HOT SPRINGS AND THE EXPLOITATION OF NATURAL HEAT RESOURCES IN ICELAND

by

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INTRODUCTION

Numerous hot springs and other manifestations of geothermal activity constitute some of the most interesting features in the physical characteristics of Iceland. The hot springs are of great interest from the scientific as well as from the economic point of view.

Since the middle of the past century a number of geologists and geophysicists have devoted a considerable effort to the study of the geothermal phenomena in Iceland. The introduction of modern concepts and methods has led to a relatively coherent picture of the conditions.

The modern exploitation of natural heat resources in Iceland was initiated in 1925. The first step consisted in the heating of a few buildings and greenhouses in a location near Reykjavik, the capital of the country. A relatively rapid development has followed. As now about 45 000 people live in houses heated by natural heat. Moreover, there is a substantial number of greenhouses and swimming pools heated by natural heat. A large scale utilization of natural steam is now planned for the generation of electric power and for industrial heating.

Drilling for hot water was initiated in 1928. As now a total of more than 60 000 meters have been drilled for this purpose. The maximum depth drilled is 2 200 meters.

Modern geological, geophysical and geochemical exploration methods are now being applied in the prospecting for the natural-heat resources. Electric, magnetic, gravity and thermal methods have been applied on a large scale with considerable success. A study of the chemical and isotopic composition of the natural water and steam has revealed a number of important facts.

The paper will give an account for the geological and geophysical basis of the exploration methods and report a few results.

GEOLOGY AND THE DISTRIBUTION OF HOT SPRINGS

Iceland is a part of the Brito-Arctic basalt province. The total series of flood basalts in Iceland is believed to reach a thickness of several kilometers.

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1) State Electricity Authority, Reykjavík.

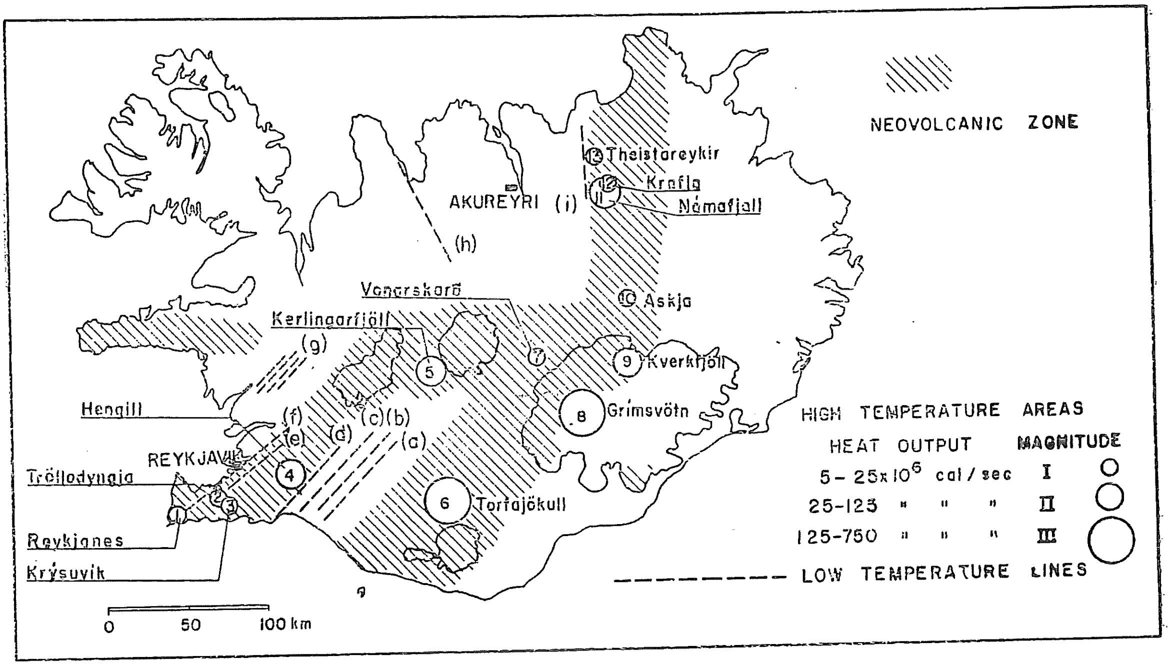

Fig. 1 Zones of recent volcanism and major thermal activity in Iceland.

The underlying formations are not known but recent seismic work by Båth (1960) appears to reveal a structure in the western parts of the country as shown in Table 1.

TABLE 1.

Crustal structure in western-Iceland.

	Thickness	P-velocity
Flood basalts	2.1 km	3.69 km/sec
Second layer	15.7	6.71
Third layer	10.0	7.38

The figures are to be regarded as average figures mainly the thickness of the flood basalts. A conspicuous feature is the total absence of a continental or so-called granitic layer.

The Tertiary basalt plateau outcrops in the western, northern and eastern parts of Iceland. The central and southern parts are, on the other hand, covered by Quaternary lava flows and tuffs, which no doubt rest on the Tertiary basalts. Post-Glacial volcanism is confined to these Quaternary districts which may be defined as the Neo-Volcanic Zone of Iceland. (See Fig. 1).

Low-temperature activity. A great number of hot springs are found in the western and the northern Tertiary districts. In a number of cases the springs are distributed in a linear pattern as shown in Fig. 1. Generally they issue only hot water and, therefore, it may be concluded that the temperature of the ascending water does not exceed 100° C very much. Thermal activity of this type is now being defined as the low-temperature activity.

There are about 250 thermal areas of this type with a total of more than 600 major springs. The integrated flow amounts to some 1 500 litres per second, and the integrated sensible (above 4° C) heat transport has been found to amount to some 10^8cal/sec, that is, the average temperature is 75° C.

Some data on the main low-temperature lines are given in Table 2.

TABLE 2.

Major low-temperature thermal lines in Iceland.

Line (see Fig. 13)	Total natural flow liters/sec	Max surface temp. ° C	Heat output magnitude	Remarks
(a)	52	100	I	
(b)	140	100	I	
(c)	60	100	I	Includes the Great Geysir, borderline case.
(d)	70	100	I	Borderline case
(e)	120	83	I	Base temp. at Reykir 98° C, 70 wells at Reykir, max depth 1 380 meters. Output of wells 320 liters/sec at 87° C.
(f)	12	87	I	Base temp. in Reykjavík 146° C, 34 wells in Reykjavík, max depth 2 200 meters. Output of wells 100 liters/sec at a max temp. of 138° C.
(g)	400	100	II	System of lines. Includes largest hot water spring at Deildartunga
(h)	70	89	I	
(i)	145	100	I	Borderline case

High-temperature activity. Large scale thermal activity is found in 13 locations in the Neo-Volcanic Zone as shown in Fig. 1. These thermal areas are characterized by a great number of steam holes and large areas of hot ground. Hot-water springs are generally absent.

