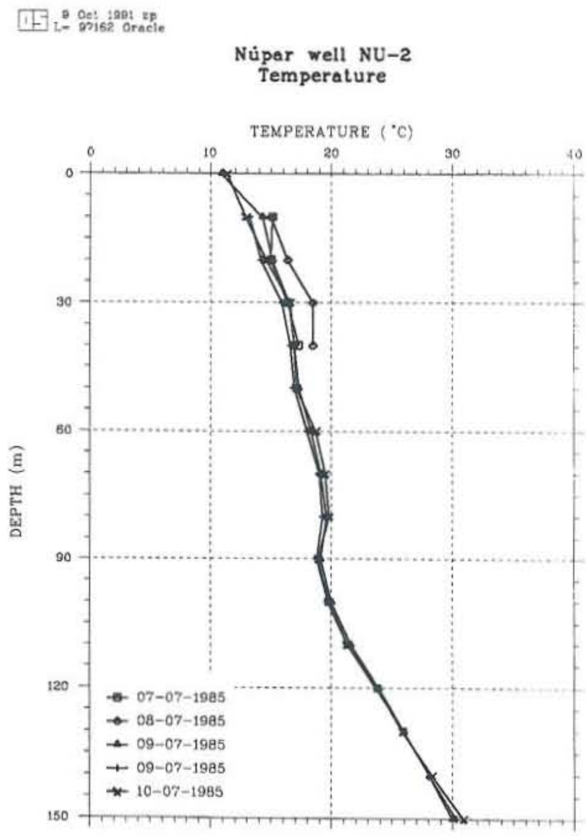
02-03-1985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Núpar well NU-2
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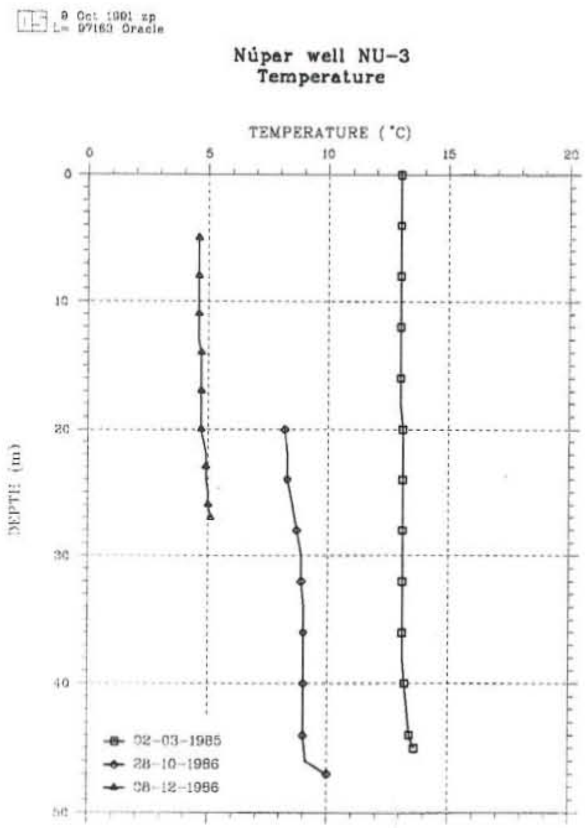
09-07-1985
10-07-1985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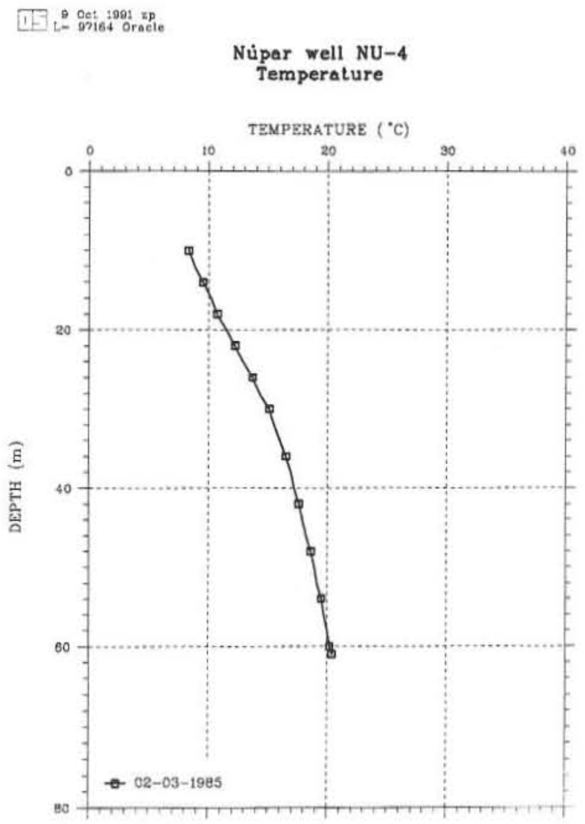
