LV-2015-098

Landsvirkjun

The Krafla Geothermal System

Research Summary and Conceptual Model Revision

Key Page

LV report no:	LV-2015-098	**Date:**	October 2015
Number of pages:	197 **Copies:**	**Distribution:**	☐ On www.lv.is ☒ Open ☐ Limited until

Title: The Krafla Geothermal System Research summary and conceptual model revision

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Abstract: The name of the report "The Krafla Geothermal System Research summary and conceptual model revision," says a lot about the content. The report discusses the vast amount of geothermal research that has been carried out over the past 40 years. The report discusses how the effects of the of the volcanic activity at Krafla are intertwined with the drilling and production history. Plans to increase the producion from the Krafla system by 150 MW led to a necessary review of historical data and additional studies. The conceptual model was reviewed with the intent of getting a more concise overview of the characteristics of the Krafla system, and a volumetric resource assessment was prepared at the same time to get a rough estimate of the production capacity. The extent of the Krafla geothermal system is estimated at some 40 km2 based on resistivity studies. The geothermal system is considered powerful and shallow magma chambers with multiple magmatic intrusions are considered the main heat sources of the system. The location of Krafla, at the center of the rift zone, increases the probability of high permeability, but highly anisotropic geology is the cause of very variable conditions within the reservoir. The results of a conservative volumetric estimate probabilistic Monte Carlos simulation indicate that the production capacity of the reservoir is 150 MW over a 50 year project life, with 90% certainty. Thus, the proposed power increase is justified. This result is in good agreement with annual reservoir survailance and an previous reservoir simulation models. Several things have not been considered in these reservoir models, e.g. the effects of magmatic gases, higly anisotropic permeability, drawdown and temperature.

Keywords: Krafla, conceptual model, geothermal system, volumetric model, geothermal resource assessment

ISBN no:

Samþykki verkefnisstjóra Landsvirkjunar

Skýrsla nr. LV-2015-098

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October 2015

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1 Introduction

The Krafla area in the Suður-Þingeyjasýslu county of Iceland is a well-known volcanic and geothermal area. Research on the feasibility of utilising the geothermal resource within the area began in 1969, in accordance with the research plan on high temperature areas in Iceland associated with Sveinbjörn Björnsson (1969). The first results were published in a research report by Guðmundur Guðmundsson (et al.) in 1971. The report showed the total surface area of the research area to be 280 km^2 and the main focus was an analysis of the Krafla and Námafjall areas. An aeromagnetic map was completed and the temperature of the geothermal system was estimated to be between 200 and 300°C. A resistivity survey was conducted in the area between 1971 and 1972 (Guðmundur Guðmundsson et al. 1971; Ragna Karlsdóttir et al. 1978).

The next few years proved to be a watershed period for the Icelandic energy industry as the proposed expansion of the Laxá Hydropower Station was met with great protest. Expansion plans were discontinued and new potential power projects were investigated in the northeast of Iceland. Krafla was chosen as the site for the development of the first geothermal power station for electricity generation purposes in Iceland. The first two exploration wells were drilled at Krafla in 1974 to a depth of 1200m and production drilling began a year later. The National Energy Authority published the results on exploration drilling that same year (Kristján Sæmundsson et al. 1975). The report contained the first interpretation of data on the geothermal reservoir at Krafla and, subsequently, a decision was made to build a 60 MW_e geothermal power station. Production drilling and construction began concurrently in 1975 but extensive volcanic activity in the area resulted in the onset of the Krafla Fires later that same year. Construction work, research and drilling continued for the next few years despite volcanic activity. Six production wells were drilled in 1976 and well logging and surface exploration was conducted in the area. Important information was gathered on the area including the fact that the Leirbotnar area has a dual (two layer) geothermal system with differing production characteristics. Magmatic gases had invaded the deeper system with unpredictable results.

Construction work was completed in 1977 and the first conceptual model of the geothermal system was introduced that same year (Valgarður Stefánsson et al. 1977b). The Krafla Geothermal Power Station began production in the following year and initially only produced 7 MW_e for the electricity network. Another well was drilled for steam extraction purposes. Various problems associated with steam extraction and the effects of volcanic activity on the geothermal system in the area resulted in extensive research on the chemical composition of gases in the natural steam flow in the Krafla area. Samples were taken from most fumaroles or geothermal emission points, wherever practical. Results from the research revealed that the Krafla area could be divided into sub-regions depending on the ratio of gases in its natural emissions (Gestur Gíslason et al. 1978; Halldór Ármannsson et al. 1981). These sub-regions included Leirbotnar (including Vítismór), Hvíthólar and Suðurhlíðar; the two latter areas remained unaffected by magmatic gases. Thirteen wells were drilled between 1980 and 1983, two of which were drilled using directional drilling methods. One of the turbines at Krafla reached full capacity a year later, producing 30 MW_e, with excess steam to spare. The installation of a second turbine unit was not considered a viable option at the time due to difficulties encountered with steam extraction.

RARIK (Iceland State Electricity) handed the operation of Krafla Geothermal Power Station over to Landsvirkjun at the beginning of 1986. Maintenance projects and small-scale research continued for the next few years but a new research period began between 1990 and 1993. Two exploration wells were drilled (KG-25 and KG-26) to assess if conditions within the deeper zones of the geothermal system had improved. Resistivity measurements were conducted using the TEM method (the method had previously been successfully used at Nesjavellir). The diminishing effects of magmatic gases on the geothermal system resulted in the decision to continue the development of the Krafla Geothermal Power Station by installing the second turbine (turbine 2), therefore doubling the capacity of the station. Drilling for the steam required by turbine 2 began in late 1996 and eight production wells had been successfully drilled by 1999. The overall result was positive and Krafla became fully operational in 1999.

The decision to conduct measurements on the entire Krafla caldera, using TEM-resistivity measurements, was approved in the year 2000. Plans to expand Krafla by 40MW were also developed during this same period and the project design and Environmental Impact Assessment (EIA) were completed the following year. The project was then put on hold as the national electricity grid did not require additional power at that time.

A milestone was reached in operations in 2002 when reinjection measures began by reinjecting 50–70 kg/s of separated brine into well KG-26 at a depth of 2000m. Chemical scaling inhibitor equipment was installed in well KJ-28 (a shallow zone well) to prevent calcium deposits from forming within the well when active. This was the first time that this type of equipment had been installed in a high temperature well in Iceland.

Plans for the expansion of Krafla and/or the construction of an additional power station have been under preparation for some time. A three year plan for research on geothermal areas in the Krafla Þeistareykjir, Bjarnarflag and Gjástykki areas was introduced in 2006 with the purpose of assessing the feasibility of producing the 400 MW_e of electricity required by the proposed aluminium smelter at Bakki by Húsavík. Landsvirkjun employed the services of Iceland Geosurvey (ÍSOR) to (i) re-assess the conceptual model for the Krafla area, (ii) assess the overall capacity of the area using the volumetric method and simplified models, and (iii) improve and re-calibrate the ten year old computational model of the geothermal system. This report shows the results for the first part of the project and the results of the volumetric assessment on potential capacity.

The term 'conceptual model' refers to the coordinated collection of ideas, pertaining to the type and nature of the geothermal system, built on all available data from the geothermal system in question at any given time. In short, a model of this type should provide information on the heat source of the geothermal system, the upflow of geothermal fluid and fluid-flow conduits. A conceptual model is a necessary foundation for the set-up and creation of computational models and also increases knowledge on the structure and nature of the geothermal system. Developing a conceptual model of a geothermal area requires the analysis of all available data, the interpretation of those data and an analysis of the context. The main data available from the Krafla area and utilised to develop a conceptual model included the following:

- Surface geology, including data on geological features, geothermal energy and fissures
- Geophysical surface exploration including resistivity measurements such as TEM and MT measurements. Magnetic surveys, both at the surface and aeromagnetic measurements as well as gravity- and geodetic surveys
- The chemical composition of water and steam from natural emissions
- Location of micro earthquakes in the last decades
- Borehole/well geology based on drill cuttings analysis and well logging
- Temperature and pressure measurements in wells as well as information on the main feed- zones
- Well tests: including step tests performed as part of the drilling program and discharge tests
- Measurements on temperature and pressure changes in the geothermal system over time (as a result of utilisation)
- The chemical composition of samples from geothermal fluid (in wells) and any changes to this as a result of utilisation
- The effects of utilisation on the energy reserve and lifetime of the area

The main results of the re-assessment of the conceptual models of the Krafla geothermal system are intended to show the following:

- The strata sequence of the area, possible fissures, faults and any other factors that could affect the flow of geothermal fluid in the geothermal system
- Initial temperature and pressure conditions
- The division of the area into sub-systems, based on the chemical composition of fluid and steam and other factors
- The location of upflow and downflow into the geothermal system
- The size of the area, both surface area and thickness
- Assessment of permeability, porosity and other characteristics
- Boundary conditions for numerical modeling
- The effects of reinjection and utilisation within the geothermal system

The first conceptual model was introduced by Valgarður Stefánsson et al. (1977b) and was based on limited data, mostly surface exploration and the results from the first eleven wells drilled in the area (Valgarður Stefánsson, 1980; 1981). Guðmundur S. Böðvarsson et al. (1982; 1984b) developed the next conceptual model which gave a much more comprehensive picture of the geothermal system, based on results from extensive drilling in the preceding years. It could be said that the latter conceptual model is still valid today. In 1988, the SHAFT-79 model of the Hvíthólar area (in the Krafla area) was introduced (Helga Tulinius & Ómar Sigurðsson, 1988) and this included wells KJ-21, KJ-22 and KJ-23. The model was two-dimensional. Work on a three-dimensional TOUGH model of the same area began between 1990 and 1991 (Helga Tulinius & Ómar Sigurðsson, 1991). A revised and more accurate conceptual model was introduced in connection with the development of a numerical model of the geothermal system 1996–1997 (Grímur Björnsson et al. 1997a).

Extensive research has also been conducted on the Krafla Fires: on the volcanic system, fissure swarms formed to the north and south and tectonic deformations in connection with volcanic activity (Gunnar V. Johnsen et.al 1980; Páll Einarsson, 1991; Kristján Sæmundsson, 1991; Axel Björnsson & Hjálmar Eysteinsson, 1998). This research has enriched expertise on the type and nature of the Krafla geothermal system.

According to historical volumetric assessments, approx. 590 PJ (PJ = 10^{15}J) can be utilised in Krafla which would be equal to 380 MW_e in 50 years or 190 MW_e in 100 years (Guðmundur Pálmason et al. 1985; Sveinbjörn Björnsson, 2006). The review of volumetric assessments outlined in the following chapters is based on the most recent information, pertaining to the size and temperature conditions of the geothermal system as well as the use of the Monte Carlo simulation method. This results in a probability distribution for the estimated production capacity of the area and margins of uncertainty are defined.

The numerical modeling of the Krafla geothermal system from 1997 (Grímur Björnsson et al. 1997a) will be reviewed and re-calibrated (as a follow-up from the development of the conceptual model and volumetric assessments) to more accurately assess the capacity and its response to utilisation. The review will be based on the conceptual model outlined here as well as all available information on the response of the area to active wells and to utilisation (from the outset).

However, the numerical model is now 10 years old and the results could show that it would be pertinent to completely re-develop a model (various work pertaining to data preparation etc. would be beneficial) but this remains to be seen. It is likely that the *TOUGH2/iTOUGH2* computer programs will be used for numerical modeling.

The Krafla geothermal system is large and energy rich and its location in the middle of the volcanic zone create high permeability within the system. These three factors should ensure a high capacity within the Krafla system but technical problems due to the chemical composition of geothermal fluid mean that the area cannot be fully utilised using current production methods. The close proximity to magma is believed to be the reason for this, the same magma that feeds the energy system. These technical problems will not be further discussed in this report.

2 Geology and geothermal surface manifestations

The Krafla area has all the characteristics of a typical central volcano. An extensive dome has developed from the basaltic lava, up to 20km in diameter. The oldest rock in the area dates back approx. 300,000 years. In the middle of this formation is a caldera, 8x10 km in size, which is surrounded by silicic tuff layers, both of which were formed approx. 110,000 years ago (Figure.1). Eruptions of basalt and rhyolite have occurred in the curved fissures outside the caldera. A large geothermal area trends east to west, traversing the mid-section of the caldera. The temperature is highest to the east of the mid-section and coldest close to the periphery. Rhyolite has erupted on the eastside of the caldera in the fissures that trend north- to- south under the glacier and during silicic pumice eruptions once the glacier had disappeared. Phreatic explosions occurred during the glacial period in the area. Traces of these include two crater rows, one in the west-side of Hrafntinnuhryggur and the other in the west-side of Krafla. Craters that lie outside Krafla are approx. 300–400 m in diameter. The volcanic materials in this area are unknown. Steam explosions from the geothermal system are likely to have hollowed out the craters. The caldera is mostly filled with hyaloclastite(s)/ palagonite(s) and lava from its own eruptions. Lava has also flowed out of the caldera via mountain passes on the north, on the east and west side. A fissure swarm traverses the central volcano. Its direction is N5-10°E north of the caldera and N15°E to the south. It is over 90 km in length and extends at least 50 km to the north of the mid-section of the caldera and approx. 40 km to the south of it. Its widest point is through the caldera (7-8 km) and it then becomes dissected towards the south. The fissure swarms can be divided into 'east flank' and 'west flank' fissure swarms (Kristján Sæmundsson, 1991). The east flank is 4 to 5 km in diameter, traversing the mid-section and eastside of the caldera. The west flank is approx. 3 km in diameter and is located in the most western point of the caldera.

Post-glacial activity has been divided between the two fissure swarms over time. The west flank was active during the late Weichselian glacial period. Andesitic lava flowed in the western part of the caldera and maars (steam explosion craters) were formed (Krókóttuvötn). The east flank then took over during the post-glacial period (8000-11,000 years ago) with lava eruptions from fissures and pumice eruptions (Hveragil). The activity shifted westward approx. 8000 years ago and remained in this area for 5000 years. There was one eruption during this extended period with small-scale lava eruptions and a maar (steam explosin crater) at Hvannstóð. The east flank has been active for the last 3000 years with six rifting events followed by volcanic activity, lava eruptions from fissures, pumice eruptions (Víti) and maars (steam explosin crater). The eruptions occurred at irregular intervals.

Rifting in the fissure swarm, in the period that has passed since the caldera was formed, has affected the direction of the drift. It is unclear how the drift has spread within the volcanic systems opposite Krafla but it is likely that the activity at Krafla is responsible for at least half of this.

Curved eruptive fissures are present in the northeast of the caldera and on the periphery of that side (Figure 1). They are signs of cone sheets (intrusions) from the shallow magma chamber. The shape of the geothermal area and its ultimately diminishing activity can be traced to intrusion activity in the magma chamber beneath the mid and eastern section. Continuous rifting episodes in the system caused the intrusion mass to disperse and cool but a limited amount was renewed. An analysis of earthquake activity revealed a magma chamber at a depth of between 3 and 7 km in the east-western belt in the mid-section of the caldera (Páll Einarsson, 1978). There is a close correlation between this and surface manifestations. The magma chamber is most active beneath the east flank (fissure swarm) at Krafla. Some of the most recent silicic or felsic eruptions have taken place in this area as well as a number of fissure eruptions in the last 3000 years. This area has the most extensive geothermal activity and surface alteration. It is unclear if the geothermal activity is connected with the curved eruptive fissures referred to earlier but extensive scoria productivity in the crater area could indicate a connection. Geothermal activity is evident in the southern periphery of the caldera as well as evidence of alteration between Leirhól and Hvíhól which could indicate an analogous weakness in the caldera on that side, at least in ascending flow from the geothermal system and even cone sheet intrusion, much like that found in the north.

The shallow magma chamber, or igneous intrusion, beneath the mid-section of Krafla is a problematic phenomenon as magmatic gases accumulate around it (SO_2, HCl, HFl, CO_2, H_2) and are dispersed into the adjacent formations when the magma solidifies. This has been previously proven to be poisonous to the geothermal system. Recent drilling has indicated that these magmatic gases are more widely distributed within the geothermal system than previously thought. Wells in Suðurhlíðar (KJ-39, RD ~2300 m), north of Víti in KJ-38 (RD >2000–2200 m, in the western slopes of Krafla KJ-33 (RD ~1800-1900 m) and in Leirbotnar, Vítismór and Leirhnjúkar have all been affected by these magmatic gases. This means that long-term wells must be no deeper than 2000 m unless they are located at the periphery of the magma chamber. The only other solution would be new developments in methods to handle low pH geothermal fluid. However, the Hveragil area has successfully utilised 2000 m boreholes for over ten years without being affected by magmatic gases.

Knútur Árnason et al. (in preparation) has come to the conclusion (using a gravity survey) that there is a younger, inner caldera within the Krafla caldera. There are no surface manifestations to confirm this as the younger caldera is likely to have formed almost immediately inside the older caldera, filling-up early on. There are two geological factors that support this idea. One factor is the presence of rhyolite mountains just outside the caldera (Jörundur, Hlíðarfjall and Rani). Their total volume is approx. 2 km^3 but much of the area must have eroded. Eruptions have occurred in cone sheets originating from Krafla's shallow magma chamber. The rhyolite mountains are similar in age and nature and one of them is dated to be 80,000 years old. The second factor relates to the distribution of surface geothermal manifestations between Leirhól and Hvíthól, the only area where the periphery of Knútur's inner caldera overlaps with the periphery of the older caldera. It is a well- known fact that intrusions seek out caldera faults during caldera ruptures. There are signs of this on the southern periphery of the Krafla caldera (Hvíthólar and the crater to the south-east in Sandabotnafjall Mountain). This type of activity could have led to localised geothermal activity/upflow.

Cold altered ground can be seen to the east of the Krafla area in the oldest rock layers outside the caldera (both by Eilífsvötn and at Jörundargrjót). This geothermal evidence predates the caldera and indicates that geothermal activity in the volcano was widespread on the eastern side before its formation. Resistivity measurements showed typical high temperature patterns outside the caldera on the eastern side but proved cold when investigated via drilling (Knútur Árnason & Ingvar Þór Magnússon, 2001; Sigurður Sveinn Jónsson et al. 2003). The formation of the caldera could possibly have affected the geothermal source beneath the area.

It is more difficult to explicate "cold" high temperature anomaly, evident in resistivity measurements, carried out in the so-called Vestursvæði (western area) of Krafla which lies south-south-west from Leirhnjúkur, westward into the main fissure swarm in the Krafla system. Temperature loggings in well KV-1 and the alteration pattern show that temperatures have reached over 250°C, whereas the temperature is now 100°C at a depth of 1000 metres and the well reveals no permeability thereunder (Sigurjón Böðvar Þórarinsson et al; 2006a, b; Bjarni Gautason et al. 2006). The geothermal source that created this alteration has been interrupted and the rock mass has cooled. A 150°C run-off channel has formed instead from the Leirhnjúkar area, southward along the fissure swarms, at a depth of 200-400 m. The well is close to the periphery of the caldera. The rate of subsidence in the fissure swarm of the volcanic system indicates that subsidence in the Krafla fissure swarm could be anything up to 400 metres since the formation of the caldera. It should also be mentioned that a piece of rock retrieved from well KJ-22, at a depth of 290 metres, is similar to "Halarauð"(Ásgrímur Guðmundsson et.al 1983b). This could indicate the rate of subsidence within the fissure swarm. It is likely that the geothermal area at Krafla was much more extensive up until this point (as mentioned earlier with regard to the area to the east of Hágöngur and east of the caldera). Alteration in KV-1 would therefore be ancient but the current geothermal system would only be present in the shallow run-off from this.

The real Vestursvæði at Krafla, surrounding the maars in Hvannstóð and Krókóttuvötn, could prove to be utilisable production areas. However, resistivity measurements indicate otherwise as high temperature patterns are not detected at the depths penetrated by TEM-measurements.

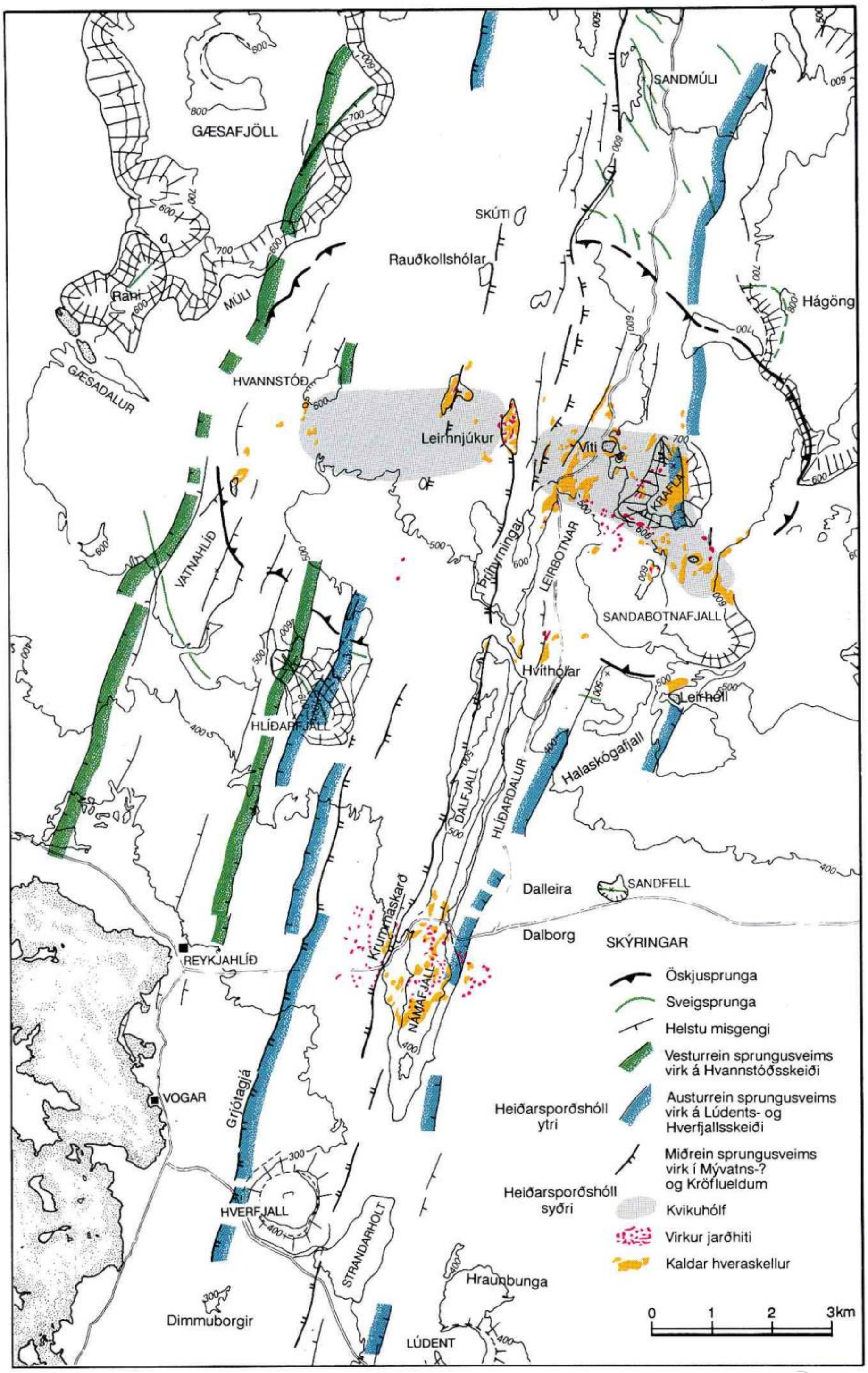


Figure 1. *Map of main fissures and warm or hot ground at Krafla and in the Námafjall Mountain area*

3 Geophysical surface exploration

Geophysical surface exploration surveys have played a significant role in research conducted in the Krafla area. Resistivity measurements have been the most extensive part of this research program but magnetic field measurements and gravity and geodetic surveys have also been conducted. The results of these measurements are discussed in this chapter. Seismographs, i.e. the location of earthquakes and research on the nature and distribution of earthquakes have provided important information on central volcanoes and the geothermal system. The results from seismographic research are discussed in chapter 3.4, hereafter. Geodetic measurements, including rate of subsidence and spreading, have been part of the monitoring pogram pertaining to volcanic activity as well as attempts to strain measurements.

3.1 Resistivity measurements

The main factors affecting rock resistivity are water content, salinity and the temperature of fluid as well as the alteration of rock formations. In short, water saturated rock conducts an electric current more efficiently than dry rock and conductivity is increased at a higher temperature. The alteration of rock formations as a result of high temperatures also affects the resistivity of rock.

TEM-resistivity measurements effectively show the alteration of rock formations in high temperature systems, especially in low salinity environment. Conventional resistivity measurements of high temperature systems show that a low-resistivity cap envelops the high-resistivity core in the middle of the geothermal system and reflects the alteration of the rock formations pertaining to high temperature. Zeolite and smectite are the dominant minerals in temperatures between 100°C and 200°C. Smectite is a clay mineral with a high conductivity level which increases at higher temperatures. This accounts for the high conductivity and therefore low resistivity in the low- resistivity cap. A mixed layer of clay minerals (smectite and chlorite) forms once the temperature reaches 200°C and chlorite becomes dominant once the temperature reaches above 230°C. Chlorite has a lower conductivity level than smectite and causes an increase in resistivity when the rock temperature reaches over 230°C (Knútur Árnason et al. 2000).

3.1.1 History of resistivity measurements at Krafla

Resistivity measurements began at Krafla in 1970. The so-called Schlumberger Method was used (a direct current (DC) resistivity method) where a current is transmitted into the ground and the voltage measured at surface. Sixty measurements were conducted in the summers of 1970 and 1971 (Guðmundur Guðmundsson et al. 1971). These measurements continued in 1976 and 1977, when 40 additional measurements were conducted as well as nine so-called dipole array measurements (Ragna Karlsdóttir et.al 1978). The final twenty Schlumberger-measurements were completed in 1983. Resistivity measurements were conducted in Hvíthólar, in Sandabotnaskarð and to the west of the Dalfjall Mountain in the Leirhnjúkshraun lava field in 1983 and 1984. The Schlumberger Method was used but measured by profile and was interpreted two-dimensionally (Knútur Árnason et.al 1984; Knútur Árnason & Ragna Karlsdóttir, 1996).

Resistivity measurement methods changed during the 1990's and TEM measurements (Transient Electro-Magnetic) became more popular (the method does not rely on sending currents through the subsurface). They generally have better depth resolution than the older method and are often less expensive in execution. TEM measurements began at Krafla in 1991 and over twenty measurements were conducted in the first phase (Knútur Árnason & Ragna Karlsdóttir, 1996). Approximately thirty further measurements were conducted in 1993 and ninety in 1999. Approximately one hundred and fifty TEM measurements were conducted overall in the Krafla area throughout this decade (Knútur Árnason & Ingvar Þór Magnússon, 2001). An extensive MT-resistivity measurements program began in 2005. These measurements explore the natural fluctuations of the Earth's magnetic field and have exploration depths of tens of kilometres. These measurements were conducted in the same location as TEM measurements and the results were jointly interpreted. The MT measurements were conducted in an attempt to identify the heat source of the geothermal system. The entire Krafla area has now been analysed using TEM and MT resistivity measurements (Knútur Árnason et al. and Hjálmar Eysteinsson & Arnar Már Vilhjálmsson, 2007).

3.1.2 Results of TEM/MT-measurements at Krafla

TEM and MT measurements have been the resistivity methods of choice in the last few years. TEM measurements give information on the resistivity distribution in the uppermost formations (usually down to approx. 1000m in depth). An analysis of resistivity at deeper levels (tens and even hundreds of kilometres into the subsurface), requires the MT measurement method (Magneto Telluric). MT measurements explore the natural fluctuations of the Earth's magnetic field. The strength of the electric field of the electromagnetic field of the Earth is both dependent on the resistivity of the Earth and the extent/intensity/magnitude of magnetic fluctuations. Concurrently measuring variations in the magnetic and electric fields at the surface level provides information about the subsurface resistivity structure. Low frequency variations of the electromagnetic field penetrate deep into the Earth but high frequency variations affect the upper layers. The methodology of MT measurements in Iceland is described in the report released by Ragna Karlsdóttir et.al (2008).

So-called static shifts create problems in interpreting MTmeasurements. Near-surface inhomogeneity distort resistivity, shifting virtual resistivity curves upward and downward (a constant shift on log-scale). TEM measurements are unaffected by these factors and shifts in MT data can be determined (identified) by interpreting TEM and MT measurements jointly. It could be said that TEM measurements therefore connect MT measurements to the surface.

Resistivity measurements at Krafla reflect the (hydro) thermal alteration in the geothermal system and show the geothermal system as a high resistivity core, where temperatures are at their highest, and an external low-resistivity cap. Low-resistivity caps can often reach the surface and can be identified by lightly coloured clay patches and surface manifestations in geothermal areas. The low-resistivity caps deepen at the periphery of the geothermal system and can be seen at its deepest level, approx. 1500-2000m, outside the geothermal systems.

Results from TEM measurements conducted at Krafla show that the low-resistivity cap covers the peak/top of four high-resistivity cores and are considered areas of particular interest (resistivity deviation A, B, C & D) connected to geothermal activity and referred to in the report published by Knútur Árnason and Ingvar Þór Magnússon (2001) on the results of TEM-measurements in Krafla (Figure 2).

- **A** is the largest and reaches from the southern slopes of Krafla, across Víti, Vítismó and Leirhnjúkar (**Krafla - Leirhnjúkur**)
- **B** is in the Vestursvæði area of Krafla, to the west of Þríhyrningur and stretches towards the south
- **C** is associated withð **Hágöngur to the east of** Hrafntinnuhryggur and to the north of Jörundur
- **D** lies beneath **Sandabotnaskarð**

The high resistivity cores of these areas are connected and form a continuous plane with a total surface of 48 km^2 at a depth of 600 metres. The temperature in this area has reached at least 230°C at some stage during the development of the geothermal system despite certain areas cooling since then. The high resistivity core at 600 m.b.s.l is shown as a red cross-marked area in Figure 2 but those areas found to be cold areas during exploratory drilling are shown as green, cross-marked areas, i.e. areas B and C.

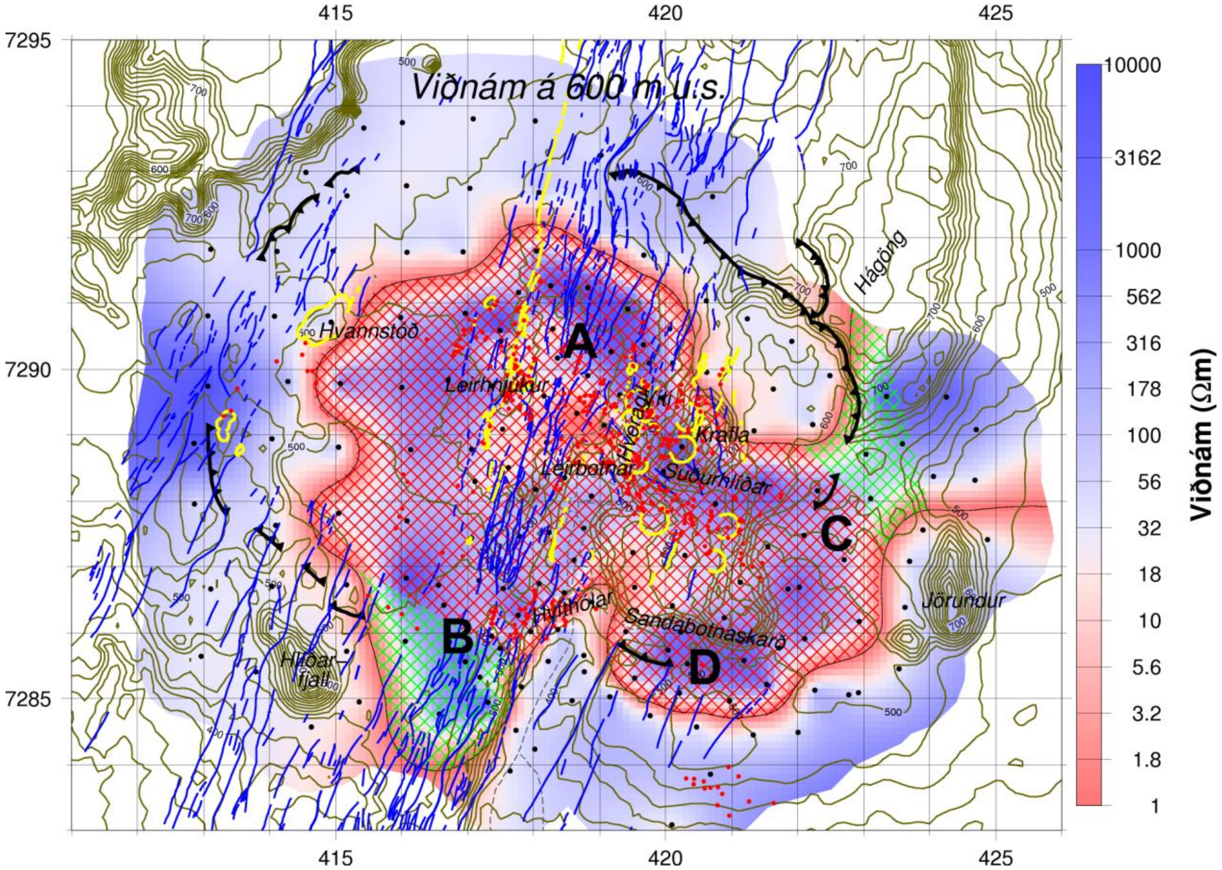


Figure 2. *Resistivity at 600 m.b.s.l in the Krafla area, according to TEM–measurements*.

MT measurements which have a better depth resolution show the low- resistivity cap as a thin layer in the top 1–2 km and a low- resistivity layer at a depth of a few kilometres. This deep-set low- resistivity layer can be seen under a large area of the country where MT measurements have been conducted. It is unclear what causes these low-resistivity layers but research conducted by ÍSOR on the earthquake area by Upptyppinga indicate that the temperature in the upper most area of the deep, low-resistivity layer is approx. 700°C (Arnar Már Vilhjálmsson et al. 2008). This deep-set, low-resistivity layer which is often at a depth of 10 -14 km in the volcanic zone (MT measurements cover this distance) curves upward and is shallower under high temperature areas. It could therefore be said that the tops/peaks of this lower, low-resistivity layer, beneath high temperature areas, are an indicator of where hot intrusions reach upward to the Earth’s crust (litosphere) and where the heat source for the high temperature area can be found. This is how these low-resistivity peaks/tops limit the upward thermal flow into the high temperature areas. These types of peaks/tops could indicate the presence of a magma chamber.

Distinctive peaks/tops in the low-resistivity layer can be seen in three areas of Krafla (Figure 3). The figure shows resistivity at a depth of 4 km below sea level and the peaks/tops appear as low resistivity. Two of these are noticeably larger and reach 2km below sea level, at their shallowest, by Leirhnjúkar and Krafla. There are actually two considerably smaller and lower peaks/tops in the third area, beneath Sandabotnaskarð:

- **Leirhnjúkur.** A large peak/top next to and to the north of Leirhnjúk which covers a surface of approx. 6 km^2 , measured at a depth of 4 km below sea level and reaches upward to 2 km below sea level.
- **Krafla.** A large peak/top similar in size to the west of Krafla Mountain around Vítismó, Hveragil and Suðurhlíðar. It reaches its shallowest point at 2 km below sea level to the

west of Krafla or close to the lower depth boundaries of the wells that have been drilled. It becomes deeper beneath Suðurhlíðar, reaching a depth of 3–4 km below sea level.

- **Sandabotnaskarð.** A peak/top, approx. 3 km^2 in size beneath Sandabotnaskarð on the eastern side and at a depth of 4–5 km below sea level. Another peak/top, considerably smaller , is located in the westernmost area of Sandabotnaskarð at the same depth.

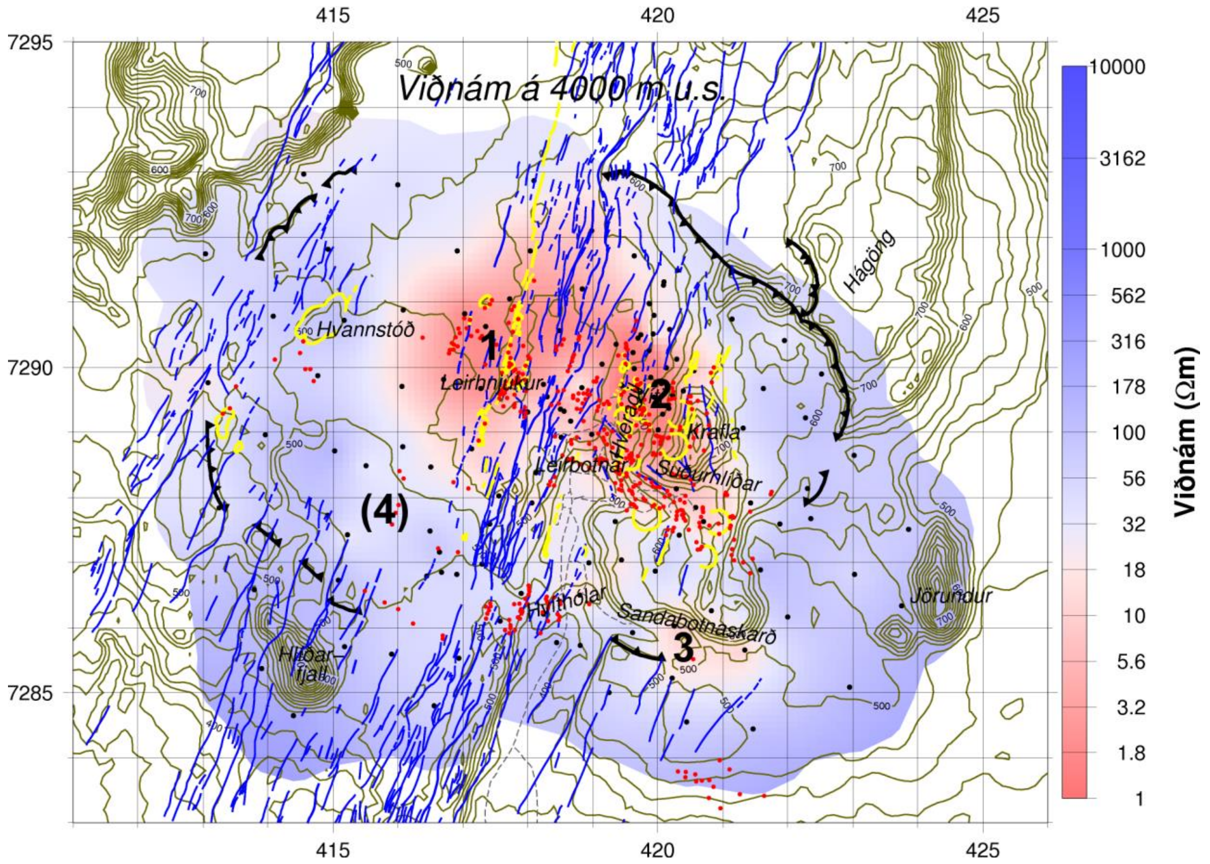


Figure 3. *Resistivity at 4 km b.s.l, according to MT-measurements*

MTmeasurements also showed a fourth peak/top in the western area of Krafla (4). The presence of this peak/top was only confirmed by one measurement but was not present in measurements conducted in close proximity. An attempt was made to repeat these measurements but the data collected were not comprehensive enough to confirm the presence of this peak/top in such a demarcated area (Hjálmar Eysteinsson and Arnar Már Vilhjálmsson, 2008). These measurements were not included in resistivity maps.

The large peaks/tops associated with Leirhnjúk and Krafla, merge with an area where a shallow magma chamber might be present (Knútur Árnason et al. in preparation). In order to better describe the shape and position of these peaks, the level which marks the surface of the low-resistivity layer was identified and a three dimensional model was created using this information and other data (Figures 99, 100 and 101). The model shows that the peaks/tops are clearly demarcated. The two large peaks/tops associated with Leirhnjúkar and Krafla reach up to the deepest level of the wells drilled in the area but the low-resistivity can be seen at the surface in Leirhnjúkar and in the area surrounding Víti (by Krafla).

The area beneath Sandabotnaskarð is actually defined as two lower peaks/tops by the caldera edge which reaches a depth of 4–5 km. There is evidence of lower resistivity above the peaks/tops than in the surrounding area which could indicate the upward flow of thermal energy.

