7 Geothermal activity in Iceland

INGVAR BIRGIR FRIDLEIFSSON
National Energy Authority, Reykjavík

INTRODUCTION

Like other constructive plate margins the Mid-Atlantic Ridge is characterized by a high heat flow in the crestal region, but with increasing distance symmetrically away from the ridge crest the mean heat flow falls until it reaches an average level for the oceans. Iceland forms a 500 km broad segment astride the ridge and falls entirely within the crestal heat flow anomaly. The regional heat flow on the island varies from about 80 mW/m^2 furthest away from the active volcanic zones crossing the country to about 300 mW/m^2 in some regions at the margins of the Reykjanes-Langjökull axial rift zone. The geothermal gradient as measured in over 100 m deep drillholes outside known geothermal fields and outside zones of active volcanism, ranges from 37°C/km to 165°C/km (Fig. 1).

Hot springs are very abundant in the country as a result of the high heat flow (Fig. 2). To date there have been recognized approximately 1000 geothermal localities in the country. Hot springs have also been identified in a few places on the sea floor surrounding the island. The thermal output varies greatly from one locality to another. In the Plio-Pleistocene and Tertiary regions the water temperature varies from a few degrees above the mean annual temperature to boiling springs, and the flow rate varies from nil to a maximum flow of about 180 l/s from a single spring. Steamfields are confined to the active zones of rifting and volcanism that run through the country. It has become customary to divide the geothermal activity into two types on basis of the base temperature (maximum temperature) in the uppermost 1 km. The base temperature is thus $\leq 150°C$ in the low temperature areas, but $\geq 200°C$ in the high temperature areas. The low temperature areas are in Plio-Pleistocene and Tertiary volcanics. Due to the oceanic climate there is heavy precipitation in the island. Some of the precipitation percolates deep into the bedrock in the highland areas and flows laterally along faults and pervious horizons for

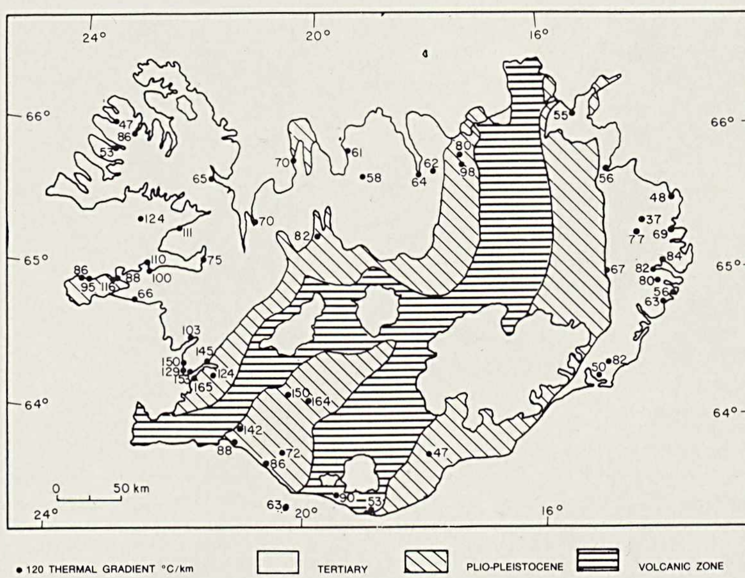


Fig. 1. Geothermal gradient measured in over 100 m deep drillholes outside known geothermal fields and outside the active volcanic zones. (Data from Pálmason et al. 1978 and files of the National Energy Authority, Reykjavík).

distances of tens of km before it appears on the surface along dykes or faults on the lowlands. The water withdraws heat from the regional heat flow during its passage through the strata. The high temperature areas are confined to or on the margins of the active zones of rifting and volcanism, and are thought to draw heat both from the regional heat flow and from local accumulations of igneous intrusions cooling at a shallow level in the crust.

LOW TEMPERATURE AREAS

The crustal thickness of Iceland varies from 8 to 15 km, and the crustal structure is known in a considerable detail from geological and seismic surveys. The crust is formed almost entirely of igneous rocks. The uppermost 4 km or so are composed of subaerial lavas and much subordinate airborne tuffs in the Tertiary areas, but of subaerial lavas intercalated with morainic horizons and thick piles of subglacially erupted pillow lavas and hyaloclastites in the Plio-Pleistocene provinces, which flank the active volcanic zones (Fig. 1). Each eruptive unit is fed by a dyke, and consequently the dyke intensity increases with depth in the crust. Below 5 km or so the crust probably consists mostly of very low porosity impermeable intrusions. This layer (the oceanic layer, $V_p = 6.5$ km/s) may form the base to water circulation in the low temperature areas. In the high temperature areas and other parts of the active rift zone the water may circulate down into the intrusive layer during its formation.

