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A COMPARATIVE STUDY OF HOT-WATER CHEMISTRY AND BEDROCK RESISTIVITY IN THE SOUTHERN LOWLANDS OF ICELAND

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ABSTRACT

The low-temperature area on the east side of the volcanic zone in SW-Iceland is investigated by means of the chemical properties of the hot water and the electrical resistivity of the bedrock. The combined geochemical and resistivity results give, along with analysis of the geological structure, a much more reliable picture of this area, than the individual methods do separately. Three distinct hydrothermal systems inferred from the Cl/B ratio of the thermal water are separated by high resistivity boundaries which are known to contain a high proportion of massive basaltic dykes and intrusions in a few localities. There is a good regional agreement between high temperatures of last equilibrium with chalcedony/quartz of the thermal water and low rock resistivity. The regional geological structure is complimented by an overall NE-SW resistivity structure and dipping formations containing thermal water are traced down to 500-1000 m depth by resistivity soundings. Superimposed on the NE-SW structure is an E-W resistivity structure which coincides with a local anomaly in the chemical composition of the thermal water. This is suggested to be connected with a seismically active E-W transform fault.

INTRODUCTION

A regional investigation of the low-temperature area on the east side of the volcanic zone in SW-Iceland has been in progress for several years. The first overall picture of the area was achieved at by geochemical methods (Arnórsson, 1970). On the basis of the Cl-B ratios in the thermal water, three hydrothermal systems could be distinguished.

Since 1970 a rather extensive resistivity survey has been performed in the area, parallel with a detailed geological mapping. The geological, geochemical, and geophysical results form together a rather comprehensive picture of the geohydrology of the area, and the conformity of three independent exploration methods improves the reliability of the model achieved at. Further, this combination of survey methods demonstrates how the characteristics of geothermal reservoir can be revealed by inexpensive surface exploration.

This paper presents the results, obtained so far, from the geochemical and resistivity methods. The results of the geological investigation have been applied in the interpretation. No attempt is, however, made to review the geological studies.

The geochemical results presented here are based on new data from the area as well as more comprehensive interpretation of the previous data (Arnórsson, 1970). Underground temperatures are estimated in three different ways and a discussion on the hydrogen sulphide and the carbonate content of the geothermal waters is given.

The specific resistivity of the area is obtained from numerous D.C. resistivity soundings. This survey is still in progress. It is, however, believed that the results, obtained so far, give a reliable general picture of the regional distribution of the resistivity.

GEOLOGICAL FEATURES

The Southern Lowlands low-temperature area is located in Quaternary rocks just east of the western active volcanic zone (fig. 1). The bedrock consists mostly of basalt lavas and hyaloclastite formations (pillow lavas, pillow breccias and hyaloclastites). Acid volcanics occur in the vicinity of Geysir and Flúdir in the northeastern and eastern parts of the area. The lavas were formed during interglacials of the Quaternary epoch whereas the hyaloclastite formations formed during the glacial periods in melt-water chambers within the ice-sheet.

The basalt lavas dip a few degrees towards northwest under the active volcanic belt. Towards the east where the rocks are oldest the hyaloclastite formations are, at least partly, reworked and tend to form sheets of variable thickness between the lavas. In the west the hyaloclastite formations form, on the other hand, mountains protruding above the plains. These mountains still reflect to some extent the shape of the melt-water chambers as a result of limited erosion.

Differentiated and intrusive rocks which characterise central complexes occur by Geysir and near Flúdir. A complex of dense basalt intrusions also occurs just north of Vördufell at the boundary of the three main hydrothermal systems.

Northeast-southwest faults, approximately parallel to the axis of the active volcanic zone, are pronounced in the area.

The regional thermal gradient is high in the area, ranging from about 140°/km at the edge of the volcanic zone to about 60°/km 50 km to the east (Pálmason, 1973). The flow of thermal water from natural springs in the whole area amounts to about 300 l/sec.

GEOCHEMICAL STUDIES

Silica temperatures, that is temperatures which correspond with equilibrium between chalcedony or quartz and unionized silica in the thermal water have been estimated for the majority of thermal springs and drillholes (fig. 5). The principles and assumptions involved in estimation of silica temperatures were outlined by Arnórsson (1975).

The silica temperatures tend to be 0-40°C higher than the measured temperatures in the springs and drillholes (fig. 2). A few samples show, however, greater supersaturation and by as much as 100°C. Several samples are undersaturated by few degrees but this undersaturation is not regarded as significant. For the majority of the thermal springs and shallow drillholes the chalcedony and quartz supersaturation are considered to have resulted from cooling of the water in the upflow zones, either by conduction or flashing so silica temperatures give an idea of underground temperature conditions below the zone of conductive cooling and flashing. Some warm spring waters around major upflow zones are considered to have formed by mixing of cold ground water with thermal water. In this case the silica temperature values bear more complicated relation to the underground temperatures since the mixing will lead to pH lowering and chalcedony and quartz supersaturation for the temperature of the mixture. In other words these factors bring about changes in the unionized silica content of the water which is not so in case of conductive cooling.

Underground temperature estimates from the Na-K-Ca geothermometer as defined by Fournier and Truesdell (1973) yield values which give the same overall picture for underground temperatures as the silica geothermometer does. This is partly reflected in figure 3. There is a considerable scatter of points in this figure, particularly at low temperatures, which reflects discrepancy between the two geothermometers. At silica temperatures above 100°C the Na-K-Ca geothermometer tends to give a little higher values than chalcedony equilibrium temperatures.

In general, the Na-K-Ca geothermometer shows greater deviation above measured temperatures in springs than does the silica geothermometer (figure 3). It is believed that the Na-K-Ca geothermometer may yield unreliable values towards high temperatures for many of the warm springs which appear in peat soil. Equilibrium may not be reached at the low temperatures of these springs and the water is likely to be high in potassium due to the relatively high mobility of this element in the soil. Discrepancy between the two geothermometers is to be expected for thermal waters which have been diluted with cold ground waters.

The thermal activity in the Southern Lowlands has been divided into 3 major hydrothermal systems on the basis of the chlorine and boron contents of the thermal waters (Arnórsson, 1970). A fourth hydrothermal system occurs to the west of hydrothermal system II (see fig. 5), and a fifth system, which is of the high-temperature type, north of hydrothermal systems I and III. New data on chlorine and boron not included in the previous study fall into the picture of the 3 main hydrothermal systems see (fig. 4). Much of the additional data include warm springs, some of which are located around major upflow zones of hot water and they are believed to have originated by mixing of this hot water with cold ground water.

