Geothermal Exploration of the Reykholt Thermal System in Borgarfjördur, West Iceland.

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ABSTRACT

The Reykholt thermal system covers an area of 250-300 km^2 in the valleys of the Upper Borgarfjördur region. The natural discharge is equivalent to about 400 l/s of boiling water. It is the largest low-temperature thermal system in Iceland. It comprises all the largest thermal fields in Borgarfjördur, incl. the Deildartunga-Kleppjárnsreykir, Hurdarbak-Sídumúli and Vellir fields. The highest base temperature is at the Reykholt-Kópareykir thermal field where it exceeds 140°C. The temperature decreases in all directions from the centre.

The thermal water is of meteoric origin and has fallen as precipitation on the Arnarvatnsheidi highlands. It percolates down to a depth of 1-3 km and is heated by regional heat flow. It flows laterally for about 50 km to southwest, driven by the hydrostatic gradient. The main aquifers appear to be permeable northeasterly faults and occasionally dykes. They are intersected in the lowlands by open northwesterly to northerly trending fractures which enable the hot water to flow to the surface.

INTRODUCTION

The Borgarfjördur thermal region in the valleys of Upper Borgarfjördur (Fig. 1) is the largest low temperature thermal region in Iceland; the second being the South Iceland thermal region (*Saemundsson and Fridleifsson* 1980). These two regions are adjacent to the Reykjanes-Langjökull axial rift zone bordering its western and eastern margin, respectively. The natural discharge of the hot springs in the Borgarfjördur region is estimated to be equivalent to about 450 l/s of boiling water.

The Borgarfjördur thermal region has been divided into five separate thermal systems mainly on the basis of the results of a resistivity survey and the chemistry of the thermal water (*Jóhannesson et al.* 1980, *Gunnlaugsson* 1980). These systems have been named after their centres: Reykholt, Baer, Brautartunga, England and Húsafell. Each system comprises a few to numerous thermal springs or spring clusters. The hot springs are often distributed along lines. One thermal field may include more than one line of hot springs. The Reykholt thermal system is by far the largest system in Borgarfjördur. It comprises many thermal fields along with numerous minor hot and warm springs.

The thermal activity in the Borgarfjördur region has in the past attracted the attention of many scientists, who have tried to explain its origin and relate the distribution of hot springs to tectonic structures. *Thoroddsen* (1891) was the first to map the hot springs in the Borgarfjördur region. He suggested that they were aligned along semicircular faults demarcating the Faxaflói bay depression.

Einarsson (1937) mapped the main geological features around the hot springs in Reykholtsdalur and suggested that the hot water ascended along dykes which acted as barriers to the regional flow of hot water through the basalt lava pile from the highlands in east. *Einarsson* (1942) proposed that the thermal water of the low temperature systems was of meteoric origin; precipitation which has fallen on the highlands. The water percolates deep into the bedrock where it is heated by regional heat flow, before it ascends to the surface. This model was later strongly supported by the deuterium studies of *Árnason* (1976).

Thorkelsson (1940) measured the radon content of the thermal waters in the Reykholtsdalur valley. The radon content increases from west to east culminating in the hot springs at Reykholt. He concluded that the Reykholt hot springs were close to the main upflow of hot water but the decreasing content of radon away from Reykholt could be explained by longer flow distances from the main upflow.

In the year 1964 a systematic mapping of the hot spring distribution and geology was initiated at the National Energy Authority (NEA). First the thermal manifestations and the main geological features were mapped and later geophysical and chemical studies were carried out (*Saemundsson et al.* 1966, *Sigvaldason* 1966)

Additional detailed geological mapping has been conducted almost continuously since 1971 under the supervision of Kristján Saemundsson at NEA, partly summarized by *Saemundsson and Noll* 1974, *Jóhannesson* 1975 and *Franzson* 1978. Geophysical and chemical studies have been carried out since 1975, both on a regional scale (*Gunnlaugsson* 1980, *Jóhannesson et al.* 1980) and detailed studies on individual thermal fields and systems (*Georgsson et al.* 1978, 1981a and 1981b, *Jóhannesson et al.* 1979). A considerable part of the data accumulated is still unpublished.

In this paper we present an overview of the Reykholt thermal system based on both the results of regional studies and detailed studies of individual thermal fields.

THE GEOLOGY OF THE BORGARFJÖRDUR REGION

The basement of the Borgarfjördur region consists of Late Tertiary basaltic lava flows. The axis of the Borgarnes anticline (*Saemundsson* 1977) runs NE-SW and marks the western margin of geothermal manifestations (Fig. 1). East of the anticline axis the lavas dip 6-10°SE, towards the active Reykjanes-Langjökull rift zone. The anticline axis plunges towards the northeast and disappears underneath the Hredavatn unconformity north of lake Hredavatn. The Hredavatn unconformity represents a major gap in the lava succession. The flows below the unconformity are believed to be as old as 13 million years and have been extruded within the former Snaefellsnes rift zone (*Jóhannesson* 1980). These older lavas were tilted and denuded before being covered by the Hredavatn sediments which subsequently were covered by younger lava flows extruded within the Reykjanes-Langjökull rift zone. The oldest flows above the Hredavatn sediments have been dated 6.5-7.0 m.y. old (*McDougall et al.* 1977). The flows become gradually younger on approaching the rift zone.

