GEOTHERMAL TRAINING PROGRAMME
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Reports 2001
Number 5

POSSIBLE ENVIRONMENTAL IMPACTS OF DRILLING EXPLORATORY WELLS FOR GEOTHERMAL DEVELOPMENT IN THE BRENNISTEINSFJÖLL AREA, SW-ICELAND

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ABSTRACT

The Brennisteinsfjöll area is located in the eastern part of the Reykjanes peninsula, SW-Iceland. It is about 20 km south from Reykjavík. Geothermal activity at the surface is sparse. A low-resistivity anomaly of 10 km^2 underlain by a high-resistivity core is associated with the geothermal field. It is one of the least known high-temperature geothermal fields in Iceland. There is interest in further exploration of the area, such as deep exploration drilling, production drilling and utilization. In this report, some possible environmental impacts are analysed and potential mitigating measures are proposed. A checklist was used for identification of the key possible impacts, while for impact prediction a matrix was applied. The author suggests that a detailed plan be carried out and submitted to the Planning Agency to decide whether an environmental impact assessment (EIA) is necessary, where to construct roads and what impacts, issues, mitigation measures and public participation should be considered, before further exploration starts.

1. INTRODUCTION

A six months' fellowship was awarded to the author to participate in the United Nations University Geothermal Training Programme, at Orkustofnun - the National Energy Authority in Iceland. The training programme started April 20th 2001 with a five-week lecture course on the basic subjects of geothermics. The next seven weeks were arranged for special lectures on environmental impact. Then a project study of the environmental impact of geothermal development in the Brennisteinsfjöll area was conducted under the supervision of Dr. Halldór Ármannsson. This report is the result of the project study.

In 1999, Iceland had a population of about 279,000 (Statistics Iceland, 2000). The annual primary energy consumption in Iceland was 434 GJ per capita, which is among the highest in the world. Geothermal energy provides about 50% of the total primary energy, hydropower 18%, oil 30% and coal 2% (Ragnarsson, 2000). About 68% of the primary energy of Iceland is produced by renewable energy sources. Electricity in Iceland is mainly produced with hydropower (84.1%) and geothermal steam (15.8%), and only 0.1% by fossil fuel. The total electricity production in 1999 was 7,186 GWh. The majority of the electricity (62.4%) is used for energy intensive industries (aluminium and, to a lesser extent, ferrosilicon smelters).

For a country such as Iceland, with no coal deposits and very limited deposits of firewood and peat, geothermal resources are a significant and precious energy source. From 1994 to 1999, the total capacity of geothermal power plants in Iceland had increased from 50 MWe for electricity generation and 1443 MWt installed capacity for direct use, to 179 MWe and 1469 MWt, respectively (Ragnarsson, 1995 and 2000). The demand for geothermal energy has increased continuously in Iceland at an average rate of 7% annually, during the last 35 years. It is very important to reasonably and effectively utilize geothermal resources.

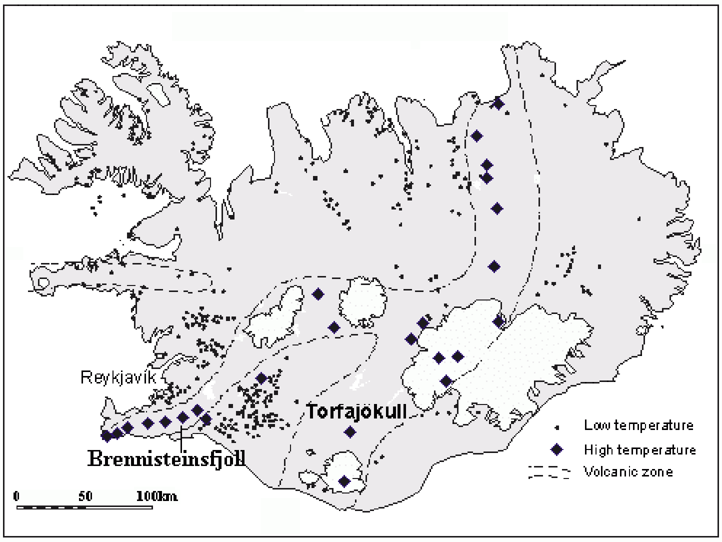

FIGURE 1: The distribution of geothermal fields in Iceland

The Reykjanes Peninsula is a product of the Reykjanes volcanic zone, which connects the Reykjanes Ridge with the volcanic zones of southern Iceland. It is, thus, a part of the global oceanic rift system of the Mid-Atlantic Ridge (Kristjánsson, 1980). Several high-temperature areas are found along the Reykjanes peninsula (Figure 1), the best known being Reykjanes, Svartsengi and Nesjavellir in the Hengill area, which have been exploited for space heating, electrical production and industry for many years. Some are unexploited and are now being explored; they are Eldvörp, Trölladyngja, Krýsuvík, Hellisheidi and Graendalur in the Hengill area and Brennisteinsfjöll. The Brennisteinsfjöll high-temperature area is located on the inner part of the Reykjanes peninsula (Georgsson, 1984). It is about 20 km southeast of Reykjavík. The city of Reykjavík and its suburbs have about 172,000 inhabitants (Statistics Iceland, 2000) and is overwhelmingly the biggest energy market.

The Brennisteinsfjöll area is situated in the east part of the Reykjanes Peninsula, SW-Iceland and is a potential high-temperature geothermal field. It is in a remote mountainous area and difficult to access. Some investigations have been done there. Jónsson (1978) mapped the geology of the area and gave detailed descriptions of the lavas. A resistivity survey was carried out in 1984 and a low-resistivity anomaly was delineated with an area of 10 km^2 (Georgsson et al., 1993). Aerial surveys with a thermal scanner were performed over the area in 1994 and 1995 (Árnason, 1995). A geological survey (Helgi Torfason, pers. comm.) has just been completed and a new geological map is being processed.

Hitaveita Sudurnesja and Orkuveita Reykjavíkur want to continue geothermal exploration in the Brennisteinsfjöll area and both have presented applications for permission to the Ministry for the Environment. An analysis of environmental impacts prior to exploration is important and necessary.

2. GENERAL INFORMATION ON THE AREA

Despite being within 20 km of Reykjavík, Brennisteinsfjöll is one of the least known high-temperature areas in Iceland. This is probably due to sparse surface geothermal manifestations and remote surroundings with almost no accessibility and no population. Fumaroles are scattered over an area of a few acres, but cold high-temperature alteration is noted at two other locations. Surface conditions are difficult; the lava terrain is generally rough with no soil and little vegetation and is only accessible on foot as no roads lead into the area (Georgsson et al., 1993).

Brennisteinsfjöll constitutes a part of the boundary between the two counties of Gullbringusýsla (in the west) and Árnessýsla (in the east). The west part of the Brennisteinsfjöll area is within the Reykjanes Country Park, the east part in the Herdisarvík Nature Reserve and the north part in Bláfjöll Country Park. The land is owned by local governments.

The surface manifestations of the high-temperature geothermal area in Brennisteinsfjöll lie at an altitude of 420-450 m. The area is in the Grindavík district, Gullbringusýsla county (Stefánsson et al., 1982). Geological strata are mostly hyaloclastites and interglacial lava covered by young lavas from historical times (after 900 A.D.).

Mr. Halldór Ármannssson, Mr. Kristján H. Sigurdsson and I drove along road number 417 and walked through the old path "Selvogsgata" southeast to Grindaskörd on August 3rd 2001. We did not see any thermal manifestations. We observed many caves with two or more floors in the rough lavas, which indicate that the young lavas have been erupted with short intervals. We also went to Lake Kleifarvatn, where there are many hot springs, mud pools and fumaroles occurring on the north shore of the lake. Sulphur crystals were deposited in the surroundings of the fumaroles. We took two samples there. These chemical analyses can be used as a reference because no samples have been collected in the Brennisteinsfjöll area.

3. HISTORICAL MINING

The name Brennisteinsfjöll means "Sulphur Mountains" and was first used in connection with sulphur mining in the middle of the 19th century. The geographical coverage of the name is unclear. It describes the southern and southeastern part of a mountain range. The area is one of the most active in the Reykjanes peninsula, both as regards crustal movement and volcanic activity. For centuries sulphur was a valuable export from Iceland. In the south there were sulphur mines in Krýsuvík and Brennisteinsfjöll. This mining was a minor industry compared with modern industry and lost out in competition with other places, when new mines were discovered in N-America with better conditions and greater resources. It seems that mining was last seriously carried out in Brennisteinsfjöll and finally terminated in the 1880's (Jónsson, 1984).

Jónsson (1984) described the sulphur mine as being located in a sloping lava northeast of Kistufell (Figure 2). The lava flowed across a high-temperature geothermal area on a gentle slope rife with sulphur springs. After that sulphur was deposited into holes and fractures in the lava and between lava layers. Therefore, it was extremely pure as it was mostly free of the clay usually formed in high temperature geothermal areas. It cannot have been very easy to mine the sulphur, as lava had to be broken up to get the sulphur and it was not known beforehand what the yield would be. There are still visible signs of the mining and it seems to have been relatively well planned, no doubt due to foreign mining experience. The mine itself is below the area where there is currently maximum geothermal activity. The easiest way to find its location is a hike from the path "Selvogsgata" northwest along "Draugahlídar", between the lava and the slope. Ruins of the miners' shack may be seen on a grassy plain a short distance above the thermal area and paths used for the transportation of the sulphur are still visible. In a fault a short distance west of Grindarskord there are signs of an ancient high-temperature geothermal area where sulphur most certainly must have been deposited. It is not known whether sulphur has been mined there and there are no signs of such mining.

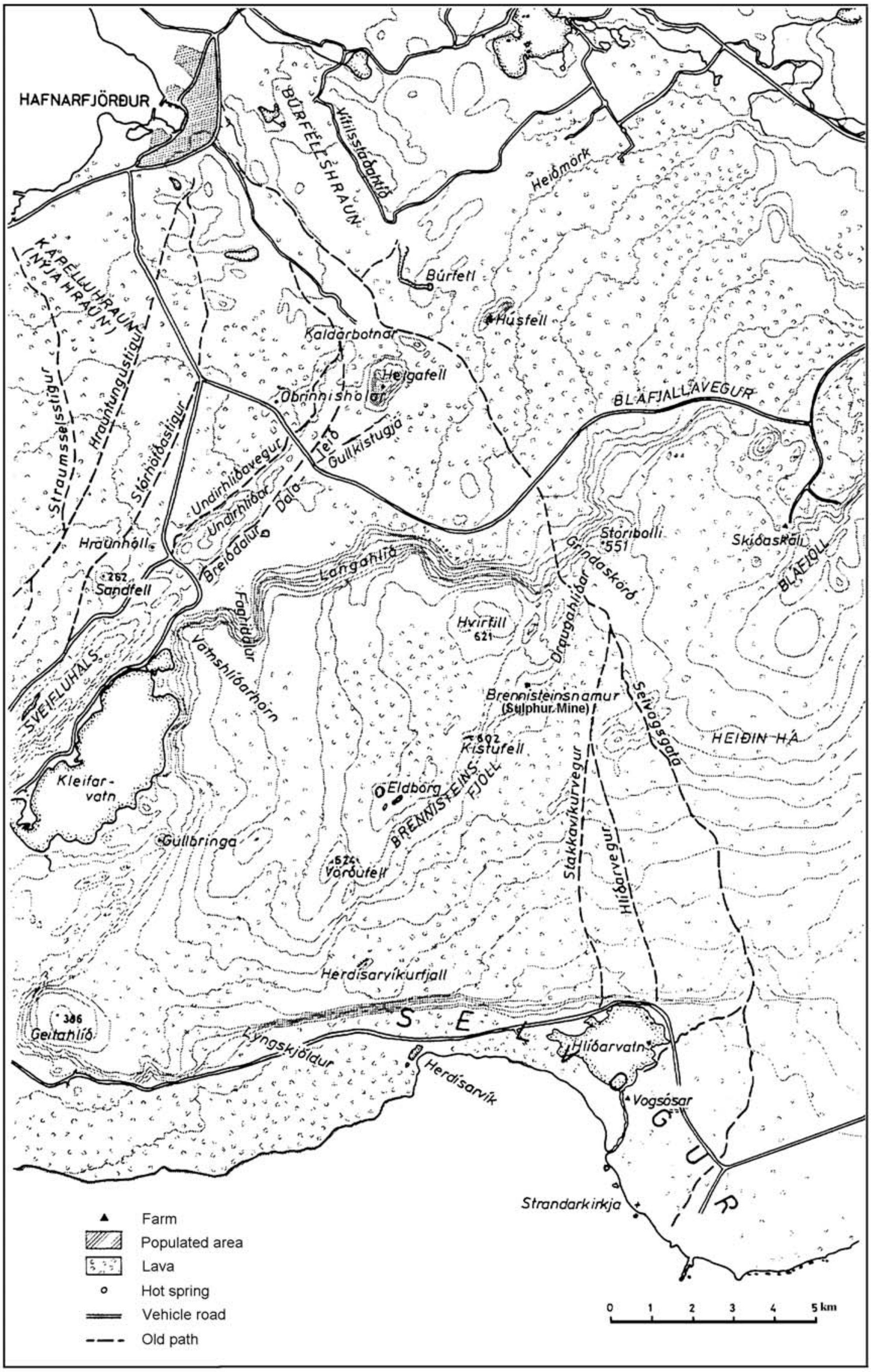

FIGURE 2: A geological map showing the location of mining and old paths (from Jónsson, 1984)

Walking to Brennisteinsfjöll is not difficult along the old path. Fishermen usually walked this way to the south in the past. Presently, some people hike along it. The ancient path from Kaldársel can be taken up across Grindarskörd. When the mountain edge is reached, there is a choice of two routes. One is along Draugahlídar to the sulphur mine and from there to Kistufell, and the other, which is more variable, past several craters south of the "Skördin" and then to the west along a fault, which is just above the edge of Draugahlídar. The subsided valley is filled with sheet lava.