For hydrothermal systems II and III the chlorine and boron concentrations fall approximately on a line between about 5-10 ppm chlorine and 0 ppm boron and the densest cluster of points corresponding to the hot waters of each system. This is what would be expected if the warm waters had really formed by mixing of hot water and cold ground waters. The cold ground waters contain 5-10 ppm of chlorine and about 0 ppm of boron.

Warm springs are rather widespread in the northwestern corner of the Southern Lowlands but no hot springs exist in that area. Due to the similar concentrations of boron and chlorine in these waters and cold ground waters, it cannot be established with any certainty to which hydrothermal system these warm springs belong or whether they really form a separate system.

Within each of the three major hydrothermal systems as defined by the chlorine and boron contents of the thermal waters, there is a rather regular distribution in the values of the silica temperatures (fig. 5). Thus, highest silica temperatures occur in the northernmost part of hydrothermal system I and in the western part of hydrothermal system II in both cases nearest to the active volcanic belt. If the warm springs discussed in the previous paragraph are excluded, the highest silica temperatures occur in the northernmost part of hydrothermal system III. Within each area the highest silica temperatures, corresponding to equilibrium with quartz are in the range of 170-180°C. If, on the other hand equilibrium with chalcedony is assumed, highest silica temperatures of 150-160°C are obtained for each hydrothermal system. On the outskirts of each system silica temperatures have dropped to some 40-80°C.

An attempt has been made to draw iso-lines for silica temperatures of 120°C (equilibrium with chalcedony) inside each hydrothermal system (fig. 5). Due to lack of hot springs and drillholes in parts of the Southern Lowlands these iso-lines should be regarded only as tentative. This refers particularly to hydrothermal system III and the iso-lines on the western boundary of systems I and II. Apparently, hydrothermal system I has the greatest areal extent.

With a few exceptions the waters from springs and drillholes in the Southern Lowlands possess chemical characteristics typical for the low-temperature areas in Iceland. The exceptions include two major hot spring centers around Laugarvatn in the northern-western corner of hydrothermal system I and those two spring localities in hydrothermal system II having the highest silica temperatures for that area. The former is characterized by an unusually high content of hydrogen sulphide (20-25 ppm) but the latter by carbonate water and the carbonate may be of juvenile origin.

The hydrogen sulphide content of boiling springs in the low-temperature areas tends to be in the range of 1-2 ppm and lower in cooler springs. Thermal waters with temperatures of less than about 50°C contain generally no detectable hydrogen sulphide or less than 0.1 ppm. By contrast some hot springs, and invariably drillholes, from the high-temperature areas contain substantial concentrations of hydrogen sulphide, or 30-250 ppm. For example thermal water at 200°C feeding drillholes in Hveragerdi in the Hengill high-temperature area contains about 30 ppm of hydrogen sulphide. Hydrogen sulphide of 20-25 ppm in the hot springs by Laugarvatn are therefore indicative of high-temperature activity rather than low-temperature activity. Laugarvatn is adjacent to the active volcanic zone and the high hydrogen sulphide content in the hot springs there could well reflect the existence of a hidden high-temperature area whether it would be located directly under Laugarvatn or within the active volcanic zone to the north or to the west.

As with many other warm carbonate waters in Iceland, the silica content of the carbonate waters in hydrothermal system II is not far from opal saturation at the temperature in the springs. Due to the high silica supersaturation, whether it refers to equilibrium with quartz or chalcedony, a doubt has been thrown on the reliability of underground temperature estimates by the silica geothermometer for such waters. Yet, the Na-K-Ca geothermometer yields temperature values which are intermediate for chalcedony and quartz equilibrium temperatures. This good comparison rather supports the interpretation that high underground temperatures really exist where the carbonate springs occur in hydrothermal system II.

RESISTIVITY STUDIES

The specific electrical resistivity of the bedrock has been obtained from direct current resistivity soundings. A symmetrical Schlumberger electrode configuration has been used and the maximum current arm AB/2 is 900-1500 m depending on local circumstances.

In the interpretation, horizontal resistivity layers have been assumed on local basis, i.e. within the range of each sounding. Comparison with theoretical master curves (Orellana and Mooney, 1966 ; van Dam and Meulenkamp, 1969) has given the resistivity layers.

The total amount of resistivity soundings in the area is to date about 180. On the basis of these measurements resistivity map on 300, 500, and 900 m depth has been made, (fig. 6, 7, and 8). This kind of representation gives an areal view of the true resistivity in the bedrock. It can easily be seen that the area is divided into several low resistivity (≤20 Ωm) areas which are more or less separated by high resistivity boundaries. However, the distribution of resistivity in the bedrock is a three dimensional problem, and the vertical variations are not easily represented on an areal map. In fig. 9 a cross section of the resistivity across the area is shown. The dip of resistivity layers are about 5 degrees towards NW, which is the same as the dip of geological formations in the area.

In the vicinity of Vördufell, where the intersection between hydrothermal systems I, II, and III is located, a rather high resistivity is found with sharp boundaries to east and west. In the cross section shown in fig. 10 an example of this high resistivity wall is shown. This high resistivity wall is found to have a SW-NE direction and can be seen in fig. 9 in the middle of the section. At this place the wall does not reach the surface.

GEOHYDROLOGICAL MODEL

The combination of the chemical and resistivity data makes it possible to obtain a model for the geothermal systems in the Southern Lowlands. In fig. 11 the main results of the chemical investigation is drawn together with the true resistivity at 500 m depth. In this way the results of the two exploration methods can be compared easily. As can be seen the Cl-B boundaries generally coincide with high resistivity in the bedrock. This correlation indicates that on the boundaries there are some kind of impermeable walls. The best location of such walls is on the boundary between hydrothermal systems I and III. Several massive basalt intrusions occur here (Fransson,1974) and they could be the cause of the high resistivity.

It can be observed, further, that several of the greatest natural springs belonging to hydrothermal system I are located near the boundaries (Thorlákshver, Laugarás, Reykholt). A possible explanation for this is that the impermeable walls bring the thermal water to the surface as is schematically shown in fig. 12. This hypothesis should be compared to the resistivity section shown in fig. 10.

Further investigation of fig. 11 shows that the centers of the hydrothermal systems, where the highest silica temperature is measured, generally coincide with low resistivity (≤20 Ωm) in the bedrock. In some places this correlation is remarkably good as for example in the Biskupstungur area (hydrothermal system I).