There is a great variety of faults and joints in the Borgarfjördur region. *Jóhannesson* (1980) suggested that they are of two different origins. Firstly are NE-SW trending fault swarms corresponding to the fissure swarms of the active rift zone which are believed to have formed by crustal tension inside the rift zone. The fault swarms are accompanied by dyke swarms. Secondly, there are faults formed in a stress field characterized by lateral shear forces. They belong to the Snaefellsnes Fracture Zone which stretches from the Snaefellsnes peninsula in the west to the Borgarfjördur region in the east. The faults of the fracture zone can be divided into 3 groups, based on their trend and age: NW-SE, N-S and NE-SW. The fracture zone was active at about 8-13 m.y. ago, but minor movements have continued up to Postglacial times. The dykes and faults are usually subvertical and those oriented parallel to the strike of the lavas usually transect the lavas at right angles.

THE DISTRIBUTION OF HOT SPRINGS

The Reykholt thermal system comprises the following major thermal fields: Klettur-Runnar, Deildartunga-Kleppjárnsreykir, Hurdarbak-Sídumúli, Vellir (including Sturlu-Reykir), Sudda, Reykholt-Kópareykir, Haegindi, Nordurreykir-Háafell, Úlfsstadir, Stóriás, Brúarreykir, Lundar and Helgavatn. The total natural discharge has been measured to be about 425 l/s, with thermal output equivalent to about 400 l/s of boiling water.

The total natural discharge of all low tempera-

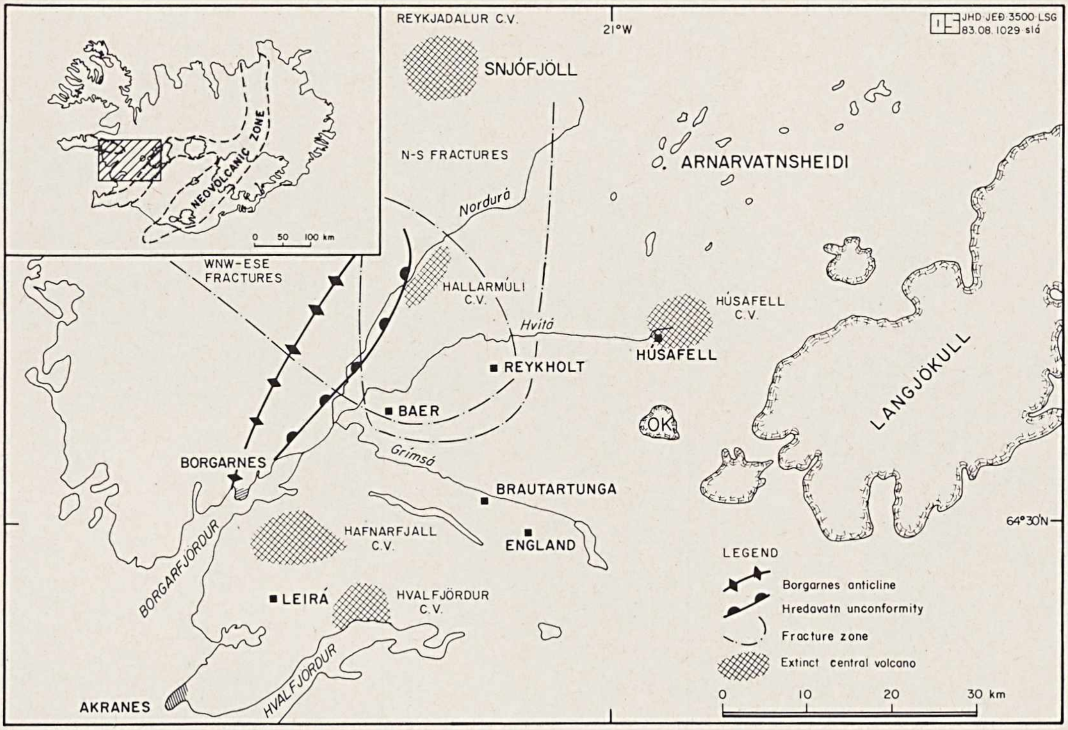

Figure 1. The Borgarfjördur region and its main tectonic features.
1. mynd. Yfirlitskort af Borgarfirði. Sýnd eru brotakerfi, megineldstöðvar, Hreðavatnsmislægið og ás Borgarnesandhverfunnar.

ture hot springs in Iceland has been estimated about 1825 l/s with a weighted average temperature of 67°C *(Gudmundsson and Pálmason* 1981). With 23% of the total discharge and 33% of the total thermal output, the Reykholt thermal system is the largest low temperature thermal system in Iceland.

Fig. 2 shows the distribution of hot springs of the Upper Borgarfjördur region. It also indicates the temperature and discharge of the hot springs. The three largest thermal fields are the Deildartunga-Kleppjárnsreykir field with the discharge 253 l/s, whereof 180 l/s belong to the Deildartunga hot spring and 70 l/s to the Kleppjárnsreykir hot spring *(Georgsson et al.* 1978), and the Hurdarbak-Sídumúli and Vellir fields with 45 l/s and 32 l/s, respectively.

