National Energy Authority
Reykjavík, Iceland

OSJHD 7530

A HYDROLOGICAL MODEL FOR THE FLOW OF THERMAL WATER IN SW-ICELAND WITH A SPECIAL REFERENCE TO THE REYKIR AND REYKJAVÍK THERMAL AREAS.

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Second United Nations Symposium on the Development
and Use of Teothermal Resources, San Francisco,
U.S.A., May 20-29 1975.

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ABSTRACT

Characteristically the temperature of thermal water in Quaternary rocks west of the volcanic zone (V.Z.) in SW-Iceland increases with distance from the V.Z., which is reciprocal to the trend of the regional heat flow, and most likely caused by a decrease in rock porosity away from the V.Z.

A comparison of a regional D/H ratio map of rain and the D/H ratio of thermal water from several springs and wells outside and from the Reykir and Reykjavik thermal fields suggests that the thermal water (100-140^{o}C) in the oldest rocks may be precipitated as rain in the interior highlands, whereas that (80^{o}C) in the younger rocks may be precipitated nearby in the V.Z.

The thermal areas in question are in Quaternary volcanics characterised by thick successions of low porosity lavas intercalated by high porosity subglacial volcanics, which form tens of km long, 1-5 km broad, and sometimes hundreds of m thick ridges within the strata parallel to the V.Z. We suggest that these high porosity volcanics may serve as channels along which water may flow at depth from the highland areas towards the coast.

A regional electrical resistivity survey (to 1500 m depth) supports a picture derived from the geological and hydrological data, wherein close to and within the V.Z. there may be a large scale circulation system of local water, but in the older rocks the water may flow long distances parallel to the V.Z. Evidence is given for mixing within a thermal system of water derived from the two recharge areas.

INTRODUCTION

Due to the islands location on a constructive plate boundary (the Mid-Atlantic Ridge) the regional heat flow is very high in Iceland (Palmason, 1973) compared to most parts of the world. Hydrothermal activity is widespread in the country (e.g. Bodvarsson, 1961). The thermal areas are divided into two categories on the basis of the maximum temperature (base temperature) in the uppermost 1 km. The base temperature is thus higher than 200°C in the high temperature areas, but lower than 150°C in the low temperature areas.

The high temperature areas are confined to, or on the margins of, the active zones of rifting and volcanism that run through the country (e.g. Palmason and Saemundsson, 1974), and the heat source to each high temperature area is thought to be a local accumulation of igneous intrusions cooling at a shallow level in the crust. The low temperature areas are, on the other hand, in Quaternary and Tertiary volcanics, and are thought to draw heat from the regional heat flow.

The present contribution deals with low temperature hydrothermal activity in early Quaternary rocks west of the active volcanic zone in SW-Iceland.

GEOLOGICAL FEATURES

The active volcanic zone in SW-Iceland is flanked symmetrically by Quaternary volcanics which in turn are flanked by Tertiary volcanics. The strata, which dips towards the volcanic zone, reflects continuous volcanic activity and crustal spreading in this part of the country during at least the last 7 M.y. (Fridleifsson, 1973; Saemundsson and Noll, 1975; Johannesson, 1975).

During the last 3 M.y. there have been over twenty major glaciations in Iceland. The Quaternary stratigraphic succession is, therefore, characterized by sequences of subaerial lava flows intercalated, at intervals corresponding to glaciations, by volcanic hyaloclastites and morainic horizons.

Subglacial volcanics tend to pile up under the ice around the eruptive orifice. Eruptive fissures are the most common form of volcanoes in Iceland. Individual fissures are commonly several km and can be tens of km long. During a major glaciation fissure eruptions can produce a series of parallel hyaloclastite ridges 1-5 km broad and several hundred m thick along the entire active volcanic zone. In subsequent subaerial eruptions lava flows will bank up against the hyaloclastites and may eventually bury them (Fig.1).

The average porosity of subglacial volcanics is approximately twice that of subaerial lavas (Fridleifsson, 1975). The hyaloclastite ridges can be looked on as high porosity channels separated by relatively low porosity lavas in the Quaternary strata. These channels are "thin" and "narrow" where the rate of volcanism has been low during any particular glaciation, but "broad" and "thick" where the extrusion rate has been higher than average.

