fissure swarm intersecting the Krafla caldera. During the last three years this volcanic ctivity has proceeded with seven rifting episodes, three of which have resulted in volcanic uptions. The magmatic activity has influenced the production characteristics of the Krafla field.

In the present paper the Krafla geothermal field and some of its production characteristics will be described. The utilization of the field has just started and the experience gained with this utilization is small.

10.2. Geological Framework

Iceland lies astride the Mid-Atlantic Ridge. The surface expressions of the ridge are the so called neovolcanic zones, which are divided into several branches. In general, the structure of the neovolcanic zones is dominated by fissure swarms and central volcanoes. The fissure swarms are usually about 10 km wide and 30 to 100 km long. Most of the fissure swarms pass through central volcanoes, which are the loci of highest lava production and are also defined by the presence of acid rock and high-temperature geothermal fields. The neovolcanic zones have been described in detail (Saemundsson, 1974; Walker, 1975; Jakobsson et al., 1978; Saemundsson, 1978), and the interaction between the central volcano in Krafla and the intersecting fissure swarm has recently been described (Björnsson et al., 1977; 1979).

The Krafla central volcano is situated on one of the five distinct fissure swarms in the northeast volcanic zone in Iceland. All fissure swarms in the northeast volcanic zone are associated with central volcanoes and have developed high-temperature geothermal fields (Figure 10.2). The Krafla central volcano developed a caldera during the last interglacial period, but since then the caldera has been almost filled with volcanic material. The caldera measures about 8 × 10 km. Figure 10.3 is a tectonic map of the area, showing the fissure swarm and the caldera.

A rifting episode, currently occurring in the Krafla fissure swarm (Björnsson et al., 1977), has shown that in the fine structure of continental drift discontinuous movements are present. During a rifting episode magma is stored temporarily in a magma trap under the Krafla central volcano from where it is expelled along the fissure swarm to form dykes. The geothermal fields are located in areas of preferred magma concentration at shallow levels in the swarm, such as in the Krafla caldera and on certain locations along the fissure swarm, e.g. in Námafjall. Figure 10.4 is a schematic picture relating the magma chamber, the fissure swarm and the geothermal fields (Björnsson et al., 1979). The longest distance of subterranean magma flow was recorded during the rifting event in December 1975, when earthquake activity progressed towards the north over a distance of about 50 km along the fissure swarm. A high-temperature geothermal field has been suggested to be present in the Axarfjördur area on the basis of surface geophysical and geochemical surveys (Stefánsson, 1979). The heat source for this field may be of a similar nature as described above for Námafjall.

The postglacial volcanism in the Krafla area has occurred in two main periods. The first was in early postglacial time and the second during the last 3000 years. In these two periods, there have been about 20 volcanic eruptions in the Krafla caldera and about 15 in the Námafjall area. The majority of the fissure eruptions are basaltic, but andesite and dacite flows have also occurred. Four subglacial silicic eruptions have produced large domes or ridges within and around the Krafla caldera. Several explosion craters are located within the caldera. The most recent one (Viti on Figure 10.5) was formed in 1724 at the beginning of the 1724–1729 volcanic and rifting episode, the Mývatn fires.

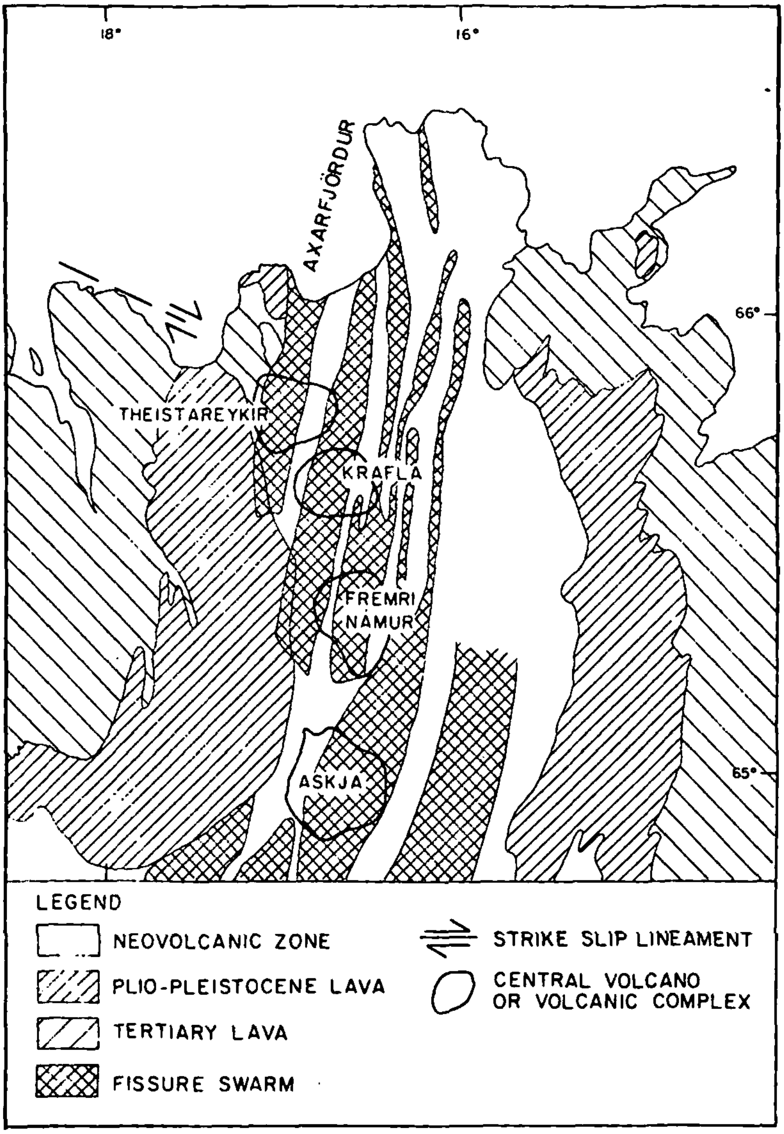

Figure 10.2. The fissure swarms and central volcanoes within the Northeast Volcanic zone in Iceland. Two volcanoes, Krafla and Askja have developed calderas. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

The high-temperature geothermal field inside the Krafla caldera is elongated NW–SE. The main surface activity is in the center of the caldera (near Leirhnjúkur) and in the southeastern part of the caldera where a series of explosion craters have formed a gully called Hveragil. The surface area covered by thermal alteration and geothermal activity is about 35 km^2. Petrological study of the rocks in the Krafla area reveals composition ranging from olivine tholeiite to rhyolite. By drilling in the area it has been found that basalt as well as granophyre intrusions occur frequently below the 1100 m depth level. Figure 10.5 shows the relation of the wells to the underlying magma chamber.

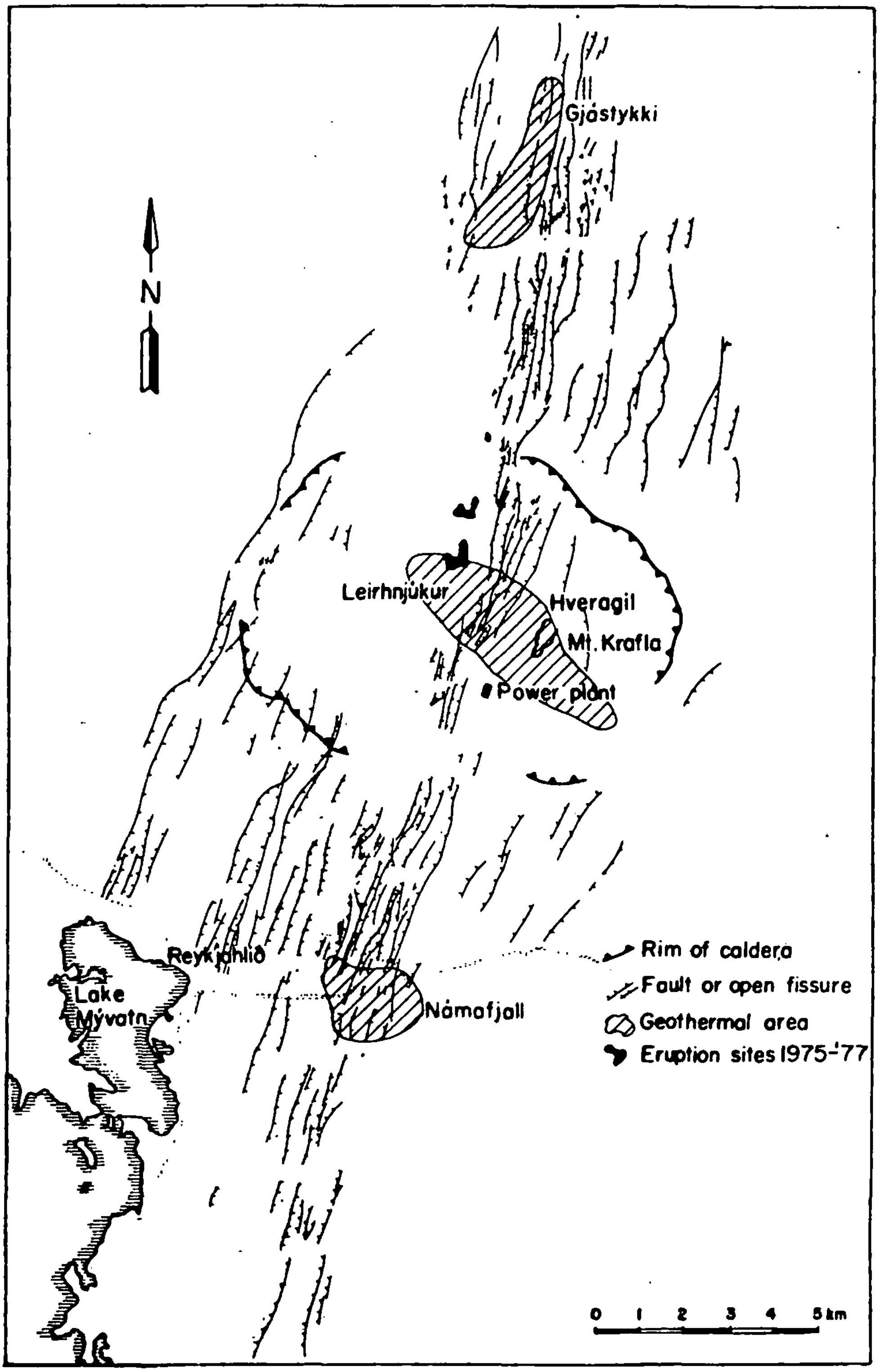

Figure 10.3. Tectonic map of the Krafla area showing the caldera and the active fissure swarm. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

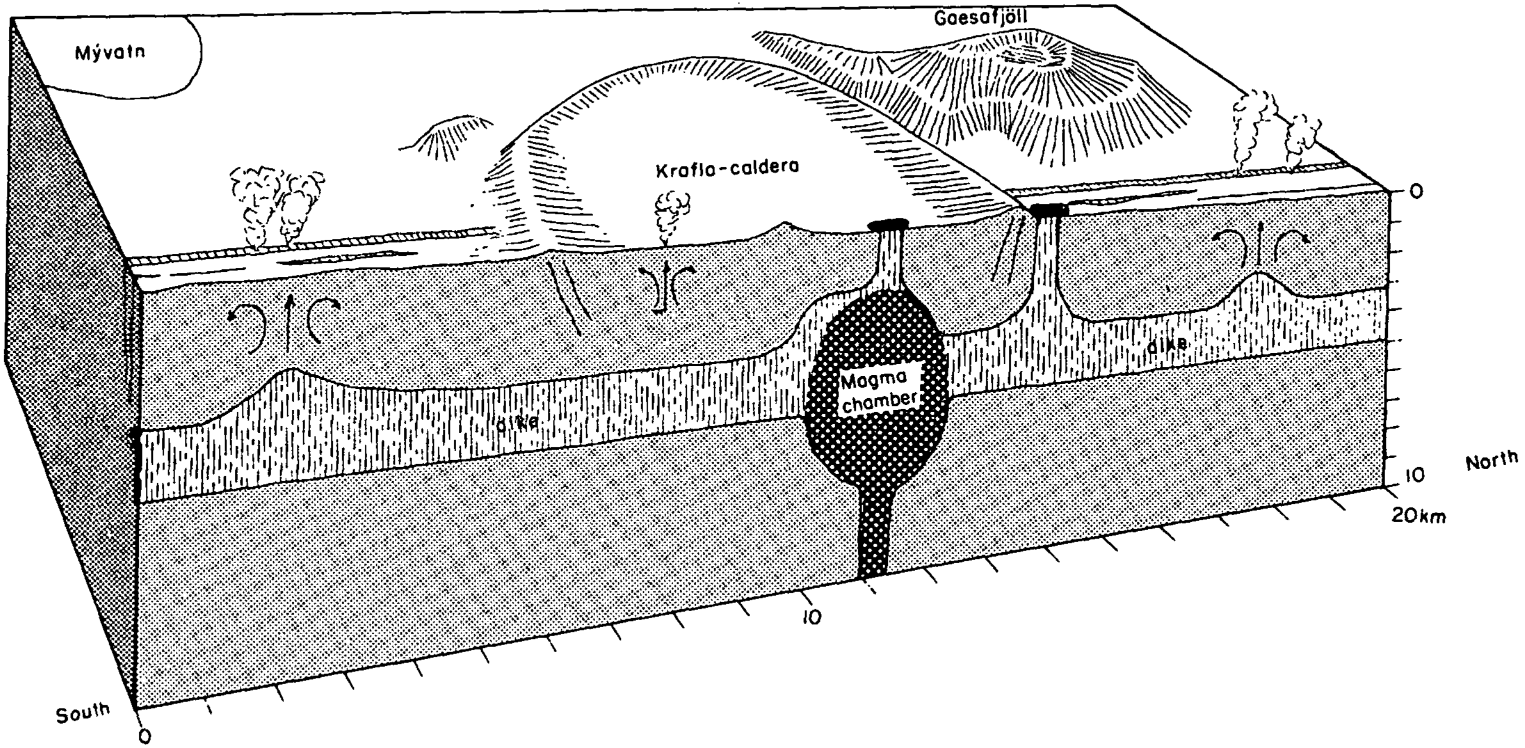

Figure 10.4. A block diagram showing schematically the magma body below the Krafla caldera and the dyke formed in the present tectonic episode. From Björnsson et al. (1979). Reproduced by permission of Orkustofnun

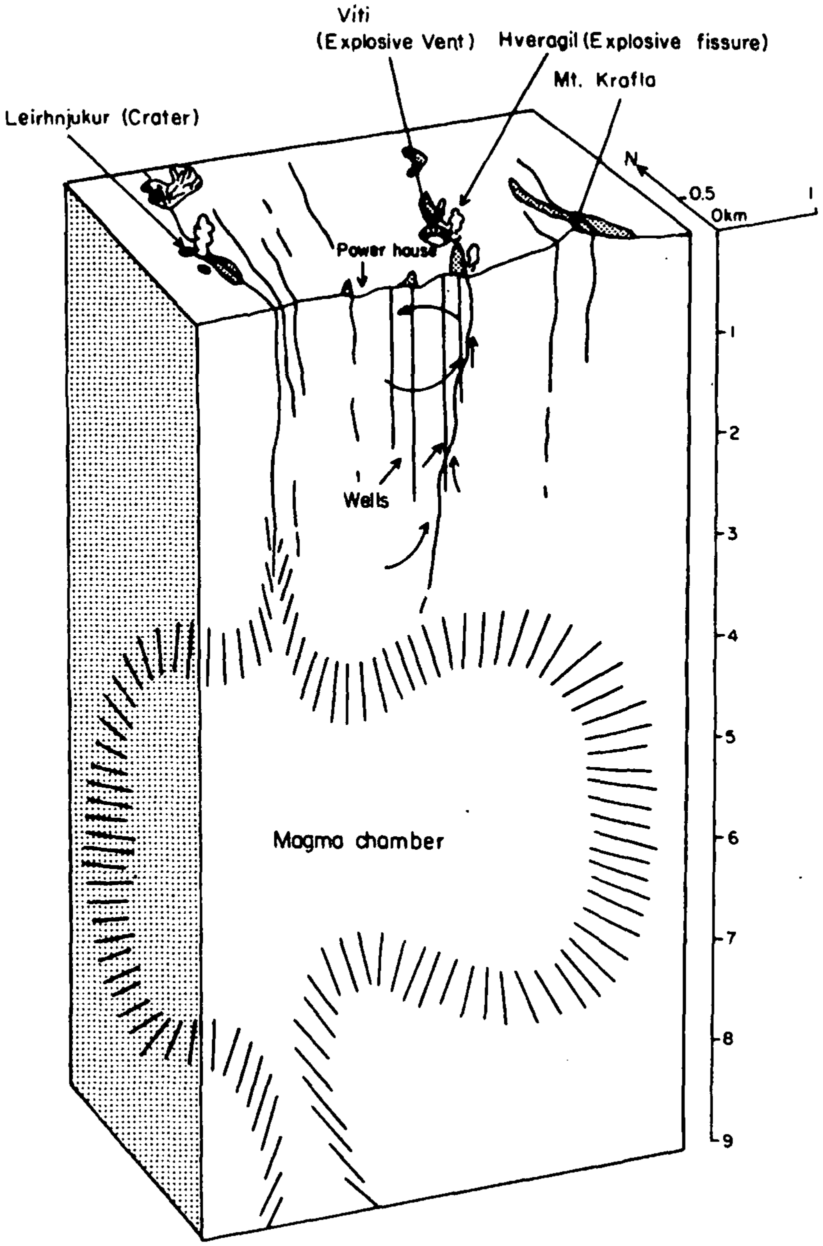

Figure 10.5. The Krafla Geothermal Field and the underlying magma body. From Gíslason et al. (1978). Reproduced by permission of Orkustofnun

10.3. Exploration History and the Model of the Field

10.3.1. *Surface Exploration*

Systematic exploration of the Krafla geothermal area started in 1970. The surface investigation included geological mapping, geochemical analysis of natural springs and fumaroles, aeromagnetic survey, resistivity survey, and seismic refraction measurements. After the start of the rifting episode in 1975, additional surface investigations (e.g. gravity measurements) have been carried out.

The geological investigation resulted in the description of the Krafla caldera and the history of volcanic activity in the area. Surface geothermal activity was mapped in detail, and the connection between tectonic manifestations and geothermal activity was found to be essential. A simplified tectonic map of the area is shown in Figure 10.3.

The investigation of the CO_2/H_2 ratio and the amount of H_2 in fumarole steam indicated that the hottest fluid (245–285°C) should be expected under the gully Hveragil.

The resistivity survey was performed in the years 1971 and 1972, and additional measurements were done in 1976 and 1977. The Schlumberger DC resistivity method has been mainly used, but several dipole soundings and magnetotelluric measurements have been done in the area as well. At shallow depth (less than 800 m) the resistivity measurements show a good correlation between surface alteration and the low resistivity region. For greater depths the resistivity measurements show a somewhat complicated picture. Inside the low resistivity region, the resistivity seems to increase beneath 800–1000 m depth. This observation could be a skin effect, but subsequent resistivity measurements in drillholes indicate that the increase in resistivity with depth is real. In Figure 10.6 the measured resistivity at 600 m depth is shown. The active geothermal area, mapped by surface alteration

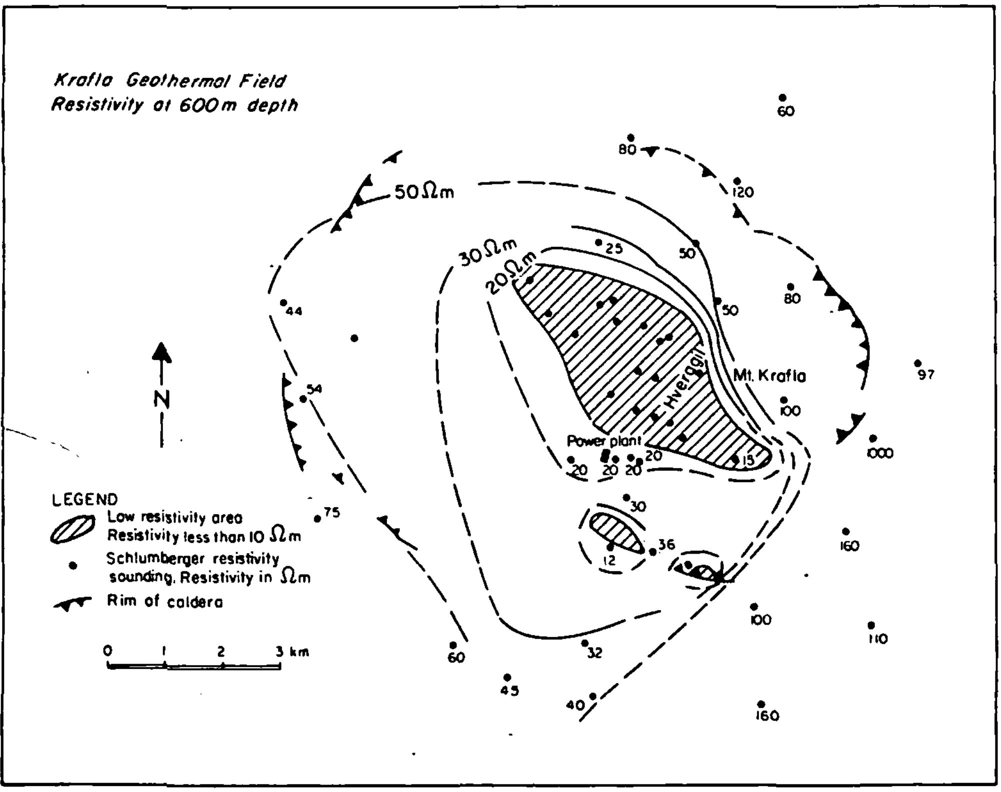

Figure 10.6. Resistivity at 600 m depth in the Krafla geothermal field. Mapped by R. Karlsdóttir. Reproduced by permission of Orkustofnun

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Geothermal Systems: Principles and Case Histories
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10. The Krafla Geothermal Field, Northeast Iceland

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10.1. Introduction

Geothermal energy is extensively utilized in Iceland. The total installed geothermal capacity is now about 600 Megawatts thermal (MWt). The geothermal energy is mainly used for space heating, and the net geothermal consumption is about 500 MWt. As the total population of Iceland is 220,000, this is a large proportion of the energy consumed in the country (Pálmason et al., 1975). In fact more than 30 per cent of the net energy consumption in the country comes from geothermal energy sources (Stefánsson, 1975; Fridleifsson, 1978). Most of the geothermal energy used in Iceland comes from the low temperature fields, where geothermal water of the temperature 60–120°C is used directly for space heating and greenhouse cultivation. Figure 10.1 shows the volcanic zones in Iceland and the high-temperature geothermal fields as solid triangles, all located within active volcanic zones. The low-temperature fields are predominantly located on the flanks of the volcanic zones (Pálmason et al., 1975).

The utilization of the high temperature geothermal field at Námafjall started in 1967. The main purpose is processing of diatomite deposits from Lake Mývatn (Ragnars et al., 1970). The decision to build the diatomite plant was taken before major drilling for steam was started in the area. A 3 MWe power station was installed at Námafjall in 1969.

In 1973 a long standing plan for a hydroelectric power plant in NE Iceland was cancelled because of strong public opposition concerning the environmental consequences of the project. Time was short, and it was believed that the construction of a geothermal power plant would take less time than any hydroelectric alternative. In 1975 it was decided to build a geothermal power plant in Krafla, a high temperature field about 10 km north of Námafjall. In order to gain time, it was decided to build the power plant concomitant with the drilling for steam.

At the time, the development of the Svartsengi high temperature field is SW Iceland was initiated (Arnórsson et al., 1975), where a 30 MWt heat exchange plant is now in operation. A 235°C saline geothermal brine is used for the heating of fresh water of good quality for space heating and domestic use. A 1 MWe electric generation is used for the plant's internal power-supply. In addition a pilot plant for the production of sea chemicals was erected in 1978 at the Reykjanes thermal brine area. The exploration work has been described by Björnsson et al. (1970, 1972).

The exploration of the Krafla geothermal field started in 1970 and was initially carried

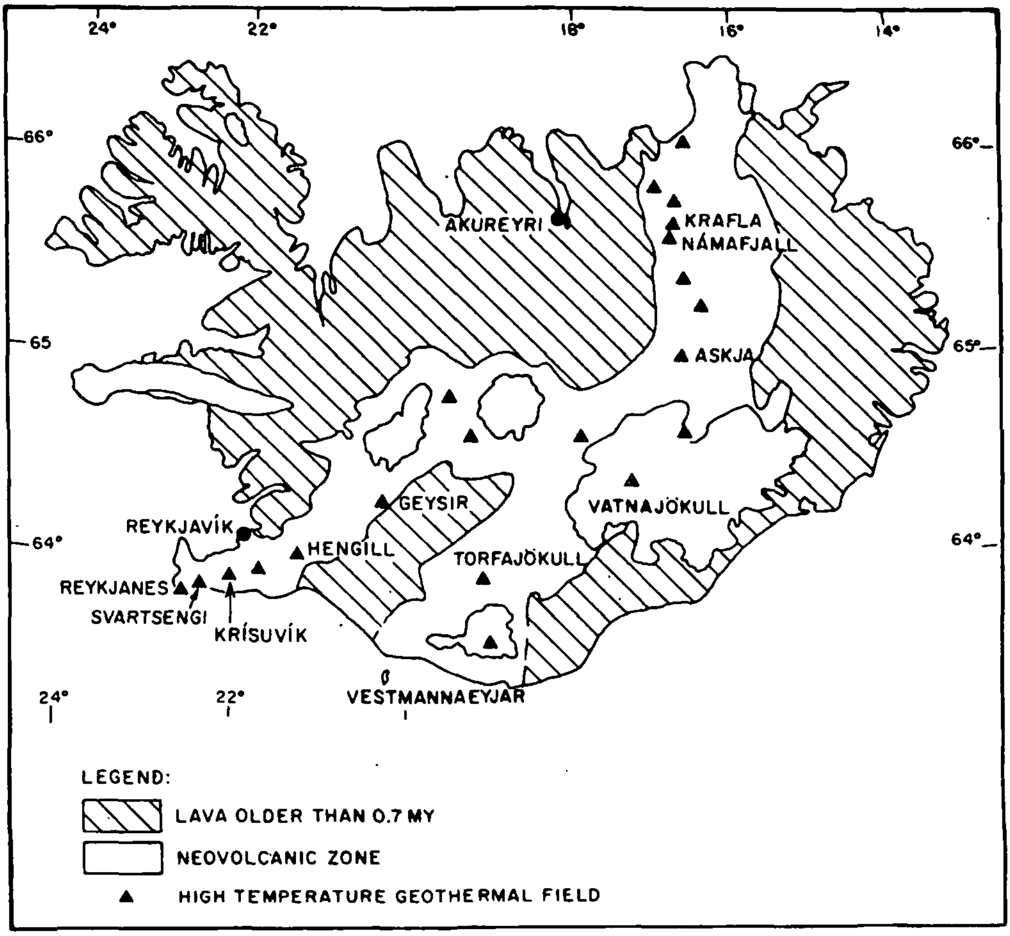

Figure 10.1. Schematic geological map of Iceland showing the high-temperature fields within the volcanic zones. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

out according to the Program for the Exploration of High Temperature Areas in Iceland (Björnsson, 1970). A consequence of the decision to build the power plant concomitant with the drilling operation was that the investigation of the production characteristics of the field could not be made until during the production drilling phase. During drilling, it was found that the reservoir was partly boiling and that the production characteristics were quite different from those of a water-dominated field. Up to that time all high-temperature geothermal fields in Iceland had been found to be water-dominated fields, with base temperatures 200–300°C.

The reservoir in Krafla has been found to be complicated, consisting of two geothermal zones: an upper water-dominated zone with 205°C temperature, and a lower zone boiling at 300–350°C temperature. These unexpected circumstances greatly influenced the plans for the power plant. When the power plant was completed in 1977, the available steam was sufficient to produce 7 MW of electricity, whereas the power plant is designed for 60 MW.

In December 1975 a volcanic eruption occurred in Leirhnjúkur about 2 km from the Krafla power plant. This volcanic eruption was the beginning of a rifting episode in the and resistivity survey is approximately 30 km². This area is relatively large compared with other investigated high-temperature fields in Iceland. Therefore, it was initially concluded that the geothermal potential of the Krafla field was high.