A comparison of the deuterium content of the thermal water and the local precipitation in the individual areas has shown that the thermal water is of meteoric origin. In most cases it is precipitation which has fallen in the highlands. There the water manages to percolate deep into the bedrock and then, driven by the hydrostatic gradient, flows laterally for distances of tens and up to 150 km before it appears on the surface along dykes or faults on the lowlands. This model was originally proposed by Trausti Einarsson in 1942. The age of the thermal waters varies from a few decades to thousands or even tens of thousands of years, depending on the distance between the hot spring areas and the recharge areas.

Fig. 3 shows the general flow pattern of thermal groundwater systems according to deuterium measurements, with arrows joining the individual hot spring areas with possible recharge localities, superimposed on a geological map of Iceland. On basis of a comparison of the flow directions with hydrostatic pressure isolines of the country, the hot water appears to flow equally in every direction away from the highlands. A close comparison of the

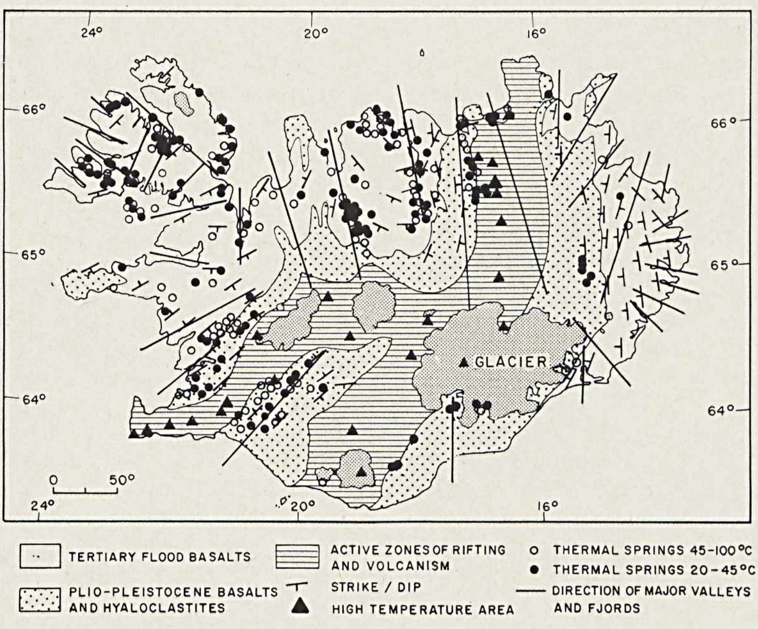
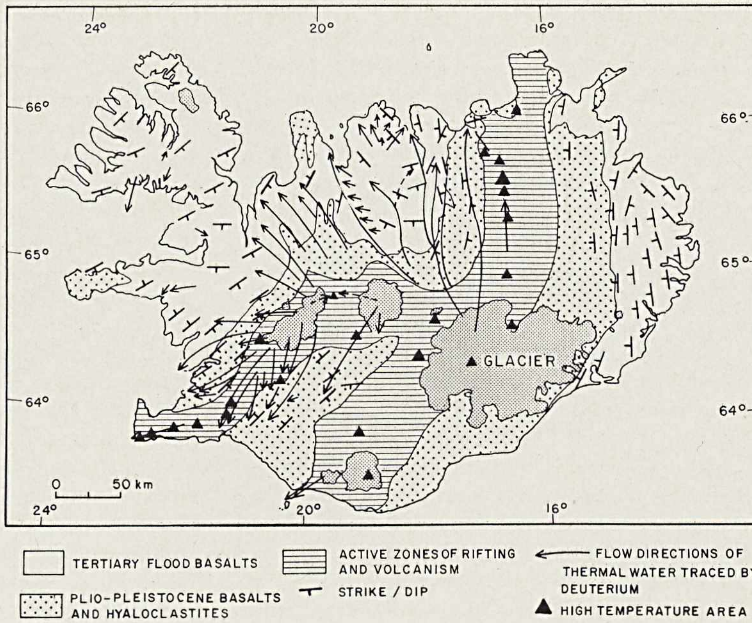


Fig. 2. Geological map of Iceland showing the distribution of natural geothermal activity, and the direction of major erosional features (valleys and fjords). The volcanic strata dip towards but age away from the active volcanic zones. High temperature areas (with temperatures above 200°C in the uppermost 1 km) are confined to the active zones of rifting and volcanism. The low temperature activity is most intense in areas where the major erosional directions are approximately parallel with the geological strike. (Slightly modified from Fridleifsson, 1978).