4. CLIMATE CONDITIONS

Climatic data on wind speed and direction, and temperature from Keflavík airport station are shown in Figures 3 and 4, respectively. Precipitation was measured in Bláfjallaskáli (altitude 500 m.a.s.l.), from

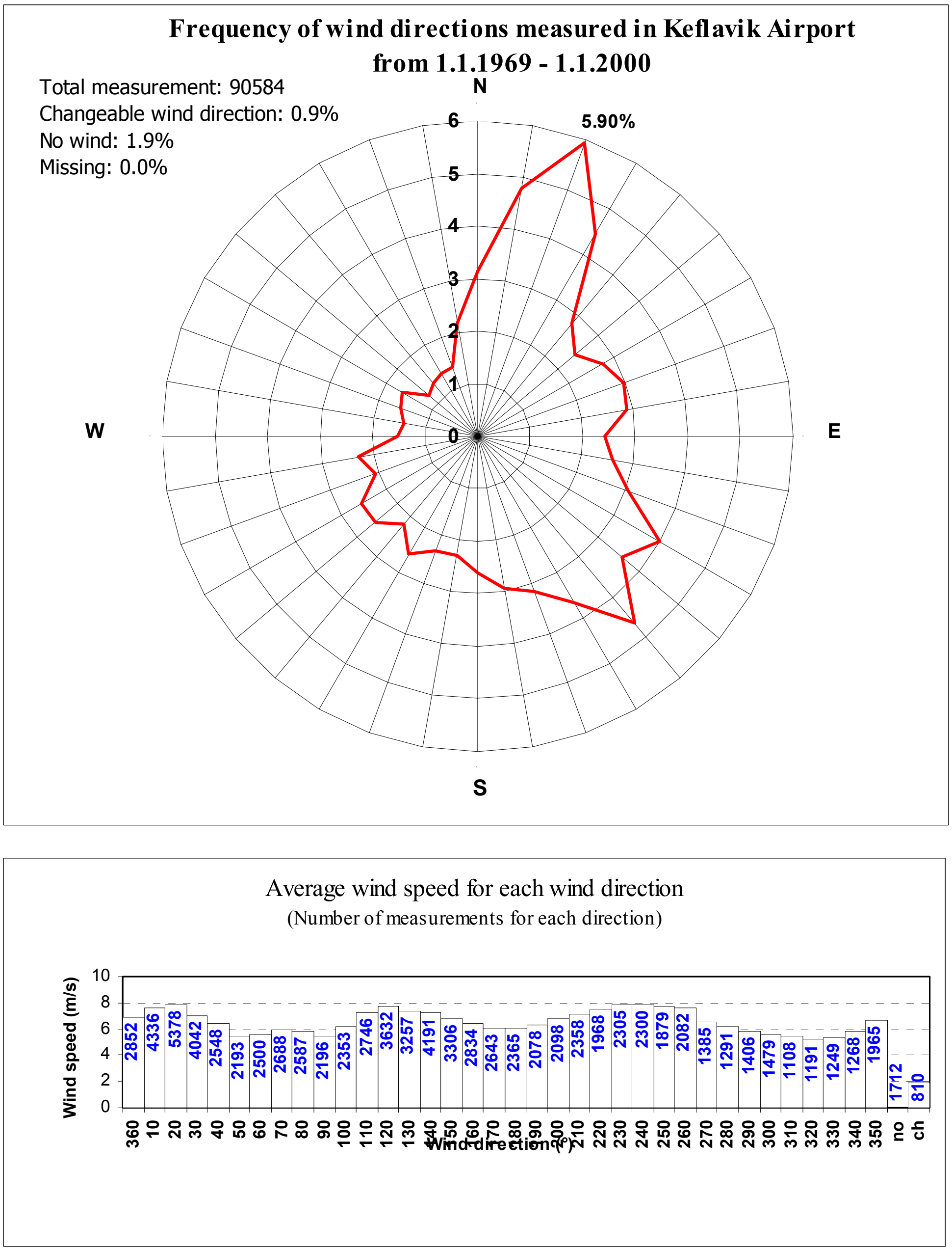

FIGURE 2: Frequency of wind directions with wind speeds
on the Reykjanes peninsula, measured at Keflavík Airport

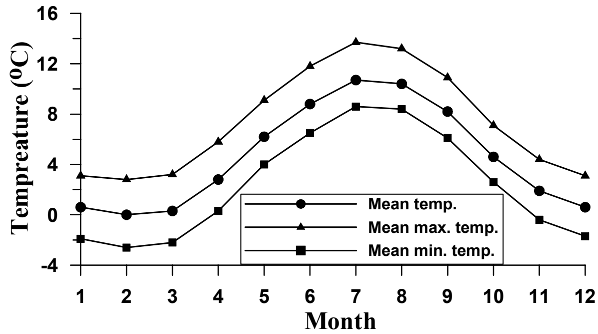

FIGURE 4: Monthly air temperatures at Keflavík Airport for the period 1.1.1991-31.1.2000

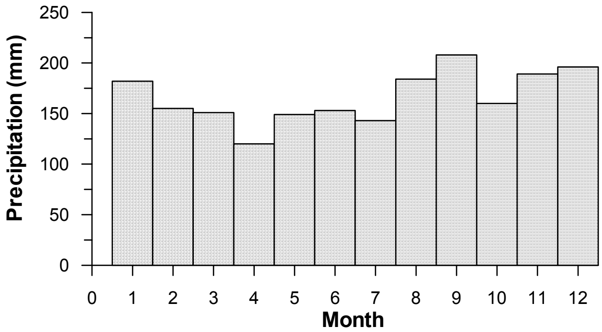

FIGURE 5: Monthly precipitation in Bláfjallaskáli during the period 1985-1997

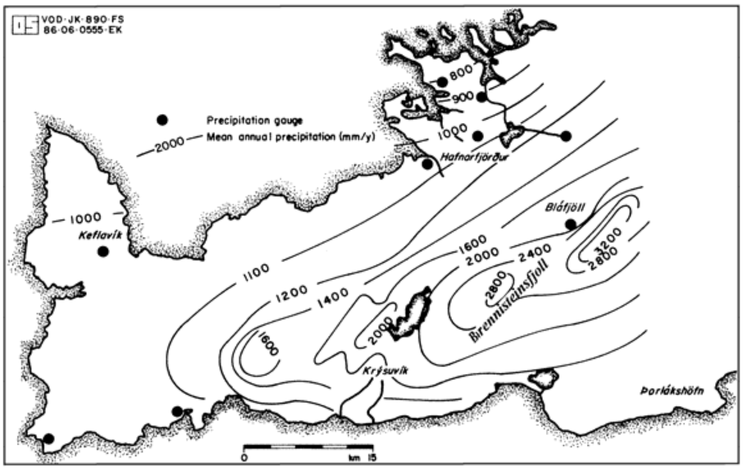

FIGURE 6: Annual precipitation rates on the Reykjanes peninsula (Sigurdsson, 1986)

1985 to 1997, with a mean annual precipitation of 2553 mm, shown in Figure 5, which might be a little higher than in the Brennisteinsfjöll area (Figure 6), because of higher elevation (about 600 m a.s.l.), and more snow during the winter. The annual mean temperature (from January 1990 to December 2000) is 4.6˚C and the maximum temperature in July, 13.7˚C, and minimum temperature in February, -2.6˚C.

5. GENERAL GEOLOGICAL CHARACTERISTICS

Iceland is located in the Atlantic Ocean, between longitudes 13˚30'-24˚32'W and latitudes 63˚24'-66˚33'N, just south of the Arctic Circle, with an area of 103,000 km^2. It lies astride a constructive plate boundary, the Mid-Atlantic Ridge, crossing Iceland from southwest to northeast. The boundary is characterized by a zone of rifting and volcanic activity, and composed entirely of volcanic lavas, breccias, tuffs and sediments derived from the volcanics. Active volcanic centres associated with fissure swarms are spread along the volcanic rift zones like pearls on a string. Due to the island's location on the plate boundary and its nature as a hot spot, the geothermal gradient is extremely high, 37-165˚C/km outside known geothermal areas. The regional heat flow on the island varies from about 80 mW/m^2 furthest away from the active volcanic zones crossing the country to about 300 mW/m^2 in some regions at the margins of the Reykjanes-Langjökull axial rift zone (Fridleifsson, 1979).

In the Brennisteinsfjöll area, geological mapping was carried out in 1978 (Jónsson, 1978). A new geological survey has just been finished and a geological map is being processed (Figure 7).

5.1 Volcanic lavas

Jónsson (1984) has described the lavas in Brennisteinsfjöll in detail. Mt. Kistufell is 602 m high with a gigantic crater on the eastern edge of the mountain and there is a steep slope from it to the southeast.

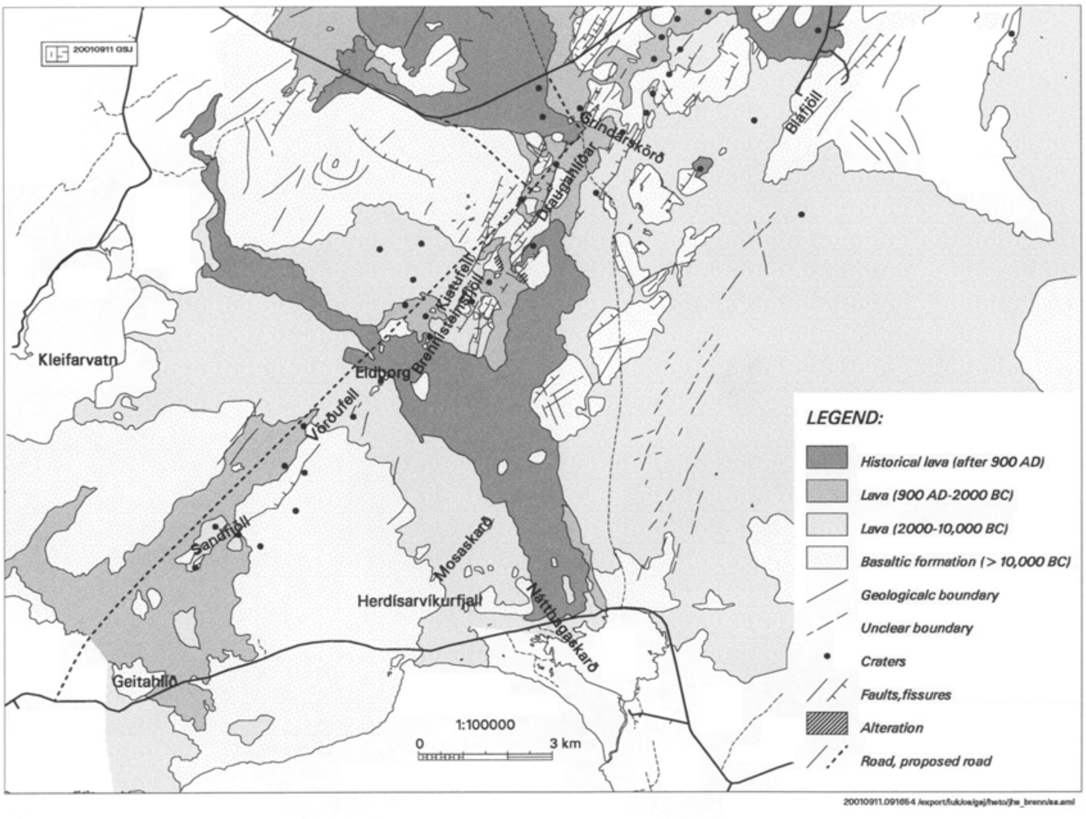

FIGURE 7: A geological map showing possible locations of roads (Helgi Torfason, in prep.)

Lavas from the crater flowed in that direction but soon disappear below younger lavas that flowed down the valley east of Brennisteinsfjöll. The crater itself is quite unique. Its upper part consists of volcanic gravel, scoria and lava splashes forming a collar around a horseshoe-shaped abyss that is surrounded by vertical columnar cliffs on three sides. Clearly a large lava lake has been present there during the eruption, which seems to have been a quiet lava eruption.

Beneath the above columnar basalt layer, irregular cube-jointed lava predominates. The columnar basalt cliffs show how far up the crater the lava lake level reached. They stand 4-6 m tall. The rock is rich in olivine and investigations show that this mineral is relatively concentrated in the lower part of the columns. It seems that the crystals sank into the molten lava during the eruption. After the eruption, when the lava lake had turned into solid rock, everything seems to have fallen into the abyss.