CHEMISTRY OF THE THERMAL WATER

In Borgarfjördur four thermal systems can be distinguished on the basis of chemistry and the fifth has been proposed from the geographical distribution of hot springs. Within each system the concentration of each element shows fairly regular distribution. Three thermal systems are adjacent to the Reykholt thermal system. The Baer system, to the west, can be distinguished from the Reykholt system by slightly different chemistry (higher salinity) and higher Cl/B ratio. The Húsafell system, to the east, has different chemical composition due to flow through acid rock, associated with the extinct Húsafell central volcano, and a different deuterium content. The Brautartunga system, to the south, has a similar chemical composition and deuterium content as the Reykholt system but is separated from it geographically. The fifth thermal system is the

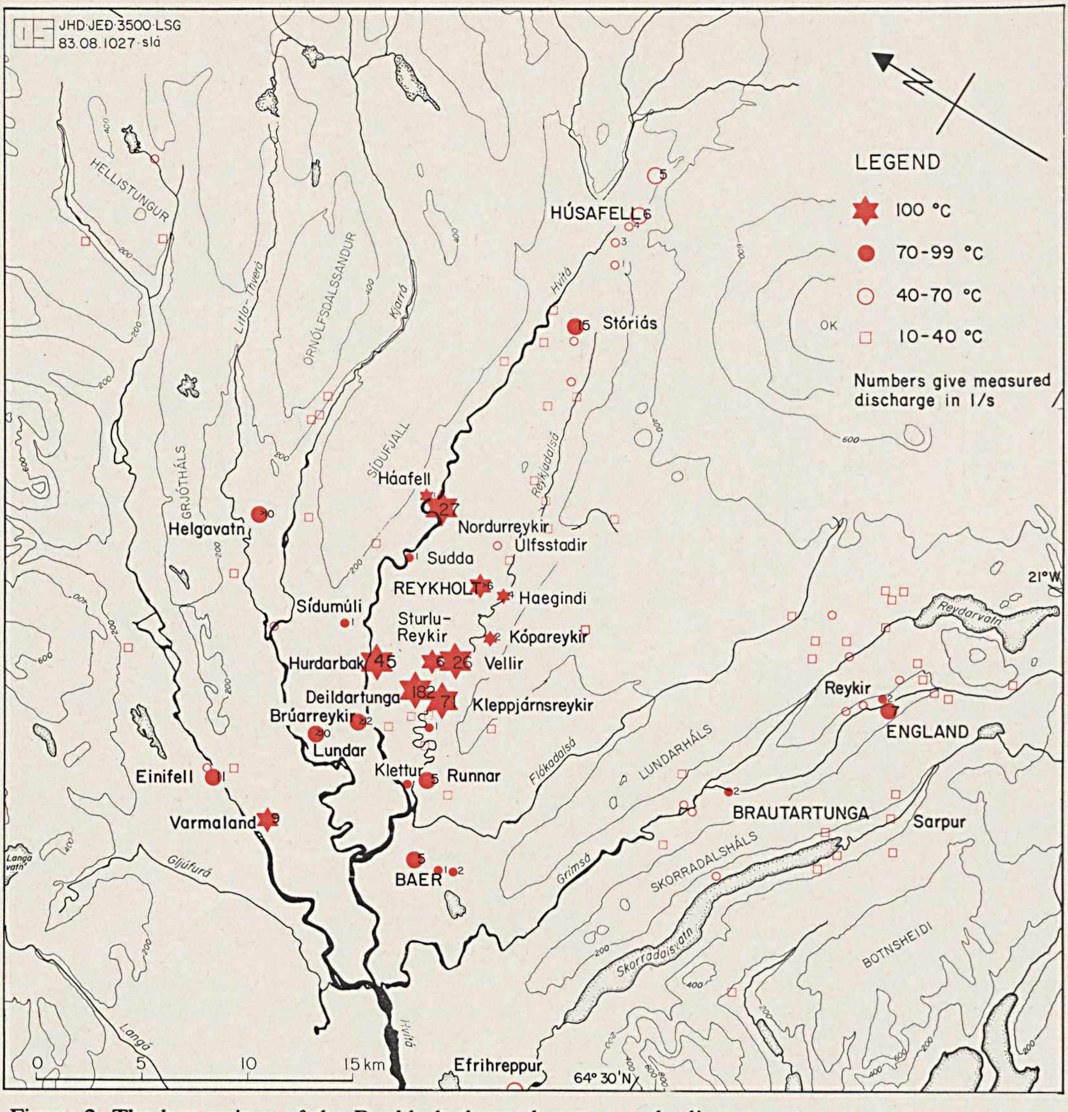

Figure 2. The hot springs of the Reykholt thermal system and adjacent systems.
2. mynd. Hverir og laugar í ofanverðum Borgarfirði.

England system east of the Brautartunga system in the upper Lundarreykjadalur valley. It is distinguished from the Brautartunga system by a different deuterium content and the distribution of temperature dependent elements.

Fig. 3 shows the base temperature distribution of the hot springs in Borgarfjördur based on silica content of the waters. The largest thermal centre belongs to the Reykholt thermal system. Highest base temperature is at the Reykholt-Kópareykir thermal field where it exceeds 140°C but decreases in all directions. The chemical composition of water from some of the major hot springs belonging to the Reykholt system is listed in Table 1. The first six columns are analyses of thermal waters from the Reykholt thermal system but the last four columns refer to the other thermal systems in Borgarfjördur.