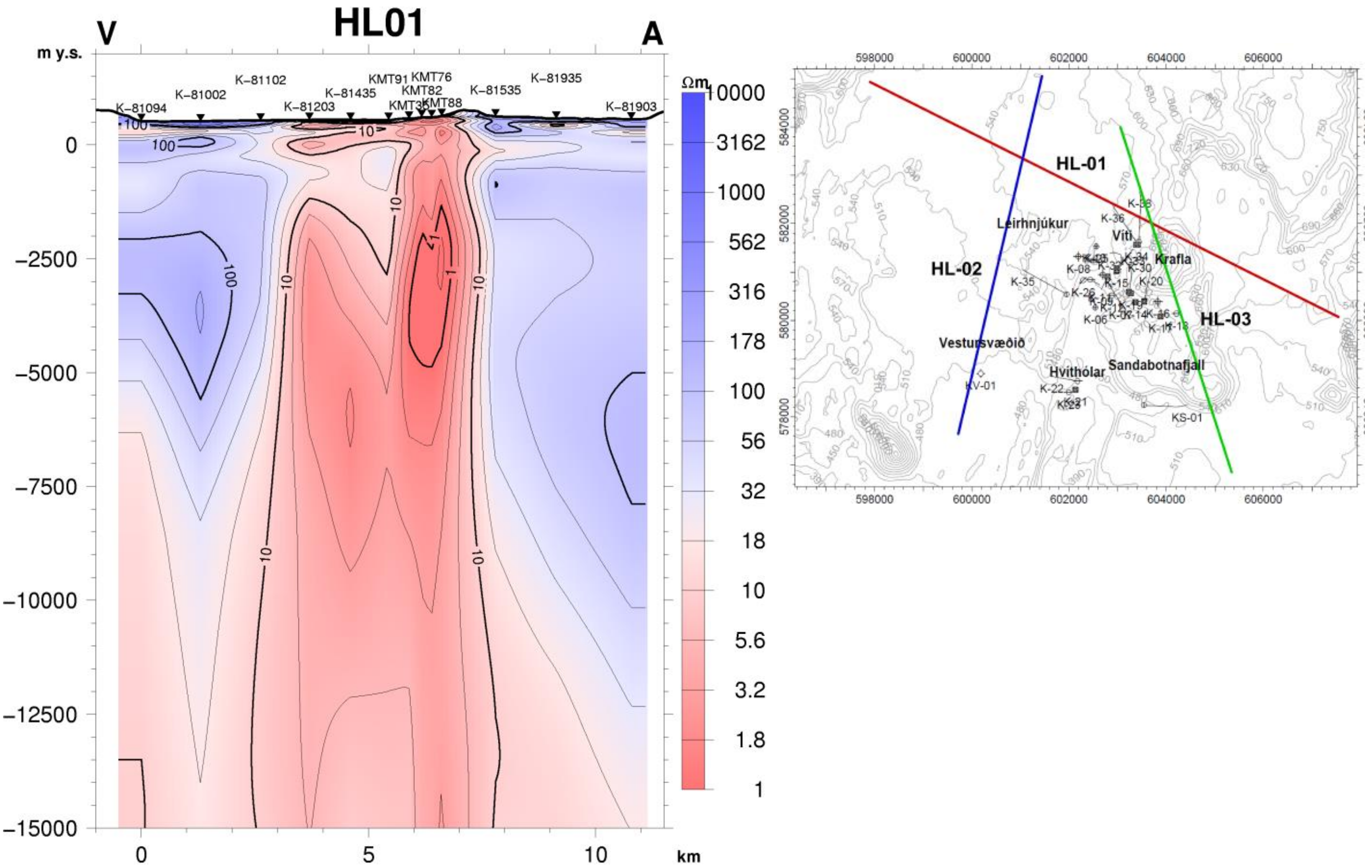


Figure 4. *Resistivity measurements HL01. NV-SA profile at Leirhnjúkar and Víti*

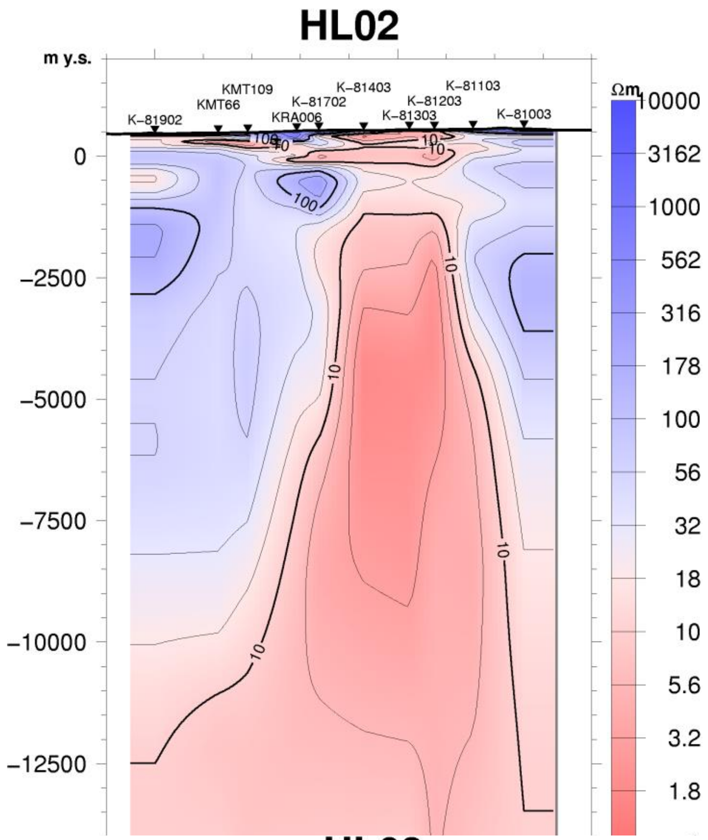


Figure 5. *Resistivity measurements HL02. NA-SV profile at Leirhnjúkar and Leirhnjúkshraun in the Vestursvæði area*

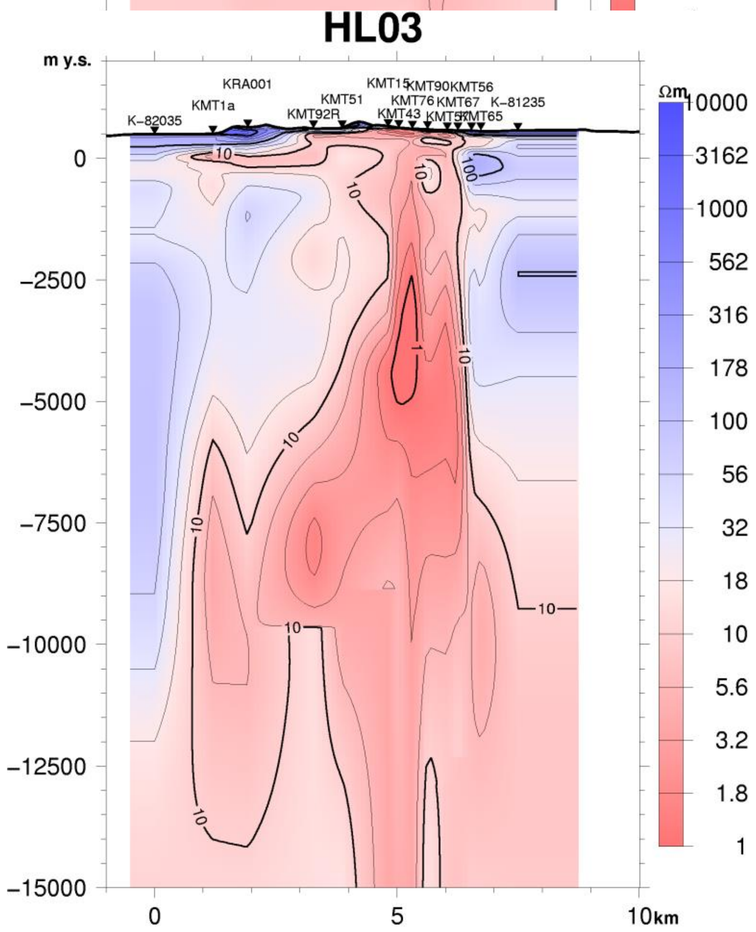


Figure 6. *Resistivity measurements HL03. NNV-SSA profile around Víti and Sandabotnaskarð.*

Three vertical profiles to a depth of 15 km are shown for further clarification. Profile HL01 lies NW-SE over the two large peaks/tops (Figure 4). The two peaks/tops are clearly demarcated; the western peak/top beneath Leirhnjúkar and the eastern peak/top beneath Víti by Krafla. The low-resistivity cap can be identified as a thin, low-resistivity layer at the surface. There is low-resistivity above the peaks/tops and up to the surface. The profile 'HL02' shows a NE-SW trend in the Leirhnjúkar area, along the fissure swarm (Figure 5). The clearly demarcated peak/top is shown and the low-resistivity above it. The third profile 'HL03' lies from Víti and south-eastward across Sandabotnaskarð (Figure 6). The large peak/top beneath Víti is shown and the low-resistivity up to the surface and above it. The smaller peak/top on the left side of profile is the peak beneath Sandabotnaskarð.

Beyond the peaks/tops is the upper surface of the lower, low-resistivity layers at a depth of 10km closest to the peaks/tops and deepening as it moves further from them. The low-resistivity layer is present in all areas of the country where MT measurements have been conducted, with the exception of areas close to the coastline. Figure 7 shows low-resistivity in the entire area (at a depth of 12km below sea level) and therefore shows that the low-resistivity layer is at this same depth in the neighbouring area of the Krafla area (or as far as measurements reach).

Resistivity increases again below this deep set low-resistivity layer but low-resistivity has been identified in one isolated location beneath this area. If low-resistivity is present in areas deeper than these MT-low-resistivity peaks/tops then it can be assumed that magma flows from the depths of the mantle and towards the surface. The lower, deep-set, low resistivity layer is analysed in the report released by Hjálmar Eysteinsson and Arnar Már Vilhjálmsson (2008). The aforementioned area beyond the peaks/tops deepens at the upper boundary, low-resistivity layer to a depth of 10 km. The thickness of the layer beneath the Krafla area is at least 5-6 km, as the resistivity contour map at 12 km below sea level shows low-resistivity in the entire Krafla area (Figure 7). There is evidence of high-resistivity occasionally at a depth of 20 km.

High-resistivity is typically identified at a depth of 25 km with the exception of three areas (Figure 8) beneath three of the four peaks/tops, in the upper surface layer mentioned earlier (Figure 3). There is an obvious resistivity deviation (anomaly) under Leirhnjúkur (1) and Víti/Krafla (2). The lowest level of resistivity at this depth is identifiable beneath Víti on the western slope of Krafla. The third low-resistivity deviation is less evident and is located beneath the eastern side of Sandabotnaskarð (3).

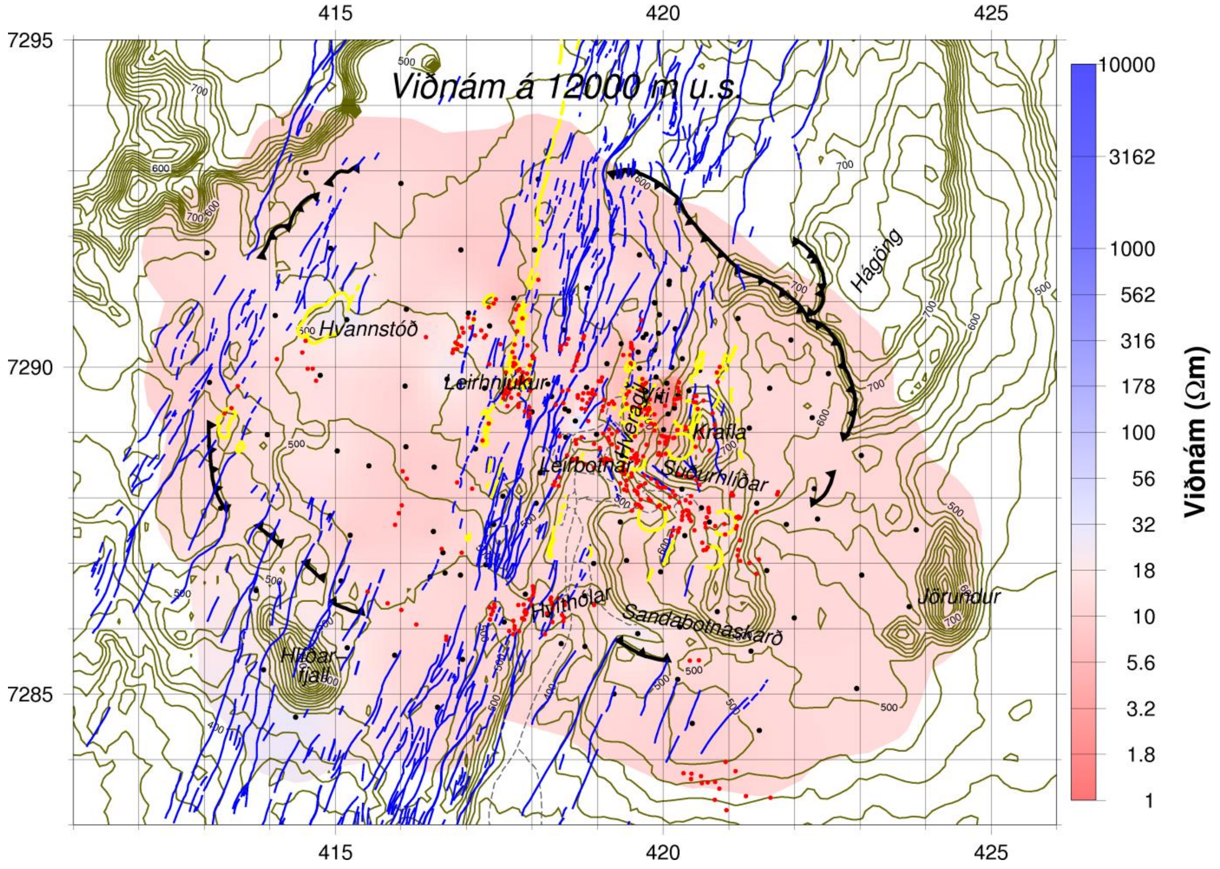


Figure 7. *Resistivity at 12 km b.s.l; according to MT-measurements*.

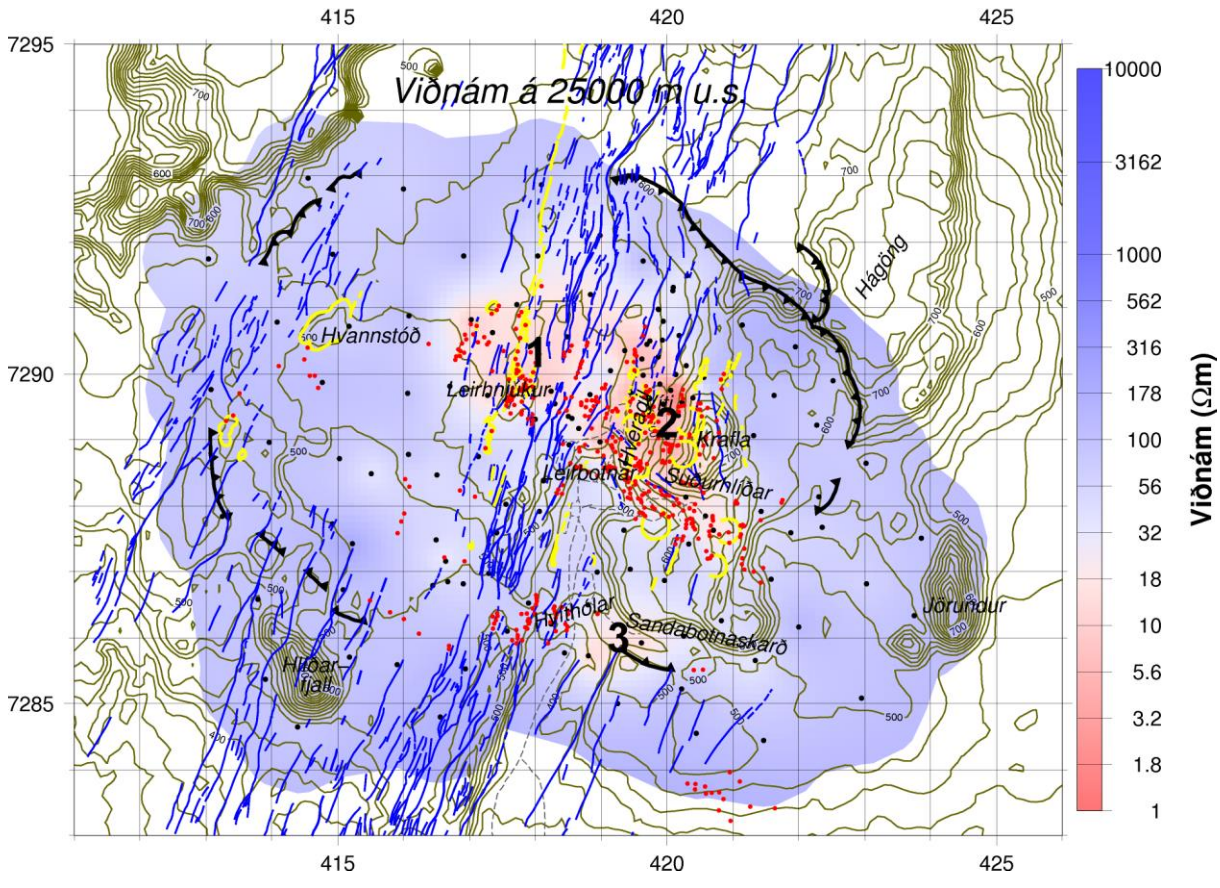


Figure 8. *Resistivity at 25 km b.s.l; according to MT-measurements*

3.2 Magnetic surveys

The Science Institute at the University of Iceland created an aeromagnetic map covering an area of approx. 180 km^2 for the National Energy Authority in 1970 (Guðmundur Guðmundsson et al. 1971). Þorbjörn Sigurgeirsson, then professor of physics at the University of Iceland flew over the area and used geomagnetic equipment(magnetic meter) he had designed and developed himself. He was accompanied by the geologist, Kristján Sæmundsson. The map covers the Krafla, Námafjall Mountain and surrounding area (Figure 9). The magnetic map shows a magnetic depression above Námafjall and in various locations at Krafla, the largest of which is above Leirbotnar. Two significant trends can be seen on the map; first and foremost a NNE to SSW trend, along the fissure swarm in the area, and a WNW to ESE trend traversing the fissure swarm in the Krafla area.

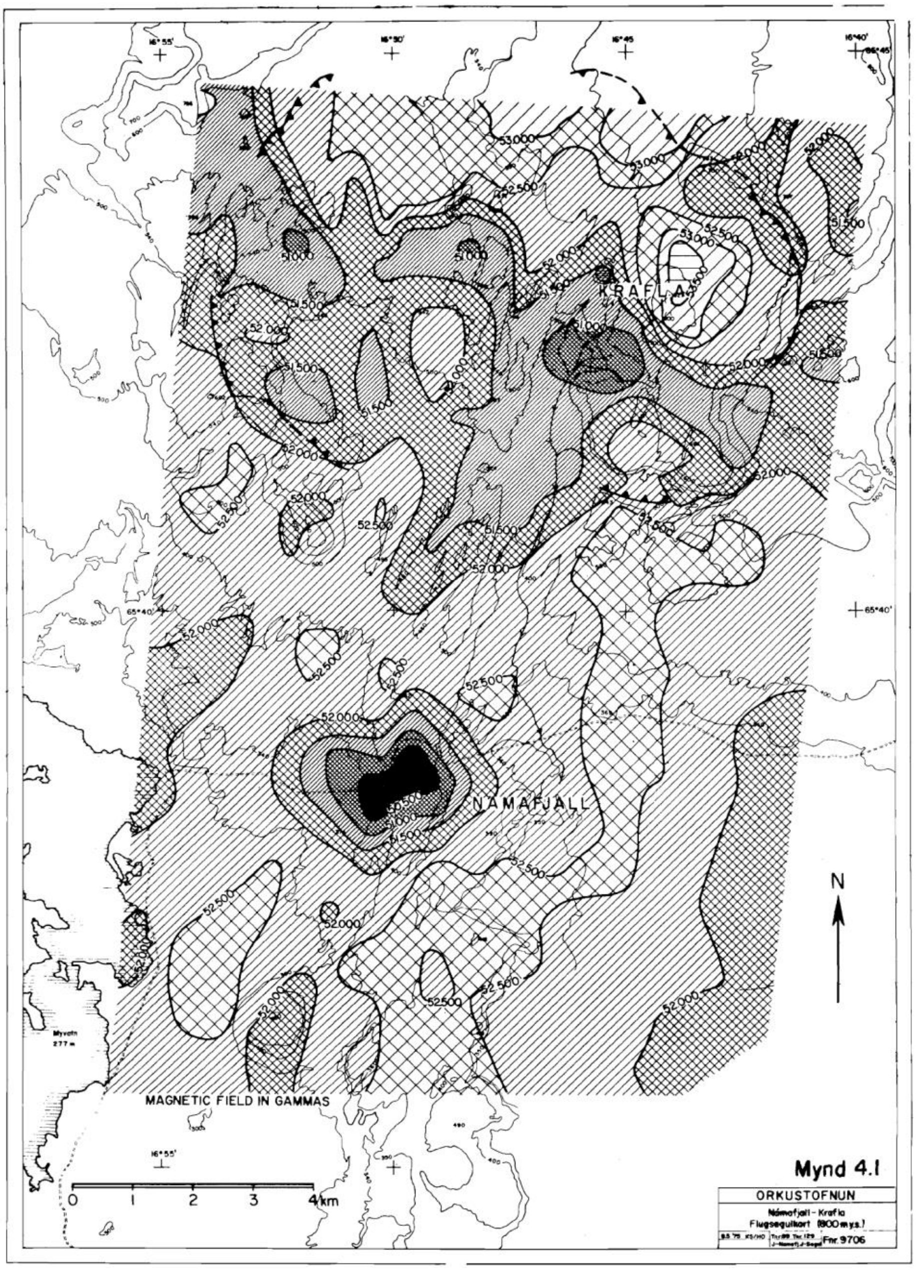


Figure 9. *Aeromagnetic map af Krafla, Námafjall and surrounding area* Tectonic deformationand the magma chamber(s) at Krafla

Extensive information was collected pertaining to the behaviour of the magma chamber beneath the Krafla caldera as a result of research conducted on tectonic deformations and seismic activity (see overview: Freysteinn Sigmundsson, 2006). Land mass continuously inflated as a result of magma injection into the shallow chamber. Once the magma chamber collapsed, magma flowed rapidly out of the chamber and into the fissure swarm. It often surfaced in volcanic eruptions in the fissure swarm at Krafla. The pattern of movement in the lithosphere makes it possible to measure the depth of the magma chamber, which proved to be 3 km. Seismic activity was consistent with tension changes in the roof of the magma chamber. Tension increased during upflow (inflation time) periods as a result of magma accumulation and earthquakes subsequently followed. There was seismic activity in the fissure swarm, during divergence events, when magma flowed from the chamber and settled in dikes (see Buck et al. 2006).

Elevation changes in the middle of the caldera, before the Krafla Fires, decisively show the behaviour of magma accumulation in the chamber. The inflation rate as a consequence of lava upflow (land elevation) and magma flow into the chamber was at its peak immediately after the divergence event but decreased with the onset of the next event. The magma flow also decreased with the onset of the Krafla Fires. This behaviour is consistent with the theory that another magma chamber was located beneath Krafla, deep in the lithosphere, or in the upper layers of the Earth's mantle and that magma flowed continuously from this area (deeper chamber) during the Krafla Fires, decreasing with time.

The magma systems within the central volcano can be complicated with shallow and/or deep chambers and with varying connections between them.

Geodetic surveys have been conducted in the Krafla area since the Krafla Fires, often at the request of Landsvirkjun. Altimetric measurement networks from Levelling network measurements from the Krafla Fires were re-calculated by the National Energy Authority and Landsvirkjun in 1995. An overview of these as well as previous measurements can be found in the report published by Axel Björnsson and Hjálmar Eysteinsson (1998). Landsvirkjun was also responsible for the re-calculation of the same network in 2000 (Stefán Már Ágústsson, 2001) concurrently with a gravity survey (Ingvar Þ. Magnússon, 2003). Altimetric measurements were also conducted in 2005 (Erik Sturkell et al. 2008). Other researchers have further contributed to research already conducted by Landsvirkjun by conducting extensive research of this nature in the area. This research includes GPS measurements by Krafla and larger areas in the north as well as precision altimetric measurements. The Nordic Volcanological Center has conducted research to gain more information on magma movement and the behaviour of magma chambers beneath Krafla. InSARmeasurements have been conducted as well as gravity surveys. These projects have been carried out in cooperation with various parties including the Iceland Meteorological Office and the Open University in the UK (see the article by de Zeeuw-van Dalfsen et al. 2006).

Tectonic deformations were identified after the Krafla Fires and were anything up to 6 cm per year. This is thought to be a result of the release of tension in the lithosphere after sheet intrusions (see Foulger et al. 1992; Sigmundsson et al. 1997). The vertical tectonic deformation closest to Krafla has been characterised by subsidence since the end of the Krafla Fires when land inflated and deflated alternately in line with magma pressure in the shallow magma chamber (at a depth of 3 km) beneath the middle of the Krafla caldera (Erik Sturkell et.al 2008). The initial rate of subsidence was approx. 5 cm per year but has now dropped to 1 cm per year. The mid-section of subsidence seems to have shifted from Leirhnjúkar (traversing the magma chamber) and over to Leirbotnar (in close proximity to the middle of the utilisation area: see Figure 10). According to this, magma pressure could be reaching some sort of balance, in the shallow magma chamber beneath Krafla, but subsidence as a result of pressure drawdown in the geothermal system could be prevalent in the next few years. Other processes cause tectonic deformations in the area. The main trend of the subsidence follow the Krafla fissure swarm (Pedersen et al.2009).

There is localised subsidence in the geothermal system in Bjarnarflag and extensive inflation (or upheave) occurs (with a mid-point in Gjástykki) approx. 10 km to the north of the Krafla caldera (most accurately detected by the InSAR-method. This inflation could be connected to the accumulation of magma close to the lithosphere and mantle, at a depth of 20 km, beneath the Krafla System between

1993 and 1998 and later (de Zeeuw-van Dalfsen et al. 2004; Freysteinn Sigmundsson et al. 2007). Another explanation could be that the inflation is connected to the release of tension in the lithosphere after the Krafla Fires, without the accumulation of magma.

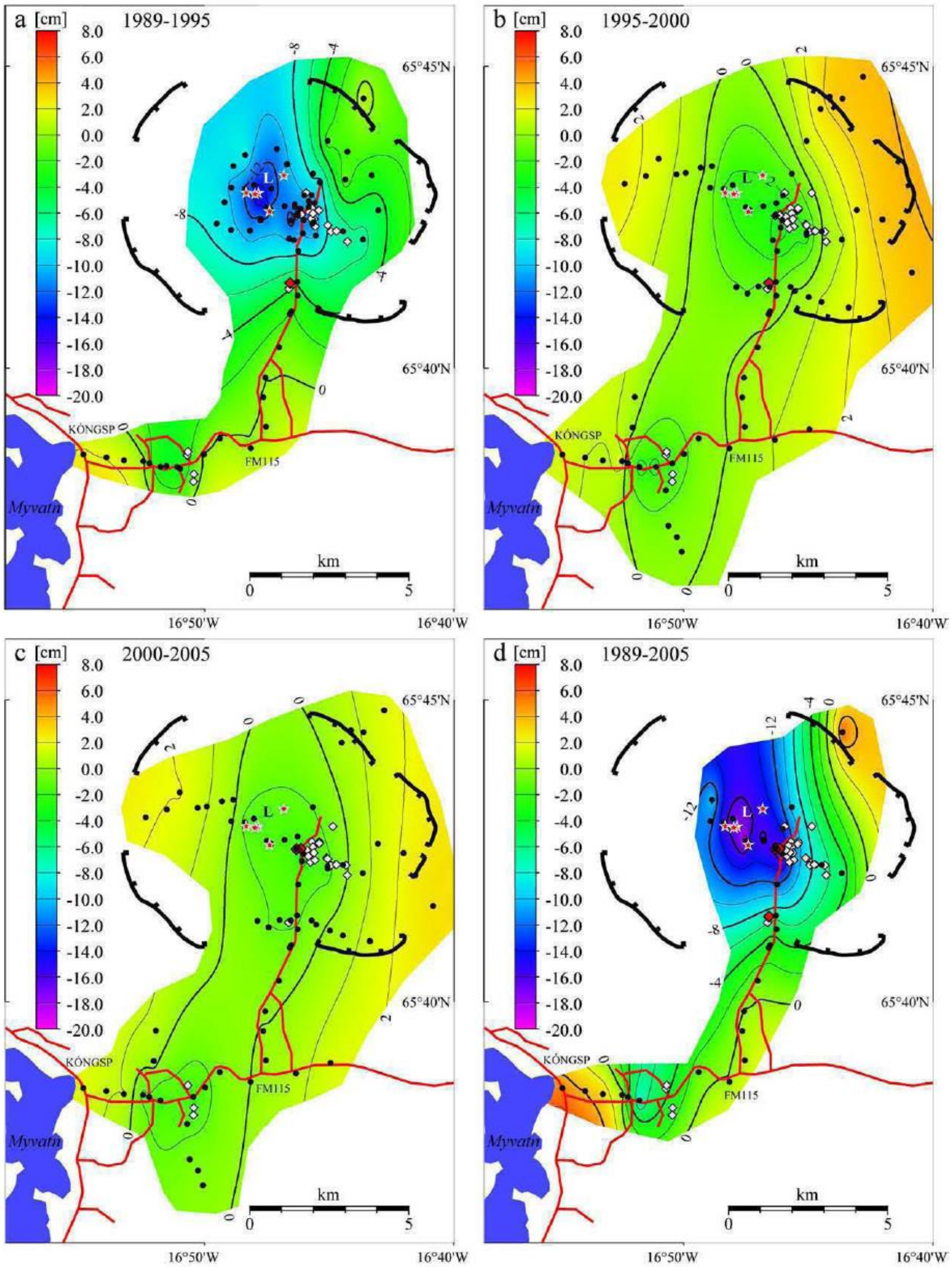


Figure 10. *Geodetic data from locations near Krafla from 1989–2005*

3.3 Seismic activity (English translation subject to further review)

Relocated earthquakes are shown in Figure **Error! Reference source not found.**. The program registers the depth of the earthquake during the location procedure, when information is not sufficient to determine their location. It should be noted that these types of earthquakes can be reasonably located within a horizontal plane, despite significant uncertainty as to the depth og forritið festi það. Figure 14 shows earthquakes where the depth cannot be confirmed by the program where information is not extensive enough to calculate the depth.

The following discussion is only based on information from more exactly located earthquakes. In instances where an attempt is made to connect rock temperature (according to information retrieved from wells) and resistivity measurements on seismic activity then only earthquakes where the hypocentric depth has been determined are used. Figure 14 provides a clearer overall picture than Figure 13.

The outer limits of the active area are sharper. Characteristics such as the obvious NNE fracture line around Vítismó (Figure 13) disappear. This line is confirmed although the depth of the earthquakes that form the line has not been determined (Figure 14).

Seismicity in the Krafla area between 2004 and 2007 is mostly bound to a belt that is 2km in width and 4 km in length and lies in a northwest direction (Figures 13 and 14). Activity is mostly bound to the production area to the south, in Hveragil and in Suðurhlíðar, where there is extensive surface deformation. Activity decreases significantly to the north and northwest in Vítismó. There is some activity trending NNW along the fissure swarm and north of Leirhnjúkar. Clusters or rows can be seen in between, heading northeast from the main tremor area. Earthquakes often follow the line of mapped fissures.

The margin of the active area in the south is rather sharp but activity decreases at a slower rate to the north. The southern periphery is probably realistic as the area is entirely inside the reference frame for the area (Figure 11). The distribution of earthquakes to the north is unclear once outside the reference frame. According to locations mapped out by the SIL network, seismic activity is evenly distributed further north than outlined here. However, there is a gap/ dead space to the south of the main activity area shown here and is comparable to these results.

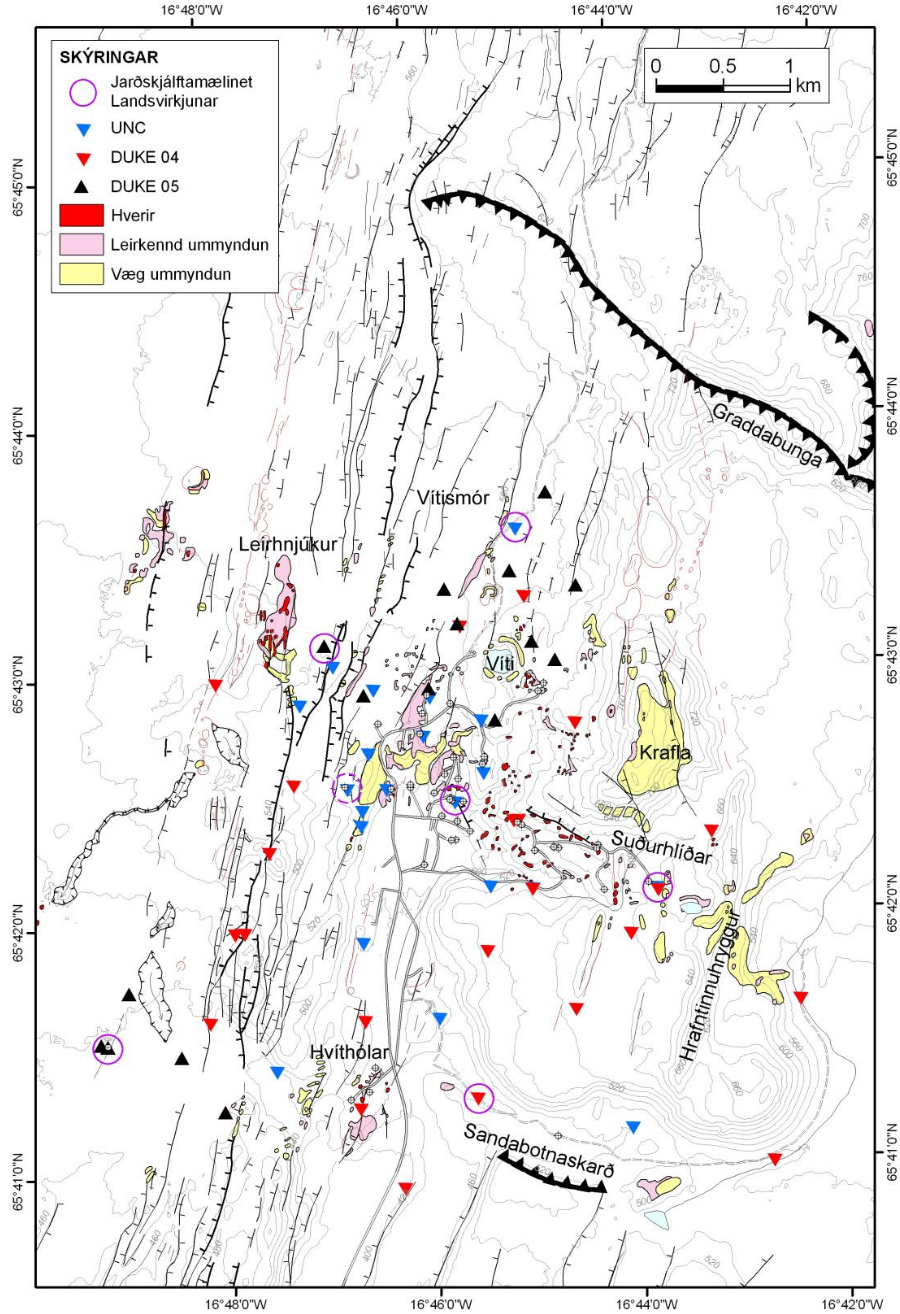


Figure 11. *Seismometer network.*

Depth distribution (Figure **Error! Reference source not found.**) shows that 95% of the earthquakes are above 2 km (based on sea level). Most earthquakes are at a depth of 0.5–1.5 km (based on sea level) and there is an obvious top/peak at 1 km. There is a scattering of earthquakes at a depth of 3.5–4 km and isolated earthquakes below 5 km. Most earthquakes deeper than 3.5 km are outside the main clusters and all earthquakes below a depth of 5 km are outside the main cluster.

A size analysis and hypocenter/epicentre analysis have not been completed. The nature of these earthquakes is therefore unknown. They could be normal earthquakes (double couple) which would be a response to the dominant, local stress field or stress alterations connected to subsidence or elevation in the Krafla caldera. There is also uncertainty as to whether these earthquakes are connected to the geothermal system mining heat from the rocks or boiling which could be accompanied by volume alteration in the epicentres.

3.3.1 General comparison with other observations

Figure **Error! Reference source not found.** shows a NNE-SSW profile from Hlíðardal and to the north of Krafla along the main cluster of earthquakes and shows the depth of earthquakes, the position of wells and their rock temperature. Figure 17 shows a profile trending WNW-ESE to the north of the main cluster. The profile shows that most of the earthquakes are within the production area for the Krafla Geothermal Power Station. The southern and eastern peripheries of the active area are rather sharp whereas the northern and western peripheries are less clear. This could be the result of a reduction in sensitivity in this direction. There are very few earthquakes within the lower, low-resistivity layer beneath Krafla. Most earthquakes occur at a rock temperature higher than 300°C, but there is no obvious connection between these factors in the profiles.

Páll Einarsson (1978) discussed the S-wave shadows in Krafla and considered it likely that the magma chamber was the culprit. According to his analysis, the shadow area is divided into two sections and is approx. 3 km in depth. The earthquake distribution shown is mostly across the eastern area and there are hardly any earthquakes below a depth of 3 km to the west of Krafla. There are hardly any earthquakes in the lower low-resistivity layer. Research indicates that the temperature in the lower low resistivity layer is around or above 700°C (Arnar Már Vilhjálmsson et al. 2008). A comparison of depth distribution and the temperature gradient (Kristján Ágústsson og Ólafur G. Flóvenz, 2005) indicates that the lower boundary of the brittle crust is around 750°C according to the most common earth crust movements. The fact that earthquakes do not occur below 3 km where there is an S-wave shadow or within the lower low-resistivity layer indicates that the temperature in these areas is above 700°C.

Most earthquakes are at a depth of 500–1500 m.b.s.l in the Leirbotnar and Suðurhlíðar areas. Production is carried out at these depths which could indicate a possible connection. However, seismicity is relatively low to the south and east of Víti, where the most powerful wells are found. Hyaloclastite(s)/ palagonite(s) are more obvious in Víti than they are in Leirbotnar and the Suðurhlíðar area where intrusions are dominant. The difference in rock matter could have an affect but further analysis including a size analysis and epicentre analysis on earthquakes will answer this question.

Figures **Error! Reference source not found.** and **Error! Reference source not found.** show less earthquakes at a depth of 1500 m.b.s.l than that found above and below this depth. There is a change in layers in the velocity model at a similar depth to where there is a shift in velocity between layers (Figure 12). This gap could be the consequence of the velocity model.

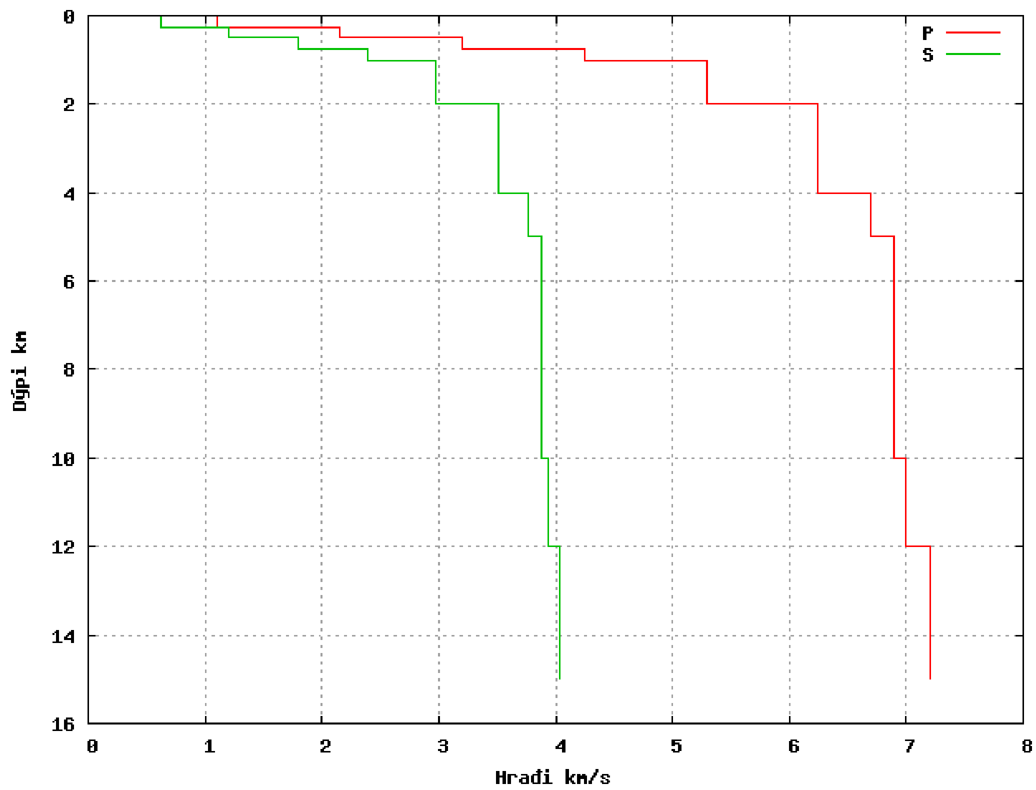


Figure 12. *Velocity model for P- and S-waves*

We have established that seismicity is mostly bound to a 2 km wide and 4 km long belt with a north-west direction. It is almost perpendicular to the main direction of the fissures and faults in the area. There are also indications of a horst (this can be seen in well data). There is a magnetic depression in the area, an anomaly in resistivity and an increased flow of CO_2 from the soil.