The aeromagnetic survey showed a prominent magnetic low in the southern part of the caldera, and the strongest magnetic anomaly is found in the southern part of the geothermal field. The NW–SE elongation of the geothermal field is also prominent in the magnetic map shown in Figure 10.7. The magnetic low associated with geothermal activity is interpreted to result from alteration effects on magnetic minerals.

The seismic refraction measurements gave inconsistent results, and these have not been used further for the geothermal investigation of the field. In 1975 three seismometers were installed in the Krafla area. The seismic investigation revealed the existence of a magma body at a depth between 3 and 7 km inside the Krafla caldera (Einarsson, 1978).

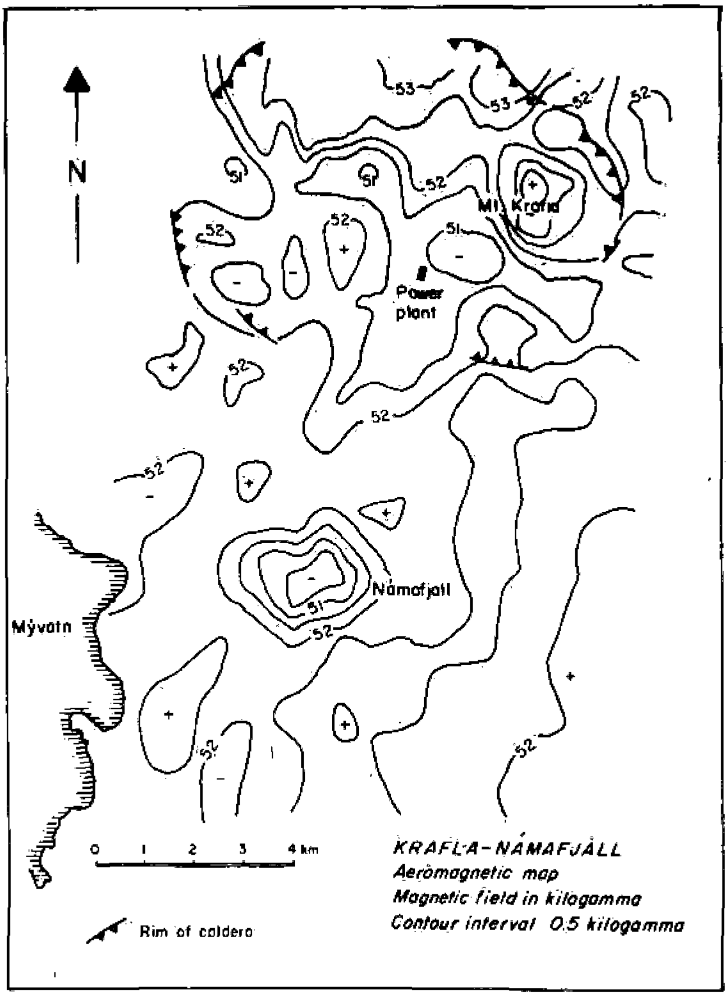

Figure 10.7. An aeromagnetic map of the Krafla-Námafjall high-temperature fields. From Pálmason (1975). Reproduced by permission of Orkustofnun

Gravity measurements have been repeated frequently in the area in connection with the rifting episode. A Bouguer map of the area is shown in Figure 10.8. The caldera effect, as well as the NW–SE elongation structure is prominent in the gravity map.

10.3.2. *Subsurface Exploration*

Two 1100 m deep exploratory wells were drilled in 1974. In one of the wells, a temperature of 300°C was found. At this stage the temperature conditions in the field were thought likely to be close to the boiling point curve. In the years 1975 and 1976 nine additional wells were drilled, and the twelfth well was drilled in 1978. The location of the wells is shown in Figure 10.9. The investigations carried out concomitant with the drilling and during flow tests were: petrological logging and mineralogical and geochemical study of the cuttings, temperature and pressure measurements in both static and flowing wells. resistivity and SP logs in wells, permeability tests both with injection and drawdown tests, measurements of enthalpy and chemical composition of the discharged fluid, production characteristics of wells, and analysis of deposits in the wells.

The subsurface rocks can be split into three main lithological units; the hyaloclastite formation, the lava formation, and the intrusive formation (Figure 10.10). The hyaloclastite formation in the uppermost 800–900 m is composed of primary and reworked products from subglacial eruptions. It is subdivided by a thick suite of subaerial lavas. Below 800–900 m depth, sequences of subaerial lava flows are dominant and hyaloclastites are rare. Dykes are common below 400 m depth. A multiple sill is located below the central part of the drilling area at 1100–1300 m depth. Below 1500–1600 m depth in the northern and southern part of the drilling area the rocks are entirely intrusive.

The compositions of the lavas and hyaloclastites are mostly near to saturated tholeite basalt, but range from olivine tholeiite to quartz tholeiite. Thin layers of acid tuff occur in the drilled section. The intrusive rocks are most frequently of basaltic composition, but granophyre intrusions appear also. The rocks in the hyaloclastite formation are completely recrystallized and the lavas are highly altered. The alteration pattern shows a fairly regular zoning (see Kristmannsdóttir, 1978). A retrograde transformation of the sheet-silicates above 1200 m depth level has been observed in some of the wells. The degree of alteration is comparable to that of zeolite to greenschist facies metamorphism. The transition between zeolite and greenschist facies alteration is at about 800 m depth.

The temperature measurements yielded values up to 345°C, which is the highest temperature recorded so far in geothermal wells in Iceland. The pressure profile of static wells indicated hydrostatic pressure in the field. The enthalpies of the wells were usually high, and the chemical composition of the fluid showed great variation within the field. In order to compile all the results and observations to a single solution, a new model of the geothermal field was necessary. The new model of the field was first presented in January 1977, but additional information confirmed its validity. All present observations are in agreement with this model.

10.3.3. *The Model of the Field*

The geothermal system in Krafla consists of two separate geothermal zones. The shallower one, extending down to ca. 1100 m depth, is a water-dominated system with a mean temperature of 205°C. The deeper zone ranges from about 1100–1300 m depth to at

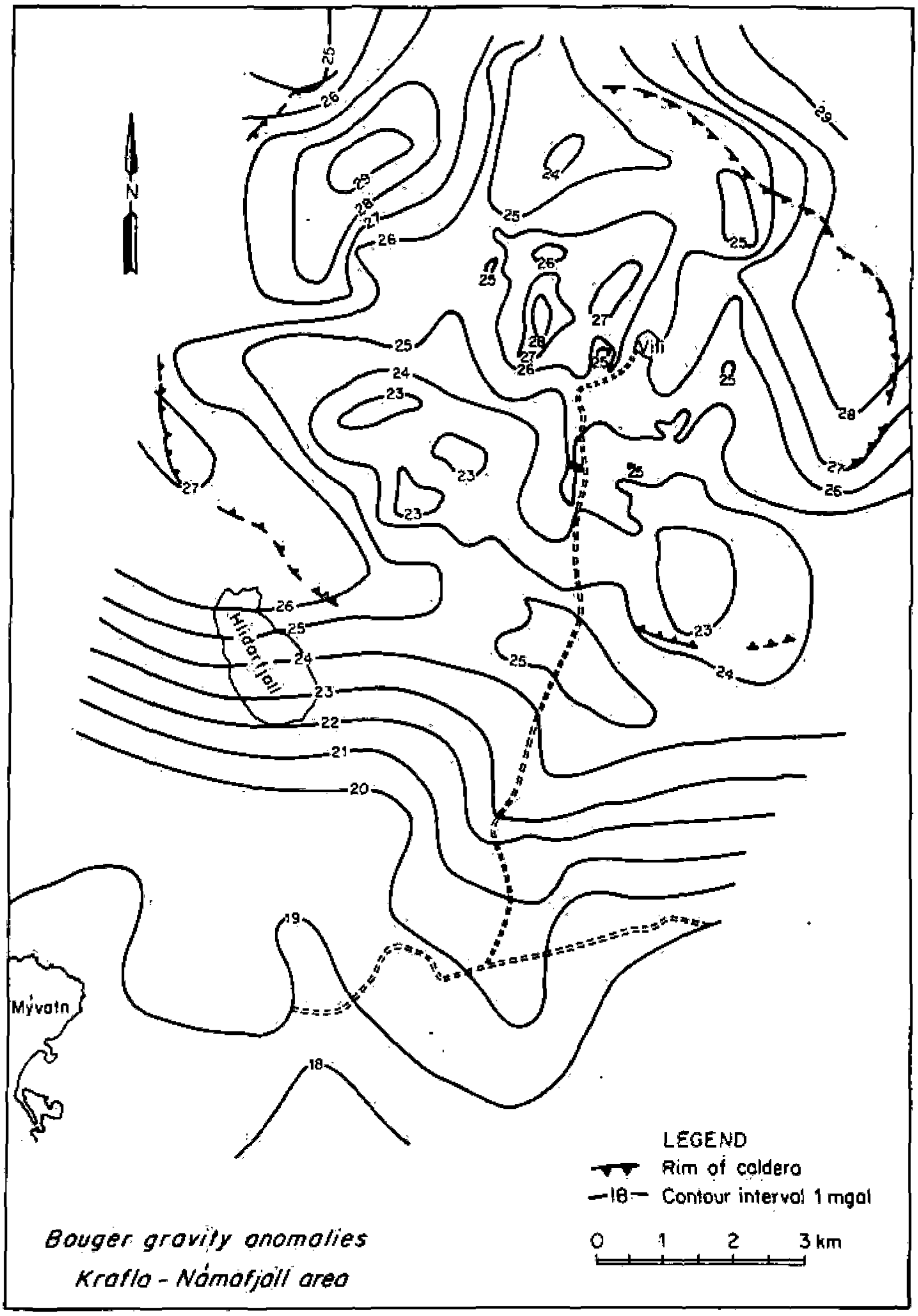

Figure 10.8. Bouguer gravity map of the Krafla area. Mapped by G. Johnsen. Reproduced by permission of Orkustofnun.

least 2200 m, which is the depth of the deepest well. The lower zone is boiling, i.e. the fluid in the formation is a mixture of steam, water and CO_2. The temperatures in this zone range from 300°C to 350°C, and both temperature and pressure are found to be close to saturation. The two zones are connected by an upflow channel near the gully Hveragil. A

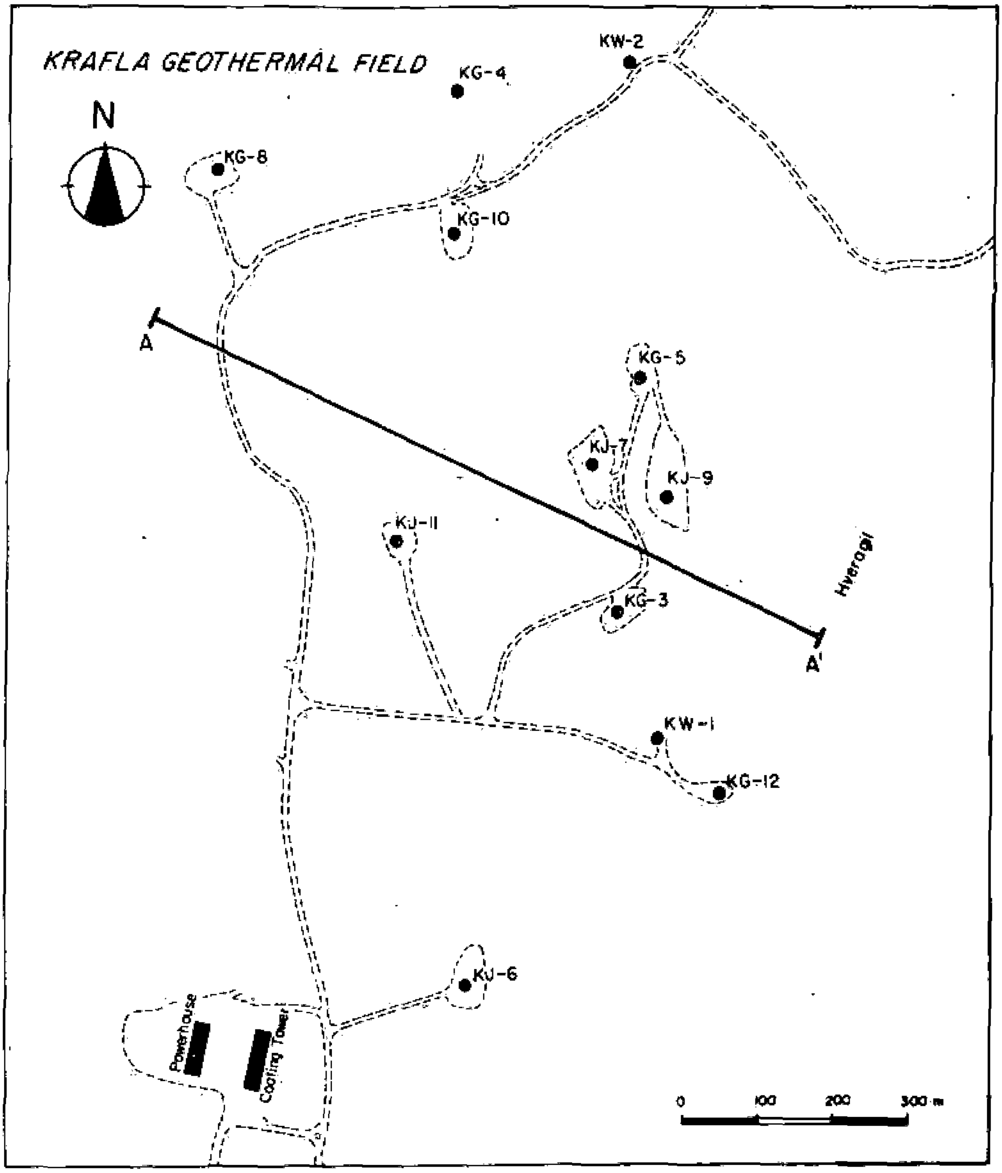

Figure 10.9. Location of the wells and of cross section in the Krafla geothermal field. A–A': trace of Figure 10.10. Reproduced by permission of Orkustofnun

simplified model of the Krafla geothermal field is shown in Figure 10.11. The facts that most of the wells have inflows from both zones and that the lower zone is a two-phase system, made the investigations more complicated. Most of the investigation methods had to be revised. As an example, all calculations of reservoir fluid chemistry had to be modified to include two-phase conditions in the initial stage. The complexity of the reservoir was realized at the same time as volcanic activity and spreading episodes began in the area. The influence of magmatic activity thus became an additional factor to be accounted for in the interpretation of the observations made in the geothermal field.

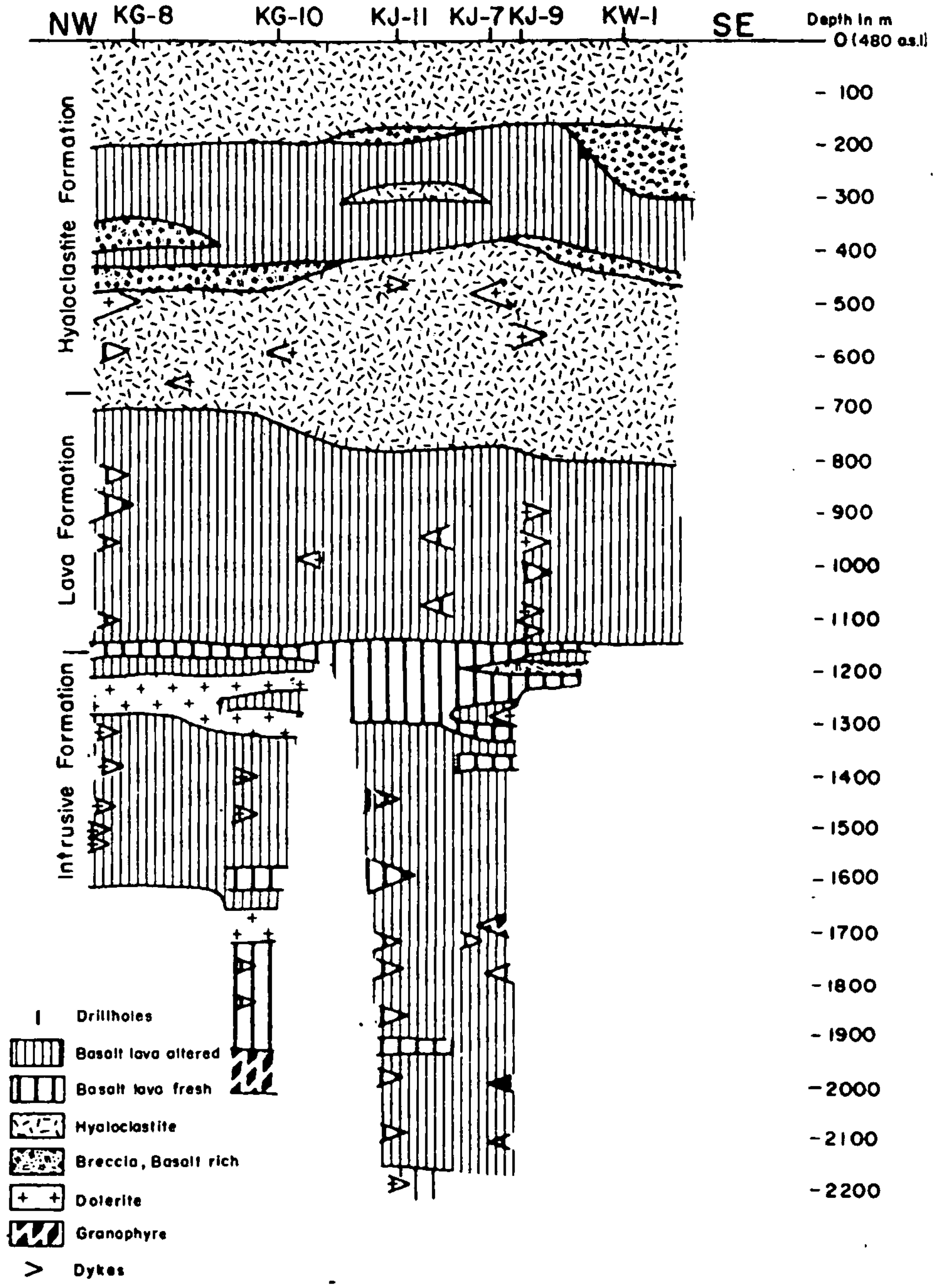

Figure 10.10. Geological cross section of the drilling area in Krafla. From Kristmannsdóttir (1978). Reproduced by permission of Orkustofnun

10.4. Production Characteristics of the Field

The production characteristics of the field cover a wide spectrum. The characteristics of the upper zone are rather uniform but quite different from the properties of the lower zone. In some of the wells an interaction between the two zones characterizes the

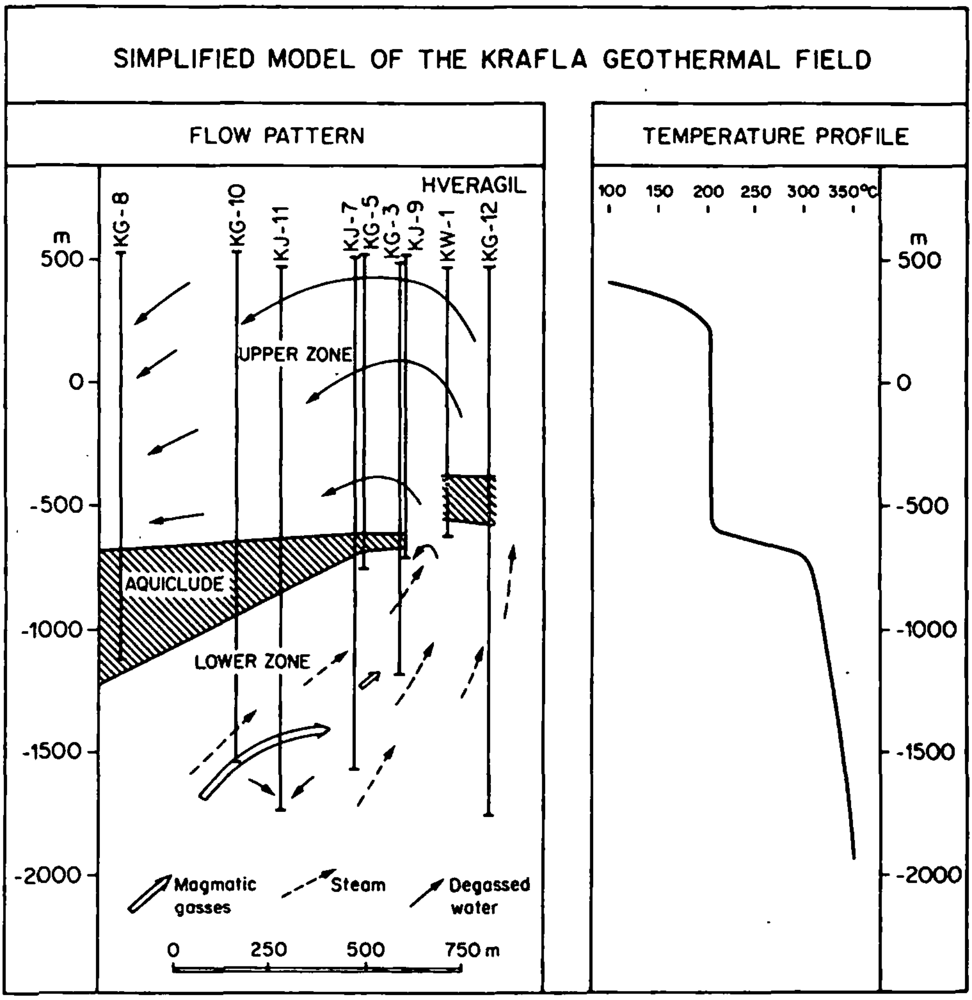

Figure 10.11. Simplified model of the Krafla geothermal field showing the main flow pattern and the average temperature profile of the field. Reproduced by permission of Orkustofnun

behaviour of the wells. Superimposed on these properties is the influence of the magmatic activity on the geothermal system.

10.4.1. *The Upper Zone*

The upper zone (200–1100 m depth) is a typical water-dominated geothermal reservoir. This zone is present in all the wells. The temperature is rather uniform, both horizontally and vertically over the 900 m thickness and is measured in the range 195–215°C, depending on the location of the wells. There is a good agreement between the measured temperature in the wells and the silica and Na–K–Ca temperatures. Pressure measurements in the discharging wells confirm the water phase nature of their inflow.

The distribution of the H_2/H_2S ratio of gases in the discharges of those wells which are fed only by the upper zone show (Figure 10.12) that the deep water in the more westerly

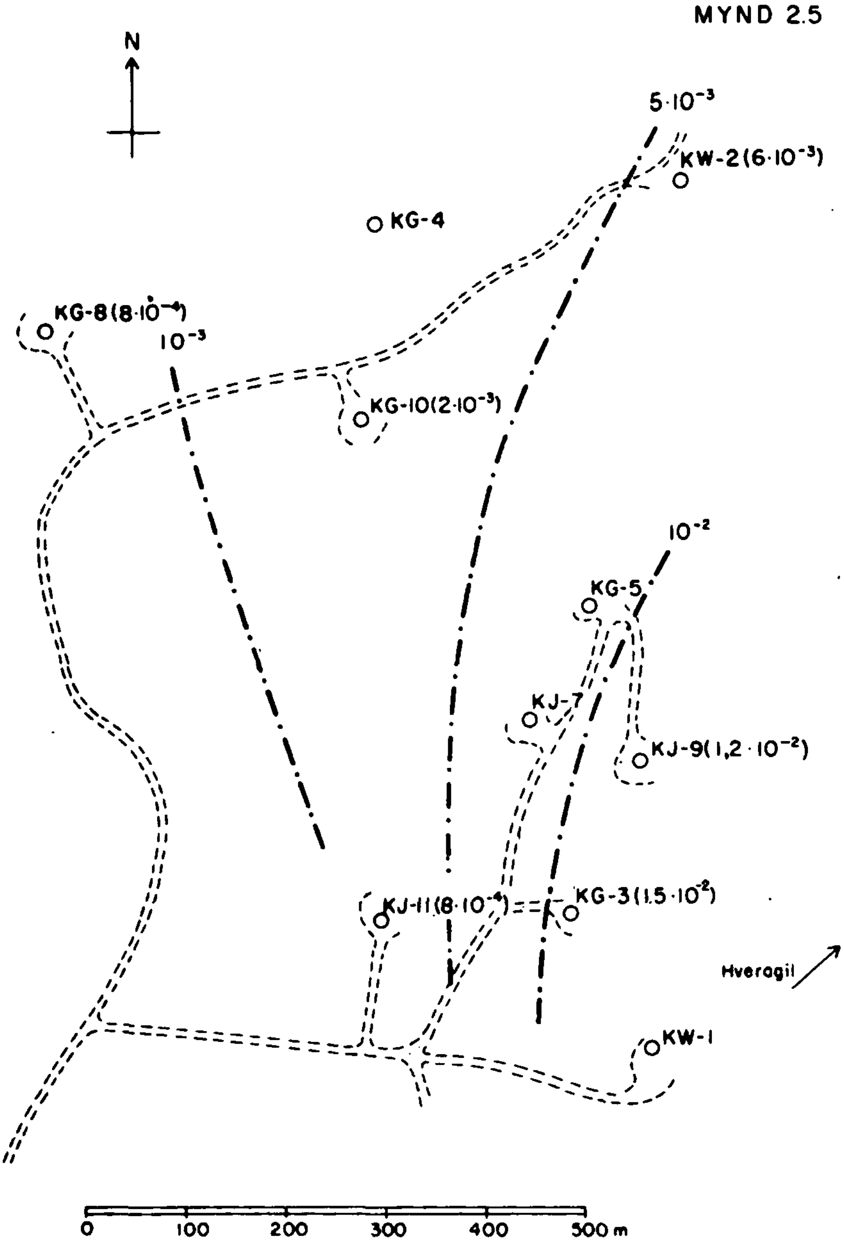

Figure 10.12. The H_2/H_2S ratio in reservoir fluid of the upper zone in Krafla. From Gíslason et al. (1978). Reproduced by permission of Orkustofnun

wells is more degassed than in the wells near Hveragil. A similar picture is found for the CO_2/H_2S ratio as well as for the total amount of gas in the discharge.

Pressure measurements in undisturbed wells indicate that pressure increases towards Hveragil. These observations indicate that the upper zone gets a through flow from the lower zone, rather than being an independent convection cell.

The chemical composition of the water from the upper zone is similar to other Icelandic water-dominated high-temperature fields. The major element composition of the unflashed reservoir fluid is shown in Table 10.1.

The water entering wells KW-2, KG-8 and KJ-9 is saturated with respect to calcium carbonate ($CaCO_3$). Degassing of flashing fluid in wells results in higher pH, which greatly increases the carbonate concentration. The calcium concentration increases upon boiling too. Due to boiling the activity product of calcium carbonate exceeds the saturation curve (Arnórsson, 1978a; 1978b). The calcium carbonate activity product for a representative upper zone well is shown in Figure 0.13 for a water decreasing in temperature as it boils. The supersaturation is greatest immediately after flashing, and the largest deposit should be formed at the level of boiling.

The rate of deposition in wells can be estimated by comparing the calcium concentration in deep water samples to that of the discharge at the well head. Such

Table 10.1. Average composition in mg/kg of the reservoir fluid in the upper zone.

pH	Na	K	Ca	Mg	SO_4	Cl	F	CO_2	H_2S	H_2	SiO_2/$TSiO_2$	
7·5	183	18·2	2·2	0·04	186	27	0·7	228.	54	0·24	300	210°C

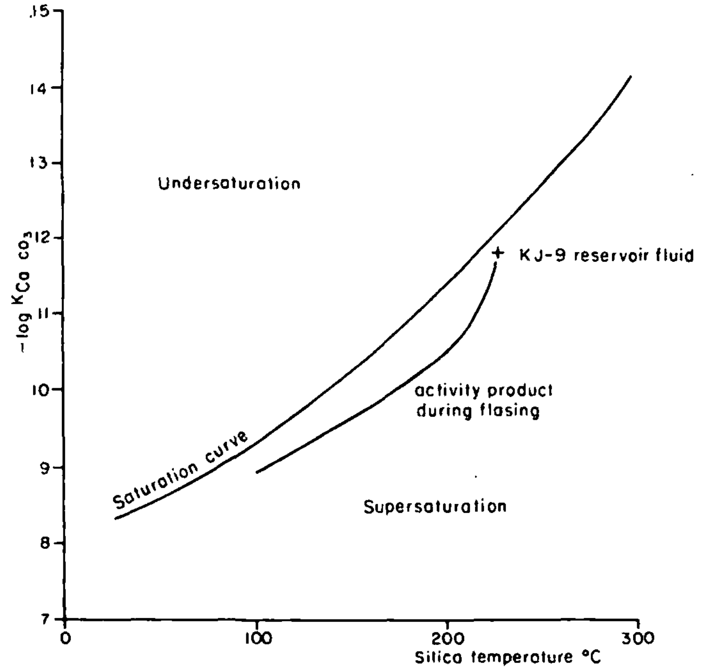

Figure 10.13. The computed activity product of Ca^{2+} and CO_3^{2-} in the geothermal water during one step adiabatic flashing in relation to the calcite solubility curve. Compiled by G. Gíslason and T. Hauksson. Reproduced by permission of Orkustofnun

investigation carried out in well KJ-9 revealed that there was an average 3·9 ppm decrease in the calcium concentration of the well fluid during boiling. For the actual flow of the well the deposition rate was 156 mg/s of $CaCO_3$, which corresponds to a deposition of 1·0 m^3 $CaCO_3$ during 180 days of flow. The well was actually worked over after a 180 days flowing period. The producing liner was pulled out of the well and the deposit measured. Its extent was greatest at the level of boiling (290 m depth), and the total volume was found to be 1·1 m^3. Chemical and X-ray analysis showed it to be almost pure calcite with traces of aragonite.