These conditions imply the upflow or convection of water of a very high temperature, that is, above 200° C. The thermal activity of the Neo-Volcanic Zone is, therefore, classified as the high-temperature activity.

A list of the high-temperature areas and their main characteristics is given in Table 3.

It is quite difficult to estimate the total outward transport of heat by the high-temperature areas. Present estimates amount to about 10^9cal/sec, that is, about 10 times the figure for the low-temperature activity.

It must be underlined that the above grouping of the thermal areas is uncertain in a number of cases. In the low-temperature group are included a number of borderline areas with a relatively high subsurface temperature. These areas are located at the border of the Neo-Volcanic Zone and may as well belong to the high-temperature group.

A detailed description of many thermal areas in Iceland has been given by Barth (1950).

TABLE 3.

High-temperature thermal areas in Iceland.

Name (see Fig. 13)	Elvation m	Area km2	Heat Output magnitude	Remarks
(1) Reykjanes	15	1	I	One well 162 m deep.
(2) Trölladyngja	120	5	I	
(3) Krýsuvík	150	10	I	15 well, max. depth 1 200 m. Base temperature ca. 220° C.
(4) Hengill	30 – 600	50	II	Base temperature ca 215° C. Numerous shallow wells, 5 deep wells, max depth 1 200 m.
(5) Kerlingarfjöll	900	5	II	
(6) Torfajökull	900	100	III	
(7) Vonarskarð	1 000		I	
(8) Grímsvötn	ca. 1 000	12	III	Under the Vatnajökull ice sheet.
(8) Kverkfjöll	1 500	10	II	
(10) Askja	1 050		I	
(11) Námafjall	350	2.5	II	A few shallow wells.
(12) Krafla	450	0.5	I	
(13) Theistareykir	330	2.5	I	

THE PHYSICAL CHARACTERISTICS OF THE HYDROTHERMAL SYSTEMS

A considerable amount of work has been devoted to the study of the thermal activity in Iceland. The well known works of Thoroddsen (1925), Thorkelsson (1940), Einarsson (1942), Sonder (1941) and Barth (1950) may be mentioned. These works are based on results obtained prior to 1940.

The increasing exploration and exploitation during the past decade has furnished new results as published by the present author (Bodvarsson 1950, 1951, 1956 and 1957). The present paper is to a large extent based on these results.

Basic concepts. In general, the hot springs of Iceland appear to be outlets for large hydrothermal circulation systems. Each system has to be composed of (I) an area, or areas, of recharge and downward percolation, (II) a zone of subsurface flow and heating and (III) zones of ascend and discharge which comprise the thermal areas. A single hydrothermal system may include a number of zones of outflow and thus generate a number of thermal areas.

On this basis the geological and physical conditions in hydrothermal systems may be characterized by the following main factors.

(1) The structural control.
(2) The nature of the heat source.
(3) The temperature of the water at the end of the heating zone which will be called the base temperature of the system.
(4) The total transport of water and heat through the system.
(5) The total amount of surplus heat accumulated in the discharge zone.

In the following the discussion will be based on these concepts.

Structural control. The seismic results given in Table 1, indicate a relatively sharp velocity contrast between the flood basalts and the underlying formation. The P-velocity jumps from 3.7 to 6.7 km/sec. The lower formation appears to be a very dense and, therefore, impermeable formation. Consequently, the circulation of water appears to be confined to the flood basalts. In the western parts of Iceland the maximum base depth should generally not exceed 2.0 to 2.5 km.

The permeability of the flood basalts is controlled by three structural conditions, that is, (1) permeable contacts between lava flows, (2) permeable dikes and sills and (3) permeable faults. The lava-contacts and the sills appear to furnish the main horizontal channels, whereas the dikes and the faults furnish the vertical passages.

A considerable part of the low-temperature areas is controlled by basaltic dikes, mainly in the northern parts of the country. The dikes often form relatively narrow swarms of a considerable length. It is possible that the low-temperature lines discussed above and shown in Fig. 1 are controlled by swarms of this type. The individual low-temperature lines may consequently represent separate hydrothermal systems.

The high-temperature areas, on the other hand, appear to be controlled by faults and fissures of relatively recent age. These areas are generally located in regions of recent volcanism and high seismicity. Many of the structures may have been formed or reopened in very recent times.

It is possible that the isostatic upwarping of Iceland at the end of the Pleistocene may have influenced the general permeability conditions in the flood basalts. The stresses which were induced by the differential movement of the individual blocks may have formed new faults, and also reopened old passages in faults and along dikes.

The heat source. The general volcanic character of Iceland immediately suggests a connection between the thermal activity and the volcanism. As a matter of fact, the volcanic processes could influence the subsurface temperature field and build up the heat sources of the thermal areas.

There appears little doubt that many of the high-temperature areas draw directly on volcanic sources of heat. On the other hand, the majority of the low-temperature areas appears to have little or no direct connection to local volcanism. This will be discussed in some detail.

The case of the high-temperature areas is relatively simple. All areas of this type are located in regions of post-Glacial and some cases very recent volcanism. The fissures controlling the areas are closely connected to the volcanic structures. Moreover, subsurface temperature of more than 200°C has been observed in shallow wells in these areas. It would be quite difficult to account for the high temperatures without relying on the presence of volcanic structures of a very recent age.

On the other hand, it is to be emphasized that the chemical and the isotopic composition of the thermal water in the high-temperatures areas is not indicative of any juvenile components in the water. Moreover, it would be quite difficult to account for the heat transport of the large areas on the basis of a heat supply by juvenile water. Therefore, it must be assumed that the circulating water has a direct contact with the source rock.

The heat supply of the low-temperature areas is closely connected to the physical conditions in the Tertiary districts. These parts of the country have apparently not been subjected to local volcanism through the Quaternary period at least. Intrusives with elevated temperatures are, therefore, not to be expected in these districts.

On the other hand, the temperature conditions in the Tertiary districts appear to be abnormal if compared to known continental conditions. Temperature measurements in both shallow and deep holes (depth up to 2 200 meters) indicate a temperature of 100°C to 150°C at a depth of 2 000 meters, that is, at the bottom of the flood basalts.

The general indications are that the average outward conduction flow of terrestrial heat in the Tertiary districts amounts to about 2 to 3 microcal/cm^2sec. This is two or three times the average for the continents.

Higher figures are observed in some areas of the Tertiary districts. For example, figures of 4 to 6 microcal/cm^2sec have been observed in a few shallow wells in the western parts of the country. These conditions may be induced by the rapid erosion during the Pleistocene (Bodvarsson 1957).

The temperature conditions in the Tertiary districts imply that water circulating to the lower parts of the flood basalts can be heated to a temperature of 100° C or more. Water percolating down through dikes and faults is heated by a contact with the hot rock and ascends again either by hydrostatic head or by convective movements.