The Reykir and Reykjavik thermal fields are in Quaternary rocks ranging in age from about 2.8 to 1.8 M.y. There are signs of ten glaciations in the volcanic succession. During this time span there were two central volcanoes active in the region; the Kjalarnes (which is older) and the Stardalur central volcanoes (Fridleifsson, 1973). The rate of volcanic eruption was much higher in the central volcanoes than in other parts of the volcanic zone of the time. This resulted in exceptionally thick accumulations of hyaloclastites in the vicinity of the volcanoes. The volcanoes were further characterized by an abundance of shallow level dykes and sheets; the latter range in thickness from less than a m to several hundred m. The emplacement of the intrusions in the strata has probably produced secondary permeability in the strata (Fridleifsson, 1975). The intrusions gave rise to high temperature fields during the life span of the volcanoes (about 0.6 and 0.3 M.y. respectively for the Kjalarnes and Stardalur volcanoes). Now the volcanoes are deeply eroded; the intrusions can be inspected on the surface and the core regions of the volcanoes are marked by positive gravity anomalies (Fig. 2) which reflect the intensity of intrusions in the strata. The Reykjavik thermal fields are situated on the southern margin of the Kjalarnes central volcano, but the Reykir field between the central volcanoes but closer to the southwestern margin of the Stardalur volcano. These low temperature thermal fields are thus superimposed on the margins of extinct, eroded high temperature fields.

The ratio of hyaloclastites to subaerial lavas in the strata is variable both within and between the thermal fields; it is lowest in the Seltjarnarnes field, which is in the oldest rocks, but highest in the Reykir field, where in 29 drillholes, 800-2043 m deep, the volume percentage of hyaloclastites ranges from 30 to 60%. Table 1 shows the occurrence of aquifers in the different rock types in these holes. Considering that in a 2 km deep hole there may be say 1000 m of lavas, 900 m of hyaloclastites and 100 m of intrusions, but perhaps only 40-50 narrow contacts (aggregate thickness of the order of 100 m) between lavas and hyaloclastites, the chances of aquifers in lavas alone or hyaloclastites alone are perhaps tenfold to those of contacts between the formations. It is thus apparent that aquifers are by far most likely to occur at contacts. The higher number of contacts between lavas and hyaloclastites the higher number of aquifers.

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Table 1

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As an extension to the geological investigations the resistivity of the bedrocks has been studied by numerous direct current resistivity soundings. A conventional Schlumberger electrode configuration has been used, and the depth of the soundings is 1000-1500 m depending on local circumstances.

In an exploration of low temperature thermal activity, resistivity measurements are largely a structural method. The porosity of the rocks has a very significant influence on the measured resistivity. An informative example of how the resistivity method can be used as a direct extension of surface geological investigations is shown in Fig. 1, where the boundaries between high porosity hyaloclastites and relatively low porosity tholeiite lavas are traced down to 1200 m below sea level.

About 70 resistivity soundings have been made in the area under discussion. On the basis of these measurements resistivity maps at various depths have been made. The true resistivity at 900 m depth is shown in Fig. 2, together with the Bouguer anomalies in the area. The gravity data are from Einarsson (1954). A general NE-SW structure can be seen in the low resistivity areas in Fig. 2, which is in agreement with the trend of the hyaloclastite ridges discussed previously.

The higher resistivity values are predominantly found in association with shallow level intrusions of low porosity. These intrusions are mainly associated with the Kjalarnes and Stardalur central volcanoes as previously mentioned, but also with the Hvalfjordur central volcano. The triple correlation: shallow level intrusions, positive gravity anomaly, and high resistivity is rather good.

HYDROTHERMAL SYSTEMS

The thermal gradients (as measured in drillholes deeper than 90 m) to the west of the volcanic zone in SW-Iceland increase fairly regularly towards the zone from about 70°C/km in Tertiary rocks 100 km west of the zone to about 165°C/km in early Quaternary rocks some 20 km west of the volcanic zone. Assuming thermal conductivity as the only form of heat transport (Palmason, 1973) the thermal gradient should continue increasing towards the volcanic zone axis. But due to water circulation in the Quaternary strata, which becomes increasingly permeable towards the volcanic zone, a trend reverse to that of the regional gradient is found.

The Reykjavik thermal areas lie within or just outside the city boundaries, but the Reykir thermal area some 15 km NE of the city centre, and slightly closer to the active volcanic zone. About 150 drillholes 100-600 m deep and 69 drillholes 800-2200 m deep have been sunk and about 1400 l/s of hot water are now pumped from these areas for domestic heating in Reykjavik and neighbourhood.

The surface thermal gradients measured in shallow drillholes in Reykjavik and vicinity are shown in Fig. 3. Four areas of thermal maxima are apparent from the isothermal lines in Fig. 3, i.e. the Alftanes, Seltjarnarnes, Laugarnes and Ellidaar areas. Only the latter three have been exploited, and hydrological (Thorsteinsson and Eliasson, 1970), thermal, chemical and isotopic data (Arnason and Tomasson, 1970) indicate that these areas constitute seperate hydrothermal systems.