Permeability of the upper zone has been investigated in different ways. Injection tests, draw-down and recovery measurements have been made on individual wells. The mean permeability thickness is of the order of $10 \cdot 10^{-12}$ m^3.

The most spectacular method of permeability determination is the use of pressure pulses occurring in the upper zone coincident with rifting events and volcanic eruptions. The change in water level in well KG-5 during the event of September 8, 1977, is shown in Figure 10.14. By matching the decay part of the pressure curve with Theis log-log type curve (see Matthews and Russell, 1967) the response time of 8 hours is obtained. The distance from the well to the eruption site was 4·3 km, and by assuming the pressure transmission to be in 200°C water and the porosity to be 0·15 we obtain the permeability of $1{\cdot}5 \cdot 10^{-12}$ m^2. Compared with the permeability · thickness of $10 \cdot 10^{-12}$ m^3, this indicates an aquifer thickness of the order of 10 m. As has been pointed out by Grant (1978), the pressure transient in Figure 10.14 is just the Green's function, and the late time response is decaying like time^{-1}. These circumstances are in agreement with the assumption of injection at a point source into a confined aquifer.

Due to the relatively low temperature of the upper zone and to the inconvenience of the calcite depositions associated with the water from the upper zone, an attempt is now made to avoid the upper zone water in the utilization of the field. This is done partly by casing off the upper zone, and partly by moving the drilling area towards the upflow channel, where the two zones are connected.

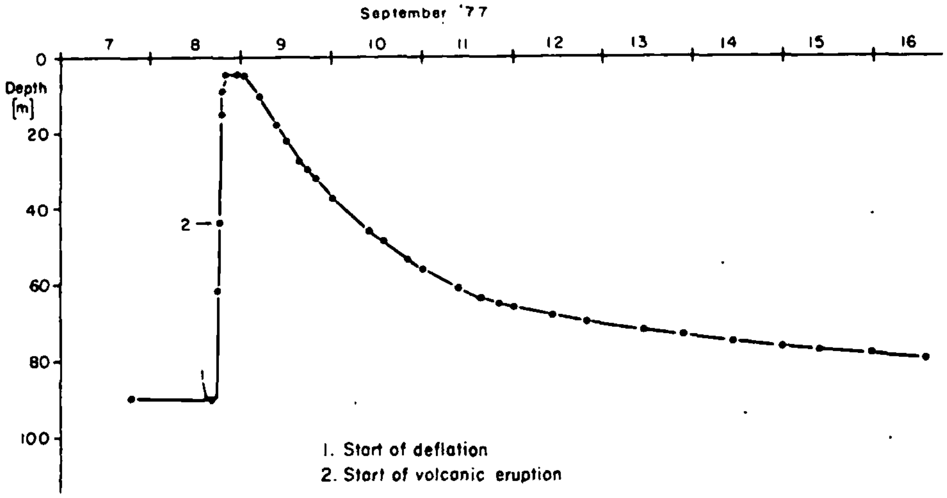

Figure 10.14. Water level in well KG-5 during the volcanic eruption of September 8, 1977. Compiled by B. Steingrímsson. Reproduced by permission of Orkustofnun

10.4.2. *The Lower Zone*

The undisturbed temperature and pressure in the lower zone are very close to saturation. The main characteristics of this zone are a high gas content and a high enthalpy of discharged fluid. Investigation of the chemical composition of the geothermal fluid has given very valuable information on the flow pattern within this zone. It has been demonstrated that volcanic gases (SO_2, H_2, CO_2) flow into the geothermal system from the underlying magma. The SO_2 is quickly reduced to H_2S during its passage through the formation. The gases CO_2, H_2S, and H_2 enter the investigated area in the neighbourhood of well KG-10 and propagate together with the steam up and eastward in the system. Other volatile elements like Hg and Rn follow this pattern closely. Radon is an interesting parameter in this respect as ^{222}Rn is radioactive with 3·8 days half life. By normalizing the Rn content to the CO_2 content in the fluid, the age of the fluid relative to the age of the fluid in well KG-10 can be determined. The following result was obtained.

	Age of fluid relative to KG-10
Well no. KG-10	0 days
Well no. KJ-7	1·9 days
Well no. KJ-6	5·4 days
Well no. KJ-9	9·9 days degassed water
Well no. KJ-11	11·2 days degassed water

For wells KJ-7 and KJ-6 this gives a flow velocity of 185 m/day.

Usual geochemical methods like silica and Na–K–Ca geothermometers cannot be used directly on a two-phase system. These methods assume the initial stage to be in pure water phase and the boiling to be isenthalpic. These conditions are not fulfilled for the lower zone in Krafla.

The main chemical characteristics of the fluid from the lower zone are shown in Table 10.2. Deposits consisting mainly of FeS, FeS_2, Fe_3O_4, and SiO_2 have been found in some of the wells tapping the lower zone fluid. The deposition rate has been most rapid in well KG-10, where the plug-in time has been recorded twice. Each time it was about three weeks. The deposition is believed to be at least partly due to magmatic influence on the geothermal fluid. The high concentration of SO_2 and other magmatic gases has a great influence on the pH-value, causing the fluid entering the wells to be highly supersaturated with respect to iron compounds.

The main characteristic of the boiling lower zone in Krafla is its response to production. Simple model calculations give that the steam fraction in the lower zone is of the order of 0·1–0·2 by volume. When utilization begins, the wells produce a mixture of steam and water, but the relative permeability of steam and water will influence the flowing history. The permeability of steam is higher than that of water, and when a certain steam fraction is reached, the water phase will be stagnant in the rock. The amount of water in the discharge will decrease while the amount of steam remains fairly constant. This means that the enthalpy of the discharge will increase. After a certain period the wells produce dry steam. The stagnant water then evaporates and contributes to the steam phase. During the evaporation, heat is withdrawn from the surrounding rock. When all the water close to the well has evaporated superheated steam will be produced.

One well, KG-12, produces exclusively from the lower zone. The flowing history of this well has followed the above description in detail.

Table 10.2. Chemical composition of fluid from wells, drawing predominantly from the Lower Zone

Well No.	KJ-6	KJ-7	KJ-9	KJ-11	KG-12
Sampling pressure MPa	0·98	0·78	1·04	0·22	0·83
Enthalpy of flow KJ/kg	1500	1900	1241	1483	2600
Steam fraction at P_s	0·37	0·58	0·23	0·44	0·92*
pH/°C of water phase	8·48/20	7·25/20	9·06/20	9·11/21	6·67/19
Ωm/°C of water phase	13·3/22	10·2/21	11·6/22	10·1/22	6·8/21
Silica† temperature (°C)	279	272	263	271	289
Chemical composition, expressed as mg/kg of total flow.					
CO_2	8436	17345	1357	5583	19048
H_2S	680	1046	75	199	801
H_2	8·1	26	1·4	1·1	49
CH_4	0·18	0.17	0·09	0·09	0·04
SiO_2	498	303	513	465	66
Na	95	82	158	132	19
K	16	12	18	22	4·8
Ca	0·79	0·98	1·3	0·95	2·1
Mg	0·006	0·008	0·008	0·006	0·01
SO_4	84	74	175	71	10
Cl	20	43	38	21	21
F	0·84	0·50	0·62	0·51	0·13
Fe	<0·06	0·21	0·13	<0·05	0·15
Total dissolved solids	831	564	962	852	140

*This flow developed into superheated steam.

†Calculated, taking enthalpy values into account.

10.4.3. *Interaction Between the Zones*

As demonstrated by the model, the two zones are connected near Hveragil, where a natural upflow channel keeps the lower zone in boiling condition. Other connections between the zones have not been discovered so far. If wells are open to both the upper and the lower zone, interference effects are observed in the behaviour of the wells. Effects like pressure oscillations during injection tests and flow from the upper aquifers down to the lower zone are common. One of the wells turned out to be very sensitive to load variation, as small pressure variation at wellhead could quench the lower aquifer.

As the discharge from wells taps fluids from both zones, the interpretation of chemical analysis becomes complicated. However, in the wells which produce from both zones it has been possible to estimate the amount of inflow from each zone by assuming the enthalpy and chemical composition of the upper zone to be fairly constant and using the total measured enthalpy of the discharge together with the measured concentration of the mixture at well head. The mass ratio of the lower zone contribution is found to be in the range 0·25 to 0·75 in the mixed wells.

10.4.4. *Influence of Magmatic Activity on the Reservoir*

As shown on Figure 10.14, the rifting events and magmatic activity cause a pressure impulse in the water-dominated upper zone. Similar pressure transients have not been detected in the lower zone. This is interpreted to be due to the two phase condition of the lower zone. The pressure transient is absorbed quickly in the two phase system. Quite noticeable magmatic influence has also been observed on the chemical composition of the lower zone fluid as shown in Figure 10.15.

The presence of magmatic gases in the reservoir has aided the mapping of the flowing directions as well as the flowing velocity in the reservoir as described in section 10.4.2. However, these same gases seem to cause serious depositions in wells. This has been strongly experienced in well KG-10, which is closest to the inflow of magmatic gases.

10.5. Experience with Utilization

The Krafla Power Plant is now operating with partial load and further drilling is needed to provide steam for the Power Plant. The experience gained with utilization is rather small.

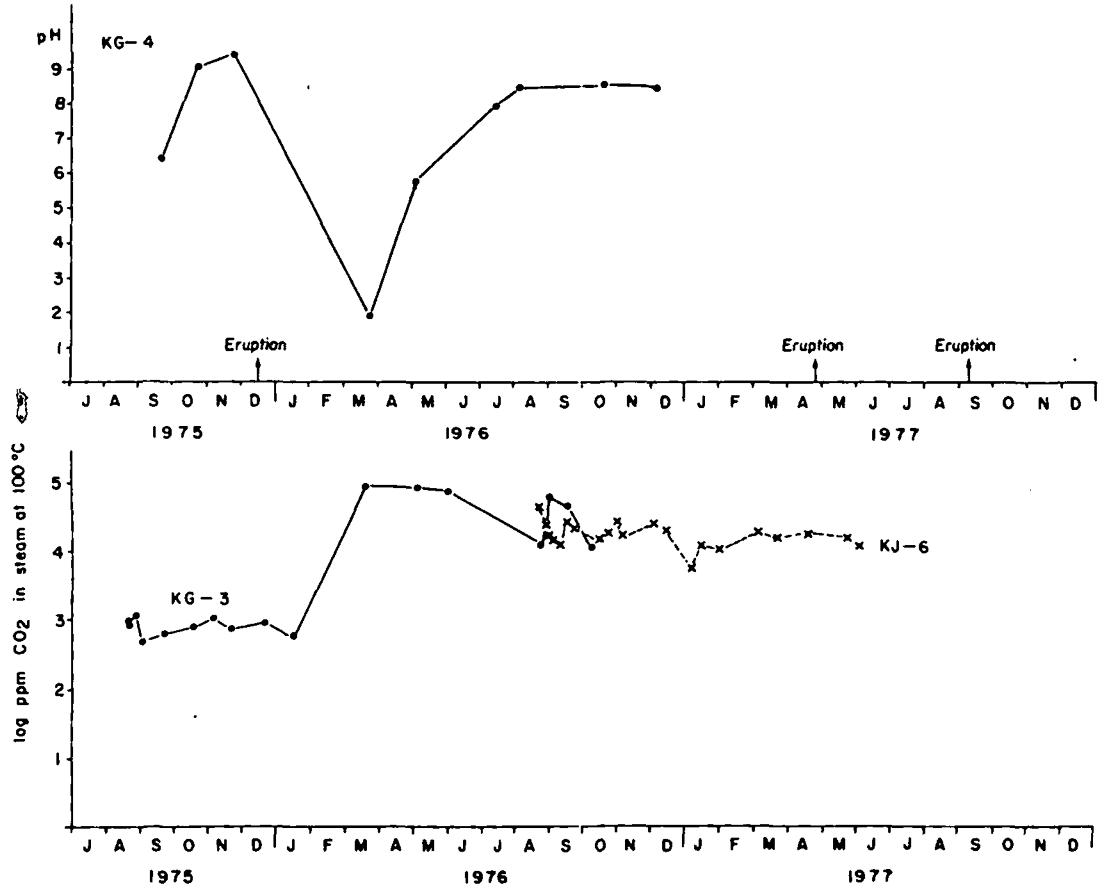

Figure 10.15. Influence of magmatic activity on the chemical properties of the geothermal fluid. Compiled by G. Gíslason. Reproduced by permission of Orkustofnun

The two turbine generators of the Krafla Power Plant consist of five stage double pressure, double flow steam turbines with 37·5 MVA brushless generators. The turbines are condensing with a direct contact condenser located under the turbine. The steam turbines have a maximum capacity of 35 MW each during the most favourable external conditions.

The steam separators are designed to separate the high pressure steam at 0·9 MPa pressure, and the HP inlet pressure of the turbine is assumed to be 0·77 MPa. The low-pressure separation is performed at 0·22 MPa pressure. The non-condensable gases (CO_2, H_2S) are removed by gas ejectors. The system can cope with 1–2 per cent of non-condensable gases in the steam. The pressure in the main condenser is estimated to be 0·012 MPa and the temperature of the condensed water 46°C. The condensate is cooled to about 22°C in cooling towers. Effluent water from the steam separators will be cooled down 10–20°C in cooling ponds and then dumped in a lava field south of the Krafla area. The first estimate of the amount of effluent water was 360 liters/s assuming the field to be water-dominated with the temperature of 270°C. The present knowledge of the field shows that utilization, restricted to the lower zone only, will give wells that produce more or less dry steam. Therefore, the environmental consequences of disposing effluent water in the area will be smaller than initially assumed.

The method of developing a geothermal field coincident with the construction phase of geothermal utilization has been experienced twice in Iceland. In the first case, the development of the Námafjall area (Ragnars et al. 1970), the risk taken did not have any consequences, as the production characteristics turned out to be more favorable than assumed. In the second case, the Krafla geothermal field, the production characteristics of the field turned out to be more complex than initially assumed, and the project became a very delicate political subject.

The experience gained in the development of the Krafla field has emphasized the necessity of the knowledge of the most essential production characteristics of a field prior to development, and that relatively higher cost for drilling should be accounted for when drilling is performed coincident with power plant construction.

The capital cost of the Krafla power plant inclusive of drilling and main transmission line is in November 1978 about 55 million U.S. dollars. The annual capital cost is estimated to be about 5 million US dollars. Additional finances will be needed for further drilling and transmission of steam.

From the scientific point of view, the experience gained in the investigation of the first proved boiling reservoir in Iceland has been very valuable. The coincidence that volcanic activity started to influence the geothermal field during the investigation has given rise to new ideas on the creation and nature of high-temperature geothermal fields in Iceland.

10.6. Current and Future Developments

The Krafla Power Plant is now operating at partial load and more drilling is needed for the production of steam. In the nearest future, additional drilling is planned east of the present drilling area in the neighbourhood of the upflow channel from the lower zone. The displacement of the drilling area in this direction is expected to result in better production characteristics of wells and less influence of magma on the reservoir fluid.

Volcanic activity is still going on in the Krafla area, and while this activity is continuing the investment in the field will probably be slow. However, assuming that volcanic activity will not cause a major damage to the Power Plant or the production wells, the aim of present and future operations in the area is to make the Power Plant operate at the rated capacity.

Acknowledgements

The present knowledge of the Krafla geothermal field is a result of an extensive team work of many people. Major contributions are due to: Dr. Halldór Ármannsson, Dr. Stefán Arnórsson, Dr. Axel Björnsson, Prof. Sveinbjörn Björnsson, Mr Gestur Gíslason,

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W/ARD

Geothermal Systems: Principles and Case Histories
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10. *The Krafla Geothermal Field, Northeast Iceland*

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10.1. Introduction

Geothermal energy is extensively utilized in Iceland. The total installed geothermal capacity is now about 600 Megawatts thermal (MWt). The geothermal energy is mainly used for space heating, and the net geothermal consumption is about 500 MWt. As the total population of Iceland is 220,000, this is a large proportion of the energy consumed in the country (Pálmason et al., 1975). In fact more than 30 per cent of the net energy consumption in the country comes from geothermal energy sources (Stefánsson, 1975; Fridleifsson, 1978). Most of the geothermal energy used in Iceland comes from the low temperature fields, where geothermal water of the temperature 60–120°C is used directly for space heating and greenhouse cultivation. Figure 10.1 shows the volcanic zones in Iceland and the high-temperature geothermal fields as solid triangles, all located within active volcanic zones. The low-temperature fields are predominantly located on the flanks of the volcanic zones (Pálmason et al., 1975).

The utilization of the high temperature geothermal field at Námafjall started in 1967. The main purpose is processing of diatomite deposits from Lake Mývatn (Ragnars et al., 1970). The decision to build the diatomite plant was taken before major drilling for steam was started in the area. A 3 MWe power station was installed at Námafjall in 1969.

In 1973 a long standing plan for a hydroelectric power plant in NE Iceland was cancelled because of strong public opposition concerning the environmental consequences of the project. Time was short, and it was believed that the construction of a geothermal power plant would take less time than any hydroelectric alternative. In 1975 it was decided to build a geothermal power plant in Krafla, a high temperature field about 10 km north of Námafjall. In order to gain time, it was decided to build the power plant concomitant with the drilling for steam.

At the time, the development of the Svartsengi high temperature field is SW Iceland was initiated (Arnórsson et al., 1975), where a 30 MWt heat exchange plant is now in operation. A 235°C saline geothermal brine is used for the heating of fresh water of good quality for space heating and domestic use. A 1 MWe electric generation is used for the plant's internal power-supply. In addition a pilot plant for the production of sea chemicals was erected in 1978 at the Reykjanes thermal brine area. The exploration work has been described by Björnsson et al. (1970, 1972).

The exploration of the Krafla geothermal field started in 1970 and was initially carried

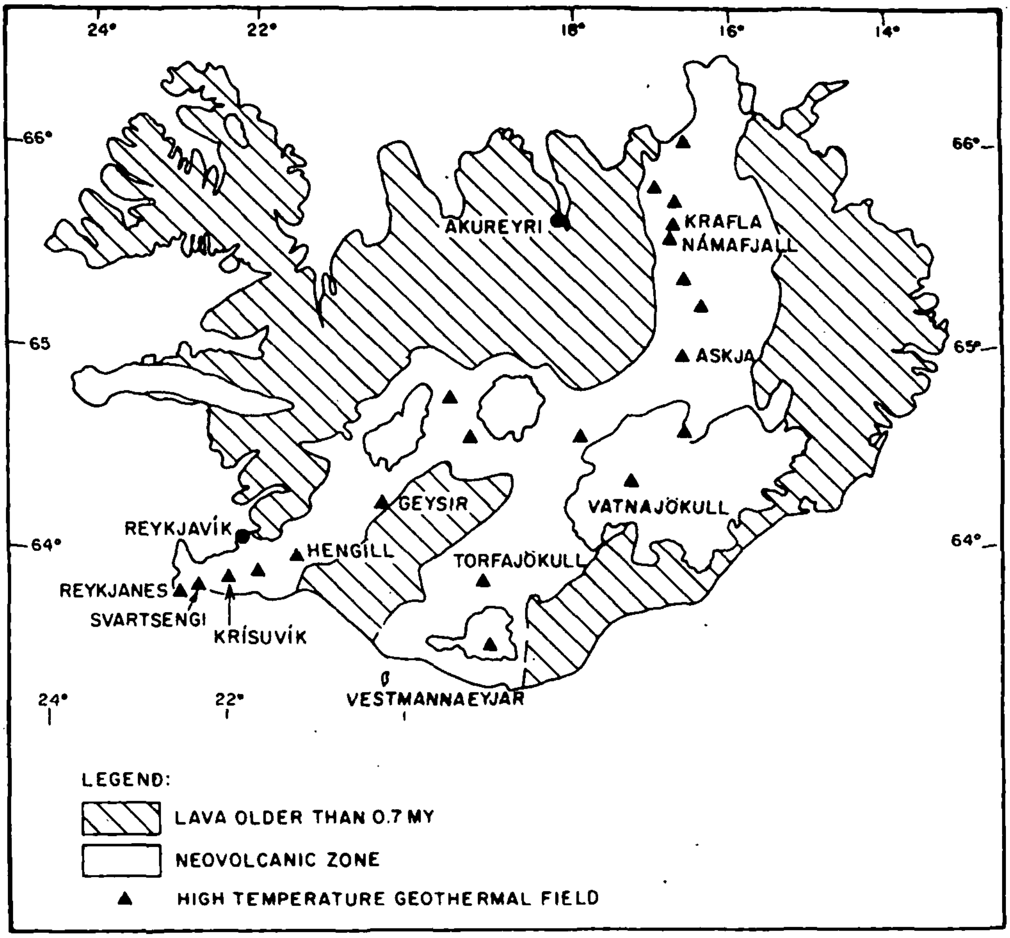

Figure 10.1. Schematic geological map of Iceland showing the high-temperature fields within the volcanic zones. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

out according to the Program for the Exploration of High Temperature Areas in Iceland (Björnsson, 1970). A consequence of the decision to build the power plant concomitant with the drilling operation was that the investigation of the production characteristics of the field could not be made until during the production drilling phase. During drilling, it was found that the reservoir was partly boiling and that the production characteristics were quite different from those of a water-dominated field. Up to that time all high-temperature geothermal fields in Iceland had been found to be water-dominated fields, with base temperatures 200–300°C.

The reservoir in Krafla has been found to be complicated, consisting of two geothermal zones: an upper water-dominated zone with 205°C temperature, and a lower zone boiling at 300–350°C temperature. These unexpected circumstances greatly influenced the plans for the power plant. When the power plant was completed in 1977, the available steam was sufficient to produce 7 MW of electricity, whereas the power plant is designed for 60 MW.

In December 1975 a volcanic eruption occurred in Leirhnjúkur about 2 km from the Krafla power plant. This volcanic eruption was the beginning of a rifting episode in the fissure swarm intersecting the Krafla caldera. During the last three years this volcanic activity has proceeded with seven rifting episodes, three of which have resulted in volcanic eruptions. The magmatic activity has influenced the production characteristics of the Krafla field.

In the present paper the Krafla geothermal field and some of its production characteristics will be described. The utilization of the field has just started and the experience gained with this utilization is small.

10.2. Geological Framework

Iceland lies astride the Mid-Atlantic Ridge. The surface expressions of the ridge are the so called neovolcanic zones, which are divided into several branches. In general, the structure of the neovolcanic zones is dominated by fissure swarms and central volcanoes. The fissure swarms are usually about 10 km wide and 30 to 100 km long. Most of the fissure swarms pass through central volcanoes, which are the loci of highest lava production and are also defined by the presence of acid rock and high-temperature geothermal fields. The neovolcanic zones have been described in detail (Saemundsson, 1974; Walker, 1975; Jakobsson et al., 1978; Saemundsson, 1978), and the interaction between the central volcano in Krafla and the intersecting fissure swarm has recently been described (Björnsson et al., 1977; 1979).

The Krafla central volcano is situated on one of the five distinct fissure swarms in the northeast volcanic zone in Iceland. All fissure swarms in the northeast volcanic zone are associated with central volcanoes and have developed high-temperature geothermal fields (Figure 10.2). The Krafla central volcano developed a caldera during the last interglacial period, but since then the caldera has been almost filled with volcanic material. The caldera measures about 8 x 10 km. Figure 10.3 is a tectonic map of the area, showing the fissure swarm and the caldera.

A rifting episode, currently occurring in the Krafla fissure swarm (Björnsson et al., 1977), has shown that in the fine structure of continental drift discontinuous movements are present. During a rifting episode magma is stored temporarily in a magma trap under the Krafla central volcano from where it is expelled along the fissure swarm to form dykes. The geothermal fields are located in areas of preferred magma concentration at shallow levels in the swarm, such as in the Krafla caldera and on certain locations along the fissure swarm, e.g. in Námafjall. Figure 10.4 is a schematic picture relating the magma chamber, the fissure swarm and the geothermal fields (Björnsson et al., 1979). The longest distance of subterranean magma flow was recorded during the rifting event in December 1975, when earthquake activity progressed towards the north over a distance of about 50 km along the fissure swarm. A high-temperature geothermal field has been suggested to be present in the Axarfjördur area on the basis of surface geophysical and geochemical surveys (Stefánsson, 1979). The heat source for this field may be of a similar nature as described above for Námafjall.

The postglacial volcanism in the Krafla area has occurred in two main periods. The first was in early postglacial time and the second during the last 3000 years. In these two periods, there have been about 20 volcanic eruptions in the Krafla caldera and about 15 in the Námafjall area. The majority of the fissure eruptions are basaltic, but andesite and dacite flows have also occurred. Four subglacial silicic eruptions have produced large domes or ridges within and around the Krafla caldera. Several explosion craters are located within the caldera. The most recent one (Viti on Figure 10.5) was formed in 1724 at the beginning of the 1724–1729 volcanic and rifting episode, the Mývatn fires.

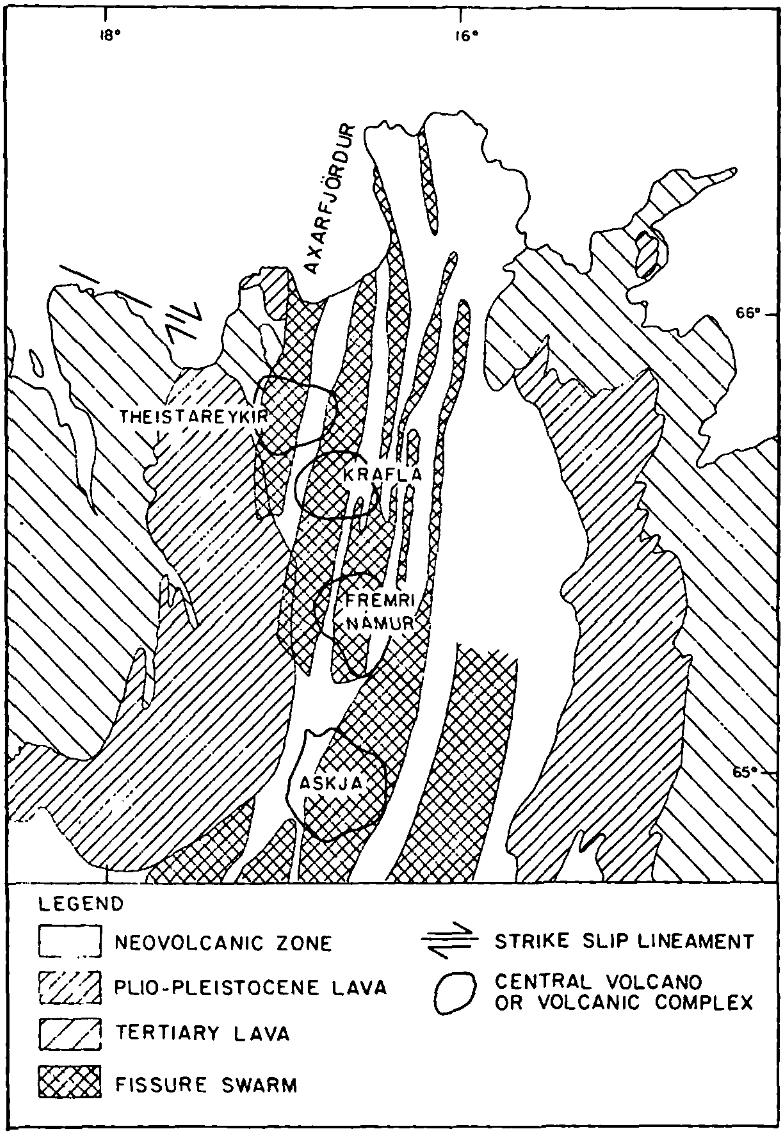

Figure 10.2. The fissure swarms and central volcanoes within the Northeast Volcanic zone in Iceland. Two volcanoes, Krafla and Askja have developed calderas. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

The high-temperature geothermal field inside the Krafla caldera is elongated NW–SE. The main surface activity is in the center of the caldera (near Leirhnjúkur) and in the southeastern part of the caldera where a series of explosion craters have formed a gully called Hveragil. The surface area covered by thermal alteration and geothermal activity is about 35 km^2. Petrological study of the rocks in the Krafla area reveals composition ranging from olivine tholeiite to rhyolite. By drilling in the area it has been found that basalt as well as granophyre intrusions occur frequently below the 1100 m depth level. Figure 10.5 shows the relation of the wells to the underlying magma chamber.