On the other hand, it is to be realized that the heat supply is of a transient nature. The rock adjacent to the channels of flow is gradually cooled and the heat supply to the circulating water decreases gradually.

In fact, it would be difficult to account for the heat supply of the largest low-temperature springs on the basis of a stationary heat supply. For example, the large spring at Deildartungu in Borgarfjördur issues about 250 litres per second of water at 100° C corresponding to a heat transport (above 4°) of 2.4×10^7 cal/sec. By a stationary outflow of terrestrial heat of the order of 2 to 3 microcal/cm^2 sec, the spring would theoretically have to drain the heat supply through an area of some 1 000 square kilometers. Actually, the heat take-up is incomplete and the area drained has to be considerably greater. This appears unreasonable especially in view of the fact that there is a number of other springs in the vicinity of the Deildartunga spring.

The base temperature. Both physical and chemical data furnish information on the base temperature.

The temperature of the ascending water decreases because of (1) heat losses to the walls of the channels of flow, (2) intermixture with cold surface water and (3) flashing in the case of water with temperatures above 100° C. The base temperature can be inferred on the basis of a reasonably correct estimate of the temperature drop due to these factors.

These factors are effective mainly in the upper few hundred meters. In general, the temperature of the water at a depth below 500 to 1 000 meters will be close to the base temperature, which can, therefore, also be measured in deep wells.

Of considerable interest is the fact that the base temperature appears to affect the chemical composition of the hot water, mainly the SiO_2 content. A survey of data from the low-temperature areas gives the following average relationship

$$SiO_2 \text{ in parts per million} = 25 + T_b,$$

where T_b is the base temperature in degrees C. The relation appears to hold for the leaching of SiO_2 from basaltic rock for T_b up to 200° C.

This phenomenon may be understood on the basis of the fact that the saturation of the water by SiO_2 depends on the temperature and the precipitation following a cooling of the water is a very slow process. If equilibrium has been reached at T_b a subsequent cooling of the water will not affect the SiO_2 content for a considerable time. The above relation has been quite useful in the study of individual areas. Base temperatures up to 217° C have been measured in boreholes.

The total transport of heat and water. Natural heat escapes from thermal areas in the following ways, (1) as the sensible heat content of hot water and steam issued at the surface, (2) by conduction from hot ground to the air, (3) by conduction from the channels of flow and (4) by underground drainage of water.

The first two factors appear to predominate. In principle there are no major difficulties in measuring the heat escaping at the surface. However, the field work involved is quite substantial and accurate determinations have not yet been carried out in any of the high-temperature areas in Iceland. The situation is better in the case of the low-temperature areas as the sensible heat content of the water predominates there, and this factor can be measured relatively easily.

On the other hand, the heat escaping from the high-temperature areas has been estimated on the basis of relatively rough methods and the results are given in Table 3. The estimate of the total heat escaping per unit time from the individual areas is given on the basis of the following magnitude scale:

Magnitude	Total heat output
I	5 – 25x10^6 cal/sec
II	25 – 125
III	125 – 750

In Table 2 the same scale is applied in the case of the low-temperature areas although more accurate figures can be given.

The accumulation of heat in the discharge zone. The rock formations in the discharge zones of the thermal areas are heated by the ascending hot water and steam. Mainly the high-temperature areas include large volumes of rock heated to elevated temperatures. The discharge zones of these areas, therefore, contain a substantial amount of surplus heat.

Rough estimates indicate that in the case of individual areas the surplus heat accumulated divided by the total heat transport gives a time of accumulation of several thousand years. The surplus heat is, therefore, a substantial part of the total heat transport during post-Glacial time.

THE HEAT RESERVOIR

The extensive drilling for hot water in a few areas in Iceland has revealed the interesting fact that the heat flow produced by the wells may be a multiple of the natural output of the area before drilling. This poses the problem of the origin of the additional heat and water.

It is possible that the wells may induce a considerable decrease of the natural impedance of the flow and thus lead to an increased general circulation in the entire hydrothermal system.

On the other hand, a transitory increase of the flow may also be obtained on the basis of the large amount of heat accumulated in the discharge zones of the individual areas. The density of water decreases with increasing temperature mainly above 100° C. The density of water at 100° C is 0.96 gr/ml, at 200° C 0.87 and at 250° C only 0.80. Therefore, cold water in the formations surrounding the thermal areas has a tendency of encroaching on the hot water within the discharge zone and drive it out. However, the cold water entering the hot rock is heated by the contact with the rock and new hot water is formed. This transitory circulation can, therefore, be maintained by the surplus heat in the rock and will last as long as there is surplus heat present.

Moreover, the steam flow from wells in high-temperature areas may partially depend on the boiling of pore-water in the hot rock. Porous rock at temperatures above 100° C and saturated with water can act as a heat reservoir in a somewhat different way. Wells drilled into the rock may induce a decrease of pressure and a subsequent boiling of the water in the pores. At a not too great porosity the boiling will largely depend on the heat content of the rock. As a matter of course, the temperature of the rock has to be near to the boiling temperature of water at the depth of the rock formations.

Both types of heat reservoirs may be encountered in the high-temperatures areas. A detailed discussion of the conditions in the Hengill thermal area in south-western Iceland has been given by the author (Bodvarsson 1951). An interesting discussion of similar conditions in the Wairakei thermal area in New-Zealand has been given by Studt (1958).

The present author (Bodvarsson 1956) has estimated the total potentialities of thermal areas in Iceland for power production at some 300 megawatts steady power and a recoverable heat reservoir of some 15 000 megawattyears.

UTILIZATION OF NATURAL HEAT

The utilization of natural heat for domestic and greenhouse heating was initiated in the early twenties. This industry is in the state of a considerable expansion. As now about ¼ of the population of Iceland lives in houses heated by natural heat and it may be possible to increase this ratio up to about ½ in relatively near future.

The Reykjavík Hot Water Supply system is the main installation of this kind. About 41 000 inhabitants of the city are served. The system derives about 320 liters per second of water at 87° C from wells in the thermal area at Reykir, some 10 miles north-east of the city, and about 100 liters per second of water with temperatures up to 138° C from wells within the city. Some data on these thermal areas are given in Table 2.

Outside Reykjavík there are 3 smaller communities with central heating installations based on natural heat resorces.

A natural steam power plant of a capacity of 15 000 kw is now being planned and is expected to be built in 1963 at Hveragerdi in the Hengill thermal area.

DRILLING METHODS

The rotary method is now applied for the drilling of steam wells as well as the major hot water wells. The basalts of the thermal areas have been subjected to thermal alteration and are a rock of medium drillability. The drilling rate of the rotary method in wells of a diameter of 220 mm varies from 1 to 10 meters/hour depending on the degree of alteration. Overall drilling rate is about 1 000 meters/month.

A natural steam power plant of a capacity of 15,000 kw is now being planned and is expected to be built in 1963 at Hveragerdi in the Hengill thermal area.