In general it seems clear that geothermal properties can be mapped by resistivity soundings, and the picture achieved at is the same as obtained by chemical methods. The main result of the comparative study is,therefore, that the reliability of the model is greatly strengthened by the use of the two independent methods instead of one.

The overall pattern of the resistivity data in the area investigated indicate SW-NE trend which is in agreement with the structural trend dominating the geology. Similar structure of resistivity data has been found in the low-temperature areas on the western side of the volcanic zone. The influence of geological structure on hydrothermal systems is discussed by (Tómasson et al., 1975). However, in the middle of the area investigated (Grímsnes) a clear E-W structure in the resistivity data is found. This E-W resistivity structure is located on a line following the 64° lattitude. From seismic activity an E-W tranform fault has been proposed in this area (Björnsson and Einarsson, 1974), see fig. 13. Further, the warm water occurring in this E-W region is very high in carbonate, and postglacial volcanic eruptions have occurred in the vicinity of the warm carbonate springs in hydrothermal system II. It seems conceivable that the warm springs in this area are mostly derived from shallow level intrusions and that the mentioned transform fault structure may aid transport of this juvenile carbonate towards the surface.

The results from the chemical and resistivity investigations are in agreement with the proposed E-W transform fault.

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van Dam, J.C., and Meulenkamp, J.J., Standard Graphs for Resistivity Prospecting, 167 p, European Ass. of Expl. Geophys., the Hague, 1969.

Figure captions

Fig. 1. The location of the Southern Lowlands low-temperature field in relation to the active volcanic zone.

Fig. 2. Supersaturation corresponding to differences between measured temperatures in springs and drillholes.

Fig. 3. Comparison between underground temperatures as estimated by (1) the Silica geothermometer, (2) the Na-K-Ca geothermometer.

Fig. 4. Cl-B relationships in thermal waters in thermal waters in the Southern Lowlands.

Fig. 5. Hydrothermal systems in the Southern Lowlands as deduced from the Cl-B content of the thermal water. Silica temperature estimates are given for the majority of thermal springs and drillholes.

Fig. 6. True resistivity at 300 m depth.

Fig. 7. True resistivity at 500 m depth.

Fig. 8. True resistivity at 900 m depth.

Fig. 9. Resistivity section across the area in NW-SE direction perpendicular to the strike.

Fig.10. Resistivity section across the intersection of two hydrothermal systems.

Fig.11. The true resistivity at 500 m depth and the hydrothermal systems as deduced from geochemical methods.

Fig.12. A schematic model for hot springs occurring at boundaries between massive and permeable formations.

Fig.13. Estimated magnitudes and locations of major destructive earthquakes in Iceland since 1700. Epicenters are shown as black dots. Encircled numbers indicate the year of occurrence and estimated surface magnitude of the earthquake. From Björnsson and Einarsson (1974).

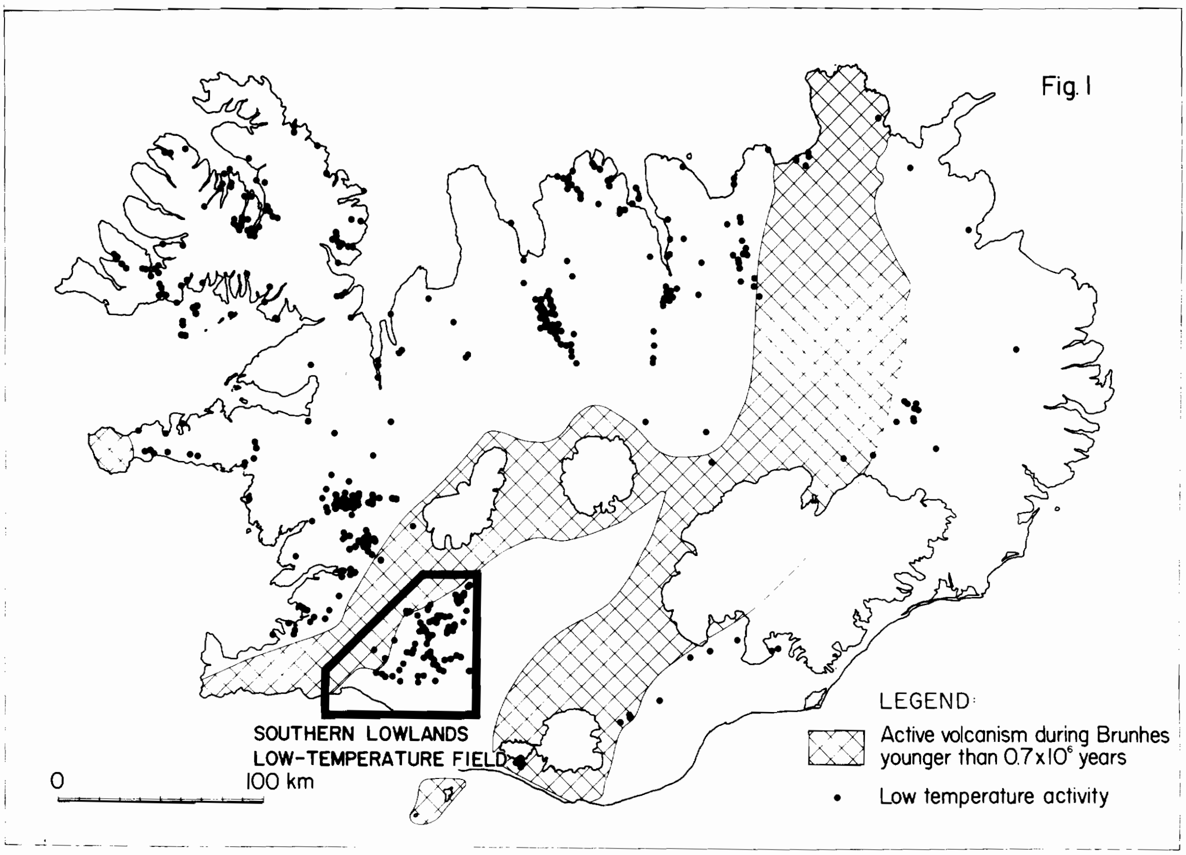
Fig. 1
SOUTHERN LOWLANDS
LOW-TEMPERATURE FIELD
0
100 km
LEGEND:
Active volcanism during Brunhes younger than 0.7x10⁶ years
Low temperature activity