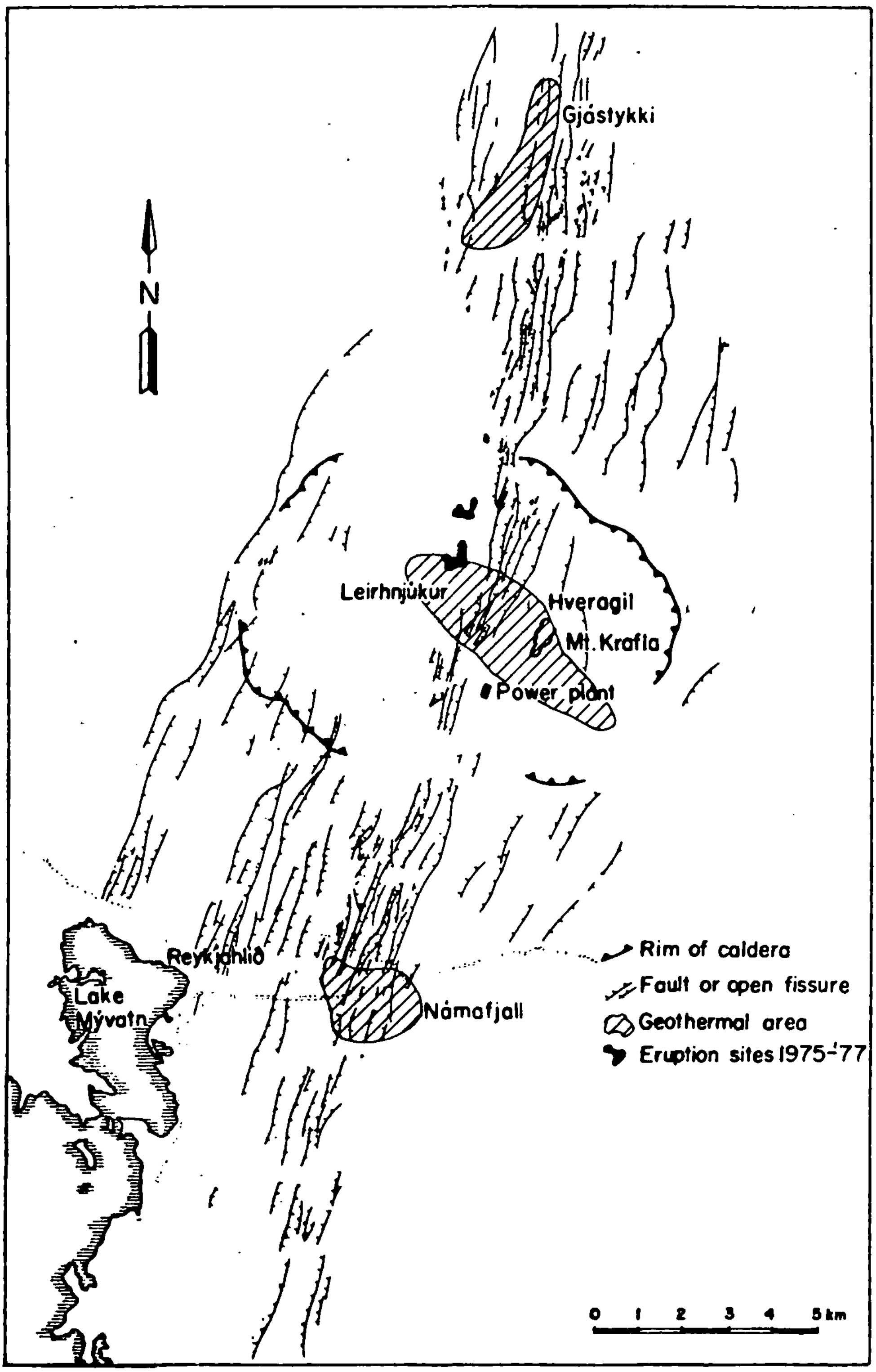

Figure 10.3. Tectonic map of the Krafla area showing the caldera and the active fissure swarm. Mapped by K. Saemundsson. Reproduced by permission of Orkustofnun

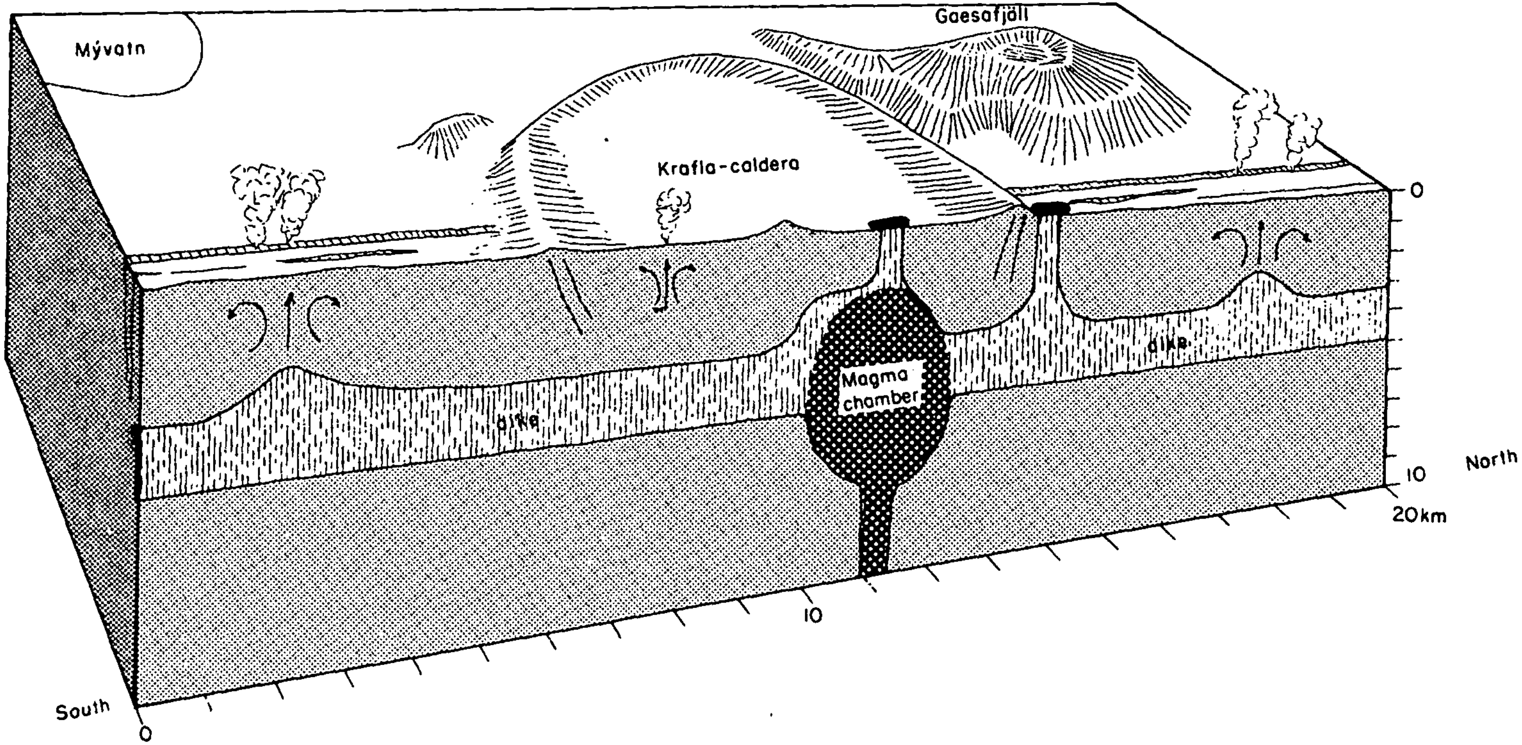

Figure 10.4. A block diagram showing schematically the magma body below the Krafla caldera and the dyke formed in the present tectonic episode. From Björnsson et al. (1979). Reproduced by permission of Orkustofnun

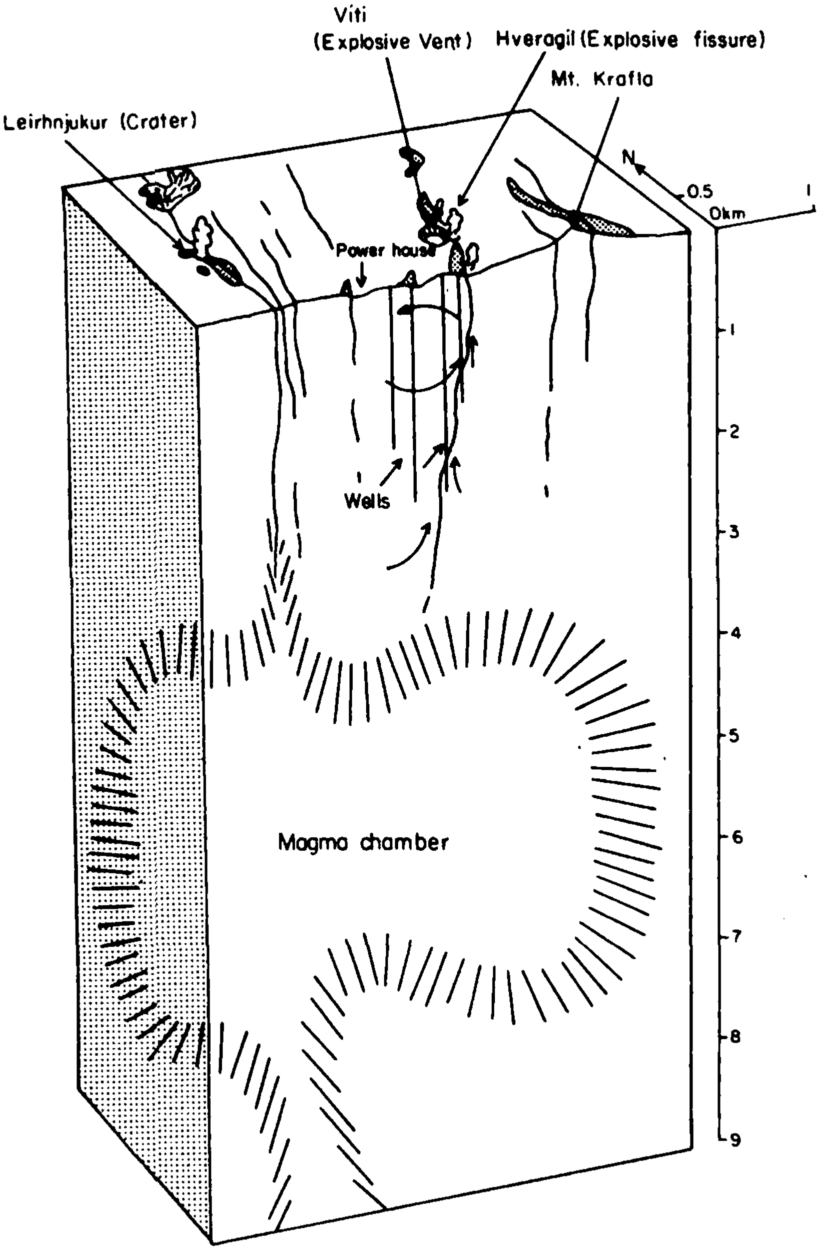

Figure 10.5. The Krafla Geothermal Field and the underlying magma body. From Gíslason et al. (1978). Reproduced by permission of Orkustofnun

10.3. Exploration History and the Model of the Field

10.3.1. *Surface Exploration*

Systematic exploration of the Krafla geothermal area started in 1970. The surface investigation included geological mapping, geochemical analysis of natural springs and fumaroles, aeromagnetic survey, resistivity survey, and seismic refraction measurements. After the start of the rifting episode in 1975, additional surface investigations (e.g. gravity measurements) have been carried out.

The geological investigation resulted in the description of the Krafla caldera and the history of volcanic activity in the area. Surface geothermal activity was mapped in detail, and the connection between tectonic manifestations and geothermal activity was found to be essential. A simplified tectonic map of the area is shown in Figure 10.3.

The investigation of the CO_2/H_2 ratio and the amount of H_2 in fumarole steam indicated that the hottest fluid (245–285°C) should be expected under the gully Hveragil.

The resistivity survey was performed in the years 1971 and 1972, and additional measurements were done in 1976 and 1977. The Schlumberger DC resistivity method has been mainly used, but several dipole soundings and magnetotelluric measurements have been done in the area as well. At shallow depth (less than 800 m) the resistivity measurements show a good correlation between surface alteration and the low resistivity region. For greater depths the resistivity measurements show a somewhat complicated picture. Inside the low resistivity region, the resistivity seems to increase beneath 800–1000 m depth. This observation could be a skin effect, but subsequent resistivity measurements in drillholes indicate that the increase in resistivity with depth is real. In Figure 10.6 the measured resistivity at 600 m depth is shown. The active geothermal area, mapped by surface alteration

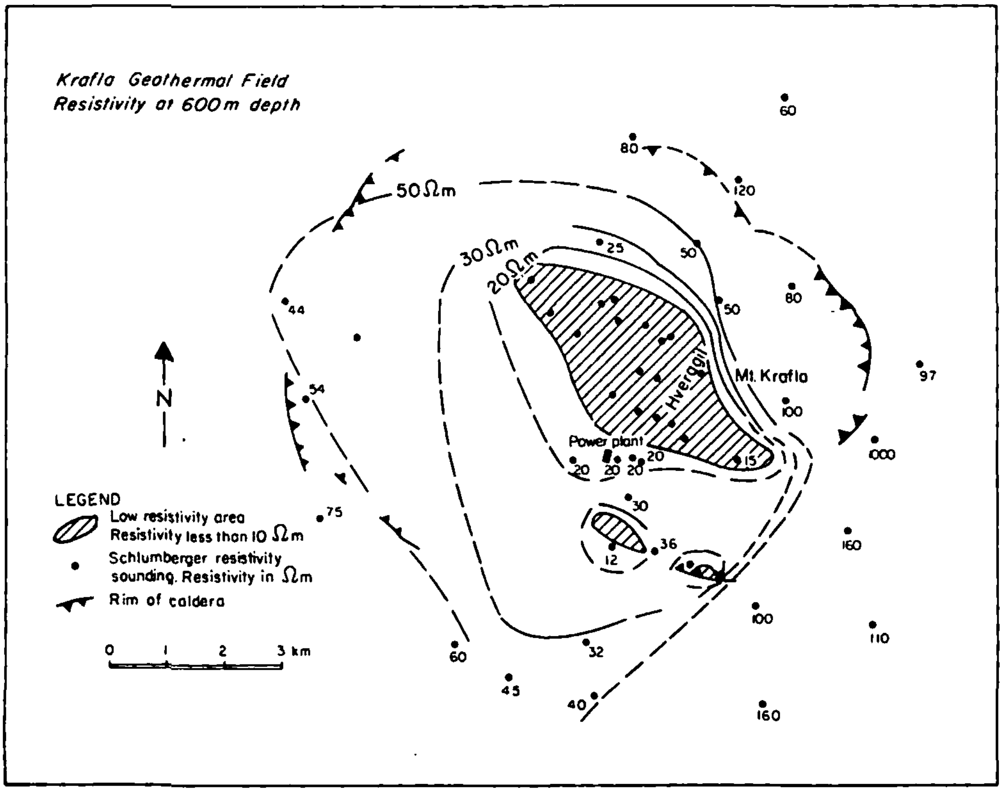

Figure 10.6. Resistivity at 600 m depth in the Krafla geothermal field. Mapped by R. Karlsdóttir. Reproduced by permission of Orkustofnun

and resistivity survey is approximately 30 km^2. This area is relatively large compared with other investigated high-temperature fields in Iceland. Therefore, it was initially concluded that the geothermal potential of the Krafla field was high.

The aeromagnetic survey showed a prominent magnetic low in the southern part of the caldera, and the strongest magnetic anomaly is found in the southern part of the geothermal field. The NW–SE elongation of the geothermal field is also prominent in the magnetic map shown in Figure 10.7. The magnetic low associated with geothermal activity is interpreted to result from alteration effects on magnetic minerals.

The seismic refraction measurements gave inconsistent results, and these have not been used further for the geothermal investigation of the field. In 1975 three seismometers were installed in the Krafla area. The seismic investigation revealed the existence of a magma body at a depth between 3 and 7 km inside the Krafla caldera (Einarsson, 1978).

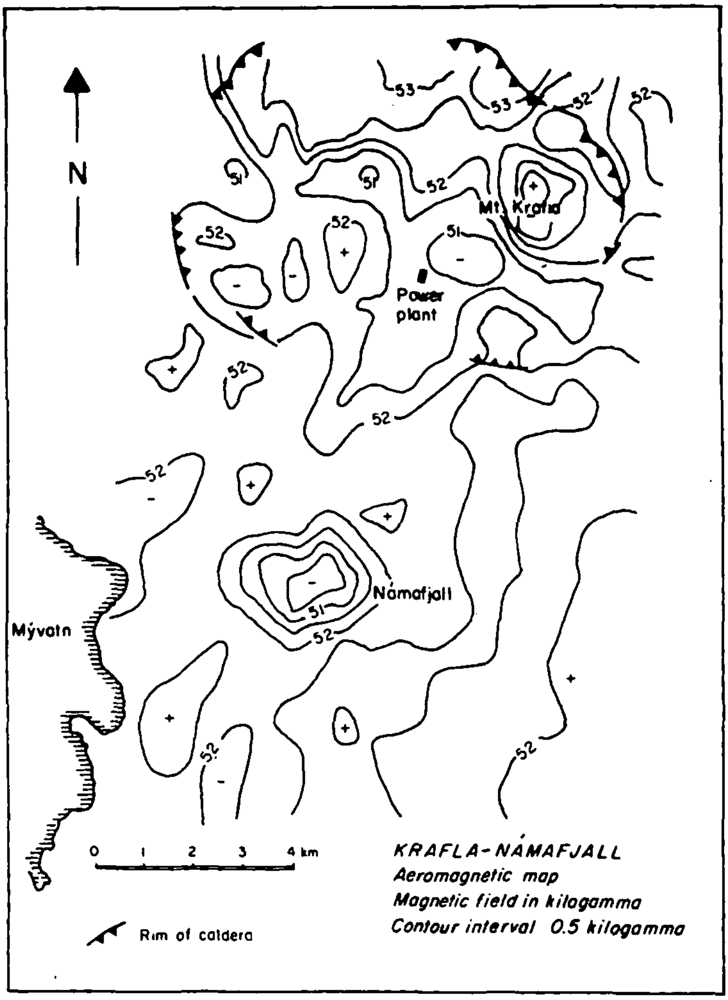

Figure 10.7. An aeromagnetic map of the Krafla-Námafjall high-temperature fields. From Pálmason (1975). Reproduced by permission of Orkustofnun

Gravity measurements have been repeated frequently in the area in connection with the rifting episode. A Bouguer map of the area is shown in Figure 10.8. The caldera effect, as well as the NW–SE elongation structure is prominent in the gravity map.

10.3.2. *Subsurface Exploration*

Two 1100 m deep exploratory wells were drilled in 1974. In one of the wells, a temperature of 300°C was found. At this stage the temperature conditions in the field were thought likely to be close to the boiling point curve. In the years 1975 and 1976 nine additional wells were drilled, and the twelfth well was drilled in 1978. The location of the wells is shown in Figure 10.9. The investigations carried out concomitant with the drilling and during flow tests were: petrological logging and mineralogical and geochemical study of the cuttings, temperature and pressure measurements in both static and flowing wells. resistivity and SP logs in wells, permeability tests both with injection and drawdown tests, measurements of enthalpy and chemical composition of the discharged fluid, production characteristics of wells, and analysis of deposits in the wells.

The subsurface rocks can be split into three main lithological units; the hyaloclastite formation, the lava formation, and the intrusive formation (Figure 10.10). The hyaloclastite formation in the uppermost 800–900 m is composed of primary and reworked products from subglacial eruptions. It is subdivided by a thick suite of subaerial lavas. Below 800–900 m depth, sequences of subaerial lava flows are dominant and hyaloclastites are rare. Dykes are common below 400 m depth. A multiple sill is located below the central part of the drilling area at 1100–1300 m depth. Below 1500–1600 m depth in the northern and southern part of the drilling area the rocks are entirely intrusive.

The compositions of the lavas and hyaloclastites are mostly near to saturated tholeite basalt, but range from olivine tholeiite to quartz tholeiite. Thin layers of acid tuff occur in the drilled section. The intrusive rocks are most frequently of basaltic composition, but granophyre intrusions appear also. The rocks in the hyaloclastite formation are completely recrystallized and the lavas are highly altered. The alteration pattern shows a fairly regular zoning (see Kristmannsdóttir, 1978). A retrograde transformation of the sheet-silicates above 1200 m depth level has been observed in some of the wells. The degree of alteration is comparable to that of zeolite to greenschist facies metamorphism. The transition between zeolite and greenschist facies alteration is at about 800 m depth.

The temperature measurements yielded values up to 345°C, which is the highest temperature recorded so far in geothermal wells in Iceland. The pressure profile of static wells indicated hydrostatic pressure in the field. The enthalpies of the wells were usually high, and the chemical composition of the fluid showed great variation within the field. In order to compile all the results and observations to a single solution, a new model of the geothermal field was necessary. The new model of the field was first presented in January 1977, but additional information confirmed its validity. All present observations are in agreement with this model.

10.3.3. *The Model of the Field*

The geothermal system in Krafla consists of two separate geothermal zones. The shallower one, extending down to ca. 1100 m depth, is a water-dominated system with a mean temperature of 205°C. The deeper zone ranges from about 1100–1300 m depth to at

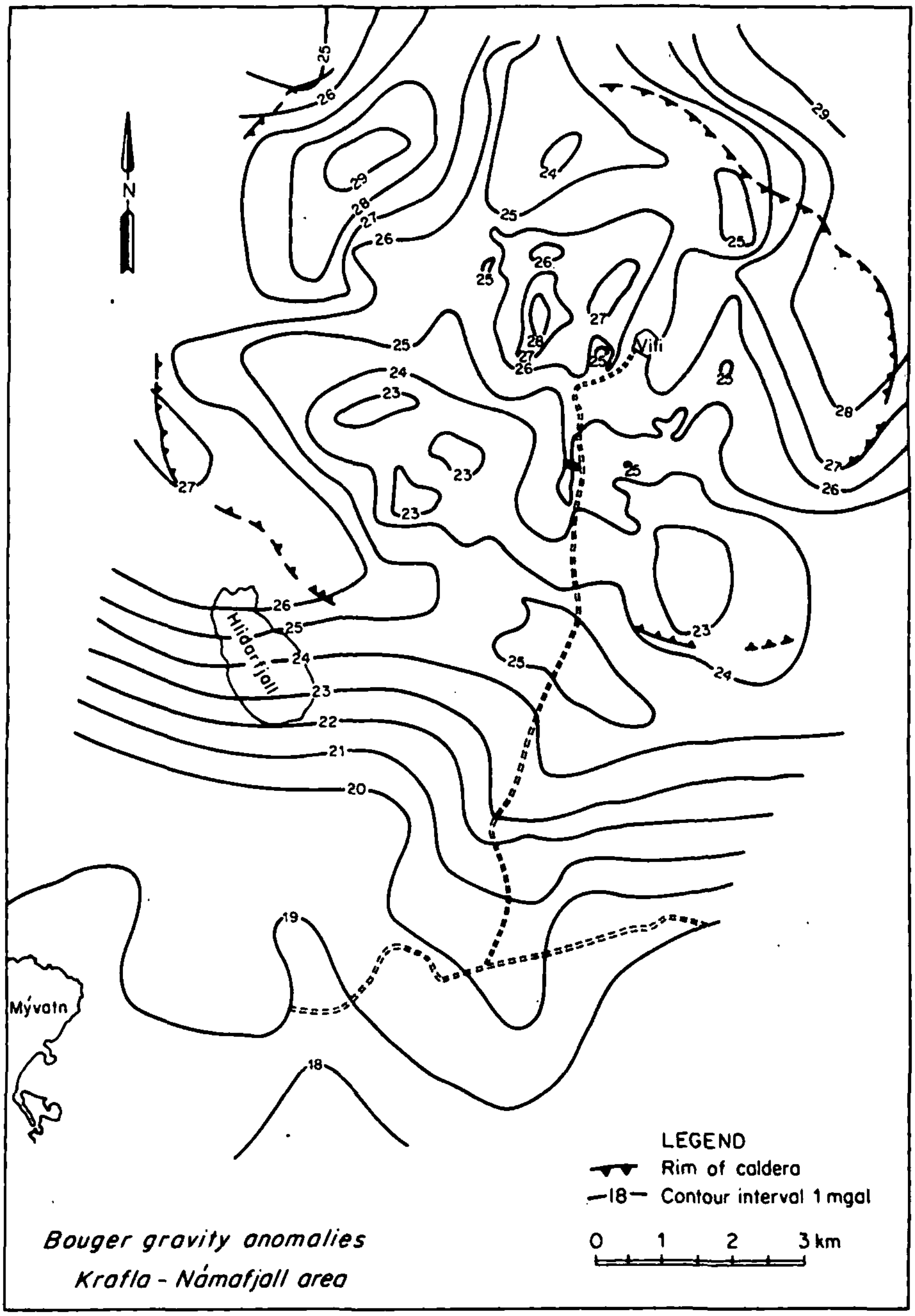

Figure 10.8. Bouguer gravity map of the Krafla area. Mapped by G. Johnsen. Reproduced by permission of Orkustofnun

least 2200 m, which is the depth of the deepest well. The lower zone is boiling, i.e. the fluid in the formation is a mixture of steam, water and CO_2. The temperatures in this zone range from 300°C to 350°C, and both temperature and pressure are found to be close to saturation. The two zones are connected by an upflow channel near the gully Hveragil. A

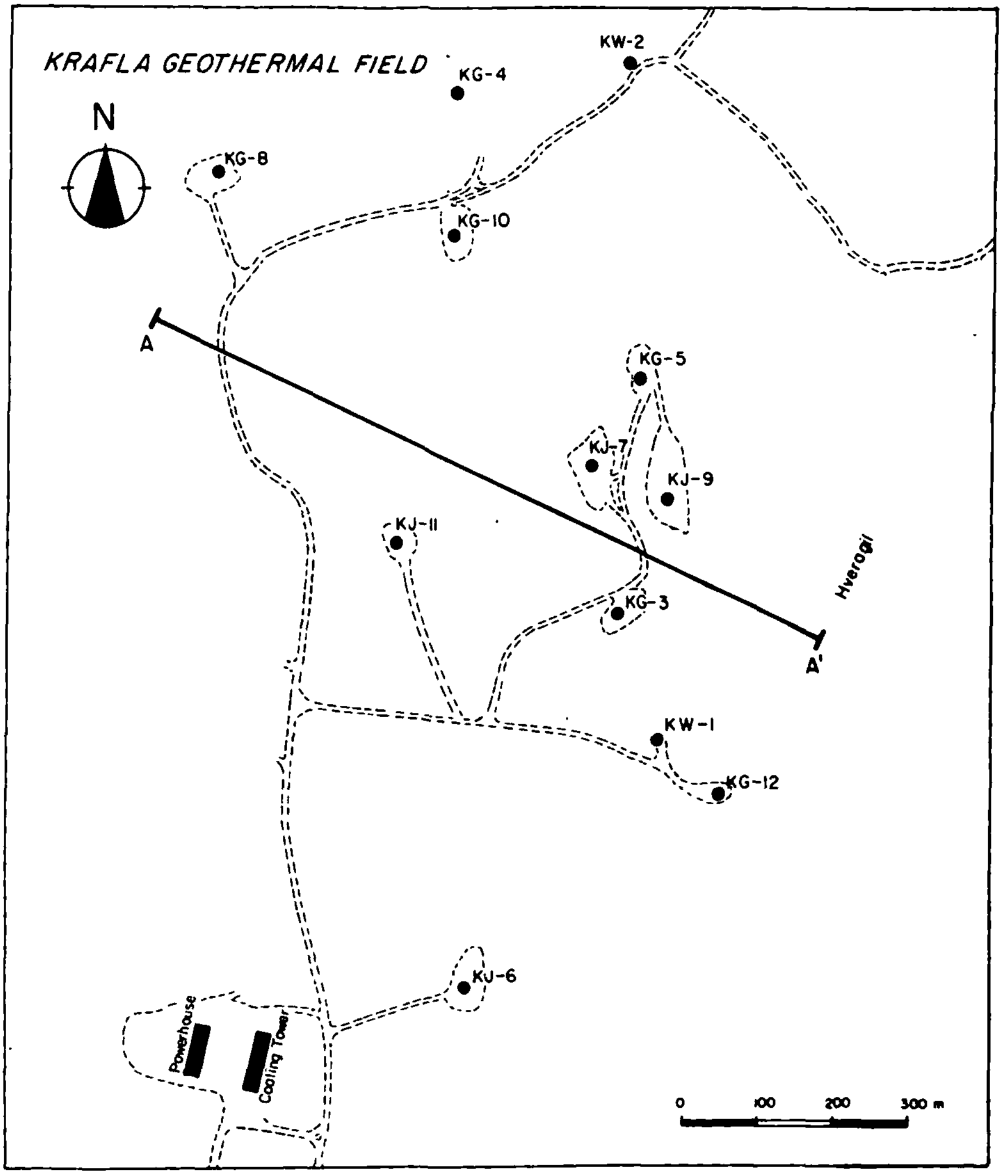

Figure 10.9. Location of the wells and of cross section in the Krafla geothermal field. A–A′: trace of Figure 10.10. Reproduced by permission of Orkustofnun

simplified model of the Krafla geothermal field is shown in Figure 10.11. The facts that most of the wells have inflows from both zones and that the lower zone is a two-phase system, made the investigations more complicated. Most of the investigation methods had to be revised. As an example, all calculations of reservoir fluid chemistry had to be modified to include two-phase conditions in the initial stage. The complexity of the reservoir was realized at the same time as volcanic activity and spreading episodes began in the area. The influence of magmatic activity thus became an additional factor to be accounted for in the interpretation of the observations made in the geothermal field.