28-10-1986
08-12-1986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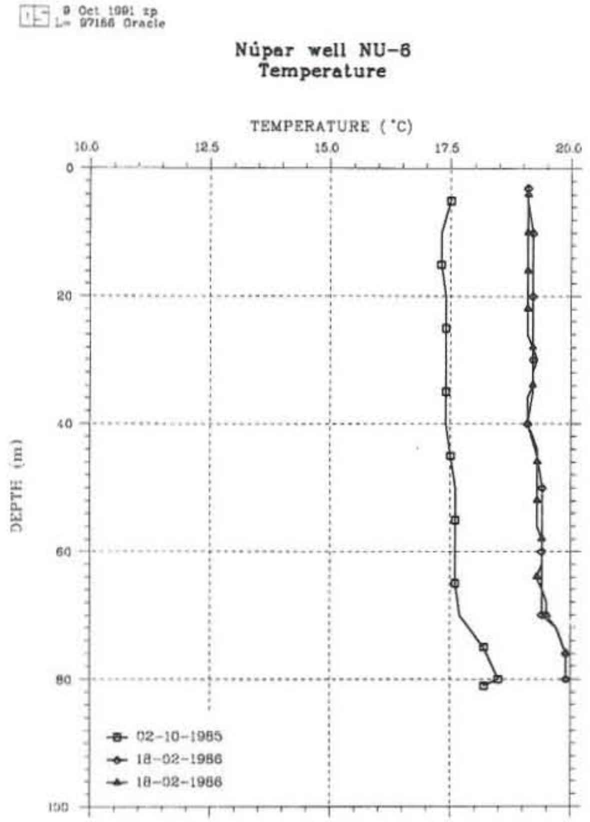
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DEPTH (m)
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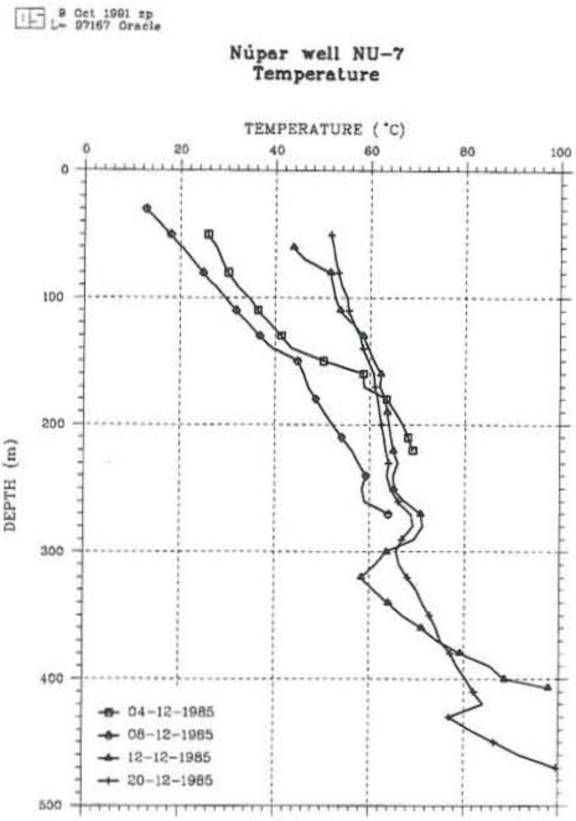