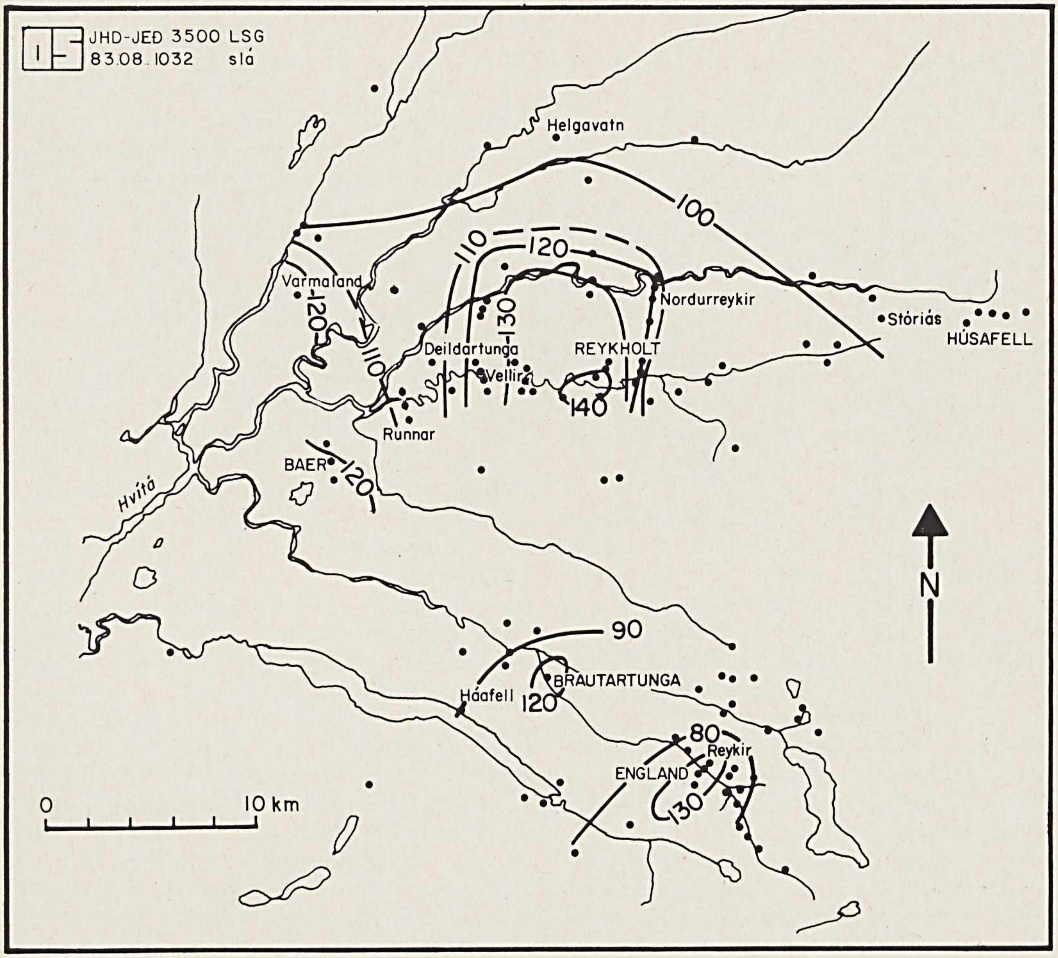

Figure 3. The base temperature distribution (°C) of the Reykholt thermal system and adjacent areas, based on the silica content of the waters.
3. mynd. Dreifing kísilhita (°C) í Borgarfirði.

Arnórsson et al. (1983) showed that major element chemistry of Icelandic geothermal waters at equilibrium is fixed by two parameters, temperature and the concentration of chloride. As a result undissociated weak acids (H_2SiO_4, H_2CO_3, H_2S, H_2SO_4, HF) and the cation/proton ratios (Na^+/H^+, K^+/H^+, Ca^{++}/H^+, Mg^{++}/H^+) only depend on temperature. The chloride content of water from the Reykholt thermal system is almost constant. Detailed study of the major element composition of the waters shows overall equilibrium conditions between water and minerals at the calculated chalcedony equilibrium temperature, assuming 20% steam loss for boiling hot springs.

According to *Árnason* (1976) the deuterium content of the water of the Reykholt thermal system is almost constant with the mean δ_D-value being -74‰, similar to the deuterium content of precipitation in areas west and northwest of the glacier Langjökull. Similar deuterium values are recorded for the Brautartunga and the Baer systems. The England system has slightly lower values, -77‰, and the Húsafell system still lower, -91‰, indicating that that the origin of the thermal water is further inland.

THE RESISTIVITY SURVEY

The bulk resistivity of Quaternary and Tertiary rocks in Iceland is practically independent of the salinity and the temperature of the pore fluid as long as the conductivity of the fluid does not exceed approx. 0.2 1/Ωm *(Flóvenz* 1980). Resistivity variations in the uppermost kilometre of the crust do therefore primarily reflect variations in the amount of interconnected pores and fractures of the rock *(Flóvenz and Georgsson* 1982, 1983). Consequently a regional resistivity survey can be used to estimate the size of geothermal systems and to map the flow pattern of thermal waters from its origin in the highlands to the geothermal areas in the lowlands. The regional resistivity survey in the Borgarfjördur region was initiated on this basis.