The main lava from Kistufell flowed to the west and, at least in two places, reached Lake Kleifarvatn. In this lava there are quite large unexplored caves; they are filled with snow most of the time so that they are difficult to enter. At least one of these caves has two floors. Openings in several places show the whereabouts of caves. Later, new lava flowed on top of caves the and lava channels from Kistufell made investigations difficult.

South of Kistufell there is a broad lava shield called Kista. It is a large volcanic edifice and very complicated. Breiddalur lava originates there. It is unsure what constitutes a specific volcano in this area. Kistufell, Kista, and Eldborg which lies a little further to the southwest, may be considered one volcano active at different times with different eruptions in different places.

Southwest of Kista a grand eruptive ridge rises and the tallest crater in the row is named Eldborg. It is among the highest peaks in Brennisteinsfjöll. From this row of craters, gigantic lava flows have fallen off the mountain, one of the main flows being to the west and into the southern part of Lake Kleifarvatn. The age of this lava is estimated as being more than 1100 years. Even so, it is obvious that the volcano is quite young because the effect of weathering on the scoria in the crater is negligible.

At the western end of Draugahlídar a high crater extends upwards, covered with a torn moss coat where what is probably the last volcanic eruption in the Reykjanes peninsula took place. An extensive lava flow fell from this crater into the valley and south along the valley east of Brennisteinsfjöll, where it has covered most older lavas. It is part of a short fissure, but has completely dominated from shortly after the start of the eruption.

5.2 Geological structures

The Reykjanes volcanic zone is oriented near to 70˚E. The eruptive fissures are situated oblique to the zone, commonly having an orientation of 30-40˚E. The hyaloclastite ridges have a similar orientation, as do the tectonic fissures and fissure zones (Figure 8). There seems to be a gradual change in the median values of the orientation from 38˚E in the western part of the peninsula to 32˚E in the easternmost part of it. In the volcanic zone more than 160 postglacial eruptive fissures or crater rows and up to 30 lava shields have been identified (Jónsson, 1978). The eruptive fissures appear in groups, forming narrow bands or volcanic strips. Brennisteinsfjöll is one of the bands with many craters orienting 30-40˚E along the fissure swarms in the same direction.

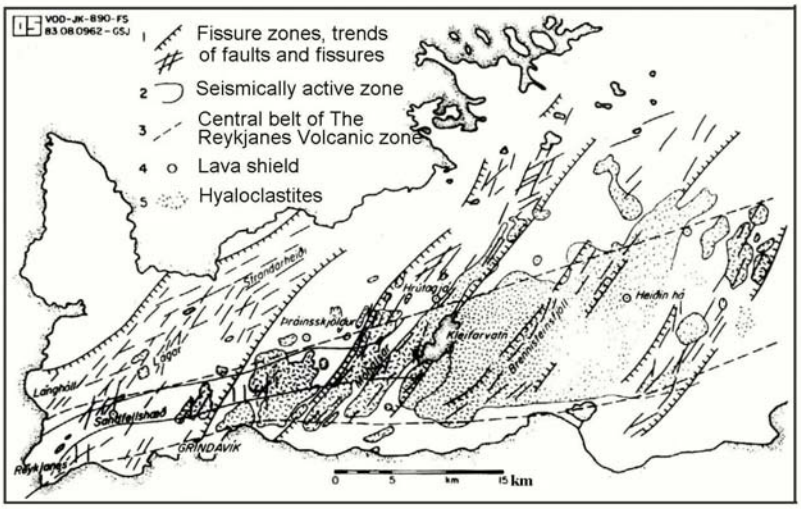

FIGURE 8: Tectonic structure of the Reykjanes peninsula (Sigurdsson, 1986)

5.3 Geothermal activity

Jónsson (1978) made detailed observations of geothermal manifestations in the Brennisteinsfjöll area. On the east side of the northern part of Brennisteinsfjöll, and 2 km north of Kistufell, there are numerous fumaroles inside lavas. They emerge from two lava flows of different ages. There is considerably greater activity within the older lava flow, but the whole active area covers hardly more than about a hectare of land. Geothermal alteration is, however, observed outside the lava just north of the thermal area. Inside the fault about 1 km further north, there is an ancient thermal manifestation with geothermal clay and sulphur and gypsum deposits where at some time there was obviously high-temperature geothermal activity, even though it was probably not extensive. This high-temperature geothermal alteration is to the north of and below a fault terrace in the southern part of the rift valley, extending to the east along the mountains south of Grindarskörd. On the slopes north of Grindarskörd, relatively high up, there is considerable geothermal alteration which seems to be connected with a local fault.

6. GAS CONCENTRATION AND CHEMICALS

The Brennisteinsfjöll geothermal field is an unexploited natural area without any industrial or other air polluting activities. Only some gases from manifestations escape to the atmosphere. The concentration of H_2S could be very high as it was a sulphur mining area, and it should be monitored.

No steam samples have been collected in the Brennisteinsfjöll area, because of few manifestations and inaccessibility. We collected two samples on the shore of Lake Kleifarvatn on 3 August 2001. The results of the analysis are shown in Table 1 and may be used as a likely composition in the absence of such data for the Brennisteinsfjöll area.

TABLE 1: Chemical composition of steam from fumaroles at the southern shore of Lake Kleifarvatn (ppm)

Sample no.	Location	CO_2	H_2S	H_2	O_2	N_2	CH_4	Ar	B	δD (‰)	δ (‰)
212a	63°54'36.0N 22°00'34.7W	28841	1249	99.27	0	6717	25.33	128.2		-54.6	-8
212b	63°54'36.0N 22°00'34.7W	18792	866	61.47	0	4224	16.32	70.72			
213	63°54'28.4N 21°59'41.4W	9053	1266	28.61	0	171.6	1.33	3.38	0.04	-52.8	-3.10

7. GROUNDWATER AND EFFLUENT WATER

In the Brennisteinsfjöll area, surface water is scarce because there are no streams due to the permeable surface lavas, but precipitation is relatively high. Some small lakes are scattered in the north. To the west, more than 20 km away, is Lake Kleifarvatn. Groundwater is abundant though as the area is situated within the centre of a fresh water lens, which is the main source of the fresh water for domestic use by Reykjavík and its suburbs. The freshwater in the western part of the Reykjanes peninsula floats on top of seawater in the rocks, like oil on water. There, the freshwater layer is relatively thin (about 50 m); farther east the rocks in the freshwater layer include more hyaloclastites and the thickness of the freshwater layer is much greater (>100 m) (Sigurdsson, 1986). The depth down to the groundwater table in the Brennisteinsfjöll area is expected to be 400-500 m.

Experience associated with the development of geothermal resources has shown that there are some impacts on the environment, although not as severe as those of conventional power plants that burn fossil fuels. The discharge of wastewater can have an impact on local and regional surface water, as well as groundwater and is considered one of the major environmental drawbacks because it can contain a variety of chemicals in suspension and solution. Many of these chemicals, such as As, Hg, Pb, Zn, B, NH_3 and S, are chemical contaminants, biologically harmful even in low concentrations, and can interfere with aquatic, animal and vegetation growth rates and reproduction processes and lead to pollution of underground water supplies. In natural geothermal features, the impact of such contaminants may be controlled by deposition near the feature or by fixation in soils and sediments. For example, mercury and arsenic are precipitated in silica sinter, and ammonia is readily taken up by soils.

8. NATURAL CONSERVATION AND PROTECTION

8.1 General

According to the Nature Conservation Act and upon suggestion from the Nature Conservation Agency, and the Icelandic Institute of Natural History or the Nature Conservation Council, the Minister for the Environment may declare protection of areas and sites if they are important for their natural characteristics, geological formations, scientific interest or beauty. Areas and sites may also be important for their biological value, special or endangered species, habitats and ecosystems and finally areas may be important for recreational use. The Nature Conservation Register was signed by the Minister for the Environment and published in section B of the Official Journal, cf. Notice no. 631/1995 concerning the Register.

The Nature Conservation Agency is a constituent institute of the Ministry for the Environment. Its main role is the protection of areas, wild plants, animals and habitats. It works in accordance with the Nature Conservation Act No. 44/1999 (Nature Conservation Agency, 2001). The primary purpose of the act is to ensure protection of the diversity of habitats, landscapes, flora and fauna in Iceland, while enhancing the nation's access to, and familiarity with, Icelandic nature by: ensuring that the interaction between man and nature does not needlessly waste or pollute life, land, sea, fresh water or air; ensuring as far as possible that the evolution of Icelandic nature follows its natural course in compliance with its own laws; protecting areas of exceptional historical or natural value; and preventing depletion or extinction of species and populations.

The Nature Conservation Agency is responsible for the daily operation of nature conservation in Iceland. Its responsibilities are quite extensive. It sees to the operation of national parks and conservation areas, and supervises the conservation of plants, nature reserves, national parks, recreation areas, and natural monuments. In its daily operation, the Nature Conservation Agency co-operates closely with local conservation committees.

The establishment of protected areas has never been as important as now. Along with the growing interest in the conservation of landscape and ecosystems, and in outdoor pursuits in unspoilt natural surroundings, there is a growing demand for the utilization of natural resources for profit, for example mining, electricity production, roads and buildings. These diverse interests are, in many cases, irreconcilable and could lead to conflicts concerning land use. There are few parts in Europe where natural and undisturbed areas are found to such an extent as in Iceland. By Notice no.184/1978, 31 species of plants are protected. The number of protected areas in the Nature Conservation Register No. 631/1995 reaches 402. The total area of protected land is 9800 km^2 (Nature Conservation Council, 1996).

8.2 International agreements

The general international trend is towards preservation of natural areas for the future and to ensure wise use of natural resources. In recent years, various international agreements which address environmental issues and nature conservation have been adopted. The main objective of these agreements is to ensure that coming generations will have natural surroundings in no worse conditions than exist at present. The international agreements, to which Iceland is a signatory and influence nature conservation and the aforementioned aims in Iceland, are notably the following (The Nature Conservation Council, 1996):

Convention on Wetlands of International Importance (Ramsar). Parties to the convention are obliged to establish protected areas in wetlands and provide satisfactory protection of such areas. Three areas in Iceland are protected under the Ramsar Convention, Thjórsárver, South Central Iceland, the Mývatn-Laxá area, NE-Iceland and Grunnafjördur, W-Iceland.

Convention on Biological Diversity (Rio de Janeiro). The necessity of conserving the natural habitats and ecosystems to protect biological diversity is dealt with in this agreement.

Convention on the Conservation of European Wildlife and Natural Habitats (Bern). Each party shall take appropriate and necessary steps to ensure the protection of habitats of wild plants and animal species, as well as endangered habitats.

Convention Concerning the Protection of the World Cultural and Natural Heritage (World Heritage). The member states shall endeavour to take appropriate steps to protect this heritage and adopt a general policy, which aims to give cultural heritage a definite role in society.

8.3 Natural protection in Iceland

Protected sites of natural interest are classified according to the Nature Conservation Act No. 44/1999 as follows:

National Park (cf. Article 51): An area of land may be declared a national park, because its landscape or biosphere is so unique, or because it has a historical significance, which gives grounds for preserving it and its natural characteristics and allows public access to it in accordance with specific rules.

Nature Reserve (cf. Point 1 of the first paragraph of Article 53): An area that is important to preserve because of its special landscape or biosphere.

Natural monuments on land (cf. Point 2 of the first paragraph of Article 53): They are natural formations, such as waterfalls, volcanoes, caves or rock outcrops, as well as locations of fossil beds, rare rocks and minerals, which are important to preserve for their scientific value, beauty or unique characteristics; *at sea* (cf. the first paragraph of Article 54): They are deemed important to preserve because of their beauty or special characteristics or they are important, from a scientific, natural historic or other cultural perspective, not to disturb.

Protected organisms, habitats and ecosystems (cf. Point 3 of the first paragraph of Article 53 and the first paragraph of Article 54): They are organisms, their habitats and ecosystems which are important, from a scientific, natural historic or other cultural perspective, not to disturb, decrease in number or eradicate, as well as natural monuments at sea.

Country Park (cf. Article 55): A specific area, which is intended for outdoor leisure and public access.

8.4 Protection operated by the local authorities in the Brennisteinsfjöll area

The protected areas are shown in Figure 9. They are Herdísarvík Nature Reserve, Reykjanes Country Park, Bláfjöll Country Park, and Eldborg in Bláfjöll and Eldborgir under Geitahlíd monuments (Egilsson, 1989).

The eastern part of the Brennisteinsfjöll area is within the Herdísarvík Nature Reserve, which was protected as a historic farm and fishing station by an announcement in Government News B, No. 121/1988, with an area of 4000 ha.