The high surface thermal gradients inside the thermal areas are due to localised transport of water from the thermal systems at depth to the surface. This is best demonstrated in the Laugarnes area, where the highest surface gradients are measured. Prior to exploitation about 10 l/s of 88°C water issued in free flow from thermal springs in that area, whereas only minor natural thermal activity was found in the other areas in Reykjavik. There is very little or no transport of water from depth in the rocks between the thermal areas, and the depth of the gradient drillholes (at least down to several hundred meters) has little influence on the measured gradients (Fig. 4) outside the thermal areas. The surface gradient of 0°C/km shown southeast of the thermal areas in Fig. 3 is due to cold ground water penetrating young volcanic rocks. This cold ground-water zone has been found to reach down to 750 m depth (measured in a 986 m deep hole) in the volcanic zone 11 km south of the Ellidaar area (Palmason, 1967).

In Fig. 4, the estimated temperature of the bedrock is shown for the four geothermal fields (Reykjavik and Reykir). These temperature curves are found from temperature measurements in closed holes in thermal equilibrium and from measurements made on the bottom of holes during drilling. From the bedrock temperature curves and from the concentration of deuterium in the thermal water, it has been concluded (Arnason and Tomasson, 1970) that the Seltjarnarnes and Laugarnes fields consist each of single hydrological systems. However, in the Ellidaar field, the scattered values of deuterium concentration were found to depend on mixing of water from two hydrological systems. The reverse temperature gradient found in the Ellidaar field (Fig. 4) supports the proposed existence of the two systems.

A schematic cross section through the Reykjavik thermal fields perpendicular to the strike of the rocks is shown in Fig. 5. The three thermal systems are separated by impermeable barriers (Thorsteinsson and Eliasson, 1970), which we suggest are swarms of dykes and associated faults. The volume percentage of intrusions in drillholes in the Ellidaar area increases towards the hydrological barrier that separates it from the Laugarnes area. It is assumed that the hydrological barriers reach down to layer 3, which is probably mostly of impermeable intrusions and forms a base to water circulation in the crust.

In the Reykir field there is also evidence for two types of hydrological systems. In the eastern part of the field (nearest to the volcanic zone) a reverse temperature gradient is observed (MG 17 in Fig. 4). The concentration of deuterium in the water from this well is $\delta = -60.0$ o/oo, but in a 1000 m deep drillhole (not reaching the deeper, cooler system) situated only 20 m from MG 17, the δ - value is found to be - 62.4 o/oo (Arnason, 1975). From mixing assumptions it is found most likely that the δ - value of the deeper system is - 58 o/oo, which is the value for local precipitation.

Outside the thermal fields the thermal gradient is about 100°C/km (see K-1 in Fig. 4). The reverse temperature gradients found in the

Ellidaar and Reykir fields can only be accounted for by the circulation of cold water at depth. This cooling effect might be similar to the surface cooling effect observed south east of Reykjavik (Fig. 3).

HYDROLOGICAL MODEL

The distribution of deuterium concentration in thermal water in SW-Iceland has been treated by Arnason and Sigurgeirsson (1967) and by Arnason and Tomasson (1970). A comparison of the deuterium content of thermal water with the distribution of deuterium in the precipitation in Iceland indicates that most of the thermal water originates from precipitation which falls in the interior highlands of the country (Arnason and Sigurgeirsson, 1967), and has been heated by descending to great depth (Einarsson, 1942).

The distribution of the deuterium content in the precipitation in SW-Iceland (Arnason et al, 1969) is shown in Fig. 6 along with the boundaries between Tertiary, Quaternary and recent rocks.

The concentration of deuterium in the thermal water increases towards the volcanic zone. A δ - value - 75 o/oo is found in the Seltjarnarnes field, - 65 o/oo in the Laugarnes field, and higher than - 64 o/oo in the Ellidaar and Reykir fields (Arnason and Tomasson, 1970; Arnason, 1975).

In the hydrological model proposed here, the thermal water is expected to flow parallel to the volcanic zone along the structural channels discussed previously. A possible path for the - 75 o/oo deuterium water is indicated in Fig. 6 by an arrow.

Nearest to the volcanic zone (in rocks of relatively high permeability), a certain movement of fresh water, $\delta = -58$ o/oo, perpendicular to the zone is allowed for in the model. This high deuterium water occurs in the thermal fields nearest to the volcanic zone (Ellidaar and Reykir) and is found at greater depth than the "channel water". Thermal water from drillholes penetrating the two water systems should show variations in the δ - values, as is observed in the Ellidaar and Reykir fields.

The thermal properties of the bedrocks, discussed in the previous section, are also in agreement with the hydrological model proposed. The high deuterium water coming directly from the volcanic zone is much colder than the low deuterium water, which has flowed some 50 or 100 km underground. The inverse temperature pattern of the rock shown in Fig. 4 supports the proposed hydrological model strongly.