THE HIGH-TEMPERATURE ACTIVITY IN THE VICINITY OF REYKJAVIK

The main high-temperature activity in the vicinity of Reykjavík is located in the Hengill-area at the Mount Hengill and in Krysuvik. These areas are located 40 km east respectively 30 km south of the city. The areas are of special importance and will, therefore, be discussed in some detail.

The Hengill-area

Geography. The main geographical features of the Hengill area are given in Fig. 2. The area is located between the Lake Thingvalla in the North and the Olfus-flatland in the South. This is a relatively rugged terrain with a maximum elevation of 803 meters in the Mount Hengill. The area is an extension of the volcanic region of the Reykjanes-peninsula. It is completely uninhabited with the exception of the Olfus-valley in the South where the community of Hveragerdi is located. A few farms are at the shore of Lake Thingvalla.

Geology. The entire area is built up of palagonites and other basic tuffs as well as basaltic lava flows. These formations are probably of a Quaternary age. The tuffs are in many locations highly altered by the thermal activity.

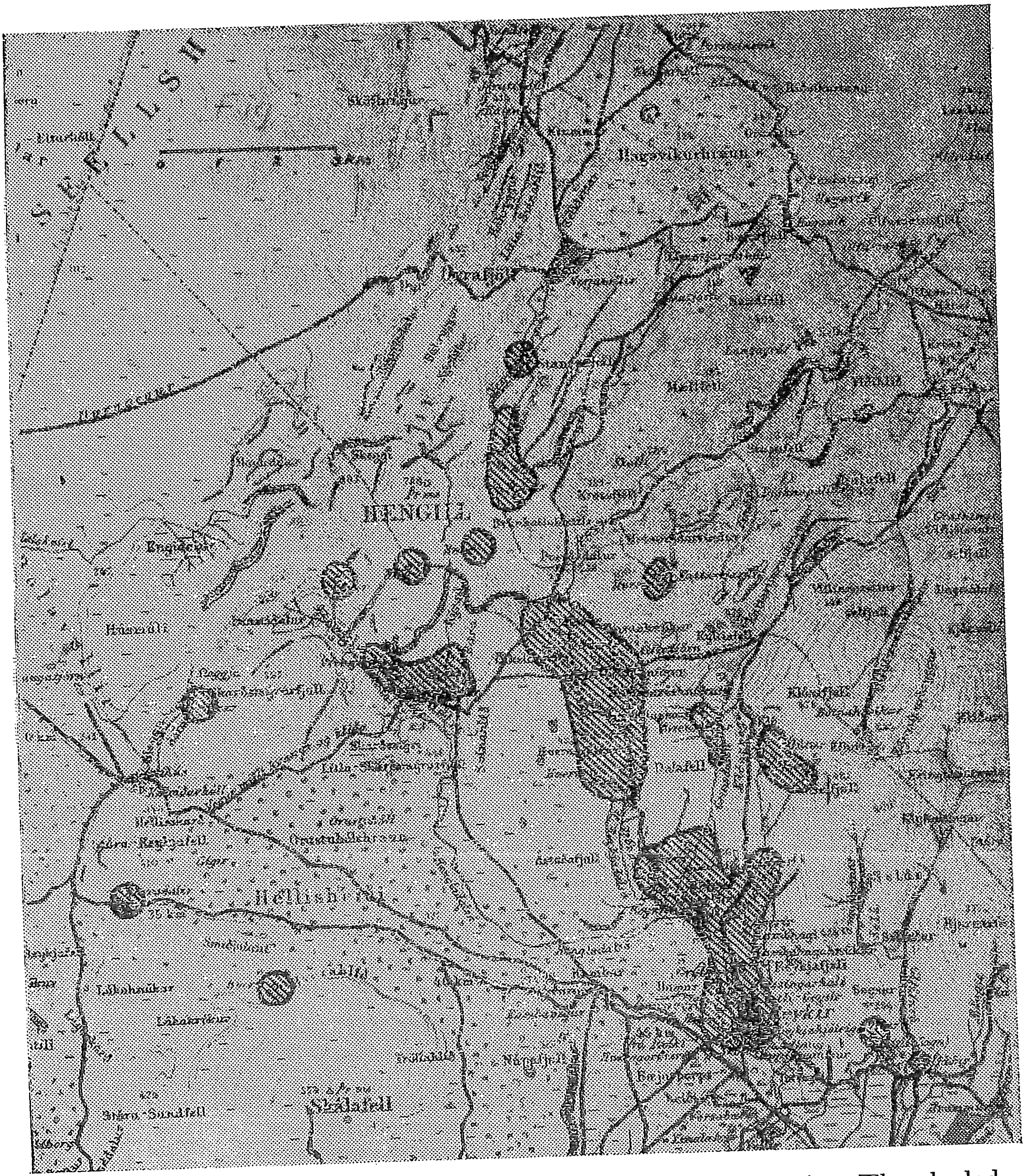

Fig. 2. The thermal area in and around the Hengill Mountains. The shaded areas are zones of surface activity.

Volcanism and tectonic forces lave been very active in the area. The most recent eruption tock place around 1,000 A.D. This eruption was a typical fissure eruption. The fissure is clearly visible from the road through the area.

The area has a high degree of seismicity. There are conspicuous fault lines which extend to the Thingvalla-region in the North where they are magnificently displayed. The Thingvalla-graben was probably formed several thousand years ago.