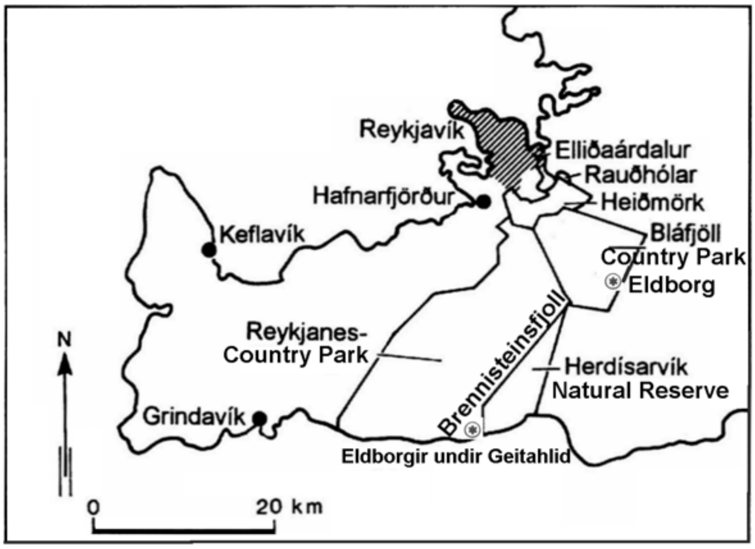

FIGURE 9: A map showing protected areas in Brennisteinsfjöll (modified from the Nature Conservation Council, 1996)

The western part is located in the Reykjanes Country Park, which was protected by an announcement in Government News B, No. 520/1975, with an area of about 30,000 ha. Variable, magnificent landscapes, numerous remarkable geological phenomena such as volcanoes and high-temperature geothermal areas characterise the park. Vegetation is in poor shape in many places due to overgrazing. The largest bird cliff in southwest Iceland, Krýsuvík Cliff, is inside the park. The area is popular for outdoor activity.

The north part is in Bláfjöll Country Park, which was protected as a country park with an announcement in Government News B, No. 97/1973. The protection terms were revised in an announcement in Government News B, No. 173/1985. The area protected is about 8400 ha, where variable, magnificent landscapes and remarkable geological formations can be seen. It is a popular outdoor activity area, especially for skiing in winter. In nearby Bláfjöll, thousands of people come skiing and the skiing season is mostly late winter, probably January to May, with March-April being most popular.

There are two natural monuments:

- Eldborg in Bláfjöll in the north, a special volcanic crater that has been protected since 1971. It became a natural monument in 1974 according to Government News B, No. 121/1974, with an area of 50 ha.
- Eldborgir at Geitahlíd in the south was protected as a natural monument according to Government News B, No. 622/1987, with an area of 10.5 ha. It is a unique, recent volcanic crater of the spatter cone type.

9. GEOPHYSICAL STUDIES

9.1 Resistivity survey

Apart from geological mapping in 1978 (Jónsson, 1978), the transient electro-magnetic (TEM) soundings survey of 1992 was the first geothermal exploration effort in the area. Sixteen soundings were carried out in a grid with about 2 km distance between soundings. The result of the TEM survey gives a very clear picture of a high-temperature geothermal area characterized by a high-resistivity core and a low-resistivity coat outside its core, similar to many high-temperature geothermal fields in Iceland (Georgsson at al., 1993). A low-resistivity (<10 ohmm) anomaly was delineated, about 10 km^2 in area at the surface, where the most intense geothermal manifestations are found about 1.5 km north of Kistufell, and elongated slightly NE-SW, along the active fissure swarm (Figure 10). It increases in areal extension at a depth of 700 m to 18 km^2 (Figure 11). Figure 12 shows a W-E cross-section through the centre of the active geothermal area, with a low-resistivity anomaly coat around a high-resistivity core. Another interesting aspect of Figure 12 is the

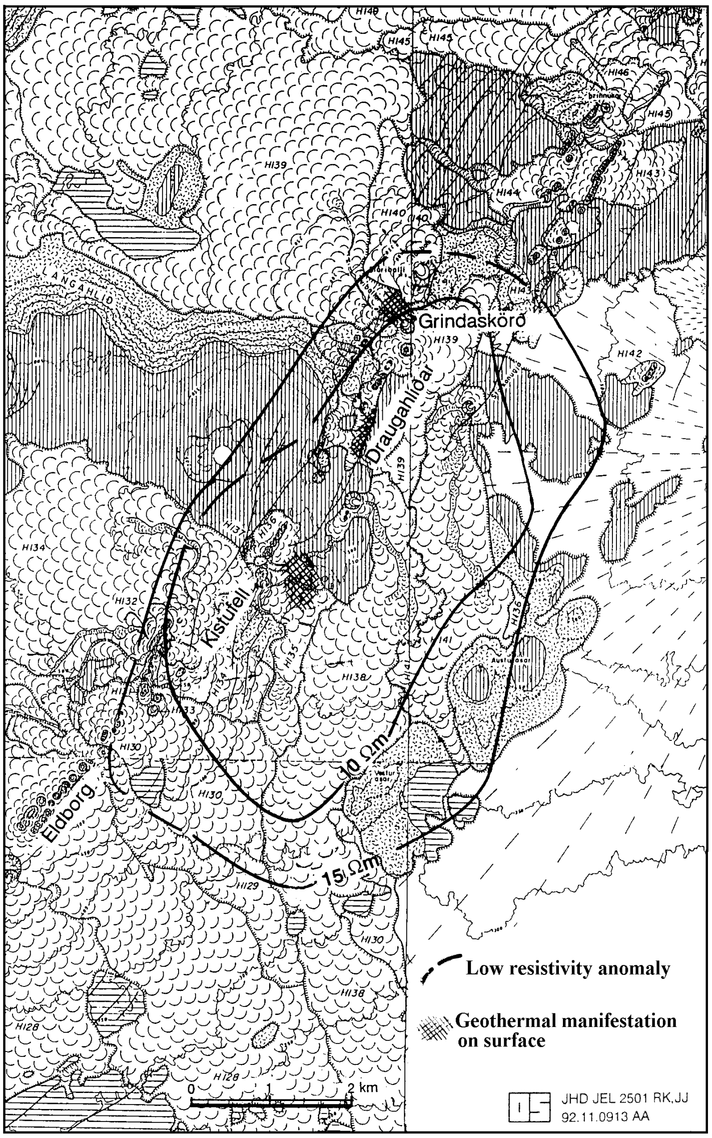

FIGURE 10: A geological map showing a low-resistivity anomaly (Karlsdóttir, 1995, modified from Jónsson, 1978)

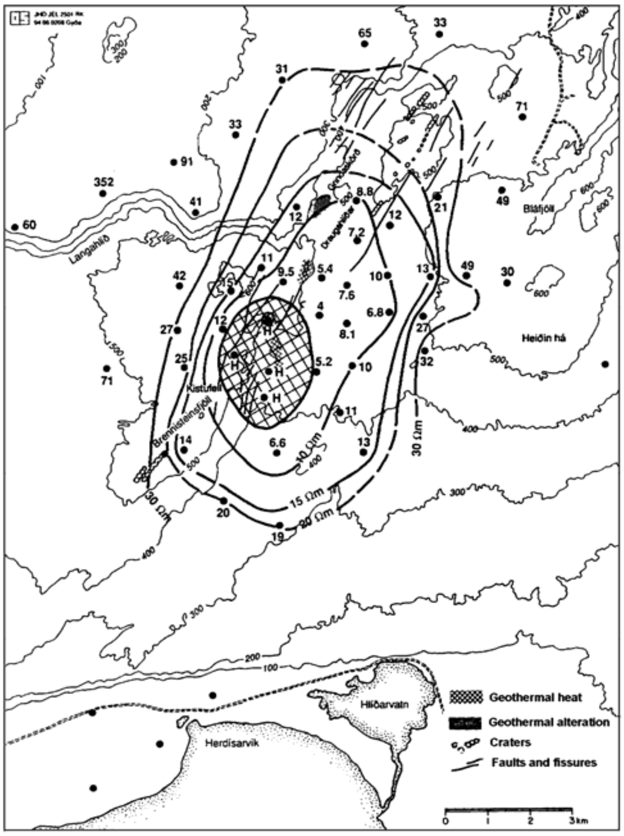

FIGURE 11: Resistivity map of the Brennisteinsfjöll area at 700 m depth below sea level (modified from Karlsdóttir, 1995)

resistivity layering. The extremely high resistivity values in the uppermost 400 m outside the geothermally active area mark the rocks above groundwater level. Below it a decrease in resistivity by two orders of magnitude is noted. At deeper levels the resistivity values drop one more order of magnitude, down to values of 20-80 ohmm. These are typical regional values for the volcanic zone (Flóvenz et al., 1985). The Brennisteinsfjöll area seems to be a typical high-temperature system with a resistive core, as is usual for Icelandic high-temperature systems.

Assuming equilibrium between the alteration minerals of the rock and the geothermal fluids at the present temperature conditions, the low-resistivity coat corresponds to the smectite-zeolite belt with a temperature of 50-200˚C. The high-resistivity core reflects the chlorite belt with a temperature of 240˚C or higher (Karlsdóttir, 1995). The most probable upflow area according to these measurements, is 1.5-2.5 km northeast of Kistufell, and the probable temperature at 700-800 m depth is 240˚C or higher, assuming equilibrium at the present temperature conditions.

The high-resistivity core suggests that the geothermal system is a freshwater system, not saturated with salt water like the geothermal systems in the westernmost part of the Reykjanes peninsula, i.e. Svartsengi and Reykjanes. Low resistivity towards south may suggest discharge from the geothermal system to the south.

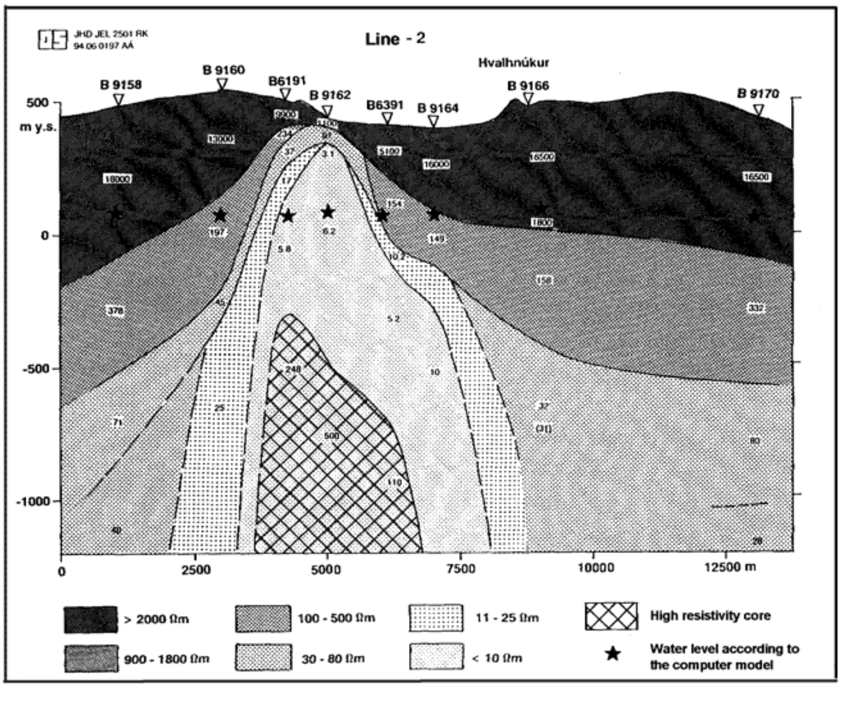

FIGURE 12: Resistivity cross-section from west to east through the central Brennisteinsfjöll area (modified from Karlsdóttir, 1995)

9.2 Remote sensing

Aerial surveys were carried out with a thermal scanner over Brennisteinsfjöll in 1994 and 1995. Surface geothermal manifestations were presented in an aerial photograph, 1.4 km long and 1.1 km wide. The geothermal manifestations are insignificant, concentrated in two weak spots with a relatively low surface temperature (Árnason, 1995). Thermal manifestations in this geothermal area are not very distinct and are confined to a small area. The thermal images show rather faint thermal features without clear-cut structures, but these images have not been studied thoroughly yet. They may include some interesting features still to be discovered (Kolbeinn Árnason, pers. comm.).

10. ENVIRONMENTAL IMPACTS

The development of geothermal energy does have some environmental impacts, most of which are associated with the exploitation of high-temperature geothermal systems. The most important environmental changes brought about by geothermal utilization are: *Surface disturbances, physical effects due to fluid withdrawal, noise, thermal effects and emissions of chemicals, both gas emissions and liquid discharge, and social and economic effects on the communities concerned* (Ámannsson and Kristmannsdóttir, 1992). In Table 2 the possibilities of environmental effects of geothermal development both for low-temperature areas and high-temperature areas are summarized (Hunt, 2000).

TABLE 2: Possibilities of environmental effects of geothermal development (after Hunt, 2000)

	Low-temperature systems	**High-temperature systems**	
		Vapour-dominated	**Liquid-dominated**
Drilling operations:			
Destruction of forests and erosion	●	●●	●●
Noise	●●	●●	●●
Bright lights	●	●	●
Contamination of groundwater by drilling fluid	●	●●	●●
Mass withdrawal:			
Effects on thermal features	●	●●	●●●
Ground subsidence	●	●●	●●●
Depletion of groundwater	○	●	●●
Hydrothermal eruptions	○	●	●●
Ground temperature changes	○	●	●●
Waste liquid disposal:			
Effects on living organisms			
surface disposal	●	●	●●●
reinjection	○	○	○
Effects on waterways			
surface disposal	●	●	●●
reinjection	○	○	○
Contamination of groundwater	●	●	●
Induced seismicity	○	○	●
Waste gas disposal:			
Effects on living organisms	○	●	●●
Microclimatic effects	○	●	●

○ No effect ● Little effect ●● Moderate effect ●●● High effect

10.1 Drilling operations

Exploitation of both low-temperature and high-temperature systems involves drilling wells to depths of 500-2500 m; this requires large drilling rigs and may take several weeks or months. For high-temperature systems the location of the drill site is important, although directional drilling techniques have reduced the total area of drill pads in recent times. The main environmental effects of drilling are discussed below.