The survey consisted of Schlumberger soundings with a maximum current arm (AB/2) of 1500 m, except in the highlands, where most of the soundings were extended to about 2200 m to get information about resistivity at deeper levels. About 100 soundings have been carried out so far. These soundings cover all thermal systems in the the valleys of Borgarfjördur and extend also into the highlands. The soundings were interpreted one-dimensionally with a computer program of *Johansen* (1977), based on an inverse interpretation of the data curves.

Fig. 4 shows the resistivity at 600 m depth below sea level for the Upper Borgarfjördur region, but the picture is similar down to at least 1000 m, except for the Baer thermal system. The largest low-resistivity anomaly coincides with the Reykholt thermal system. The 30 Ωm resistivity contour seems to define its boundaries. It includes all major thermal fields in Reykholtsdalur and the neighbourhood except the Stóriás field, covering an area of 250-300 km^2. The area of most intense geothermal activity is within the 20 Ωm contour. The shape of the anomaly indicates two centres of thermal activity in Reykholtsdalur, the Reykholt-Kópareykir thermal field whose main feature is the high geothermometer temperatures, and the Deildartunga-Kleppjárnsreykir thermal field, which is characterized by enormous natural discharge. Even though it must be assumed that the main flow of thermal waters from the highlands towards Reykholtsdalur is at deeper levels, the elongated shape of the anomaly suggests that it is from northeast, thus indicating a recharge area in the Arnarvatnsheidi region.

The large low-resistivity anomaly which stretches from the Upper Nordurárdalur valley south towards Varmaland with resistivity values below 20 Ωm, is associated with the Baer thermal system. The shape points towards Snjófjöll as a probable recharge area. The boundaries between the Reykholt and Baer thermal fields are diffuse, but soundings within the Baer thermal system differ by showing higher resistivity at deeper levels, indicating decreasing fracture porosity with depth.

No boundaries are observed between the Reykholt and Brautartunga thermal systems in the outer part of Lundarreykjadalur. The low-resistivity anomaly in the inner part of Lundarreykjadalur is associated with the England thermal system.

The boundaries between the Reykholt and Húsafell thermal systems are well defined but no low-resistivity anomaly is associated with the latter. The high resistivity values in the Húsafell region relate to intrusive rocks associated with the extinct Húsafell central volcano.

DISCUSSION

The geothermal activity in the Reykholt system is confined to a Late Tertiary lava pile of low primary porosity which is to be contrasted with the other major low temperature systems in South and Southwest Iceland, which are in Quaternary rocks with far higher primary porosity.

A detailed study has been carried out at many of the major thermal fields of the Reykholt thermal system. These include the Deildartunga-Kleppjárnsreykir and the Klettur-Runnar fields *(Georgsson et al.* 1978), the Vellir thermal field *(Georgsson et al.* in prep.), and the Hurdarbak field *(Georgsson and Haraldsson* in prep.). Similar study has also been carried out at thermal fields of the Baer system *(Georgsson et al.* 1981a and b, *Jóhannesson et al.* 1979) and the Brautartunga system *(Flores* 1981). The hot springs of the major thermal fields in Borgarfjördur are aligned along young fractures with northwesterly or northerly trend (Fig. 5). Most of the major hot springs are found at the intersection between these fractures and northeasterly trending faults and dykes. The resistivity survey suggests that the