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TABLE 1

Rock type	Aquifers ≤ 2 l/s	 >2-20 l/s	 >20 l/s	 Total number
Lavas	44	27	2	73
Hyaloclastites*	29	12	4	45
Dolerites		1	1	2
Lavas + hyaloclastites*	53	38	20	111
Lavas + dolerites	13	1	3	17
Hyaloclastites* + dolerites	5	2	1	8

* Included in this group are reworked hyaloclastites and detrital beds.

FIGURE CAPTIONS

Fig. 1. A combined geological (above sea level) and resistivity (below sea level) section of early Quaternary strata. The location of the section is shown in Fig. 2. Prominent high porosity hyaloclastite bodies can be traced to depth of >1 km by resistivity soundings.

Fig. 2. Map of the true resistivity at 900 m below sea level. Prominent high porosity hyaloclastite bodies can be traced at depth several km along the strike of the rocks by resistivity soundings. The low resistivity areas in the upper part of the map are thought to outline two high porosity "channels" in the strata. Note the coincidence of high resistivity and positive Bouguer anomalies. The exploited low temperature fields discussed in the paper are in low resistivity (high porosity) rocks on the outskirts of the central volcanoes. which are marked by positive Bouguer anomalies.

Fig. 3. Map of the surface thermal gradients in Reykjavik and vicinity.

Fig. 4. Estimated rock temperature in four thermal fields. The location of the holes, except MG 17 (Reykir), is shown in Fig. 3. The drillhole K-1 is between the thermal fields, and shows the regional thermal gradient.

Fig. 5. A schematic cross section through the Reykjavik thermal fields showing the isotopic composition and temperature of the thermal water in the fields.

Fig. 6. Map of the concentration of deuterium in the precipitation (from Arnason et al, 1969), and the boundaries of the active volcanic zone, Quaternary and Tertiary rocks in SW-Iceland. The arrow indicates the direction of flow at depth of low deuterium water parallel to the volcanic zone, but the shaded area indicates local connection of -58 o/oo warm water perpendicular to the volcanic zone.