10.1.1 Impact of access and field development

The construction of road access to drill sites may involve the destruction of forests and vegetation, which can result in erosion. Such erosion can cause large amounts of silt being carried by the streams and rivers draining the development area. The amount of land that is disturbed by road construction during geothermal development may be quite large (Brown, 1995); about 12 hectares are estimated for road construction alone when drilling 15 wells. In general, geothermal systems are often located in volcanic environments, where the terrain is steep and access difficult. Road construction in these steep situations normally involves extensive intrusion into the landscape and can often cause slumping or landslides with consequent loss of vegetation. The lack of vegetation can in turn lead to greatly accelerated erosion with the possibility of further slumping or landslides.

Most of the warm springs are located on the rim of the volcanic system or just outside it. This is a sparsely vegetated and relatively inaccessible region, which is almost devoid of vehicle tracks. The weather is frequently inclement. Winter snowfall is heavy. Therefore road construction in such a remote area is difficult, stabilization of the roads in such an environment is also difficult and land affected by development is correspondingly increased.

10.1.2 Effects of drilling operations

On a drill site, one drill pad occupies about 0.4 hectares, which should be cleared of vegetation and compacted, or the exposure of the area around each well site will create a major erosion hazard. Erosion of cut slopes takes place by runoff and slumping, but much of the sediment is deposited at the foot. Erosion of the fill slopes is more serious because of the lack of compaction and because the sediment is likely to be carried further down slope. Runoff water usually finds its way out through the fill slope, and where this is not vegetated, the potential for gully erosion is high. A drill rig is seen from afar during drilling and may be regarded as visual pollution but it is removed after drilling. Unplanned, careless and disorganized removal can cause further loss of habitat. Once the structures are removed the sites can be left to recover or be rehabilitated to achieve status comparable with the neighbouring area.

Drilling also creates noise, fumes and dust that can disturb animals and humans living nearby. Typical noise levels (in approximate order of intensity) are:

- Air drilling – 120dB (85 dB with suitable muffling);
- Discharging wells after drilling (to remove drilling debris with no muffling) – up to 120 dB;
- Well testing – 70-110 dB (if silencers are used);
- Heavy machinery (earth moving during construction) – up to 90 dB;
- Well bleeding – 85 dB (65 dB if a rock muffler is used);
- Mud drilling – 80 dB;
- Diesel engines (to operate compressors and for electricity) – 45-55 dB, if suitable muffling is used.

The characteristics of the site (e.g. its topography) and meteorological conditions will also influence noise levels. To put the above noise levels into context, 120 dB is the pain threshold (at 2-4000 Hz), noise levels in a noisy urban environment are 80-90 dB, in a quiet suburban residence about 50 dB and in a wilderness area 20-30 dB (Dipippo, 1991; Ármannsson and Kristmannsdóttir, 1992). Noise is attenuated by distance travelled in air; there is an attenuation of approximate 6 dB when the distance is doubled, but it is attenuated less at low frequencies than at high frequencies. Thus, the low rumbling noise from drill rigs and silencers travels much further than high frequency steam discharge noise.

Continuous drilling involves the use of powerful lamps to light the work site at night which can disturb local residents, domestic and wild animals.

10.1.3 Disposal of waste drilling fluid

Water is required for drilling; a typical shallow well requires 1000 m^3/day, which may be lost to the formation. A deeper well may require up to 3000 m^3/day (Brown, 1995) for periods up to several months. Completion testing and injection testing can use up to 10,000 m^3/day of water. In Iceland up to 40 l/s or 35,000 m^3 of water are required for 24 hours of drilling.

After use, drilling muds are produced as solid alkaline waste that may contain many other chemicals (Table 3, from Ármannsson, 1997). Drilling muds are either lost to the circulation in the well or end up in the drilling sumps as solid waste for disposal. A drilling mud like bentonite is mostly used when hole clearing is inadequate or when well stability is a problem.

TABLE 3: Chemical composition of bentonite and perlite (% of mass)

Material	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	LOI 1)	WS 2)	AS 3)
Bentonite	64.1	20	3.66	0.16	1.52	2.38	2.18	0.49	6.26	0.1	0.5
Perlite	73	12.5	0.7	0.1	1	0.5	4.5	4.8	1.3		

1) LOI = Loss on ignition; 2) WS = Water solubility; 3) AS = Acid solubility

As drilling takes place, cuttings from the drill head are flushed out with water, and frequently mixed with drilling detergent to assist in the collection of cuttings. The detergent used must be capable of withstanding high temperature. Bentonite drilling mud mixed with some barium is often used. If the well erupts, a heavy substance barium sulphate is usually added. This is essentially an inert material but can smother plants and does not support plant growth and is, in this respect, similar to a hard compacted surface.

If the waste fluids from drilling and testing are discharged, care must be taken to have them disposed of into a well designed for this purpose, as the quality of the waste fluids can be affected by suspended solids and change in chemical content (Brown, 1995). Otherwise, they can create serious gullying, and contaminate surface water and groundwater, if discharged directly to the surface, e.g. into valleys. This can be a problem in steep parts of an area, if proper disposal methods are not adopted.

10.2 Mass withdrawal

Large-scale exploitation of liquid-dominated high-temperature geothermal systems involves the withdrawal of large volumes of geothermal fluid. Even if all the waste liquid is reinjected, there may be a large mass loss (up to 30% of that withdrawn) associated with discharge of water vapour into the atmosphere from the power station. A major consequence of the mass loss from parts of the field is the formation of a 2-phase (steam+water) zone in the upper part of the reservoir, and as production continues, this zone increases in size and the pressures (both in and below this zone) decrease. Pressure decline in the reservoir, as a result of mass withdrawal and net mass loss, is an important cause of environmental changes at or near the surface.

Effects on thermal features. In their natural and unexploited state, many high-temperature geothermal systems are manifested at the surface by thermal features such as geysers, fumaroles, hot springs, mud pools, sinter terraces and thermal ground with special plant species. Some natural thermal features, especially geysers, will be affected during the development and initial production stages of most high-temperature geothermal systems, particularly in the liquid-dominated reservoirs, due to the decrease in pressure. But in some cases, decrease in pressure leads to increased boiling and steam formation and steam finds its way more easily to the surface than liquid water which, in turn, causes greatly enhanced fumarole activity. In the Brennisteinsfjöll area there are small surface manifestations, so this would not be a serious consideration.

Depletion of groundwater. Most high-temperature geothermal systems are overlain by a cold groundwater zone. If exploitation of the system results in a large pressure drop in the reservoir, the groundwater may be drawn down into the upper part of the reservoir in places where there are suitable high-permeability paths (such as faults); such a situation is called a cold downflow. Reservoir engineering methods should predict how much can be produced from the field to avoid this situation. The utilization of a geothermal reservoir in Iceland has never been abandoned because of depletion of the reservoir (Stefánsson et al., 1995).

Ground deformation. Withdrawal of fluid from an underground reservoir can result in the reduction of formation pore pressure, which may lead to compaction in rock formations having high compressibility and result in subsidence at the surface. Horizontal movements also occur. Such ground movements can have serious consequences for the stability of pipelines, drains and well casing in a geothermal field, buildings and the equipment of the plant, and can also break road surfaces. If the field is close to a populated area, then subsidence could lead to instability in dwellings and other buildings; in other areas, the local surface watershed systems may be affected.

The largest recorded subsidence in a geothermal field (15 m) is in part of the Wairakei field New Zealand. Subsidence in liquid-dominated fields is usually greater than in vapour-dominated fields, mainly because a much larger mass is usually drawn from liquid- than vapour-dominated fields, and also the former are often located in young, relatively-poorly compacted volcanic rocks and the latter are generally in older rocks having lower porosity.

Before exploitation, a baseline levelling survey and gravity measurements with installation of levelling stations need to be undertaken. There should be a number of separate surveys to cover as long a time as possible before exploitation so that local tectonic level changes, if any, can be subtracted from those due to exploitation.

Ground temperature changes. The formation and expansion of a 2-phase zone in the early stages of exploitation of a liquid-dominated geothermal system can also alter the heat flow. Steam is much more mobile than water; it can move through small fractures that are impervious to water and can move much more quickly through larger fractures. The generation and movement of steam can, therefore, result in increased heat flow and ground temperatures so that vegetation becomes stressed or killed.

10.3 Waste liquid disposal

Most geothermal energy developments bring fluids to the surface in order to mine heat contained within them. In high-temperature liquid-dominated geothermal fields, the volume of the resultant liquid waste involved may be large. The quantity of the waste liquid depends on the size of the plant and steam fraction. Generally, for vapour-dominated systems it is less, and for low-temperature systems it is very much less on location. The efficiency of geothermal power plants is much lower than that of other types of power plants. Waste heat per MW of electricity generated in geothermal power plants is much larger than in other types of power plants and needs to be dissipated in an environmentally acceptable way. The waste fluid is disposed of by putting it into waterways or evaporation ponds (or lagoons), or reinjecting it deep into the ground. Surface disposal causes more environmental problems than reinjection.

Environmental problems are not only due to the volumes involved, but also to the relatively high temperatures and toxicity of the waste fluid. The chemistry of the fluid discharge is largely dependent on the geochemistry of the reservoir, and the operating conditions used for power generation and will be different for different fields (Webster, 1995).

Effects on living organisms. There is a danger that high-temperature geothermal bore water may contain at least one of the following toxic chemicals: Li, B, As, H_2S, Hg, and sometimes NH_3. As untreated hot waste is released into a waterway, the increase in temperature may kill fish and plants near the outlet. Chemicals which remain in solution, if in high concentrations, may be taken up by aquatic vegetation and fish (Webster and Timperly, 1995), and some can also move further up the food chain into birds and animals residing near the river.

In many geothermal fields there are areas of steaming ground, springs, and other features where special thermal habitats have been established. The roots of most plants cannot survive temperatures much above 50˚C and, in addition, the soil in this type of ground is frequently very acidic. In these cases, only very tolerant species can survive and a unique flora may evolve. At a temperature between about 50 and 70˚C, only mosses and lichens can survive. Above this temperature, vegetation is generally absent. Changes in thermal areas, such as increased steam flow due to exploitation, may change the distribution of these thermally adapted plants with the possibility of rendering some of the species vulnerable to extinction.

Effects on waterways. The release of large volumes of wastewater into a waterway may increase erosion, and if uncooled and untreated, there may be precipitation of minerals such as silica near the outlet surface disposal.

Contamination of groundwater. Release of wastewater into cooling ponds or waterways may result in shallow groundwater supplies becoming contaminated and unfit for human use.

Induced seismicity. By their nature, geothermal fields usually occur in regions of high seismic activity and earthquakes that are not related specifically to the exploitation of the geothermal field occur naturally. Microearthquakes are seismic events that are of a very low magnitude and can only be detected instrumentally. Seismic activity seems to be present in geothermal systems whether they are being actively exploited or not, and is thought to be related to the flow of water through subsurface channels (Brown, 1995). Injection of fluids into deep formations has been recognized as a cause of seismicity, but there has been no record of geothermal production causing damaging levels of seismicity anywhere in the world, but it does frighten people. A study of monitoring microearthquake activity in Svartsengi geothermal field in Iceland showed that there were no detectable microearthquake occurrences in that field (Brandsdóttir et al., 1994). Large earthquakes have occurred in the Brennisteinsfjöll area, e.g. M=6.0, in 1968 (Tryggvason, 1973).

10.4 Waste gas disposal

One of the main effects of geothermal exploitation on the environment is the emission of gases with geothermal steam (Axtmann, 1975; Ármannsson and Kristmannsdóttir, 1992). Gas discharges from low-temperature systems usually do not cause significant environmental impacts. In high-temperature geothermal fields, power generation using a standard steam-cycle plant may result in the release of non-condensable gases (NCG) and fine solid particles (particulates) into the atmosphere (Webster, 1995). In vapour-dominated fields in which all waste fluids are reinjected, non-condensable gases in steam will be the most important discharges from an environmental perspective.

The emissions are mainly from the gas ejectors of the power station, often discharged through a cooling tower. Gas and particulate discharges during well drilling, bleeding, clean-outs and testing, and from line valves and waste bore water degassing, are usually insignificant. The concentration of NCG varies not only between fields but also from well to well within a field, thus changes in the proportion of steam from different wells may cause changes in the amounts of NCG discharged.

Gas concentrations and composition cover a wide range, but the predominant gases are carbon dioxide and hydrogen sulphide.

Carbon dioxide. Carbon dioxide frequently occurs in geothermal fluids, especially in high-temperature systems. Carbon dioxide is often the most abundant NCG. It is colourless and odourless, and is heavier than air and can thus accumulate in topographic depressions where there is still air. It is not highly toxic (c.f. hydrogen sulphide) but at high concentrations it can be fatal due to alteration of pH in the blood. A 5% concentration in the air can result in shortness of breath, dizziness, and mental confusion. At 10%, a person will normally lose consciousness and quickly be asphyxiated. There is some evidence that in high-temperature fields the amount of CO_2 discharged (per unit mass withdrawn) decreases with time as a result of de-gassing of the deep reservoir fluid, and a decline in heat transfer from the formations occurs.