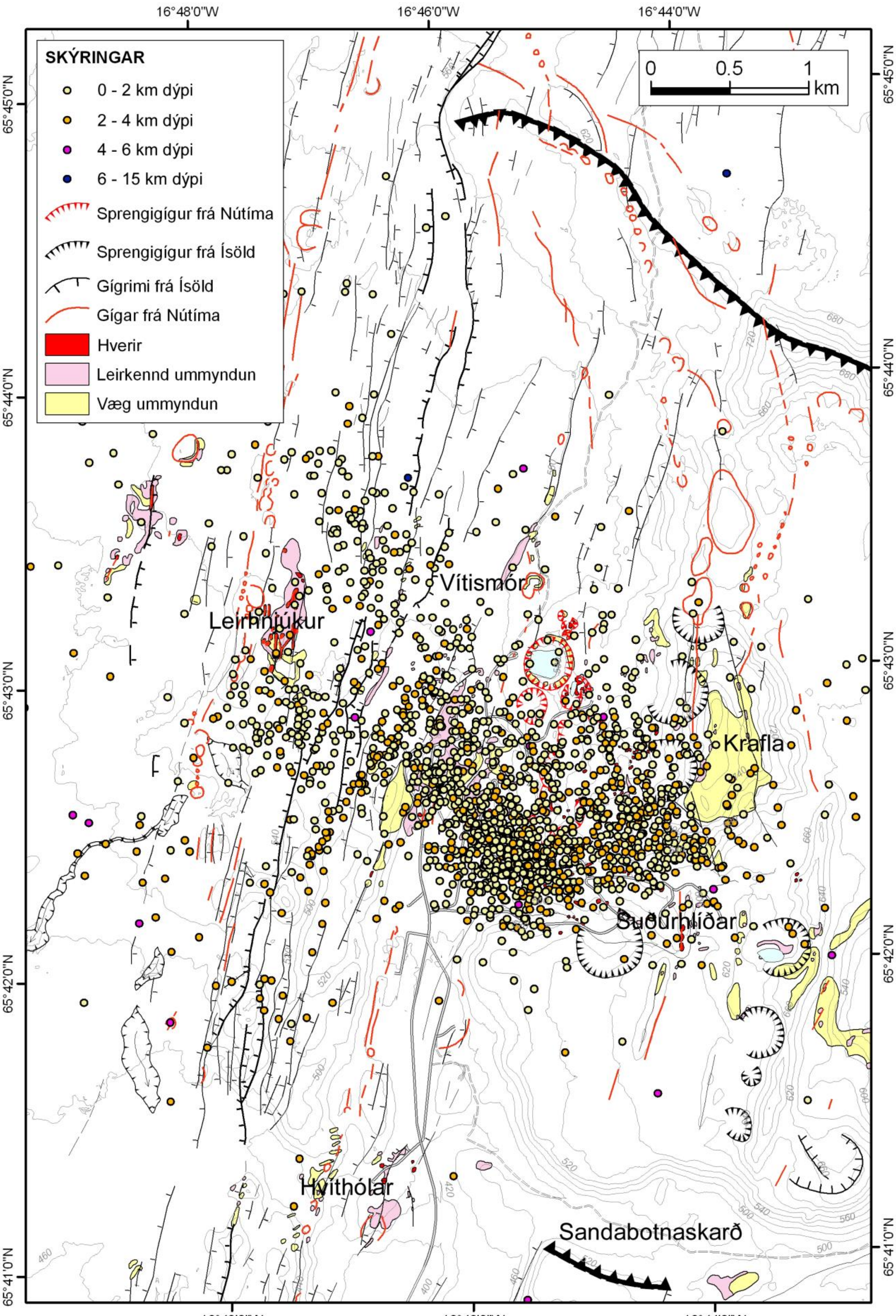


Figure 13. *Earthquakes in the Krafla area 2004–2007*

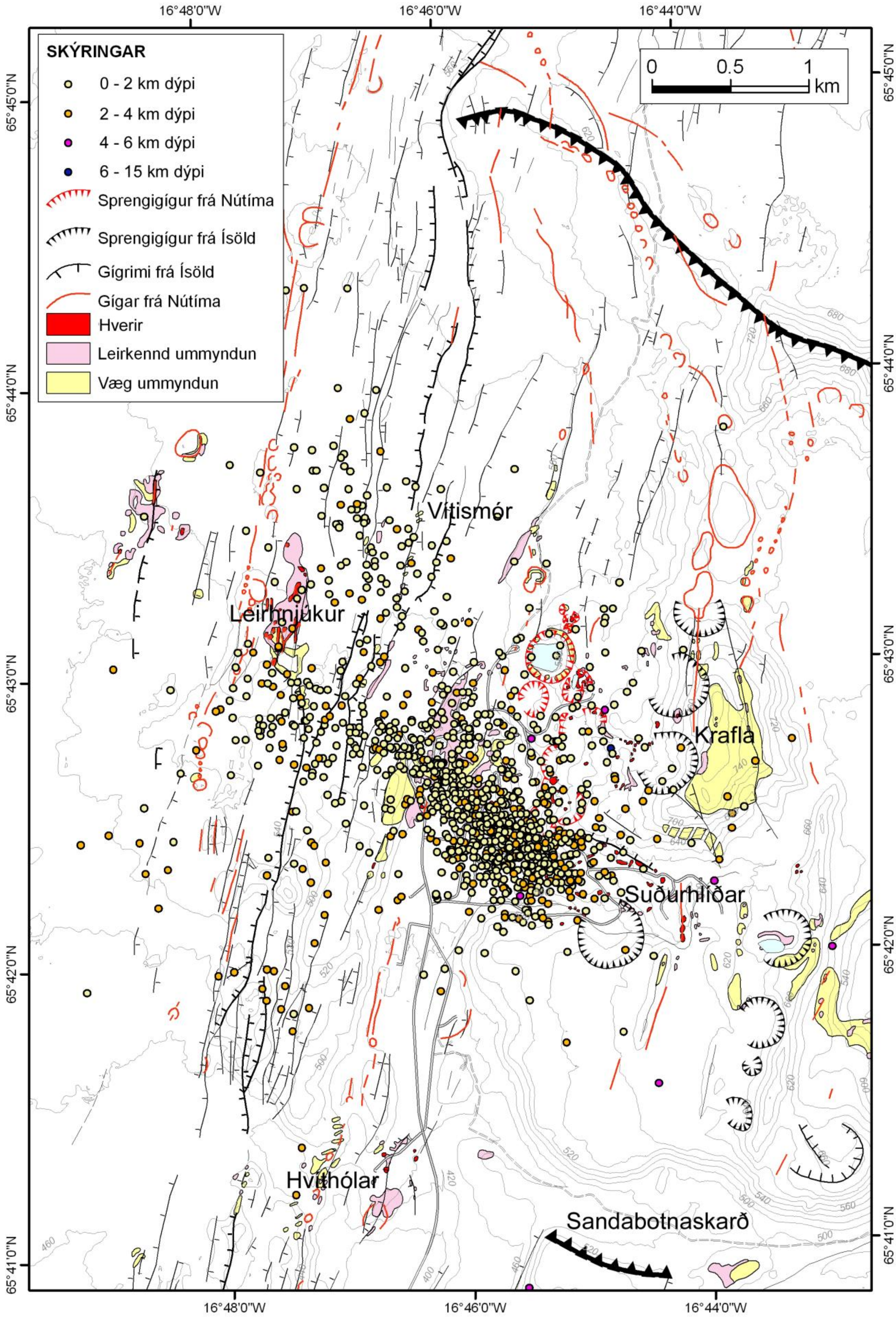


Figure 14. *Earthquake locations at depth in the Krafla area 2004–2007*

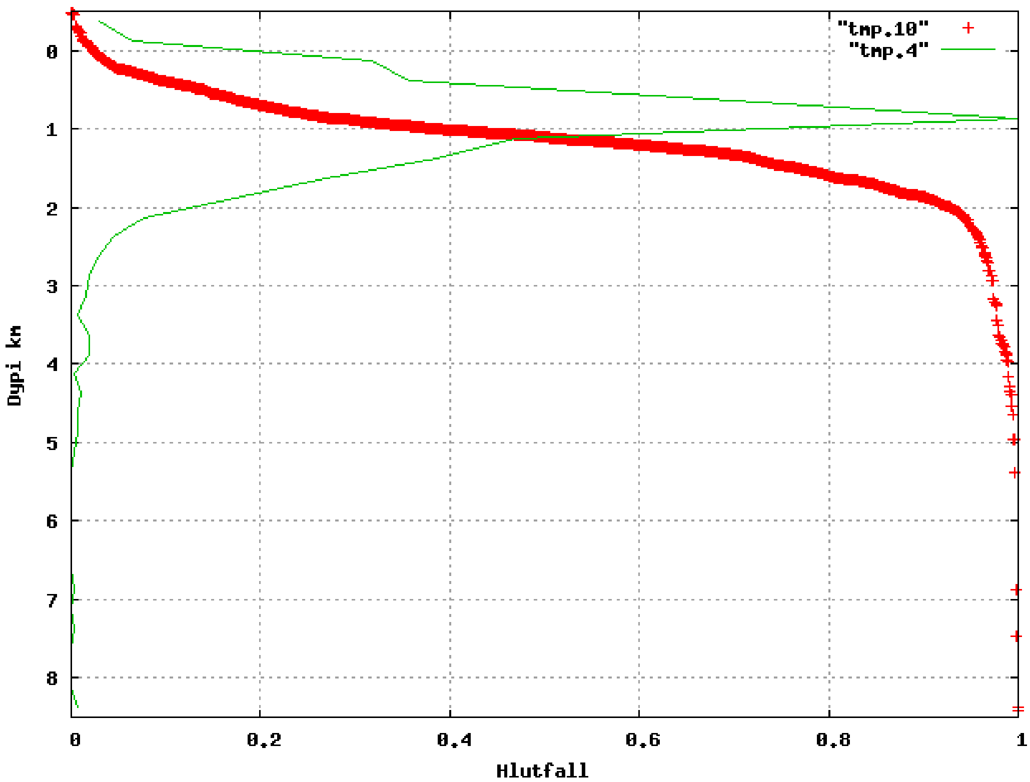


Figure 15. *Depth distribution as a fraction of the lagest number of tremors per depth interval, and the cumulative number of tremors above a given depth as a fraction of the total number of termors*

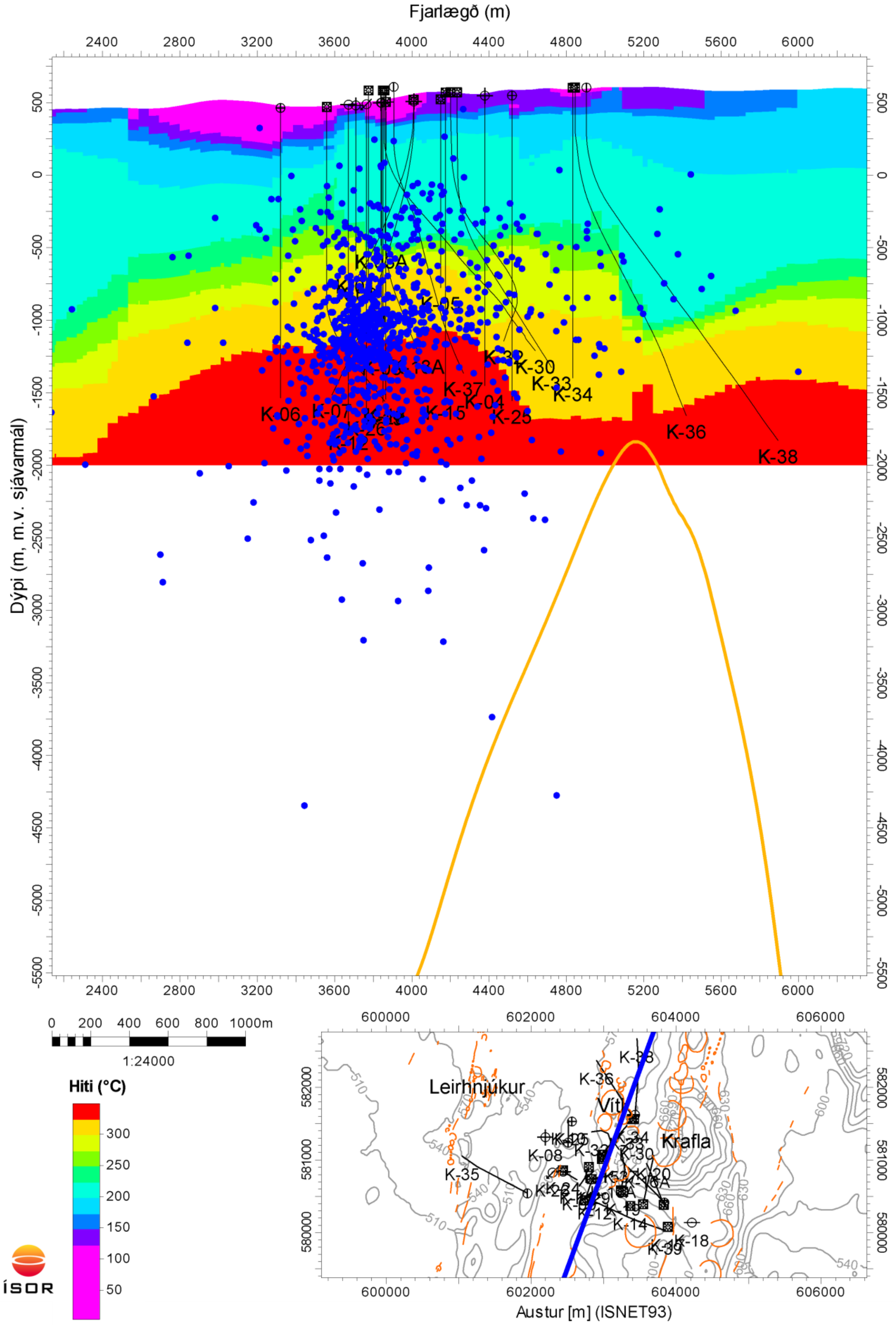


Figure 16. *The upper section of the figure shows the NNE-SSW profile which shows earthquakes, rock temperature and the surface of the lower low- resistivity layer according to MT-measurements.*

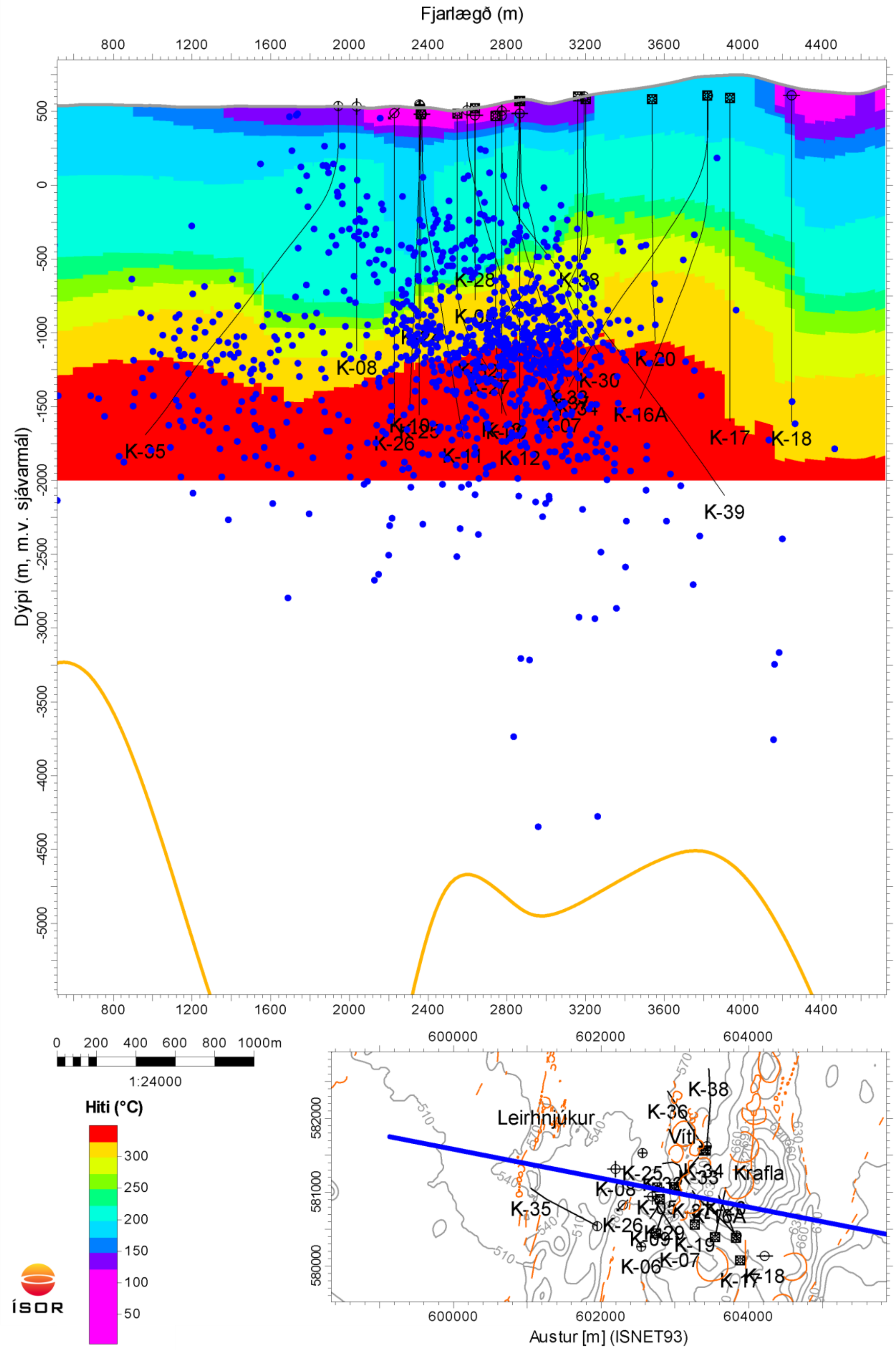


Figure 17. *The upper section of the figure shows the WNW-ESE profile which shows earthquakes, rock temperature and the surface of the lower low- resistivity layer according to MT-measurements.*

4 Drilling history

Drilling began at Krafla in the summer of 1974 when the first exploratory wells were drilled. Wells were drilled down to a depth of between 1,138 - 1,204 metres using a drilling rig from Jardboranir hf., the state drilling company. Figures 19 and 20 show the well locations. Production casing reached a depth of 200-300 metres and the liner reached the wellbottom. Casings were kept shallow, taking into account the experience acquired from Bjarnarflag, where 9 wells were drilled between 1963 and 1970. The results of research conducted on these two wells can be found in a report published by the National Energy Authority (Kristján Sæmundsson etal. 1975). The report recommended the utilisation of the area for energy production. Expectations were high as this was preparation for the first big geothermal power station to produce electricity in Iceland. The wells were named in numerical order but the letters in front of the identification number was related to the area (K for Krafla) and the drill used (G for Gufubor, J for Jötunn etc.) See Table 1.

Drilling began on production wells in 1975. Dofri (known as Gufuborinn) drilled the first three wells. Production casing was extended and reached a depth of approx. 600m. Drilling in KG-3 was completed without disruption and the drilling of KG-4 ran smoothly until near completion of drilling. The temperature in the well rose rapidly and began to release water and steam once equipment had been removed from the well. Fortunately, drilling equipment was removed without major damage and without human accident. However, work could not be completed on the well-head and the well continued to discharge uncontrollably via the main valve, subsequently blowingout head equipment with only the crater (Sjálfskaparvíti) remaining which discharged approx. 200kg/s. The geothermal fluid became acidic (measuring pH < 2) shortly after the New Year began and after the onset of the Fires. The drill was moved from KG-4 to KG-5 but drilling was also discontinued at a depth of 1,300 metres. A decision was made to re-assess drilling plans for Krafla as well as finishing work on wells. Construction work on the powerhouse also began in 1975 but volcanic activity at the end of the year (at Leirhnjúkar) would have unforeseeable consequences for the project.

Thirty five years have passed since drilling began at Krafla and extensive changes have been made to preparation measures, implementation and monitoring pertaining to high temperature drilling. The first two wells were exploratory wells approx. 1,200 m in depth. Design work has been based on production well drilling since the third well was drilled. Many incidents have resulted in the re-assessment of design work. The incident at KG-4 is a clear example of this, resulting in the re-evaluation of the lining/casing program, a greater emphasis on safety equipment and an emphasis on the need for as much detailed information as possible on drilling work. Damage to the liner, as a result of an increase in temperature in the wells after drilling completion, led to the re-assessment of arrangements for the casting process of casings, both the process itself and its success rate.

Jardboranir hf. have been responsible for all drilling work with the exception of the clean-up/cleaning and recycling of an old well which was completed by Ísbor. Three drills have been used during the process with the exception of pre-drilling, repairs and clean-ups/cleaning.

The names of the drills used were Glaumur, Gufubor/Dofri and Jötunn. Both Gufubor (Dofri) and Jötunn were used in 1976. Six wells were drilled in 1976 using Jötunn and Gufubor and each was given a name beginning with KG or KJ. There were also plans to complete KG-5 but damage to the liner/casing prevented the drill string from entering the well. The liner/casing in KG-3 split at a shallow depth and the well discharged into a fracture that reached the surface during drilling for KG-9. Rock matter and clay burst into the air and on-site workers at Krafla were afraid that the incident could provoke a phreatic explosion similar to that which created Víti at the beginning of the Mývatn Fires. The concern proved unwarranted and well KG-3 was filled with sand and concrete. Jötunn was relocated to KJ-11 which was completed late in November of that year. The drill was then moved to well 9 which was drilled to a depth of 1,101m in December of that year. A 7⅝" slotted liner was installed in the well. Gufubor drilled wells KG-8 and KG-10 in Vítismó during this period. There were numerous problems with a collapse by an aquifer at a depth of 1,118 m in well KG-8. The aquifer was filled with concrete and drilling continued to a depth of 1,658 m. Well KG-10 was located just to the south of Sjálfskapavíti and drilling was more successful this time, with a suitable BOP stack.

The success of the project did not meet expectations and the Krafla geothermal system proved to be more complex than anticipated. Substantial knowledge was acquired that year and valuable experience proved useful in the near future. The Leirbotnar area, which had been a drilling zone up until this point (Vítismór included), turned out to be a geothermal reservoir consisting of two separate geothermal zones, a shallow zone and a deeper zone. This would be difficult to combine in one well. The deeper zone proved to be a 'boiling' system. Output was weak in well KJ-6, and KJ-7 was initially powerful but dwindled within the first year. Well KG-8 was always low pressure (< 6 bar) and low temperature. Well KJ-9 was drilled in phases, well KG-10 was powerful but became plugged with scaling material after only a few weeks of discharging and well KJ-11 was a powerful well but was a combination of the shallow and deeper zones, which would not be reliable in operations.

The design of liner/casing was re-assessed as a result of drilling success in 1976 and changes were implemented in 1977. There was no new drilling carried out that year but the design of KJ-9 was altered as a result of the outcome of well tests carried out during the winter months and the project was continued. A loose liner was removed and production casing was cemented to a depth of 1,074 m. This was the first time that casing had been cemented down to such a deep level in Iceland. The well was completed to a depth of 1,264m with complete loss of circulation at the bottom. The well was then put back into production. Well KJ-7 was cleaned that same year and the uppermost part of the lining in KJ-11 was removed. The casing ran to a depth of 1,200 m and was cemented to block off the upper system (shallow system).

Well KG-12 was drilled in the autumn of 1978 to the east of the separating station and the production casing reached a depth of approx. 1000 m. The well was 2,222 m in depth, quite porous and was the deepest well at Krafla for some time. However, a new challenge presented itself once the well began discharging as the well discharged super-heated steam with a highly corrosive chloride concentration.

Drilling ceased until the spring of 1980 and once KG-12 had been completed. The geothermal system beneath Leirbotnar was clearly affected by magmatic gases and increasing the size of the drilling area became necessary as a result. However, the new well (well KJ-13) was drilled just to the west of Hveragil and slightly to the east of well KG-3. The production casing reached a depth of 1,060 m. The well proved to be weak, dwindled within the first year and was put back into production later on. Drilling began on KJ-14 in a new drilling area in the southern slopes of Krafla. This proved to be a success and the well gave approx. 7 MWe of electricity. The well proved to be typical of the area (as mentioned elsewhere in this summary). Well KJ-15 was next in line and was drilled to the west of Hveragil, northeast of KJ-13. The well proved to be gas rich, rather weak and difficult to utilise for the first 10 years. However, the well proved useful in monitoring gas changes in the lower Krafla system.

Wells KJ-16, KJ-17 and KJ-18 were drilled in 1981 in Suðurhlíðar with differing success. There was a vast difference in temperature when well KJ-18 was compared with the other wells in the Suðurhlíðar area (the well was much colder at the upper level). Wells KJ-19 and KJ-20 were drilled in Suðurhlíðar a year later. Well KJ-19 was drilled north from well KJ-14 with great success. Drilling methods changed with the introduction of directional drilling. Well KJ-20 was the first well to be drilled using directional drilling in Iceland. Well KJ-20 was located to the east of well KJ-14 (between KJ-14 and KJ-16) in a NNE direction and in close proximity to the main fracture zone. The well was 1,823 m in depth and deviated horizontally approx. 650m from vertical, but drilling was not trouble-free. The well was quite porous, gave approx. 3 MWe of electricity but was gas rich.

The introduction of directional drilling and GIRO measurements resulted in a change to drilling methods. Older wells that were easily accessible were assessed using GIRO measurements and the results were unexpected. The results showed that many of the wells had altered in course during drilling and were like they had been drilled using the directional drilling method. Well KJ-9 pointed towards the separation station and the wellbottom was approx. 220 m south of the well head (figure

18). Well KJ-7 pointed towards Suðurhlíðar and straight towards well KJ-13 which explained why the well became wet when well 13 was drilled. Wells KG-10 and KG-11 were also measured and were well outside the designated area. Extensive monitoring on the incline of drilling began during and after the drilling of well 12 to ensure that drilling remained as close to the designated area as possible (unless otherwise decided). GIRO measurements were carried out in KJ-13 to assess its angle as it did not penetrate the Hveragil fracture/fissure (the angle was 5°). The well was at the same angle as the fracture/fissure and therefore did not penetrate it.

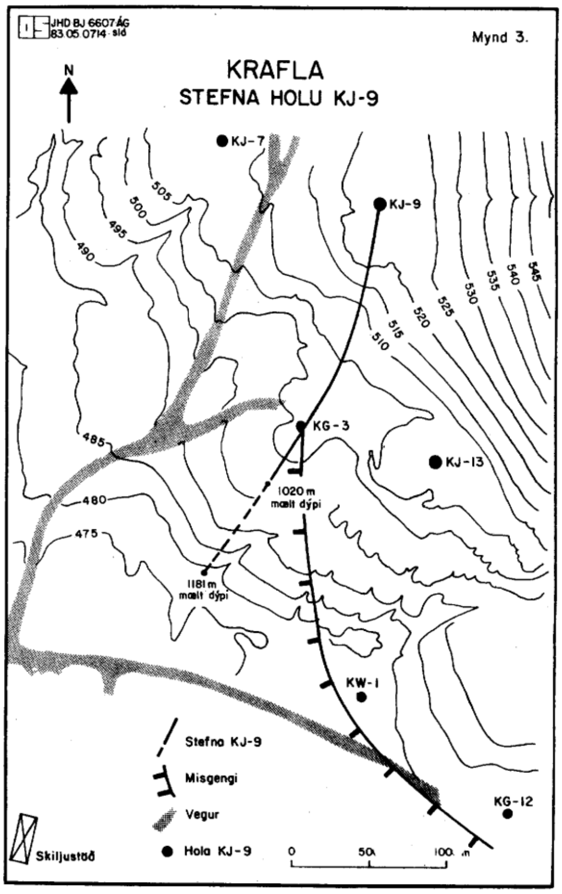


Figure 18. *History of well KJ-9, according to GIRO measurements in 1982*.

In 1982, a new drilling area was established by Hvíthólar, an area free from magmatic gases, and changes were made to the drilling process. Well KJ-21 was drilled in phases. The well was drilled to a depth of 300 metres for anchor casing and was then drilled to a depth of 1,200 m (as a temporary production well- section) and lined with a 7" slotted liner. The term “temporary production well-section” refers to a section that can be lined and deepened when and if it needed. Since this process had not been utilised previously the well was given the name “Idiot” which turned out to be a misnomer as the well was the most productive well at Krafla for quite some time. The well was completed in 1984 and the entire well was lined with a 9⅝" liner. The top 300 metres were cemented (between liners) but the liner was slotted in the production section. The final project for 1982 was the re-drilling of KJ-9 as the initially powerful well had begun to dwindle. The project was problematic but reached completion.

The first drilling project of the year was well KJ-22 in Hvíthólar which was directionally drilled in a westward direction through the Dalelda fracture/fissure. The well was positioned approx. 200 metres to the north of KJ-21. The first 150 metres were difficult in execution but the project was otherwise successful. Directional drilling was then successfully carried out in KJ-13, through its production casing and in an eastern direction through Hveragil. The renewed well was given the name KJ-13A. The next drilling project was the drilling of KJ-23 at a vertical angle towards Hvíthólar. Drilling was successful but the well had little permeability and not suitable for production. The well was therefore used for monitoring purposes in 1991 and 1992. The final project of the year was the drilling of well- KJ-3A. The well was given this name as it was drilled on the same drilling platform as KG-3. The well was drilled to release steam from the upper system (shallow system) and was therefore only drilled to a depth of 1000 metres. Drilling was successful and the well turned out to be quite porous. A decision was made to experiment with the well by not installing a liner, the result of which was the complete collapse of the production zone. Attempts were made to clean up the collapse but this was unsuccessful so a liner was installed in the collapsed area. The well collapsed again but this time between the production casing and liner.

There was little drilling activity in the next few years. Attempts were made to fix well KG-8 but the lining/casing was damaged just below a depth of 100 metres. Repair work was discontinued and the well was filled with concrete and gravel. The well platform has since been used as a carpark for tourists walking on Leirhnjúkar. Well KG-24 was drilled on the platform of KJ-11 in the summer of 1988, to a depth of 1,400 metres, and was drilled to serve as a low-pressure well which would only work within the upper system (shallow system). There was little permeability in the well during drilling but attempts to open up the well were successful and the well is still in use. Well KJ-13A was cleaned in 1989 due to ferro silica precipitation blocking the liner.

In 1990, well KG-25 in Vítismó was drilled just to the north of Sjálfskaparvíti as a result of detected changes to the concentration and percentage division of gases in well KJ-15, showing signs of improvement within the geothermal system. Drilling was successful and the well seemed to fulfil the initial objectives of the drilling project. However, the fluid from the well turned out to be acidic and corrosive. Preliminary drilling was carried out that summer for KG-26 in the slope above “Auga við veg” and then on the drilling platform to the east of Víti where KJ-34 was drilled nine years later.

Well KG-26 was drilled in two phases in 1991. Initially, a 1,200 m well was drilled in order to confirm the existence of an upper system (shallow system). The well was tested during the summer period until the autumn and turned out to be an upper system (shallow system) well. Production casing was cemented to a depth of 1,200 m in November and December and the well was drilled deeper to a depth of 2000 m. Discharge tests showed that the fluid was in fact acidic and a decision was made to quench the well to prevent it from becoming damaged. A failed attempt was made to remove the liner in the autumn of 1996. The well has been utilised as a reinjection well since the beginning of 2002.

An attempt was made to recycle well KG-25 in the summer of 1991. The top section of the liner was removed but the well could only be penetrated to a depth of 1,660 m. A second attempt was made in the autumn of 1996, but unfortunately, the drill string was cemented in place just below the production casing and the well was abandoned.

In 1996, a decision was made to install turbine unit 2 at Krafla Geothermal Power Station and to drill for the necessary steam supply. The repair of wells KG-25 and KG-26 was part of this plan. Wells KJ-27 and KJ-28 were planned to a depth of 1,100 m to utilise low-pressure steam from the upper system (shallow system) in Leirbotnar. Well KJ-28 was successful and was drilled to a depth of 1000 m to the north of the separating station. A decision was made to deepen well KJ-27 (located between KJ-11 and KJ-3A). This was executed a year later in October and November when the production casing was installed in the well and it was successfully drilled directionally to the east.

Drilling in 1997 began with well KJ-29. The well was drilled at a vertical angle to the east of the separating station in Leirbotnar. However, at a depth of 1400 m, the decision was made to drill the well at an incline in a northward direction toward well KJ-13. Well KJ-30 was directionally drilled northward in the western slopes of Krafla from the drilling platform of KJ-19. This is one of the most powerful wells in the area despite the fact that collars and a motor were left in the well. Well KJ-16 was directionally drilled in a north-eastward direction during mid-summer and the depth reached 2,191 m. The well was not a successful venture considering the difficulties encountered. Well KJ-31 was drilled vertically on the drilling platform of KJ-20 which had been directionally drilled 15 years earlier. The danger of collapse meant that KJ-31 could be no deeper than 1,440 m. The well was quite porous and had a good injectivity-index but was overall rather unproductive.

Well KJ-32 was the only well drilled in 1998 and was located on the same wellpad as KJ-15. The plan was to drill the well in a northeast direction. New equipment, which was still under development, was chosen to control the direction and incline. However, this proved to be unsatisfactory for the task as the drill became constrained at a depth of just over 1,800 m and further drilling was impossible. Giro measurements, conducted after drilling completion, revealed that the well had veered north and then west which was completely different to that shown by the new equipment. The well has been called "Sigðin" ("the Sickle") ever since. However, the well is a successful production well, despite all these difficulties

The last two wells to be drilled, as a result of the expansion of Krafla, were wells KJ-33 and KJ-34. Well KJ-33 was directionally drilled from drilling platform KJ-15 according to the initial design outline for KJ-32. This was successful except for the fact that the bottom drill string was left behind as well as the motor. The well was highly productive for one year but then diminished significantly.

Well KJ-34 was drilled vertically to a depth of 2,002 m just to the east of Víti. The project ran successfully and it is one of Krafla's most powerful wells (18 Mwe). There was a hiatus in drilling at Krafla until 2006 when the extensive research project "NA-landsboranir" began. This covered all geothermal areas in the northeast of Iceland, from Námafjall to Þeistareykir. Exploratory drilling began in the Vestursvæði area in Leirhnjúkar lava field in 2006. The execution of this was based on resistivity measurements supported by geology. Well KV-1 which had been drilled vertically to a depth of 300 m showed that there was not much justification for the search. The basin temperature was no higher than 240°C and a decision was therefore made to abandon the Vestursvæði area. Well KH-6 (a core well) was drilled to gain more information. The well was positioned to the west of Þríhyrningur at the end of an eruptive fissure from the Mývatn Fires. This gave some hope that the northern end of Vestursvæði could be utilised, for the area can be reached by drilling to the east from the current drilling site.

In 2007, well KS-1 was directionally drilled in Sandbotnaskarð in an easterly direction along the caldera fault and across the NS fracture structure which lies alongside Hrafntinnuhryggur. The well was average in production and was porous with a good temperature level. The objective of this plan was to seek out areas outside the current production area. The next location was the drilling platform to the west of Rauðhól where preliminary drilling had been carried out twenty five years previously but had not been further explored. Well KJ-35 was directionally drilled from this location in a WNW direction towards the main crater of the Mývatn Fires. The well reached a depth of 1 km, confirming the existence of the upper system (shallow system) and that acid, corrosive fluid was present in the basin of the well. Well KJ-36 was directionally drilled from drilling platform KJ-34 to the east of Víti in a WNW direction under the Víti and Hólseldar fracture. A powerful but corrosive geothermal system was discovered beneath the Hólseldar fracture and this needed to be cemented off. However, the fluid from the Víti fracture proved to be suitable for production purposes at a depth of 1,500-1,600 m. Well KJ-37 was directionally drilled from well KJ-16 in Suðurhlíðar towards well KJ-15. Drilling also took place alongside the transverse faults in Suðurhlíðar and there were plans to penetrate the fracture system by Hveragil. The risk of collapse meant that drilling could not reach the Hveragil fracture. The well was porous but did not turn out to be productive, much like other drilling projects in Suðurhlíðar.

Two wells were drilled in 2008. The first well was located on the drilling platform to the east of Víti and was directionally drilled northward. The length of the well measured 2,700 m. The upper system (shallow system) reached a greater depth than otherwise encountered and corrosive fluid was discovered at a depth of 2000-2,500 m. Well KJ-39 was drilled from drilling platform KJ-29 in an easterly direction under Grænagil. The well reached a depth of 2,865 m and penetrated magma. The wellbottom was cemented and the fluid extracted from the well turned out to be corrosive.