Fig. 3. The general flow pattern of thermal ground-water systems in Iceland according to deuterium measurements (Árnason, 1976) superimposed on a simplified geological map of Iceland. The arrows join the thermal areas in the lowlands with possible recharge areas in the highlands, and are modified such that they are almost perpendicular to the isolines of average topographic heights based on rectangular areas of 520 km^2. The arrows were drawn independently of the geological map. Note how closely the flow direction arrows generally fall with the geological strike. (Slightly modified from Fridleifsson, 1978).



geological map and the flow pattern arrows, however, shows a remarkably good correlation between the flow directions and the geological strike. This suggests that the water may flow along the same pervious horizons in the strata and/or dykes and faults along the strike all the way from the highlands to the lowlands.

Further indication of the preferential flow of the water along stratiform horizons and/or dyke swarms (which generally have a direction deviating 0°—30° from the strike) is seen in the distribution of hot springs with regard to erosional features. Although hot springs are very widely distributed in Iceland (Fig. 2) there are certain areas, particularly in the eastern part of the country, that are almost devoid of thermal activity. A comparison of the distribution of hot springs and geological strikes with the direction of major erosional features, such as fjords and valleys, shows that all the major low temperature areas of the country are characterized by the erosional directions being approximately parallel to the strike. This implies that water can flow undisturbed along the same permeable horizons from the recharge areas in the mountains to the outflow areas in the lowlands. The regions that are devoid of hot springs, such as the Eastern Fjords, are on the other hand characterized by the erosional directions being nearly perpendicular to the strike directions. This can be interpreted in the way, that water that seeps into the bedrock in the mountains in these areas cannot flow for but a few kilometers along strike, as the permeable horizons and the transecting dykes and faults are intersected by erosional features (valleys and fjords) at relatively short intervals. As the flow distance is so short and the hydrostatic gradient much disturbed, the water does not get the same opportunity to withdraw heat from the regional heat flow as water that flows undisturbed for tens of kilometers. Indeed the few hot spring localities in eastern Iceland are in areas where the erosional directions are nearly parallel to the strike of the bedrock (Fig. 2).

The total natural flow from hot springs in the low temperature areas has been estimated 1200 l/s. The bulk of the hot springs has a flow rate of less than 5 l/s, but both in the Plio-Pleistocene and Tertiary strata individual springs may have flow rates of several tens of l/s. The largest springs are commonly accompanied by a localized cluster of smaller springs. The main upflow zones are generally controlled by dykes and/or faults. Many hot spring localities are associated with regional dyke and fault swarms. Similarly hot springs are common on the outskirts of extinct and eroded central volcanoes characterized by abundant intrusives and faulting. Intrusive activity, faulting and tilting clearly play an important role in creating secondary permeability and in directing the flow of water from reservoirs at depth towards the surface.

In many areas the free flow of thermal water has been increased significantly by deep drilling. A 1 km drillhole by a spring giving ≤ 1 l/s commonly yields several and sometimes tens of l/s of water that also is most often significantly warmer than the natural spring. The free flow is, however, much affected by the regional topography; high mountains create a high hydrostatic head so that a spring or a drillhole in a deep valley has a much higher natural flow rate than a spring fed by a similar aquifer in a lowland region. This difference is overcome by the effective use of downhole pumps in geothermal wells in the lowland regions. Typical temperature profiles of drillholes are shown in Fig. 4.