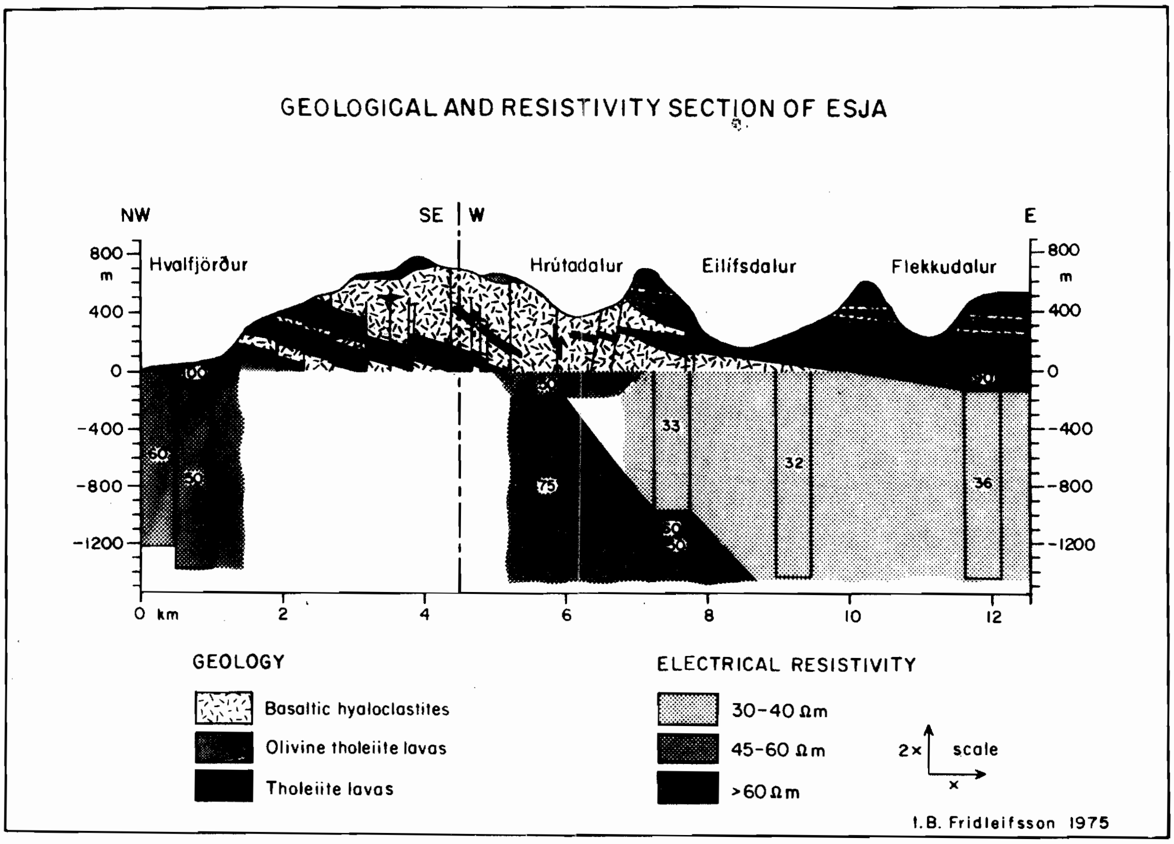

GEOLOGICAL AND RESISTIVITY SECTION OF ESJA
NW
SE
W
E
800 m
400
0
-400
-800
-1200
Hvalfjörður
Hrútadalur
Eilífsdalur
Flekkudalur
100
60
50
50
75
33
32
36
30
30
20
0 km
2
4
6
8
10
12
GEOLOGY