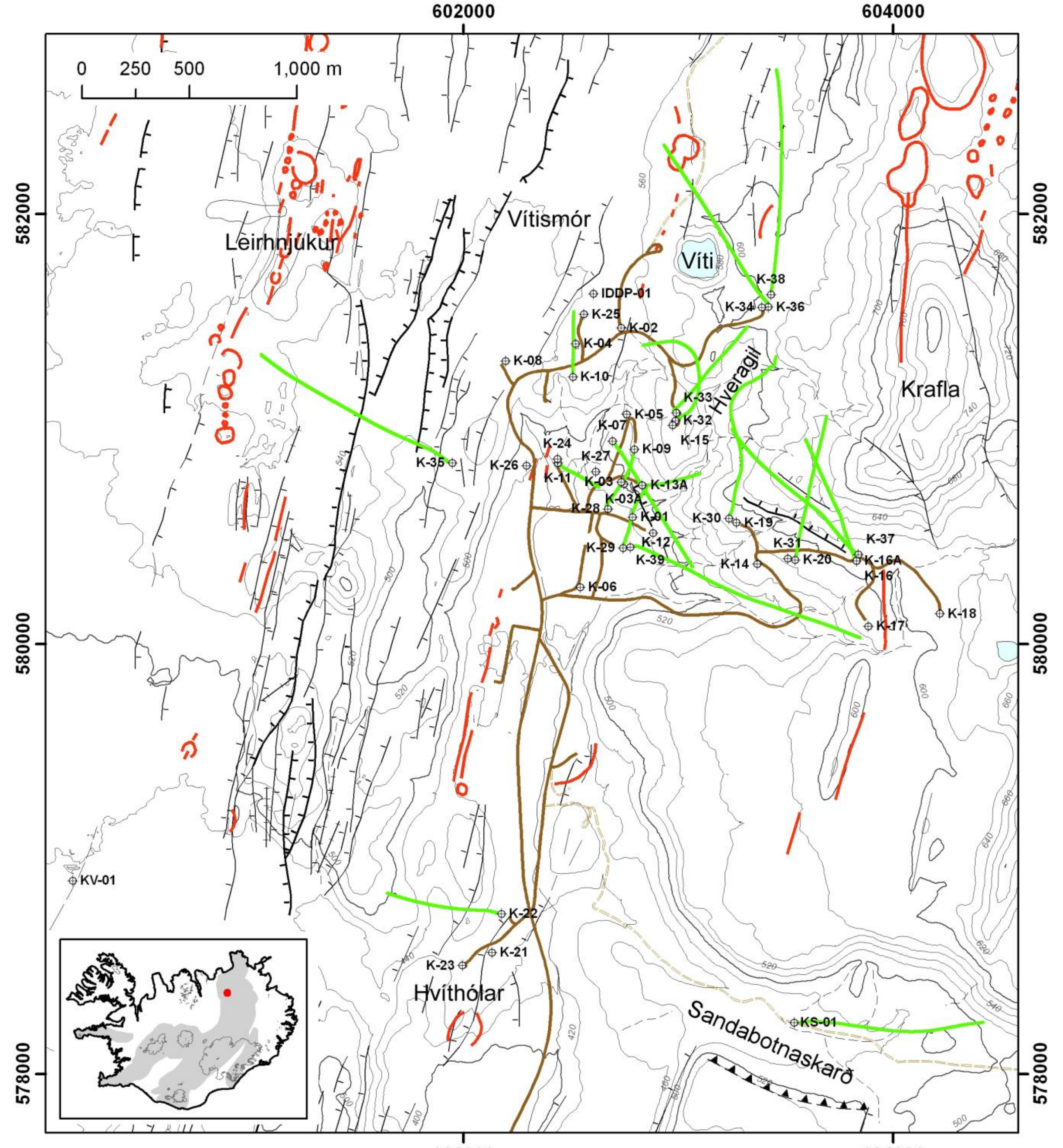


Figure 19. *Location of wells in the Krafla area.*

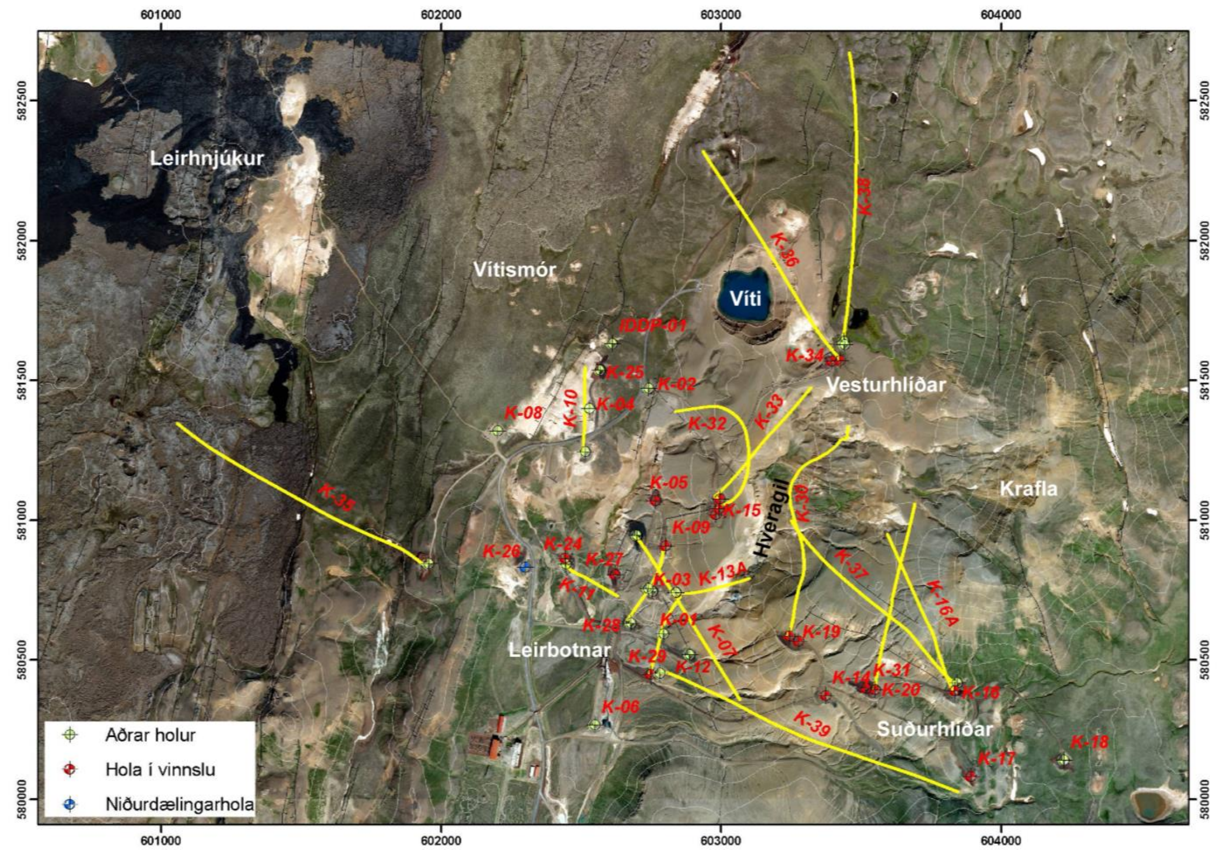


Figure 20. *Wells at Krafla. Production wells in 2008.*

Table 1. *Wells at Krafla (either the full name or a K and number reference).*

Hola	OS nafn	Staðar nr.	Svæði	Ár	X	Y	Z	TD	Öryggis-fóðring	Vinnslu-fóðring	Leiðari	Hönnun	Ástand
KW-01	K-01	58001	Leirbotnar	1974	602789	580590	482.0	1138	80.0	227.5	1132.5	Bein hola	Ónýt
KW-02	K-02	58002	Vítismór	1974	602736	581470	553.5	1204		299.0	910.5	Bein hola	Ónýt
KG-03	K-03	58003	Leirbotnar	1975	602734	580753	499.8	1720	114.2	604.2	1671.1	Bein hola	Ónýt
KJ-03A	K-03A	58103	Leirbotnar	1983	602748	580744	499.9	985	331.9	663.4		Bein hola	Ótengd
KG-04	K-04	58004	Vítismór	1975	602524	581397	549.0	2000	113.4	593.6		Bein hola	Ónýt
KG-05	K-05	58005	Leirbotnar	1975	602760	581068	523.0	1299	114.4	642.9		Bein hola	Í vinnslu
KJ-06	K-06	58006	Leirbotnar	1976	602544	580265	464.5	2000	142.3	576.2	1936.3	Bein hola	Ótengd - Eftirlitshola
KJ-07	K-07	58007	Leirbotnar	1976	602694	580944	509.0	2165	276.0	808.9	2106.2	Bein hola	Ónýt
KG-08	K-08	58008	Vítismór	1976	602196	581317	535.0	1658	141.9	537.0	1645.9	Bein hola	Ónýt
KJ-09	K-09	58009	Leirbotnar	1976	602796	580906	522.0	1280	274.9	1074.0	1264.0	Bein hola	Í vinnslu. 1977: Dýpkuð 163 m í 1264 m. 1982: Endurboruð í 1280 m.
KG-10	K-10	58010	Vítismór	1976	602510	581242	542.0	2082	275.3	805.5	2060.0	Bein hola	Ónýt - Eftirlitshola
KJ-11	K-11	58011	Leirbotnar	1976	602440	580841	483.2	2217	275.0	788.4	2193.5	Bein hola	Lokuð
KG-12	K-12	58012	Leirbotnar	1978	602883	580516	487.0	2222	282.8	985.3	2213.8	Bein hola	Lokuð
KJ-13	K-13	58013	Leirbotnar	1980	602834	580739	505.0	2050	279.1	1057.9	2018.0	Bein hola	Lokuð - Útúrborun
KJ-13A	K-13A	58113	Leirbotnar	1983	602834	580739	505.0	1780			1698.5	Skáhola	Í vinnslu
KJ-14	K-14	58014	Suðurhlíðar	1980	603367	580371	571.1	2107	206.5	699.1	2094.9	Bein hola	Í vinnslu
KJ-15	K-15	58015	Leirbotnar	1980	602975	581017	571.0	2097	290.2	1086.6	2093.3	Bein hola	Í vinnslu
KJ-16	K-16	58016	Suðurhlíðar	1981	603829	580387	609.3	1981	201.3	662.1	1946.4	Bein hola	Lokuð - Útúrborun
KJ-16A	K-16A	58116	Suðurhlíðar	1997	603829	580387	609.3	2191		662.1	2171.8	Skáhola	Í vinnslu
KJ-17	K-17	58017	Suðurhlíðar	1981	603886	580081	593.1	2190	201.3	685.3	1958.9	Bein hola	Í vinnslu
KJ-18	K-18	58018	Suðurhlíðar	1981	604217	580140	611.0	2215	193.3	662.6		Bein hola	Ótengd - Eftirlitshola
KJ-19	K-19	58019	Suðurhlíðar	1982	603270	580564	584.2	2150	195.1	642.1	2004.8	Bein hola	Í vinnslu
KJ-20	K-20	58020	Suðurhlíðar	1982	603544	580392	584.4	1823	206.3	641.3	2020.4	Skáhola	Í vinnslu
KJ-21	K-21	58021	Hvíthóll	1982	602134	578563	448.2	1200	23.5	281.4	1035.6	Bein hola	Í vinnslu. Viðgerð í 1984. Niðursetning 9 ⅝" fóðring og leiðara
KJ-22	K-22	58022	Hvíthóll	1983	602177	578743	446.9	1876	150.3	558.6	1845.9	Skáhola	Lokuð
KJ-23	K-23	58023	Hvíthóll	1983	601997	578504	446.1	1968	186.0	529.7		Bein hola	Lokuð
KG-24	K-24	58024	Leirbotnar	1988	602439	580861	483.2	1400	54.9	405.6	1196.2	Bein hola	Í vinnslu
KG-25	K-25	58025	Vítismór	1990	602562	581533	549.9	2105	389.4	1144.6	2089.0	Bein hola	Steypt upp að ~1205 m
KG-26	K-26	58026	Leirbotnar	1991	602295	580829	490.0	2127	417.9	1199.8	2114.4	Bein hola	Niðurdæling
KJ-27	K-27	58027	Leirbotnar	1997	602616	580802	486.2	1771	376.3	1093.8	1744.5	Bein hola	Í vinnslu
KJ-28	K-28	58028	Leirbotnar	1996	602673	580628	475.3	1003	2.8	55.8	973.5	Bein hola	Lokuð
KJ-29	K-29	58029	Leirbotnar	1997	602744	580447	471.1	2103	388.6	997.2	2076.0	Skáhola	Í vinnslu
KJ-30	K-30	58030	Suðurhlíðar	1997	603238	580584	584.2	2054	280.6	804.6	1787.0	Skáhola	Í vinnslu
KJ-31	K-31	58031	Suðurhlíðar	1997	603511	580397	584.6	1440	294.0	780.0	1387.0	Bein hola	Í vinnslu
KJ-32	K-32	58032	Vítismór-Vesturhlíðar	1998	602988	581039	571.8	1875	286.0	1069.5	1832.0	Skáhola	Í vinnslu
KJ-33	K-33	58033	Vesturhlíðar	1999	602990	581074	571.8	2011	307.8	1103.3	1869.0	Skáhola	Í vinnslu
KJ-34	K-34	58034	Vesturhlíðar	1999	603390	581566	603.1	2002	365.0	1021.0	1984.8	Bein hola	Í vinnslu
KJ-35	K-35	58035	Leirhnjúkur	2007	601951	580842	538.7	2508	261.3	1286.1	2480.3	Skáhola	Ótengt
KJ-36	K-36	58036	Vítismór	2007	603420	581567	604.4	2501	289.6	1102.9	2432.6	Skáhola	Í vinnslu - steypt upp að 1700 m
KJ-37	K-37	58037	Suðurhlíðar	2008	603838	580416	609.3	2194	228.8	759.4	2186.0	Skáhola	Í vinnslu
KJ-38	K-38	58038	Vesturhlíðar-Vítismór	2008	603435	581626	605.0	2700	299.3	1038.4	2640.4	Skáhola	Ótengd
KJ-39	K-39	58039	Suðurhlíðar	2008	602777	580451	471.0	2865	289.0	973.3	2614.4	Skáhola	Ótengd – steypt upp að 2612 m
KV-01	KV-01	58701	Vestursvæðið	2006	600184	578899	475.0	2894	278.4	795.9	2878.2	Bein hola	Ótengd
KS-01	KS-01	58801	Sandabotna-skarð	2007	603541	578238	473.0	2502	272.2	891.7	2445.2	Skáhola	Ótengd
IDDP-01	IDDP-01	28501	Vítismór	2009	602607	581630	549.0	2104	791.5	1958.2	2080.0	Bein hola	Ótengd

5 Origin of geothermal fluid and geothermal surface activity

5.1 Origin of fluid

There is available data on stable isotopes (^{2}H and ^{18}O) in well fluid from Leirbotnar, Suðurhlíðar and Hvíthólar but isotope analyses have not been conducted on samples from wells younger than KG-26 and isotope percentages in the fluid from wells in Vesturhlíðar are therefore unknown. However, results from measurements on oxygen isotopes, in fluid from KJ-34 and KJ-35, have recently been released, but results for hydrogen isotopes are still required. It is therefore not appropriate to include these in this interpretation at this time. Darling and Ármannsson (1989) interpreted these isotope results in such a way that two types of origin were discussed, that local rainwater came from Leirbotnar wells, whereas water in the wells in Suðurhlíðar and Hvíthólar originated from the nearby highland area further south (shown in a simple model in Figure 21). They believed that the latter originated from Hágöngur. It could also have originated from the groundwater which flows from the Dyngjufjöll Mountains to Öxafjörður. The water in the Námafjall system is thought to originate from this groundwater system (Arnar Hjartarson et al. 2005).

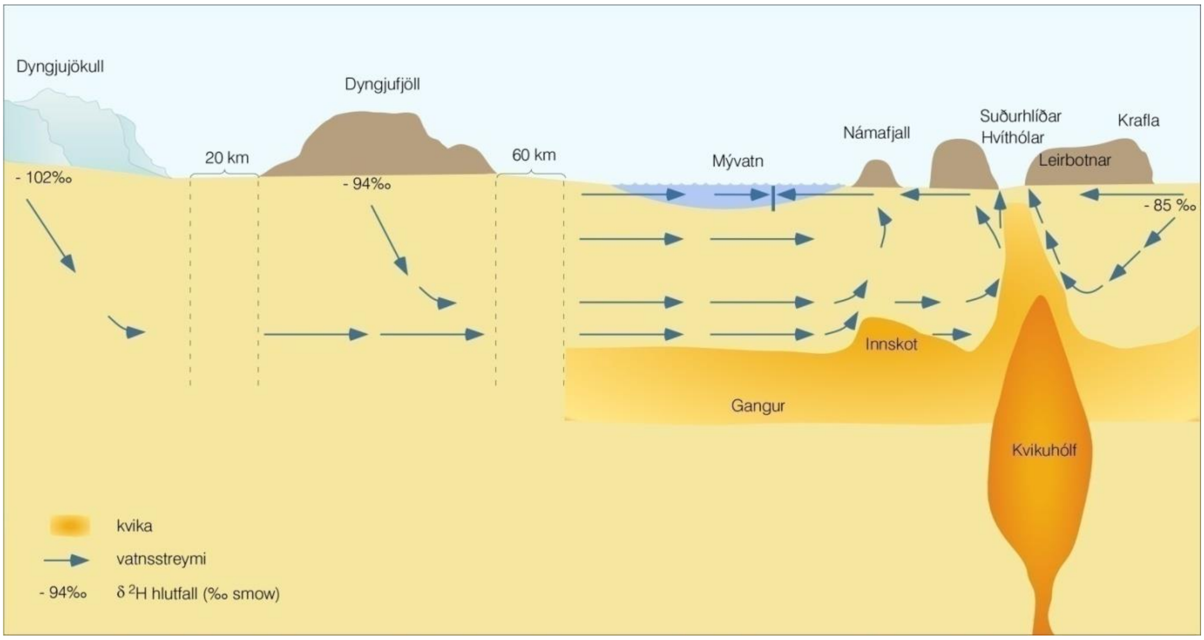


Figure 21. *Possible origins of water in the Mývatn area*

5.2 Gas emissions through the surface at Krafla

The flow of CO_2, through the surface, was measured in an extensive area of Krafla between 2004 and 2006. Initially, only a few lines were measured, but a survey grid later revealed the fact that gas emissions exceeded levels usually expected from organic soil. The first survey grids were located in Leirhnjúkar, Suðurhlíðar and the Vesturhlíðar area at Krafla. The flux of CO_2 was substantial in Suðurhlíðar and in Vesturhlíðar and by Leirhnjúkar, but levels were low in Leirbotnar (Ármannsson et al. 2007). Further measurements were conducted in the north of Víti and to the west of Hveragil in the summer of 2008. These measurements confirmed the overall picture previously outlined, that gas emissions were less to the west of Hveragil than to the east. Gas emissions were also low in the area to the north of Víti. Figure 22 shows the results of all gas emission measurements conducted at Krafla between 2004 and 2008. The shape of the gas emission anomaly in the slopes of Krafla, Leirbotnar and to the north of Víti indicate that gas travels upward to the surface along fissures (Figure 22). Two or even three anomalies trending WNW can be seen in the southernmost part of the area. This can also be seen in fissures at the surface and stratigraphic connections between wells have also indicated that faults trending in this direction are beneath the surface. The gas emissions anomaly in the Vesturhlíða area of Krafla trends NNE and a parallel anomaly can be seen to the west of Hveragil although it is much less defined. Faults trending NNE are prominent in the area. Increased gas emissions can probably be detected to the north of Viti, trending NNW but they are rather weak. It should be noted that gas emissions to the north of Víti are barely traceable and all interpretation of these results should be without prejudice.

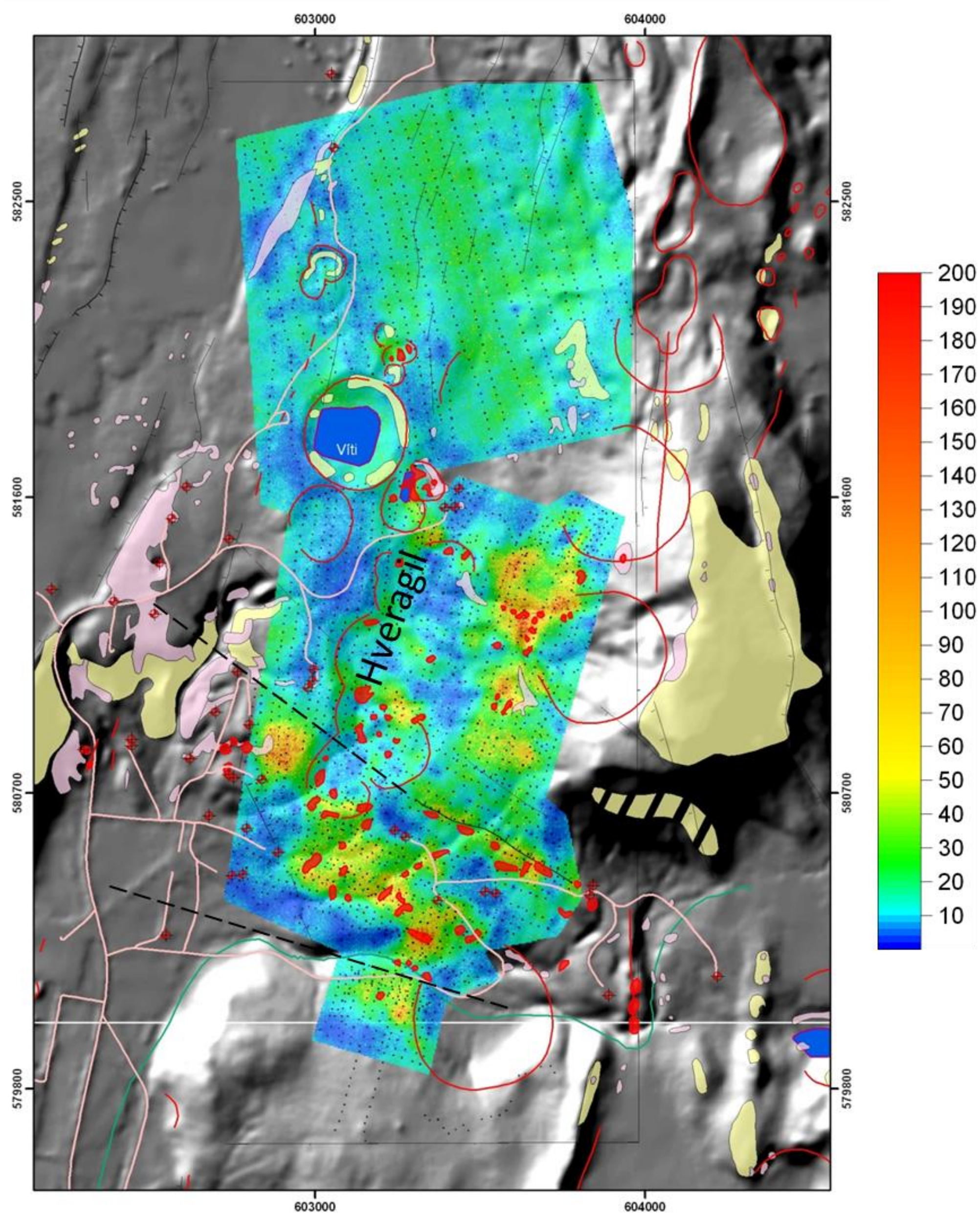


Figure 22. *The flow of CO_2, through the surface in the Krafla area (measured between 2004–2008)*

The quantity of calcites in cuttings/filings in wells at Krafla has been measured (Figure 23). The first results indicate that more calcite is bound to the formation in Leirbotnar and reaches a greater depth than that in the Suðurhlíðar and Vesturhlíðar area (Ármannsson et al. 2007). This is consistent with the idea that calcite is more likely to bind itself in colder fluid, in the upper region of the Leirbotnar system, than it is in the Suðurhlíðar or Vesturhlíðar area where the steam temperature is significantly higher and the rock temperature follows boiling point depth curve to the surface.

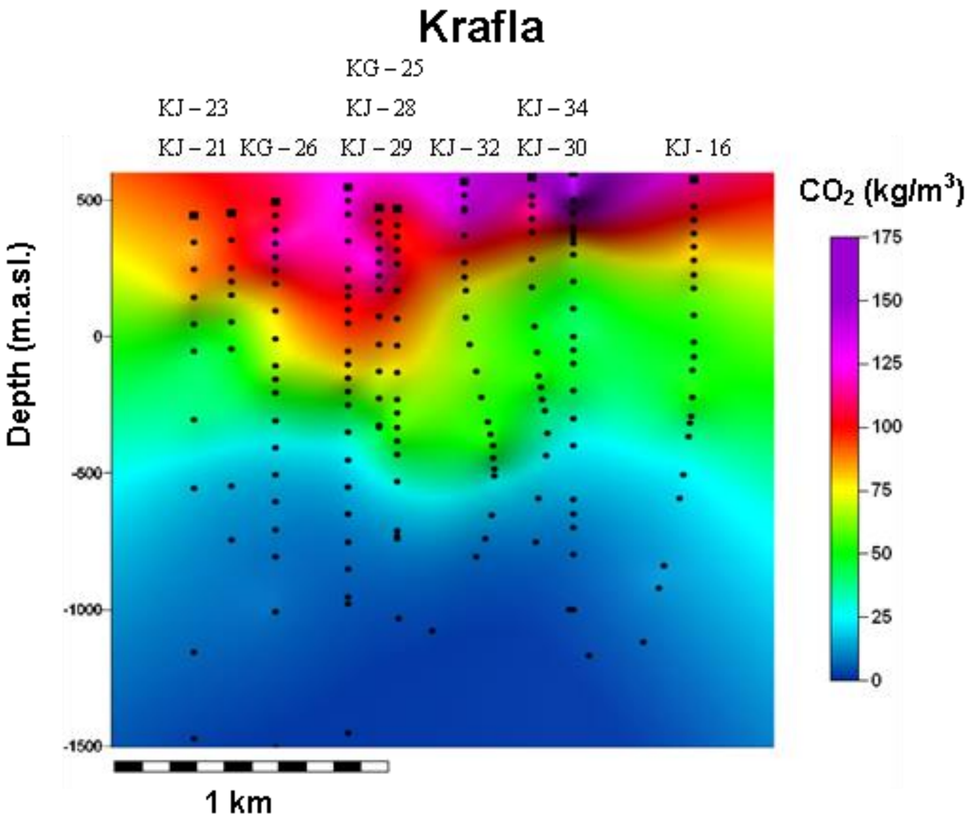


Figure 23. *CO_2 bound in strata at Krafla. The fill color shows CO_2 in kg per cubic meter*

5.3 Changes to surface activity

It could be said that surface activity in the geothermal area at Krafla mostly follows the magma chamber that lies beneath the area. This applies to hot springs, fumaroles and geothermal alteration. Changes to surface activity have been closely monitored since the Krafla Fires and since utilisation in the area began by assessing warm or hot ground in the area, when weather conditions allow. The data dates back to 1977 (Gestur Gíslason et al. 1978). Monitoring has been overseen by Jón Benjaminsson and Trausti Hauksson in the last few years. An overview of warm or hot ground in the area between 1977 and 2004 can be seen in Figures 24 and 25. Figure 24 shows the results from the years 1977, 1990 and 1995 and Figure 25 from the years 1999, 2001 and 2004. Initially, monitoring on warm or hot ground did not cover the area southward up to Hvíthólar and is therefore not included in Figure 24. The Figures are based on data from the following years: 2nd of November (Gestur Gíslason et al.. 1978); 7th of October, 1990 (Jón Benjamínsson & Trausti Hauksson, 1990); November 1995 (Jón Benjamínsson & Trausti Hauksson, 1995); 30th of October, 1999 (Jón Benjamínsson, 1999); 21st of October, 2001 (Jón Benjamínsson & Trausti Hauksson, 2001); 29th of November to the 2nd of December, 2004 (Jón Benjamínsson & Trausti Hauksson, 2004). The same conditions and methodology are not used in all warm or hot ground mapping. In 1977, patches were drawn up according to aerial photographs. In 1995 they were marked on the ground and photographs were used later on. It is unlikely that surface activity has increased during this period. In fact, if Figures 24 and 25 are compared then it has actually decreased. Activity also seems to have shifted to the southeast. Jón Benjaminsson and Trausti Hauksson (1998) created an overview of the changes to activity in the various areas in the Krafla area. Shifts had occurred in Leirhnjúkar, activity had somewhat increased in close proximity to Víti and there was a decrease (mainly a shift) in Hveragil. Significant outflow (the chimney) had occurred in the western slopes in 1984 and was at its peak in 1989. An increase had occurred elsewhere in Vesturhlíðar. Steam was still visible in Hrafntinnuhryggur and warm or hot ground areas in Grænagilsöxl were found in the northernmost area as well as warm or hot ground to the east beneath its northern side. Activity increased in Hvíthólar in 1980 and continued to increase with some fluctuations until 1997.

Warm or hot ground was analysed in the Krafla area in the autumn of 2004 (Jón Benjamínsson & Trausti Hauksson, 2004) in the same manner that it had been analysed annually for many years. Warm or hot ground and steam flow were at a minimum in the Leirbotnar area and only two areas were bare. The steam flow had increased in Leirhnjúkar and in Hrafntinnuhryggur, but had decreased in most areas of the Hveragil area, in Vesturhliðar and in the upper area of Suðurhlíðar. Steam flow had decreased by the hot spring in Hvíthólar but had increased in the fault area.

Research on the chemical composition of gases emitted from fumaroles and hot springs in the Krafla area has a long history although the research gathered and interpreted was rather sparse in nature. The earliest results from gas concentration analyses is from 1889 (Christensen, 1889) and the next archive dates back to 1906 (Thorkelsson, 1910), 1950 and 1951 (Jarðboranir ríkisins, 1951). The geothermal department at the National Energy Authority began preliminary research on the Krafla and Námafjall area in the summer of 1970 (Guðmundur Guðmundsson et al. 1971). Samples of gas were gathered and analysed. Detailed information on the chemical composition of gases in the Krafla area has been available since (Gestur Gíslason et al. 1978). Jón Benjamínsson and Trausti Hauksson (2004) have been responsible for monitoring surface activity and the chemical composition of gases in fumaroles, on behalf of Landsvirkjun, for the last few years. Significant changes were identified in the chemical composition of steam released from fumaroles. There was a significant change to the chemical composition of gases from fumaroles when there was an increase in gas emissions at the onset of the Krafla Fires. There was an increase in CO_2 in Hveragil and Víti and in the Leirhnjúkar area, but levels were minimal in the Suðurhlíðar and Hvíthólar area (Níels Óskarsson, 1978; Gestur Gíslason et al. 1978). CO_2 levels have increased in the Suðurhlíðar area since then. The concentration of CO_2/H_2S has been used as an indicator of magmatic gases; the percentage rose significantly in those areas in Krafla affected by magmatic gases (Halldór Ármannsson et al. 1989). Figure 26 shows the CO_2/H_2S percentage of gases in a number of fumaroles, including samples form 1889-2004. This shows the percentage to be well below 30. It increased significantly during the Krafla Fires but decreased rapidly and had reduced to below 30 in most areas (minimal affects) in 1999. However, the effects of acid, magmatic gases are still apparent in Krafla.

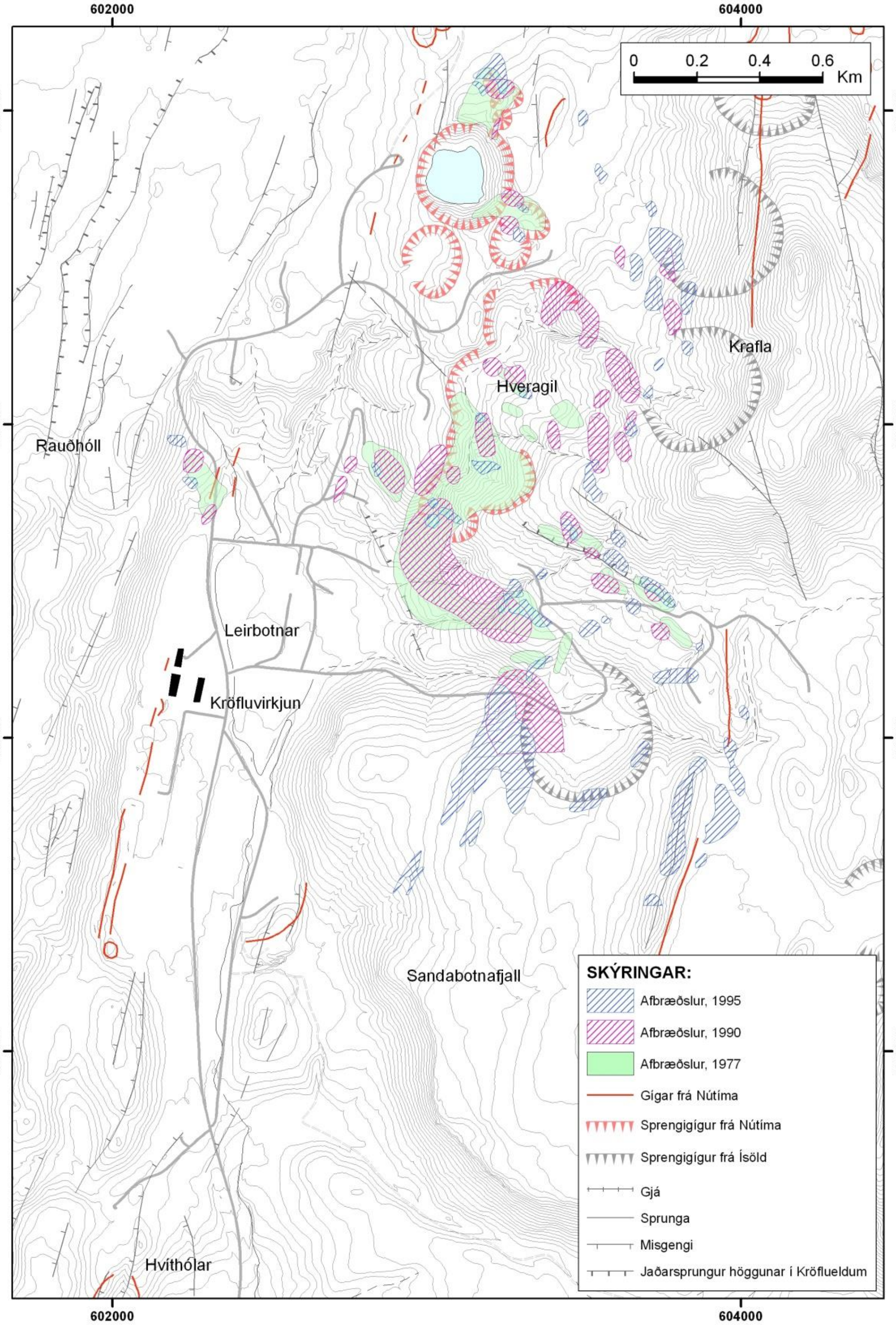


Figure 24. *An overview of warm or hot ground at Krafla in the years 1977, 1990 and 1995.*

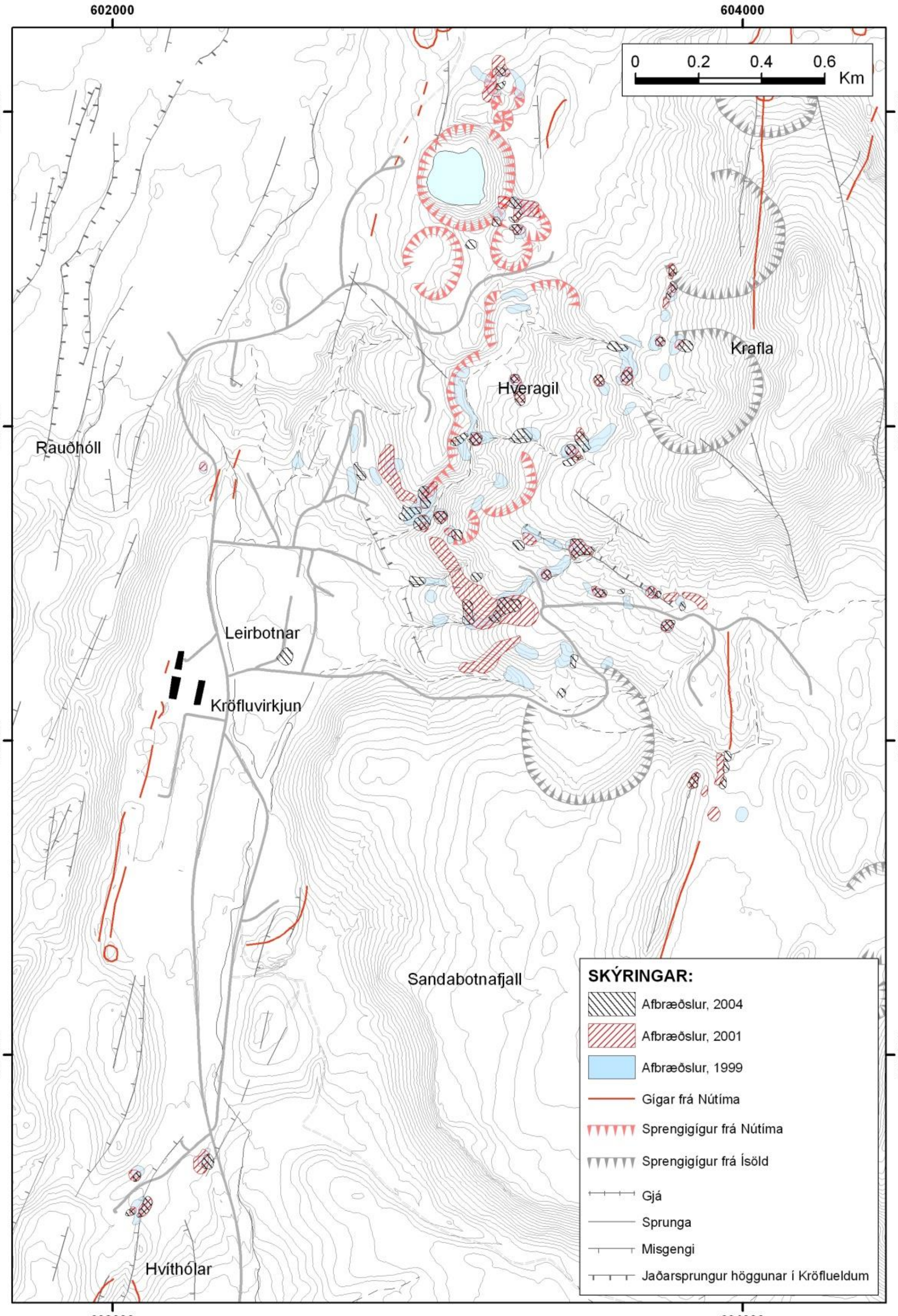


Figure 25. *An overview of warm or hot ground at Krafla in the years 1999, 2001 and 2004*

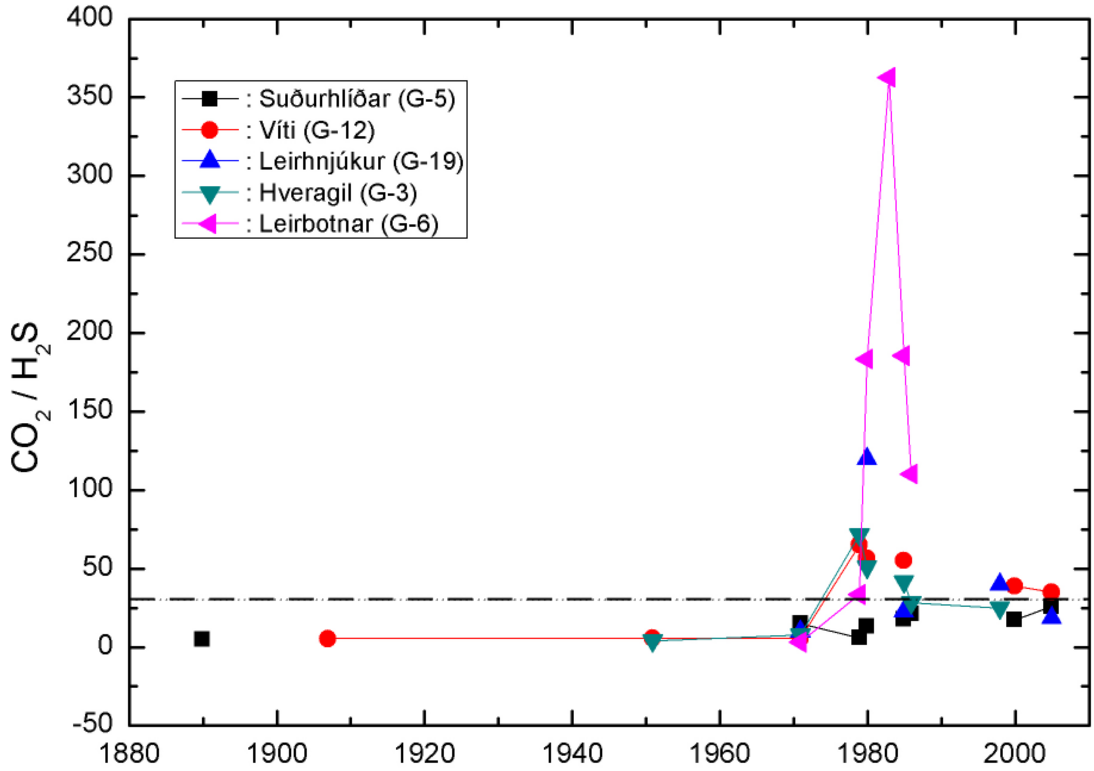


Figure 26. *The CO_2/H_2S percentage of gases in a number of fumaroles, including samples from 1889-2004.*

6 Lithology and alterations in boreholes at Krafla

Drilling began at Krafla in 1974 and 43 wells had been drilled for steam extraction purposes by the autumn of 2008. All these wells are located within the Krafla caldera. Most of the wells have been drilled in an area that reaches from the Suðurhlíðar area of Krafla and westward up to Leirhnjúkar. The drilling areas are called Suðurhlíðar, Vesturhlíðar, Leirbotnar og Vítismór. Three wells have also been drilled in the Hvíthólar area, which is on the southern margin of the caldera. Exploratory drilling has been carried out in three new areas in the last few years: Sandbotnaskarð (by the southern margin of the caldera and approx. 1.5 km to the east of Hvíthólar), Vestursvæði in the Leirhnjúkar lava field area (approx. 2 km to the west by Hvíthólar) and Leirhnjúkar (to the west of the current production area). See Figure 19.

6.1 Initial lithology and alteration profiles

Alteration profiles and lithology have been analysed systematically via drill cutting samples and these results provided the basis for the development of a profile of the stratigraphic formations at Krafla. The first model was based on information from wells KW-1 to KJ-11 which were drilled in the Leirbotnar and Vítismó areas (Hrefna Kristmannsdóttir, 1978). The knowledge base on the structure of the lithosphere increased with further drilling in the east at Suðurhlíðar and to the south at Hvíthólar. The strata layer and alteration profile of the Krafla system was improved by utilising this research (Ásgrímur Guðmundsson, 1983; Ármannsson et al. 1987), see Figure 27. The second profile was based on information from 23 wells. The results showed that the stratigraphic formations stratum/stratigraphy at Krafla can be roughly divided in two: piles of surface formations are dominant to a depth of 1200-1300 m (based on surface level), but intrusions become dominant beneath this area. Piles of surface formations were divided into five formations: two palagonite formations and three lava successions (M1-M2; B1-B3), but the lower lava succession (B3) can be traced back to a warmer period before the formation of the caldera (Ásgrímur Guðmundsson, 1983; Ármannsson et al. 1987). There is also a 200 to 300 m thick series of acidic intrusions at a depth of 1000 - 1400 m (based on surface level) beneath Suðurhlíðar. Gabbro intrusions are found at a depth of 1800 to 2000 m (based on surface level) in the wells in this area (Figures 27 and 28).

Twenty wells have been drilled in the area since the last geology and alteration profiles were developed and the production area has grown by 1 km to the north of Víti. Exploratory drilling has taken place in Sandabotnaskarð, Vestursvæði and in the direction of Leirhnjúkar for research purposes, pertaining to the proposed expansion of Krafla Geothermal Power Station. A simplified stratigraphic and alteration profile based on research from the latest wells is shown in Figures 29-32. Information on strata, alteration and water sources in wells are based on research published in interim reports on the wells (Ásgrímur Guðmundsson et al.1981a, b; Guðmundur Ómar Friðleifsson et al.1981a, b, c, d; Ásgrímur Guðmundsson et al.1982a, b; Benedikt Steingrímsson et al.1982; Ásgrímur Guðmundsson et al.1983a, b, c, e, f, g; Ásgrímur Guðmundsson et al.1988a, b, c; Ásgrímur Guðmundsson et al.1990a, b, c; Ásgrímur Guðmundsson et al.1991a, b; Ásgrímur Guðmundsson et al.1992; Ásgrímur Guðmundsson et al.1996; Ásgrímur Guðmundsson et al.1997a, b, c, d, e, f, g; Hjalti Franzson et al.1996; Ásgrímur Guðmundsson et al.1998b, c, d; Hjalti Franzson et al.1998; Arnar Hjartarson et al.1999; Ásgrímur Guðmundsson et al.1999a, b, c; Benedikt Steingrímsson et al.1999; Anett Blischke et al.2004; Bjarni Gautason et al.2006; Sigurjón Böðvar Þórarinsson et al.2006a, b; Anette K. Mortensen et al.2007a, b, c; Ásgrímur Guðmundsson et al.2007a, b, c; Bjarni Gautason et al.2007a, b; Ásgrímur Guðmundsson et al.2008a, b; Bjarni Gautason et al.2008a, b, c, d; Magnús Á. Sigurgeirsson et al.2008a, b; Auður Ingimarsdóttir et al.2009a, b). Three east-west profiles have been collected; they cover Vítismó; Suðurhlíðar-, Leirbotnar and the Leirhnjúkar area and Sandabotnar-, Hvíthólar and the Vestursvæði (Figure **Error! Reference source not found.**).