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Núpar well NU-7
Temperature
TEMPERATURE (°C)
DEPTH (m)
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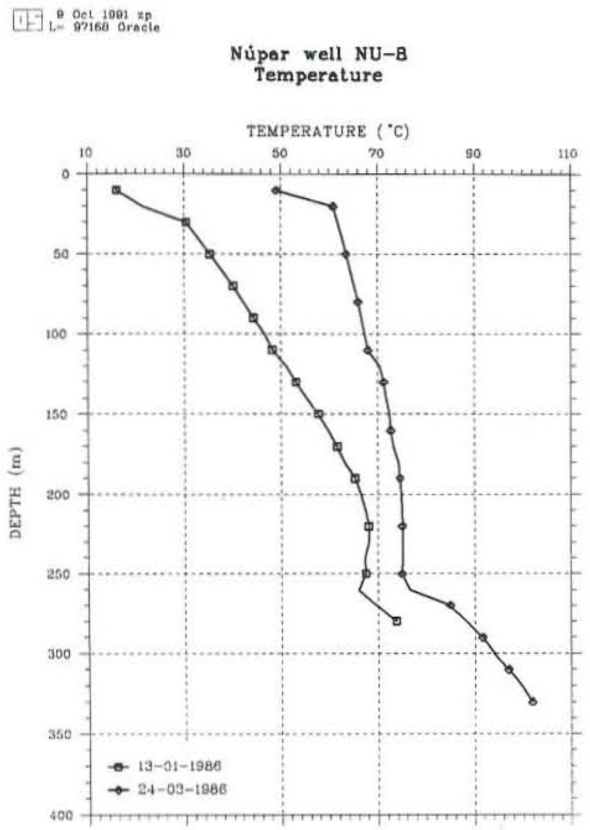
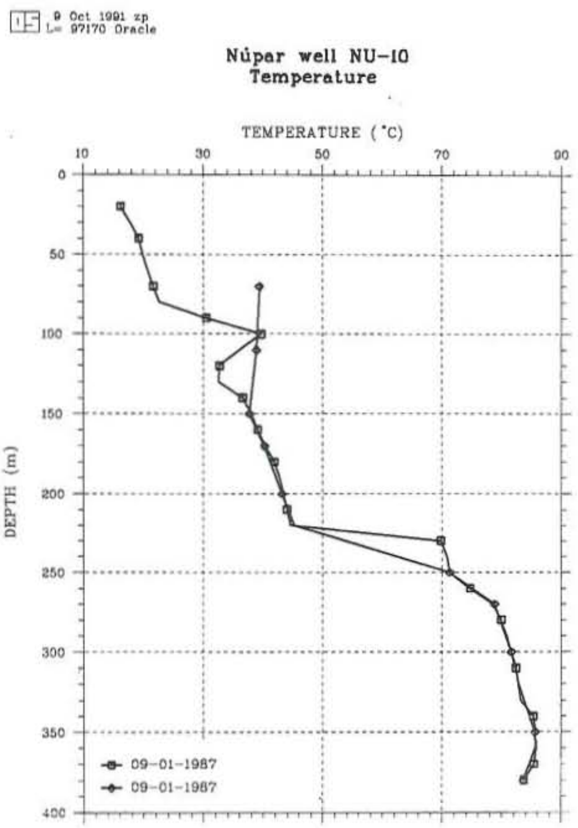
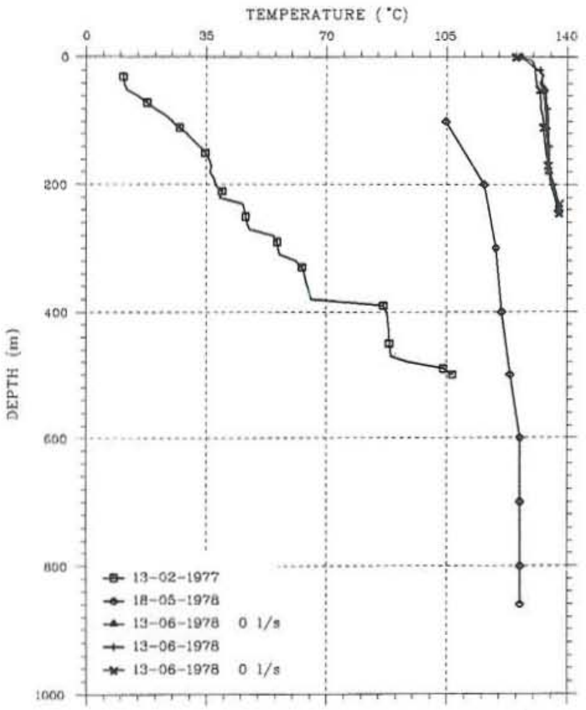
08-12-1985
12-12-1985
20-12-1985