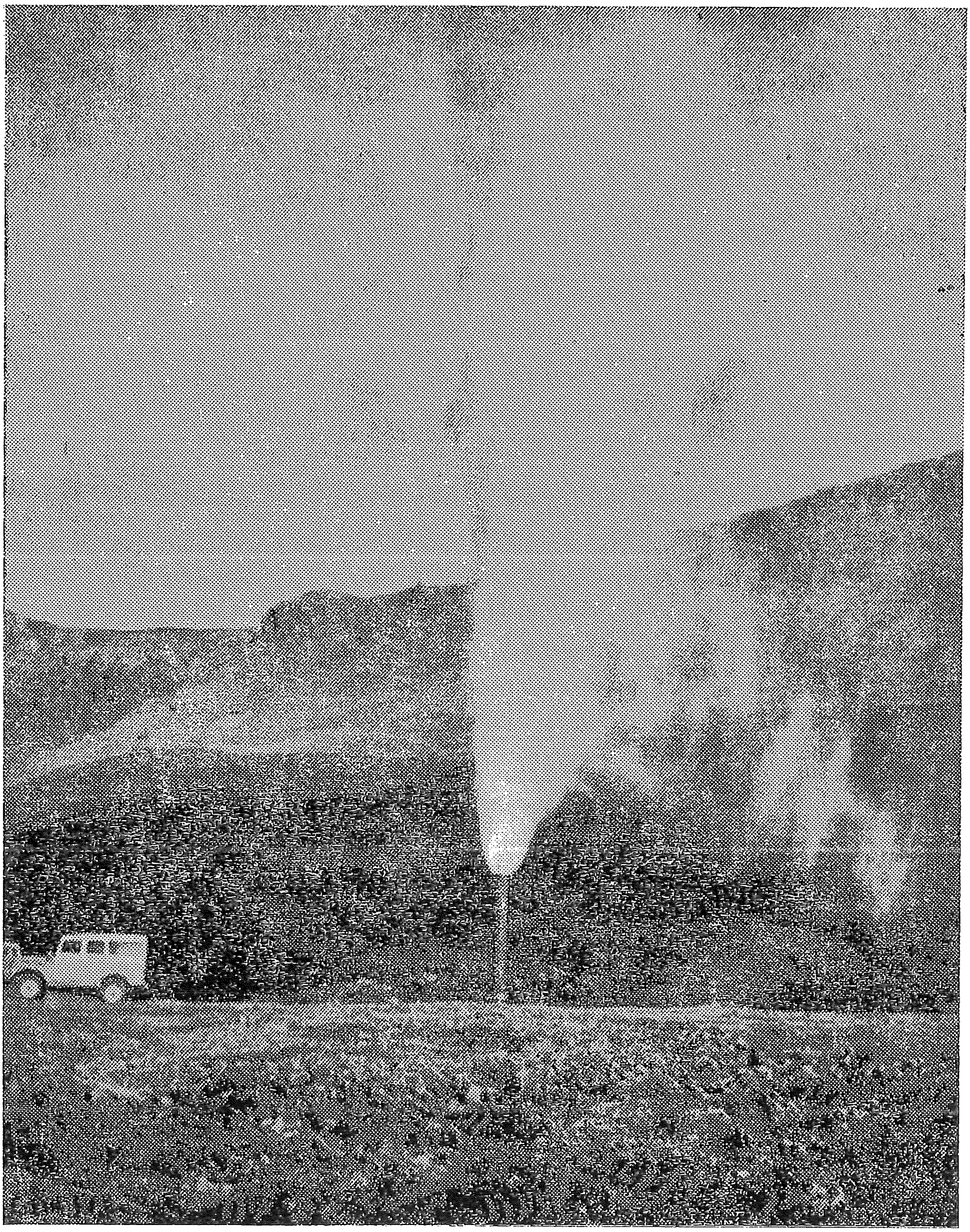

Fig. 3. Well no. (2) at Hveragerdi.

Hot springs and steam holes. The Hengill-area is the only high-temperature area where both hot-water springs and steam holes are present. The springs are found within an area of some 50 km². The hot springs, mostly issuing boiling water, are located at an elevation of 40 to 60 meters in the

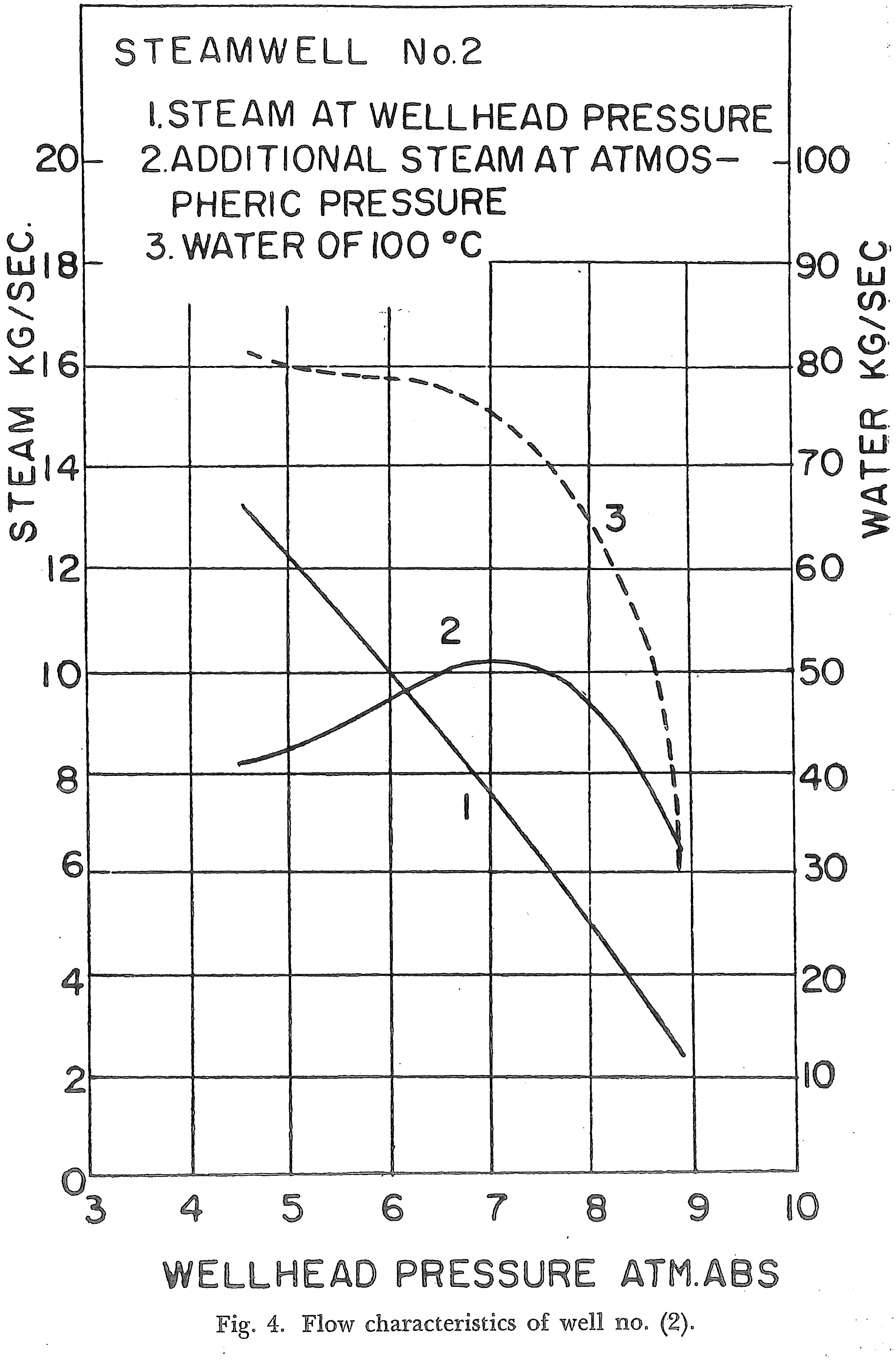

Fig. 4. Flow characteristics of well no. (2).