Figure 30 shows the north-south profile of Víti, Suðurhlíðar and Sandabotnaskarð. Stratigraphic sections are simplified based on drill cuttings and well testing. The strata has been divided into rough sections according to rock type and connected between wells to give an overview of strata sequence. However, a more detailed review will come later. Aquifers can be located by using temperature logs and circulation losses during drilling. The position of aquifers has been connected to strata, eruptive fissures and faults (shown as grey arrows in Figures 29 and 30). The alteration belt is shown based on temperature dependent alteration minerals, identified in drill cuttings, from wells and via an XRD analysis of clay. XRD studies have not been conducted on all wells and in some cases the alteration belt has been defined using clay analyses from other wells (in close proximity), where XRD studies have been conducted.

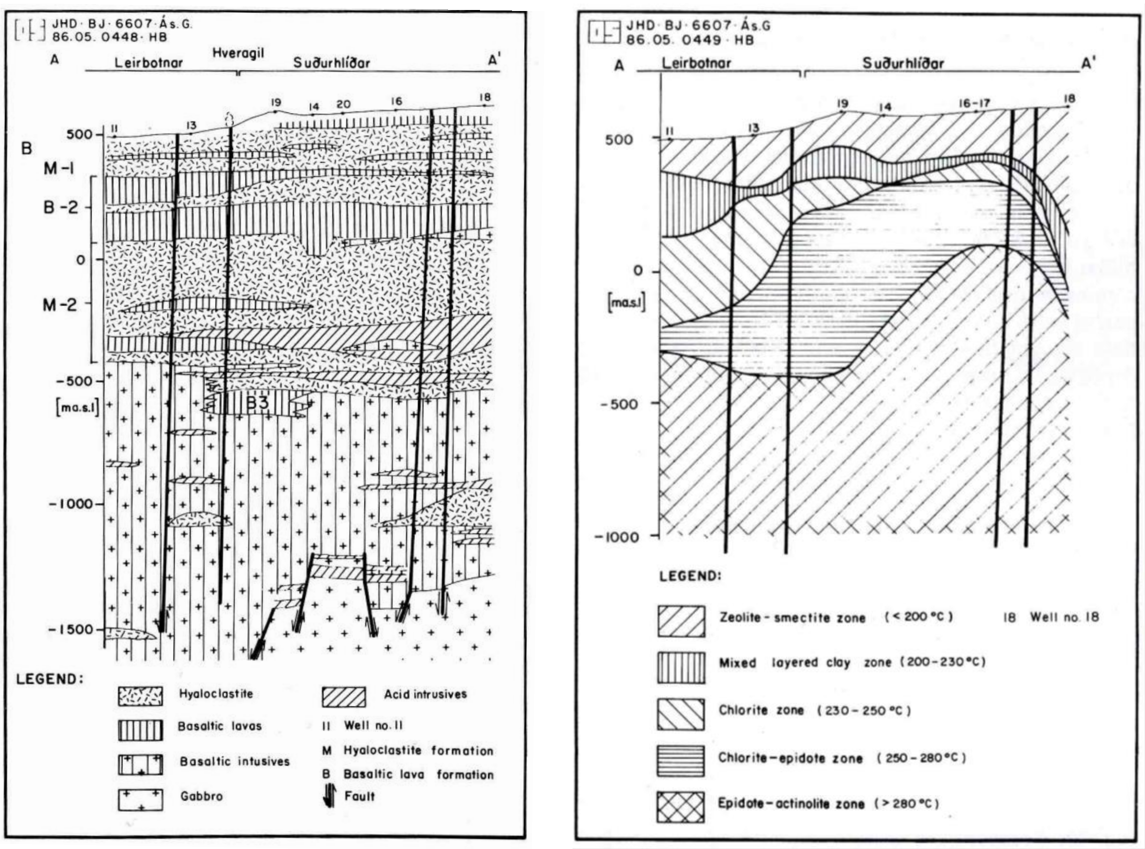


Figure 27. *Strata layer and alteration profile of Leirirbotnar and Suðurhlíðar*

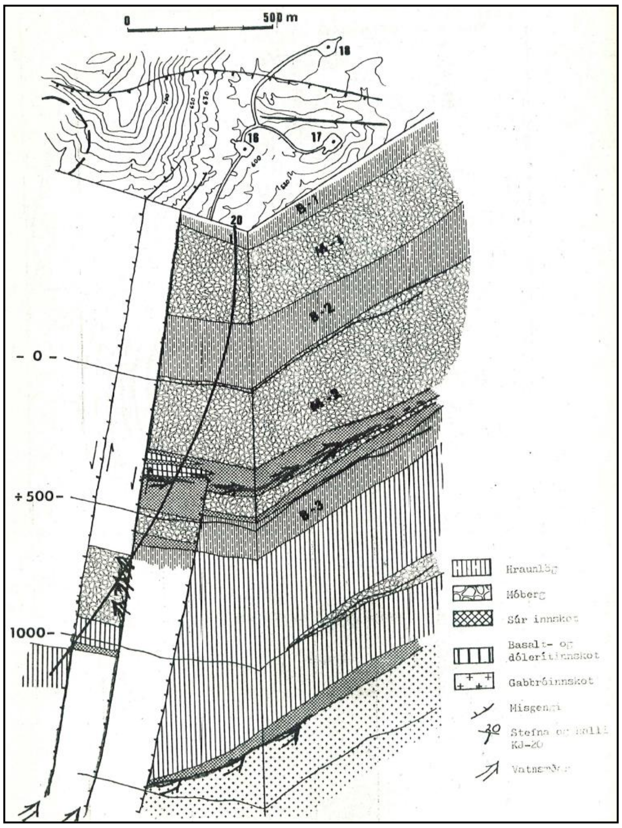


Figure 28. *Stratigraphic section of Suðurhlíðar and A-V faults*

6.2 Stratigraphic cross section of Suðurhlíðar, Leirbotnar and Vítismó

The stratigraphic and alteration profile is shown from east to west, across Suðurhlíðar and Leirbotnar in Figure 27 (Ármannsson et al.1987). The stratigraphic section in Figure 29B lies in the same position as the older profile but reaches further west, south of Leirhnjúkar and is based on information from well KJ-35. Broadly speaking, the strata sequence is the same as that found in previous results; accumulation rock (hyaloclastite(s)/ palagonite(s) and lava successions/series) are dominant down to a depth of 900 to 1200 m (based on surface level) and basalt intrusions are dominant beneath this area. There is also a 200 to 400 m thick acidic intrusion series beneath Suðurhlíðar and the largest aquifers in the wells in Suðurhlíðar are often directly connected to these intrusions. Acidic intrusions are not as obvious to the west of Hveragil and in the east of Suðurhlíðar. However, thin, acidic intrusions are present at different depths in Leirbotnar and Vítismó and are often connected with high permeability. Acidic magma has also been found at a shallow depth in the stratigraphic formation. Drilling has penetrated magma on two occasions: at Suðurhlíðar (below 2500 m) in well KJ-39 (based on surface level) and at Vítismó, at a depth of approx. 2100 (based on surface level) in well IDDP-1. Initial results indicated that the magma in IDDP-1 originated from a greater depth and had pushed its way upward in the lithosphere, whereas the magma in KJ-39 was localised.

The strata in well KJ-35, which is drilled at an incline westward beneath the crater from the Mývatn Fires to the south of Leirhnjúkar, differs somewhat to what is usually found in wells at Leirbotnar as host rock is dominant to a depth of 1800 m (based on surface level) and intrusion rates are low. However, intrusions are dominant in the lowest 500 m of the well. The low intrusion rates can be explained by the fact that the majority of intrusions are almost vertical and form a fissure swarm. These appear as thin, adjacent intrusions in inclined wells. The wells at Leirbotnar and Vítismó are mostly vertical and if these wells come in close proximity to thin, vertical intrusions then they can form a thick layer in the well. The strata in most wells at Leirbotnar and Vítismó are mostly intrusions (>90%) below a depth of 1000 to 1200 m (based on surface level) and are drilled from one intrusion to another without any indication of a host rock. This can partly be explained by the position of wells as their chosen location is often above or by a fracture and/or intrusion swarm. Furthermore, small inclined intrusions probably lie from the magma chamber and to the central volcano. The intrusion rate in the wells to the north by Víti is low compared with the wells in Leirbotar and Suðurhlíðar (Figure 29). Host rock can be seen at a greater depth in well KJ-20 than in other wells in Suðurhlíðar (the well is directionally drilled in a northward direction, beneath the Krafla Mountain. Palagonite formations are obvious at a depth of 1000 m (based on surface level) in directionally drilled wells on the drilling platform to the east of Víti and are more common there than elsewhere at Krafla. One explanation for this could be the presence of a horst lying in an east-westward direction almost traversing the dominant fissure swarm. The southern margin was thought to lie in and around Grænagil, heading southward above Leirhnjúkar, and this is supported by a fracture at the surface and resistivity and aeromagnetic measurements. The northern margin was not as well defined (Ásgrímur Guðmundsson, 1983).

Well KJ-38 was drilled at an incline, northward and past the Hveragil fracture in the summer of 2008. Lava successions are dominant from a depth of 300 m.b.s.l and down to 1200 m.b.s.l (Figure 30) which is unlike other wells to the east of Víti. The difference in stratigraphic formations in the wells at Víti can be explained by faults which thus far have not been detected at the surface or in surface measurements. Another possible hypothesis pertaining to deep palagonite formations by Víti is that they are simply older palagonite formations that lava has reached.

6.3 Stratigraphic cross section of Sandabotnaskarð, Hvíthólar and Vestursvæði

Drilling has been carried out in three areas to the south of the periphery of the caldera. A well was directionally drilled eastward in Sandbotnaskarð, three wells were drilled by Hvíthólar (one of these was directionally drilled westward) and in the western area in the Leirhnjúkar lava field (Figure 29C).

East-westerly profiles between the areas are approx. 4 km. Palagonite formations are dominant to a depth of between 100 and 300 m.b.s.l, by the southern margin of the caldera, apart from a series of lava layers (approx. 100m thick), which can probably be traced from the current period to the Weschelian period. There are no traces of obvious lava successions in palagonite formations like those found in Leirbotnar and Suðurhlíðar. Lava successions are dominant to a depth of at least 1600 m.b.s.l, deep under the hyaloclastite(s)/ palagonite(s). The break between the hyaloclastite(s)/ palagonite(s) and the lava successions are possibly evidence of the slower subsidence of the southern margin after the formation of the caldera. This could indicate that the Krafla caldera is complex and the greatest subsidence is in the mid-section. The lava successions can probably be traced back to the last warm period but hyaloclastite(s)/ palagonite(s) were probably formed in the last glacial period. The lava succession at a depth of 300-100 m.b.s.l in Leirbotnar and Suðurhlíðar, in the mid-section of the Krafla caldera, could possibly be connected with volcanic activity after the formation of the caldera. It is not uncommon for volcanic activity to shift into the middle of the volcano after an extensive eruption.

The intrusion rate is usually lower in wells by the southern margin of the caldera and increases at a greater depth than that of wells in Leirbotnar and Suðurhlíðar. The intrusion rate is low, down to a depth of 1300 to 1600 m.b.s.l in the Vestursvæði area, Hvíthólar and Sandabotnaskarð (Figure 29C). The wells in Hvíthólar do not reach more than 1600 m.b.s.l whereas the intrusion rate is significantly higher in well KS-01 in Sandbotnaskarð. A thick block of silicic intrusions (diorite or granodiorite) has been identified below 1200 m.b.s.l in well KS-01, solely by analysing drill cuttings. The percentage of acidic rock is low by the caldera edge (with the exception of well KS-01) and forms only a thin layer in the profile in Figure 29C.

6.4 Alteration

Alteration has been mapped according to depth in the Krafla area, based on drill cuttings, slices and XRD measurements. Various alteration minerals are formed with increasing temperatures. There is a correlation between this and the dominant temperature at any given time, and remains stable in many cases despite the cooling of the area. This is therefore some sort of testament to previous thermal conditions. Thermal alteration in a typical Icelandic high temperature area (the central volcano) can be divided into an alteration belt associated with particular temperature dependent minerals like zeolite-smectite, a mixed layer of clay minerals, chlorite, chlorite epidote and epidote-actinolite which reveal information on the temperature status.

XRD clay studies are not available for wells KG-24, KJ-27, KJ-31, KJ-32, KJ-33, KJ-36 and KJ-37. The alteration belt for these wells has been defined by using clay studies from wells in close proximity.

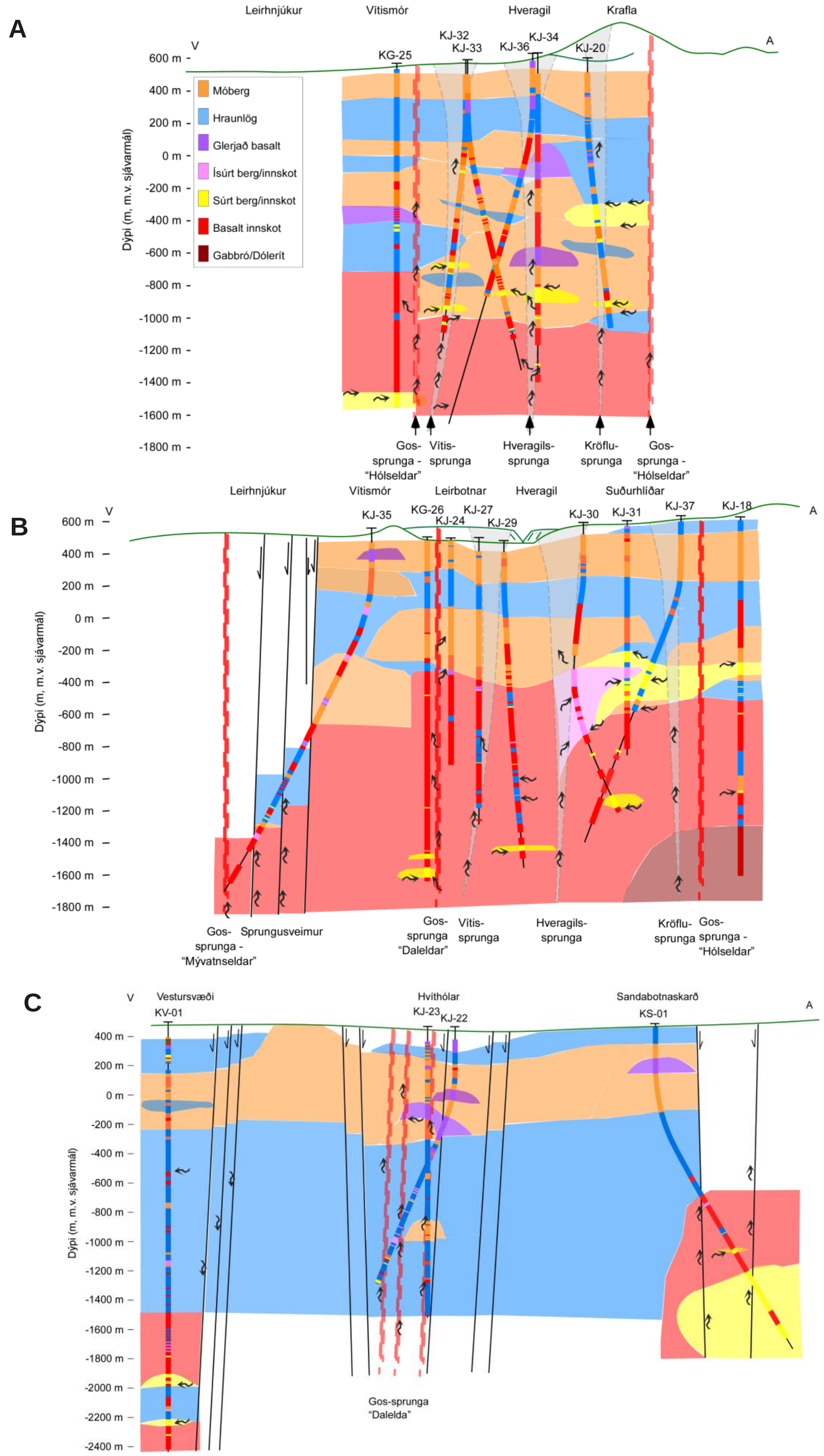


Figure 29. *A simplified stratigraphic and alteration profile of A: Vítismó & Víti, B: Leirhnjúkar, Leirbotnar and Suðurhlíðar, C: Vestursvæðið, Hvíthólar and Sandabotnaskarð*

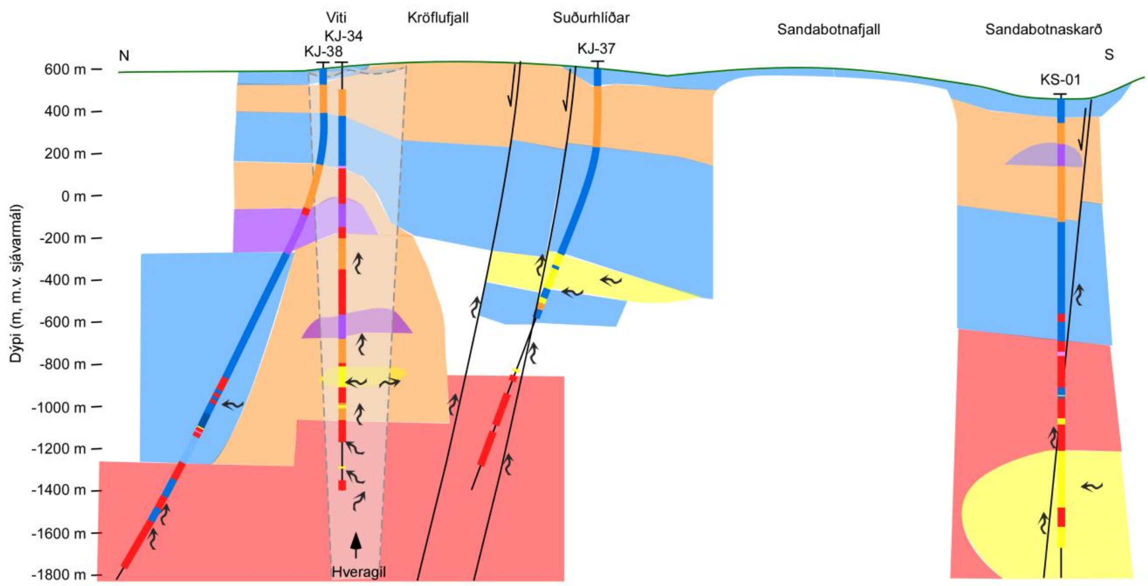


Figure 30. *A simplified stratigraphic and alteration profile of Víti, Suðurhlíðar and Sandabotnaskarð.*

Suðurhlíðar – Leirbotnar – Vítismór

Previous results show that there is a break in alteration by Hveragil (Figure 27 and 31). High-temperature alteration can be found at a shallow depth to the east of Hveragil beneath Suðurhlíðar, and the chlorite-epidote belt can be found at a depth of 200 to 300 m. There are no signs of significant cooling, but the increase in alteration is so rapid that this would indicate that the rock temperature beneath Suðurhlíðar is around boiling point. Alteration does not increase rapidly according to depth in well KJ-18 in the easternmost part of Suðurhlíðar which indicates that this is in close proximity to the eastern margin of the geothermal system in Suðurhlíðar or that the system is deepening.

A 200 to 400 m thick, almost horizontal intrusion series of acidic rock, is prominent in stratigraphic formations in Suðurhlíðar. The largest aquifers in wells are often connected to these intrusions which is also an indication of high permeability. However, there is the possibility that a poor, vertical porous area is located in the shallow depths of the system whilst the higher pressure in Suðurhlíðar keeps the upper system (shallow system) separated and that this could be the reason for the boiling temperature below Suðurhlíðar. Maars (phreatic eruption sites) are evidence that the temperature in the Suðurhlíðar system has been near boiling point for some time and have mostly formed around and to the east of Hveragil. Zeolite-smectite and the blended layer belt can be found at a shallow depth in Leirbotnar to the west of Hveragil, but the alteration level increases at a slower rate according to depth and first reaches the chlorite-epidote belt below 100 to 200 m.b.s.l. Alteration in the upper system (shallow system) in Leirbotnar and Vítismó (down to a depth of 500 to 800 m.b.s.l) is otherwise characterised by calcite, which is rather common and epidote is overprinted by calcite and clay, which is irrefutable evidence of cooling before the epidote was formed. There is a similar distribution of alteration minerals to the east and west of Hveragil, further north by Víti. However, calcite can be identified in certain areas down to a depth of 1300 m.b.s.l in well KJ-38. The well was drilled almost directly north from Víti alongside the Hveragil fracture and this is a sign of cooling (Figure 32). TEM and MT measurements show a sharp northern margin of the geothermal system quite far north of the basin of well KJ-38, which is well within the resistivity depression. The depth of the deeper system in well KJ-38 can be interpreted as a localised invasion of colder water along the fissure system to the north. The relatively slow increase in temperature with increased depth according to alteration in the Leirbotnar and Vítismó areas is consistent with a dual system. The upper system (shallow system) is characterised by temperatures between 180–220°C which can clearly be seen down to a depth of 1000 m.b.s.l in well KJ-35 which is directionally drilled in the direction of Leirhnjúkar. According to the analysis of fluid inclusions in alteration minerals in the upper system (shallow system) of Leirbotnar (Ásgrímur Guðmundsson, 2008), then alteration would indicate higher temperature conditions than currently found in the upper system (shallow system) and temperatures would have been similar to those beneath Suðurhlíðar but would then have cooled (as confirmed by calcite overprinting).

A theory has been put forward that the cooling of the upper system (shallow system) in Leirbotnar and Vítismó is relatively new and would have occurred after the Víti eruption in 1724 (Guðmundur Böðvarsson, 1980). It is more likely that a rapid rate of eruptions with the divergence of fissures would have provided a more open path for close by cold groundwater into the upper section of the geothermal system.

There is a break between the upper and deeper systems in the Leirbotnar and Vítismó areas approx. 200 to 400 m below the palagonite formation. Alteration shows that cold water would have had easy access to the upper section and is likely to have travelled along fractures and easily channelled, horizontal planes between stratigraphic layers.

The mid-section of the rift zone traverses the middle of the Krafla central volcano. The volcanic history of the area shows that the volcanic rift zone has shifted within the volcano (Kristján Sæmundsson, 1991). The main volcanic activity after the Ice Age took place during the Mývatn and Krafla Fires. During the Dalelda Fires (just after the settlement of Iceland) the eruptive fissure was located to the east of Þríhyrningur and the powerhouse for the Krafla Geothermal Power Station actually stands on the eruptive fissure. An eruption occurred in the fissures to the northwest of Víti and in Sandbotnafjall over 200 years ago during the Hólselda Fires. This shift opened fractures which could facilitate the type of cooling found in the upper system (shallow system). The profile from the east, beneath Suðurhlíðar and up to Leirhnjúkar in the west shows an increase in the rate of fissures and faults to the west up to Leirhnjúkar (maps 1 and 2). The high fault and fracture rate increases permeability in stratigraphic formations and would possibly open a channel for invading water and the mixing of cold groundwater (localised and from the north and south) with the upflow of hot water from the deeper system.

Alteration is so extensive at a depth of between 200 and 300 m in Suðurhlíðar, Leirbotnar and Vítismó that it is likely that rock temperature was in fact above the current boiling point depth curve. This discrepancy could be due to alteration being evidence of earlier temperature conditions in the system when the water level was higher in the area. This could have occurred during the last glacial period when a glacier covered Krafla.

Sandabotnaskarð – Hvíthólar – Vestursvæði

Alteration by the southern margin of the caldera is different to that found in the three drilling areas (Figure **Error! Reference source not found.**C). High-temperature alteration is found at a shallow depth in Hvíthólar. An epidote-actinolite belt appears just below sea level and calcite even seems to disappear at that depth. The alteration temperature is reversed below a depth of 500-600 m.b.s.l with calcite overprinting consistent with the temperatures in the system by Hvíthólar (Figure 52). Alteration increases slowly and steadily in Sandbotnaskarð and the temperature within the system correlates with alteration.

Drilling work on well KV-01 in the Vestursvæði area revealed that the system had cooled significantly and there were obvious indications of calcite overprinting and even a reversal in alteration. Alteration in the upper section of well KV-01 shows a rapid increase in temperature similar to that in Hvithólar and a chlorite-epidote belt takes over at a depth of 100 m. However, calcite and laumontite (stable <180°C) overprinting occurs at a depth of 700 to 800 m. There is an obvious difference once the epidote-actinolite belt is reached (it is found at the same depth in well KS-01 in Sandbotnaskarð) and this would indicate that the temperature would never have been higher than 280°C, at a depth of 1400 m. This is evidence that the thermal source would have been as deep-set as it is currently in Sandbotnaskarð.

Well KV-01 is to the west of the fissure swarm, which traverses Krafla, where the fracture rate is high and divergence is extensive. TEM and MT measurements indicate that the geothermal system was wide spread in Vestursvæði. However, alteration indicates that the area was characterised by ongoing activity (much like Leirbotnar) which probably came as a result of cold water easily accessing the system via fractures. Fractures and divergence in the area is likely to have increased permeability significantly and therefore facilitated deep activity/cooling in the system.

6.5 Permeability and faults

The porosity and permeability of rock differs according to rock type. Porosity in fresh hyaloclastite(s)/ palagonite(s) is generally 25–35% whereas porosity in basaltic rock is approx. 5– 15% (Ómar Sigurðsson & Valgarður Stefánsson, 1994). Deposit filled vesicles are formed during thermal alteration which often cut off the connection between pores, and the permeability of the rock is therefore compromised significantly.

There is little evidence of fresh rock in stratigraphic formations in Vítismó, Leirbotnar and Suðurhlíðar as the geothermal system is at a shallow depth. Alteration increases in Suðurhlíðar and the temperature increases rapidly with increased depth. Cooling has caused calcite to fill vesicles in the rock in the shallow zone beneath Leirbotnar and Vítismó (Figure 23).

There is low permeability in the Krafla geothermal system as a result of porosity in accumulation rock which is mostly due to alteration and deposits. Permeability in wells is therefore mostly connected to faults, fissures and intrusions. Wells have been positioned and designed in such a way that they cut through fractures, intrusions and faults. Initially, wells were drilled 'straight' (vertically) but directional drilling has been used more frequently in order to minimise disturbance at the surface and to steer the direction of the wells with more precision. Inclined wells show the connection between permeability and the faults and fissures 'aimed for', much more efficiently than ´straight´wells.

The main fracture zone in Krafla trends NNE-SSW. High permeability was discovered in the fissure swarm (during drilling) connected to the tephra ring row at the Víti fracture system and the Hólselda and Dalselda volcanic craters. Well KJ-35 was also drilled into the fracture zone to the south of Leirhnjúkar and up to the Mývatn Fires eruptive fissure (Figure 33). Most of the faults trend NNE-SSW, but E-W faults that shifted slightly during the Krafla Fires are present beneath Suðurhlíðar. Wells KJ-16A, KJ-20 and KJ-37 were directionally drilled through A-V faults and aquifers opened up in the wells at a depth that corresponds with the determined cut-through point by the fault. There is also a fracture that trends N-S to NNW-SSE (the Leirbotnar fracture) which shifted during the Krafla Fires and which shows that high permeability is connected to the fracture.

The permeability of wells by the southern margin of the caldera is determined by the dominant NNE-SSW trend of the eruptive fissures and faults as well as the caldera fault. There was low permeability in well KV-01 in the Vestursvæði area despite the fact that the well was positioned on the western side of the NNE-SSW fissure swarm. The area turned out to be cooled and the low permeability is partly due to deposits (particularly calcite and clay) blocking most vesicles in the rock and fissures. The well is almost vertical like the fracture and there is a possibility that the well did not cut through the fracture.

Permeability is also obvious in wells by acidic intrusions. The wells cut through thin, acidic intrusions at various depths in the Leirbotnar and Vítismó area. There are also thick and widespread intrusions of granophyric composition at a depth of 1500 m.b.s.l beneath the Vítismó area where powerful aquifers were cut through with acidic fluid in most deep wells. The largest aquifers in the wells in Suðurhlíðar are usually connected to a 200 to 400 m thick intrusion succession from acidic rock which is found at a depth of 200 - 600 m.b.s.l (Figure 29).

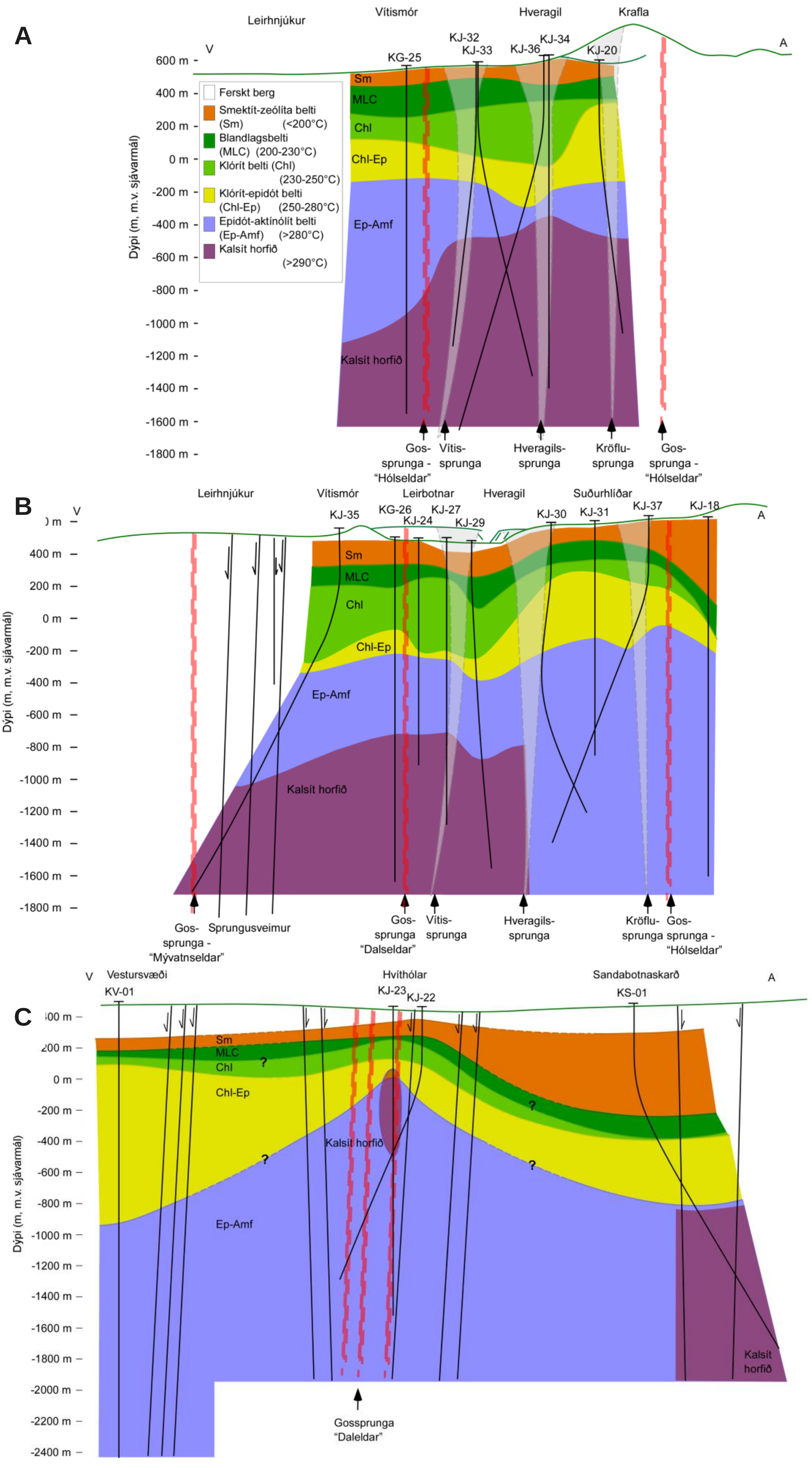


Figure 31. *East- west alteration profile of A: Vítismó and Víti, B: Leirhnjúkar, Leirbotnar and Suðurhlíðar and C: Vestursvæðið, Hvíthólar and Sandabotnaskarð.*

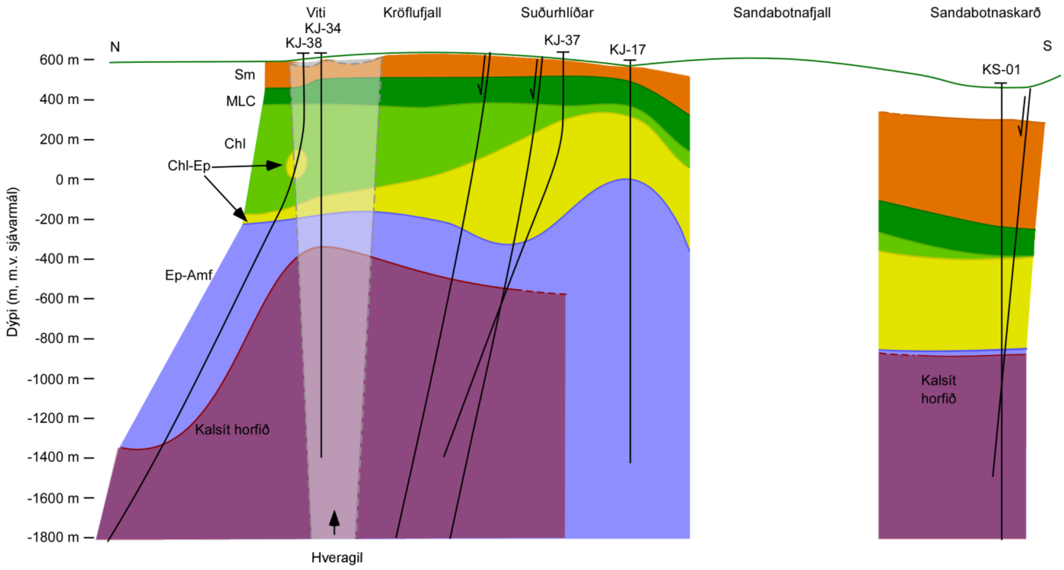


Figure 32. *North-south alteration profile of Víti, Suðurhlíðar and Sandabotnaskarð*

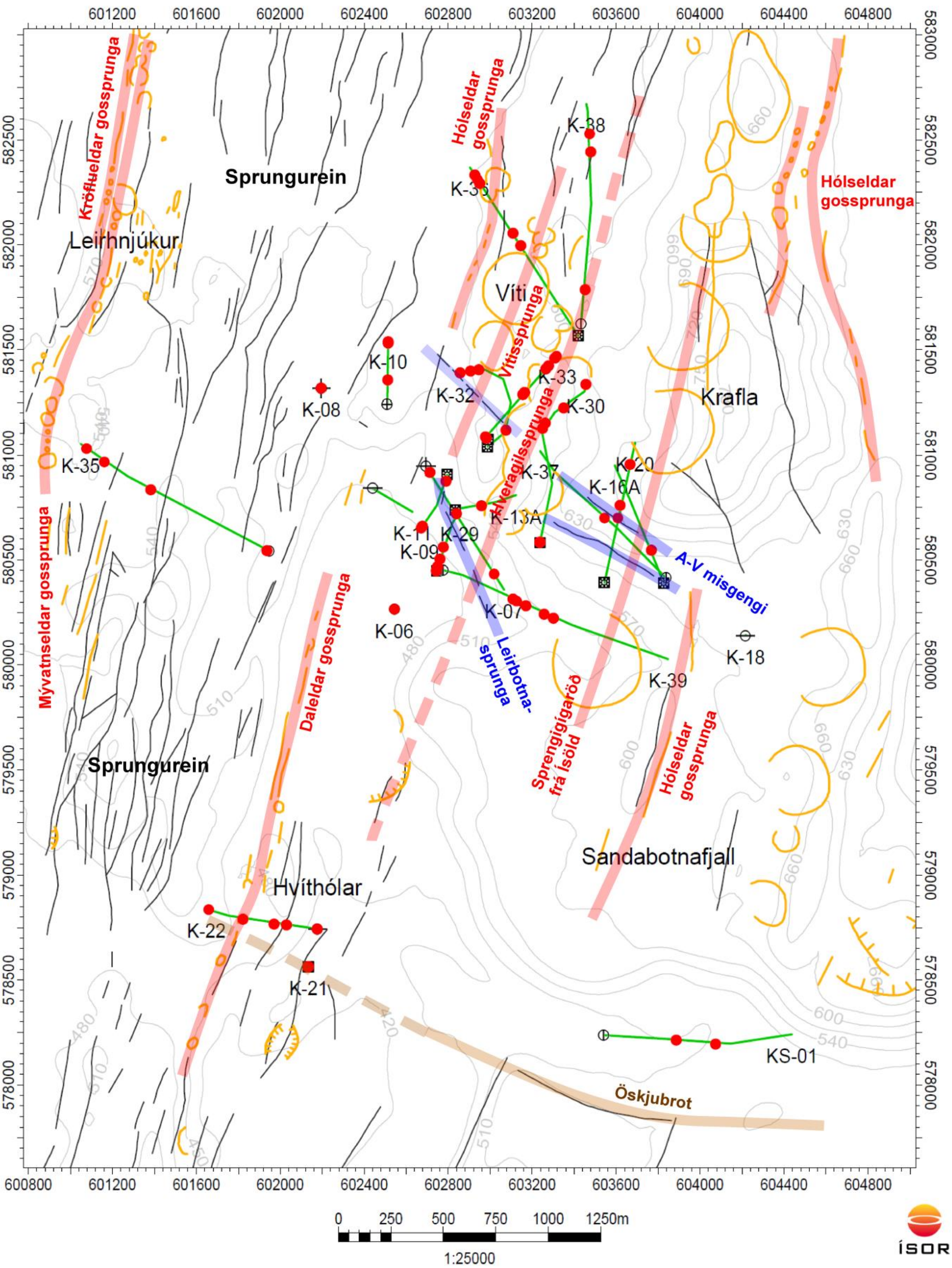


Figure 33. *Overview of faults, eruptive fissures and craters, chosen wells and larger feed zones in wells.*

7 Temperature and pressure logs in wells at Krafla

The temperature and pressure of a well is determined once it has been drilled. Measurements are conducted during drilling (measured while drilling MWD) but efforts are made to leave the well to heat-up by resting it for some time after drilling is completed. The temperature and pressure are measured once the well has been closed for some time and these measurements show the natural state of the system which is close to equilibrium. The length of this process varies and the determination of the initial state often requires interpretation. The water temperature at eqilibrium correlates with the temperature in the rock and the temperature process that is determined is therefore called the rock temperature profile. The pressure curve/process is called the initial pressure but is in fact the system pressure when measured. Rock temperature and initial pressure have been determined in most wells in the Krafla area. Rock temperature profiles can be seen in Figures 34-40 and initial pressure can be seen in Figures 41-47. The wells at Krafla were drilled between 1974 and 2008 (table 1). Production from older wells therefore affects the initial state of those wells drilled later on. This makes it difficult to co-interpret data as these effects are not included. This is particularly relevant with regard to geothermal systems where the temperatures and pressure are at boiling point. Pressure drawdown, as a result of utilisation in the system, magnifies boiling and the temperature lowers to boiling point accordingly. The research area has been divided into Leirbotnar, Vítismó, Suðurhlíðar, Hvíthólar and Vesturhlíðar. Wells KV-01 to the west of Hvíthólar (in the Vestursvæði area) and KS-01, to the east of Hvíthólar (in Sandbotnaskarð) were drilled in 2006 and 2007. When formation temperature profiles are categorised according to area it becomes clear that each area has strong characteristics. Figures 34-36 show temperatures according to metres above sea level in wells KW-01, KG-03, KG-05, KJ-06 KG-07, KJ-09, KJ-11, KG-12, KJ-13, KJ-13A, KJ-15, KG-24, KG-26, KJ-27, KJ-28, KJ-29 and KJ-35 (located in Leirbotnar). Well KJ-35 is still categorised as a Leirbotnar well despite the fact that it is located on the western periphery of Leirbotnar and is directionally drilled westward. The temperature profiles are characterised by a step at 300 - 800 m.b.s.l, which shows that the geothermal system is divided into two zones beneath Leirbotnar. The temperature in the shallow zone is generally between 180–220°C but the temperature in the deeper zone is consistent with the temperature in the boiling point depth curve and reaches 340°C at a depth of 1500 m.b.s.l in the deepest wells.

Two wells stand out from the others, wells KJ-06 and KJ-29, on the southern periphery. The temperature in well KJ-29 is consistent with the boiling point depth curve much like the wells in Suðurhlíðar (see Figure 36). Figure 34 shows the wells that produce from the shallow zone in Leirbotnar and Figures 35 and 36 show wells that produce from the deeper zone. Signs of this dual geothermal system can be seen in Figure 37 which shows the temperature according to depth in wells KW-02, KG-08, KG-10, KG-25, KJ-32, KJ-36 and KJ-38 in Vítismó. The temperature change occurs somewhat deeper than that found in the Leirbotnar wells or 500 to 1000 m.b.s.l.