Hydrogen sulphide. H_2S is characterized by a "rotten egg odour" detectable by humans at very low concentrations of about 0.3 ppm. At such concentrations it is primarily a nuisance, but as the concentration increases, it may irritate and injure the eye (10 ppm), the membranes of the upper respiratory tracts (50-100 ppm), and lead to loss of smell (150 ppm). At a concentration of about 700 ppm, it is fatal. Because H_2S is heavier than air it can accumulate in topographic depressions where there is still air, such as well cellars and the basements of buildings near the gas ejectors. The disappearance of the characteristic smell at concentrations greater than 150 ppm is especially dangerous because it leads to people failing to recognize potentially fatal concentrations. In sparsely populated areas, H_2S emissions may not prove a problem, and at many sites, there are already natural emissions from fumaroles, hot springs, mud pots, etc. H_2S emissions can vary significantly from field to field, depending on the amount of H_2S in the geothermal fluid, and the type of plant used to exploit the reservoir.

H_2S dissolved in water aerosols, such as fog, reacts with atmospheric oxygen to form more oxidized sulphur-bearing compounds; some of these compounds have been identified as components of "acid rain", but a direct link between H_2S emission and acid rain has not been established. Precipitation effectively washes H_2S from the air and the oxidation of H_2S appears to be relatively slow in air, so only a small fraction of the H_2S discharged from the geothermal fields is believed to end up as SO_2 (Kristmannsdóttir et al., 2000).

Other gases. Geothermal power stations do not emit oxides of nitrogen (NOx), which combine photo-chemically with hydrocarbon vapours to form ground-level ozone that harms crops, animals and humans. However, geothermal gases may contain ammonia (NH_3), trace amounts of mercury (Hg) and boron (B) vapour, and hydrocarbons such as methane (CH_4). Ammonia can cause irritation to the eyes, nasal passages and respiratory tract, at concentrations of 5 to 32 ppm. Inhalation or ingestion of mercury can cause neurological disorders. Boron is an irritant to the skin and mucus membranes, and is also phyto-toxic at relatively low concentrations, but these chemicals are generally emitted in such low quantities that they do not pose a human health hazard. Chemicals may also be deposited on soils and, if leached from there, they may contribute to groundwater contamination.

Effects on living organisms. The impacts of H_2S discharge will depend on local topography, wind patterns and land use. The gas can be highly toxic, causing eye irritation and respiratory damage in humans and animals, and has an unpleasant odour. Boron, NH_3, and (to a lesser extent) Hg, are leached from the atmosphere by rain, leading to soil and/or vegetation contamination (Webster, 1995). Boron, in particular, can have a serious impact on vegetation. Contaminants leached from the atmosphere can also affect surface waters and aquatic life. Details of biological impacts of these gases are given by Webster and Timperley (1995).

Microclimatic effects. Even in geothermal power schemes which employ reinjection, a considerable amount of gas (mainly steam) may be lost to the atmosphere. Such discharges of warm water vapour may have an effect on the climate in the vicinity of the power station, depending on the topography, rainfall, and wind patterns. Under certain conditions there may be increased fog, cloud or rainfall but they are unusual. Microclimatic effects are mainly confined to large power schemes in high-temperature fields; exploitation of low-temperature geothermal systems does not cause significant microclimatic effects.

10.5 Waste solids disposal

Geothermal development produces significant amounts of solid wastes. Suitable disposal methods need to be found because of the heavy metals produced (Brown, 1995). These heavy metals must be disposed of safely. Other solid wastes include drilling muds and cement not normally considered hazardous. The other principal solid waste is construction debris and normal maintenance debris. Maintenance debris can be considered hazardous due to the presence of asbestos in insulation material. Disposal of hazardous solid wastes on site is a big problem. If possible, it is advantageous to dispose of drilling muds, sludge and scale in the form of slurry into deep reinjection wells cased to protect the meteoric aquifers. If this is not possible, then total containment with no significant emissions to air, surface water or groundwater, as in landfill disposal systems, should be employed. When transporting waste, care must be taken to avoid spills. Solid waste disposal sites need to be periodically monitored and such sites could be a long-term liability.

10.6 Landscape impacts

Land use. Power plants must be built on the sites of geothermal reservoirs because long fluid transmission pipes are expensive, and they result in losses of pressure and temperature. At the site, land is required for well pads, fluid pipelines, power station, cooling towers and an electrical switchyard. The actual area of land covered by the total development can be significantly larger than the area required for these components.

Visual intrusion. A geothermal plant must be sited close to the resource, so there is often little flexibility in the location of the plant. Geothermal plants generally have a low profile, and need not have a tall stack like coal and oil fired power plants. However, their visual impact may still be significant, as geothermal fields are often situated in areas of outstanding natural beauty. Any associated natural thermal features (e.g. geysers and hot pools) may be a tourist attraction or have historical and cultural significance. Visual impact may be particularly high during drilling due to the presence of tall drill rigs.

10.7 Catastrophic events

Like any large engineering development, catastrophic events may occur during the construction and operation of a large-scale geothermal power scheme.

Landslides. For schemes in areas of high relief and steep terrain, landslides are a potential hazard. Landslides may be triggered either:

a) Naturally, by heavy rain or earthquake; or
b) As a result of construction work, which may have removed the "toe" of the slide.

In certain kinds of terrain, they place severe constraints on the placement of both wells and power plants or other facilities. Well blowouts may occur due to casing failure as a result of landslide movement. Locating well pads on islands of stable bedrock and drilling one or more slant holes from a single site makes it possible to maintain the bottom hole spacing in the producing horizons needed to adequately develop the resource while locating well heads on stable ground. The costs of necessary onsite geologic and soil stability studies, though high, are small compared with the loss of a well as the result of a blowout. Similar but more stringent considerations control the siting of power plants. The costs of slope failure either upslope from or beneath a power plant would involve much more serious losses. Limitations on the distance steam can be carried by pipeline place severe constraints on the selection of available sites (Crittenden, 1981). Such events are relatively rare but the result may be severe, such as for the landslide on 5 January 1991 in Zunil field (Guatemala), when 23 people were killed (Goff and Goff, 1997).

Hydrothermal eruptions. Although relatively rare, hydrothermal eruptions do occur and hence need to be assessed. Eruptions occur when steam pressure in the near surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected to form a crater, which varies in diameter (15-500 m) and in depth (generally less than 10 m). This happened in The Ahuachapan field in El Salvador in 1990 (Goff and Goff, 1997) and in Wairakei field in New Zealand (Hunt, 2000). Eruptions have occurred in Krafla, and Krýsuvík, south of Kleifarvatn in Iceland. In assessing the likelihood of a hydrothermal eruption hazard evidence of previous hydrothermal eruptions, increasing steam flow to the surface from reservoir pressure drawdown or an expanding steam zone are some of the factors to be considered. Other points to be considered are, shallow gas pockets, and kicks or blowouts during drilling. Drilling can also cause eruptions if the casing string is set too shallow, or if the casing develops a leak. Reinjection under pressure of fluids at temperatures >100°C also needs care as there is a possibility that such water will rise rapidly to the surface and heat the local groundwater, resulting in an eruption.

10.8 Socio-economic impacts

A socio-economic study aims to determine the changes in the conditions within the geothermal project, which have evolved as direct and indirect impacts of the project. The study provides a guide on how the geothermal project can be kept in consonance with the socio-cultural and economic situations in the area. Due to its nature, geothermal energy is frequently exploited in remote, sometimes relatively undisturbed places. A temporary increase in employment and the import of an outside workforce calling for various services may put a strain on the traditional way of life and leave a scar when the construction work is finished. The building of roads will "open up" the area and most probably make it attractive to tourists, thus creating a new industry. All such effects and solutions to possible problems should be considered in an environmental impact report prepared prior to exploitation after discussions with all involved (Ármannsson and Kristmannsdóttir, 1992).

The purpose of any socio-cultural and economic impact assessment is to determine ways to attain the social acceptability of the project. To gain social acceptability, each sector has a role to play. The proponent must facilitate public participation, the government or local authority must ensure that the benefits and burden of the project are equitably distributed and the affected sectors must weigh the quality and quantity of the benefits they will acquire as well as the costs that they will have to bear because of the project (De Jesus, 1995).

11. ENVIRONMENTAL LAWS IN ICELAND

11.1 General introduction

Environmental impact assessment (EIA) in Iceland has been carried out since May 1994. The basic law is an EC Directive from 1985 and No. 11/1997. The newest law is *Environmental Impact Assessment Act* No. 106, 25 May 2000. The Minister for the Environment is ultimately responsible for issues covered by this Act a. The Planning Agency shall advise the Minister and carry out supervision of the implementation of the Act, and provide guidelines in accordance with it. The Planning Agency shall issue a ruling on EIA of a project and its resulting activities, and decide whether a project shall be subject to EIA.

The act shall apply to all projects that may involve significant environmental effects, whether they are on land, in Icelandic territorial waters or air space, or in Icelandic pollution jurisdiction.

Projects that shall always be subject to EIA, Annex 1 are

a) Geothermal >50 MWe installed power;
b) Hydropower >10 MWt, 3 km^2;
c) Roads >10 km;
d) Overhead power lines >66 kV, or submarine cables >132 kV or >20 km, etc.

Projects considered to have significant effects on land, within territorial waters and air or in the pollution territorial of Iceland, Annex 2, criteria Annex 3, such as in protected areas, should be subject to EIA. These include the following:

a) Deep drillings, in particular;
b) Drilling of production wells and exploration wells in high-temperature geothermal regions;
c) Geothermal drilling in low-temperature areas where mineral sources or hot springs are on the surface or in the near proximity;
d) Drilling for the storage of nuclear waste material, etc.

11.2 Methods and techniques for EIA

Various techniques have been developed such as checklists, matrices, networks and overlay maps. Matrices are the most commonly used technique for impact identification and are often associated with checklists.

12. ENVIRONMENTAL ASSESSMENT FOR DRILLING

12.1 Checklist

In recent years there has been a remarkable growth of interest in environmental issues such as sustainability and better management of development in harmony with the environment. Environmental impact assessments are important and necessary before project development. A project such as deep drilling in protected areas is subject to EIA in accordance with the act. The possible environmental impacts of drilling in the Brennisteinsfjöll area are listed in Appendix I (based on Roberts, 1991). The impacts that could result if the project was implemented are also discussed where appropriate. The parts of the environment, which may be impacted or might be considered to produce cumulative effects, are included in the discussion. Since exploration is sparse, it is not realistic to estimate various needs. For impact assessment of drilling, a matrix is useful and is used for this study because it is more detailed than a mere checklist (Table 4).

12.2 Natural conditions

Land. During road construction and drill site preparation, unstable earth conditions and changes in geological substructure can occur. The Brennisteinsfjöll field terrain is steep, relatively inaccessible and almost devoid of vehicle tracks. The area is generally devoid of appropriate vegetation cover, so it is exposed to erosional agents. Also, a fresh unvegetated lava is a fairly unique natural phenomenon, which

TABLE 4: Matrix used for impact analysis for drilling

IMPACT	Execution									Operation				End	
	Road construction	Pad construction	Cable tool drilling	Transport	Water provision	Drilling	Casing	Cementing	Demobilization	Warm up	Initiation of flow	Flow rest	Logging	Final road track	Equipment
Change in landscape	Y	Y	N	N	P	N	N	N	N	N	N	N	N	Y	Y
Increased earthquake activity	N	N	N	N	N	N	N	N	N	N	P	P	N	N	N
Changes in groundwater flow	N	N	P	N	P	P	N	N	N	N	N	N	N	N	N
Changes in effluent flow to groundwater	N	N	P	N	Y	Y	N	N	N	N	N	N	N	N	N
Changes in amount of water	N	N	N	N	N	Y	N	P	N	N	Y	Y	N	N	N
Emission	N	N	N	N	N	Y	Y	N	N	N	Y	Y	N	N	N
Odour	N	N	N	N	N	P	N	N	N	N	Y	Y	N	N	N
Local climate change	N	N	N	N	N	N	N	N	N	N	P	P	N	N	N
Noise	N	N	N	N	N	N	N	N	N	N	P	P	N	N	N
Changes in vegetation	N	N	N	N	N	Y	Y	Y	N	N	Y	Y	N	N	N
Changes in fauna	P	P	N	N	P	N	N	N	N	N	Y	Y	N	N	N
Effect on outdoor amenities and tourism	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Aesthetics-appearance	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	Y
Light and glare	N	N	P	N	N	P	P	P	P	N	N	N	N	N	N

Y = Yes; N = No; P = Possibly.

will be destroyed by interference such as road construction. With high precipitation (>2500 mm annually) in the field, erosion by water is likely to be heavy when the area is opened for road and pad construction. The field is subject to a high erosion hazard as part of the area is steep with very fragile soils, which are easily erodible. Careful attention should be given to re-vegetation with grass and trees on the cut slopes, fill slopes and well pads themselves. For drilling pads in the steep part of the area, the solution to erosion and landslides will be to drill a number of directional wells from a single drilling pad. In this way a large volume of the reservoir can be tapped at depth, while requiring only a small area, which can be situated on stable land at the surface. During well testing, care should be taken not to discharge the waste water directly to steep areas. Sumps should be made to contain this waste water, as failure to do this can cause serious gullying.