The flow channels from the recharge areas in the highlands to the hot spring areas in the lowlands are thought to vary from the Tertiary to the Plio-Pleistocene provinces. In the subaerially erupted Tertiary volcanics the flow channels appear to be mainly dykes and faults but to a less extent thin high porosity stratiform horizons. In the Plio-Pleistocene strata, which are characterized by successions of subaerial lavas intercalated with thick piles of subglacially erupted pillow lavas, hyalocastites and detrital beds, potential flow channels are much more abundant. There the most effective large scale reservoirs and flow channels are thought to be the pillow lava cores of hyaloclastite ridges and high porosity stratiform horizons of fragmental material which are likewise cut by dykes and faults. There is a significant difference between the aquifers encountered by drilling in the Tertiary and the Plio-Pleistocene areas. In the Tertiary strata the aquifers appear most often to be narrow and connected with vertical structures (dykes and faults). Data is available on the transmissivity in drillholes in three thermal areas in Tertiary rocks (Table 1). The transmissivity is of the order of $10^{-3} m^2/s$, and thus an order of magnitude lower than that of the most permeable Plio-Pleistocene strata. The most intensely drilled thermal area in Tertiary strata is at Laugaland near Akureyri in N-Iceland. The strata is of basaltic lavas with minor sedimentary interbeds. The hot springs are associated with dykes. But at depth particulary one dyke out of a whole dyke swarm acts as a main aquifer. Small aquifers have been found connected with both individual dykes and clastic interlayers, but the best aquifers have apparently been encountered at the intersection of permeable dykes and the interlayers.

In Plio-Pleistocene strata the major aquifers tend to be horizontal and occur most commonly at the contacts of lithological units such as lavas and hyaloclastites. The transmissivity is up to the order of $10^{-2} m^2/s$, and as the aquifers are more numerous the intrinsic permeability tends to be one or two orders of magnitude higher than that of Tertiary

TABLE 1.

Transmissivity (measured) and intrisic permeability (calculated) in selected hydrothermal systems in Iceland. (Compiled by Snorri Páll Kjaran, National Energy Authority, Reykjavík).

	Transmissivity m^2/s	Instrinsic permeability millidarcy
LOW TEMPERATURE AREAS		
Tertiary:		
Laugaland	2.6×10^{-3}	50
Ytri-Tjarnir	2.1×10^{-3}	50
Baer	1.1×10^{-3}	30
Plio-Pleistocene:		
Sydri-Reykir	2.5×10^{-2}	13700
Ellidaár	3.5×10^{-3}	6200
Laugarnes	6.0×10^{-3}	4100
HIGH TEMPERATURE AREAS		
Svartsengi	1.2×10^{-2}	1000
Krafla	6×10^{-5} to 6×10^{-3}	1 to 100

strata (Table 1). The most intensely drilled thermal area in Plio-Pleistocene strata is at Reykir in Mosfellssveit, SW-Iceland. The production area is in a heavily tilted and blockfaulted zone just outside a two million year old caldera. Basaltic lavas form 40—70% of the strata and these are intercalated by thick and thin beds of subglacially erupted pillow lavas and hyaloclastites as well as detrital beds. Table 2 shows the occurrence of aquifers in the different rock types in drillholes in the area. It is apparent that large aquifers are by far more likely to occur at the contacts of lithological units than in lavas alone or in subaquatic volcanics alone. Several individual 2 km wells in the area can give 100 l/s with pumping and a drawdown of a few tens of m.

The largest natural hot spring in Iceland is at Deildartunga in Reykholtsdalur, W-Iceland. The strata is of Tertiary age and mostly of basaltic lavas, but extrapolation from surface outcrops indicates that at 0.5—1 km depth under the hot spring area sediments may amount to 30% of the strata. There is a 1.4 km long line of hot springs spread along a NW-trending relatively young fracture. The Deildartunga hot spring, with a discharge of about 180 l/s of boiling water, is at the northern end of the line where the fracture cuts a NE-trending dyke and an associated fault. The Kleppjárnsreykir hot spring, with a discharge of about 70 l/s of boiling water, is at the southern end of the line and close to this spring the fracture also cuts a NE-trending dyke. The total discharge along the line is about 253 l/s, which shows that the numerous hot springs along the line between the big end members have insignificant discharge. There are several other tectonically controlled lines of hot springs in the Reykholtsdalur area, some of which are associated with historically active faults. There was movement on one of these faults (Helgavatn fault) during an earthquake episode in 1974 and a hot spring disappeared for about 3 weeks and then reappeared with hotter water and greater discharge than before.

The thermal waters of the low temperature areas are characteristically alkaline with dissolved solids of the order of 200—400 ppm. The composition is dominantly governed by the temperature of the water and the rock type which it flows through and leaches. There has been noted a general although subtle increase of the chlorine content of the thermal waters towards the coast indicating some infiltration of seawater into the strata. Table 3 shows the chemical composition of typical waters from the low temperature areas. Carbonate springs (both cold and warm) are found in a few localities in Tertiary and Plio-Pleistocene strata and most commonly in the vicinity of deeply eroded central volcanoes. The carbon dioxide is considered to be mostly of juvenile origin.