Figure 38 shows the temperature in wells KJ-14, KJ-16, KJ-16A, KJ-17, KJ-18, KJ-19, KJ-20, KJ-31, KJ-37 and KJ-39 in Suðurhlíðar. The temperature in these wells is consistent with the boiling point depth curve with the exception of well KJ-16, KJ-17 and KJ-18, which are located in the easternmost area. The temperature profile is reversed in wells KJ-16 and KJ-17 which, would indicate that these wells are on the periphery of the upflow (upward flow) area. Well KJ-18 is the coldest of all the wells in Suðurhlíðar and the profile is different to those found in wells KJ-16 and KJ-17 despite the fact that there is only a 500 m distance between them. The temperature in wells KJ-21, KJ-22 and KJ-23 by Hvíthólar is shown in Figure 39 and the profiles are reversed. The rock temperature in wells KV-01 and KS-02 is also shown in Figure 39. KV-01 is in a cold area and the rock temperature is between 100–200°C to a depth of 2000 m.b.s.l. The temperature in the wellbottom (2894 m) reaches 240°C. The temperature in well KS-01 is 250°C at a depth of 300 m.b.s.l is 300°C at 900 m.b.s.l and reaches 340°C at the wellbottom.

Wells KJ-30, KJ-33 and KJ-34 are located in Vesturhlíðar and their temperature is shown in Figure 40. Well KJ-30 lies from Suðurhlíðar over to Vesturhlíðar and well KJ-33 lies from Leirbotnar and over to Vesturhlíðar. The well head of KJ-33 is by well KJ-15, but the bottom of the well lies approx. 100 to 200 m from the bottom of KJ-34 (a straight well, drilled into the western slope of Krafla). Wells KJ-36 and KJ-38 are drilled from the same platform as KJ-34, but they are thought to utilise the system beneath Vítismó and are therefore included in that category. The temperature in well KJ-30 is thought to be consistent with the boiling point depth curve (much like Suðurhlíðar). The temperature in wells KJ-33 and KJ-34 shows indications of a dual geothermal system much like that found in Leirbotnar and in

Vítismó. The temperature step occurs at a depth of 400-500 m.b.s.l in KJ-33 but at a depth of 200 - 300 m.b.s.l in KJ-34, which is in close proximity to Hveragil.

Warm-up measurements are available for all wells with the exception of well KG-04. Warm-up measurements, measurements while drilling (MWD) and in some cases rock temperature profiles from nearby wells are all utilised to determine rock temperature. This mainly affects the positioning of the division (separation) between the shallow and deeper zones of the geothermal system in the Leirbotnar and Vítismó wells. The temperature in the shallow zone is generally based on the feed zone temperature from a shallow feed zone. The temperature in the deeper reservoir (below the step) is estimated by 'measurements while drilling' which show a hot feed zone at a particular depth. It is therefore not always exactly clear where the step is or how rapidly the temperature rises according to depth along the separation between the two systems (shallow and deep) despite the fact that the temperature above and below the step is known.

Initial pressure in wells at Krafla is shown in Figures **Error! Reference source not found.**–**Error! Reference source not found.**. Signs of drawdown as a result of utilisation can be seen in Figures 41-45 which show the initial pressure in Leirbotnar, Vítismó and Suðurhlíðar. The pressure in wells KG-24 to KJ-32, drilled in Leirbotnar and Vítismó between 1988 and 1999 is lower than that found in older wells in the area. There is significantly less pressure in wells KJ-31 (1991) and KJ-37 (2007) in Suðurhlíðar than that found in wells KJ-16, KJ-17 and KJ-18. It can be assumed that the pressure and temperature at a depth of between 0 and 1000 m in the area by well KJ-37 would have been similar to that found in well KJ-16 when it was drilled in 1981. Based on these assumptions, the pressure at a depth of 250 m.b.s.l (in Suðurhlíðar) has decreased by 20-30 bars as a result of utilisation during the period between 1981 and 2007.

Pressure and temperature profiles that show the initial state of wells are used to develop sections, both vertical and horizontal throughout the area and are shown hereafter. The fact that wells are drilled over a 30 year period and that parts of the area have already been utilised affects the interpretation of the natural state.This makes joint interpretation difficult, e.g. by mapping out cross sections, because these maps do not account for development over time.

However, the data from all wells have been used, with the exception of KJ-37 and KJ-39 as they show too much of a pressure drop when compared with other wells in the Suðurhlíðar area.

Figure**Error! Reference source not found.** shows the temperature and pressure of the W-E profile hich lies from well KJ-35, south-eastward through Leirbotnar and Hveragil and ends between wells KJ-17 and KJ-18 in Suðurhlíðar. The figure shows the duality of the system beneath Leirbotnar. The separation between the two systems is deepest in the mid-section of Leirbotnar but disappears to the east of Hveragil. A significant decrease in temperature is evident in wells KJ-16 and KJ-17 and up to well KJ-18 (the temperature in KJ-18 is much lower than that found in other wells in the area). Wells KJ-16 and KJ-17 seem to be located on the periphery of the upflow (upward flow) area where fluid reaching the surface is over 280°C and spreads out when it reaches above 1000 m.b.s.l. The temperature increases towards the southeast (as described earlier) in the shallow zone of the system. The temperature rises to above 300° at a depth of 1000 m.b.s.l in the entire area with the exception of wells KJ-16, KJ-17 and KJ-18. The pressure drops below 1000 m.b.s.l in a westward direction along the profile line between Suðurhlíðar and Leirbotnar.

Figure 49 shows the W-E profile which lies from well KG-25 in Vítismó through the area between Leirbotnar and Vesturhlíðar and ends to the north of wells KJ-20 and KJ-16. The figure shows the dual system beneath Leirbotnar and Vítismó. The deeper zone is obviously found at a greater depth beneath Vítismó. The separation between the shallow and deep zones is found at a shallower depth than if the profile is followed eastward. There is an obvious pressure drop in the mid-section of the area between wells KJ-36 and KJ-30 and a drawdown as a result of utilisation. This is not surprising as the wells in this area were drilled after 1997, whereas other wells were drilled before 1990.

Figure 50 shows temperature and pressure in a N-S profile through the Krafla area and the profile reaches from Vesturhlíðar, southward through Leirbotnar and ends by wells KJ-21, KJ-22 and KJ-23 (by Hvíthólar). The figure shows the cooling of the area southward from Vesturhlíðar and up to Hvíthólar. There are signs of the upflow of hot geothermal fluid at a depth of between 0 - 500 m.b.s.l in the wells by Hvíthólar. The figure shows this as a bubble of hot fluid at a depth of 0 m.b.s.l beneath Hvíthólar but the isotherm should connect with isotherms either to the south or north, east or west. Figure 52 shows the connection of geothermal lines beneath Hvíthólar eastward to well KS-01 by Sanbotnaskarð. However, it is unlikely that the upflow flow would be found there as resistivity measurements show a cold channel (high-resistivity) between Hvíthólar and KS-01. The pressure slump is deep-set in wells KJ-34, KJ-33 and KJ-30 (they merge at 1000 m.b.s.l). See Figure 50. The pressure slump is believed to be a result of utilisation in well KJ-30.

Figure 51 shows the temperature and pressure in a N-S profile from well KJ-36 in Vesturhlíðar through Suðurhlíðar and ends by well KS-01 by Sandbotnaskarð. There is no evidence of a connection between Suðurhlíðar and well KS-01 but the areas could be connected to two different upflow areas. The pressure drops from Suðurhlíðar to Vesturhlíðar and is indicative of a pressure slump. The same pressure slump is found in the wellbottoms of KJ-34, KJ-30 and KJ-13A and can be seen in Figure**Error! eference source not found.**.

Figure 52 shows temperature and pressure in a W-E profile which reaches from well KV-01 in the Vestursvæði area through Hvíthólar and along the profile KS-01 by Sandbotnaskarð. The area by Sanbotnaskarð is cold (<150°C) in the uppermost 500 m but the area is substantially warmer than that found at Hvíthólar at a depth of 1000 m.b.s.l. There are signs of an upflow of geothermal fluid in the wells by Hvíthólar at a depth of 0 - 500 m.b.s.l. The figure shows isotherms connecting eastwards, up to well KS-01, and the upflow seems to be located between. However, resistivity measurements rule out this connection and the upflow by Hvíthólar is probably located in a tight area just to the east of well KJ-21.

Temperature and pressure is shown in planes in Figures 53-56. Figure 53 shows the physical properties at sea level; at a depth of 500 m, in wells in the Leirbotnar area which stands at 500 m above sea level. The greatest temperature at this depth is found in Suðurhlíðar, Vesturhlíðar and by Hvíthólar. There is a break (separation) by well KJ-18 in the easternmost area of Suðurhlíðar. Well KJ-18 is the easternmost well so the possibility of localised effects by well KJ-18 cannot be determined. A cold area to the east of the well cannot be confirmed either but it should be noted that there is a steam vent in Hrafntinnuhryggur to the east of KJ-18. However, cooling between KJ-16, KJ-17 and KJ-18 can be confirmed. There is generally a temperature difference between Leirbotnar and Vítismó and also between Suðurhlíðar and Vesturhlíðar. The temperature rises south-eastward up to Suðurhlíðar.

The temperature by Hvíthólar and in Vesturhlíðar and Suðurhlíðar is over 240°C at sea level and reaches over 240°C at a depth of 400 m.b.s.l by Sandbotnaskarð (Figure 54). The temperature reaches above 300°C, at a depth of 800 m.b.s.l, in an extensive area to the west and east of Hveragil (Figure 55). Hvíthólar is quite cold at this depth (approx. 200°C). The temperature is over 320°C at a depth of 1200 m.b.s.l beneath a large part of the production area in Leirbotnar, Vítismó, Suðurhlíðar and Vesturhlíðar. The pressure drops southward at sea level from Vesturhlíðar and Suðurhlíðar (towards Hvíthólar and the Vestursvæði area).

The same gradient can be seen at a depth of 400 m.b.s.l but the pressure is more stable in the Leirbotnar area. A pressure slump can be seen beneath Krafla as a result of low pressure in the deeper zone beneath Vesturhlíðar. A pressure slump is present at a depth of 800 m.b.s.l between wells KJ-30 and KJ-34 and a pressure-high is present to the east of Suðurhlíðar. This pattern is more apparent at a depth of 1200 m.b.s.l and pressure drops north-westward from Suðurhlíðar to Leirbotnar and Vesturhlíðar.

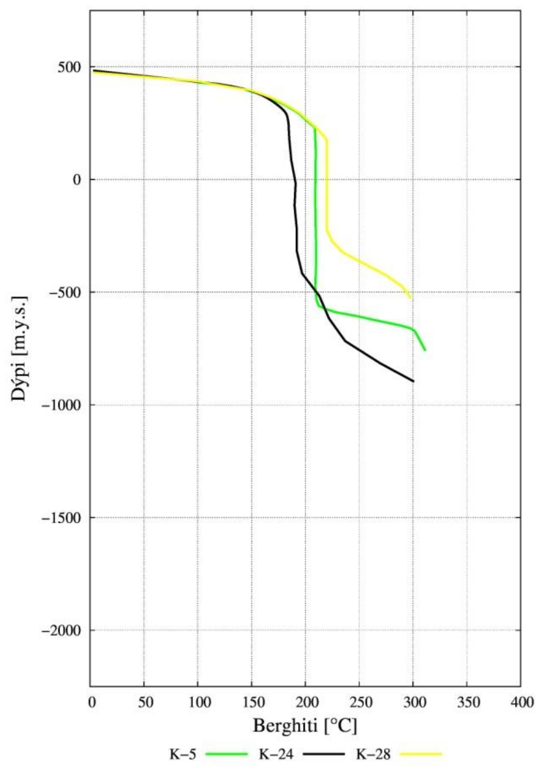
Thermal imaging shows that the main upflow flow within the drilling area is by Hveragil between Suðurhlíðar and Vesturhlíðar and Leirbotnar. There is a dual system to the west of Hveragil and the temperature in Leirbotnar and Vítismó shows the same characteristics.

The boiling point depth curve is in the top 0 to 300 m, the temperature is constant at a depth of between 200 and 1000 m (1500 m) and then reaches boiling point below 1000-1500 m. This is indicative of cooling as a result of inflow into the fissure system.

The separation (break) between the deeper and shallower systems deepens in a north-western direction from Hveragil is temperature constant to a depth of between 300 - 800 m.b.s.l in Leirbotnar and 500 - 1000 m.b.s.l in Vítismó. The rock temperature in well KJ-35 shows a continuing dual system to the west of Leirbotnar and the depth of the deeper system is similar to that of well KG-26. Drilling confirms a powerful geothermal system around Leirhnjúkar where surface manifestations and resistivity measurements show another upflow (Chapters 2 and 3). The Suðurhlíðar system shows temperature profiles that are at the boiling point depth curve.

Wells KJ-33 and KJ-34 in Vesturhlíðar both show dual systems and the separation (break) between systems is shallower in KJ-34, which is closer to the main upflow by Hveragil. Pressure is higher in Suðurhlíðar than in Vesturhlíðar which is indicative of linfow to Vesturhlíðar. This could also indicate that the upflow by Hveragil is closer to Suðurhlíðar than Vesturhlíðar.

Temperature logs show another upflow flow area to the east of Hvíthólar by Sandbotnaskarð. Resistivity measurements rule out the idea that the geothermal energy by Hvíthólar originates from this area. Resistivity measurements show that Hvíthólar is actually on the periphery of the so-called Vestursvæði. Well KV-01 is the only well to be drilled in this area and turned out to be cold. This geothermal system would therefore now be categorised as a low-temperature area. The origin of the geothermal energy by Hvíthólar is unclear; it could be due to localised small-scale geothermal upflow by the periphery of the caldera or a result of outflow from the Leirbotnar area.



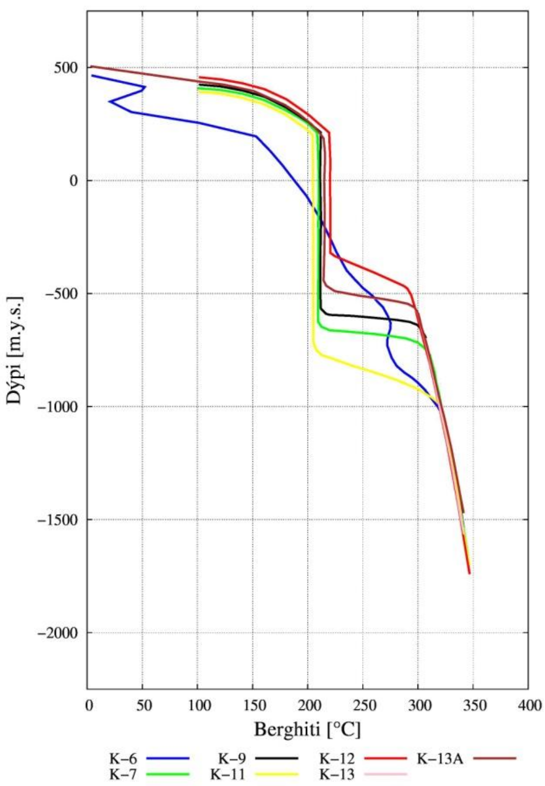


Figure 34. *Rock temperature profiles in wells in shallow systems in Leirbotnar.*

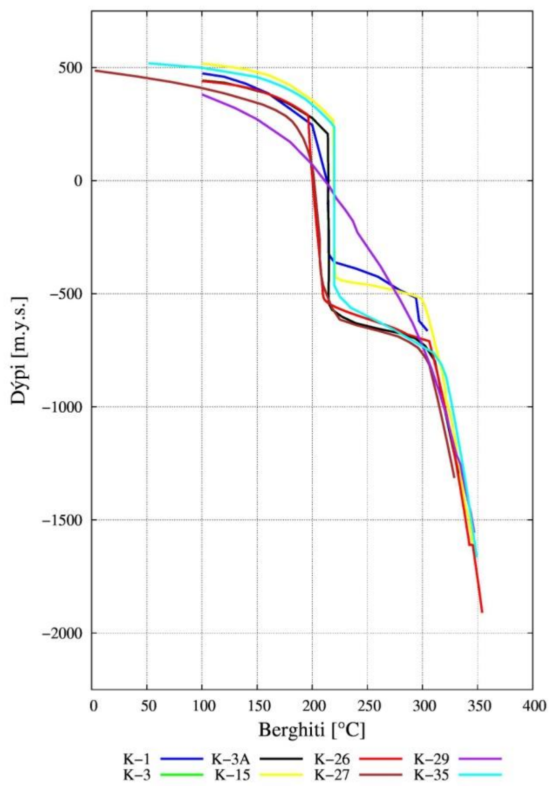


Figure 35. *Rock temperature profiles in wells in deeper systems in Leirbotnar.*

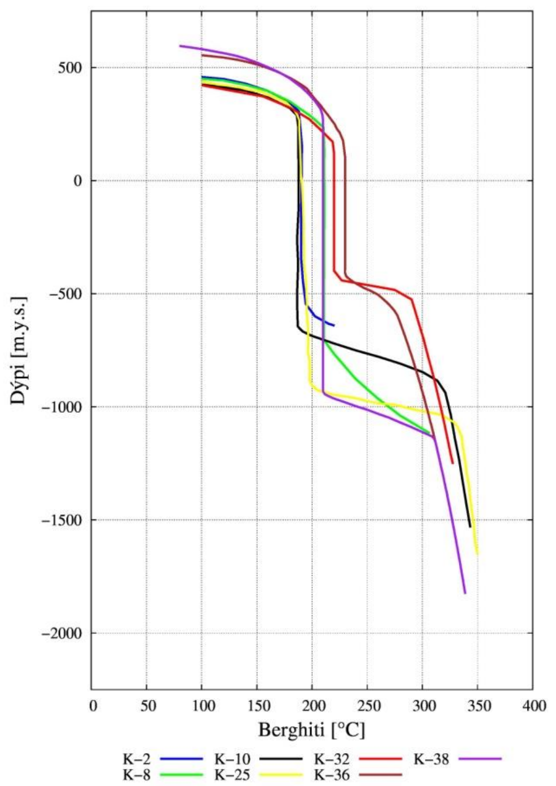


Figure 36. *Rock temperature profiles in wells in deeper systems in Leirbotnar*

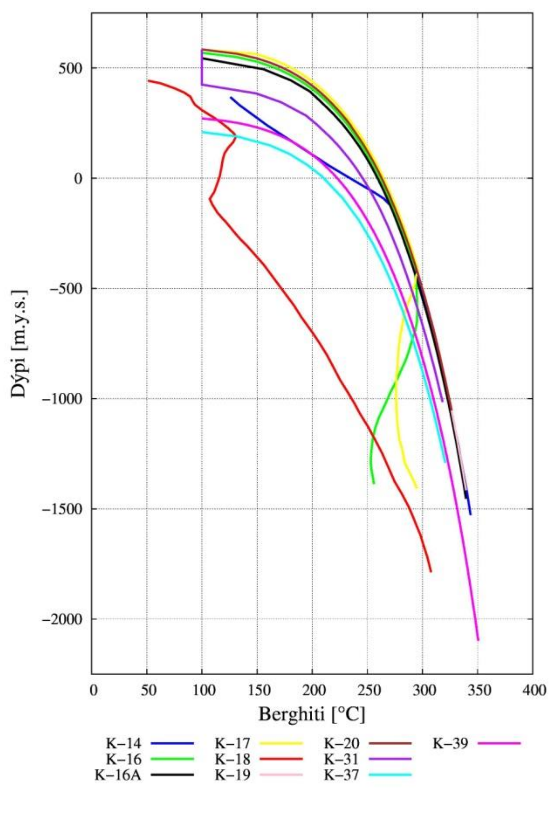


Figure 37. *Rock temperature profiles in wells in Vítismó*

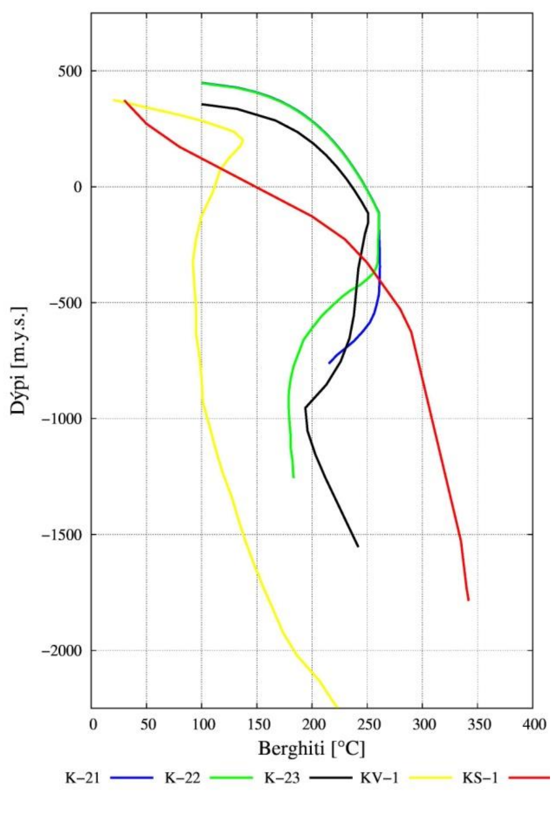


Figure 38. *Rock temperature profiles in wells in Suðurhlíðar*

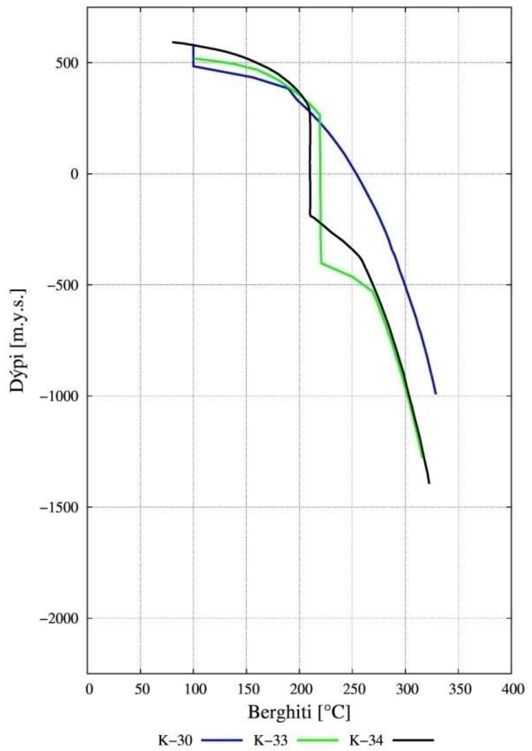


Figure 39. *Rock temperature profiles in wells by Hvíthólar in the Vestursvæði area and by Sandabotnaskarð*

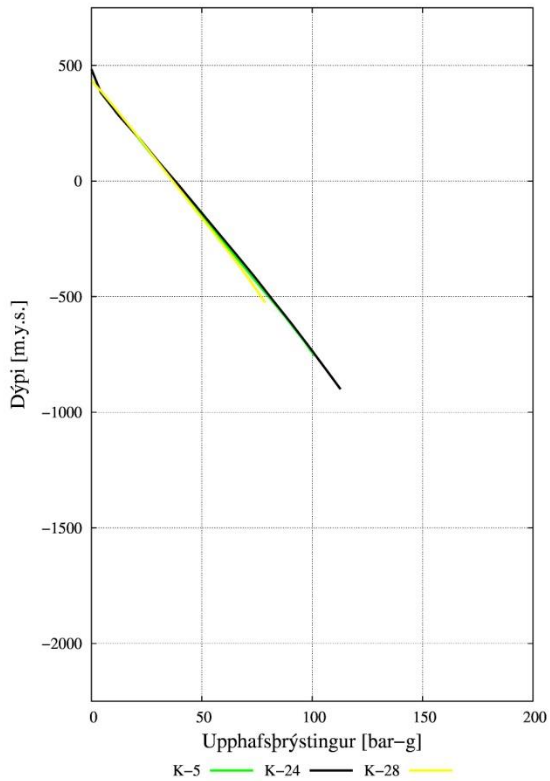


Figure 40. *Rock temperature profiles in wells in Vesturhlíðar*

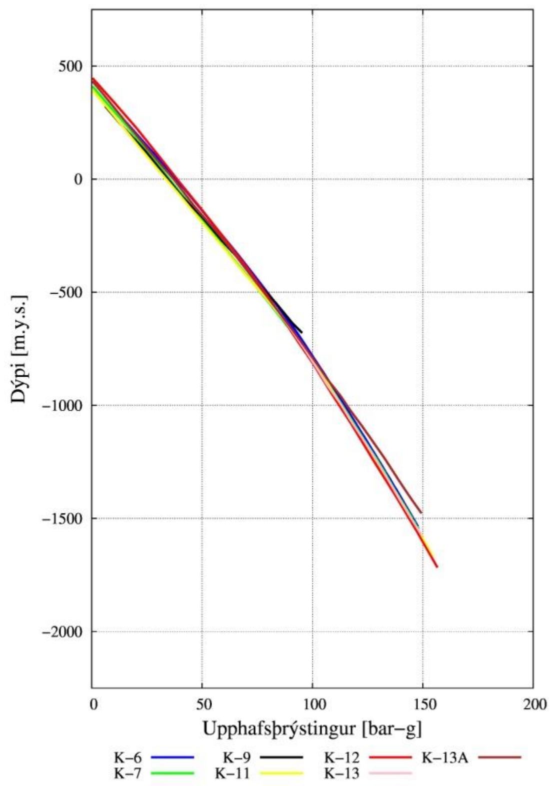


Figure 41. *Initial pressure in wells utilising the shallower systems in Leirbotnar*

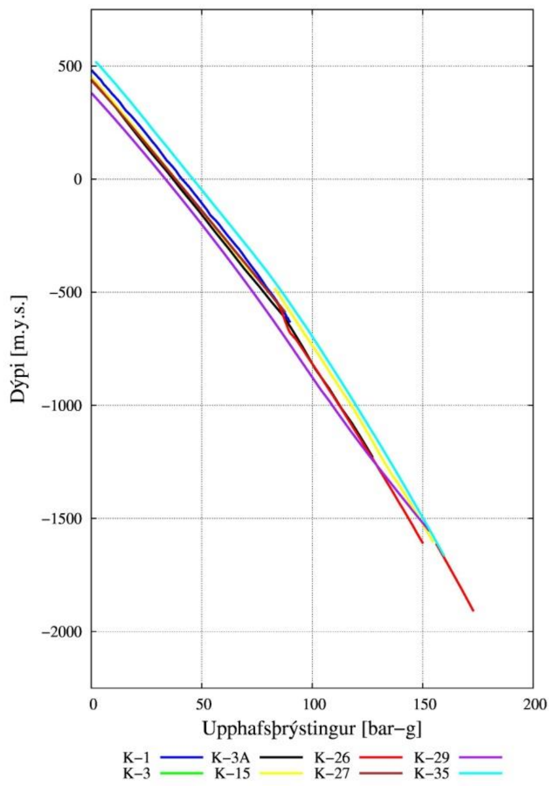


Figure 42. *Initial pressure in wells utilising the deeper systems in Leirbotnar*

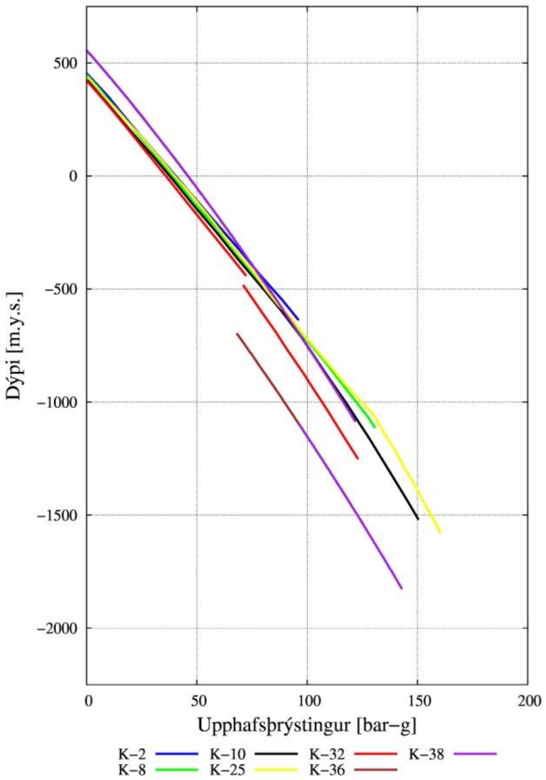


Figure 43. *Initial pressure in wells utilising the deeper systems in Leirbotnar.*

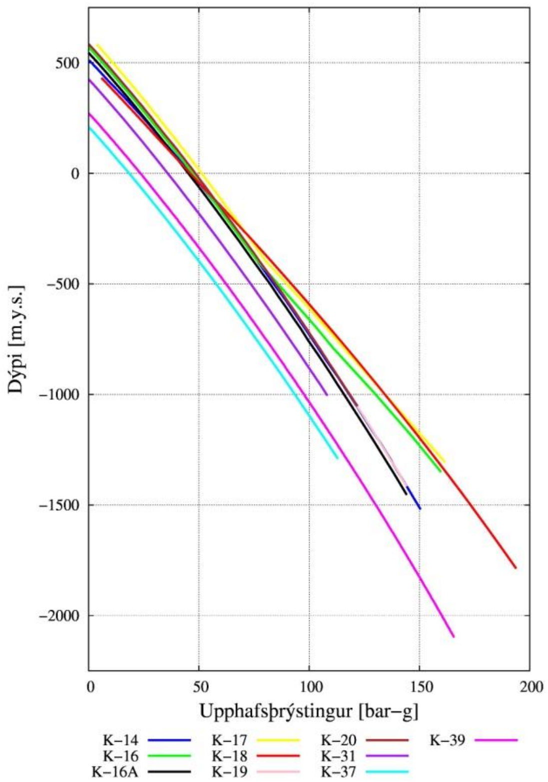


Figure 44. *Initial pressure in wells in Vítismó*

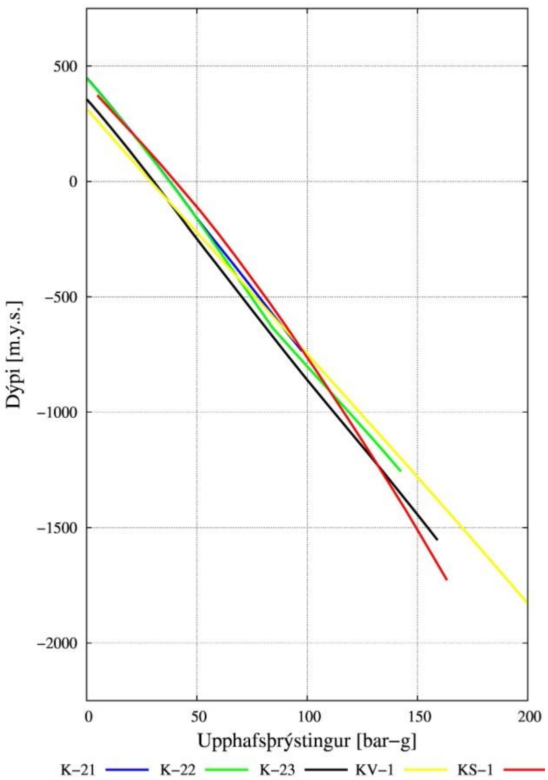


Figure 45. *Initial pressure in wells in Suðurhlíðar*

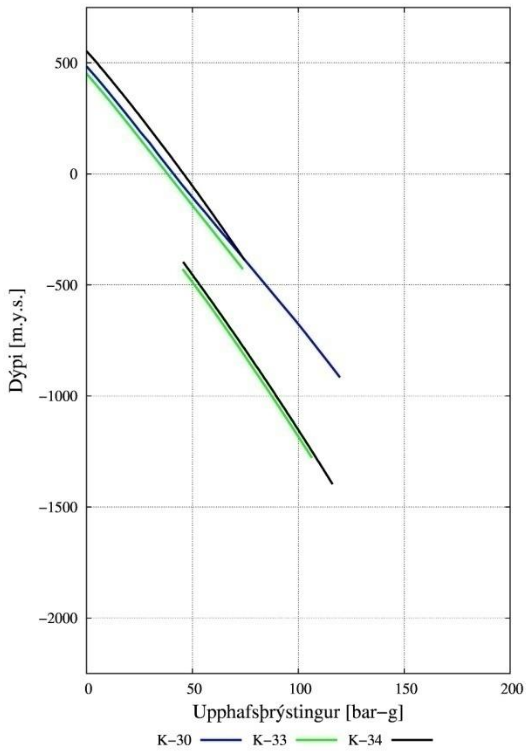


Figure 46. *Initial pressure in wells.*

Figure 47. *Initial pressure in wells in Vesturhlíðar*

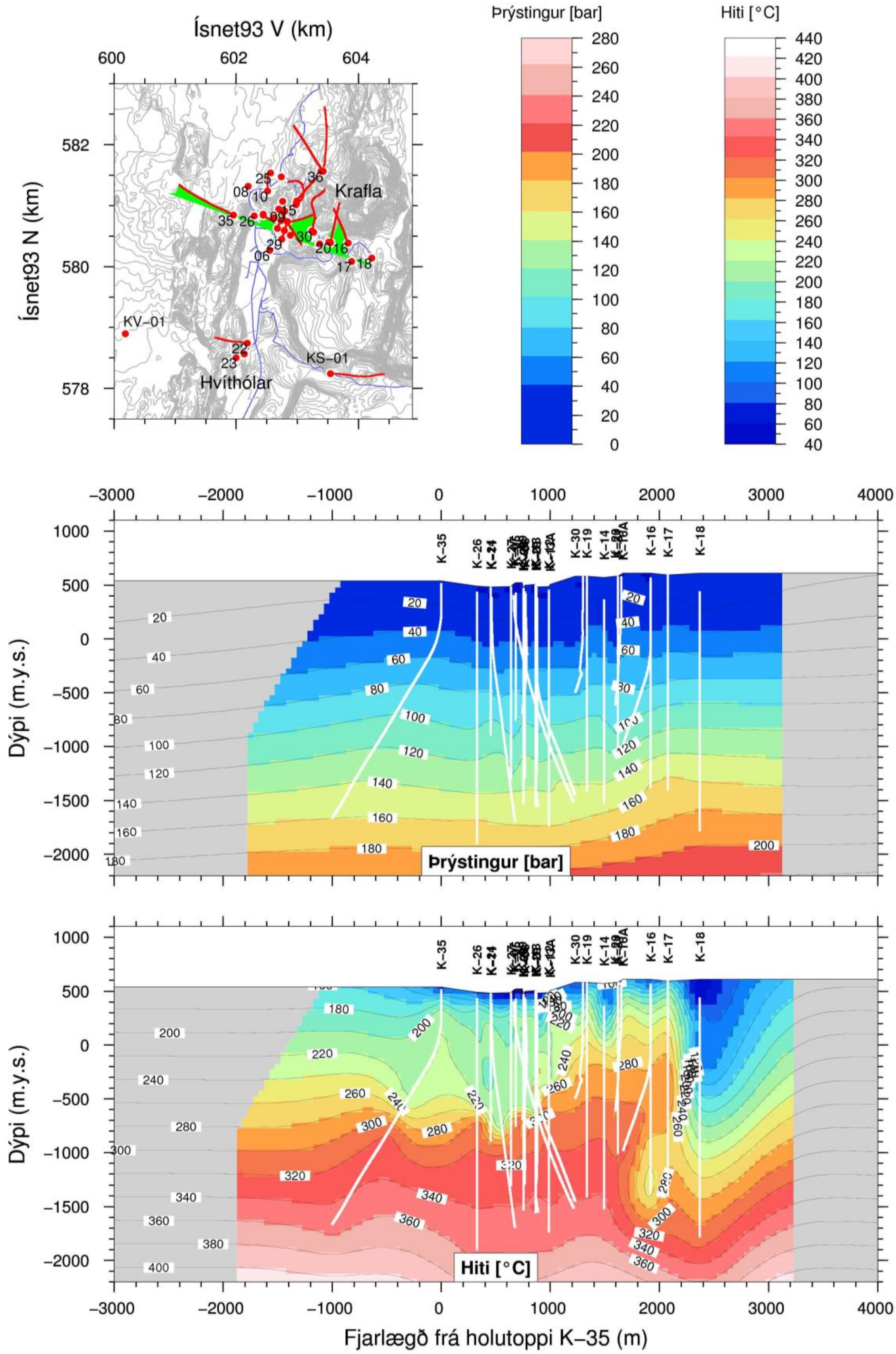


Figure 48. *Pressure and temperature of profile from well KJ-35 and through Leirbotnar and Suðurhlíðar*

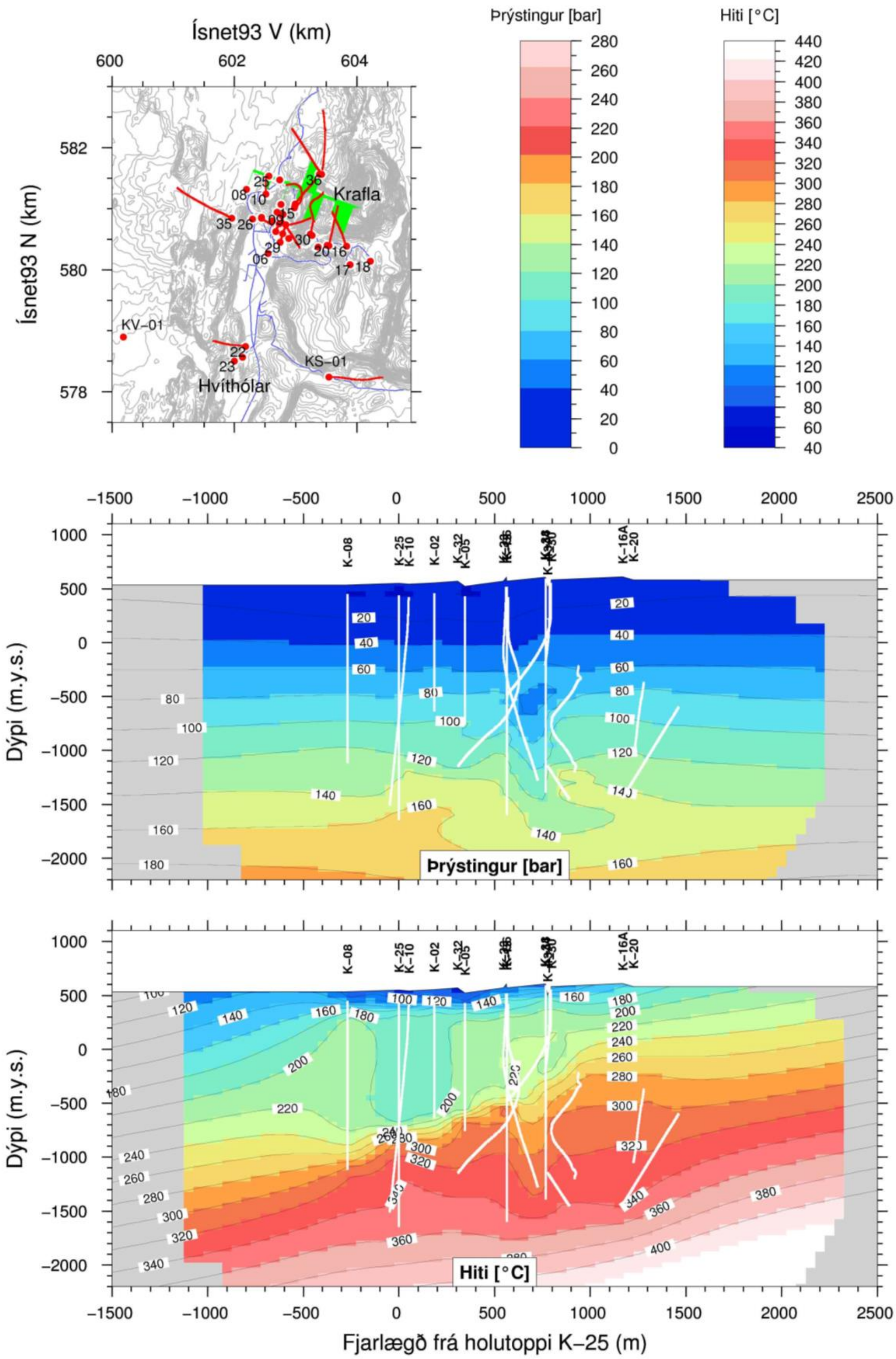


Figure 49. *Pressure and temperature of profile between Vítismó and Vesturhlíðar*