Three possible roads are shown in Figure 7, the first one is in the north and extends southeast along the same way as the old path to the mountain and then turns southwest towards the area with alteration and manifestation on the surface, where drill sites may be situated. It is easy to build but it might affect people hiking this way. The second one is located to south of the first one and leads directly to the geothermal manifestation area. This road may affect more landscape than the first one but is probably the shortest way to the drill sites. If wells in the alteration area are successful and high-temperature fluid is obtained, then further drilling will be shifted to the southwest, and the third road could be constructed from southwest to northeast along the northwest slope of the Brennisteinsfjöll. This road may be as long as 10 km and may result in severe damage to the landscape.

Air. During drilling, air pollution can result from the emission of non-condensable gases, and exhaust gas from generators, compressors and vehicles. There may be objectionable hydrogen sulphide odours. During well testing, steam and spray can have an adverse effect on the vegetation with trees and grass being scalded. Hydrogen sulphide produces an unpleasant odour. Eye irritation and respiratory damage may not be of any significance, as the Brennisteinsfjöll area is not inhabited. As drilling is a temporary activity, no significant long-term impacts on air quality are expected, but long term monitoring of hydrogen sulphide, sulphur dioxide and possible heavy metals, such as mercury, in atmospheric air should be implemented.

Water. Water is required as a drilling fluid. The wells to be drilled in this area will be deep and may require at least 4000 m^3/day of water supply; during well testing, up to 10,000 m^3/day of water may be used. Fresh water wells should be drilled to supply water for drilling fluid because of the lack of surface water. The amount of water used as drilling fluid is enormous and should be discharged with utmost care into specially designed sumps or possibly re-injected, as this can affect the quality of the groundwater.

TABLE 5: A list of the high plant flora found in Brennisteinsfjöll area (H. Kristinsson, pers. comm.)

Species		Place
Common lady's-mantle	*Alchemilla glomerulans*	Brennisteinsfjöll
Alpine rock-cress	*Arabis alpina*	Kerlingaskard, Reykjanes
Alpine bistort	*Bistorta vivipara*	Brennisteinsfjöll
Lance-leaved Moonwort	*Botrychium lanceolatum*	Brennisteinsfjöll
Stiff Sedge	*Carex bigelowii*	Brennisteinsfjöll
Hare's-foot Sedge	*Carex lachenalii*	Brennisteinsfjöll
Cassiope	*Cassiope hypnoides*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Arctic Mouse-ear	*Cerastium arcticum*	Brennisteinsfjöll
Starwort Mouse-ear	*Cerastium cerastoides*	Brennisteinsfjöll
Starwort Mouse-ear	*Cerastium fontanum*	Brennisteinsfjöll
Lichen spp.	*Cladonia ecmocyna*	Brennisteinsfjöll
Lichen spp.	*Cladonia furcata*	Brennisteinsfjöll
Lichen spp.	*Cladonia uncialis*	Brennisteinsfjöll
Alpine Hair-grass	*Deschampsia alpina*	Brennisteinsfjöll
Alpine Hair-grass	*Diphasiastrum alpinum*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Rock Whitlow-grass	*Draba norvegica*	Brennisteinsfjöll
Crowberry	*Empetrum nigrum*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Alpine Willow-herb	*Epilobium anagallidifoliu*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Scheuchzer's Cotton-grass	*Eriophorum scheuchzeri*	Kerlingaskard Reykjanes
Hawkweed	*Hieracium*	Brennisteinsfjöll
Fin Dub-moss	*Huperzia selago*	Brennisteinsfjöll
Three-leaved Rush	*Juncus trifidus*	Brennisteinsfjöll
Trailing Azalea	*Loiseleuria procumbens*	Kerlingaskard Reykjanes
Curved Wood-rush	*Luzula arcuata*	Brennisteinsfjöll, Vördufell
Spiked Wood-rush	*Luzula spicata*	Brennisteinsfjöll
Dwarf Cudweed	*Omalotheca supine*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Beech Fern	*Phegopteris connectillis*	Brennisteinsfjöll
Alpine Cat's-tail	*Phleum alpinum*	Brennisteinsfjöll
Alpine Meadow-grass	*Poa alpina*	Brennisteinsfjöll, Kerlingaskard, Grindaskörd, Reykjanes
Wavy Meadow-grass	*Poa flexuosa*	Brennisteinsfjöll
Common Winter-green	*Pyrola minor*	Brennisteinsfjöll
Meadow Buttercup	*Ranunculus acris*	Brennisteinsfjöll
Roseroot	*Rhodiola rosea*	Brennisteinsfjöll, Kerlingaskard, Reykjanes
Tufted Saxifrage	*Saxifraga caespitosa*	Brennisteinsfjöll
Mossy Saxifrage	*Saxifraga hypnoides*	Brennisteinsfjöll
Alpine Snow Saxifrage	*Saxifraga nivalis*	Brennisteinsfjöll
Alpine Brook Saxifrage	*Saxifraga rivularis*	Brennisteinsfjöll, Grindaskörd, Reykjanes
Starry Saxifrage	*Saxifraga stellaris*	Brennisteinsfjöll
Slender Snow Saxifrage	*Saxifraga tenuis*	Brennisteinsfjöll, Kerlingaskard, Reykjanes
Alpine Meadow-tree	*Thalictrum alpinum*	Brennisteinsfjöll
Bilberry	*Vaccinium myrtillus*	Kerlingaskard, Reykjanes
Bog Bilberry	*Vaccinium uliginosum*	Kerlingaskard, Reykjanes
Alpine Speed Well	*Veronica alpina*	Brennisteinsfjöll
Alpine Marsh Violet	*Viola palustris*	Brennisteinsfjöll, Grindaskörd, Reykjanes

Noise. Noise is one of the most ubiquitous disturbances to the environment from geothermal development particularly during the construction and operation phases. Noise can be considered as unwanted sound and an attempt should be made to minimise this impact. Brennisteinsfjöll is in a remote area and not inhabited, but during winter many people go to Bláfjöll and ski there. It can be speculated that the effects of drilling and discharging might be greatest at that time and should probably be avoided. Noise impacts during drilling, well testing, tripping and cementing are temporary and will decline when all the wells have been drilled and tested.

Vegetation. The flora of Iceland consists of 438 species. Of these, 63% or 273 species are found in the Reykjanes country park (Kristinsson, 1984). In Brennisteinsfjöll several high-altitude species are found, which are not found in the lowland such as curved wood-rush (*Luzula arcuata*), arctic mouse-ear (*Cerastium alpinum*) and wavy meadow-grass (*Poa flexuosa*) (H. Kristinsson, pers. comm.). In general vegetation is relatively scarce in the area due to lack of soils. Although moss covers the lava fields, the carpet is broken by sharp joints, and in deep depressions where soil accumulates, species like dwarf shrubs and low herbs become frequent. On the plateau east of Lake Kleifarvatn, snow beds are frequent in the moss heath, intermingled with dwarf willows and mosses. The largest continuous heaths are in Postglacial lava fields in the Brennisteinsfjöll area. Grass species, mosses and sedges are most important in the grass-dominated heath. In general, the flora of the Reykjanes country park can be classified as follows: Mosses 45.5%, open country vegetation 11.5%, the rest 22% (grass, bush, wetland, etc.) or 78% vegetated (Thorvaldsdóttir, 1987). A list of the high-plant flora found in the Brennisteinsfjöll area is shown in Table 5 (H. Kristinsson, pers. comm.). Kristinsson (1998) lists protected plants in Iceland. None of these have been found in the Brennisteinsfjöll area.

Animal life. Wild mammals on the Reykjanes Peninsula are foxes that are rare, minks that are common, and rats and mice about which there is little information although field mice are expected to be common (Petersen and Ólafsson, 1986). On the whole peninsula at least 43 bird species are known to nest, 26 of them every year, in the cliffs at the south coast. There are few birds that nest in Brennisteinsfjöll, so there will be no impact on animals in the area as it is unlikely that drilling will take place near the cliffs.

Light and glare. Some light and glare is seen when drilling is in operation during night, but they will not be serious because the area is remote with no population and only a few hikers occasionally walk there.

Transportation. The transportation of the drill rig to Brennisteinsfjöll could be rather difficult. A popular backpacking trail passes through the northeast part of this area, which is otherwise relatively inaccessible and almost devoid of vehicle tracks. New roads need to be built, and great care should be taken to avoid distorted views as much as possible in the protected areas.

13. CONCLUSIONS AND RECOMMENDATIONS

1. The Brennisteinsfjöll area is a potential high-temperature geothermal field according to manifestations and the resistivity survey. It is one of the least known high-temperature areas in Iceland. This is probably due to minor surface geothermal manifestations and remote surroundings with almost no accessibility. It is located within protected areas. Possible environmental impacts, potential mitigation and protection measures should be taken into account before any further exploration.

2. According to EIA law in Iceland, a project involving drilling deep wells should be announced to the Planning Agency for a decision on whether it needs an EIA or not. Local authority can give permission for a single project (a single drilling hole) but it must get that approved by the Planning Agency in advance. If a company wants to carry out geothermal exploration, it should have a detailed plan of the layout of drill holes and roads.

3. Because of its location within protected areas and being inaccessible, construction of roads is needed for further exploration in the Brennisteinsfjöll area, which may cause damage to the landscape. A

permit from the Nature Conservation Agency is needed. In article 38 of the Nature Conservation Act, No. 44/1999, it is clearly written that the Nature Conservation Agency's authorisation is needed for projects where there is a risk of damage to protected sites of natural interest. The local government's authorisation must also be granted according to the planning and building act (No. 73/1997).

4. Regarding sustainable development that is defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their needs"(UNCED, 1992), some people have opposing viewpoints on geothermal development in Iceland, especially in the Reykjanes peninsula, where three high-temperature geothermal fields have already been explored and/or developed for electricity generation. Some think electricity is in sufficient supply, and developing more high-temperature geothermal fields for generating electricity is unnecessary. Why don't we let future generations decide? Public participation in a project is important and necessary. A master plan for hydro and geothermal energy resources in Iceland is now focusing on carefully thought-out decision-making (www.landvernd.is/natturuafl/).

5. The annual primary energy consumption in Iceland is among the highest in the world, which means that the waste of primary energy is also the highest. The efficiency of geothermal power plants is much lower than that of other types of power plants. Waste heat per MW of electricity generated is much larger than in other types of power plants. The question is how to effectively use geothermal resources. One way of reducing heat wastage is the cascaded use of resources as suggested by Líndal (1973). But cascaded utilization of geothermal resources has still a long way to go. It would, however, make such development in Brennisteinsfjöll more attractive, if direct use for industry or space heating was involved.

ACKNOWLEDGEMENTS

I would like to give my grateful thanks to Dr. Ingvar B. Fridleifsson, director of the UNU Geothermal Training Programme, for offering me the opportunity to participate in this special training, Mr. Lúdvík S. Georgsson, deputy director, for his helpful guidance, and Mrs. Gudrún Bjarnadóttir for her efficient help and kindness during the six months' stay in Iceland. I sincerely thank my supervisor, Mr. Halldór Ármannsson, for providing me with his patient instruction and advice and for sharing his knowledge and experience in the environmental impacts of geothermal development. I thank Mr. Hreinn Hjartarson for providing the meteorological data, Mr. Hördur Kristinsson for supplying the data on vegetation, Mr. Kolbeinn Árnason for sending me the remote sensing data, Mr. Thóroddur F. Thóroddsson for consultation on environmental law in Iceland, Mr. Helgi Torfason for the latest geological information on this area, Mrs. Gudrún Sigrídur Jónsdóttir for drawing the geological map and Mr. Kristján H. Sigurdsson for gas sampling and analyses. I would like to thank everyone who in one way or another helped me during the course of training and the preparation of this paper. I am also grateful to my UNU Fellows for mutual support over these six months.

REFERENCES

Ármannsson, H., 1997: *Reykjanes, a preliminary investigation for environmental assessment.* Orkustofnun, Reykjavík, report OS97031 (in Icelandic), 58 pp.

Ármannsson, H., and Kristmannsdóttir, H., 1992: Geothermal environmental impact. *Geothermics, 21-5/6,* 869-880.

Árnason, K., 1995: *Remote infrared temperature sensing from an aeroplane 10th Nov. 1995.* University of Iceland Information and Signal Laboratory, report UNH F95 1202 (in Icelandic), 38 pp.

Axtmann, R.C., 1975: Emission control of gas effluents from geothermal power plants. *Environmental Letters, 8*, 135-146.

Brandsdóttir, B., Einarsson, P., Árnason, K., and Kristmannsdóttir, H., 1994: *Refraction measurements and seismic monitoring during an injection experiment at the Svartsengi geothermal field in the summer 1993*. Orkustofnun, Reykjavík, report OS-94016/JHD-05 (in Icelandic), 28 pp.

Brown, K.L., 1995: Impact on the physical environment. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, 39-55.

Crittenden, M.C., 1981: Geothermal systems: principles and case histories. In: Rybach, L., and Muffler, L.J.P. (editors), *Environmental aspects of geothermal development*. John Wiley & Sons, 199-217.

De Jesus, A.C., 1995: Socio-economic impacts of geothermal development. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, 57-76.