Geysers (erupting springs) can at present be inspected in two low temperature areas; Árhver in the Tertiary strata of Reykholtsdalur, W-Iceland, erupts irregularly a meter or two, whereas Ystihver in the Plio-Pleistocene strata of Reykjadalur, N-Iceland, erupts at a few minutes interval up to about five meters. A few erupting springs in the low temperature areas have been captured for utilization.

TABLE 2.

Occurrence of aquifers in the different rock types of 29 drill holes (800—2043 m deep) in the Reykir thermal area (from Tómasson et al, 1975).

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

1) The term hyaloclastite is here used in a collective sense for all subaquatic volcanic products, thus comprising pillow lavas, pillow breccias, and tuffs. Included in this group are also reworked hyaloclastites and detrital beds.

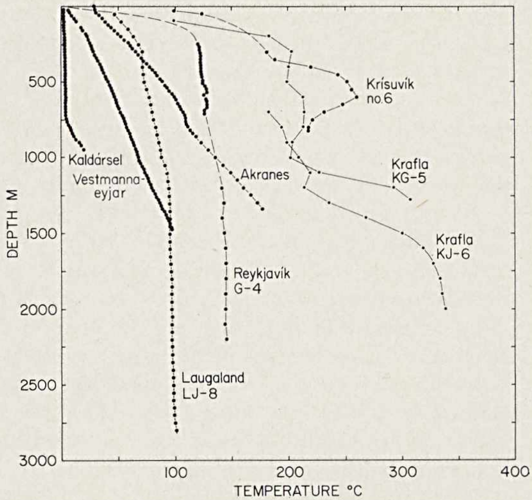


Fig. 4. Typical temperature profiles from deep drillholes inside and outside geothermal areas in Iceland. Kaldársel is within the active volcanic zone but far away from high temperature areas and shows nearly zero thermal gradient down to about 700 m. Holes in the Westman Islands and Akranes show thermal gradients nearly undisturbed by water convection. Laugaland LJ-8 and Reykjavík G-4 are typical for production holes in low temperature areas, whereas the holes Krafla and Krísuvík are in high temperature areas. (Slightly modified from Pálmason et al. 1978).

HIGH TEMPERATURE AREAS

According to the plate tectonics theory the highest heat flow on a constructive plate margin should be along the volcanic zone, which is the surface expression of the plate boundary. This is not always apparent on the surface as recent volcanics are normally highly pervious and cold groundwater percolates deep into the surface formations. In one drillhole in the volcanic zone of SW-Iceland a zero thermal gradient was encountered down to 700 m. With increasing compaction of the strata and sealing by precipitation from warm water the geothermal gradient increases with depth, and it is likely that magmatic temperatures (1000—1200°C) prevail at 10 km depth or less under the entire volcanic zone of Iceland. The high temperature areas are like chimneys that extend from the hot zone below and all the way to the surface. The high temperature areas are always associated with volcanotectonic features such as volcanic fissure swarms or more commonly central volcanoes with intermediate and acid volcanics, fault swarms, and sometimes calderas. At such sites there is a great abundance of dykes, sheets and other minor instrusions cooling at a shallow depth in the crust. These intrusions, in addition to the general heat flux of the volcanic zone, form the heat source for the hot water convection systems of the high temperature areas. The mineral content of the water increases with its temperature. Precipitation of mainly silica and calcium carbonate occurs where the high temperature water meets cold groundwater. This seals the hot water cell off and with time allows it to extend up through the pervious surface formations.

Several new high temperature areas have been identified with increasing research during the last decade. To date there are considered to be 22 certain and 3 potential high temperature areas in the country. The surface manifestations are in the form of steam holes, boiling mudpools and highly altered ground. The high temperature areas vary greatly in size and have an aggregate coverage of about 500 km^2. Three areas cover approximately 100 km^2 or more, but the bulk of the areas are 1—20 km^2. The size of the individual high temperature areas is a function of the age of the systems, the extent of the magmatic heat source and the lithology and structure of the strata in which the high temperature convection systems are formed. The total natural heat discharge of the high temperature areas is poorly known, but has been estimated at about 4000 MW.