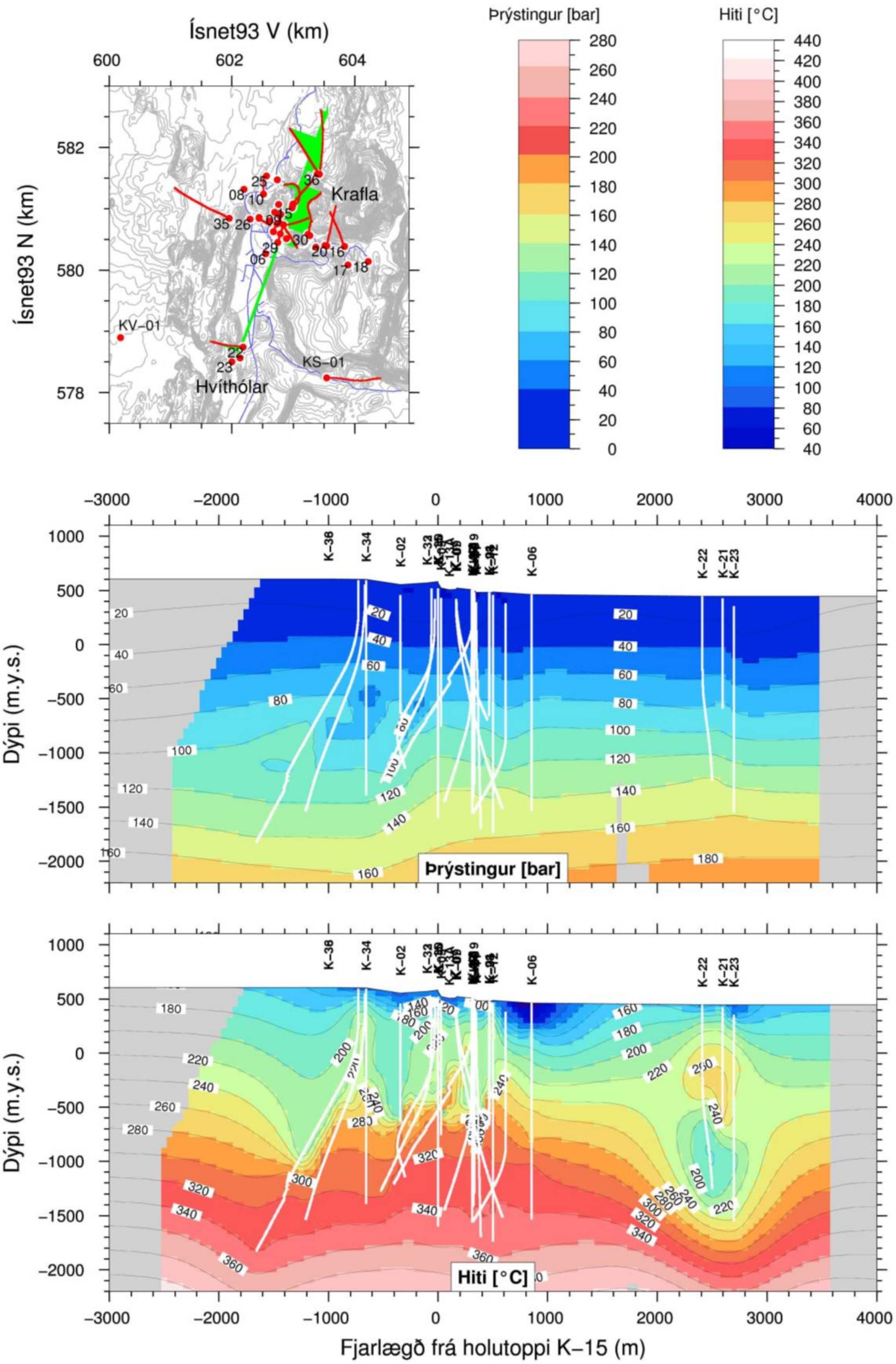


Figure 50. *Pressure and temperature of profile from Vesturhlíðar through Leirbotnar and to Hvíthólar*

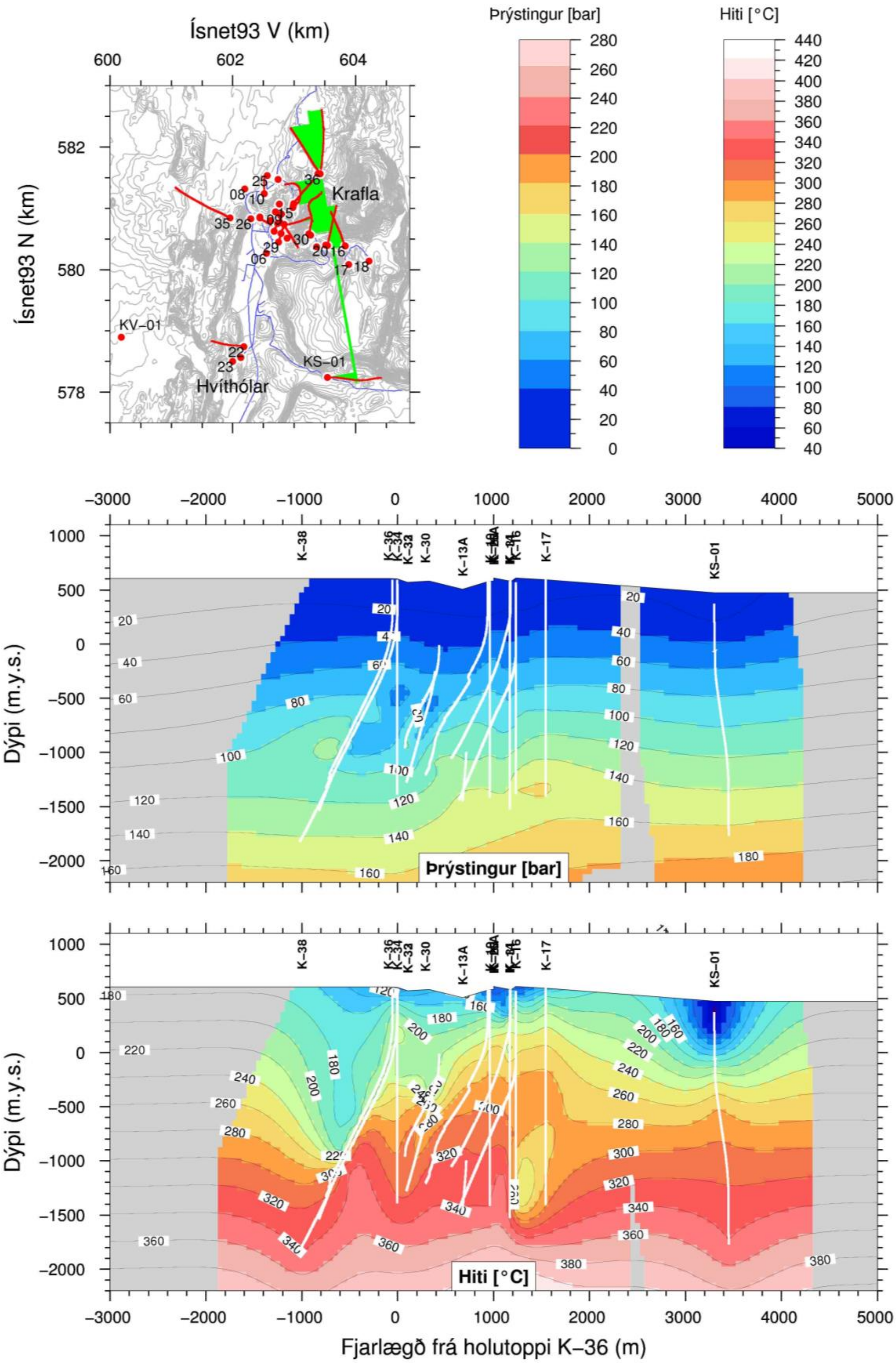


Figure 51. *Pressure and temperature of profile from Vesturhlíðar, through Suðurhlíðar and up to well KS-01 by Sandabotnaskarð*

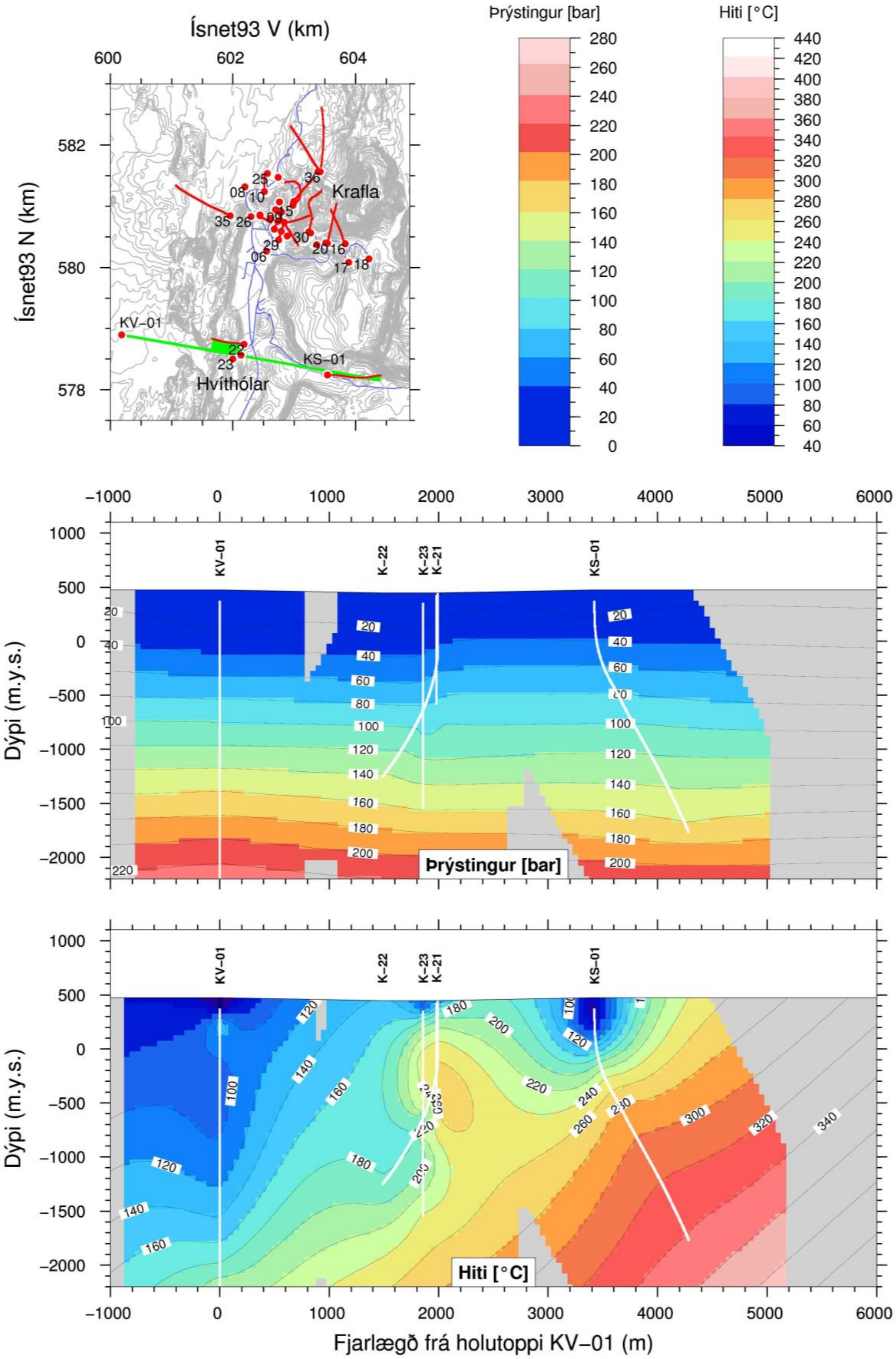


Figure 52. *Pressure and temperature of profile from KV-01 to KS-01 through Hvíthólar*

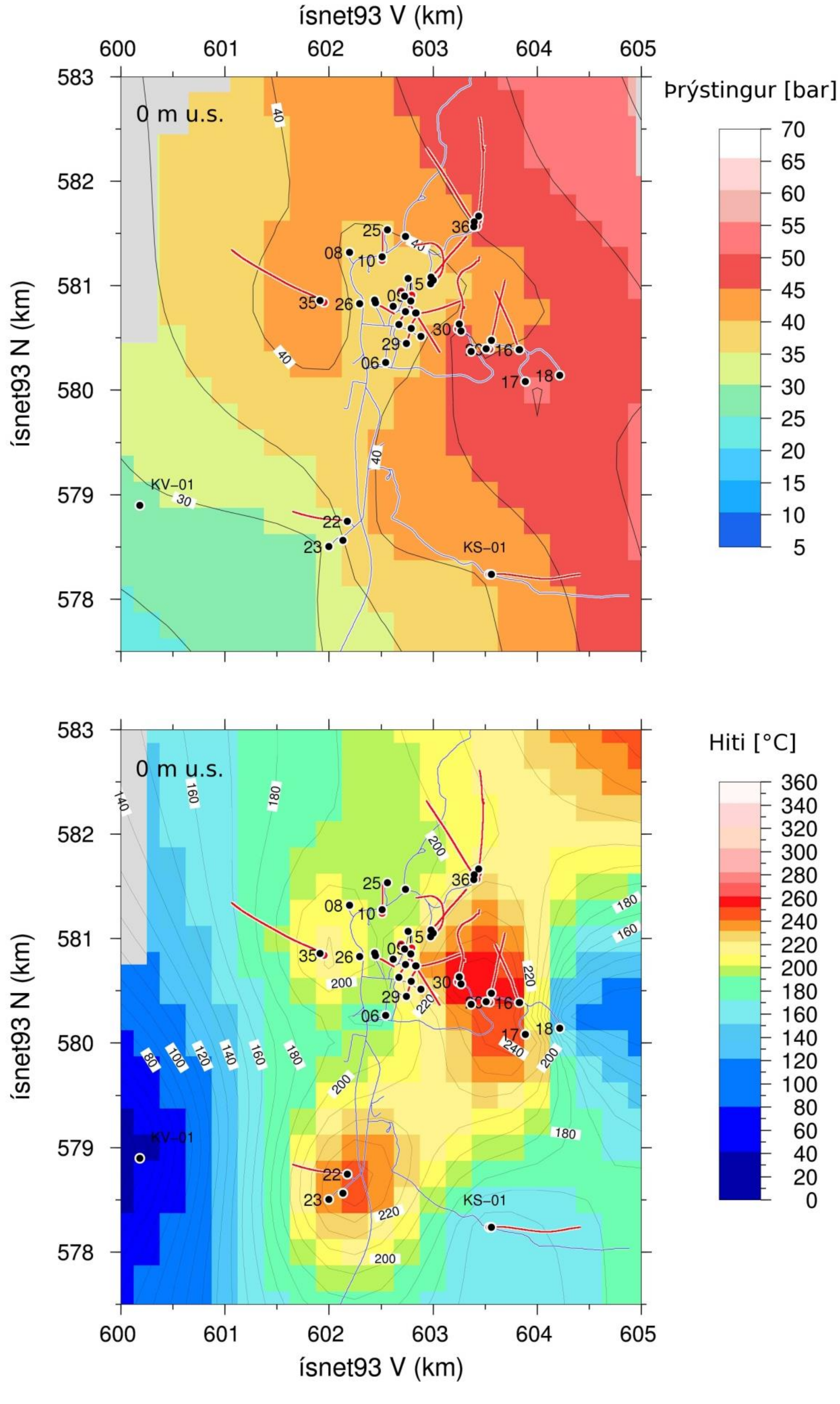


Figure 53. *Pressure and temperature at 0 m.b.s.l in the Krafla area*

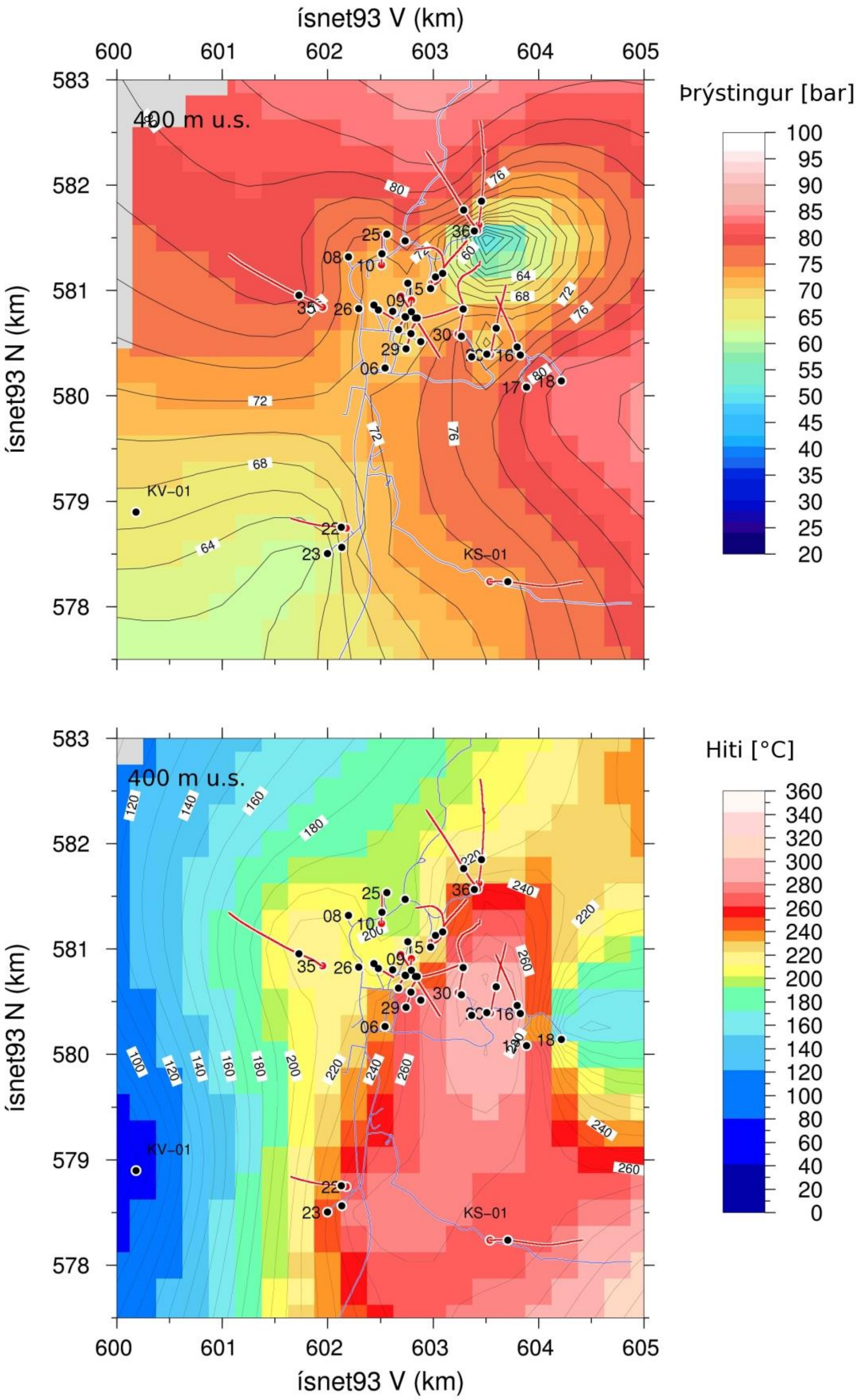


Figure 54. *Pressure and temperature at 400 m.b.s.l in the Krafla area*

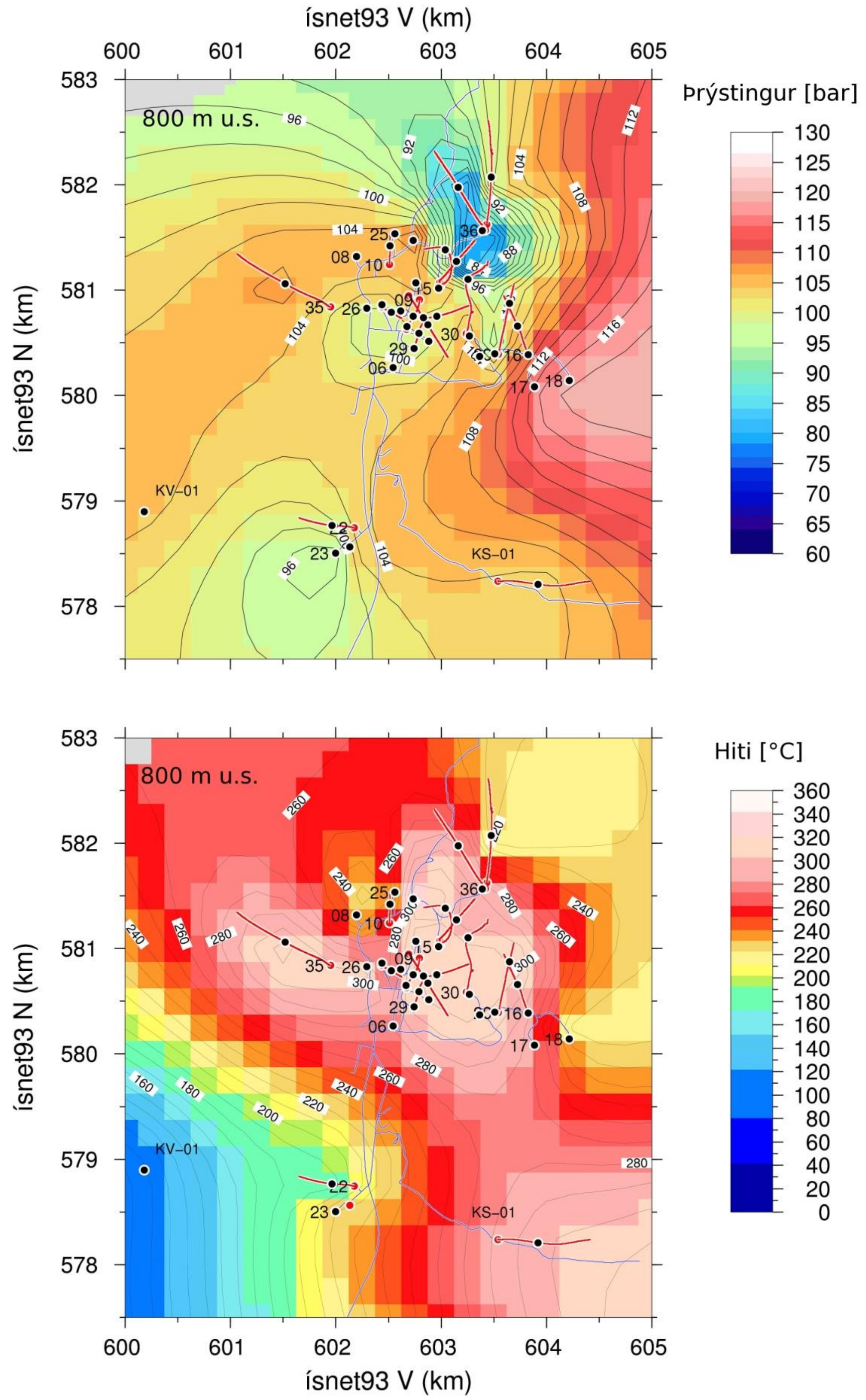


Figure 55. *Pressure and temperature at 800 m.b.s.l in the Krafla area*

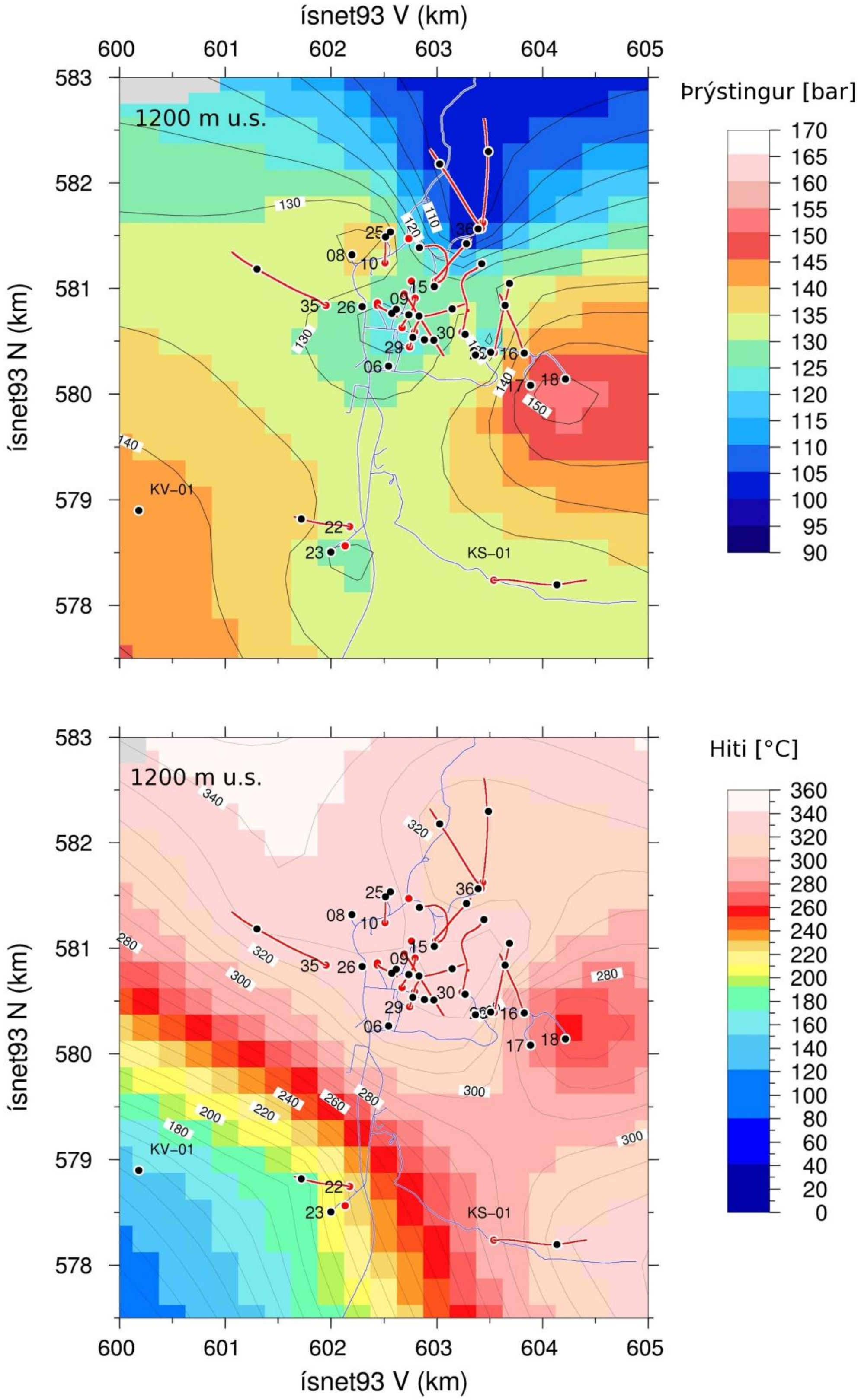


Figure 56. *Pressure and temperature at 1200 m.b.s.l in the Krafla area*

8 Well tests at Krafla

Table**Error! Reference source not found.** shows an overview of wells that have been injection tested t Krafla as well as parameters that have been determined by utilising measurements obtained during testing. The injectivity-index or transmissivity of the well has been determined by an analysis of measurements. The injectivity-index (II) is defined by the ratio of the change in the injection flow rate to the change in reservoir pressure measured in the well:

$$II = \frac{\Delta Q}{\Delta P}$$

The index shows how well connected the well is to the geothermal system. Transmissivity (T) is defined as the ratio of permeability thickness, kH, and the dynamic viscosity of geothermal fluid, μ, which indirectly assesses the permeability of the area surrounding the well.

$$T = \frac{kH}{\mu}$$

Transmissivity reveals the ability of the geothermal reservoir surrounding the well to transmit fluid. Transmissivity reveals how much water can flow into or out of the well given a unit change in pressure. The transmissivity for wells at Krafla is shown in table 2. Guðmundur Böðvarsson et al. (1984) collected information on discharge tests in wells 6-18. Transmissivity is shown as permeability thickness and can be seen in the column far right in table 2. Transmissivity has in these cases been calculated using m^3/Pa s by using the value 1.2 10^{-4} Pa s for dynamic viscosity. In some reports 'T' has been assessed in units m^2/s and pressure changes have not been measured directly (the change to the height of the water level in the well is measured). In these instances transmissivity has been measured using m^3/Pa s by using the value 9.81 m/s^2 for gravity acceleration, g, and 840 kg/m^3 for the density of geothermal fluids. Both values on dynamic viscosity and density are based on a water temperature of 220°C at a pressure of 60 bars. Both these characteristics change during temperature changes and this can cause inaccuracies in the comparison of these values.

Well KJ-9 was first utilised in 1977 but was re-drilled in 1982. The well was injection tested after re-drilling and the permeability of the well proved to be less than when it had been initially drilled. This explains why two values have been determined for transmissivity in the area surrounding well KJ-9: 1.23 10^{-8} m^3/Pa s (Ásgrímur Guðmundsson et al.1983d) and 3.3 10^{-8} m^3/Pa s (Guðmundur Böðvarsson et al.1984). The well was directionally drilled in 1982 and the ´well process´ was therefore different to original plans. The shifting of fissures in the area surrounding the well in connection with seismic activity between 1975 and 1982 could also have affected permeability. In this case more current values are considered to be more reliable and are similar to those of the surrounding wells. However, well KJ-32 has a similar value to the original value for well KJ-9, but well KJ-32 lies towards the north (towards Víti). Two values have been determined for well KJ-9 and well KJ-13; in this case the values are consistent.

The injectivity-index has been determined for most wells at Krafla, including all wells drilled after 1996 (shown in table 2). Figure 57 shows the injectivity-index in wells at Krafla and Figure 58 shows how transmissivity is distributed between wells. The location of well heads is shown in the figures and it is assumed that the value for transmissivity is at that point. This can be misleading as many of the wells are drilled at an incline.

The average injectivity-index of wells in the Krafla area is 3.9 (l/s)/bar, according to table**Error! eference source not found.**. The injectivity-index is highest in wells KJ-28 and KJ-36, 8 and is 11 (l/s)/bar. The figure shows the peak level in Vesturhlíðar where KJ-34 and KJ-36 are located. Another peak level can be seen in the Leirbotnar area surrounding well KJ-28. The injectivity-index of KJ-21 and KJ-22 is higher than the average injectivity-index in the area and the injectivity-index for KS-01 by Sandabotnaskarð.

The average transmissivity in the Krafla area is 3.0 10^{-8} $m^3/(Pa\ s)$, according to table 2. Transmissivity is highest in the areas surrounding wells KJ-21 and KJ-28, i.e. 20 and 15 $m^3/(Pa\ s)$. The figure also shows that transmissivity is also high at well KS-01. Peak permeability levels are found at well KJ-21 by Hvíthólar and peaks surrounding KJ-27 in Leirbotnar and KG-25 in Vítismó. Transmissivity in Vesturhlíðar is approx. 2-2.5 $m^3/(Pa\ s)$. The high levels of transmissivity by KS-01 show that it would be interesting to investigate the area surrounding Sanbotnaskarð further.

Table 2. *Information on wells that have been well tested*

Hola	Númer	Dags.	Heimild	II [(l/s)/bar]	T [10^{-8}·m^3/(Pa·s)]	T [m^2/s]	T [Dm]
K-06	58006		Guðmundur Böðvarsson o.fl. (1984)		1,3		1,6
K-07	58007		Guðmundur Böðvarsson o.fl. (1984)		1,5		2,1
		24.09.1976	Hrefna Kristmannsdóttir o.fl. (1977)	2,7	1,8		
K-08	58008	10.03.1977	Guðmundur Böðvarsson o.fl. (1984)				1,75
		26.10.1982	Ásgrímur Guðmundsson o.fl. (1983d)	3,0	1,23		
K-09	58009		Guðmundur Böðvarsson o.fl. (1984)		3,3		4,0
K-10	58010		Guðmundur Böðvarsson o.fl. (1984)		2,1		2,5
K-11	58011		Guðmundur Böðvarsson o.fl. (1984)		1,3		1,6
			Valgarður Stefánsson o.fl. (1982)	2,8	1,3	1,10E-4	
K-12	58012		Guðmundur Böðvarsson o.fl. (1984)		1,5		1,8
		10.07.1980	Valgarður Stefánsson o.fl. (1982)	2,0	1,3	1,10E-4	
K-13	58013		Guðmundur Böðvarsson o.fl. (1984)		1,3		1,5
K-13A	58113	26.09.1989	Ásgrímur Guðmundsson o.fl. (1989)	3,0			
K-14	58014	21.08.1980	Guðmundur Böðvarsson o.fl. (1984)		1,8		2,2
K-15	58015		Guðmundur Böðvarsson o.fl. (1984)		1,3		1,5
K-16	58016		Guðmundur Böðvarsson o.fl. (1984)		0,75		0,9
K-16A	58116	02.09.1997	Ásgrímur Guðmundsson o.fl. (1998a)	1,5	1,1-1,4		
K-17	58017	12.08.1981	Guðmundur Böðvarsson o.fl. (1984)	4,0	2,1		2,5
K-18	58018		Guðmundur Böðvarsson o.fl. (1984)		0,083		0,1
K-20	58020	20.08.1982	Ásgrímur Guðmundsson o.fl. (1982b)	3,1	1,6	1,6E-4	
K-21	58021	14.09.1982	Ásgrímur Guðmundsson o.fl. (1982c)	7,2	20,0	16,2E-4	
K-22	58022	14.07.1983	Ásgrímur Guðmundsson o.fl. (1983c)	4,6	3,1		
K-23	58023	21.09.1983	Ásgrímur Guðmundsson o.fl. (1983g)	1,0	0,7		
K-24	58024	02.09.1988	Ásgrímur Guðmundsson o.fl. (1988c)	4,0	2,2		
K-25	58025	02.09.1990	Ásgrímur Guðmundsson o.fl. (1990c)	3,0	3,2		
			Gagnagrunnur ÍSOR	2,6			
K-26	58026	15.12.1991	Ásgrímur Guðmundsson o.fl. (1992)		1,05		
			Gagnagrunnur ÍSOR	3,6			
K-27	58027	07.11.1997	Ásgrímur Guðmundsson o.fl. (1997a)		2,50		
			Gagnagrunnur ÍSOR	8,2			
K-28	58028	24.11.1996	Hjalti Franzson o.fl. (1996)		14,5		
K-29	58029	13.06.1997	Gagnagrunnur ÍSOR	3,2	1,2		
K-30	58030	26.07.1997	Gagnagrunnur ÍSOR	1,0	0,9		
K-31	58031	07.10.1997	Gagnagrunnur ÍSOR	4,6	1,7		
			Ásgrímur Guðmundsson o.fl. (1998b)				
K-32	58032	14.09.1998	Ásgrímur Guðmundsson o.fl. (1999d)	3,0	3,80		
			Ásgrímur Guðmundsson o.fl. (1999a),				
K-33	58033	08.08.1999	Ásgrímur Guðmundsson o.fl. (1999d)	3,5	1,7		2,0
K-34	58034	09.09.1999	Ásgrímur Guðmundsson o.fl. (1999d)	5,5	4,5		
K-35	58035	05.07.2007	Anette K. Mortensen o.fl. (2007c)	3,0	1,59		
K-36	58036	18.11.2007	Ásgrímur Guðmundsson o.fl. (2008b)	11,0	2,5		
K-37	58037	18.01.2008	Ásgrímur Guðmundsson o.fl. (2008a)	3,7	2,5		
K-38	58038	20.07.2008	Magnús S. Sigurgeirsson o.fl. (2008b)	3,0	1,8		
K-39	58039	31.10.2008	Sigurveig Árnadóttir o.fl. (2009)	6,6	2,6		
KS-01	58801	27.05.2007	Bjarni Gautason o.fl. (2007a)	5,3	4,71		

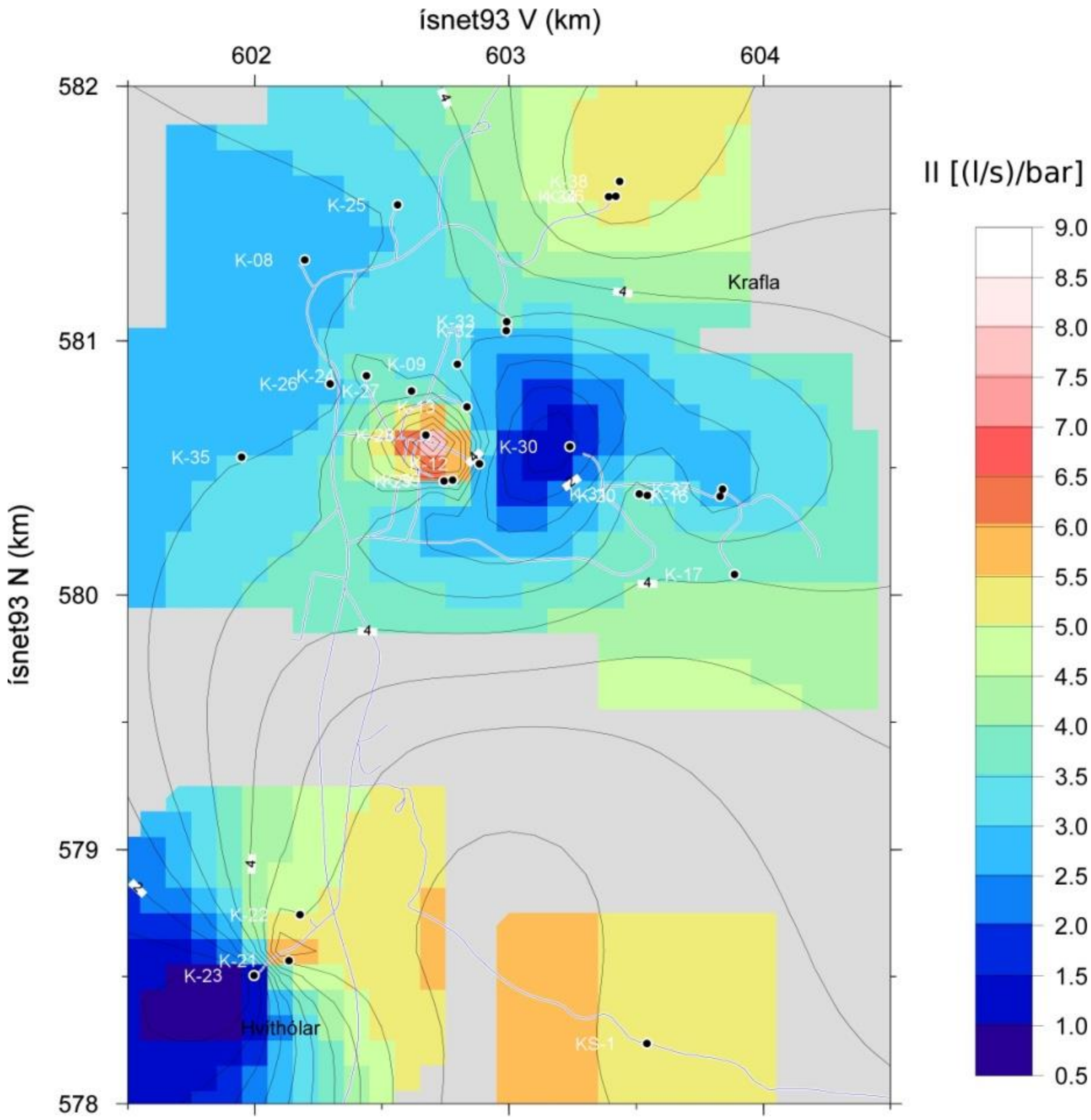


Figure 57. *Injectivity-index (II) in the Krafla area determined by measurements from well testing*

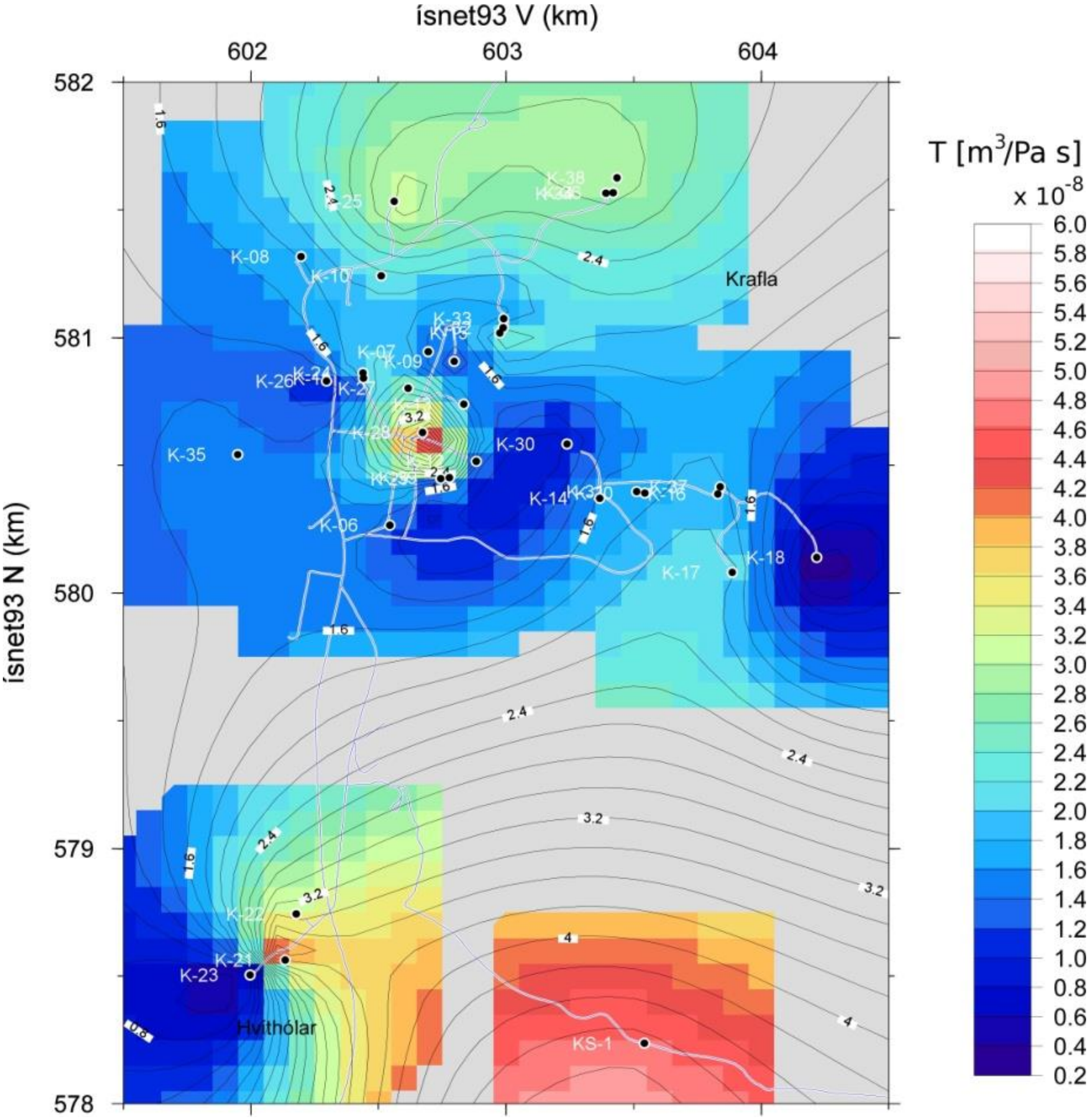


Figure 58. *Hydraulic conductivity (T) in the Krafla area determined by measurements from well testing*

9 Discharge tests and utilisation history

9.1 Production boreholes

Initial plans for the Krafla Geothermal Power Station show that the average well was expected to produce enough steam to generate 4.4 MWe of electricity and that the steam flow could diminish by 4% annually. This was based on the experience gained at Bjarnarflag and in international geothermal areas (National Energy Authority, 1972). The results of initial drilling (KW-01 and KW-02) at Krafla did not indicate the need for any alteration to this assessment (Kristján Sæmundsson et al. 1975).