Fig. 1

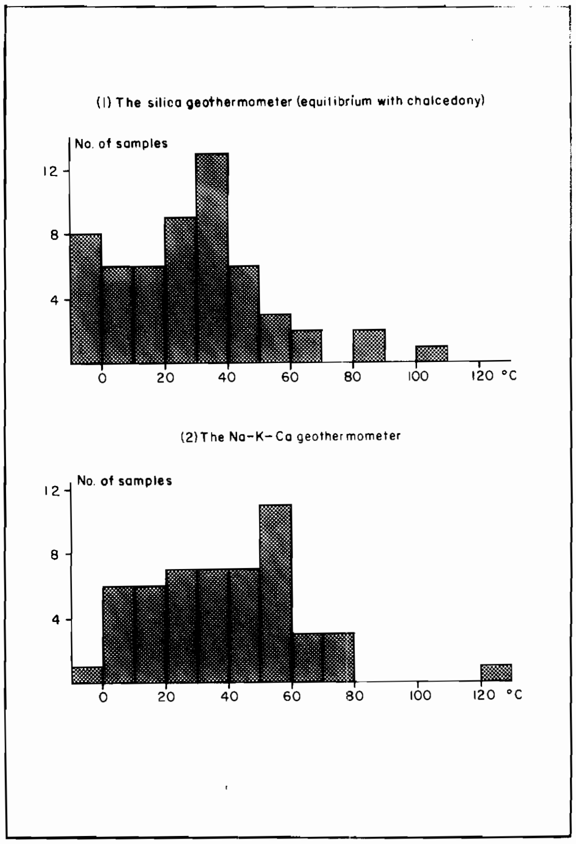
(1) The silica geothermometer (equilibrium with chalcedony)
No. of samples
12
8
4
0
20
40
60
80
100
120 °C
(2) The Na-K-Ca geothermometer
No. of samples
12
8
4
0
20
40
60
80
100
120 °C

Fig. 2

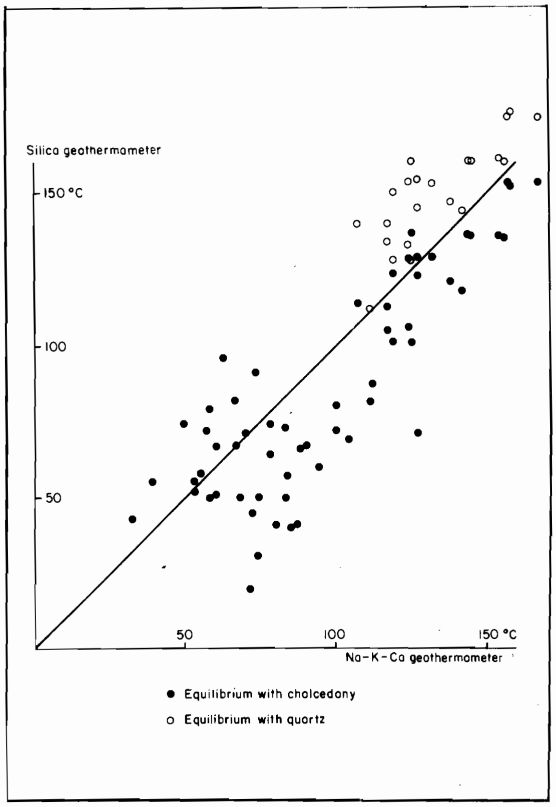
Silica geothermometer
150 °C
100
50
50
100
150 °C
Na-K-Ca geothermometer
● Equilibrium with chalcedony
○ Equilibrium with quartz