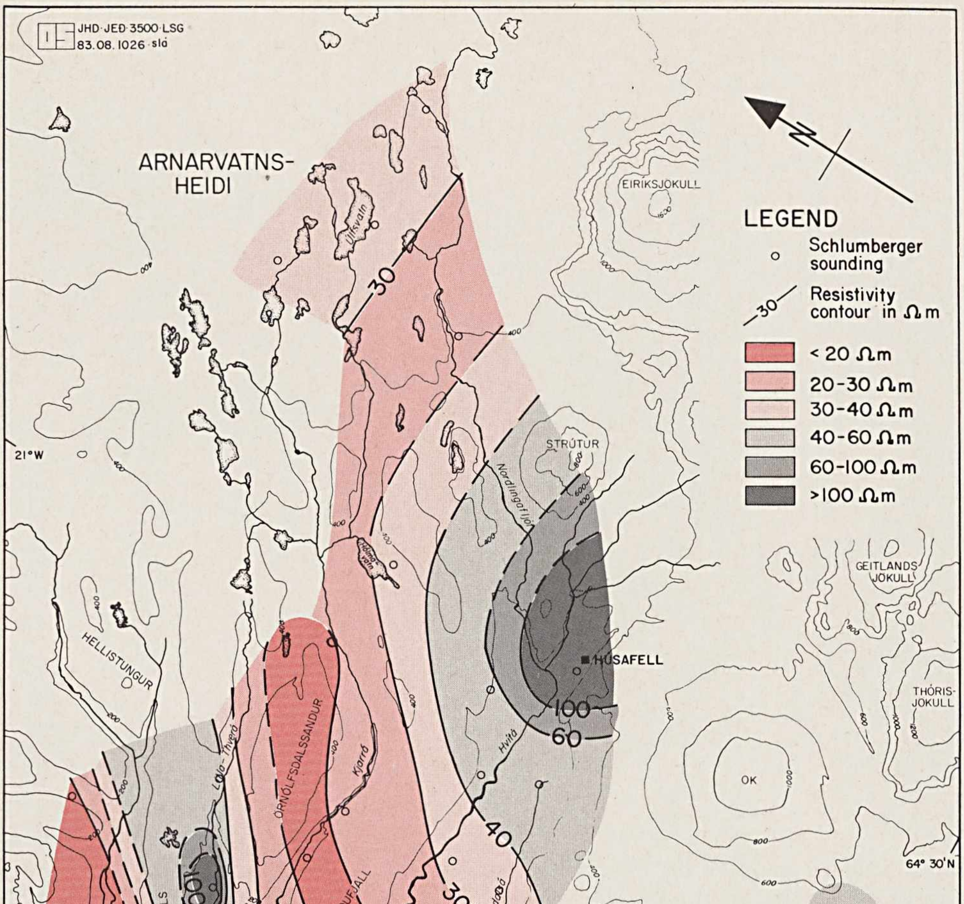

Figure 4. The resistivity of the upper Borgarfjördur region at a depth of 600 m below sea level.

4. mynd. Kort af eðlisviðnámi bergs í ofanverðum Borgarfirði á 600 m dýpi undir sjávarmáli.

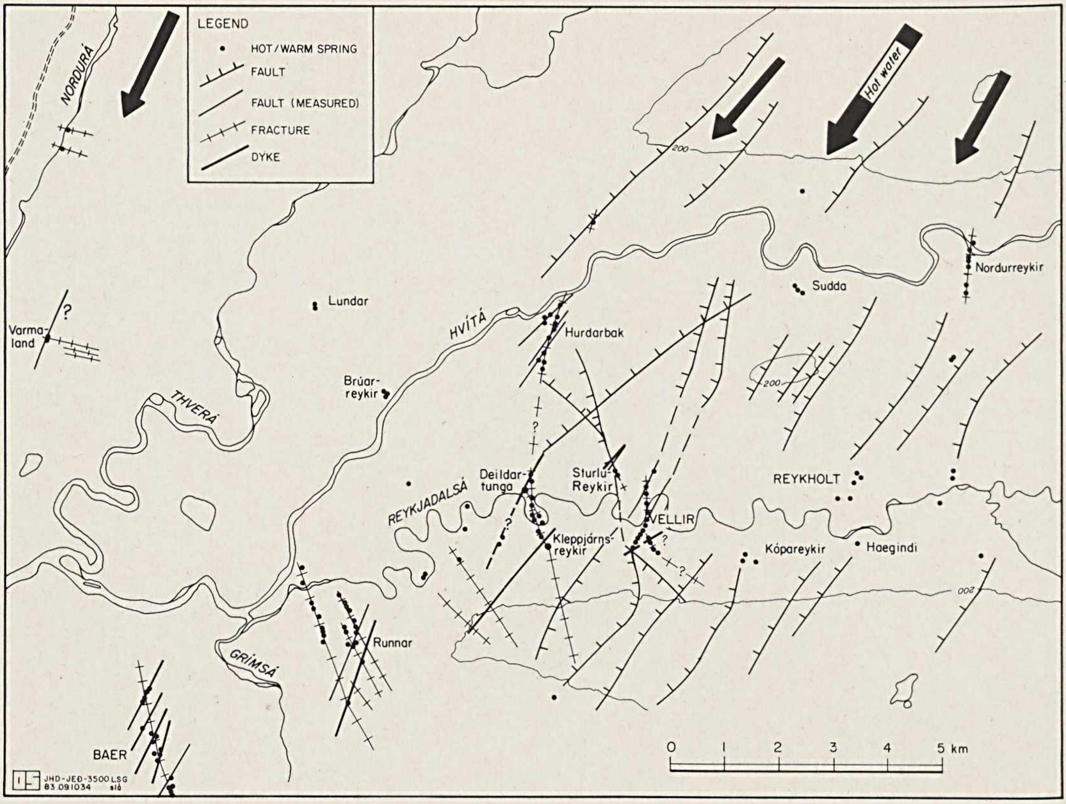

Figure 5. The tectonic features of the Reykholt thermal system.
5. mynd. Höggun og hverir í Reykholtsdal og nágrenni.

northeasterly trending faults operate as main channels for regional flow from the highlands towards the thermal fields. Where these aquifers are intersected in the lowlands by open fractures the water flows to the surface.

The best example is the Deildartunga hot spring *(Georgsson et al.* 1978). The spring is located at the intersection of a fracture trending N20°W and a dyke trending N30°E (Fig. 5). The dyke was traced up to the hills by a ground magnetic survey, showing a combined anomaly of a dyke and a fault. About 1 km northwards the anomaly from the dyke disappeared. The fault was traced further north where it is exposed at the surface.