The heat exchange between the intrusives and the meteoric water can to some extent be inspected in the deeply dissected roots of Tertiary and Plio-Pleistocene central volcanoes. These are characterized by a great abundance (locally 50—100%) of minor intrusions. Centrally inclined sheet swarms (cone sheets) have been found in the majority of dissected central volcanoes investigated to date in Iceland. The sheets are commonly 1—2 m thick. Minor dolerite, gabbro and granophyre intrusions are also common. The host rock is intensely altered and the cores of the central volcanoes are characterized by a cupola of propylitized rocks which delineates the shape of the extinct high temperature convection system. The outer part of the aureole is characterized by quartz and platy calcite, but these minerals are accompanied by laumontite and epidote and in rare cases garnet and amphibole in the central part.

The association of magmatic activity with a high temperature hydrothermal system has been clearly demonstrated during the current rifting episode of the Krafla volcanic system in northern Iceland. A magma chamber has been located below the center of the 8 km broad Krafla caldera. A high temperature thermal area lies right above it. Magma that flows steadily into the magma chamber causes inflation of the caldera and during sudden deflation events magma is expelled laterally into the fissure swarm that transects the caldera. Since 1975 small basaltic fissure eruptions have occurred three times in or just outside the caldera. The hydrothermal activity inside the caldera has increased dramatically along the eruptive fissure, and the most powerful new springs have thrown mud and rocks and formed craters that are about 15 m deep and up to 50 m in diameter. These look like explosion craters, but have been formed by steam erosion rather than single explosions. Surface hydrothermal activity has increased even more in two other geothermal areas on the fissure swarm, one lying about 7 km north of the caldera and the other (Námafjall) about 7 km south of the caldera. In a deflation event in 1977 a small volcanic eruption occurred on a fissure near the northern rim of the caldera. Seismometers indicated that magma was also moving southwards and nearly five hours later about 3 tons of basaltic scoria were erupted up through a 1138 m drillhole in the Námafjall steam field, about 12 km south of the active crater in the north. The rifting events and the magmatic activity have caused pressure impulses in the water-dominated part of the Krafla geothermal field. Magmatic gases have similarly had pronounced effects on the chemistry of the thermal fluid and caused serious deposition in boreholes. In one of the magmatic pulses the pH of the discharge from a well changed from about 9 to about 2 for a short while. Examples of such injections of volcanic gases into geothermal fluids can be seen in the secondary mineral assemblages of some of the most deeply dissected cores of extinct central volcanoes.

Deep drilling has been conducted in seven high temperature fields in Iceland. Five of these have been found to be entirely water-dominated, with base temperatures of 200—300°C, but two fields have been found to be partly boiling. The reservoir in the Krafla geothermal field has been found to be rather complex consisting of two geothermal zones, an upper water-dominated zone with temperatures of about 200°C and a lower boiling zone with temperatures of 300—350°C.

Isotope studies indicate the hydrological cycle in the high temperature areas to be much more localized than that of the low temperature areas. Local precipitation seeps deep into the bedrock; it has an easy route along open fissures in the active fault swarms that commonly extend through the high temperature areas. The water is heated up by contact with the hot rock, the ultimate heat source being the general heat flux of the volcanic zone and the shallow level intrusions in the core of the high temperature system. The ascending hot water may flash to steam at a depth of 1 km or less, and on flashing the dissolved gases (carbon dioxide, hydrogen sulphide, and hydrogen) are transferred into the steam. When the steam mixes with local groundwater the carbon dioxide may give rise to carbonate springs but the hydrogen sulphide is oxidized to sulphur or sulphate and the resulting water is acid. This acid water leaches the rock and is responsible for the intense alteration of the surface rock in the high temperature areas. The grey colour of the mud pools is due to tiny floating specks of pyrite as well as clay (kaolinite and montmorillonite). The white colours are due to silica, calcite, aragonite and gypsum; the bright yellow colours in hot patches are due to sulphur; the yellowish, red, brown and green colours are mostly due to iron oxides. Two high temperature areas are known to be infiltrated by sea water (Reykjanes and Svartsengi) and the resulting geothermal fluids are brines. Chemical analyses of selected waters from the high temperature areas are shown in Table 3. Typical temperature profiles are shown in Fig. 4.

The strata of the active high temperature areas are like the Plio-Pleistocene strata composed of layers of subaerial lavas intercalated by thick piles of subglacially erupted pillow lavas and hyaloclastites. The proportion of intrusives normally increases with depth. Most of the intrusives are relatively fine grained basaltic dykes and sheets but dolerites and granophyres have also been encountered in some areas. The strata are generally highly faulted. Measurements show the transmissivity to be highly variable between areas and within individual fields (Table 1). No statistical analysis is available on the occurrence of aquifers. The maximum temperature measured is 346°C, the maximum flow rate (total flow) from a single well is

TABLE 3.