Fig. 3

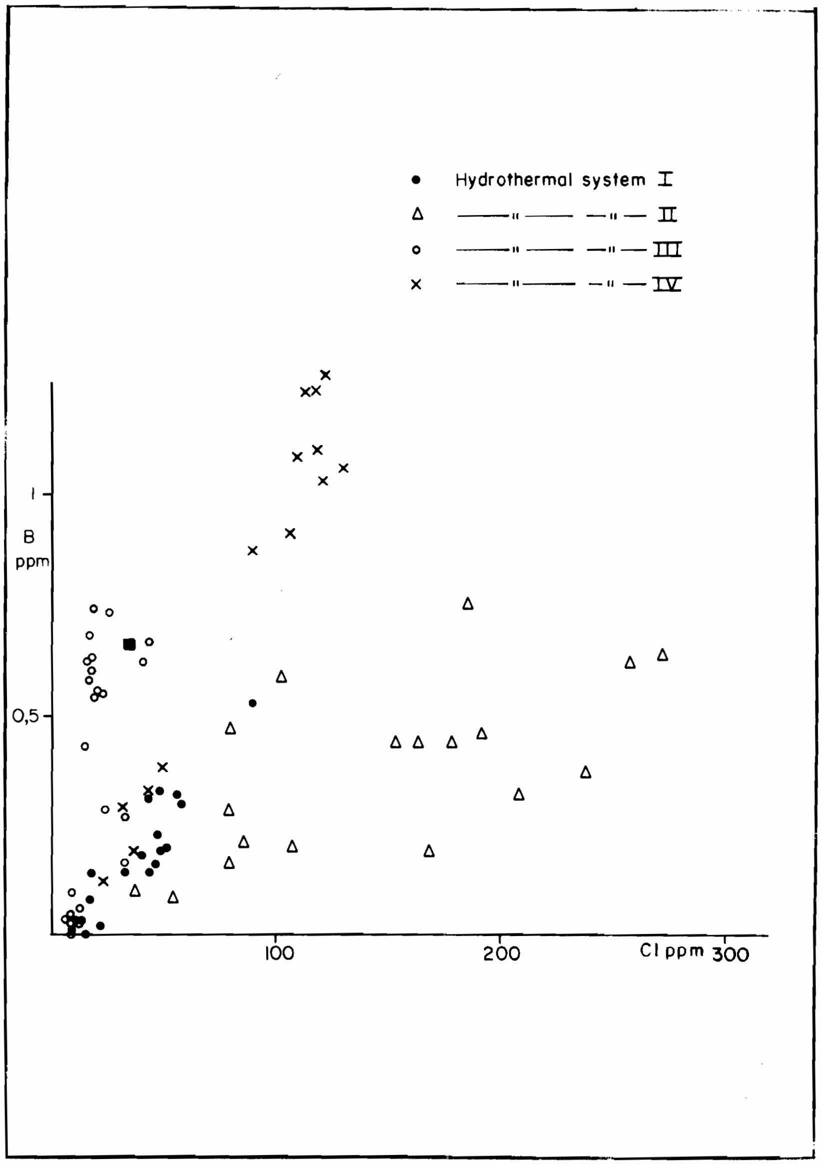

Fig. 4

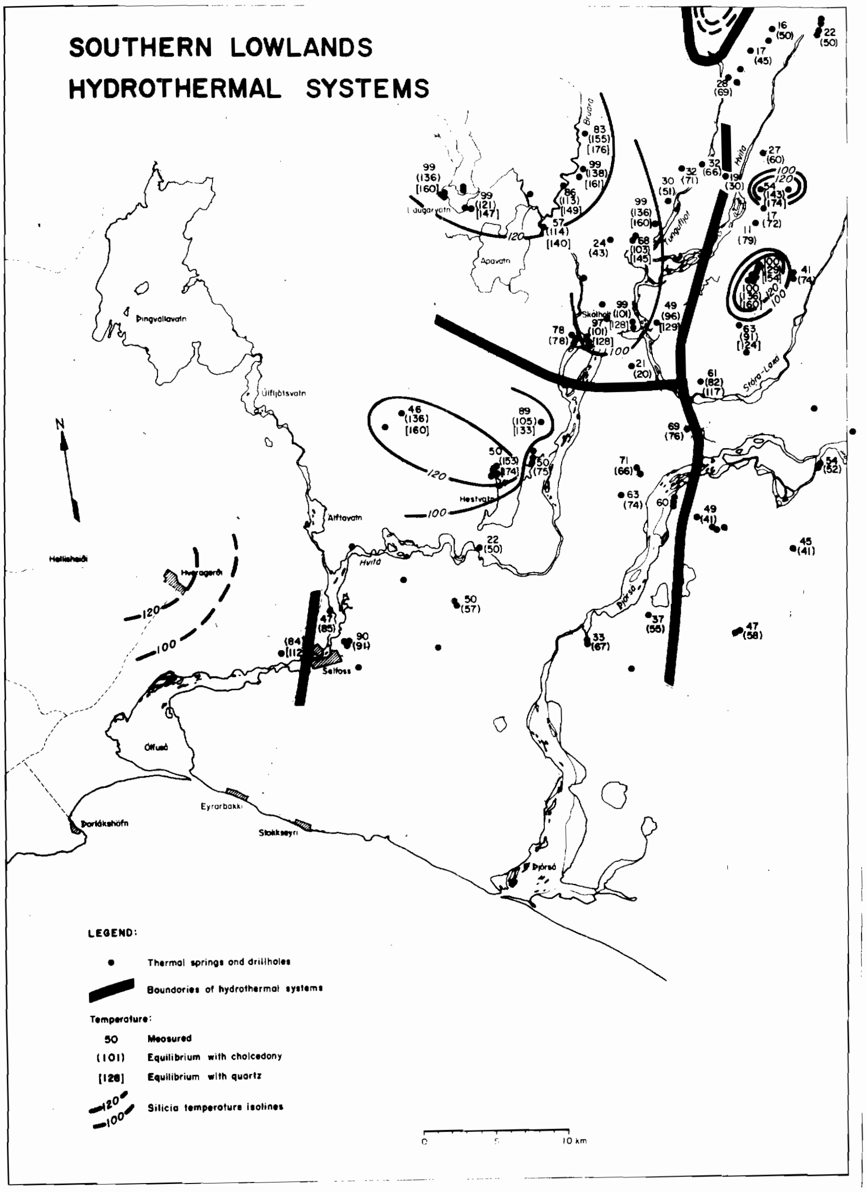
SOUTHERN LOWLANDS
HYDROTHERMAL SYSTEMS
LEGEND:
Thermal springs and drillholes
Boundaries of hydrothermal systems
Temperature:
50 Measured
(101) Equilibrium with chalcedony
[128] Equilibrium with quartz
120 100 Silica temperature isolines
0 5 10 km
N
Þingvallavatn
Úlfljótsvatn
Álftavatn
Hestvatn
Laugarvatn
Apavatn
Skálholt
Hveragerði
Hellisheiði
Hvítá
Brúará
Tungufljót
Stóra-Laxá
Þjórsá
Selfoss
Ölfusá
Eyrarbakki
Stokkseyri
Þorlákshöfn

Fig. 5

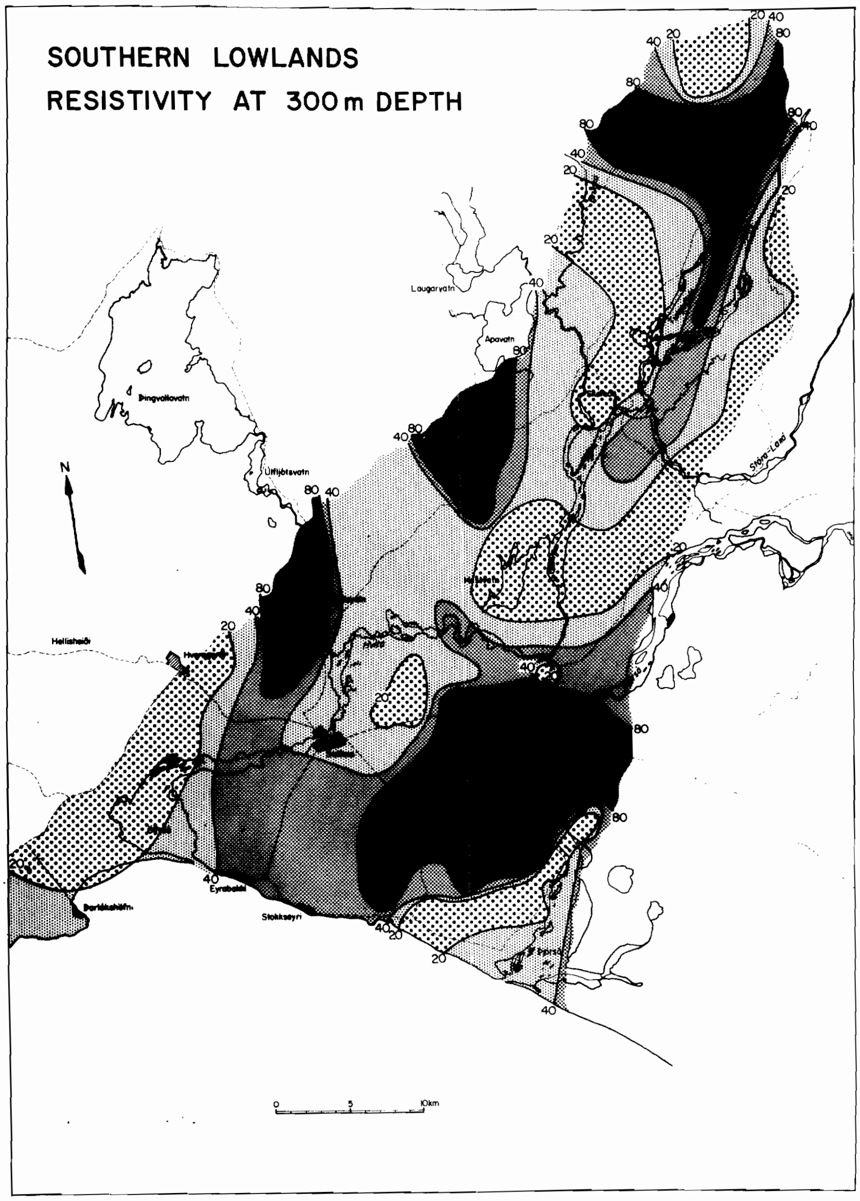
SOUTHERN LOWLANDS
RESISTIVITY AT 300m DEPTH
N
Laugarvatn
Apavatn
Þingvallavatn
Úlfljótsvatn
Hellisheiði
Hveragerði
Eyrabakki
Stokkseyri
Þorlákshöfn
Stóra-Laxá
Þjórsá
20
40
80
0
5
10km