The close relation between active faults and the flow of hot water was emphasized in the Borgarfjördur earthquakes in 1974. The active seismic zone was 15-20 km north of Reykholtsdalur. The main epicentral zone showed a westerly trend, but was intersected by a secondary zone with a northeasterly trend *(Einarsson et al.* 1977). The latter coincides with the northern part of the 20 Ωm low resistivity anomaly of the Reykholt thermal system. The Deildartunga fault stretches to northeast towards the same area. The effect of the earthquakes on thermal activity was most notable at Helgavatn. The thermal water disappeared for three weeks, reappearing with substantially increased discharge and slightly higher temperature. Increased discharge was also noted at the Lundahver hot spring, and at Varmaland flow measurements indicate an increase of around 50%. In numerous springs the water turned milky, gradually returning to normal in a few weeks time.

The active tectonics play an important role in the existence of the Reykholt thermal system.

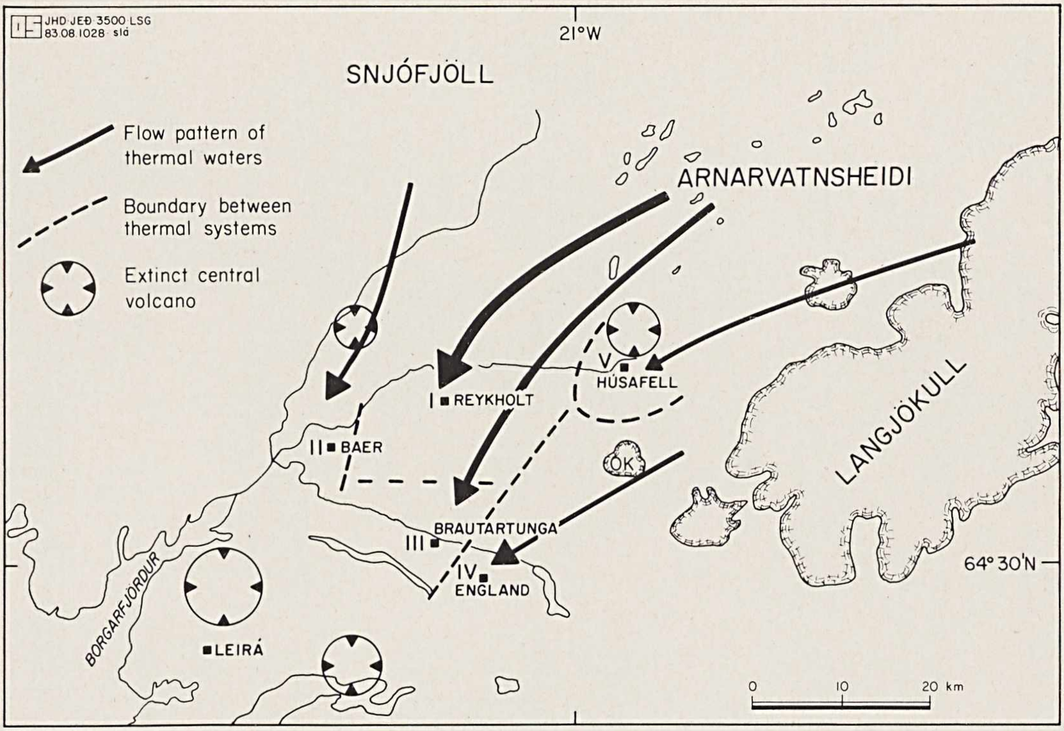

Figure 6. The Borgarfjördur thermal systems.
6. mynd. Jarðhitakerfi í Borgarfirði, myndin sýnir líklegar rennslisleiðir jarðhitavatnsins og skilin milli jarðhitakerfa.

Not only do the northeasterly faults serve as the main flow channels for the system and the fractures open the way for the water to the surface but the associated seismicity of the area keeps them open, as it counteracts low temperature zeolitization or sealing which otherwise would gradually fill the channels.

The flow pattern of the thermal waters of the five thermal systems of the Upper Borgarfjördur region and their recharge areas (Fig. 6) can be inferred from the combined results of the geological studies and the regional resistivity survey, in addition to the deuterium measurements by *Árnason* (1976). The Arnarvatnsheidi region is the probable recharge area for the Reykholt thermal system. There numerous active northeasterly and easterly faults *(Saemundsson* 1967) form favourable geological conditions for percolation of meteoric water. This is best demonstrated in the easterly trending Urdhaedir-fault, where open fissures are observed for several km. The water reaches 1-3 km depth and driven by the hydrostatic gradient, it flows laterally for about 50 km towards the lowlands in southwest.

By using natural discharge and a mean base temperature of 125°C, the thermal power of the Reykholt system can be estimated about 210 MW. No thermal gradient holes have been drilled in the region, but according to *Pálmason et al.* (1979) the regional thermal gradient can be expected to be 100-150°C/km. Using 125°C/km as an estimate and a thermal conductivity of 1.7 W/m°C *(Pálmason et al.* 1979) the energy dissipation corresponds to a total conduction heat flow of an area of 1000 km^2. However, total thermal drainage is impossible to accomplish. Thus it can be assumed, that the Reykholt thermal system needs a recharge area that is at least twice that size.

It is of interest to compare these results with calculations based on time-dependent heat sources. *Bödvarsson* (1982) calculated the energy balance of the Reykholt thermal system based on

TABLE 1: Chemical composition (in mg/l) of major elements in thermal water from the Reykholt thermal system and other thermal systems in Borgarfjördur.

TAFLA 1: Efnagreiningar á jarðhitavatni (í mg/l) frá Reykholtsjarðhitakerfinu og öðrum jarðhitakerfum í Borgarfirði.