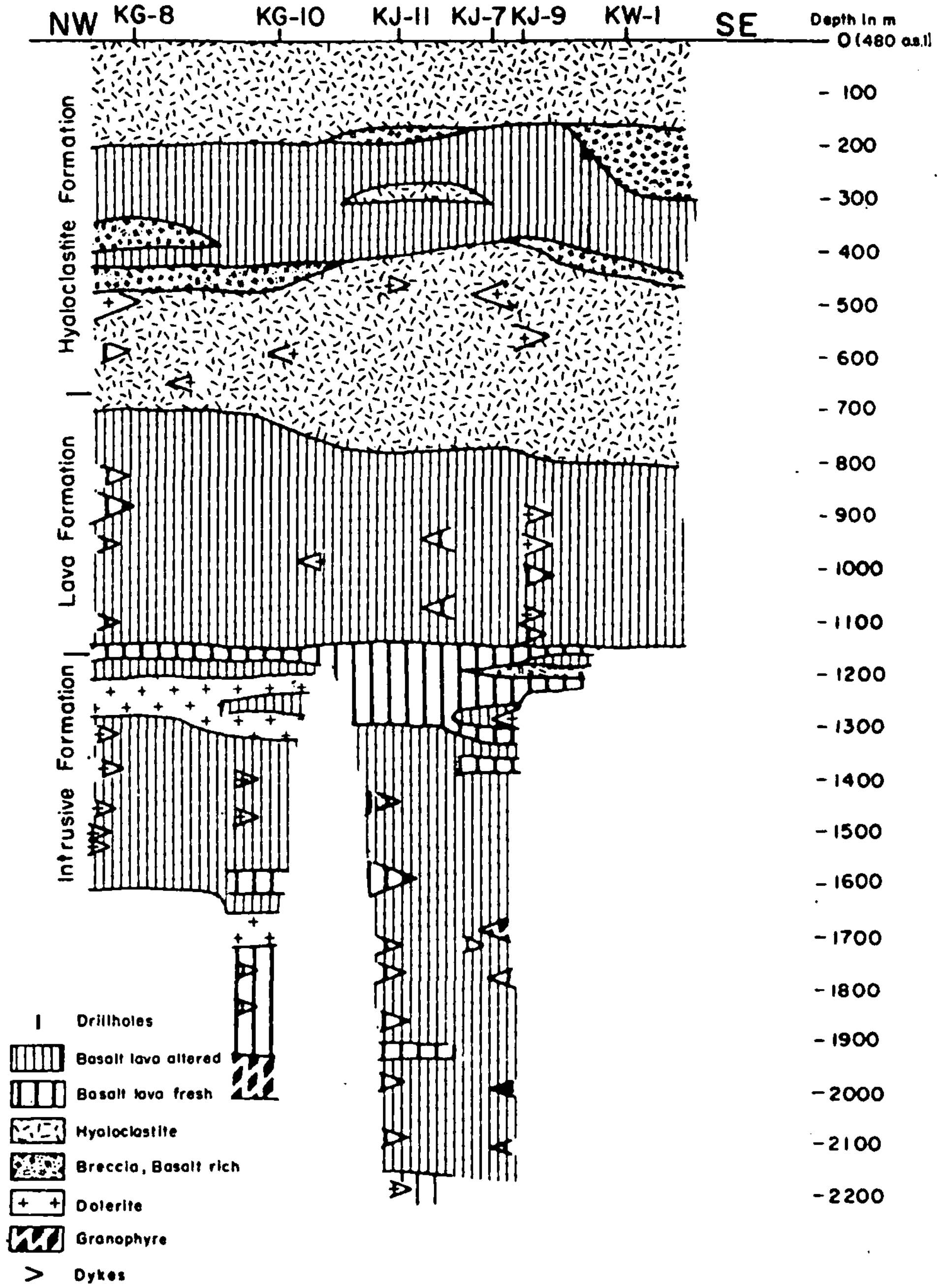

Figure 10.10. Geological cross section of the drilling area in Krafla. From Kristmannsdóttir (1978). Reproduced by permission of Orkustofnun

10.4. Production Characteristics of the Field

The production characteristics of the field cover a wide spectrum. The characteristics of the upper zone are rather uniform but quite different from the properties of the lower zone. In some of the wells an interaction between the two zones characterizes the

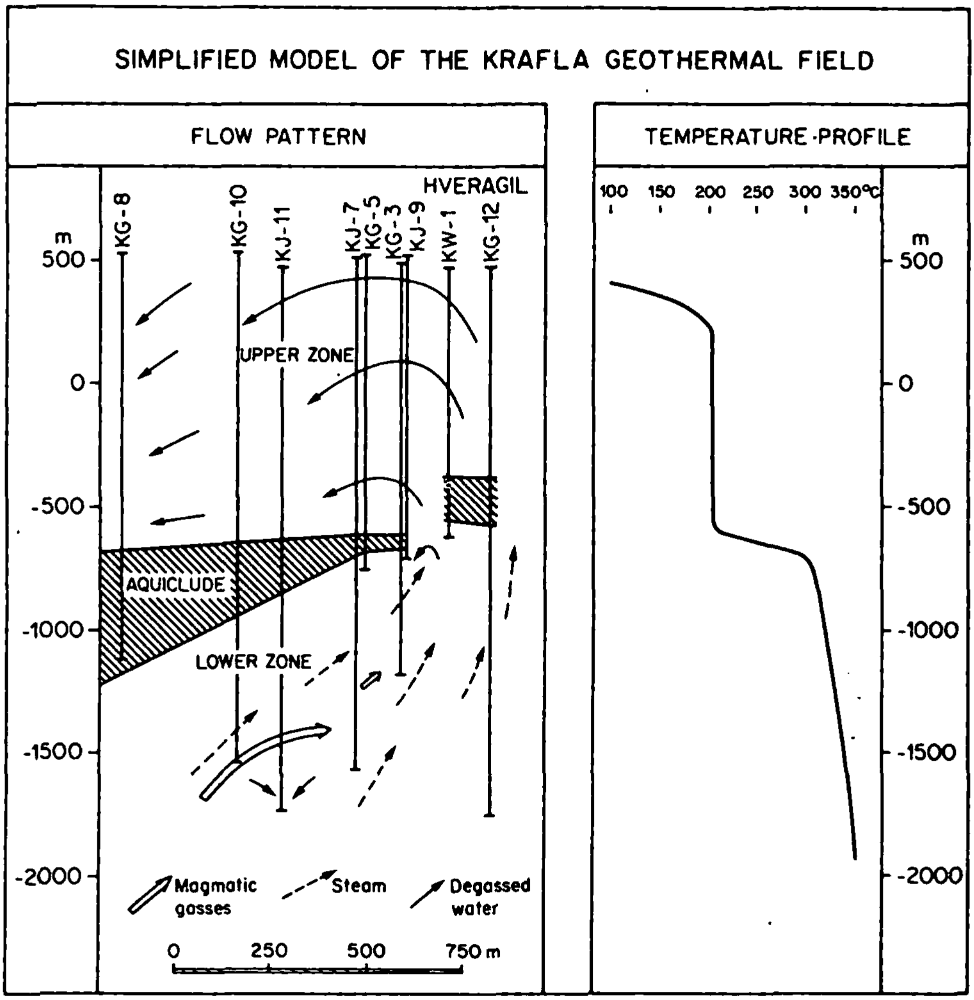

Figure 10.11. Simplified model of the Krafla geothermal field showing the main flow pattern and the average temperature profile of the field. Reproduced by permission of Orkustofnun

behaviour of the wells. Superimposed on these properties is the influence of the magmatic activity on the geothermal system.

10.4.1. *The Upper Zone*

The upper zone (200–1100 m depth) is a typical water-dominated geothermal reservoir. This zone is present in all the wells. The temperature is rather uniform, both horizontally and vertically over the 900 m thickness and is measured in the range 195–215°C, depending on the location of the wells. There is a good agreement between the measured temperature in the wells and the silica and Na–K–Ca temperatures. Pressure measurements in the discharging wells confirm the water phase nature of their inflow.

The distribution of the H_2/H_2S ratio of gases in the discharges of those wells which are fed only by the upper zone show (Figure 10.12) that the deep water in the more westerly

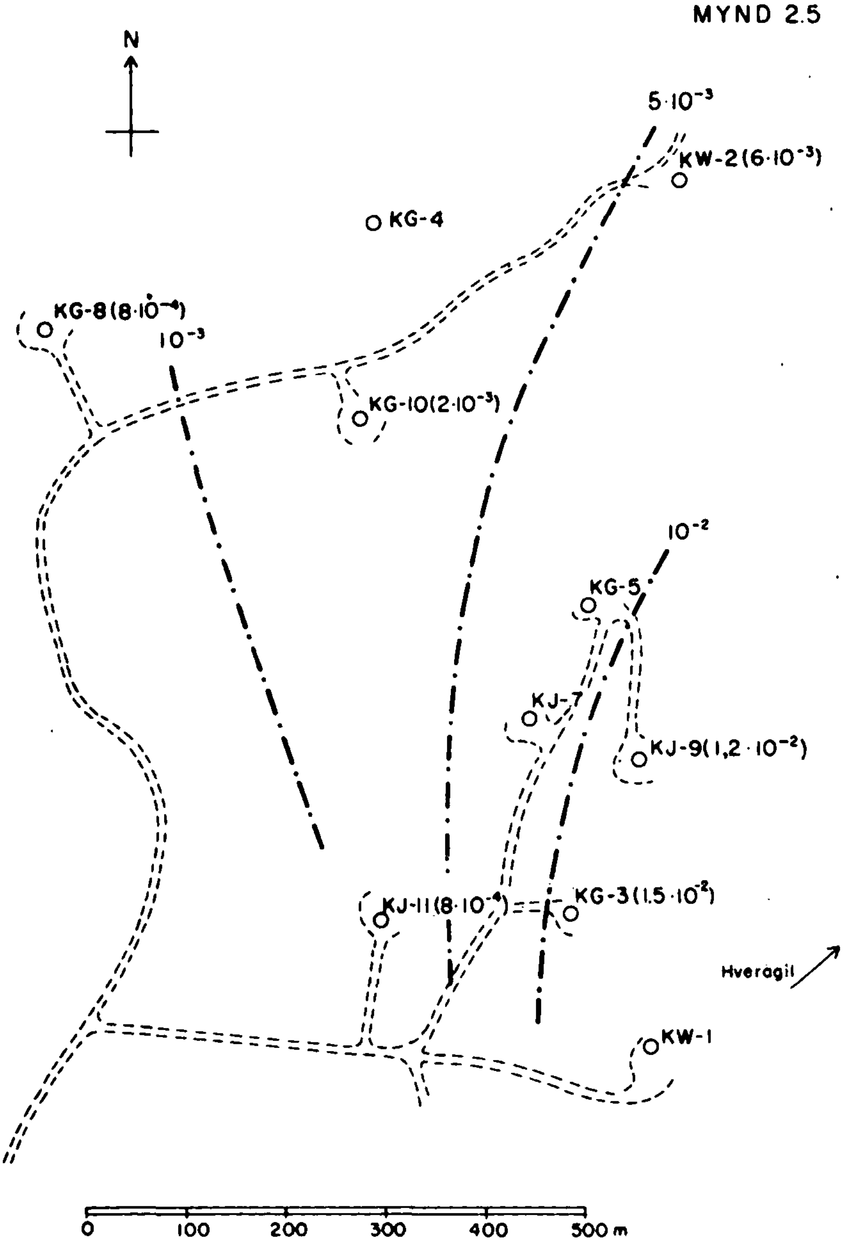

Figure 10.12. The H_2/H_2S ratio in reservoir fluid of the upper zone in Krafla. From Gíslason et al. (1978). Reproduced by permission of Orkustofnun

wells is more degassed than in the wells near Hveragil. A similar picture is found for the CO_2/H_2S ratio as well as for the total amount of gas in the discharge.

Pressure measurements in undisturbed wells indicate that pressure increases towards Hveragil. These observations indicate that the upper zone gets a through flow from the lower zone, rather than being an independent convection cell.

The chemical composition of the water from the upper zone is similar to other Icelandic water-dominated high-temperature fields. The major element composition of the unflashed reservoir fluid is shown in Table 10.1.

The water entering wells KW-2, KG-8 and KJ-9 is saturated with respect to calcium carbonate ($CaCO_3$). Degassing of flashing fluid in wells results in higher pH, which greatly increases the carbonate concentration. The calcium concentration increases upon boiling too. Due to boiling the activity product of calcium carbonate exceeds the saturation curve (Arnórsson, 1978a; 1978b). The calcium carbonate activity product for a representative upper zone well is shown in Figure 0.13 for a water decreasing in temperature as it boils. The supersaturation is greatest immediately after flashing, and the largest deposit should be formed at the level of boiling.

The rate of deposition in wells can be estimated by comparing the calcium concentration in deep water samples to that of the discharge at the well head. Such

Table 10.1. Average composition in mg/kg of the reservoir fluid in the upper zone.

pH	Na	K	Ca	Mg	SO_4	Cl	F	CO_2	H_2S	H_2	SiO_2/$TSiO_2$	
7·5	183	18·2	2·2	0·04	186	27	0·7	228	54	0·24	300	210°C

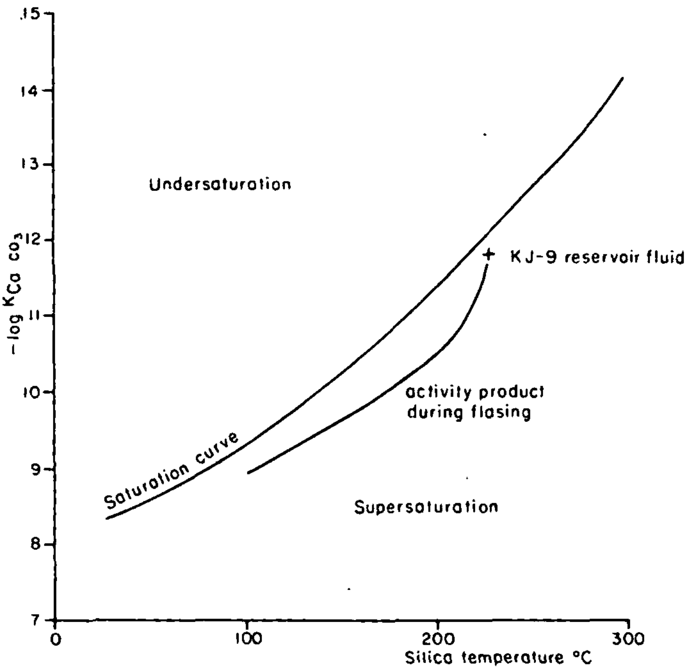

Figure 10.13. The computed activity product of Ca^{2+} and CO_3^{2-} in the geothermal water during one step adiabatic flashing in relation to the calcite solubility curve. Compiled by G. Gíslason and T. Hauksson. Reproduced by permission of Orkustofnun

investigation carried out in well KJ-9 revealed that there was an average 3·9 ppm decrease in the calcium concentration of the well fluid during boiling. For the actual flow of the well the deposition rate was 156 mg/s of $CaCO_3$, which corresponds to a deposition of 1·0 m^3 $CaCO_3$ during 180 days of flow. The well was actually worked over after a 180 days flowing period. The producing liner was pulled out of the well and the deposit measured. Its extent was greatest at the level of boiling (290 m depth), and the total volume was found to be 1·1 m^3. Chemical and X-ray analysis showed it to be almost pure calcite with traces of aragonite.

Permeability of the upper zone has been investigated in different ways. Injection tests, draw-down and recovery measurements have been made on individual wells. The mean permeability thickness is of the order of $10 \cdot 10^{-12}$ m^3.

The most spectacular method of permeability determination is the use of pressure pulses occurring in the upper zone coincident with rifting events and volcanic eruptions. The change in water level in well KG-5 during the event of September 8, 1977, is shown in Figure 10.14. By matching the decay part of the pressure curve with Theis log-log type curve (see Matthews and Russell, 1967) the response time of 8 hours is obtained. The distance from the well to the eruption site was 4·3 km, and by assuming the pressure transmission to be in 200°C water and the porosity to be 0·15 we obtain the permeability of $1{\cdot}5 \cdot 10^{-12}$ m^2. Compared with the permeability·thickness of $10 \cdot 10^{-12}$ m^3, this indicates an aquifer thickness of the order of 10 m. As has been pointed out by Grant (1978), the pressure transient in Figure 10.14 is just the Green's function, and the late time response is decaying like time^{-1}. These circumstances are in agreement with the assumption of injection at a point source into a confined aquifer.

Due to the relatively low temperature of the upper zone and to the inconvenience of the calcite depositions associated with the water from the upper zone, an attempt is now made to avoid the upper zone water in the utilization of the field. This is done partly by casing off the upper zone, and partly by moving the drilling area towards the upflow channel, where the two zones are connected.

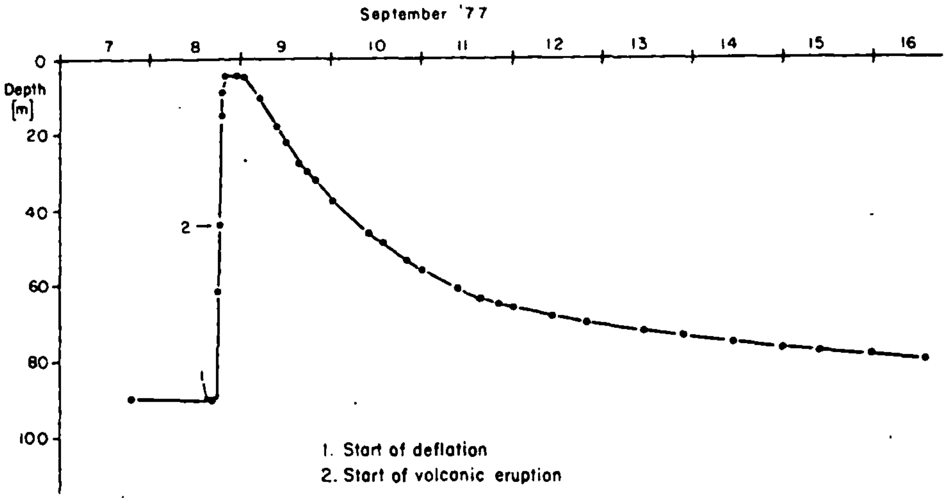

Figure 10.14. Water level in well KG-5 during the volcanic eruption of September 8, 1977. Compiled by B. Steingrímsson. Reproduced by permission of Orkustofnun

10.4.2. *The Lower Zone*

The undisturbed temperature and pressure in the lower zone are very close to saturation. The main characteristics of this zone are a high gas content and a high enthalpy of discharged fluid. Investigation of the chemical composition of the geothermal fluid has given very valuable information on the flow pattern within this zone. It has been demonstrated that volcanic gases (SO_2, H_2, CO_2) flow into the geothermal system from the underlying magma. The SO_2 is quickly reduced to H_2S during its passage through the formation. The gases CO_2, H_2S, and H_2 enter the investigated area in the neighbourhood of well KG-10 and propagate together with the steam up and eastward in the system. Other volatile elements like Hg and Rn follow this pattern closely. Radon is an interesting parameter in this respect as ^{222}Rn is radioactive with 3·8 days half life. By normalizing the Rn content to the CO_2 content in the fluid, the age of the fluid relative to the age of the fluid in well KG-10 can be determined. The following result was obtained.

	Age of fluid relative to KG-10
Well no. KG-10	0 days
Well no. KJ-7	1·9 days
Well no. KJ-6	5·4 days
Well no. KJ-9	9·9 days degassed water
Well no. KJ-11	11·2 days degassed water

For wells KJ-7 and KJ-6 this gives a flow velocity of 185 m/day.

Usual geochemical methods like silica and Na–K–Ca geothermometers cannot be used directly on a two-phase system. These methods assume the initial stage to be in pure water phase and the boiling to be isenthalpic. These conditions are not fulfilled for the lower zone in Krafla.

The main chemical characteristics of the fluid from the lower zone are shown in Table 10.2. Deposits consisting mainly of FeS, FeS_2, Fe_3O_4, and SiO_2 have been found in some of the wells tapping the lower zone fluid. The deposition rate has been most rapid in well KG-10, where the plug-in time has been recorded twice. Each time it was about three weeks. The deposition is believed to be at least partly due to magmatic influence on the geothermal fluid. The high concentration of SO_2 and other magmatic gases has a great influence on the pH-value, causing the fluid entering the wells to be highly supersaturated with respect to iron compounds.

The main characteristic of the boiling lower zone in Krafla is its response to production. Simple model calculations give that the steam fraction in the lower zone is of the order of 0·1–0·2 by volume. When utilization begins, the wells produce a mixture of steam and water, but the relative permeability of steam and water will influence the flowing history. The permeability of steam is higher than that of water, and when a certain steam fraction is reached, the water phase will be stagnant in the rock. The amount of water in the discharge will decrease while the amount of steam remains fairly constant. This means that the enthalpy of the discharge will increase. After a certain period the wells produce dry steam. The stagnant water then evaporates and contributes to the steam phase. During the evaporation, heat is withdrawn from the surrounding rock. When all the water close to the well has evaporated superheated steam will be produced.

One well, KG-12, produces exclusively from the lower zone. The flowing history of this well has followed the above description in detail.

Table 10.2. Chemical composition of fluid from wells, drawing predominantly from the Lower Zone

Well No.	KJ-6	KJ-7	KJ-9	KJ-11	KG-12
Sampling pressure MPa	0·98	0·78	1·04	0·22	0·83
Enthalpy of flow KJ/kg	1500	1900	1241	1483	2600
Steam fraction at P_s	0·37	0·58	0·23	0·44	0·92*
pH/°C of water phase	8·48/20	7·25/20	9·06/20	9·11/21	6·67/19
Ωm/°C of water phase	13·3/22	10·2/21	11·6/22	10·1/22	6·8/21
Silica† temperature (°C)	279	272	263	271	289
Chemical composition, expressed as mg/kg of total flow.					
CO_2	8436	17345	1357	5583	19048
H_2S	680	1046	75	199	801
H_2	8·1	26	1·4	1·1	49
CH_4	0·18	0.17	0·09	0·09	0·04
SiO_2	498	303	513	465	66
Na	95	82	158	132	19
K	16	12	18	22	4·8
Ca	0·79	0·98	1·3	0·95	2·1
Mg	0·006	0·008	0·008	0·006	0·01
SO_4	84	74	175	71	10
Cl	20	43	38	21	21
F	0·84	0·50	0·62	0·51	0·13
Fe	<0·06	0·21	0·13	<0·05	0·15
Total dissolved solids	831	564	962	852	140

* This flow developed into superheated steam.
† Calculated, taking enthalpy values into account.

10.4.3. *Interaction Between the Zones*

As demonstrated by the model, the two zones are connected near Hveragil, where a natural upflow channel keeps the lower zone in boiling condition. Other connections between the zones have not been discovered so far. If wells are open to both the upper and the lower zone, interference effects are observed in the behaviour of the wells. Effects like pressure oscillations during injection tests and flow from the upper aquifers down to the lower zone are common. One of the wells turned out to be very sensitive to load variation, as small pressure variation at wellhead could quench the lower aquifer.

As the discharge from wells taps fluids from both zones, the interpretation of chemical analysis becomes complicated. However, in the wells which produce from both zones it has been possible to estimate the amount of inflow from each zone by assuming the enthalpy and chemical composition of the upper zone to be fairly constant and using the total measured enthalpy of the discharge together with the measured concentration of the mixture at well head. The mass ratio of the lower zone contribution is found to be in the range 0·25 to 0·75 in the mixed wells.

10.4.4. *Influence of Magmatic Activity on the Reservoir*

As shown on Figure 10.14, the rifting events and magmatic activity cause a pressure impulse in the water-dominated upper zone. Similar pressure transients have not been detected in the lower zone. This is interpreted to be due to the two phase condition of the lower zone. The pressure transient is absorbed quickly in the two phase system. Quite noticeable magmatic influence has also been observed on the chemical composition of the lower zone fluid as shown in Figure 10.15.

The presence of magmatic gases in the reservoir has aided the mapping of the flowing directions as well as the flowing velocity in the reservoir as described in section 10.4.2. However, these same gases seem to cause serious depositions in wells. This has been strongly experienced in well KG-10, which is closest to the inflow of magmatic gases.

10.5. Experience with Utilization

The Krafla Power Plant is now operating with partial load and further drilling is needed to provide steam for the Power Plant. The experience gained with utilization is rather small.