Basaltic hyaloclastites
Olivine tholeiite lavas
Tholeiite lavas
ELECTRICAL RESISTIVITY
30-40 Ωm
45-60 Ωm
>60 Ωm
2× scale
x
I.B. Fridleifsson 1975

Fig. 1

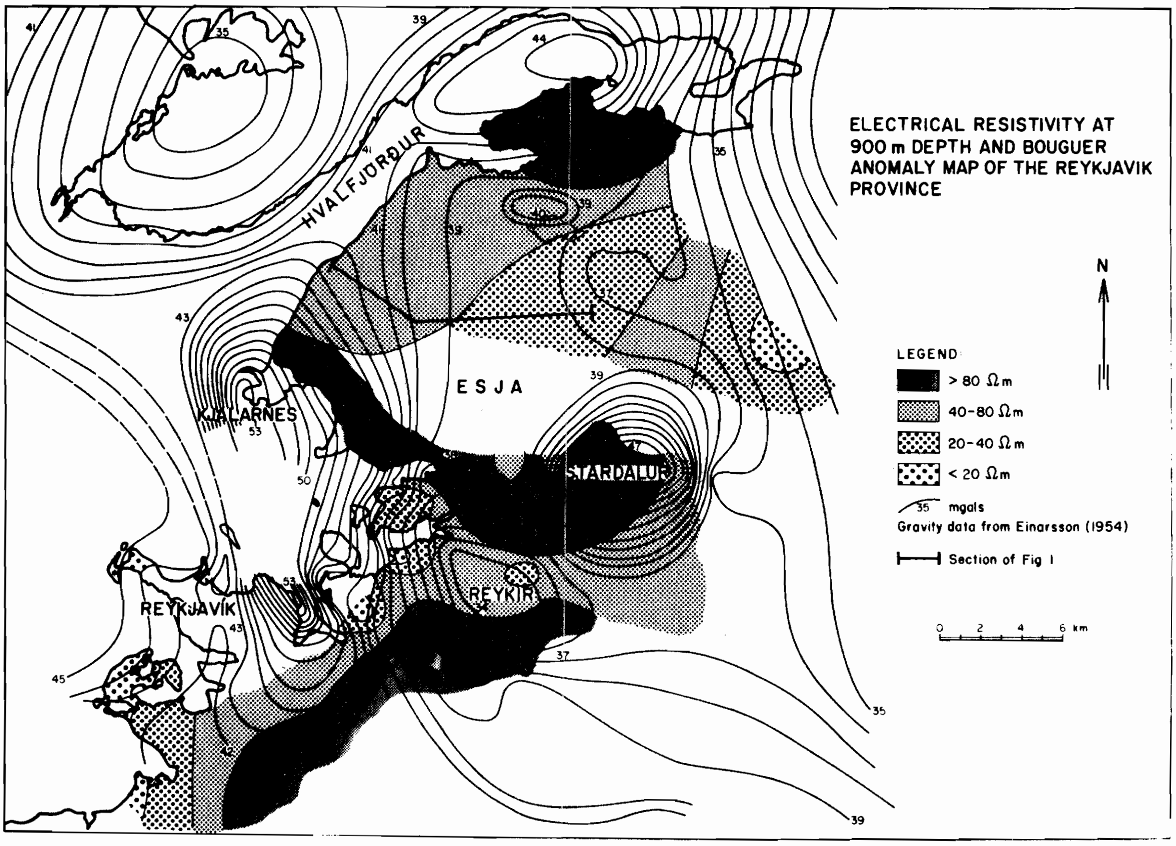
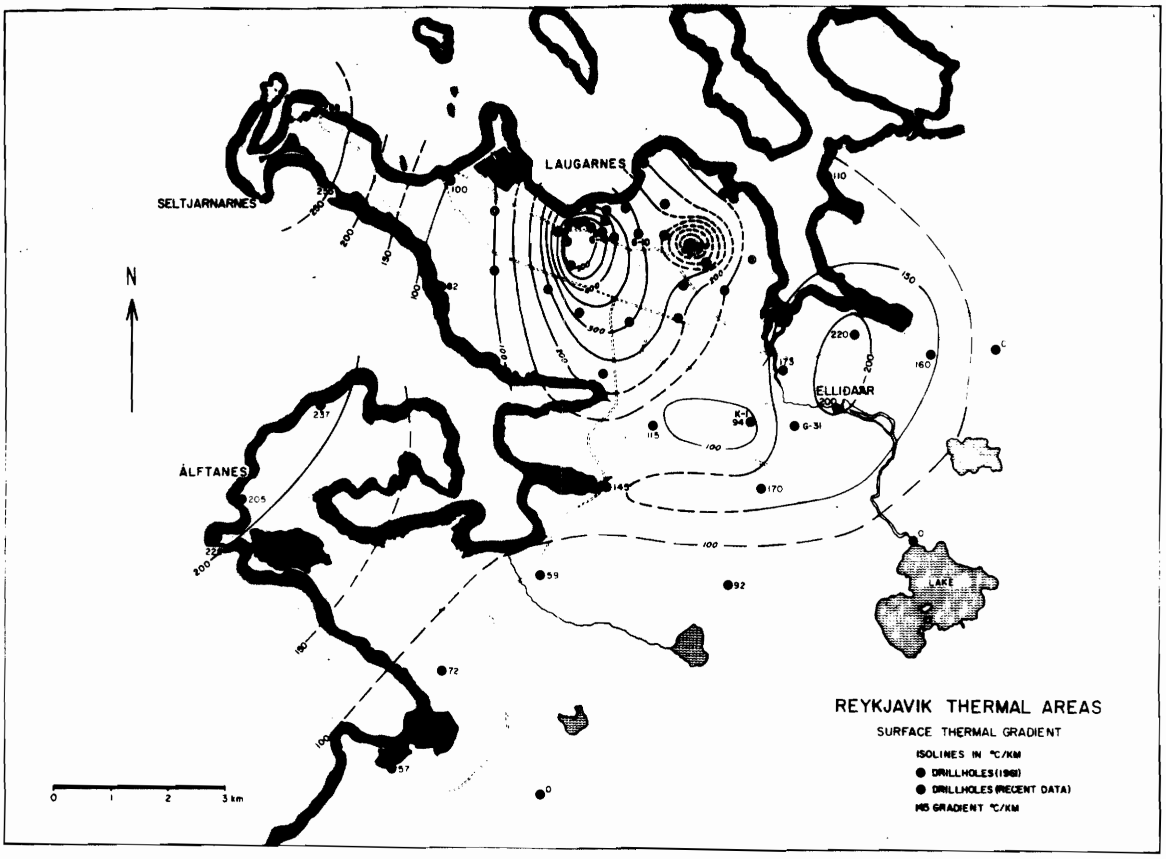