Composition of representative samples of thermal water in Iceland. Concentrations in ppm. (Selected from Arnórsson, 1979 and National Energy Authority files).

Location	Temp. °C	pH/°C	SiO_2	Na	K	Ca	Mg	CO_2[d]	SO_4	H_2S[e]	Cl	F	Diss. solids
High temperature areas:													
Krafla, well 7[a]	>342[b]	6.88/248	172	60.6	11.3	0.7	0.01	36280	46.9	311.1	29.1	0.27	379
Námafjall, well 10[a]	300[b]	7.31/272	607	118	22.8	0.5	0.02	23.2	26.6	232.0	82.3	0.75	1036
Svartsengi, well 4[a]	243[b]	6.08/240	461	6440	987	1053	1.14	539	35.5	5.8	12791	0.11	24006
Low temperature areas:													
Reykir, well MG15	85[c]	9.82/19	91	43.2	0.9	2.38	0.01	19.0	23.0	0.6	24.9	0.68	163
Laugaland, well LJ7	93[c]	9.88/16	102	51.1	1.2	1.8	0.003	25.5	27.2	0.17	10.3	0.38	206
Seltjarnarnes, well 3	102[c]	8.44/28	116	368	10.8	144.0	0.17	5.0	205.0	0.1	685.0	0.73	1631
Lýsuhóll	57[c]	6.72/19	219	452	34.2	86.8	20.7	1495	41.2	< 0.1	80.0	5.00	1649

a Calculated composition of total well discharge. b Maximum measured downhole temperature. c Measured temperature discharge. d Total carbonate ($H_2CO_3 + HCO_3^{\div} + CO_3^{\div 2}$). e Total sulphide ($H_2S + HS^{\div} + S^{\div 2}$).

approximately 80 kg/s, and the steam flow from a single well ranges up to 25 kg/s at atmospheric pressure.

Geysers are active in two high temperature areas in the country at present. Gunnuhver in the Reykjanes field, SW-Iceland, was reactivated in an earthquake in 1967 and erupts at a few minutes intervals to about five meters. The most famous geyser in Iceland is of course the great Geysir in Haukadalur, S-Iceland, which has given name to all erupting springs in the international geological terminology. Geysir has been mostly dormant for the last decades but erupts at least once during most years. Its highest eruptions were up to about 70 m and lasted for about 10 minutes. It has a 20 m deep vertical surface pipe. Measurements show the eruption to originate at about 10 m depth in the pipe. The boiling temperature at that depth is about 120°C, but the water is sometimes superheated by 5—6°C before it is instantly flashed to steam. The volume of steam at this pressure (depth) and temperature is about seventeen times that of the water and it is the steam explosion that throws the water column above into the air. A small geyser in the Geysir field, Strokkur, was reactivated by drilling in 1963. It erupts every few minutes up to 10—15 m. The first written record of geyser activity in the Geysir field is from annals in 1294 describing earthquakes in the area.

GEOTHERMAL UTILIZATION

Geothermal energy is very important for the national economy of Iceland as nearly one third of the net energy consumption of the country is from geothermal resources, the other two thirds being nearly equally divided between hydropower and fossil fuel, the latter of which has to be imported.

Although hot springs were widely used for washing and bathing through the 1100 years of settlement of the country it was not until in the last five decades that the distribution of hot springs started markedly affecting the distribution of population centres in the country with the growth of villages and school centres built at hot spring localities in the farming communities. Large scale utilization of geothermal for space heating started in the nineteen-forties. At present nearly 70% of houses in the country are geothermally heated. There are about twenty main district heating services operating with a total installed capacity of about 600 MW_t (thermal), the largest of which is the Municipal Heating Service of Reykjavík with about 450 MW_t installed. The geothermal water used for space heating is mostly from low temperature areas; the mineral content is low (200—400 ppm) and the water can be used directly. A plant has recently started operating in the Svartsengi steam field where a 240°C brine (⅔ seawater) is used for district heating with the use of heat exchangers. Some of the steam is used for generating electricity for in-plant needs. The present installed capacity is 50 MW_t, but will later expand to 100 MW_t. A remarkable experiment has been in operation for three years in the Westman Islands where heat is extracted from a thick partly molten lava flow for space heating of a town of 5000 people. About 15% of the houses are now heated in this way, and the system is being extended over the whole town. The heat source (the lava erupted in 1973) is estimated to last at least 15 years.