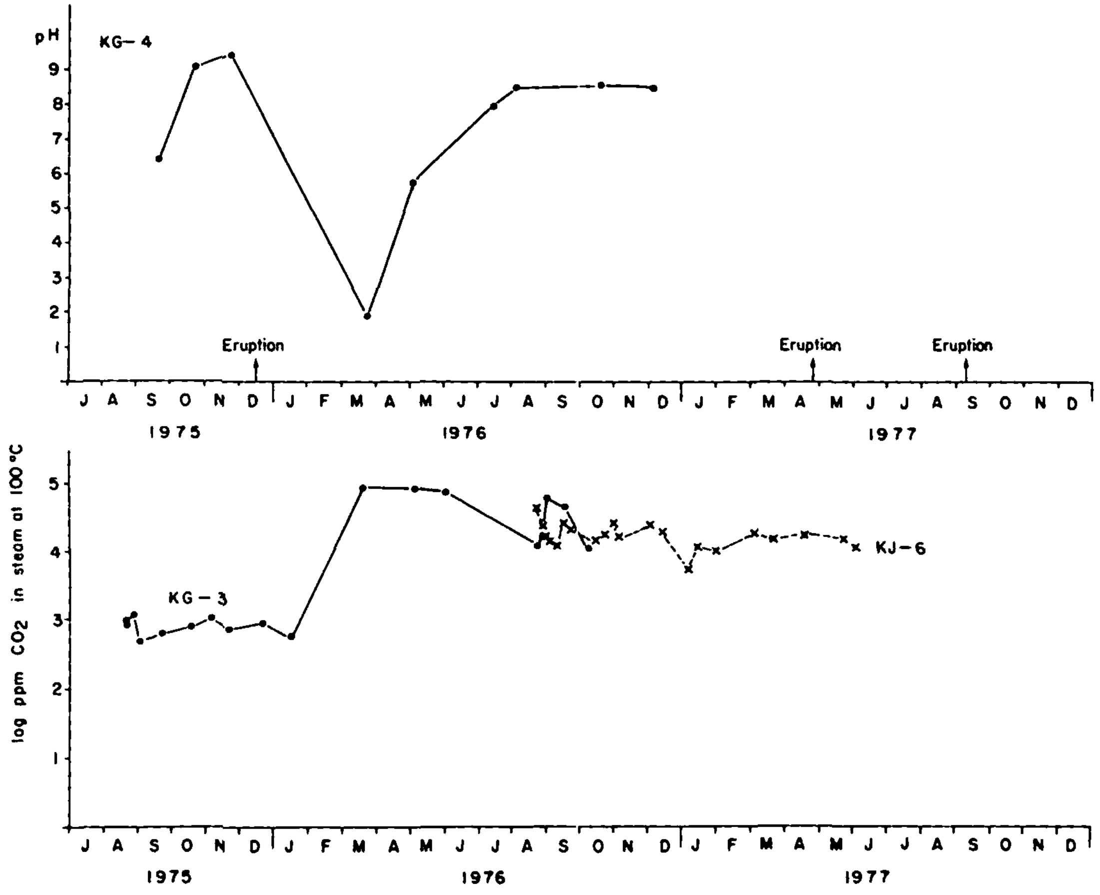

Figure 10.15. Influence of magmatic activity on the chemical properties of the geothermal fluid. Compiled by G. Gislason. Reproduced by permission of Orkustofnun

The two turbine generators of the Krafla Power Plant consist of five stage double pressure, double flow steam turbines with 37·5 MVA brushless generators. The turbines are condensing with a direct contact condenser located under the turbine. The steam turbines have a maximum capacity of 35 MW each during the most favourable external conditions.

The steam separators are designed to separate the high pressure steam at 0·9 MPa pressure, and the HP inlet pressure of the turbine is assumed to be 0·77 MPa. The low-pressure separation is performed at 0·22 MPa pressure. The non-condensable gases (CO_2, H_2S) are removed by gas ejectors. The system can cope with 1–2 per cent of non-condensable gases in the steam. The pressure in the main condenser is estimated to be 0·012 MPa and the temperature of the condensed water 46°C. The condensate is cooled to about 22°C in cooling towers. Effluent water from the steam separators will be cooled down 10–20°C in cooling ponds and then dumped in a lava field south of the Krafla area. The first estimate of the amount of effluent water was 360 liters/s assuming the field to be water-dominated with the temperature of 270°C. The present knowledge of the field shows that utilization, restricted to the lower zone only, will give wells that produce more or less dry steam. Therefore, the environmental consequences of disposing effluent water in the area will be smaller than initially assumed.

The method of developing a geothermal field coincident with the construction phase of geothermal utilization has been experienced twice in Iceland. In the first case, the development of the Námafjall area (Ragnars et al. 1970), the risk taken did not have any consequences, as the production characteristics turned out to be more favorable than assumed. In the second case, the Krafla geothermal field, the production characteristics of the field turned out to be more complex than initially assumed, and the project became a very delicate political subject.

The experience gained in the development of the Krafla field has emphasized the necessity of the knowledge of the most essential production characteristics of a field prior to development, and that relatively higher cost for drilling should be accounted for when drilling is performed coincident with power plant construction.

The capital cost of the Krafla power plant inclusive of drilling and main transmission line is in November 1978 about 55 million U.S. dollars. The annual capital cost is estimated to be about 5 million US dollars. Additional finances will be needed for further drilling and transmission of steam.

From the scientific point of view, the experience gained in the investigation of the first proved boiling reservoir in Iceland has been very valuable. The coincidence that volcanic activity started to influence the geothermal field during the investigation has given rise to new ideas on the creation and nature of high-temperature geothermal fields in Iceland.

10.6. Current and Future Developments

The Krafla Power Plant is now operating at partial load and more drilling is needed for the production of steam. In the nearest future, additional drilling is planned east of the present drilling area in the neighbourhood of the upflow channel from the lower zone. The displacement of the drilling area in this direction is expected to result in better production characteristics of wells and less influence of magma on the reservoir fluid.

Volcanic activity is still going on in the Krafla area, and while this activity is continuing the investment in the field will probably be slow. However, assuming that volcanic activity will not cause a major damage to the Power Plant or the production wells, the aim of present and future operations in the area is to make the Power Plant operate at the rated capacity.

Acknowledgements

The present knowledge of the Krafla geothermal field is a result of an extensive team work of many people. Major contributions are due to: Dr. Halldór Ármannsson, Dr. Stefán Arnórsson, Dr. Axel Björnsson, Prof. Sveinbjörn Björnsson, Mr Gestur Gíslason, Dr Jón S. Gudmundsson, Mr Gísli. K. Halldórsson, Mr Trausti Hauksson, Mr Gunnar Johnsen, Ms Ragna Karlsdóttir, Ms Hrefna Kristmannsdóttir, Dr Kristján Saemundsson, Mr Ómar Sigurdsson and Mr Benedikt Steingrímsson.

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WARD

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5 Earthquakes in Iceland

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Most of the seismicity of Iceland is related to the mid-Atlantic plate boundary that crosses the country. The boundary approaches Iceland from the southwest along the crest of the Reykjanes Ridge (Fig. 1) and from the north along the Kolbeinsey Ridge. In Iceland the plate boundary is displaced to the east by two major fracture zones, the South Iceland seismic zone in the south and the Tjörnes Fracture Zone in the north. Because of the lack of a clear topographic expression, both zones are defined primarily by their high seismicity, earthquake focal mechanisms and configuration with respect to the spreading axes. The largest earthquakes in Iceland occur within these zones and may exceed magnitude 7. Earthquakes also occur along the volcanic rift zones between the fracture zones, but they only rarely exceed magnitude 5. A large part of this seismicity appears to be related to central volcanoes.

Epicenters of earthquakes of the period 1962—77 large enough to be located by seismograph networks outside of Iceland are shown in Fig. 1. The map includes events down to magnitude 4, but is complete for magnitude 4.5 and larger events. Single event focal mechanism solutions available so far are also shown. This map shows many of the characteristics of the Icelandic seismicity, even though some of the locations are in error by as much as 40 km. Concentration of activity is seen in the Tjörnes Fracture Zone near the coast of N-Iceland, and in SW-Iceland on the Reykjanes Peninsula and in the South Iceland seismic zone. The focal mechanisms indicate strike-slip faulting. If the easterly striking nodal planes are taken as the fault planes, the sense of motion is right-lateral in N-Iceland and left-lateral in SW-Iceland, which is consistent with a transform fault interpretation of these zones. Outside of the fracture zones clusters of activity are seen in the Borgarfjördur area in W-Iceland, in the volcanic zone in Central Iceland, and near the volcanoes Katla in S-Iceland and Krafla in N-Iceland. Each of these zones will be considered separately.

Reykjanes Peninsula

The Reykjanes Peninsula is an area of high seismicity and recent volcanism that forms a transition between the Reykjanes Ridge to the west, and the western volcanic zone and the South Iceland seismic zone to the east (Fig. 2). The mid-Atlantic plate boundary as defined by the seismicity enters Iceland near the tip of Reykjanes and then runs along the peninsula in an easterly direction (Fig. 2). Detailed studies show that the seismic zone is less than 2 km wide in most places. The earthquakes are mostly at the depth of 1—5 km and are not located on a single fault. The seismicity seems to be caused by deformation of the brittle crust above a deeper seated and aseismic deformation zone. Small scale structures can be resolved in the seismicity within the zone. Several seismic lineations or faults can be identified, striking obliquely or even transversely to the main zone.

Focal mechanisms have been determined for a large number of small earthquakes, using data from dense, local networks, and for two earthquakes larger than magnitude 5 using teleseismic data. The minimum compressive stress is consistently oriented in a horizontal, NW direction. The maximum compressive stress rotates between the vertical direction, causing normal faulting on NE-striking faults, and the horizontal NE direction, causing strike-slip faulting on N or E striking faults. Thus the stress regime is characterized by the NW-trending minimum stress. The other principal stresses are probably nearly equal and may change directions according to local, or time dependent conditions. Dykes open up against the minimum stress and strike NE, in accordance with the eruptive fissures observed on the surface.

The mode of strain release changes systematically along the peninsula. Near the tip of Reykja-

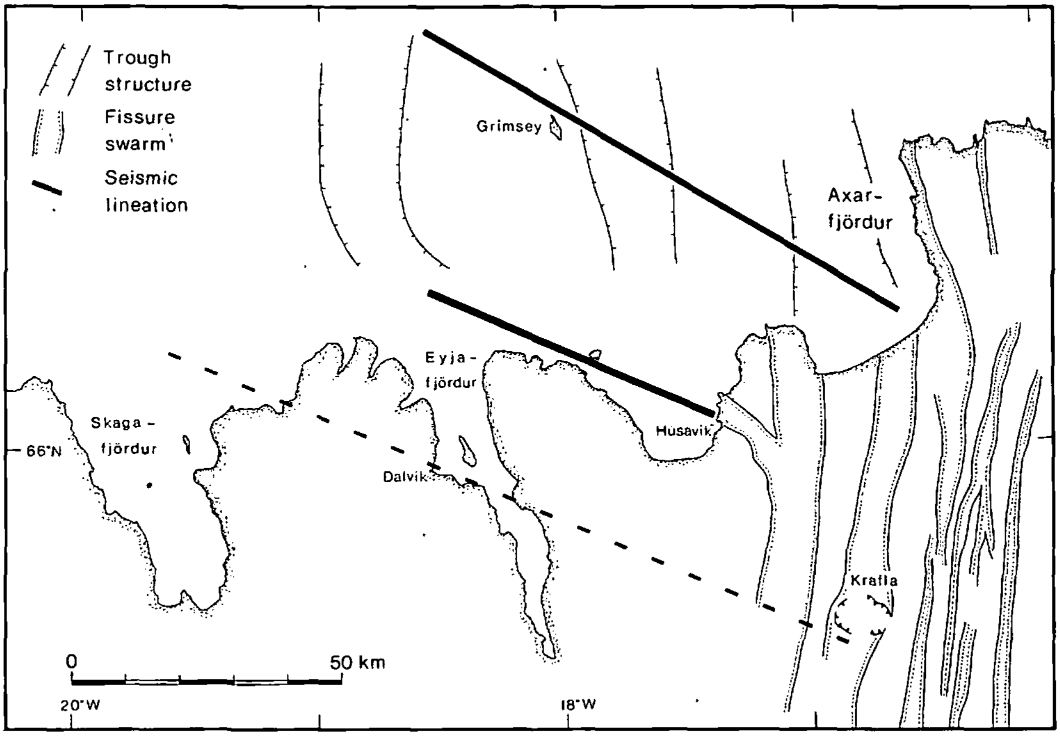

Fig. 3. Map of the main tectonic features of North Iceland. The fissure swarms in the volcanic zone are taken from a map by Saemundsson in Björnsson et al. (1977). The trough structures are based on McMaster et al. (1977), and the seismic lineaments are based on Einarsson (1976) and later data.

are not accurate enough for detailed tectonic interpretation. Detailed studies have shown that a considerable part of the seismicity is associated with a WNW trending line that runs slightly north of the island Grímsey and joins the Krafla fissure swarm in the Axarfjördur Bay (Fig. 3). The sense of motion along this seismic line is right-lateral strike-slip as evidenced by two focal mechanism solutions. The Grímsey seismic line has no clear expression in the topography. Instead, the surface structure in this area is characterized by northerly trending troughs and ridges that are arranged *en echelon* with respect to the fracture zone and the seismic line. In some respects this structural relationship resembles that in SW-Iceland, where the epicentral belts also lack a surface expression.

Even though the Grímsey seismic line has been responsible for the majority of earthquakes in this area for the last decade, it is not the only seismically active line. The Húsavík faults form a distinctive fault swarm exposed on the Tjörnes Peninsula. The faults can be traced from the shore near the town Húsavík east-south-eastwards into the volcanic rift zone (Fig. 3). Off shore the fault can be traced as a topographic offset of the Grímsey shoal and a strong, negative anomaly in the free air gravity field. Earthquake locations in recent years have shown that significant earthquake activity occurs on the Húsavík faults, and large, historic earthquakes have been accompanied by surface faulting near Húsavík.

In addition to the Grímsey and the Húsavík faults a third major WNW-striking earthquake fault near the town Dalvík has been suggested (Fig. 3). The main evidence for the existence of this fault is the earthquake (M = 6¼) that caused extensive damage in Dalvík in 1934, the topography on the east side of Eyjafjördur and the alignment of low temperature geothermal springs between Eyjafjördur and Skagafjördur. The 1963 earthquake (M = 7) in the mouth of Skagafjördur possibly occurred on this fault. The fault plane solution of that earthquake would imply right-lateral strike-slip along the fault. The seismicity of this region has been very low in recent years, and the fault remains to be confirmed by geological mapping. Its existence should therefore be considered speculative.

One can conclude that a large part of the seismicity of the Tjörnes Fracture Zone can be attributed to the activity along two and possibly three WNW-striking faults. The existence of further seismic zones can certainly not be excluded. The transform motion is thus taken up by at least two parallel faults within a broad deformation zone.

Volcanic zones

Earthquakes in the volcanic zones are generally smaller than in the fracture zones. Volcanic eruptions are usually accompanied by earthquakes, but between eruptions most parts of the volcanic zones are seismically quiet. A few areas of persistent seismic activity are found, the most prominent ones in Central Iceland and near the subglacial volcano Katla in South Iceland (Fig. 1).

The seismic area in Central Iceland is largely covered by the ice cap Vatnajökull, and the tectonic structure is poorly known. Recent studies of ERTS images of this area seem to indicate that the structure is dominated by a group of central volcanoes and it is tempting to relate the earthquakes to volcanic processes. The seismic activity of this area has been unusually high in recent years. Six earthquakes of magnitude 5 and larger occurred in the period 1974—79, but before 1974 no such large events were known.

The Katla volcano is located near the southern end of the eastern volcanic zone, south of its junction with the South Iceland seismic zone. The structure of this part of the zone is characterized by several central volcanoes, rifting structures are less significant. Historic eruptions of Katla have been preceeded by felt earthquakes, and because of the potential danger of future eruptions the seismicity at Katla is monitored by a relatively dense seismograph network. The epicenters located so far delineate two active areas. One is under the SE-part of the Mýrdalsjökull ice cap and coincides with the eruption sites in the latest Katla eruptions. The other area is under the SW-part of Mýrdalsjökull, about 15 km W of the first one. The depths of hypocenters in both areas are in the range 0—30 km. The hypocenters thus delineate two chimney-like features that penetrate the crust and extend well into the anomalous upper mantle.

The seismic activity in the Mýrdalsjökull area shows a pronounced annual cycle. The probability of an earthquake occuring within a given time interval is several times higher in the second half of the year than in the first half. This annual cycle was first noted by E. Tryggvason (1973) for the years 1952—58 and has been confirmed by later data.

The Heimaey eruption in 1973 was preceeded by an intensive swarm of small earthquakes that started 30 hours before the eruption. Earthquakes also accompanied the eruption, but the seismicity declined as the lava production diminished. No shock reached magnitude 4. The earthquakes during the eruption occurred at the depth of 15—25 km and occupied a spherical volume centered under Heimaey. It seems likely that the erupted magma either was stored or formed within this volume.

The depth of the Heimaey and Katla earthquakes is much larger than observed elsewhere in Iceland. In these areas the upper boundary of the anomalous mantle underlying Iceland is at the depth of 12—15 km. Earthquakes at the depth of 20—30 km may be taken to imply brittle failure in the mantle where creep or ductile behaviour is normally assumed. In these volcanic regions it is possible, however, that high strain rates associated with magmatic processes may cause brittle failure in material that would be ductile at lower strain rates.

A major rifting episode has been in progress since 1975 in the volcanic rift zone in NE-Iceland. The activity has been confined to the Krafla central volcano and its associated fissure swarm (Fig. 3), and provides a demonstration of a process that seems to play an important role in Icelandic tectonics. The activity is characterized by repeated cycles of relatively slow inflation and rapid deflation of the volcano. Magma apparently accumulates at a constant rate under the volcano during the inflation periods and during the deflation events the magma escapes from the reservoir area. Each cycle of activity is accompanied by a characteristic pattern of seismic activity. Continuous volcanic tremor starts in the caldera region at about the same time as the deflation. Small earthquakes also occur in the caldera, but the epicentral area is soon extended along the Krafla fissure swarm to the north or to the south. The rate of propagation of the seismic activity is highest during the first few hours, typically 0.5 m/sec., but the speed decreases as the deflation rate decreases and the epicentral zone is extended. The earthquake activity culminates after the maximum in tremor and deflation rate is reached. The largest earthquakes are located within a well defined, but each time different section of the fissure swarm. The magnitude only rarely exceeds 4.5. The depth of hypocenters is in the range 0—6 km. Extensive fault movements, both normal faulting and fissuring, occur in the area of maximum earthquake activity. The propagating seismic activity suggests that the magma escaping from the Krafla reservoir is injected laterally into the fissure swarm to form a dyke. The dykes may be as long as 40—60 km.

The first and the most violent deflation event started on Dec. 20, 1975. The deflation of the caldera exceeded 2 m and the accompanying earthquake swarm lasted about 8 weeks. Most of the epicenters that appear in the northern part of the volcanic zone in Fig. 1 belong to this swarm. The largest earthquakes were confined to two separate areas. One area was within the caldera and the earthquakes were apparently associated with faulting above the magma reservoir. Depth of most hypocenters was 0—4 km. The largest earthquakes reached magnitude 5. The other epicentral area was near the junction between the Krafla fissure swarm and the Grímsey fault (Fig. 3). The largest earthquake was of magnitude 6 and the focal mechanism shows right-lateral strike-slip along the Grímsey fault. This earthquake sequence demonstrates well the relationship between rifting along the diverging plate boundary and transform faulting in the fracture zone. The present Krafla events are assumed to be the result of interaction between magma pressure under the Krafla volcano and rifting of the plate boundary. The rifting is triggered by increasing magma pressure in the reservoir and a fluid filled extensional crack propagates horizontally along the Krafla fault swarm. The driving force of this process is the tectonic stress at the plate boundary, but the mode of strain release is modified by the presence of fluid.

Intraplate earthquakes

Earthquakes are rare outside of the volcanic zones and the seismic zones in South and North Iceland. Intraplate earthquakes are known in the Iceland region, however, for example near the insular shelf margin east of Iceland. A very significant sequence of intraplate earthquakes occurred in Borgarfjördur in West Iceland in 1974. The sequence lasted more than two months and culminated with a shock of $m_b = 5.5$. The epicenters were located in two intersecting linear zones. The main epicentral zone was about 25 km long and had an E-W trend. The second zone had a NE-SW trend and intersected the first one in the middle. The depth of the hypocenters was 0—8 km. Focal mechanism was determined for the main shock and several small shocks in the western part of the epicentral zone. All the obtained solutions show normal faulting, consistent with observed surface faults. The Borgarfjördur area seems to be undergoing horizontal extension. The direction of the least compressive stress rotates from the WNW in the center of the epicentral zone to N-S or even NNE in the western part. Here the epicentral zone is spatially related to the Snaefellsnes volcanic zone, where the tectonic structure is characterized by block faulting on WNW striking faults and volcanism on WNW trending lines. This structure also implies horizontal extension in the NNE-SSW direction. The crustal extension in West Iceland may be caused by subcrustal flow radially away from a mantle plume under Central Iceland, but could also be the result of gravitational stresses induced by the regional topographic high of Iceland.

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GEOTHERMAL RESEARCH AND DEVELOPMENT IN ICELAND 1982

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ABSTRACT

About one third of the total energy consumed in Iceland is derived from geothermal resources. Most of the geothermal energy is used for space heating and obtained from low temperature fields in the Tertiary and Plio-Pleistocene strata outside the volcanic zone. Higher permeability is encountered in the Plio-Pleistocene strata characterized by subaerial lavas intercalated by subglacial volcanics (pillow lavas and hyaloclastites) than in the Tertiary strata which consist mostly of subaerial lavas. The close association of magmatic activity with high temperature hydrothermal systems within the volcanic zone has been demonstrated during the current rifting episode in the Krafla volcano. Some recent advancements in geothermal research are mentioned and a review given of recent advances in the development of both the low and the high temperature fields in Iceland.

INTRODUCTION

Geothermal energy is very important for the national economy of Iceland as over one third of the net energy consumption is from geothermal resources. In 1978 44% of the total energy consumption of the country were derived from imported fossil fuel, 36% from geothermal and 20% from hydropower (Zoega et al., 1981). Most of the geothermal energy is used for space heating. In May 1982 75% of the Icelandic population lived in houses heated by geothermal water. The district heating systems are mostly owned and operated by the municipalities. The Municipal Heating Service of Reykjavik serves about 114,400 people and is the largest geothermal heating service in the world. Its operations started in 1930. Presently it supplies hot water to heat the houses of nearly half the population of Iceland.

Figure 1 shows the growth of geothermal heating during the period 1960-1980. The figure shows that already at the beginning of the oil crisis in the early 1970's over 40% of the population heated their homes with geothermal water. With the rapid increase in oil prices projects that had previously been marginal all of a sudden became economically viable. The Government supports local authorities in the various parts of the country in financing geothermal research and development. By 1985 about 80% of houses in the country are expected to be heated by geothermal and the remaining 20% mostly by electricity generated in hydropower stations. Thus burning of oil to heat houses will be mostly eliminated.

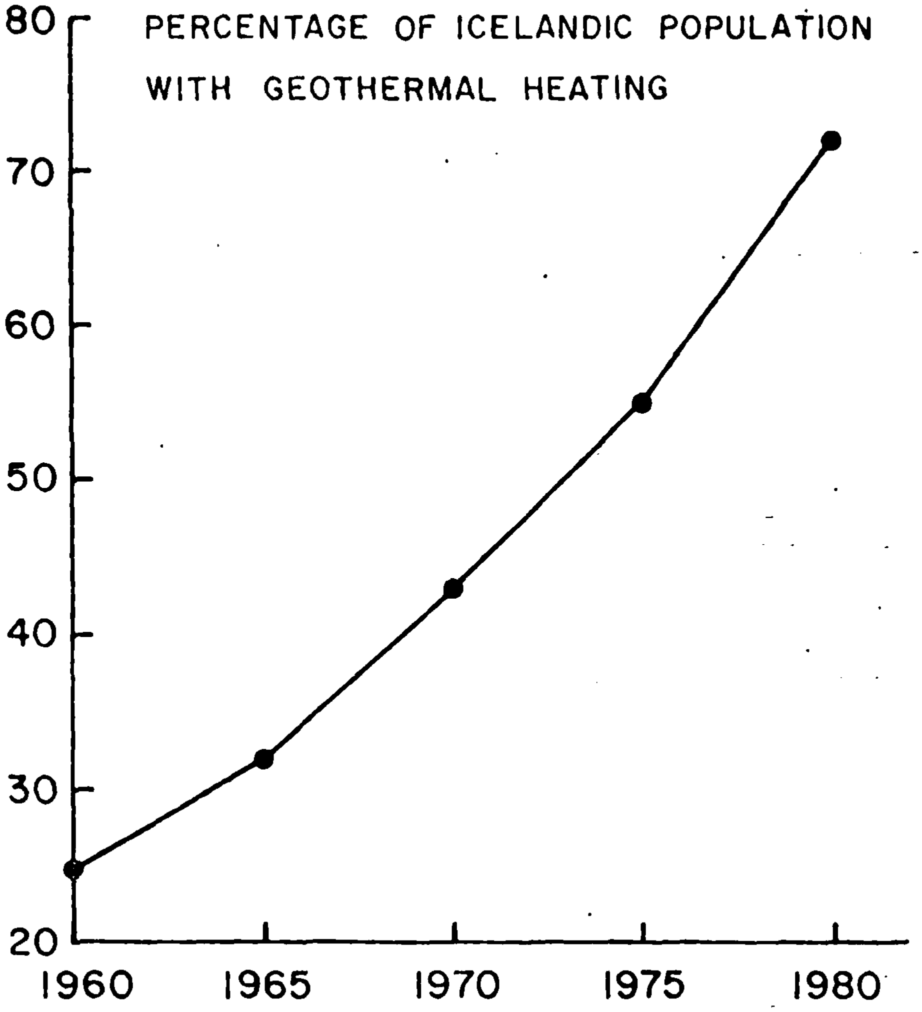
PERCENTAGE OF ICELANDIC POPULATION WITH GEOTHERMAL HEATING
80
70
60
50
40
30
20
1960
1965
1970
1975
1980

Figure 1

In May 1982 the total installed capacity of geothermal energy in Iceland was as follows (MWt=thermal, MWe=electric) : space heating 836 MWt, greenhouses 51 MWt, swimming pools 21 MWt, industrial 50 MWt, fish culture 2 MWt and electricity 41 MWe. The installed thermal capacity (total 960 MWt) is calculated with a disposal temperature of 35'C which is common in the space heating systems in Iceland. Using the average air temperature in Iceland 5'C as the reference temperature the total would be approximately 1480 MWt. Detailed statistics of the installed capacities for the various types of utilization in the low and the high temperature fields in 1980 are reported by Gudmundsson (1982) and Gudmundsson et al. (1981) respectively.

Due to the abundant potential of hydropower in Iceland, electricity has so far been produced from geothermal energy on a small scale. Electricity was first generated on an experimental basis in Iceland in Hveragerdi in 1944, but it was not until in 1969 that a geothermal power plant (3MWe) was commissioned in Namafjall for continuous operation. Large scale production of electricity from geothermal is not likely in Iceland in the near future, but co-generation of electricity in plants established for direct industrial application of geothermal steam seems favourable. Along with a natural growth of the space heating market the growth of geothermal utilization in Iceland in the next decades is likely to be mainly in the industrial sector.

Due to the importance of geothermal for the national economy much effort is put into geothermal research as well as development. Most of the geothermal exploration and research work in the country is executed by the Geothermal Division of Orkustofnun, the National Energy Authority of Iceland. The 1982 budget for the Geothermal Division is about 2.5 million US$ excluding drilling funds.

This paper summarises the main geological features of the geothermal fields, some recent advancements in geothermal research are mentioned and a review is given of some recent advances in the development of both the low and the high temperature fields.

GEOLOGY OF THE GEOTHERMAL FIELDS

Iceland lies astride the Mid-Atlantic Ridge. The crustal thickness varies from 8-15 km, and the crustal structure is known in considerable detail from geological and seismic surveys (Palmason and Saemundsson, 1974). The crust is formed almost entirely of igneous rocks. The uppermost 3-5 km are composed mostly of subaerial lavas in the Tertiatry provinces, but of subaerial lavas intercalated (at intervals corresponding to glaciations) with morains and subglacial volcanics in the Plio-Pleistocene provinces and within the active volcanic zones. The lower part of the crust probably consists mostly of very low ÞBporosity impermeable intrusions and intensely altered lavas. This layer (the oceanic layer, Vp=6.5 km/s) may form the base to water circulation in the crust outside the volcanic zones (low temperature areas). In the high temperature areas and other parts of the active volcanic zones the water may circulate down into the intrusive layer during its formation.

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/m2 furthest away from the active volcanic zones crossing the country to about 300 mW/m2 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 (Palmason, 1973).

Hot springs are very abundant in the country as can be expected from the high heat flow. 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. It has become customary to divide the goetherml activity into two types, low and high temperature areas, on basis of the subsurface temperature. The base temperature is thus <150'C in the low temperature areas, but >200 'C in the high temperature areas (Bodvarsson, 1961). 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 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 (Einarsson, 1942). The high temperature areas are within 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. Deuterium isotope studies (Arnason, 1976) indicate the hydrological cycle in the high temperature systems to be much more localized than in the low temperature areas. The thermal manifestations vary greatly from one locality to another with water temperatures ranging from a few degrees above the mean annual temperature to boiling springs, and the flow rates ranging from nil to a maximum flow of about 180 l/s from a single spring. The total natural flow of springs >20'C is estimated about 1800 l/s (Saemundsson and Fridleifsson, 1980).