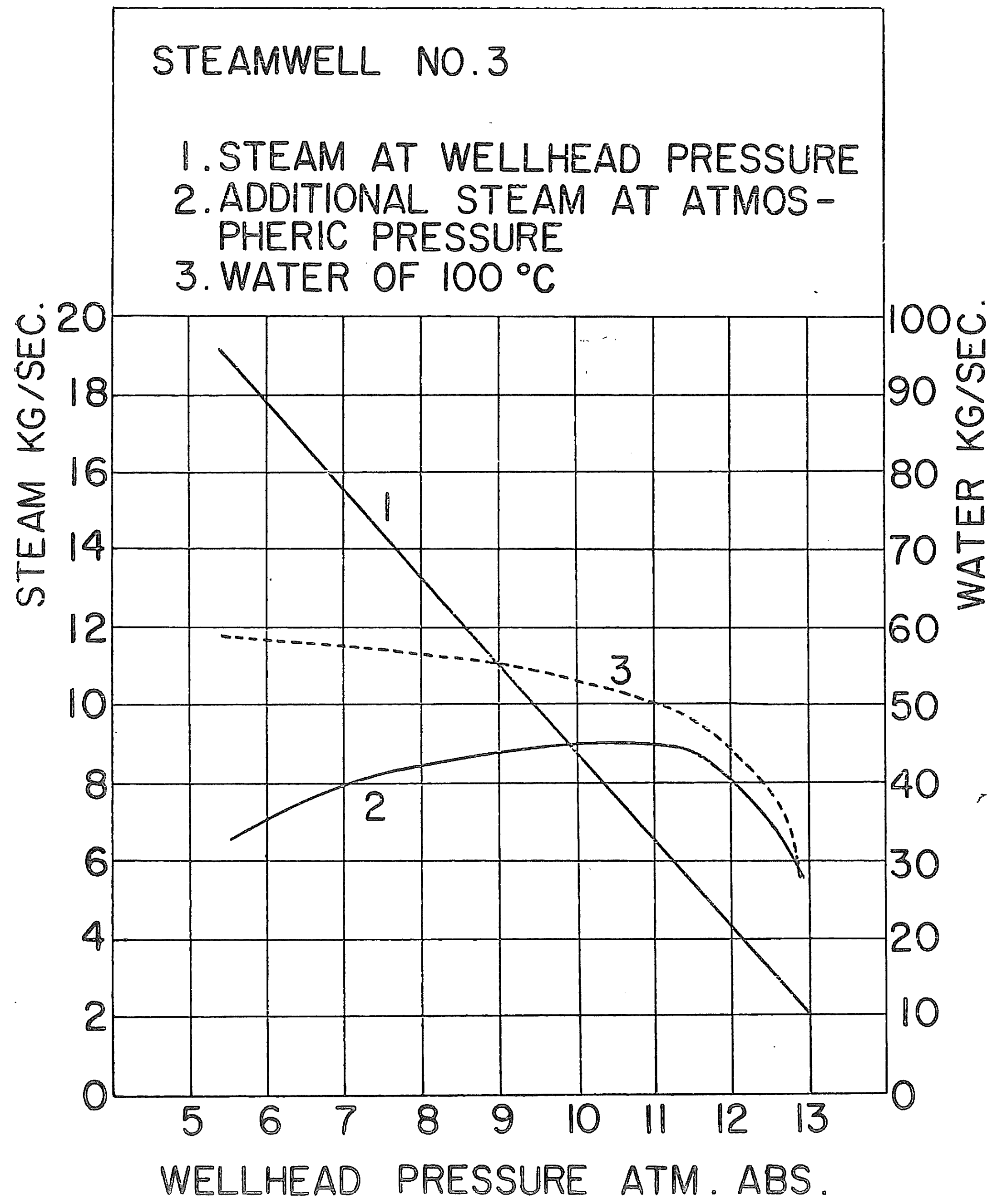

Fig. 5. Flow characteristics of well no. (3).

Olfus-valley, that is, on the lowland around and north of Hveragerdi. The hot springs are very numerous and are characterized by a high degree of thermal alteration of the surrounding rock and large amount of silica-sinter. The total integrated natural flow has varied from 50 to 100 liters per second.

The steam holes are scattered over the entire area. Some are located at the tops of mountains at an elevation of 500 to 600 meters. The rock surrounding the steam holes is completely altered by the thermal activity.