There are nearly 140.000 m^2 of geothermal greenhouses used for growing vegetables and flowers; artificial lighting is used on a small scale to lengthen the growing season. Geothermal water and steam is used for various purposes such as fish hatching, fish drying, wool washing, hay drying, and candy making. Industrial utilization on larger scale includes a factory for drying and cleaning of diatomaceous slurry and a factory for drying seaweed for alginate production. A pilot plant has recently been built for extracting salt out of a geothermal brine in the Reykjanes field. Due to the ample hydropower resources of the country electricity has only been produced from geothermal on a small scale as yet. A 60 MW_e (electric) power station is at present under construction in the Krafla field in N-Iceland. The project has been seriously affected and delayed by volcanic activity in the area, and the power station is only producing about 6 MW_e at present. A 3 MW_e power plant operating since 1968 in the Námafjall field had to be closed in 1978 due to volcanic activity.

SELECTED REFERENCES

Árnason, B., 1976: Groundwater systems in Iceland traced by deuterium. Soc. Sci. Islandica, 42: 236 pp.

Arnórsson, S., 1975: Application of the silica geothermometer in low-temperature areas in Iceland. Am. J. Sci., 275: 763—784.

Arnórsson, S., 1979: Hydrochemistry in geothermal investigations in Iceland, techniques and applications. Nordic Hydrology, 10: 191—224.

Barth, T.F.W., 1950: Volcanic geology, hot springs and geysers of Iceland. Carnegie Institution Publication 587: 174 pp.

Björnsson, A., G. Johnsen, S. Sigurdsson, G. Thorbergsson, and E. Tryggvason, 1979: Rifting of the plate boundary in North-Iceland 1975—1978. J. Geophys. Res., 84: 3029—3038.

Björnsson, S., S. Arnórsson, and J. Tómasson, 1972: Economic evaluation of the Reykjanes thermal brine area. Bull. Am. Ass. Petrol. Geol., 56: 2380—2391.

Bödvarsson, G., 1961: Physical characteristics of natural heat resources in Iceland. Jökull, 11: 29—38.

Einarsson, T., 1942: Über das Wesen der heissen Quellen Islands. Soc. Sci. Islandica, 26: 91 pp.

Fridleifsson, I.B., 1978: Applied volcanology in geothermal exploration in Iceland. Pageoph., 117: 242—252.

Kristmannsdóttir, H., 1979: Alteration of basaltic rocks by hydrothermal activity at 100—300°C. International Clay Conference 1978, Mortlan M.M. and V.C. Farmer, (Ed.): 359—367. Elsevier, Amsterdam.

Pálmason, G., 1973: Kinematics and heat flow in a volcanic rift zone, with application to Iceland. Geophys. J.R. astr. Soc., 33: 451—481.

Pálmason, G., S. Arnórsson, I.B. Fridleifsson, H. Kristmannsdóttir, K. Saemundsson, V. Stefánsson, B. Steingrímsson, J. Tómasson, and L. Kristjánsson, 1978: The Iceland crust: Evidence from drillhole data on structure and processes. Maurice Ewing series III, Talwani, M. (Ed.), (in press).

Pálmason, G. and K. Saemundsson, 1974: Iceland in relation to the Mid Atlantic Ridge. Ann.Rev. Earth Plan. Sci., 2: 25—50.

Tómasson, J., I.B. Fridleifsson, and V. Stefánsson, 1975: A hydrological model for the flow of thermal water in SW-Iceland with special reference to the Reykir and Reykjavík thermal areas. Second UN Geothermal Symposium Proceedings. Lawrence Berkeley Laboratory, Univ. of California, 1: 643—648.

Stefánsson, V., 1979: The Krafla geothermal field, NE-Iceland. Geothermal resources, Rybach, L. and L.J.P. Muffler, (Ed.): John Wiley & Sons Ltd., (in press).

Thórhallsson, S., 1979: Combined generation of heat and electricity from a geothermal brine at Svartsengi in SW-Iceland. Geothermal Resources Council Transactions, 3: 733—736.

Walker, G.P.L., 1960: Zeolite zones and dyke distribution in relation to the structure of the basalts of eastern Iceland. Jour. Geology, 68: 515—528.