Fig. 6


SOUTHERN LOWLANDS
RESISTIVITY AT 500m DEPTH
N
Laugarvatn
Apavatn
Þingvallavatn
Úlfljótsvatn
Hellisheiði
Hveragerði
Þorlákshöfn
Eyrarbakki
Stokkseyri
Brúará
Stóra-Laxá
20
40
80
0
5
10km

Fig. 7

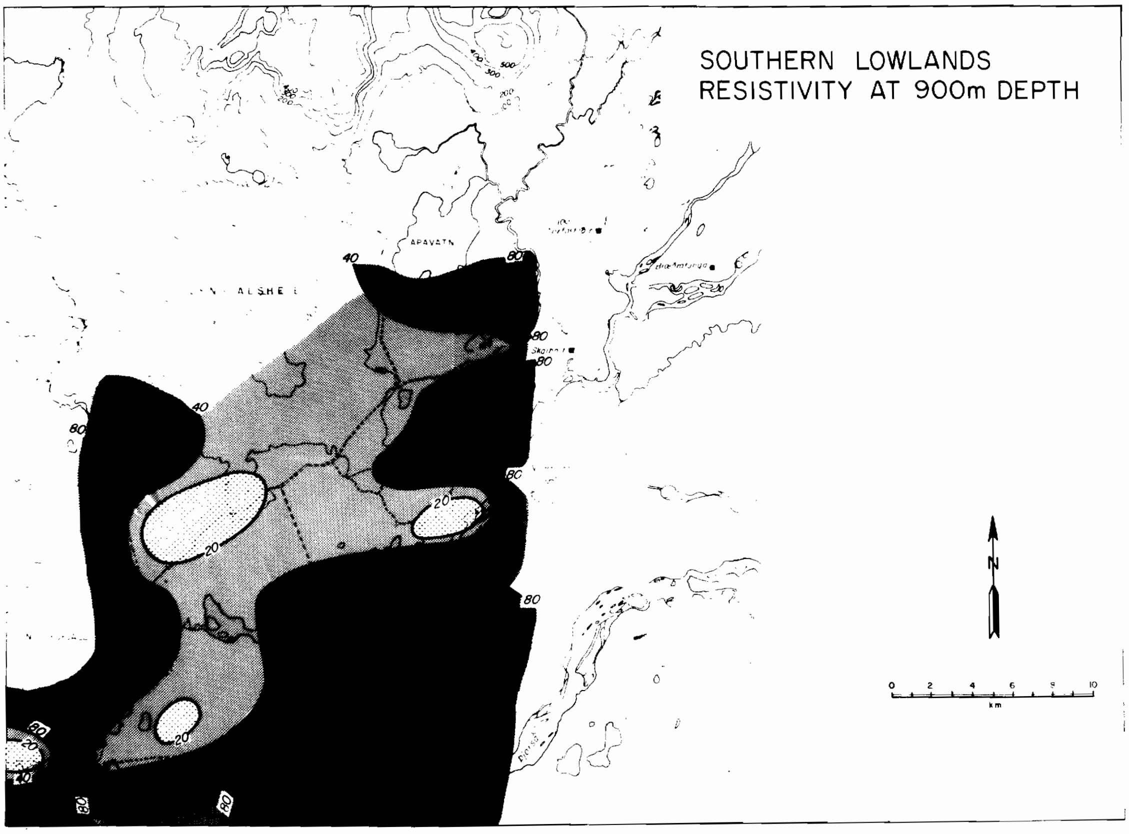
SOUTHERN LOWLANDS
RESISTIVITY AT 900m DEPTH
APAVATN
400
500
300
200
100
40
80
20
Skálholt
N
0
2
4
6
8
10
km