9 Oct 1991 zp
L= 97168 Oracle
Núpar well NU-8
Temperature
TEMPERATURE (°C)
DEPTH (m)
13-01-1986
24-03-1986


9 Oct 1991 zp
L= 97170 Oracle
Núpar well NU-10
Temperature
TEMPERATURE (°C)
DEPTH (m)
09-01-1987
09-01-1987

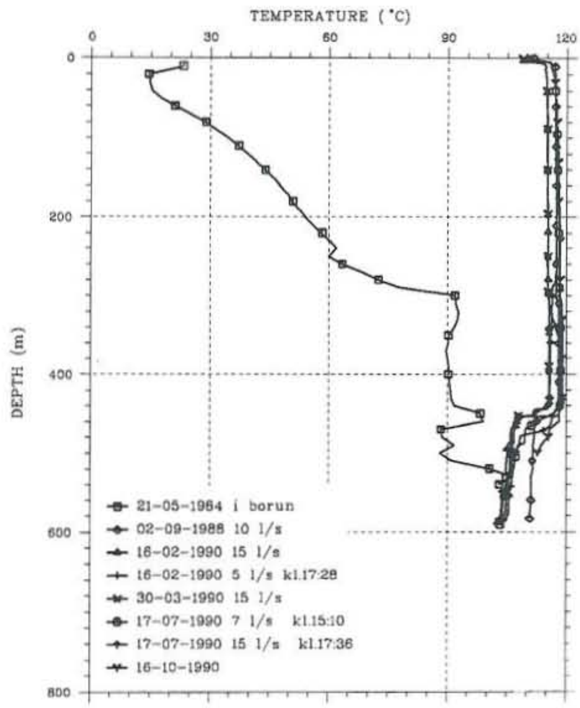
OS 9 Oct 1991 zp
L= 96681 Oracle

Bakki well BA-01
Temperature



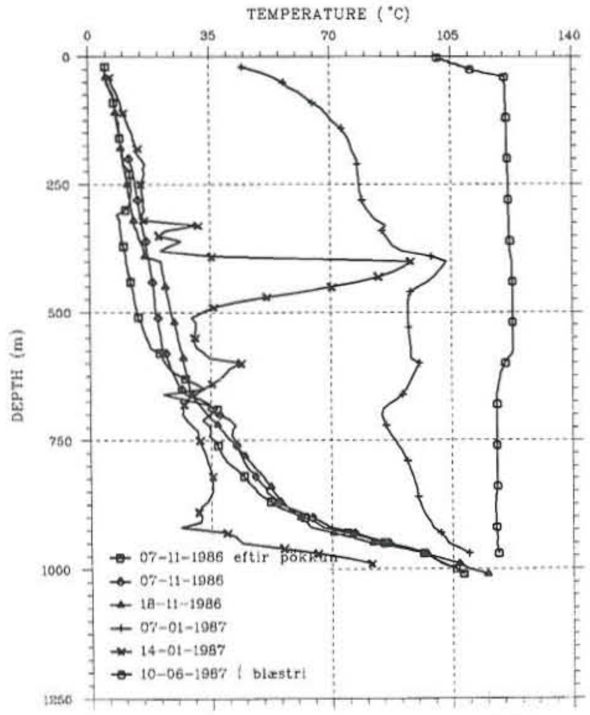
OS 10 Oct 1991 wl
L= 96811 Oracle

Hjallakrókur (Bakki) well HJ-01
Temperature



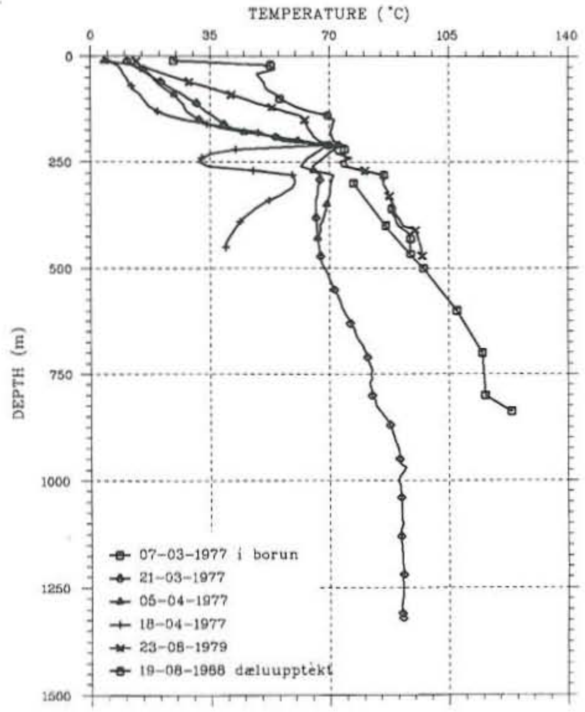
OS 10 Oct 1991 wl
L= 96701 Oracle

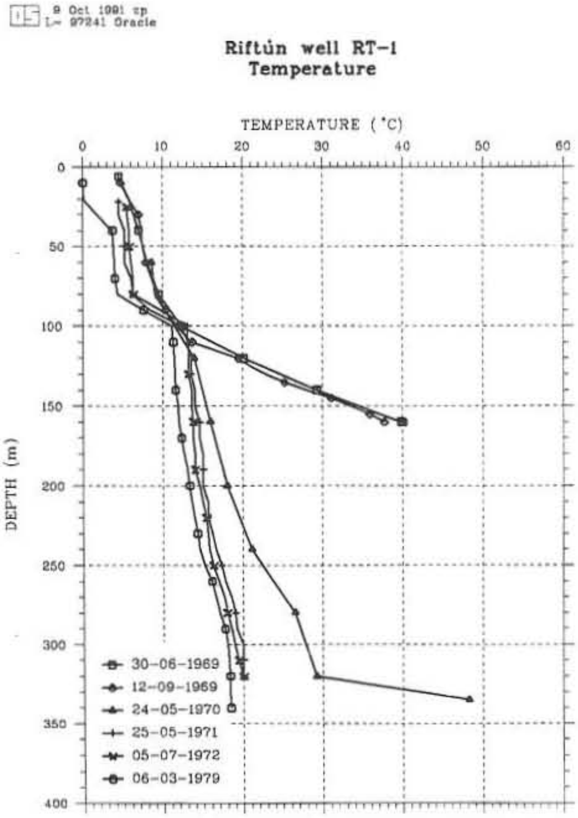