Due to the high geothermal gradient in Iceland it is never a problem to find temperatures high enough for utilization by drilling, but finding good aquifers can be difficult and expensive. Although the primary porosity of the volcanics is high the permeability of the strata is reduced immensely both as a result of zeolites filling vesicles and cracks and by compaction and general alteration of the rocks. Primary permeability is thus reduced in some of the volcanic rock formations to almost zero and secondary permeability becomes prevailent. The secondary permeability is related to fractures, faults and dykes that formed under extension within the axial rift zones during the growth of the volcanic pile or fractures and faults that formed later, sometimes under different stress conditions outside the zones of crustal growth. Thermal modelling indicates that thermal stresses are likely to play a significant role in enchancing the vertical permeability of the crust to a depth of several km (Bodvarsson and Lowell, 1972; Lister, 1980; Palmason, 1981). Secondary permeability may also be formed by dissolution of the wall rock of major aquifers in the deeper parts of geothermal systems (Bodvarsson, 1951). As an example of the potential of the last mentioned type of permeability it can be mentioned that the largest hot spring in Iceland, Deildartunguhver, with a flow rate of 180 l/s of boiling water carries about 2,000 tonnes of dissolved solids per year or about 20 million tonnes in the last 10,000 years (Saemundsson and Fridleifsson, 1980).

Low temperature areas

Most of the geothermal power utilized in Iceland is obtained from the low temperature areas. Utilization and successful prospecting for geothermal water has mostly been limited to known geothermal localities. The produduction wells in individual geothermal areas are, however, commonly sited by aid of geological, geochemical and geophysical exploration methods some distance from the natural hot springs. By drilling and pumping the natural flow in the low temperature areas is commonly increased 10-20 times without signs of overexploitation.

Regional exploration studies as well as drilling data and pumping tests have been used to make reservoir models of the main geothermal fields under exploitation in Iceland. The flow channels from the recharge areas in the highlands to the hot spring areas in the lowlands apparently vary from the Tertiary to the Plio-Pleistocene provinces (Fridleifsson, 1978). 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, hyaloclastites and detrital beds, potential flow channels are much more abundant. There in addition to faults and dykes, effective large scale reservoirs and flow channels are thought to be in the pillow lava cores of hyaloclastite ridges and high porosity stratiform horizons of fragmental material. There is a significant difference between the aquifers encoutered 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; the transmissivity is of the order of 10-3m2/s, an order of magnitude lower than that of the most permeable Plio-Pleistocene strata (Fridleifsson, 1979). The most intensely drilled thermal area in Tertiary strata is at Laugaland near Akureyri in N-Iceland (Björnsson 1981). The strata is of basaltic lavas with minor sedimentary interbeds. The hot springs on the surface are associated with dykes, but at depth particularly 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 the 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 10-2m2/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 strata (Fridleifsson, 1979). The most intensely drilled thermal area in Plio-Pleistocene strata is at Reykir in Mosfellssveit, SW-Iceland (Thorsteinsson, 1976). 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 hyaloclasties as well as detrital beds. By analysing the occurrence of aquifers in the different rock types in 29 drillholes (800-2043m deep) in the area Tomasson et al (1976) showed that large aquifers (>20 l/s) are by far more likely to occur at the contacts of lithological units than in lavas alone or in subaquatic volcanics alone. Several individual 1000-2000m deep wells in the area can give >70 l/s with pumping and a drawdown within the wells of 10-50m.

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 700m. With increasing compaction of the strata and sealing by precipitaton from warm water the geothermal gradient increases. The high temperature areas are like chimneys that extend from the hot zone below 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 some times calderas. At such sites there is a great abundance of dykes, sheets and other minor intrusions 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 convection systems of the high temperature areas.

To date there have been identified 28 potential high temperature areas in the country (Saemundsson and Fridleifsson 1980). Some of these are, however, largely covered by glaciers and cannot be exploited. 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 km2. One area covers approximately 140 km2 but the bulk of the areas are 1-25 km2.

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 (Walker, 1974; Fridleifsson, 1977). 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 cupolas of propylitized rocks which delineate the shapes of the extinct high temperature convection systems. The outer part of the aureoles are characterized by quartz and platy calcite, but these minerals are accompanied by laumontite and epidote and in rare cases garnet and amphilbole in the central parts (Walker, 1960; Kristmannsdottir, 1979). The heat transfer mechanism by which magma can act as a heat source for hyrdothermal systems in Iceland and elsewhere has recently been reviewed by Stefansson and Björnsson (1982).

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 at 3-7 km depth below the center of the 8 km broad Krafla caldera. The high temperature thermal area that presently is being exploited for power production lies right above it. Magma that flows steadily into the magma chamber at a rate of approximately 5 m3/s causes inflation of the caldera and during sudden deflation events magma is expelled laterally into the fissure swarm that transects the caldera (Björnsson et al 1979). Since 1975 small basaltic fissure eruptions have occurred eight 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 as much as by separate explosions. Surface hydrothermal activity has also increased significantly in two other geothermal areas on the fissure swarm, one about 7 km north of the caldera and the other (Namafjall) 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 tonnes of basaltic scoria were erupted up through a 1138 m drillhole in the Namafjall 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 (Stefansson, 1981). Magmatic gases have similarly had pronounced effects on the chemistry of the thermal fluid (Armansson et. al 1982) and caused serious deposition. The concentration of CO2 increased abruptly 100 times, followed by an increase in SO4 which seemed to be caused by the release of magmatic SO2 into the hydrothermal system. Cl2 gas has similarly been found in unusual quantities in one well with dry steam. 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.

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 encoutered in some areas. The strata are generally highly faulted. Deep drilling has been conducted in seven high temperature fields in Iceland (Hveragerdi, Krafla, Krisuvik, Namafjall, Nesjavellir, Reykjanes, Svartsengi). Although largely water-dominated, parts of several of the high temperature systems in Iceland are apparently boiling (two phase) with the pressure gradient close to the hydrostatic gradient (Stefansson, pers. comm., 1982). Measurements show the transmissivity to be highly variable between areas and within individual fields, the highest values recorded are of the order of 10-2 m2/s in Svartsengi (Kjaran et al., 1979). No statistical analysis is available on the occurrence of aquifers in high temperature wells in Iceland. The maximum flow rate (total flow) from a single well is approximately 180 kg/s.

RECENT ADVANCEMENTS IN GEOTHERMAL RESEARCH

The applications of geological, geochemical and geophysical exploration methods in Iceland have been summarised by Fridleifsson (1978), Arnorsson (1979) and Palmason (1976) respectively. Along with detailed geological mapping the most useful surface exploration methods in the last few years have been Schlumberger soundings and detailed ground magnetic surveys (Björnsson, 1981; Björnsson and Hersir, 1981; Georgsson, 1981; Georgsson et al., 1981). The interpretation of the resistivity soundings is done with the aid of one- and two-dimensional resistivity computer models (Dey, 1976; Johansen, 1977). The head-on resistivity profiling (Cheng, 1980) has recently been successfully applied to detect nearly vertical permeable structures (Flovenz and Georgsson, 1982) in low temperature areas.

Significant advancements have been made in the logging of geothermal wells in recent years with the acquisition of logging equipment for nuclear logs (natural gamma, gamma-gamma, neutron-neutron), electrical logs (resistivity and self potential) in addition to the more classical temperature and pressure logs. Caliper, cement bond and casing collar locator logs have further been of great value during drilling and cementing operations. Valuable comparison of geophysical logs with measurements on core were obtained in a 1900m continously cored well in eastern Iceland in 1978 (Jonsson and Stefansson, 1982). A new interpretation method for natural gamma ray logs in the volcanic strata of Iceland has been demonstrated (Stefansson et al.,1982).

Chemical geothermometers have recently been recalibrated with data from deep wells in Iceland; the CO2 gas thermometer appears to be very promising for the detection of upflow zones in high temperature systems (Arnorsson et al.,1982; Armannsson et al.,1982).

Much effort has been put lately into reservoir engineering studies of the high temperature geothermal fields (Kjaran et al.,1979; Stefansson and Steingrimsson, 1980;Bödvarsson et al.,1981).

An international training programme in advanced geothermal research and technology has been operated in Iceland since 1979 (Fridleifsson, 1982).

RECENT DEVELOPMENTS IN GEOTHERMAL UTILIZATION

Low temperature utilization

The geothermal water used for space heating is mostly from low temperature areas (<150'C); the mineral content is low (200-400 ppm) and the water can in most cases be used directly. Corrosion problems have been encountered where the hot water has been contaminated by oxygen. High chlorine content can also cause corrosion, such as in the Seltjarnarnes Municipal Heating Service where water with Cl-content above 500 ppm had been used directly for several years but heat exchangers have lately had to be installed at the intake of houses because of corrosion in the radiators. Production wells are commonly 1000-2000m deep the deepest well being 3085 m in Reykjavik.

The thermal water is in most cases pumped to the surface with shaft driven pumps placed at 100-200 m depth. Such pumps have been used in Reykjavik since 1960 at temperatures of up to 130'C. Due to the lower transmissivity of the geological formations in the Tertiary provinces larger drawdown is commonly experienced than in wells in the thermal areas of the Plio-Pleistocene provinces such as near Reykjavik.The largest municipal heating service obtaining water from a Tertiary lava formation is in Akureyri in N-Iceland (Björnsson, 1981). A submergible pump with the motor at 360 m depth has been operated successfully there for about two years at a water temperature of 81'C.

REDA
PUMP.

Long carrier pipelines in Iceland are either of mild steel or asbestos cement, the latter being cheaper but allowing much less effective insulation. Steel pipelines larger than 10" are commonly insulated with rock wool and either placed inside concrete tunnels or above surface covered with an aluminium jacket. Slimmer steel pipes are insulated by polyurethane insulation with a high density polyethylene plastic jacket. Asbestos cement pipes are most commonly covered directly by soil for insulation. For transporting 100 l/s the temperature drop will typically be 0.7'C/km for an asbestos cement pipe covered with soil, but 0.2'C/km for a steel pipe in rock wool and aluminium jacket. The longest steel pipeline in the country is 30 km. A 64 km long asbestos cement pipeline was taken into operation in W-Iceland in late 1981. It is the longest geothermal pipeline in the world and a worthy challenge to the common opinion of geothermal being a site specific type of energy. It is mostly of asbestos cement but a steel pipe is used where the pipeline crosses rivers or rocky hills where the pipe lies on bare bedrock. The pipe (400-450 mm in diameter) is placed on a bed of volcanic scoria and covered by approximately 70 cm of soil.The top of the pipe is insulated by hard pressed rock wool that covers 2/3 of the circumference of the pipe. The maximum capacity of the pipeline all the way to Akranes is 205 l/s. During the first winter of operation the average flow was 115 l/s. The water temperature was 97'C where it entered the pipe and the temperature drop was normally about 20'C but as much as 25'C during wet spells when the soil covering the pipe was saturated with water (Hrolfsson, pers. comm. 1982). The temperature drop was thus 0.3-0.4 'C/km. This is the first time rock wool has been used to insulate an asbestos cement transmission pipeline in Iceland. In Siglufjordur in N-Iceland polyurethane is used to insulate asbestos cement pipes; an aluminium jacket with a slot at the base is placed between the pipe and the polyurethane insulation to form a vapour barrier against the water seeping through the asbestos. The diameter of this pipe is 200 mm, the flow is 26 l/s, the distance 4.7 km and the temperature drop only 1'C or about 0.2'C/km. The choice of material for both pipe and insulation is based on the economics involved. In many of the municipal heating services in the country future increase in the energy demand can be met by replacing poorly insulated pipelines with well insulated pipes rather than by more drilling and pumping from the geothermal fields under exploitation.

Despite a drawdown commonly of 100-200 m in pumped wells it is noteworthy that influx of cold water has only been noticed in two thermal systems under exploitation in Iceland. This is in Selfoss in S-Iceland where cold groundwater seeps into the geothermal reservoir both through natural cracks and through old drillholes with faulty casing (Tomasson and Halldorsson, 1981), and in Egilsstadir in E-Iceland where the natural hot springs are at the bottom of a lake and the drawdown in production wells leads to cold ground water seeping into the geothermal system.

High temperature utilization

In 1976 a plant started operating in the Svartsengi high temperature field where a 240'C brine (2/3 seawater) is used for district heating by the use of heat exchangers (Thorhallsson, 1979). The installed capacity of this plant is 125 MWt. The high pressure steam is also used for co-generation of electricity (installed capacity 8 MWe). Ten production wells and one reinjection well have been drilled. Reinjection experiments are planned to start in Svartsengi in the autumn of 1982. This will be the first time reinjection is applied in Iceland.

DRAW
DOWN
IS A
SERIOUS
PROBLEM

The Krafla geothermal field is still seriously affected by the volcanic activity that started in 1975 and does not show any signs of abating. The geothermal system has been found to consist of a shallow liquid dominated zone with temperatures of about 210'C and a boiling zone (two phase) with temperatures ranging from 300'C at the top at 1000m depth to 340'C at about 2000m depth (Stefansson and Steingrimsson, 1980; Stefansson, 1981). A 30 MWe turbine installed in the Krafla power station (Eliasson et al., 1980) was commissioned in 1978 and has been limited to an output of 10-15 MWe due to a meagre steam supply. The chemical composition of the geothermal fluid has been very seriously affected by volcanic gases associated with the magmatic activity in the area as mentioned previously. This has caused a rapid precipitation of mainly iron silicates within the rock formation surrounding the producing aquifers. This is considered to be a significant factor in the rapid decline in the productivity of the wells. At the end of 1981 altogether 16 production wells had been drilled. The accumulated steam productivity of the wells (value for each well taken after a flow test of one month or more ; interferance between individual wells has been observed minimal probably because of the two-phase conditions in the reservoir) is equivalent to 50 MWe production, but the steam supply is only sufficient for about 15 MWe (Stefansson, 1982). Attempts are made to site wells outside the area most affected by the volcanic gases. A production field has already been identified where the fluid is not markedly contaminated by the magmatic gases. The extension of this new field is, however, rather limited and will probably not sustain more than about 30 MWe production (Stefansson, 1982). Three wells will be drilled in 1982. Directional drilling techniques were used for the first time in Iceland in one of the wells in Krafla in 1982. The planned capacity of the Krafla power station is 60 MWe.

A 3 MWe turbine commissioned in 1969 in the Namafjall field was removed in 1978 due to the volcanic/tectonic activity mentioned previously. The turbine was reinstalled in 1981. The steam in Namafjall is primarily used for a diatomite plant that started operating in 1967 (Ragnars et al.,1970). The present production in the plant is about 24,000 tonnes/year of diatomite. The thermal energy used in the plant is about 35 MWt (Gudmundsson et al., 1981).

A 0.3 MWe turbine was installed in the Nesjavellir field in SW-Iceland in 1980; it provides power for a pilot plant where heat exchanging processes are being tested by the Reykjavik Municipal Heating Service.

A pilot plant for the production of salt from a geothermal brine was operated in the Reykjanes high temperature area in 1979-1981 (Lindal et al. 1982). A demonstration plant with a capacity of 4,000 tonnes/year is under construction, and there are plans to increase the size of the demonstration plant to 8,000-12,000 tonnes/year. Depending of the success of the demonstration plant a salt factory with a capacity of 40,000-60,000 tonnes/year may be built which would satisfy the demand for salt in Icealnd.

A remarkable experiment has been in operation for five years in the Westmann Islands where heat is extracted from a thick, partly molten lava flow (erupted in 1973) for space heating of a town of 5,000 people. It is estimated that the heat source will last at least 15 years.

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GEOTHERMAL TRAINING IN ICELAND

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ABSTRACT

An international training programme in geothermal energy research and technology has been operated in Iceland under the auspices of the government of Iceland and the UN University since 1979. Twenty two participants from leading energy agencies in Africa, Asia and Central America have received 6-8 months specialized training and eight scientists and engineers have come for shorter study tours. Specialized training is offered in geological exploration, borehole geology, geophysical exploration, borehole geophysics, chemistry of thermal fluids, reservoir engineering, geothermal utilization and drilling technology. A summary is given in the paper of the conclusions of an international committee which reviewed training needs in geothermal energy in developing countries in 1980.

INTRODUCTION

The development of geothermal resources requires a dedicated group of highly skilled specialists from many scientific disciplines. Because of its diversity, geothermal energy research is not taught as a separate subject at universities, but is a field where practical training is required at post-graduate level. This was the guideline in the proposal of the Icelandic Government to the United Nations University (UNU) in 1978 to establish jointly a training programme in geothermal energy research and technology in Iceland for scientists and engineers from developing countries.

Prior to the establishment of the training programme the UNU sponsored an international workshop in Iceland in 1978 (United Nations University, 1979). The workshop was attended by geothermal scientists from 12 countries, including scientists from Italy and Japan where international geothermal training courses have been organized since 1970, and from New Zealand where a post graduate diploma course was due to start in 1979. Present at the meeting were also representatives from the UN agencies that have sponsored geothermal work in developing countries (UNESCO and UNDP). The workshop concluded after consideration of the existing courses in the world that the training programme proposed in Iceland was an important addition to existing training courses.

The UNU Geothermal Training Programme in Iceland was formally started on 1 March 1979. The cost of the training programme is born by the Government of Iceland and the UNU, with the latter providing grants (UNU Fellowships) for the travel and living allowances of the participants. Priority for Fellowships is given to candidates from developing countries where geothermal exploration and development is already under way.

Twentytwo UNU Fellows from leading energy agiencies in China (5), El Salvador (1), Honduras (1), Indonesia (2), Kenya (3), Mexico (1), Nicaragua (1) and the Philippines (8) have come for 6-8 months training. One UNDP Fellow from India has come for 3 months training and seven UNU Special Fellows from China (5), Indonesia (1) and the Philippines (1) for shorter study trips.

GEOTHERMAL TRAINING PROGRAMME

The UNU Geothermal Training Programme is executed by the Geothermal Division of the National Energy Authority of Iceland, but is also linked with the University of Iceland. Supervisors and instructors are drawn from the staffs of both institutions, and in some cases from other specialized institutions in Iceland as required. A studies board is responsible for the academic contents of the training. An attempt is made to integrate the training of participants into the geothermal exploration and utilization projects that are in progress in Iceland at the time of training. In some cases, however, participants bring with them data from geothermal projects in their home countries and work on the data under the supervision of specialists.

The aim is to provide practical training that will enable successful participants to return to their countries and work independently in their chosen fields. Participants are expected to have a university degree in science or engineering and preferably some practical experience in geothermal work in their home countries. The training is conducted in English, which the participants must speak fluently. The curriculum of the training programme is shown on the next page. In general, all participants are expected to attend an introductory lecture course (exemptions can be given to those participants who have already participated in the geothermal courses in Italy, Japan and New Zealand). The lecture course is followed by practical training under close supervision in a specialized field. During the training, study tours are arranged to all the main geothermal fields in Iceland.

The introductory lecture course is composed of lectures on a wide range of topics related to geothermal energy, including geothermal energy around the world; geology, geophysics, and chemistry of thermal fluids in geothermal exploration; drilling, borehole geology and geophysics; safety aspects of geothermal drilling, well testing and reservoir engineering; utilization of geothermal resources, environmental factors; planning and execution of geothermal projects, and case histories of selected geothermal projects around the world. The purpose of this lecture course is to provide a general background knowledge concerning most aspects of geothermal energy and to generate an appreciation of the interrelationship between the various diciplines necessary in geothermal projects from the first to the last stages. In addition to the formal lecture course carried out by Icelandic specialists, a guest lecturer with international reputation is invited every year to give a lecture series related to his speciality and to lead

TRAINING PROGRAMME IN GEOTHERMAL ENERGY IN ICELAND

Week	Geological Exploration	Borehole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Geothermal Utilisation	Drilling Technology
1								
2	Introductory lecture course on all aspects of geothermal energy and short field excursions							
3								
4								
5	Field Geology R	Drilling P	Heat flow PF	Logging & well testing PR		Chemical thermodynamics LR		Introduction R
6	• R	Petrological RP	• FI	PR		• LR		• R
7	Maps & Photos P	logging RP	Magnetics P	RI		Sampling RP		Medium size rig P
8	Structure Anal. P	• P	& tectonic F	Well completion & stimulation PF		Chemical features LR		• P
9	Hydrogeology RP	• P	structure I	PF		Deposition LR		• P
10	FP Field excursions	Field excursions	Field excursions	Field excursions	Field excursions	Field excursions	Field excursions	Field excursions
11	FP •	•	•	•	•	•	•	•
12	Mapping P	Petrolgical PI	DC-Resistivity P	P-T-Ωm- LR	Reservoir LR	Sampling & RP	Fluid flow LR	Produc. size rig P
13	Field work in F	logging PI	soundings F	Caliper logs LR	properties & LR	analysis P	Collection & LR	• P
14	deeply eroded F	Report PI	• I	LR	well performance LR	P	disposal LR	• P
15	volcanic strata F	Alteration RP	Project PI	Field work F	LR	Geothermometers RP	Corrosion LR	Prep.& planning LR
16	F	• RP	• P	F	Well testing F	• P	Deposition LR	Selec. equipm. RP
17	Field work F	• RP	• F	Logging PR	Well testing PR	• P	Reservoir LR	Techniques R
18	in recent F	X-ray RP	Report I	Project PR	Project PR	W/R Interact. RP	Plants LR	• R
19	volcanic fields F	• RP	• F	• F	• P	• LR	• LR	Completion P
20	F	Report IP	• I	• F	• F	• P	• LR	Practices P
21	Report PI	•	Special methods P	Report I	Report I	• P	Project P	Management RP
22	• PI	Clay minerals RP	(Electrical or F	I	I	Project P	• P	• RP
23	• I	P	gravity & seismic)	I	I	• P	•	
24	•	Aquifers	F		Modelling RL	• P	• P	
25		Geological P	I		& RL	• P	• P	
26		modelling I	I		assessment RL	• PI	• PI	
27					of a PI	• PI	• PI	
28					reservoir PI	• PI	• PI	
29					I	• PI	• PI	
30					I	Report I	Report I	
31					I	•	• I	
32					I	•	• I	

F = Field work
I = Interpretation
L = Lecture
P = Practical exercises
R = Reading & seminars

discussion sessions with the trainees. The visiting lecturers have stayed from about two weeks to two months. The following have been visiting lecturers of the training programme: Dr. Donald E. White of the US Geological Survey in 1979, Mr. Christopher Armstead, geothermal engineering consultant from England in 1980, Prof. Derek Freeston of the Geothermal Institute, Auckland University in 1981 and Prof. Stanley H. Ward of the University of Utah Research Institute is expected in September 1982.

An essential feature of the training programme is to provide participants with sufficient understanding and practical experience to permit the independent execution of projects within a selected discipline in their home countries. This is an ambitious goal and requires dividing the training into several courses. Each participant is expected to follow mainly one of the eight courses. The training takes approximately six months, including the introductory lecture course and field excursions. If a participant follows more than one specialized course, the training period becomes correspondingly longer. UNU Certificates are awarded to participants who complete the training satisfactorily.

Short descriptions are given of the specialized training courses in the following section. As the number of participants is limited to 5-10 each year, only two or three courses may be offered in any given year. The selection of the courses that are run depends on the demand shown by the recipient countries for the various courses and to some extent on the availability of supervisors in the specialized fields. The training programme normally starts in mid April and ends in mid October each year.On their way home from training in Iceland the participants have gone on study tours to geothermal fields and/or research organizations in Italy, Denmark, France or the USA.

SPECIALIZED COURSES

The curriculum is divided into eight specialized courses and each participant normally receives training in one such course.

Attempts are made to suit the training to the background of the individual participant and the needs of his organization, so the following description of the specialized courses serves only as a guideline.

a. Geological exploration. This course offers practical training in basic geological mapping, which is commonly the first step in the geothermal exploration of an area. Participants analyse the geological structure of an area with regard to siting drill holes and can be trained in mapping surface geothermal manifestations. The fieldwork is conducted partly in deeply dissected strata, where the roots of extinct volcanoes and geothermal systems can be inspected, and partly in active geothermal fields. Participants from countries where geothermal fields are associated with active volcanoes can receive special training in volcanic surveillance methods applied in Iceland.

One participant from Mexico has been trained in this course. He specialized in the application of paleomagnetic mapping and tephrochronology in geothermal exploration in volcanic regions (Flores, 1981). A geologist from India was trained for three months in siting geothermal wells (Saxena, 1980).

b. Borehole geology. In this course participants are trained in making geological logs from drill cuttings. They are introduced to alteration studies and their use in geothermal exploration. They may receive practical training in the application of x-ray diffraction and other methods for mineral identification. They can also be trained in providing geological advice regarding production drilling, in recording of aquifers with temperature logs and hydrological methods, and in making geological models of geothermal reservoirs from their own data and data from other disciplines.

Three participants have been trained in this course and the fourth (from Indonesia) is presently receiving training. Two participants from the Philippines specialized in analysing rock cuttings from their own country (Bagamasbad, 1979; Reyes, 1979), but a participant from Honduras worked on the borehole geology of an Icelandic geothermal field (Flores, 1980).

c. Geophysical exploration. This course requires a solid prior knowledge of geology, geophysics, physics or engineering. Emphasis is placed on practical training in how to conduct geophysical surveys of geothermal fields and in interpretation of geophysical data. The essentials of heat-flow studies, ground magnetic surveys and their relation to tectonic structure, DC-resistivity depth soundings and profiling are covered. During the last six weeks a selection can be made among (a) further training in electrical survey methods such as dipole, MT, EM, AMT and SP, (b) training in gravity and magnetic surveys and (c) training in seismology with emphasis on microearthquakes and ground noise studies.

One participant from the Philippines has been trained in this course specializing in the application of computer programmes for the interpretation of resistivity data and for one- and two-dimensional resistivity modelling of geothermal fields (Layugan, 1981). Three participants from Indonesia, Kenya and the Philippines are receiving training in 1982.

d. Borehole geophysics. The training covers the essentials of geophysical measurements in boreholes used for geothermal investigations, with the main emphasis on pressure and temperature measurements, but including resistivity, SP, caliper, porosity and density logs. The purpose is to provide practical experience for the planning and execution of the measurements necessary to obtain adequate information on: geological structure, the location of aquifers, hydrological characteristics, chemical composition of deep water, well performance and modelling of geothermal systems. The course is in two main parts; practical and theoretical instructions in the various methods are followed by the design,execution and interpretation of the results of a logging project under the supervision of an instructor.

Three participants from China, El Salvador and the Philippines have participated in the course. Two of them specialized in the interpretation of various types of logs from single wells (Sarmiento, 1980; Zuniga, 1980), and one interpreted temperature data from typical high and low temperature geothermal fields (Zhou, 1980).

e. Reservoir engineering. The purpose of this course is to provide practical training in the reservoir engineering methods required to obtain information on the hydrological characteristics of a geothermal reservoir. The course covers both surface and downhole measurements and the interpretation of well tests. This course requires a sound background in mathematics.

One participant from the Philippines has been trained in this course. He specialized in mathematical modelling of geothermal reservoirs and in methods to predict the response of a geothermal field to long term exploitation (Regolado, 1981). Another Philippino received two months training in the theoretical part of the course.

f. Chemistry of thermal fluids. The objective is to provide an insight into the role of thermal fluid chemistry in geothermal exploration and exploitation, including sampling, analysis of major constituents and interpretation of the results. Towards the end of the training period a special exercise on a geochemical problem is undertaken and a final report prepared. Participants can also bring chemical data from their home countries and interpret these data under the supervision of a specialist.

Three participants from China, Nicaragua and the Philippines have been trained in this course and two from Kenya and the Philippines are receiving training in 1982. They have all specialized in the interpretation of geochemical data from geothermal fields in their home coutries (Baltasar, 1980; Martinez, 1981; Yao, 1980).

g. Geothermal utilization. The purpose of this course is to give advanced training in the use of geothermal resources. The course deals with the mechanical and chemical engineering aspects of geothermal fluids in pipes, equipment and plants. The feasibility of projects and environmental factors are also considered. The training aims at providing sufficient experience and knowledge to understand the engineering required in geothermal utilization projects and in carrying out some of the tasks independently. A university degree in engineering is a prerequisite.