Fig. 8

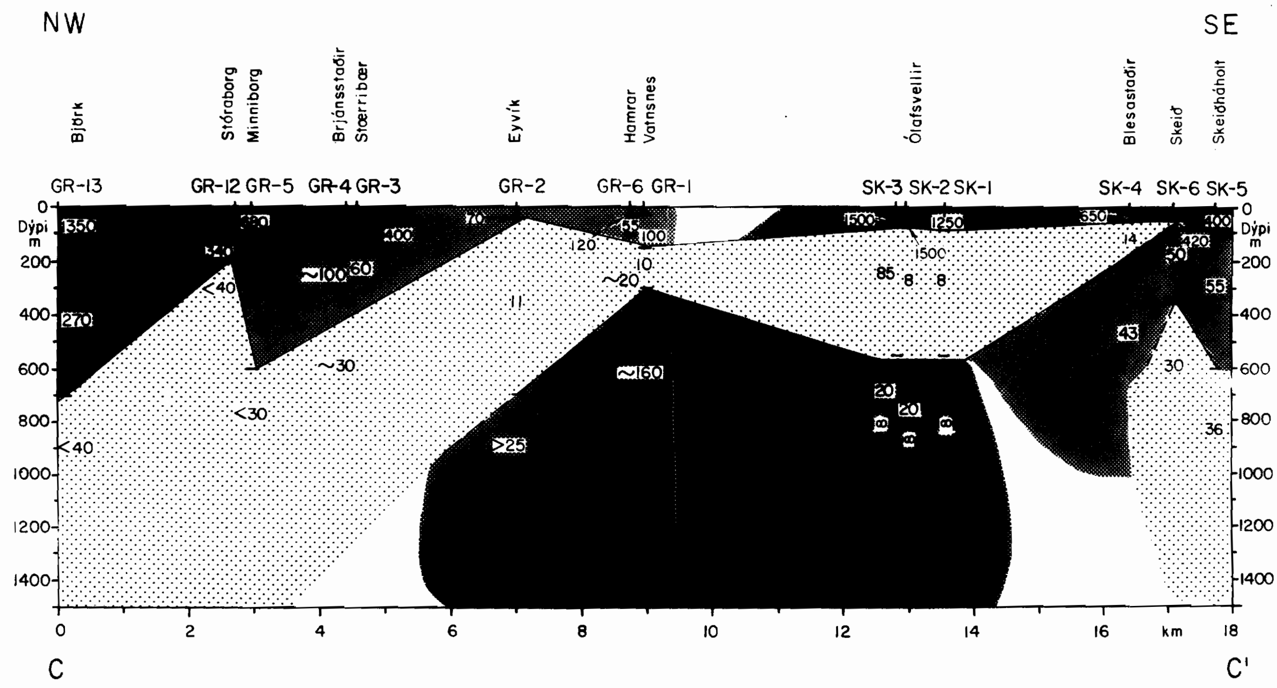
NW
SE
Björk
Stóraborg
Minniborg
Brjánsstaðir
Stœrribœr
Eyvík
Hamrar
Vatnsnes
Ólafsvellir
Blesastaðir
Skeið
Skeiðháholt
GR-13
GR-12
GR-5
GR-4
GR-3
GR-2
GR-6
GR-1
SK-3
SK-2
SK-1
SK-4
SK-6
SK-5
Dýpi
m
0
200
400
600
800
1000
1200
1400
1350
270
<40
340
380
<40
~100
60
400
~30
<30
70
11
55
100
120
10
~20
~160
>25
1500
1250
1500
85
8
8
20
20
18
18
18
650
14
400
420
50
55
43
30
36
0
2
4
6
8
10
12
14
16
km
18
C
C'

Fig. 9

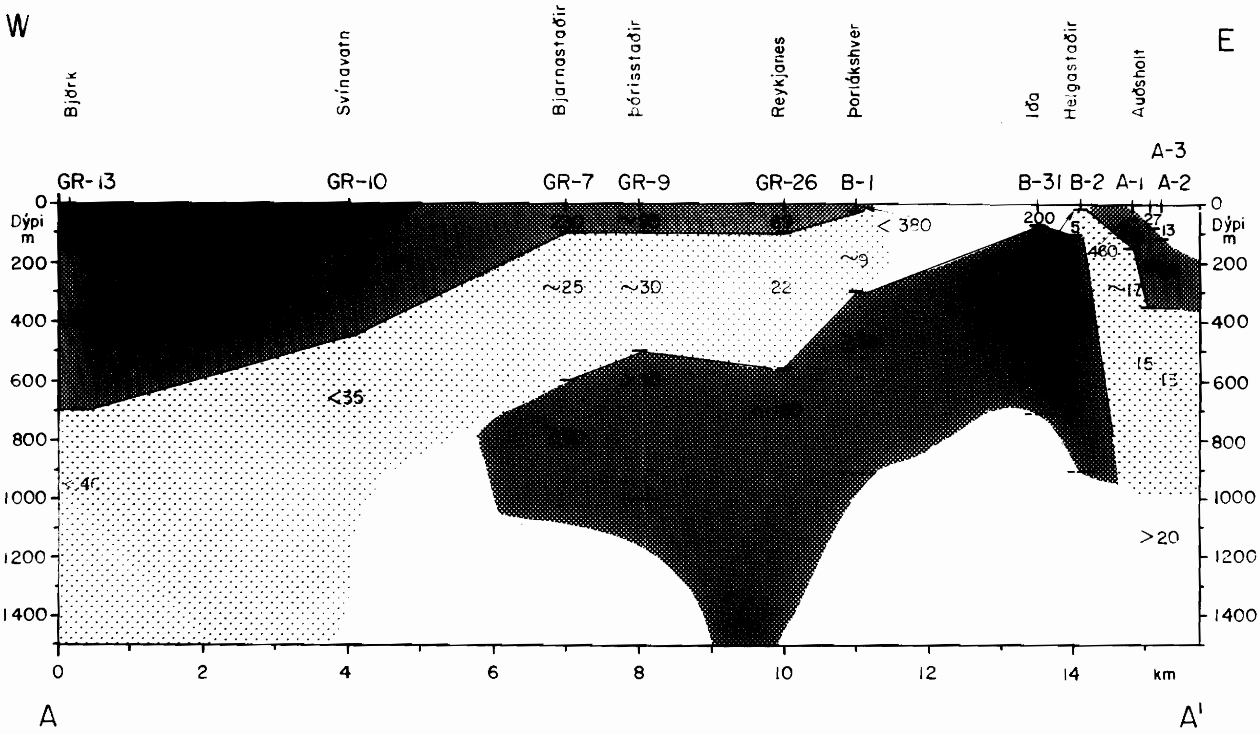
W
E
Björk
Svínavatn
Bjarnastaðir
Þórisstaðir
Reykjanes
Þorlákshver
Iða
Helgastaðir
Auðsholt
GR-13
GR-10
GR-7
GR-9
GR-26
B-1
B-31
B-2
A-1
A-3
A-2
0
Dýpi
m
200
400
600
800
1000
1200
1400
< 380
~9
~25
~30
22
<35
~40
200
5
460
27
13
~17
15
13
>20
0
2
4
6
8
10
12
14
km
A
A'