Eystri-Bakki well EB-01
Temperature

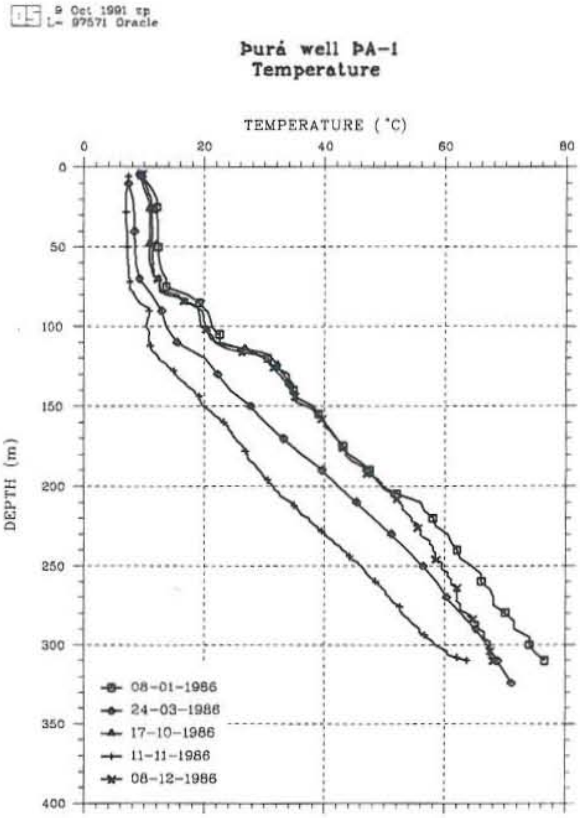


OS 9 Oct 1991 zp
L= 97541 Oracle

Þóroddsstaðir well ÞS-1
Temperature




9 Oct 1991 sp
L= 97241 Oracle
Riftún well RT-1
Temperature
TEMPERATURE (°C)
0
10
20
30
40
50
60
DEPTH (m)
0
50
100
150
200
250
300
350
400
30-06-1969
12-09-1969
24-05-1970
25-05-1971
05-07-1972
06-03-1979


9 Oct 1991 sp
L= 97571 Oracle
Þurá well ÞA-1
Temperature
TEMPERATURE (°C)
0
20
40
60
80
DEPTH (m)
0
50
100
150
200
250
300
350
400
08-01-1986
24-03-1986
17-10-1986
11-11-1986
08-12-1986