	Runnar	Deildar-tunguhver	Vellir	Sudda	Reykholt/ Skrifla	Kópareykir	Baer/ well 3	Húsafell	Brautar-tunga	Reykir í Lundar-reykjadal
	1)	2)	1)	1)	2)	1)	2)	2)	1)	1)
°C	92	100	100	70	100	100	100	56	86.5	76
pH/°C	9.49/25	9.20/20	9.48/17	9.29/21	9.15/20	9.12/25	8.92/20	8.81/20	9.32/22	9.29/22
SiO_2	116.0	127.6	166.5	178.0	188.2	191.0	112.2	64.4	152.5	163.5
B		0.26			0.34		0.20	0.38		
Na	77.0	71.7	81.0	78.9	79.7	80.8	105.7	68.5	84.3	76.9
K	2.0	2.54	2.8	2.7	4.32	4.0	3.74	1.67	3.2	2.0
Ca	3.3	3.10	2.9	2.3	2.22	2.2	10.7	5.12	3.4	2.4
Mg	0.01	0.06	0.09	0.05	0.01	0.01	0.05	0.12	0.03	0.01
CO_2	22.2	22.8	29.9	35.6	27.2	36.9	11.2	25.7	32.2	40.0
SO_4	58.0	56.2	57.2	62.7	63.9	59.1	71.4	61.9	83.8	59.7
H_2S	0.2	0.53	1.84	0.24	1.09	3.98	0.14	0.19	0.44	0.41
Cl	49.6	36.0	33.4	28.2	35.1	36.0	109.9	25.5	43.4	18.4
F	2.26	2.59	3.22	2.57	2.49	4.43	2.06	12.0	2.24	1.17
Diss. solids	350.0	390.0	388.0	383.0	456.0	427.0	476.0	312.0	391.0	332.5
δ_D (‰) 3)	-73.8	-72.4	-72.8		-74.3	-75.0	-75.0	-91.3	-73.0	-78.4
T_{chd} (°C)	99	115	130	133	140	142	111	81	122	127

1) *Gunnlaugsson* (1980). 2) *Arnórsson et al.* (1983). 3)*Árnason* (1976).

the hypothesis that hydrothermal circulation must be severely curtailed during periods of glaciation because of a limited ground water recharge. He suggests that the rock/water heat transfer processes supplying the low-temperature thermal activity in Iceland today are not a steady state phenomenon, but of a transient nature, dating back to the end of the last glaciation about 10,000 years ago. His calculations for various transient heat transfer models lead to a recharge area which is an order of magnitude smaller than the above value.

ACKNOWLEDGEMENTS

This work was financed by the Geothermal Division of the National Energy Authority. We wish to express our thanks to Kristján Saemundsson and Ólafur G. Flóvenz for reading and improving an early version of the manuscript.

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ÁGRIP

REYKHOLTSJARÐHITAKERFIÐ Í BORGARFIRÐI.

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Öflugasta lághitasvæði á Íslandi er í ofanverðum Borgarfirði (1. mynd) og jafngildir náttúrlegt rennsli um 450 l/s af sjóðandi vatni. Á grundvelli viðnámsmælinga og efnasamsetningar heita vatnsins má skipta jarðhitanum í fimm aðskilin jarðhitakerfi. Þau eru kennd við Reykholt, Bæ, Brautartungu, England og Húsafell. Hvert kerfi samanstendur af nokkrum hvera- eða laugasvæðum. Innan hvers svæðis liggja hverir og laugar gjarnan á línum. Í þessari grein er gefið yfirlit yfir rannsóknir undanfarinna ára á Reykholtskerfinu.

Reykholtskerfið er langstærsta jarðhitakerfið í Borgarfirði og reyndar einnig á Íslandi og gefur af sér 425 l/s af vatni með varmagildi sem samsvarar um 400 l/s af sjóðandi vatni. Innan þess eru öll stærstu hverasvæðin í Borgarfirði, svo sem Deildartunga-Kleppjárnsreykir, Hurðarbak-Síðumúli, Vellir (ásamt Sturlu-Reykjum), Reykholt-Kópareykir og Norðurreykir-Háafell (2. og 5. mynd).

Efnasamsetning heita vatnsins gefur til kynna að miðja kerfisins sé hverasvæðið sem kennt er við Reykholt og Kópareyki. Þar er hiti í djúpkerfi talinn a.m.k. 140°C en lækkar út frá því (3. mynd).

Viðnámsmælingar (4. mynd) sýna mjög stórt lágviðnámssvæði, 250-300 km^2, sem nær yfir mestan hluta Reykholtsdals og teygir sig þaðan í norðaustur í átt að Arnarvatnsheiði.

Í greininni eru leiddar líkur að því, að niðurstreymissvæðið sé á Arnarvatnsheiði og kemur það heim við tvívetnisstyrk vatnsins. Þar hripar regnvatn niður eftir sprungum og hitnar af snertingu við heitt berg. Síðan streymir vatnið til suðvesturs niður á láglendi Borgarfjarðardala, líklega að mestu eftir misgengjum og göngum. Þar skera opnar norðlægar eða norðvestlægar sprungur vatnsleiðarana, og heita vatnið á greiða leið til yfirborðs (5. og 6. mynd).