Fig. 10

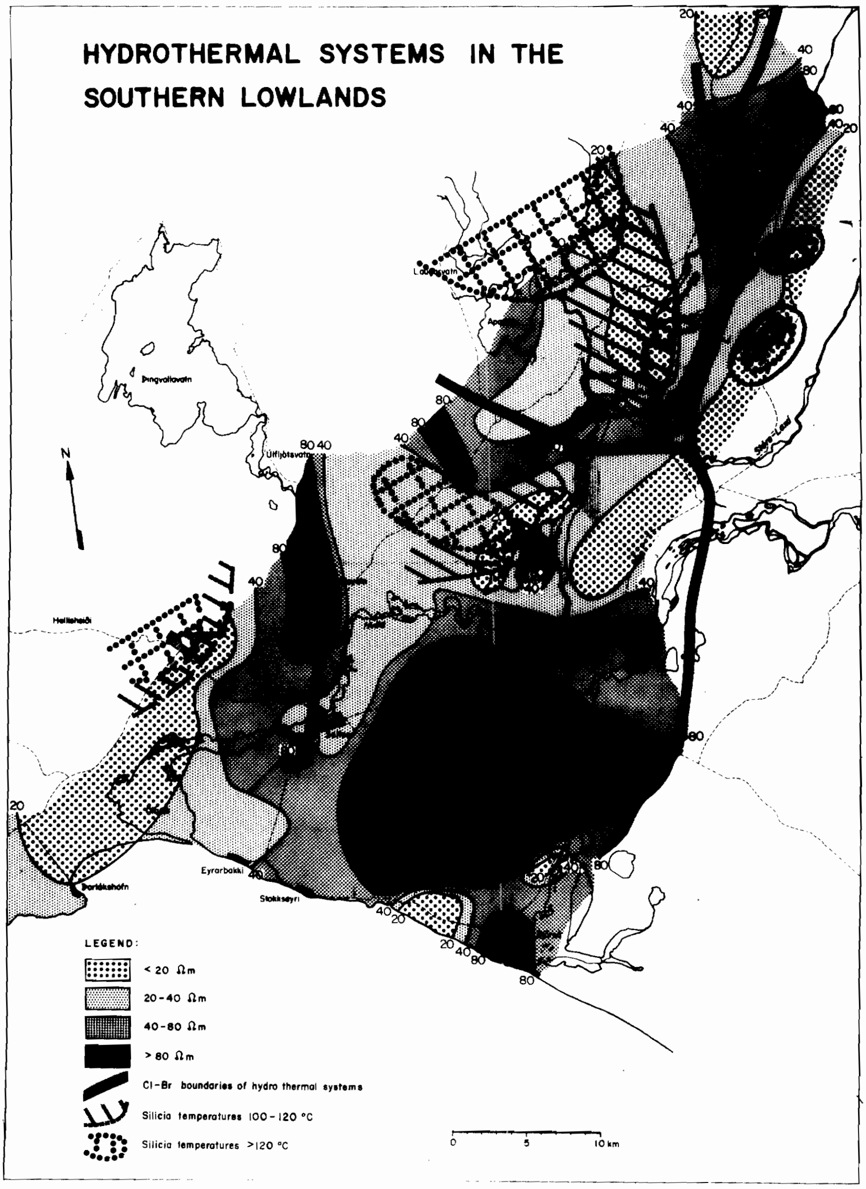
HYDROTHERMAL SYSTEMS IN THE SOUTHERN LOWLANDS
N
Þingvallavatn
Úlfljótsvatn
Hellisheiði
Þorlákshöfn
Eyrarbakki
Stokkseyri
LEGEND:
< 20 Ωm
20-40 Ωm
40-80 Ωm
> 80 Ωm
Cl-Br boundaries of hydro thermal systems
Silicia temperatures 100-120 °C
Silicia temperatures >120 °C
0
5
10 km
20
40
80

Fig. 11

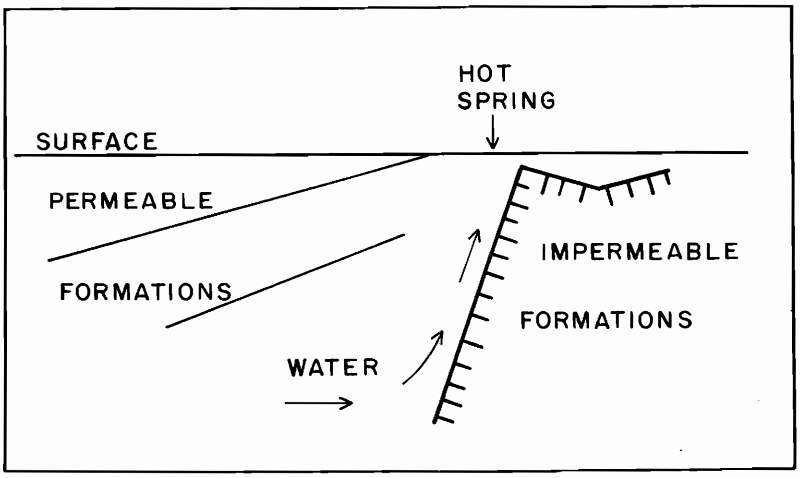
HOT
SPRING
SURFACE
PERMEABLE
FORMATIONS
IMPERMEABLE
FORMATIONS
WATER

Fig. 12

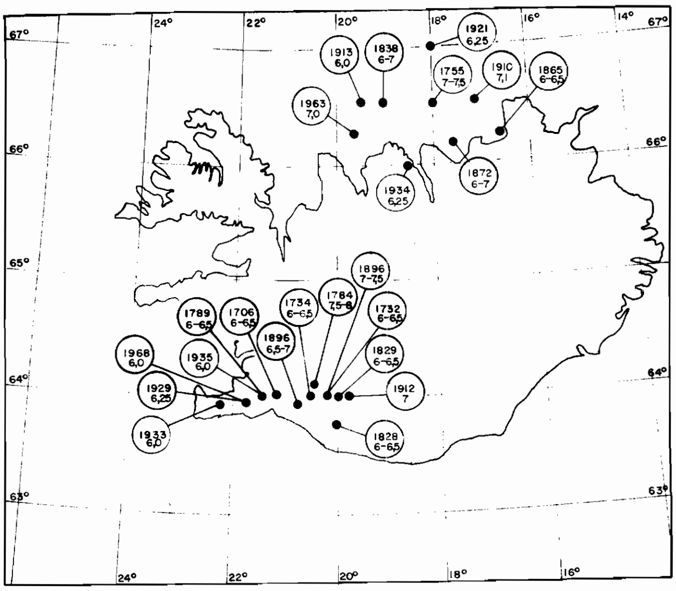
24°
22°
20°
18°
16°
14°
67°
66°
65°
64°
63°
1921 6,25
1913 6,0
1838 6-7
1755 7-7,5
1910 7,1
1865 6-6,5
1963 7,0
1934 6,25
1872 6-7
1896 7-7,5
1784 7,5-8
1734 6-6,5
1732 6-6,5
1789 6-6,5
1706 6-6,5
1896 6,5-7
1829 6-6,5
1968 6,0
1935 6,0
1929 6,25
1912 7
1933 6,0
1828 6-6,5

Fig. 13