Two engineers from China have participated in this course. One specialized in the application of a computer in solving geothermal utilization problems such as the selection of well pumps, heat and pressure losses in geothermal transmission pipes and for evaluating design temperatures for district heating systems (Shen, 1981). The other specialized in the design and feasibility studies of district heating systems and made suggestions for future development of the geothermal heating system in Tianjin in China based on systems he studied in operation in Iceland (Sun, 1981).

h. Drilling technology. The aim is to provide engineers with the information and on-site training necessary to prepare them for work as drilling supervisors. The course begins with seminars on the techniques and equipment used in drilling for hot water and steam, followed by practical training on the drill site to provide a feeling for the real work involved in geothermal drilling. Participants have an opportunity to observe equipment of different sizes in operation. Seminars are held on the criteria for the selection of equipment and methods appropriate for each task. The course is not training for the task of drilling itself but the planning and supervision of geothermal drilling.

One engineer from China has participated in the course. He was trained in general aspects of drilling in high temperature geothermal fields (Tang, 1981). An engineer from Kenya is receiving training in 1982. He specializes in cementing techniques for long production casings.

SELECTION OF PARTICIPANTS

To harness geothermal energy a team of highly specialized experts is needed in the fields of geology, chemistry, physics and engineering. With this in mind the participants with UNU Fellowships have been selected from leading energy organizations in a few countries or regions which are closely tied geographically and culturally, so as to assist these countries/regions in building up their own cadre of specialists. One can foresee these organizations in the near future providing regional geothermal training facilities for their own nationals or neighbours in the various continents. The participants have come from China, Indonesia, Kenya, Philippines and Central America. All of the recipient countries are deeply involved in geothermal work, and are generally highly dependent on foreign consultants, who mainly come from France, Iceland, Italy, Japan, New Zealand and the USA.

Much care has been taken in selecting the participants. Site visits have been made by staff members of the training programme to 11 developing countries which have started geothermal work and an assessment made of their energy policy, geothermal potential and institutional capacities in the field of geothermal research and development. By interviews and visits to laboratories as well as geothermal fields the training needs of the countries have been assessed. On this basis directors of energy institutions have been invited to nominate candidates for training in the specialized fields that are considered most relevant to promote geothermal development in the respective countries. All candidates are interviewed personally by a representative of the training programme. Attempts have been made to identify and train persons that are both capable of working independently as specialists and of responding to the multidisciplinary nature of their responsibilities as leaders within their organizations.

The participants must have some practical experience in geothermal work prior to training and most of them have assumed leading roles within their organizations upon conclusion of training. In many instances they are the only moderately qualified people in their specialized fields in their countries. They bring a lot of geothermal literature and training texts home and this material is used by their organizations for training of new recruits.

Since 1979 all the participants have obtained UNU Fellowships that cover international travel and living cost in Iceland. In the future qualified candidates sponsored by equivalent grants from their own institutions or international organizations can also be accepted. The training is financed by the Government of Iceland as a contribution to development aid and no fees have been requested of participants. Nominations for participation in the training programme should be sent by managers of institutions to the office of the training programme at the National Energy Authority in Iceland. The curriculum vitae of candidates must be sent with the nominations. Nominations must be received in Iceland at the latest on 1 August each year for participation in training commencing in April of the following year.

REPORTS OF THE TRAINING PROGRAMME

For many of the specialized courses no textbooks are available and a large amount of text material and manuals have been collected or written by the supervisors of the individual specialized courses for the benefit of the trainees. Some of the training texts have been or are in the process of being published (Stefansson and Steingrimsson, 1980; Eliasson,1980; Karlsson, 1982; Kjaran and Eliasson, 1982). These are used by the participants both as working manuals and to train their colleagues back home. Similarly some of the lectures of the visiting lecturers have been published (Armstead, 1981; Freeston, 1982). Papers on the status of geothermal development in various countries of the world presented at a meeting of the

UNU sponsored Standing Advisory Comittee on Geothermal Training held in Italy 1980 have also been published by the training programme (Fridleifsson, 1982).

The participants in the training spend a few weeks writing their project reports all of which are published in 100-200 copies. Many of the project reports are written in such a way that they can serve as manuals for performing certain measurements or interpretations dealt with in the respective reports. The subjects of the reports by trainees were referred to in a previous chapter. Copies are available of most of the reports of the training programme and these can be mailed upon request.

TRAINING NEEDS IN DEVELOPING COUNTRIES

At the recommendation of the international workshop on training needs in geothermal energy held in Iceland in 1978 (United Nations University, 1979) the UNU Geothermal Training Programme has established an international Standing Advisory Committee on Geothermal Training (SACGT) that has the role of co-ordinating all geothermal training sponsored by the UN system. The statues for this committe were constructed at the 1978 workshop. This committee is the only forum that has been established within the UN system for the co-ordination of geothermal energy training and dissemination of geothermal information. Three UN agencies presently sponsor geothermal energy training. UNESCO has since 1970 sponsored yearly group-oriented courses at Pisa in Italy (9 months) and Kyushu in Japan (3 months). UNDP has since 1979 sponsored an academic course at Auckland University in New Zealand (9 months) and several short (few weeks) regional seminars in Central America, China and the Philippines. UNU has since 1979 sponsored the project-oriented specialized training in Iceland (6 months).

At a meeting of the SACGT held in Italy in November 1980 a group of international geothermal experts concluded that: the geothermal industry in the world needs more of specialized courses than presently avail[illegible]d the speciality options of the existing courses should be increased; to meet the growing demand of the developing countries training opportunities within regions should be strengthened and, where necessary, established; present training centres should consider how best to train their students in teaching their own nationals; more stimulus be given to local training of high quality technicians; suitable training texts and possibly audio-visual aids be prepared for use in regional seminars; geothermal institutions should be encouraged and helped in establishing basic libraries related to geothermal work.

The SACGT meeting estimated the training needs of geothermal personnel in the developing countries to be about 250 per year for the next 10 years. This is far beyond the capacity of the existing international geothermal courses, and most of the people will have to receive on the job training in their home countries. Similarly language difficulties and the finances involved in international travel make national and regional training centres highly desirable. The most severe limiting factor in setting up national and regional training centres is, however, the lack of qualified instructors locally. This cannot be solved quickly. Experience has shown that once national geothermal programmes have started the urgency of the energy demand causes all qualified personnel to be absorbed in activites leading to quick energy production, and little time is left for scholarly activities or training. It is, however, essential to have a cadre of specialists in each country that is seriously developing its geothermal resources. Initially these have to be trained abroad. These people commonly start working in geothermal as counterparts with foreign consultants, then go for specialized training to gain wider experience and confidence to gradually take over from the foreign consultants. At the international geothermal training centres they obtain training material and learn how to train their colleagues at home. Experience in several countries has shown that the best way to secure that technological knowhow of foreign consultants is left in a country is to send counterpart scientists and engineers to training centres abroad. The SACGT meeting stressed that more specialized courses are needed than presently available for countries with established capacities for geothermics. These courses should be of short duration and co-ordination between training centres would be required to avoid needless duplication.

An increased effort should be made to assist the recipient countries in establishing training courses on the national level for technicians and specialists. This is already being done to some extent by UNDP and UNESCO. These courses are presently in the form of seminars lasting from a few days to a few weeks. These courses are most useful in countries where a group of geothermal specialists has already been established by training at international courses and by working side by side with foreign consultants. The value of such courses is, however, very limited in countries where only one or two people have a sound background knowledge of the subject. People who attend short crash courses can even gain a false sense of security and competence which can be very costly to their countries. It should be kept in mind that an average geothermal production well costs approximately 1 million US$. Geothermal is a field of energy technology where gains can be high but mistakes are expensive. A high priority should be given to promote co-operation between geothermal training centres operated under the auspices of UN agencies, regional and national organizations in various parts of the world. The training task is so large that significant results can only be obtained through a dynamic international co-operation.

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PROSPECTING FOR NEAR VERTICAL AQUIFERS IN LOW TEMPERATURE GEOTHERMAL AREAS IN ICELAND

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ABSTRACT

This paper deals with the problem of locating permeable near vertical dykes, faults and fractures which serve as aquifers in low temperature areas in Iceland.

Four different methods are discussed, geological mapping, ground magnetic measurements, head-on resistivity profiling and shallow temperature gradient holes. Examples of successful use of the methods are given.

INTRODUCTION

The Mid-Atlantic ridge crosses Iceland from southwest to northeast. The neovolcanic zone in Iceland is the landward continuation of the ridge and is characterized by recent volcanism and rifting (fig.1). The Icelandic crust is mainly composed of basaltic lavas with some acid and intermediate rocks in volcanic centers. The lava pile dips generally towards the active volcanic zone. Regional heatflow is high in Iceland. The temperature gradient outside the volcanic zone varies between 50 and 150 °C/km, generally decreasing away from the volcanic zone (Palmason 1973).

The geothermal areas in Iceland are divided into two types: high temperature areas and low temperature areas. The former are characterized by temperatures exceeding 200°C at depths of few hundred meters. They are always associated with recent volcanism and are exclusively found within the neovolcanic zone. The heat source is usually connected with recent shallow intrusions. The low temperature areas have temperatures ≤ 150°C in the uppermost kilometer. Most of the major low temperature areas are found just outside the neovolcanic zone in rocks of quarternary age, but minor areas are found almost all over the country (fig.1).

The low temperature geothermal water is mainly used for space heating or greenhousing and today $\approx 75\%$ of the population of Iceland are provided with geothermal space heating.

The geothermal water in the low temperature areas is meteoric and generally originates as precipitation in the central highlands. It percolates deep into the bedrock where it is heated by the high heat flow. It then flows laterally along permeable dykes, faults, fractures and horizons driven by the hydrostatic gradient, before it appears on the surface in the lowlands (Einarsson 1942).

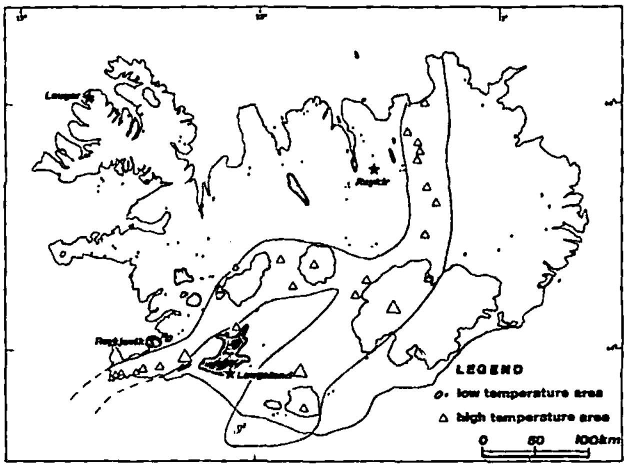

Figure 1. Geothermal areas in Iceland. Areas discussed in this paper are marked with an asterix. Modified after Saemundsson and Fridleifsson 1980.

Intensive drilling in Iceland indicates that aquifers are mostly connected with some near vertical structures such as dykes, faults or fractures. It is common that hot springs are found at the intersection between two such structures where one acts as an aquifer and the other as an aquiclude. Thus it can be said that the main problem of low temperature geothermal exploration in Iceland is to locate dykes, faults and fractures, estimate their dip and find out which of these structures are permeable. Experience shows that only few of the numerous faults and dykes in Iceland are permeable. This paper deals with this problem.

GEOLOGICAL MAPPING

The first and the least expensive step in exploring a new geothermal area is detailed geological mapping. The main purpose is to map all visible structures and to find out the regional dip and strike.

The simplest case is when the hot water flows to the surface along an exposed dyke or fissure. It is usually assumed that dykes or fractures are

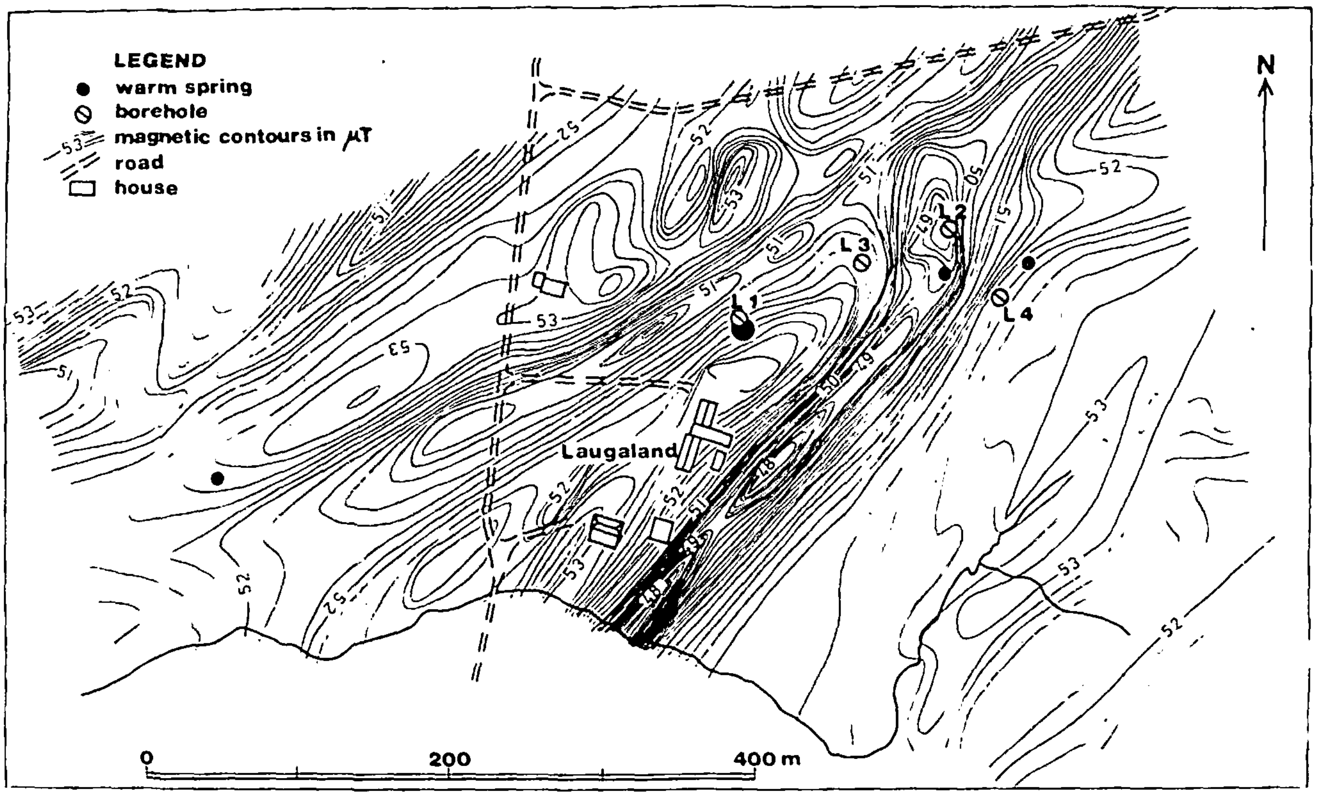

Figure 2. A magnetic contour map from Laugaland in southern Iceland

near perpendicular to the lava pile, and as the dip of the lava pile is usually better known, dips of near vertical structures can be inferred. The drillsite is then selected in order to cut a particular dyke or fault at a certain depth. This method often gives satisfactory results, but unfortunately it fails in many cases. In cases of failure or when the basement is covered with sediments or soil, geophysical exploration methods are necessary. It must however be stressed that knowledge of the regional geology is necessary to understand the nature of the geothermal systems and to interpret the results of the geophysical surveys..

GROUND MAGNETIC MEASUREMENTS

Ground magnetic measurements are widely used in geothermal prospecting in low-temperature areas in Iceland. The method is powerful to find dykes, faults and other linear structures when the basement is covered with relatively thin soil or sediments. The usual procedure is to measure the total magnetic field with a proton precession magnetometer along lines approximately perpendicular to the strike. Readings are normally made every 5 meters along the lines and a typical spacing between lines is 20-40 meters. The results are often easy to enterpret without any processing. In some cases, however, processing such as filtrering or removal of topographic effects is necessary.

A good example of the advantages of this method is shown in fig. 2. At Laugaland in S-Iceland four warm springs (T_{max} =43°C) are distributed along a 600 m straight line striking N75°E. Two old shallow wells (L-1 and L-2) yielded 4-5 l/s of nearly 50°C water. When geothermal exploration was restarted in 1977, it was concluded that this linear distribution of the warm springs was due to a fracture in the basement. Well no L-3 was sited to intersect this fracture. The result was, however, very poor, only 1 l/s from a 1308 m deep well. The temperature in the borehole was on the other hand encouraging since it indicated a geothermal system of approx. 90°C at 700-1000 m depth. Magnetic anomalies (fig. 2) indicate two reversely magnetized dykes crossing the line of the warm springs. One of the springs turned out to be at the intersection between the line of the warm springs and one of the dykes. A new well was sited to cut that dyke at 500-800 meters depth near this intersection. The well (844 m) was a success, yielding initially 20-25 l/s of 94°C hot water in free flow from aquifers at 750-837 m depth. Fig. 3 shows a model of

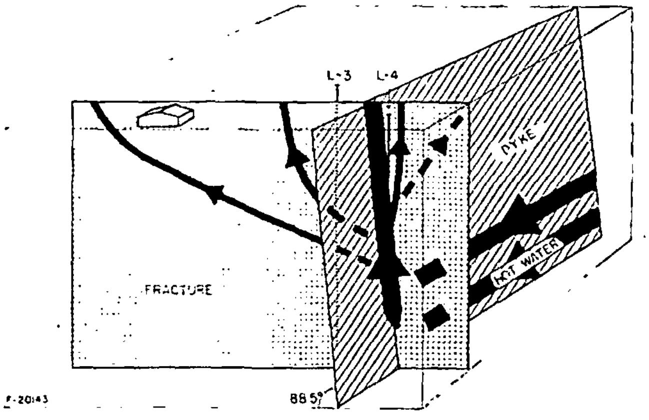

Fig. 3. Simplified model of the geothermal system at Laugaland in southern Iceland.

of the geothermal system based on surface exploration and well logging.

RESISTIVITY MEASUREMENTS

Opposite to ground magnetic measurements, which only give structural information, resistivity measurements can be directly related to geothermal parameters such as amount of interconnected pores and fissures, temperature and salinity of the geothermal fluid. In low temperature areas in Iceland, the salinity of the water is usually quite low. Hence the electrical conduction mostly takes place as surface conduction in waterfilled fractures and interconnected pores. This means that the bulk resisitivity, as measured for instance by Schlumberger soundings, is practically independent of the salinity and the temperature of the pore fluid as long as the conductivity of the fluid does not exceed certain limits (Flovenz 1980). In the basaltic crust of Iceland this limit seems to be of the order 1 siemens/m. Resistivity variations in the Icelandic crust do therefore primarily reflect variations in amount of interconnected pores and fractures in the rock.

Schlumberger soundings are quite useful in pointing out areas of low resistivity. They can be used to compare different areas and together with thermal gradient measurements they may be helpful in selecting promising fields for further investigation. The resolution of the Schlumberger soundings is, however, too limited to detect and map a single waterbearing dyke or fracture. The prospecting method which seems to be the most powerful one in locating permeable, near vertical structures is the so called head-on restivity profiling (Cheng 1980). This method differs from usual profiling with Schlumberger arrangement by the use of a third current electrode, (C), placed at infinity. The apparent resistivity is measured as the current is sent between each two pairs of the current electrodes, A,B and C. This gives three values for apparent resistivity called rho_{AB}, rho_{AC} and rho_{BC}, two of which are independent. In the case of homogenous horizontally layered earth, all these values are identical. Near vertical resistivity contrasts, the curves for rho_{AC} and rho_{BC} versus location behave in a different way. A theoretical head-on resistivity profile across a low resistivity dyke covered with 25 m thick surface layer is shown in fig. 4. The plot of rho_{AB} shows a minimum directly above the dyke but the curves for rho_{AC-AB} ($=\text{rho}_{AC} - \text{rho}_{AB}$) and rho_{BC-AB} ($=\text{rho}_{BC} - \text{rho}_{AB}$) have a different sign on each side of the dyke and cross directly above it. The picture is not always as obvious as this. Other values for the resistivity contrasts and the thickness of the surface layer may give a local maximum for rho_{AB} above the low resistivity dyke, flanked by two minima. This could easily lead to misinterpretation of the rho_{AB} data. The curves for rho_{AC-AB} and rho_{BC-AB} will on the other hand always intersect directly above the dyke, making interpretation safer and easier.

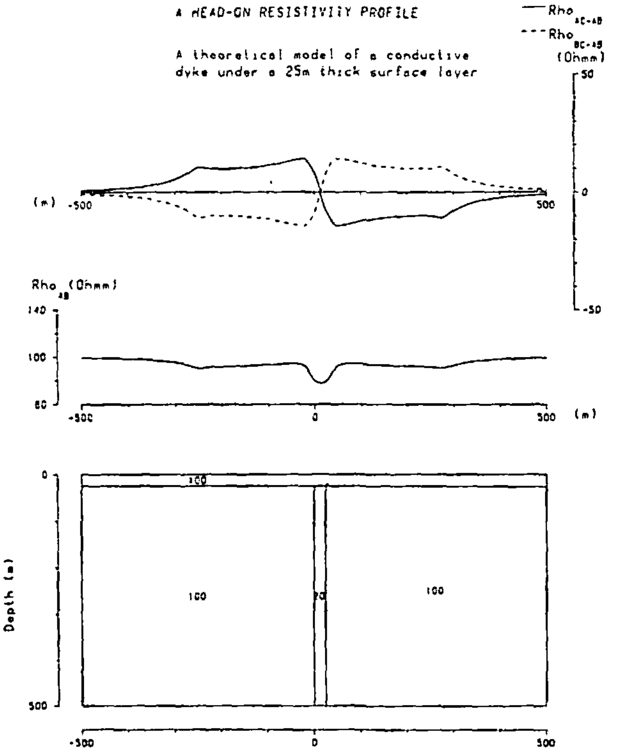

Fig. 4 Theoretical head-on resistivity profiles based on the finite difference algorithm by Dey (1976) with modifications by Halldor Halldorsson (Nat.En.Auth.)

At the low temperature area in Laugar in Sugandafjordur in NW-Iceland this method was used to select a drillsite. The only surface manifestation of the geothermal field was a single warm spring. Drilling directly into the spring gave reasonably good results, but more water was needed. A ground magnetic survey showed that the warm spring was situated on a NW-striking fault and that this fault intersected a N-striking dyke 120 m east of the warm spring. A second well was drilled, intended to intersect the fault in the sama way as the former one, but 300 m westwards along the fault. A continuous core was taken. The fault turned out bo be inpermeable and no aquifers were observed in the 521 m deep well. At this stage head-on resistivity profiles were measured. Lines crossing the dyke showed a well defined minimum in rho_{AB} just above the dyke and the curves for rho_{AC-AB} and

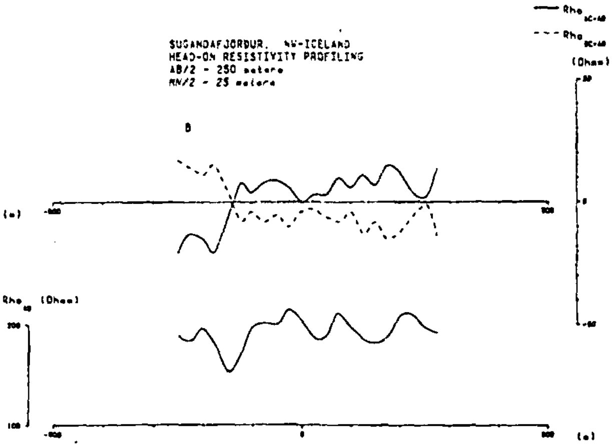

Fig. 5 Head-on resistivity profiles from Laugar in Sugandafjordur, NW-Iceland, measured across a permeable dyke.

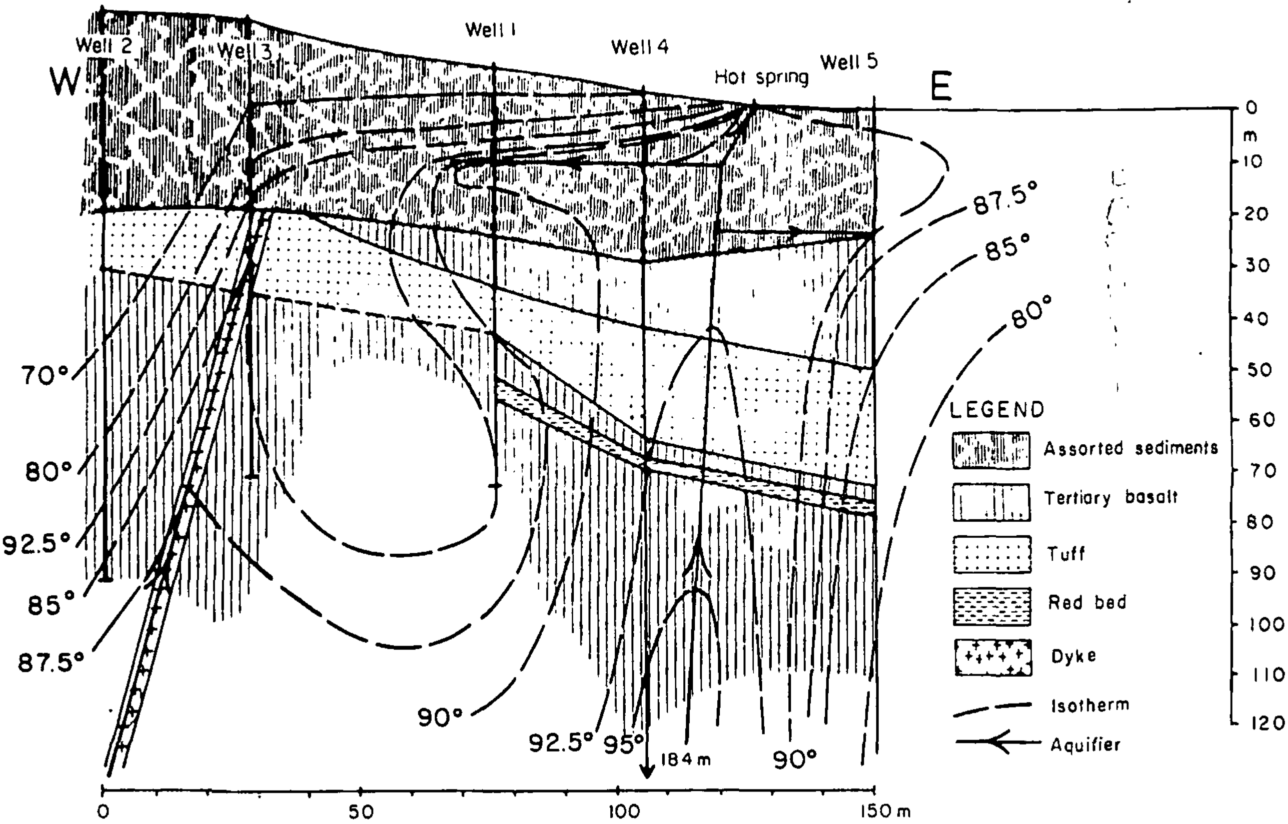

Fig. 6 A simplified geological cross-section through the wells at Reykir in Fnjoskadalur, N-Iceland (made by Asgrimur Gudmundsson, Nat.En.Auth.), and the location of the main aquifers as calculated from the temperature distribution.

rho$_{BC-AB}$ did intersect at the same place. It was therefore concluded that the aquifers were associated with the dyke. This conclusion has been confirmed by drilling. A typical head-on profile across this dyke is shown in fig. 5. Profiles crossing the fault only showed low resistivity above the fault close to the dyke-fault intersection.

THERMAL METHODS

Measurements of thermal gradient in shallow boreholes can be quite useful in locating steeply dipping aquifers. This method is expensive since it demands drilling. An example of the use of such method may be taken from the low temperature field at Reykir in Fnjoskadalur in N-Iceland. About 7 l/s of 90°C hot water flow to the surface through 20-30 m thick sediments in a narrow walley. The Schlumberger soundings showed a north-south elongated body of low resistivity below the hot springs. The depth to the basement was too large for getting high resolution information from the ground magnetic- survey, and the rugged topography made head-on resistivity profiling impossible. Therefore, five 80-197 m deep wells were drilled along an east-west striking line crossing the hot springs. The result is shown in fig. 6. Several small aquifers were cut in the wells but most of them were associated with horizontal layers. The temperatur distribution in the wells indicates strongly two steeply dipping aquifers. A computer program which computes the temperature distribution around aquifers with known temperature has been used to establish the temperature model shown in fig. 6. According to this model the hot springs are fed by a westward dipping aquifer. Consequently deepening of well 4 was recommended. This deepening will be done in late 1982.

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