Hydrology. The flow of subsurface water through the area is probably

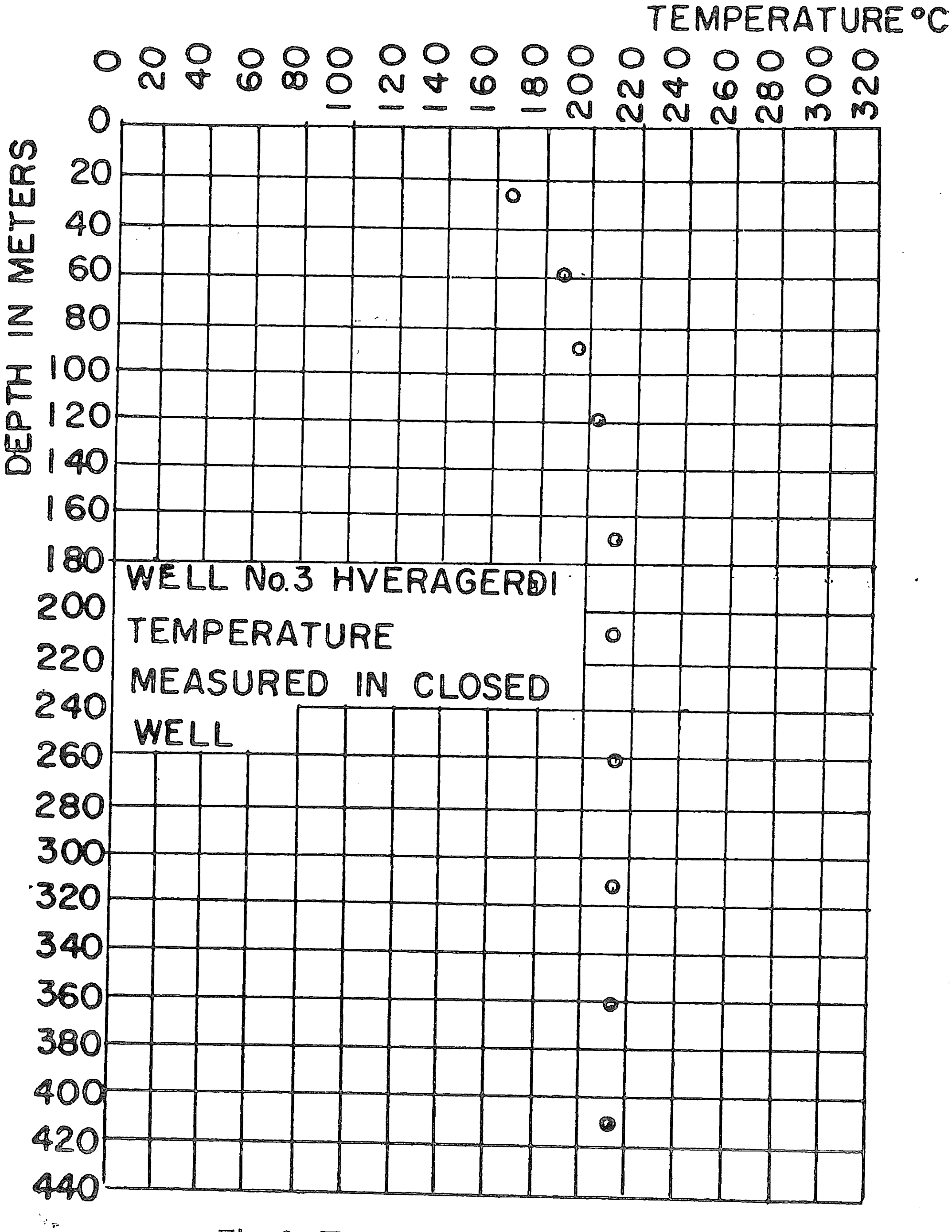

Fig. 6. Temperature in well no. 3.

controlled by the large fault lines displayed in the northern parts. The Lake Thingvalla has an elevation of 103 meters. Water from the lake probably percolates through the permeable structures and is discharged by the hot springs at Hveragerdi.

Heat Output. The total heat escaping from this area has been estimated as follows (Bodvarsson, 1951).

Hot springs and steam holes	20x10⁶ cal/sec
Hot ground	35x10⁶ —
Total	55x10⁶ —

The figures are to be regarded as a very rough and probably a somewhat low estimate.

Accumulation of heat. Temperature measurements in wells in the southern parts of the area indicate a base temperature of not less than 220° C. On the other hand, the results of Båth, indicate a base depth of some 2 km and consequently a total volume of hot flood basalts under the area of 100 km^3.

Based on these figures the total amount of surplus heat accumulated in the flood basalts under the area can be very roughly estimated at some 10^{19} cal. As the total heat escaping per unit time has been estimated at some $55x10^6$ cal/sec the time of accumulation is found to be some 6,000 years.

Drilling. Numerous shallow wells have been drilled in and near to Hveragerdi. These wells have been utililized for the heating of homes and greenhouses. Most of them are less than 100 meters deep. The wells issue steam and water but are generally unstable and unreliable.

In 1958 a modern rotary rig was put into operation in the area. The rig has completed 5 wells with a main diameter of 9 inches. Four of the wells are producers whereas the fifth well was drilled mainly for the purpose of measuring the temperature at depth. The main data on the wells are given in Table 4 below.

TABLE 4.

Major wells at Hveragerdi

No.	Depth	Production depth	Production of water at free flow	
			quantity	temperature
(1)	660 meters	350 meters	10 liters/sec	
(2)	400 —	390 —	100 —	180° C
(3)	652 —	350 —	85 —	217
(4)	690 —	672 —	25 —	
(5)	1 200 —			

The data on the production are here given in terms of the inflowing water which has a temperature close to the base temperature of the area. The figures in Table 4 refer to the production into an open well, that is, when the pressure at the well-head is at minimum. Wells (2) and (3) are supercritical as the pressure measured at the outlet of the wholly open well is 3.8 respectively 3.0 atmosphere gauge. Well No. (2) is shown in Fig. 3. Data on the flow are given in Fig 4.

Moreover, Fig. 5 gives the flow characteristics of well (3) and Fig. 6 the temperature in the well.

Drilling of these wells has not presented any difficulties. The thermally altered rock is of a good drillability and drilling rates of 50 to 100 meters/day are common. The pressure of water and steam is controlled by the drilling mud. The wells have a surface casing and a main casing of 9—5/8 inches o.d. down to a depth of 200 meters.

Chemical composition of water and steam. Analyses of the water and steam from Hveragerdi are given in Tables 4 and 5. The samples were collected from one of the older shallow wells but the results are similar to less complete anlytical data obtained on samples collected from the new wells. The composition is similar in the major wells. It is to be realized that the data given on the water in Table 4 are not indentical with the composition of the thermal water flowing into the well. The sample was taken at the top of the blowing well and is, therefore, a residue after a flashing of the original thermal water.

TABLE 5.

Chemical composition of water from steam wells in the Hengill- and the Krysuvik-areas

Analyses: U.S. Geological Survey, Menlo Park, California

	Hengill-area *Well at Hveragerdi*	Krysuvik-area *Well at Seltun*
Date of coll.	Aug. 31st, 1958	Oct. 9th, 1958
SiO_2	283 ppm	425 ppm
Al	0.37	0.10
Fe	0.12	0.02
Mn	0.00	0.00
Cu	0.00	0.00
Pb	0.00	0.00
Zn	0.00	0.00
As	0.08	0.00
Ca	2.8	8.7
Mg	0.0	0.5
Na	174	500
K	10	68
Li	0.1	0.6
NH_4	0.1	0.0
HCO_3	24	0
CO_3	57	50
SO_4	72	67
Cl	152	735
F	2.1	0.7
Br	0.5	4.8

	Hengill-area *Well at Hveragerdi*	Krysuvik-area *Well at Seltun*
Date of coll.	Aug. 31st, 1958	Oct. 9th, 1958
I	0.0	0.1
NO_2	0.00	0.03
NO_3	0.0	0.4
PO_4	0.08	0.15
B	0.85	1.7
Sulfides as H_2S	5.2	7.0
Dissolved solids, residue at 180° C	913	2,030
Hardness as $CaCO_3$	0	0
pH	9.4	9.3
Specific conductance micromhos/cm at 25° C	941	2,760

TABLE 6.

Chemical composition of steam from wells in the Hengill- and the Krysuvik-areas
Analyses: Department for Natural Heat, Reykjavik

	Hengill-area *Well at Hveragerdi*	Krysuvik-area *Well at Seltun*
Liters gases per kilogram of steam	1.34	7.60
Composition of gases		
CO_2	1.21 liters	6.37 liters
H_2S	0.07	0.73
H_2	0.03	0.41
CH_4	0	0.01
Residue (N_2 etc.)	0.12	0.08

Ultimate capacity of the area. According to the estimates above the flood basalts under the area appear to contain about 10^{19} cal of surplus heat which is available for exploitation. Moreover, there is a steady influx of heat into the area.

The surplus heat corresponds to a quantity of $5x10^{10}$ tons of water at 200° C which by flashing at 100° C yields 10^{10} tons of steam. This gives $2x10^8$ tons per year during a period of 50 years, that is, about 23 000 tons per hour during the same time.

As a matter of course, the extraction of the heat can never be complete and only a fraction of the surplus heat can be utilized. Figures of a few per cent appear reasonable. This would give a steam flow of 500 to 1 000 tons/hour during a period of 50 years.