ELECTRICAL RESISTIVITY AT 900 m DEPTH AND BOUGUER ANOMALY MAP OF THE REYKJAVIK PROVINCE
HVALFJÖRÐUR
ESJA
KJALARNES
STARDALUR
REYKIR
REYKJAVIK
N
LEGEND
> 80 Ωm
40-80 Ωm
20-40 Ωm
< 20 Ωm
35 mgals
Gravity data from Einarsson (1954)
Section of Fig I
0 2 4 6 km
41
35
39
44
35
41
39
46
43
53
50
53
43
45
42
37
35
39

Fig. 2



SELTJARNARNES
LAUGARNES
ÁLFTANES
ELLIDAÁR
LAKE
N
0
1
2
3 km
100
110
150
160
200
220
237
205
22
145
115
K-1
94
G-31
170
173
100
59
92
72
57
0
REYKJAVIK THERMAL AREAS
SURFACE THERMAL GRADIENT
ISOLINES IN °C/KM
● DRILLHOLES (1961)
● DRILLHOLES (RECENT DATA)
145 GRADIENT °C/KM

Fig. 3

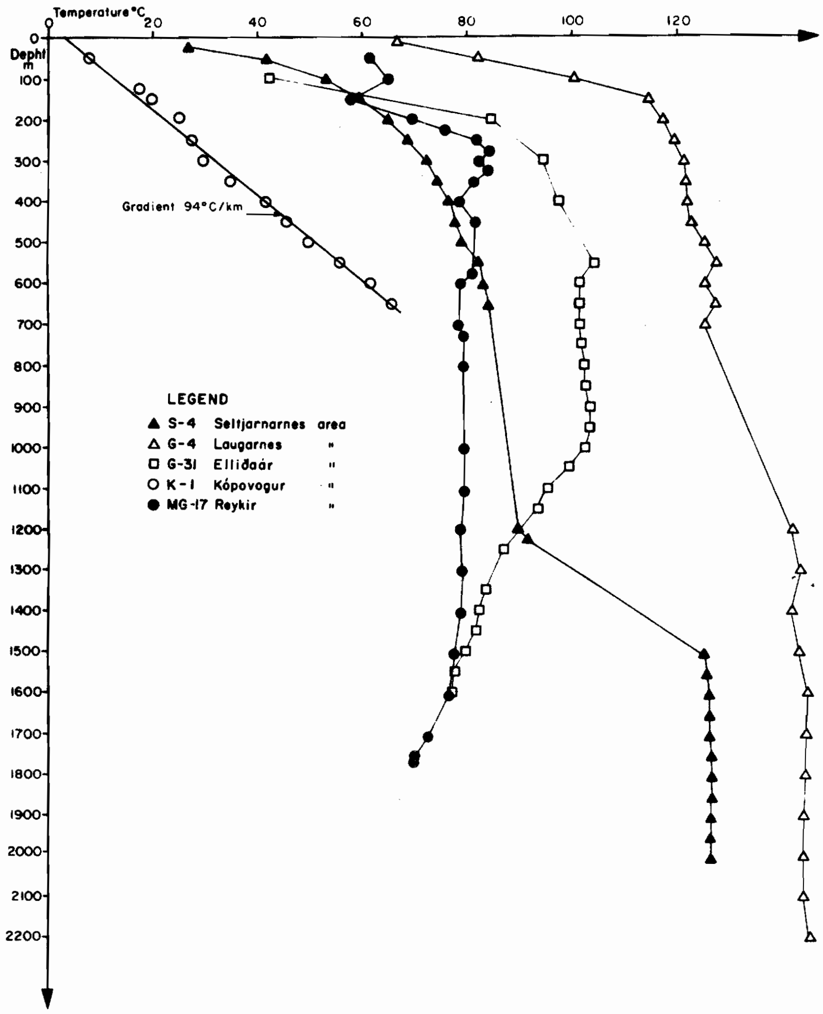

Temperature °C
0
20
40
60
80
100
120
Depht m
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Gradient 94°C/km
LEGEND
▲ S-4 Seltjarnarnes area
△ G-4 Laugarnes "
□ G-31 Elliðaár "
○ K-1 Kópovogur "
● MG-17 Reykir "