Dipippo, R., 1991: Geothermal energy: Electricity generation and environmental impact. *Energy Policy, 19,* 798-807.

Egilsson, K. (Editor), 1989: *Natural conditions in the southern part of the Reykjanes peninsula*. The Natural History Institute, Co-operative Committee on Planning in Sudurnes, Reykjvík, 85 pp.

Flóvenz, Ó.G., Georgsson, L.S., and Árnason, K., 1985: Resistivity structure of the upper crust in Iceland, *J. Geophys. Res., 90-B12,* 10,136-10,150.

Fridleifsson, I.B., 1979: Geothermal activity in Iceland. *Jökull, 29*, 47-56.

Georgsson, L.S., 1984: Resistivity and temperature distribution of the outer Reykjanes Peninsula, Southwest Iceland. *54th Annual International SEG Meeting, Atlanta, Expanded Abstracts*, 81-84.

Georgsson, L.S., Árnason, K., and Karlsdóttir, R., 1993: Resistivity sounding in high-temperature areas in Iceland, with examples from Öxarfjördur, N-Iceland and Brennisteinsfjöll, SW-Iceland. *14th PNOC-EDC Geothermal Conference, Manila, Philippines,* 9 pp.

Goff, S., and Goff, F., 1997: Environmental impacts during development: Some examples from Central America. *Proceedings of NEDO International Geothermal Symposium, Japan,* 242-250.

Hunt, T.M., 2000: *Five lectures on environmental effects of geothermal utilization*. UNU G.T.P. Iceland, report 1, 103 pp.

Jónsson, J., 1978: *A geological map of the Reykjanes Peninsula*. Orkustofnun, Reykjavík, report OS/JHD 7831 (in Icelandic), 333 pp and maps.

Jónsson, J., 1984: On heaths and lavas. In Jónsson, Th. (Editor), *The Touring Club of Iceland Yearbook 1984 - Reykjanes west of Selvogsgata*. The Touring Club of Iceland, Reykjavík, 51-112.

Karlsdóttir, R., 1995: *Brennisteinsfjöll, TEM resistivity measurements*. Orkustofnun, Reykjavík, report OS-95044/JHD-06 (in Icelandic), 41 pp.

Kristinsson, H., 1984: On vegetation in the Reykjanes peninsula. In Jónsson, Th. (Editor), *The Touring Club of Iceland Yearbook 1984 - Reykjanes west of Selvogsgata*. The Touring Club of Iceland, Reykjavík, 113-125.

Kristinsson, H., 1998: *A guide to the flowering plants and ferns of Iceland* (2nd edition). Mál & Menning, Reykjavík, 312 pp.

Kristjánsson, L., 1980: The shelf area around Iceland. *Jökull, 29,* 3-6.

Kristmannsdóttir, H., Sigurgeirsson, M., Ármannsson, H., Hjartarson, H., and Ólafsson, M., 2000: Sulphur gas emissions from geothermal power plants in Iceland. *Geothermics, 29,* 525-538.

Líndal, B., 1973: *Industrial and other applications of geothermal energy, except poser production and district heating.* Geothermal Energy, Paris, UNESCO, LC 7297, 135-148.

Nature Conservation Agency, 2001: *Website:* www.nattururvernd.is .

Nature Conservation Council, 1996: *The Nature Conservation Register. A list of protected areas and other sites of special interest*. The Nature Conservation Council, 62 pp.

Petersen, Ae., and Ólafsson, E., 1986: Animal life in Sudurnes. In: Egilsson, K. (Editor), *Sudurnes - Natural conditions, relics and land use*. Nátturufraedistofnun, Reykjavík, report (in Icelandic), 31-48.

Ragnarsson, Á., 1995: Iceland country update. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, 1,* 145-161.

Ragnarsson, Á., 2000: Geothermal development in Iceland 1995-1999. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, 1,* 363-375.

Roberts, J.A., 1991: *Just what is EIR?* Global Environmental Services, Sacramento, CA, 209 pp.

Sigurdsson, F., 1986: Hydrogeology and groundwater on the Reykjanes peninsula, *Jökull, 36,* 11-28.

Statistics Iceland, 2000: *Statistical yearbook of Iceland, 2000*. Statistics Iceland, 320 pp.

Stefánsson, V., Axelsson, G., Sigurdsson, O., and Kjaran, S.P., 1995: Geothermal reservoir management in Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, 3,*1763-1768.

Stefánsson, V., Gíslason, G., Torfason, H., Georgsson, L.S., Sigurmundsson, S.G., and Thórhallsson, S., 1982: *A programme for exploration of the high-temperature areas of Iceland.* Orkustofnun, Reykjavík, report OS-82093/JHD-13 (in Icelandic), 176 pp.

Thorvaldsdóttir, E.G., 1987: *Flora and vegetation conditions in the Reykjanes country park*. Report prepared for the management of Reykjanes country park (in Icelandic), 141 pp.

Tryggvason, E., 1973: Seismicity, earthquake swarms and plate boundaries in the Iceland region. *Bull. Seismol. Soc. Am.*, *63*, 1327-1358.

UNCED, 1992: *The global partnership for environment and development (3-4 June, 1992)*. UNCED, Rio de Janeiro, Brazil, 16 pp.

Webster, J.G., 1995: Chemical impacts of geothermal development. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, 79-95.

Webster, J.G., and Timperley, M.H., 1995: Biological impacts of geothermal development. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, 97-117.

APPENDIX I: Environmental impact checklist for geothermal development in the Brennisteinsfjöll area

Subjects	*Exploration*			*Drilling*			*Operation*		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
1. Earth. Will the proposal result in:									
a. Unstable earth conditions or in changes in geologic substructures ?	✗			✗					✗
b. Disruptions, displacements, compaction or over covering of the soil ?			✗			✗			✗
c. Change in topography or ground surface relief features ?			✗			✗			✗
d. The destruction, covering or modification of any unique geologic or physical features ?			✗		✗			✗	
e. Any increase in wind or water erosion of soils, either on or off the site ?			✗			✗			✗
f. Changes in deposition or erosion of beach sands, or changes in siltation, deposition or erosion which may modify the channel of a river or stream or the bed of the ocean or any bay, inlet or lake ?			✗			✗			✗
g. Exposure of people or property to geologic hazards such as earthquakes, landslides, mudslides, ground failure, or similar hazards ?			✗			✗			✗
2. Air. Will the proposal result in:									
a. Substantial air emissions or deterioration of ambient air quality ?			✗		✗			✗	
b. The creation of objectionable odours ?			✗	✗			✗		
c. Alteration of air movement, moisture, or temperature, or any change in climate, either locally or regionally ?			✗			✗			✗
3. Water. Will the proposal result in:									
a. Changes in currents, or the course of direction of water movements, in either marine or fresh waters ?			✗			✗			✗
b. Changes in absorption rates, drainage patterns, or the rate and amount of surface runoff ?			✗		✗			✗	
c. Alteration to the course or flow of flood waters ?			✗			✗			✗
d. Change in the amount of surface water in any water body ?			✗	✗			✗		
e. Discharge into surface waters, or in any alteration of surface water quality, including but not limited to temperature, dissolved oxygen or turbidity ?			✗			✗			✗
f. Alteration of the direction or rate of flow of ground waters ?			✗		✗			✗	
g. Changes in the quantity or quality of ground water, either through direct additions or withdrawals, or through interception of an aquifer by cuts or excavations ?			✗	✗			✗		
h. Substantial reduction in the amount of water otherwise available for public water supplies ?			✗			✗			✗
i. Exposure of people or property to water related hazards such as flooding or tidal waves ?			✗			✗			✗

Subjects	***Exploration***			***Drilling***			***Operation***		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
4. Plant life. Will the proposal result in:									
a. Changes in the diversity of species, or number of any species of plants (including trees, shrubs, grass, crops, and aquatic plants) ?			✗			✗		✗	
b. Reduction of the numbers of any unique, rare or endangered species of plants ?			✗		✗			✗	
c. Introduction of new species of plants into an area, or in a barrier to the normal replenishment of existing species ?			✗			✗		✗	
d. Reduction in acreage of any agricultural crop ?			✗			✗			✗
5. Animal life. Will the proposal result in:									
a. Change in the diversity of species, or number of any species of animals (birds, land animals such as reptiles, fish and shellfish, benthic organism or insects) ?			✗			✗		✗	
b. Reduction of the numbers of any unique, rare or endangered species of animals			✗			✗		✗	
c. Introduction of new species of animals into an area, or a barrier to the migration or movement of animals ?			✗			✗		✗	
d. Deterioration to existing fish or wildlife habitat ?			✗			✗			✗
6. Noise. Will the proposal result in:									
a. Increases in existing noise levels ?			✗	✗			✗		
b. Exposure of people to severe noise levels ?			✗			✗			✗
7. Light and glare. Will the proposal produce new light or glare ?			✗	✗			✗		
8. Land use. Will the proposal result in a substantial alteration of the present or planned land use of an area ?									
Present :			✗			✗	✗		
Planned :			✗			✗	✗		
9. Natural resources. Will the proposal result in:									
a. Increases in rate of use of any natural resources ?			✗	✗			✗		
b. Substantial depletion of any nonrenewable natural resources ?			✗			✗			✗
10. Risk of upset. Will the proposal involve:									
a. A risk of an explosion or the release of hazardous substance (including, but not limited to, oil accident, chemical or radiation) in the event of an accident or upset conditions ?			✗			✗			✗
b. Possible interference with an emergency response plan or emergency evacuation plan			✗			✗			✗

Subjects	***Exploration***			***Drilling***			***Operation***		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
11. Population. Will the proposal alter the location, distribution, density, or growth rate of the human population of an area ?			✗	✗			✗		
12. Housing. Will the proposal affect the existing housing, or create a demand for additional housing ?			✗	✗			✗		
13. Transportation/circulation. Will the proposal result in:									
a. Generation of substantial additional vehicular movement ?		✗		✗			✗		
b. Effects on existing parking facilities, or demand for new parking ?			✗	✗			✗		
c. Substantial impact upon existing transportation systems ?			✗	✗			✗		
d. Alteration to present patterns of circulation or movement of people and/or goods ?			✗	✗			✗		
e. Alteration to waterborne, rail or air traffic ?			✗			✗			✗
f. Increase in traffic hazards to motor vehicle, bicyclists or pedestrians ?			✗	✗			✗		
14. Public services. Will the proposal have an effect upon, or result in a need for new or altered governmental services in any of the following areas:									
a. Fire protection ?			✗			✗			✗
b. Police protection ?			✗			✗			✗
c. Schools ?			✗			✗			✗
d. Parks or other recreational facilities ?			✗			✗			✗
e. Maintenance of public facilities, including roads ?			✗	✗			✗		
f. Other governmental services ?			✗			✗		✗	
15. Energy. Will the proposal result in:									
a. Use of substantial amounts of fuel or energy ?			✗	✗			✗		
b. Substantial increase in demand upon existing sources of energy, or require the development of new sources of energy ?			✗			✗			✗
16. Utilities and service systems. Will the proposal result in a need for new systems, or substantial alterations to the following utilities:									
a. Power or natural gas ?			✗			✗	✗		
b. Communications systems ?			✗			✗			✗
c. Water ?			✗	✗			✗		
d. Sewer or septic tanks ?			✗		✗		✗		
e. Solid waste and disposal ?			✗	✗			✗		
17. Human health. Will the proposal result in:									
a. Creation of any health hazard or potential health hazard (excluding mental health)			✗	✗			✗		
b. Exposure of people to potential health hazards ?	✗			✗			✗		

Subjects	Exploration			Drilling			Operation		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
18. Aesthetics. Will the proposal result in the obstruction of any scenic vista or view open to the public, or will the proposal result in the creation of an aesthetically offensive site open to public view ?			✗			✗		✗	
19. Recreation. Will the proposal result in an impact upon the quality or quantity of existing recreational opportunities ?			✗	✗			✗		
20. Cultural resources. Will the proposal:									
a. Result in the alteration of or the destruction of a prehistoric or historic archaeological site ?			✗			✗			✗
b. Result in adverse physical or aesthetic effects to a prehistoric or historic building structure, or object ?			✗			✗			✗
c. Have the potential to cause a physical change which would effect unique ethnic cultural values ?			✗			✗			✗
d. Restrict existing religious or sacred use within the potential impact area ?			✗			✗			✗
21. Mandatory finding of significance.									
a. Does the project have the potential to degrade the quality of the environment, substantially reduce the habitat of a fish or wildlife species, cause a fish or wildlife population to drop below self-sustaining levels, threaten to eliminate a plant or animal community, reduce the number or restrict the range of a rate or endangered plant or animal or eliminate important examples of the major periods of history or prehistory ?			✗			✗			✗
b. Does the project have the potential to achieve short-term, to the disadvantage of long-term, environmental goals ? (A short-term impact on the environment is one which occurs in a relatively brief, definitive period of time while long-term impacts will endure well into the future.)			✗			✗			✗
c. Does the project have impacts which are individually limited, but cumulatively considerable ? (A project may have a relatively small impact on each resource, but the effect of the total of those impacts on the environment is significant.)			✗			✗			✗
d. Does the project have environmental effects which will cause substantial adverse effects on human beings, either directly or indirectly ?			✗			✗			✗