The above figures should represent a low estimate as the steady influx of heat into the area has not been taken into account.

It may at this juncture be remarked that the large low-temperature area at Reykir near to Reykjavík (line (e) in Table 2) has now been exploited for about 20 years. About $2x10^{16}$ cal have been extracted from this area during this period. The figure indicates an efficiency of extraction of a few per cent at least.

The Krysuvik-area

Geography and geology. The Krysuvik area belongs to the volcanic region of the Reykjanes-peninsula and, therefore, to the same general system as the Hengill-region. The main thermal area is located south of Lake Kleifarvatn which has an elevation of 135 meters. The area is uninhabited with the exception of the farm Krysuvik.

The area is built up of palagonites and other basic tuffs, sediments as well as basaltic lava flows. These formations are all of a Quaternary and partially post-Glacial age. Volcanism has been active in the area during post-Glacial time. Conspicuous lava cones are located south of the area and the large explosion crater Lake Graenavatn was formed during post-Glacial time. The lava flow Ogmundarhraun was erupted in historical time.

The Trolladyngja thermal area is located north-west of the Krysuvik area as shown in Fig. 7 where the geographical features of both areas are given. There may be little reason in treating them as separate areas as has been done there. The reason is more geographical than geological.

Steam holes and heat data. No hot-water springs are found in the Krysuvik area. On the other hand, there is a large number of steam holes. The activity is concentrated in two groups which are apparently controlled by recent faults which are separated by a distance of approximately 1 km.

The eastern group contains the Nyihver which is one of the largest steam holes in Iceland. This outlet was formed during an earthquake in 1924. The western group is concentrated along the eastern slopes of the Austurhals-ridge. The elevation of the hot springs varies from 150 to 300 meters.

The heat escaping from the Krysuvik-area amounts possibly to $1/5$ to $1/3$ of the Hengill-area, that is, to 10 to $20x10^6$ cal/sec. The surplus heat and the ultimate capacity of the area may possibly be computed on the basis of the same ratio to the Hengill-area.

Drilling and chemical characteristics. A few wells have been drilled in the western part of the Krýsuvík-area. A steam well was drilled in 1952. It has a depth of 236 meters and a casing of 10 inches i.d. It produces about 15 tons/hour of steam at zero gauge well-head pressure. Chemical data on this well are given in Tables 5 and 6. The deepest well in the Krýsuvík area was drilled in 1960 and reaches a depth of 1 270 meters. A base temperature of 220°C is indicated in this well.

Economic importance of the Krysuvik- and the Hengill-areas. The natural heat in the Hengill- and the Krysuvik-areas may be exploited for a large scale production of heat and power. Of major importance is the fact that the Krysuvik-area is located only 30 km from the city of Reykjavik where there is a considerable market for the heat. Present estimate indicate that water at a tempera-

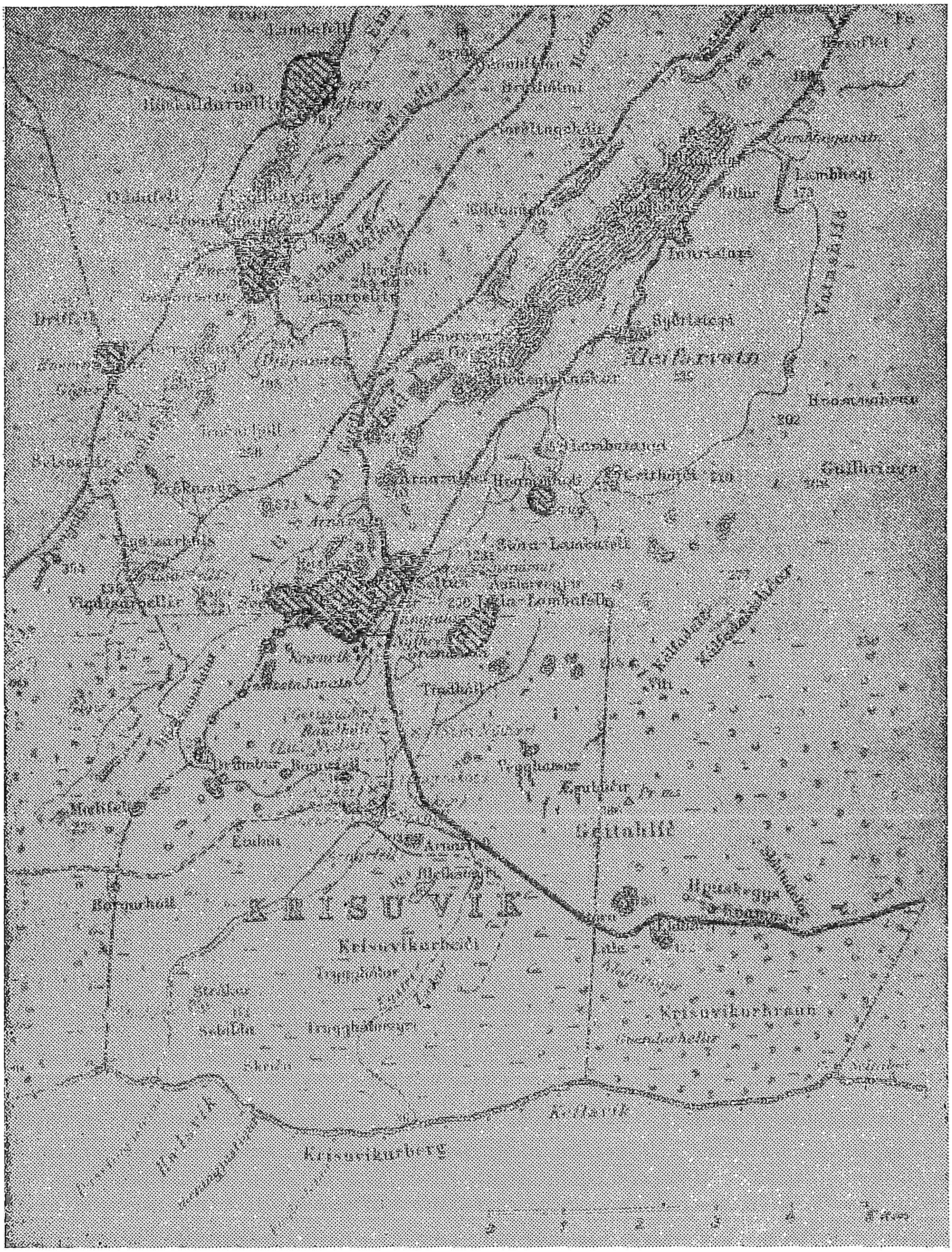

Fig. 7. The thermal area at Krýsuvík. The shaded areas are zones of surface activity.

ture of 150 to 180° C may be piped from Krysuvik to Reykjavik at a price per unit heat which corresponds to about 1/3 of the price in Western-Europe.

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