Fig. 4

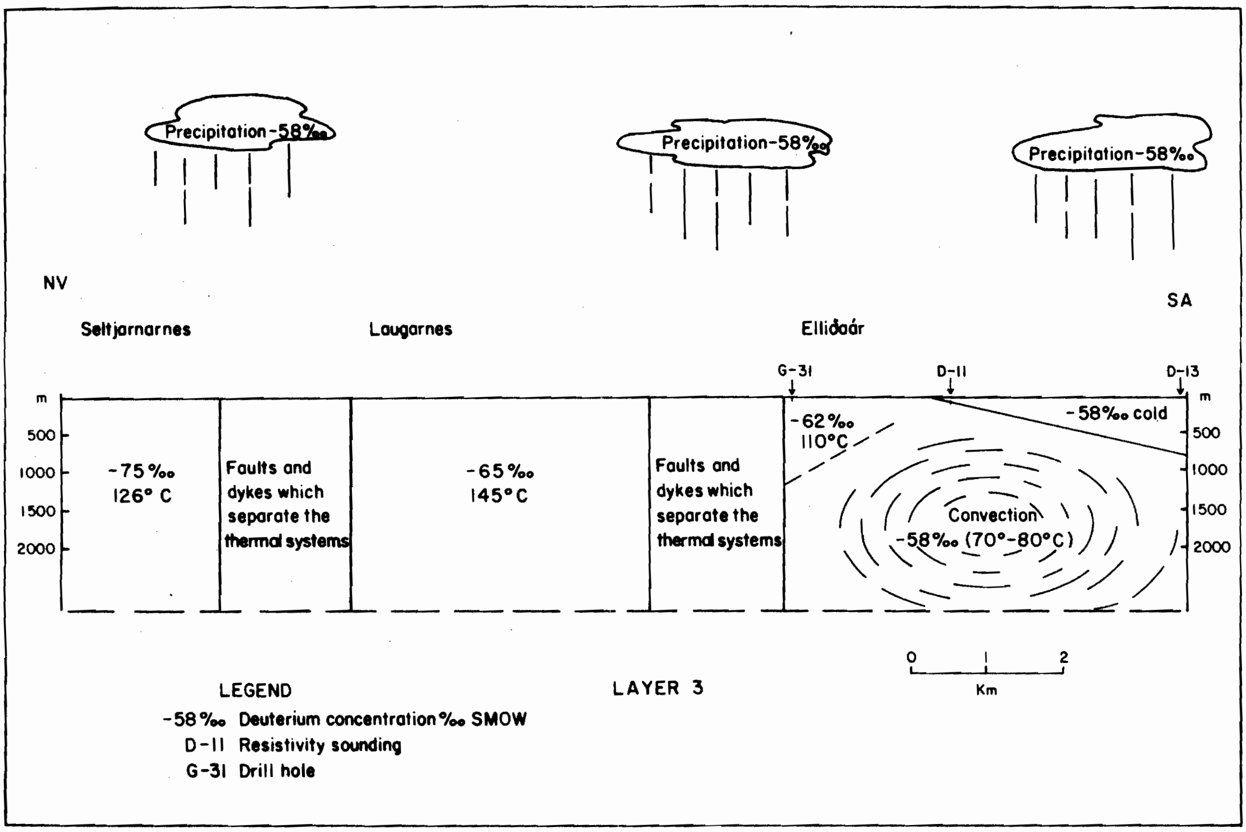

Precipitation-58‰
Precipitation-58‰
Precipitation-58‰
NV
SA
Seltjarnarnes
Laugarnes
Elliðaár
G-31
D-11
D-13
m
500
1000
1500
2000
-75‰
126° C
Faults and dykes which separate the thermal systems
-65‰
145°C
Faults and dykes which separate the thermal systems
-62‰
110°C
-58‰ cold
Convection
-58‰ (70°-80°C)
0 1 2
Km
LEGEND
-58‰ Deuterium concentration ‰ SMOW
D-11 Resistivity sounding
G-31 Drill hole
LAYER 3

Fig. 5

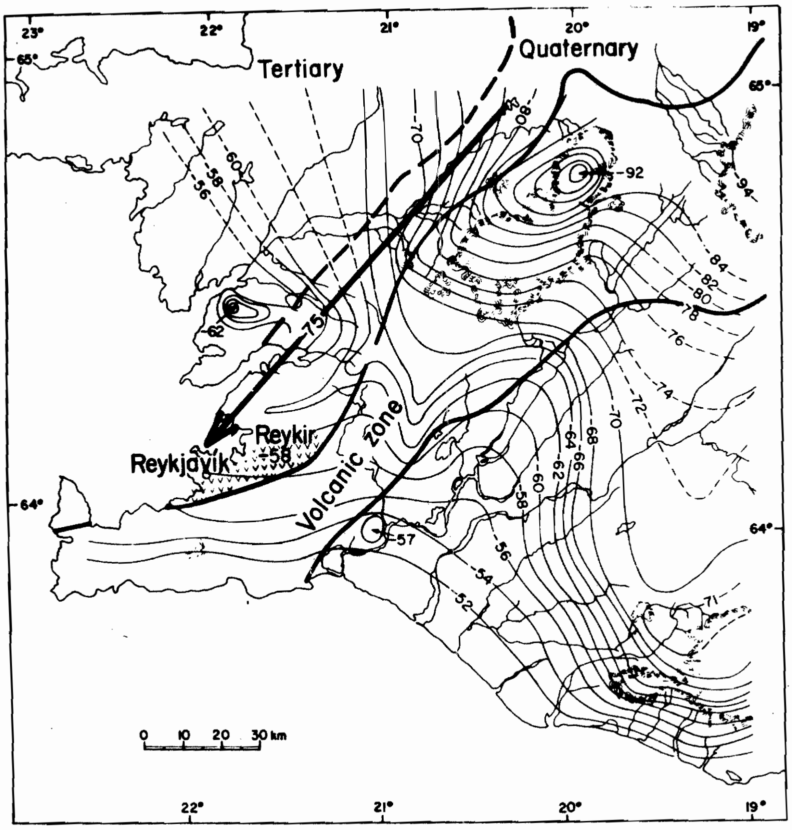

23°
22°
21°
20°
19°
65°
64°
Tertiary
Quaternary
Reykjavík
Reykir
-58
-75
-62
-92
-57
Volcanic zone
-56
-58
-60
-70
-80
-94
-84
-82
-80
-78
-76
-74
-72
-70
-68
-66
-64
-62
-60
-58
-56
-54
-52
-71
0 10 20 30 km

Fig. 6