These criteria were put forward as the basis for a feasibility assessment which proved positive. The power station was designed for two 30 MWe turbines and calculations showed that 15 wells could provide the steam requirements for the station.

Drilling began in 1974 at Krafla and twelve wells were drilled in the utilisation area for the power station over a period of four years. The wells provided steam for the generation of 40 MWe of electricity when active, approx. 3.3 MWe on average (Benedikt Steingrímsson & Gestur Gíslason, 1978).

Many of the wells were damaged as a result of corrosion and scaling which rapidly diminished their capacity. The cause was determined to be the inflow of acidic magmatic gases into the geothermal reservoir during the Krafla Fires, which began in 1975, shortly after the power project began. This was particularly obvious in the so-called Vítismó area to the west of Víti. The wells in the area (KG-04 and KG-10) were powerful initially, but were destroyed in a matter of weeks and months. The wells in Leirbotnar were less powerful but better than the wells at Vítismó. Well KG-12 in Leirbotnar was lined to a significant depth in order to block off the cold shallow system. The well provided super-heated steam containing hydrochloric acid and initially supplied approx. 5 MW, but rapidly diminished in capacity.

In 1984, these twelve wells only supplied 12 MWe of electricity after six years of production. The second turbine was therefore kept in storage.

New drilling areas were explored between 1980 and 1983 including the Suðurhlíðar area of Krafla and the geothermal system by Hvíthólar. Thirteen wells were drilled, producing an average of 2.9 WMwe. The quality of geothermal steam was better and operations were more successful as a result (the turbine included). Only one well needed to be drilled (KG-24) to provide low-pressure steam until the installation of the second turbine unit in 1997. However, the wells had declined during this period and this was rectified with increased steam production at Hvíthólar and by connecting well KJ-15 (the well’s production capability had increased as a result of lower gas concentrations in the steam).

The Hvíthólar area is not large but has a high production capacity. Well KJ-21 produces steam from a steam cushion at a depth of 600 m, formed when the drawdown began as a result of utilisation. Two wells were not productive because of low temperature and permeability – these were KJ-18 in Suðurhlíðar and KJ-23 by Hvíhólar.

Two new wells were drilled at Krafla between 1990 and 1991 to explore new drilling areas. It was deemed essential to source steam for the second turbine from areas outside the current drilling area as Suðurhlíðar could potentially only provide 15–20 MWe and the Leirbotnar area was difficult to utilise. Well KG-25 was drilled in Vítismó to assess whether or not the geothermal system had recovered after the influx of magmatic gases during the Krafla Fires. The well turned out to be higly prolific but the power diminished rapidly and the well was damaged beyond repair (because of acidic brine) after only three months of use.

Well KG-26 was drilled on the west-side of Leirbotnar by a small steam vent by the road up to Vítismó. The well was initially only drilled to a depth of 1200 m since it was not clear whether it would find the shallow (relatively cold) system (much like that in Leirbotnar). The shallow system turned out to extend to the location of KG-26 and the well was therefore lined and deepened. The deepened well proved to be a below average producer. The fluid also proved to be acidic and a decision was therefore made to shut-in the well to protect it from damage. In the meantime the well was used for reinjection until more steam was needed for the power station.

The installation of the second turbine began in 1997 and drilling to increase steam production resumed. Well KG-26 was cleaned without much success and therefore it continued to be used for reinjection purposes.

Nine wells were drilled between 1996 and 1999. The success rate was better than in previous drilling endevours and the wells initially produced an average of 7.7 MWe.

Wells were drilled in the shallower parts of the Leirbotnar area to source low-pressure steam. Well KG-28 proved powerful but became blocked with calcium deposits. Equipment was set up to mix inhibitors with the well fluid (deep in the well) and this proved successful. Well KJ-29 was a deep well in Leirbotnar. Corrosive steam entered the well and it rapidly diminished in capacity. The success rate of wells drilled at Suðurhlíðar was inconsistent. The best well was KJ-30 which had been directionally drilled into and beneath the western slopes (Vesturhlíðar) of Mt.Krafla. Three other wells were drilled into or beneath the Vesturhlíðar area of Krafla and KJ-34 proved to be the most powerful. These wells have provided full production capacity for the power station since the year 2000.

A total of thirty seven drilling projects were carried out at Krafla until 2000, initially producing 4.2 W on average MWe. The wells have diminished in capacity and many have been destroyed as a result of corrosion and scaling. The production capacity of the wells is barely enough to support the current 60 WMwe power station.

Seven additional wells were drilled for the next phase of the Krafla Geothermal Power Station between 2006 and 2008. Two new areas were explored to the east and west of Hvíthólar. Well KS-1 in Sanbotnaskarð is average and the steam quality is good. Well KV-1 (drilled in the Leirhnjúkar lava field) proved to be cold. Well KJ-35 was drilled in the new area to the west of Leirbotnar in the direction of Leirhnjúkar, The well was initially quite powerful but diminished significantly as a result of corrosion and liner/ casing damage. Well KJ-36 which was located to the southeast of Víti was initially very powerful but the capacity diminished rapidly as a result of corrosion and liner damage created by acidic steam from the deepest feed zones in the well. The deepest feed zones of the well were therefore blocked off after which the well produced 3.5 MW and is now connected to the station. Well KJ-37 which was drilled in Suðurhlíðar is low in capacity and produces 1 MW. The quality of the steam from the well is acceptable and the well is therefore connected to the station. Well KJ-38 was drilled northward roform the same drilling platform as well KJ-36 but corrosive fluid entered the well. The same problem occurred with well KJ-39 which was drilled underMt.beneath Sandbotnafjall. The well penetrated magma and its lower section was plugged with concreted as a result. Steam from the well proved acidic and damaged the liner. The liner was partially retrieved and the well is being reassessed for future utilisation.

The six drilling projects pertaining to the second phase of the Krafla Geothermal Power Station (KJ-35, KJ-36, the shutdown of the lower sections of KJ-36, KJ-37, KJ-38 and KJ-39) initially produced an average of 7.3 Mwe and a total of 44 MW. The capacity has diminished significantly and is approx. 18 MW when this is written (2009). Some wells are damaged because of corrosive fluid. Approx. 5 MW are now utilised by the Krafla Geothermal Power Station. Approx. 13 MW are not utilised because of corrosive characteristics in the wells.

Table 3 shows productivityshortly afterafterafterwells they were first discharged andhad reached a quasi-steady state. Work-over wells are included. Figure 59 shows initial production. The most prolific wells are located in the northern part of the area but the inflow of acidic brinefromfromfrommatter the deeper feed zones has meant that many of them are subject to damage if drilled too deep.

The p capacity ofofofofProduction wells at Krafla have been monitored regularly. The results of these measurements are published in annual monitoring reports (Trausti Hauksson and Jón Benjamínsson, 2009).

The production of shallow wells in Leirbotnar is shown in Figures 60 and 61. Wells KJ-9 and KJ-28 have been blocked by calcium and need to be cleaned regularly. Measured production levels are therefore irregular. The capacity of well KJ-9 has decreased whereas wells KG-5 and KG-24 remain stable.

The capacity of deeper wells in Leirbotnar is shown in Figures 62 and 63. The flow from the wells has increased and the enthalpy has decreased. This is probably due to the inflow of colder fluid but this has slowed down in the last few years. This developed long before reinjection began in well KG-26 and it is therefore difficult to connect the cool-down with reinjection.

The production wells in Suðurhlíðar are shown in Figures **Error! Reference source not found.** and **Error! Reference source not found.**. The enthalpy of geothermal fluid has been high in all wells from the beginning with the exception of well KJ-20. However, the enthalpy in this well has increased at a stable rate and is now almost dry. Enthalpy is highest in wells KJ-14, KJ-19 and KJ-31 which are almost dry.

There has been a drop in capacity levels in almost all wells in Suðurhlíðar with the exception of well KJ-17 and KJ-20 which have maintained their capacity. Well KJ-37 was drilled in Suðurhlíðar and has proven to be low in capacity despite a promising injectivity-index. This indicates that the capacity drop in the wells at Suðurhlíðar is due to a drop in pressure in the geothermal reservoir as opposed to corrosion or blockages.

The enthalpy of geothermal fluid from well KJ-21 in Hvíthólar has decreased in the last few years. This is due to increased water flow from the well and decreased steam flow (Figures **Error! Reference source not found.** and **Error! Reference source not found.**).

The capacity level of wells in Vesturhlíðar and Vítismó is shown in Figures **Error! Reference source not found.** and **Error! Reference source not found.**. The enthalpy of geothermal fluid from well KJ-32 in Vítismó has decreased at a stable rate in the last few years as a result of increased water flow from the well and decreased steam flow. The capacity of KJ-34 has decreased at a stable rate since it was taken into utilisation. Water flow has been low and enthalpy has been high.

The total capacity level for the Krafla geothermal area is shown in Figure 70 and the enthalpy of geothermal fluid from drilling areas is shown in Figure 71 (Trausti Hauksson and Jón Benjamínsson, 2008). Enthalpy has remained stable in the shallower parts of the Leirbotnar area. The enthalpy of geothermal fluid from the deeper wells in Leirbotnar and Hvíthólar has decreased after production was doubled in the area between 1997 and 1999. Enthalpy has increased further in Suðurhlíðar but decreased in the wells at Vesturhlíðar and Vítismó since utilisation began.

Table 3. *Initial production wells.*

Hola	Borað	Dýpi	Vermi	Rennsli	Varmaafl	Rafafl	Athugasemdir
	ár	m	kJ/kg	kg/s	MW	MWe	
KW-01	1974	1138	1676	4,7	7,1	1,2	
KW-02	1974	1204	903	16,8	12,4	1,5	
KG-03	1975	1720	1070	80	71,4	6,2	
KJ-03A	1983	985	903	20,2	14,9	1,8	
KG-04	1975	2000					Sjálfskaparvíti
KG-05	1975	1299	925	20,2	15,3	1,4	
KJ-06	1976	2000	1673	10,6	15,9	2,3	
KJ-07	1976	2165	1624	17,1	24,8	3,5	
KG-08	1976	1658	871	13,7	10,7	1,0	
KJ-09	1976	1101	939	18,1	13,9	1,3	Fyrir dýpkun
KJ-09	1977	1280	1316	41,3	47,5	6,1	Fóðruð og dýpkuð.
KG-10	1976	2082	1331	48,2	56,1	7,2	
KJ-11	1976	2217	2121	6,5	12,6	2,0	Eftir endurfóðrun
KG-12	1978	2222	2891	9,8	27,0	4,5	
KJ-13	1980	2050	2668	6,0	15,1	2,5	
KJ-13A	1983	1780	2202	14,6	29,8	4,7	Stefnuboruð að Hveragili
KJ-14	1980	2107	2630	17,0	41,9	6,9	
KJ-15	1980	2097	2675	4,2	10,4	1,7	
KJ-16	1981	1981	1695	7,9	12,1	1,8	
KJ-16A	1998	2191	2203	5,3	10,1	1,6	Stefnuboruð undir Kröflu
KJ-17	1981	2190	1814	8,9	14,2	2,1	
KJ-18	1981	2215					Þétt – Hefur ekki blásið
KJ-19	1982	2150	2658	8,7	21,7	3,6	
KJ-20	1982	1823	1714	14,0	21,7	3,2	
KJ-21	1982	1200	1683	34,8	52,8	7,6	
KJ-22	1983	1876	1213	20,9	21,9	2,6	
KJ-23	1983	1968					Þétt – Hefur ekki blásið
KG-24	1988	1400	891	22,4	16,2	1,4	
KG-25	1990	2105	1938	41,5	73,5	11,2	
KG-26	1991	1200	1013	21,1	17,9	1,8	Fyrir dýpkun
KG-26	1991	2127	2595	8,0	19,4	3,2	Fóðruð og dýpkuð
KJ-27	1997	1771	1163	31,1	30,9	3,6	
KJ-28	1996	1003	1047	60,6	53,3	5,7	
KJ-29	1997	2103	2674	10,3	25,8	4,3	
KJ-30	1997	2054	2389	33,2	73,9	11,9	
KJ-31	1997	1440	2676	7,1	17,9	3,0	
KJ-32	1998	1875	2676	13,2	33,2	5,5	
KJ-33	1999	2011	2676	25,4	63,6	10,5	
KJ-34	1999	2002	2632	45,7	112,7	18,4	
KJ-35	2007	2508	2562	19,1	45,8	7,5	
KJ-36	2007	2501	2676	45,1	113	18,7	
KJ-36	2008	1700	2027	11,3	21,0	3,2	Steypt upp að 1700 m
KJ-37	2008	2194	2672	9,4	23,6	2,6	
KJ-38	2008	2700	2305	16,7	35,6	6,4	
KJ-39	2008	2822	2450	14,9	34,1	5,5	Steypt upp í 2612 m
KS-01	2007	2502	1623	14,2	20,7	3,0	Sandabotnaskarð
KV-01	2006	2894					Leirhnjúkshraun - Köld
Samtals				**900**	**1413**	**206**	
Meðaltal				**19,6**	**30,7**	**4,5**	

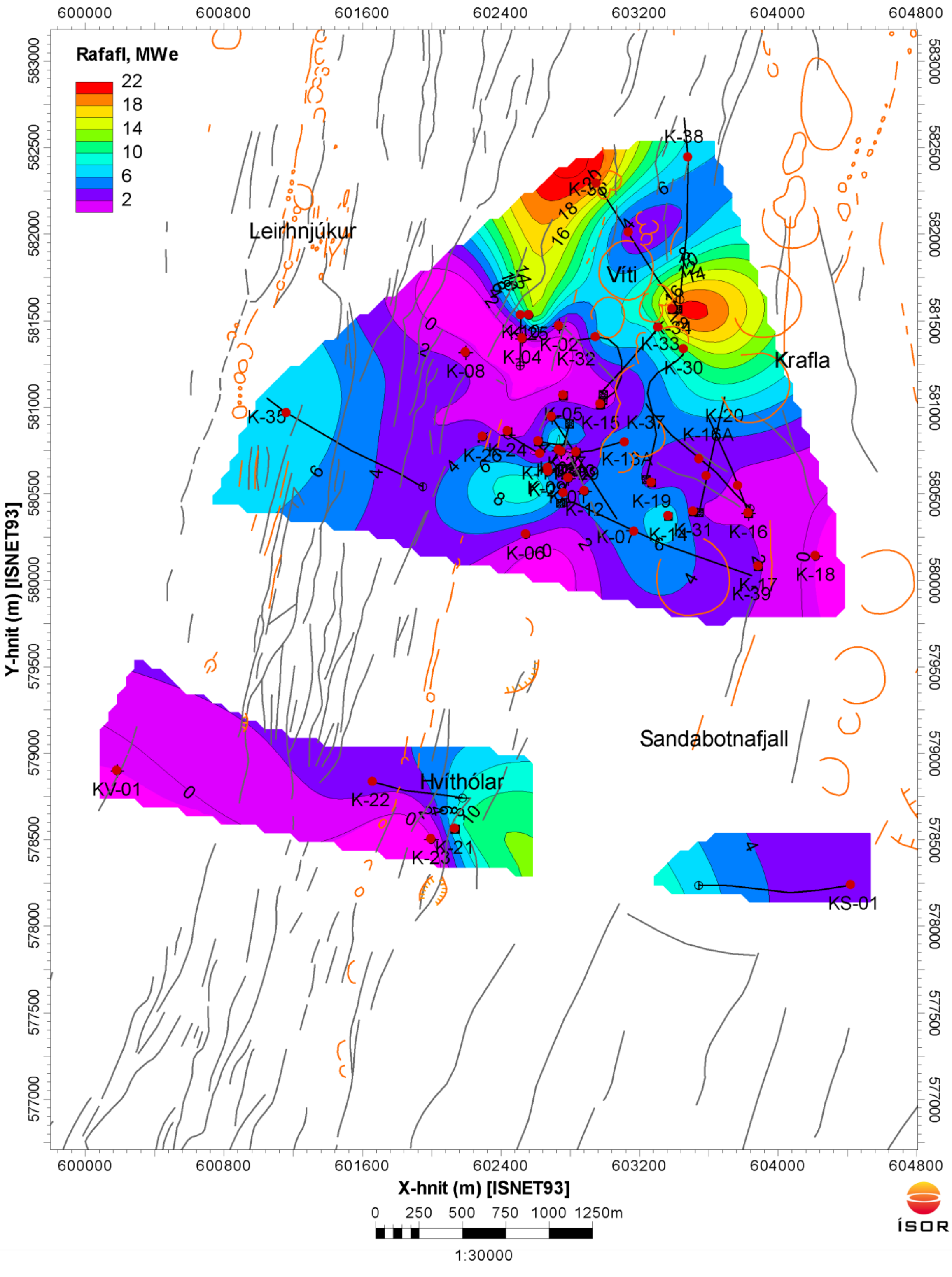


Figure 59. *Initial production wells.*

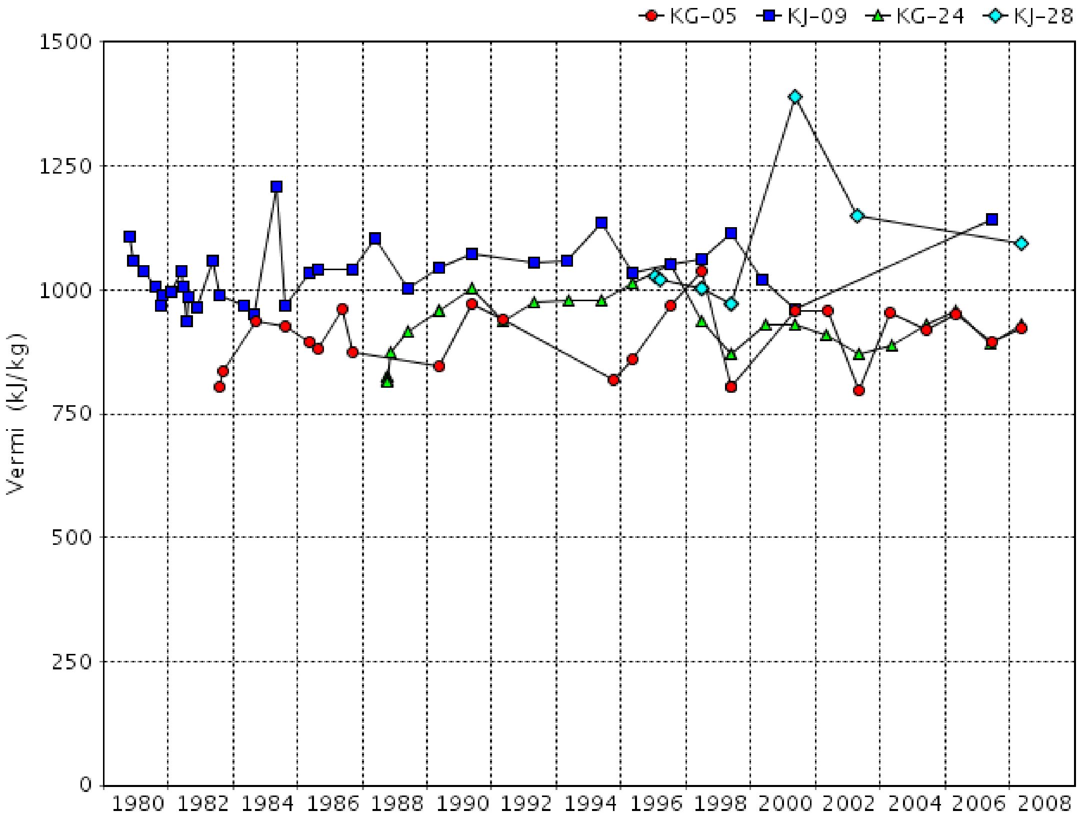


Figure 60. *Leirbotnar. Enthalpy in shallow wells.*

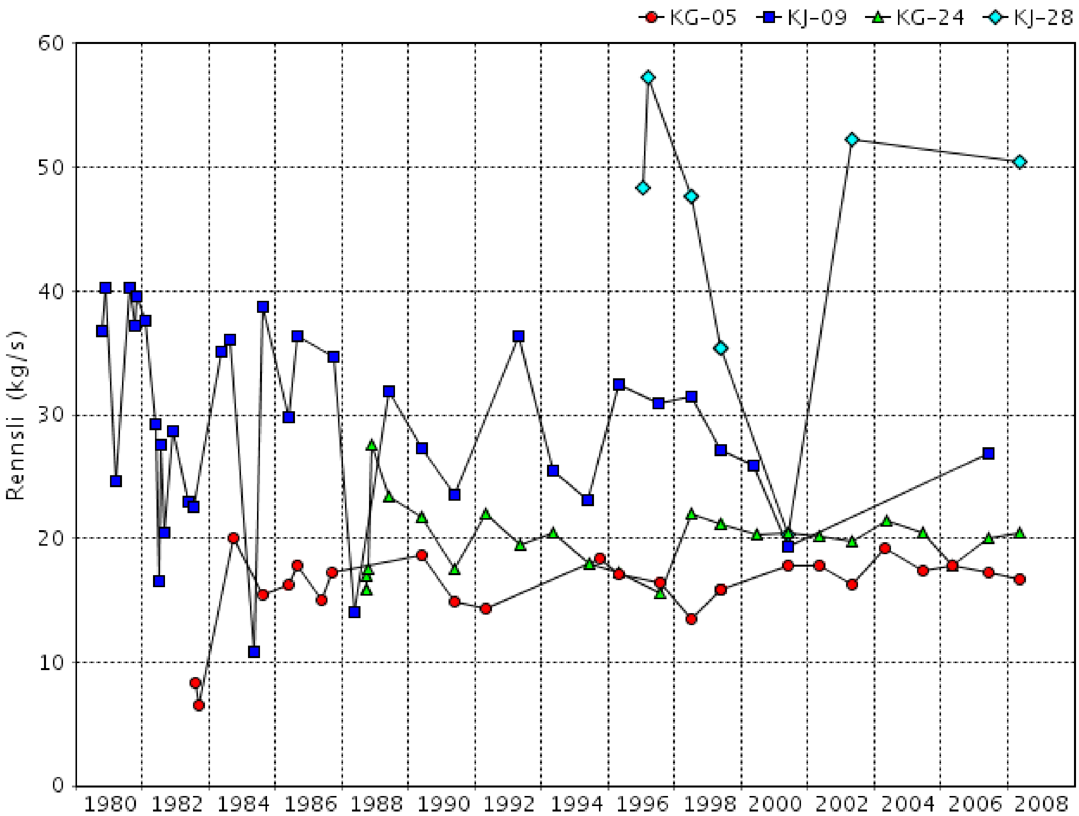


Figure 61. *Leirbotnar. Total discharge from shallow wells.*

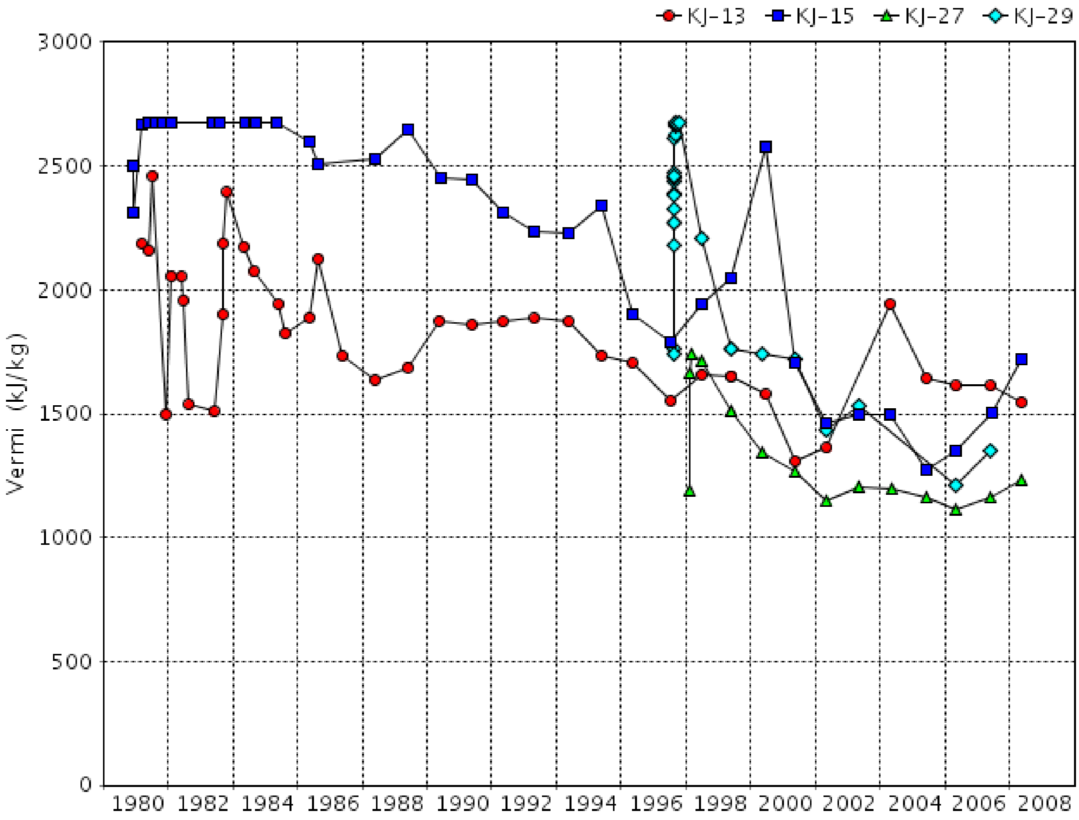


Figure 62. *Leirbotnar. Enthalpy in deep wells.*

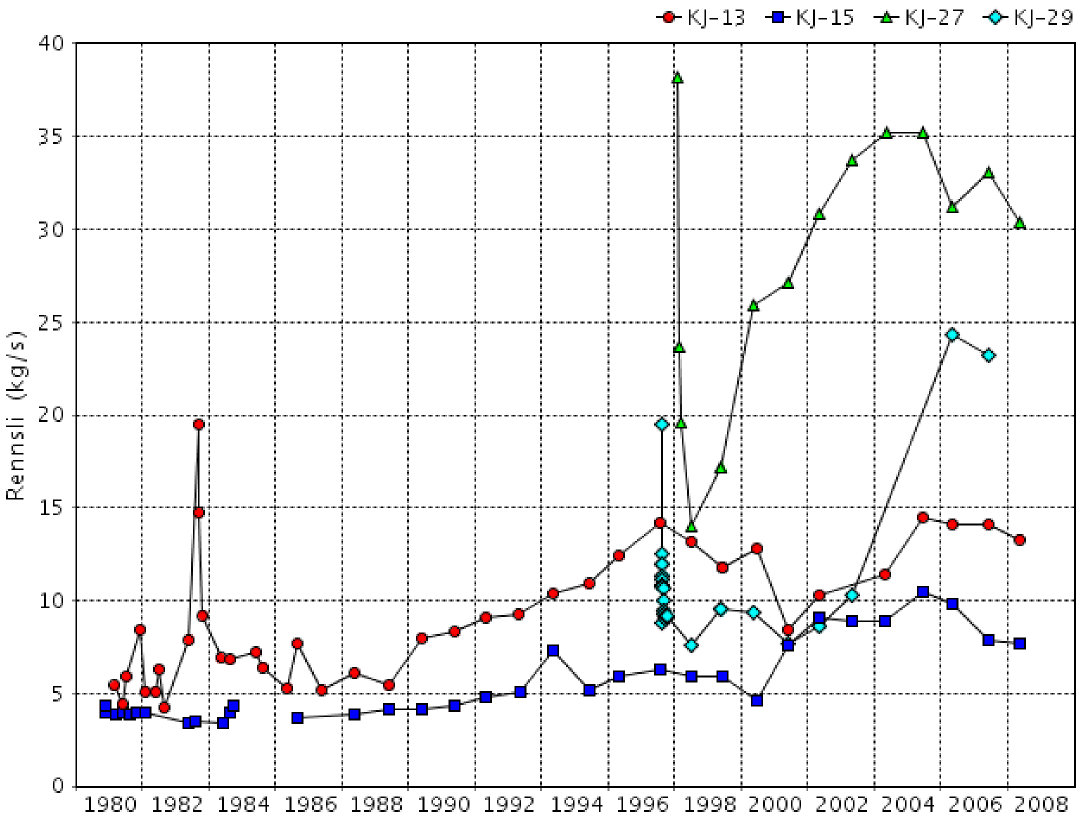


Figure 63. *Leirbotnar. Total discharge from deep wells*

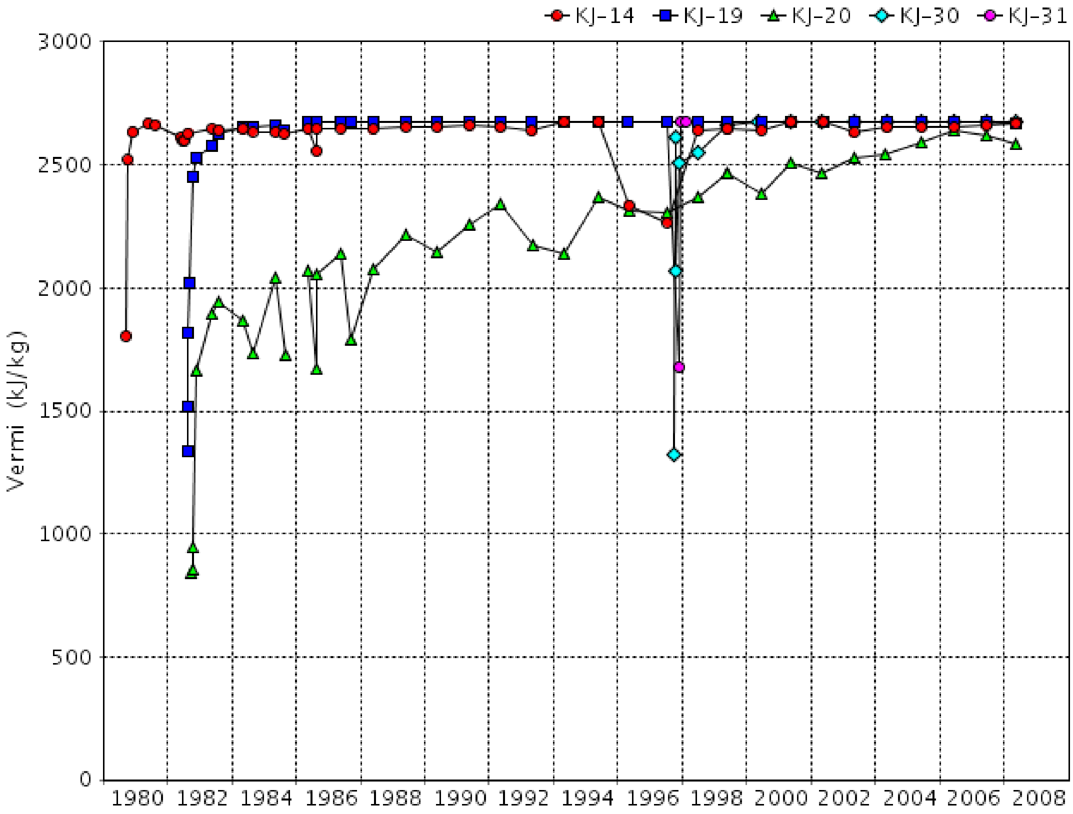


Figure 64. *Suðurhlíðar. Enthalpy in wells.*

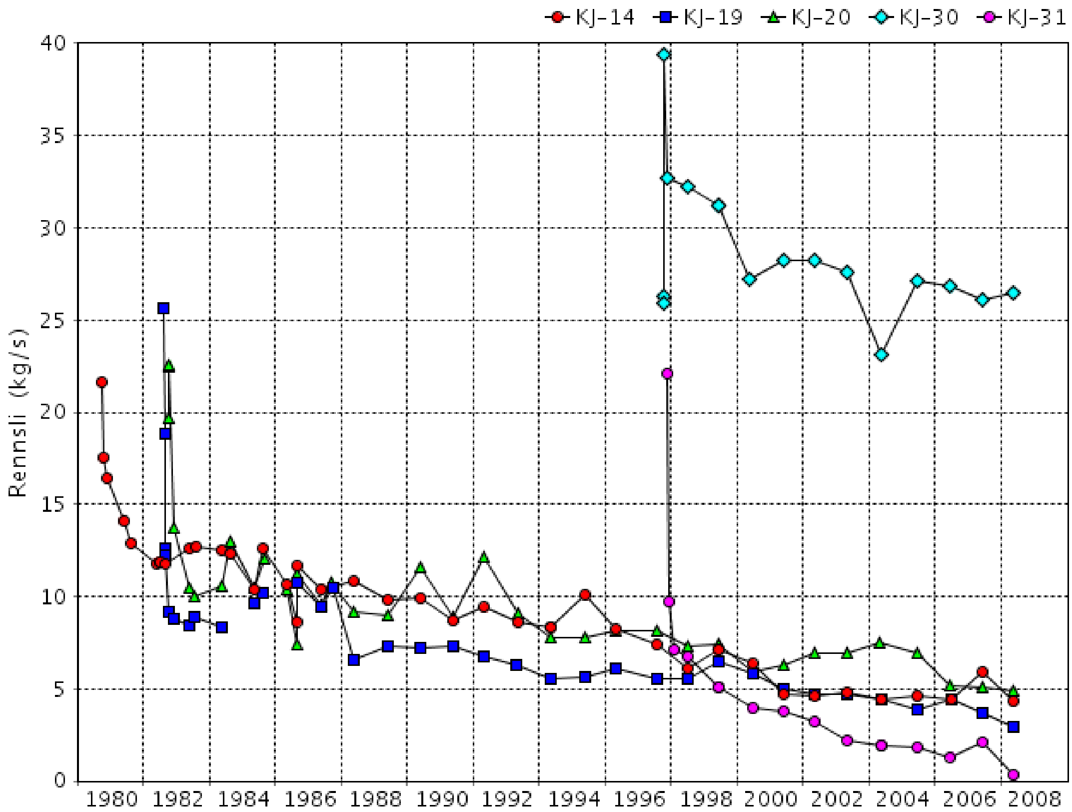


Figure 65. *Suðurhlíðar. Total discharge from wells.*

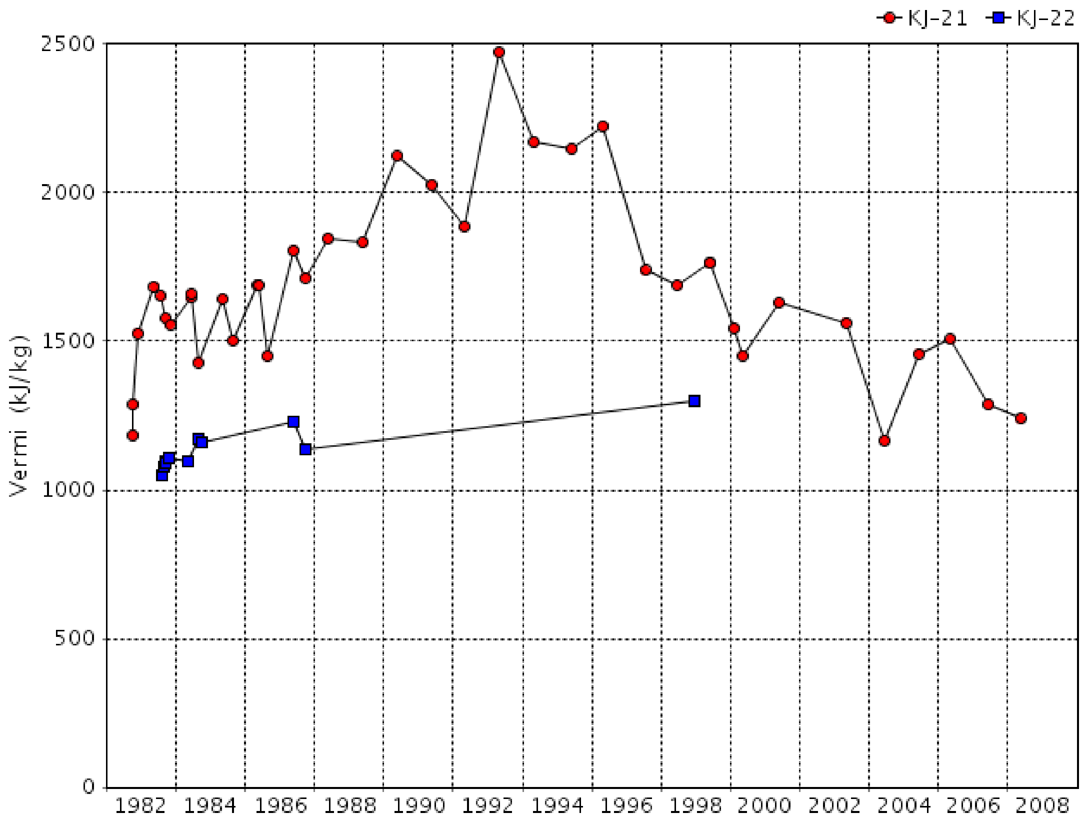


Figure 66. *Hvíthólar. Enthalpy in wells.*

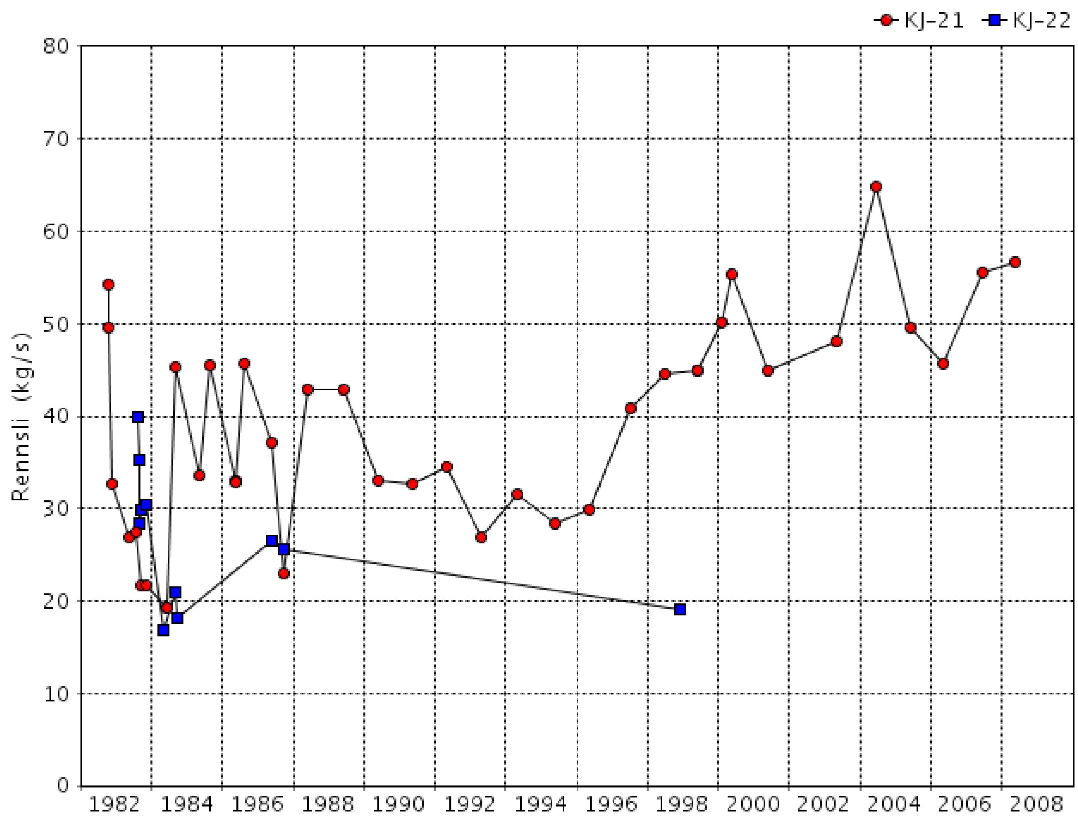


Figure 67. *Hvíthólar. Total discharge from wells.*

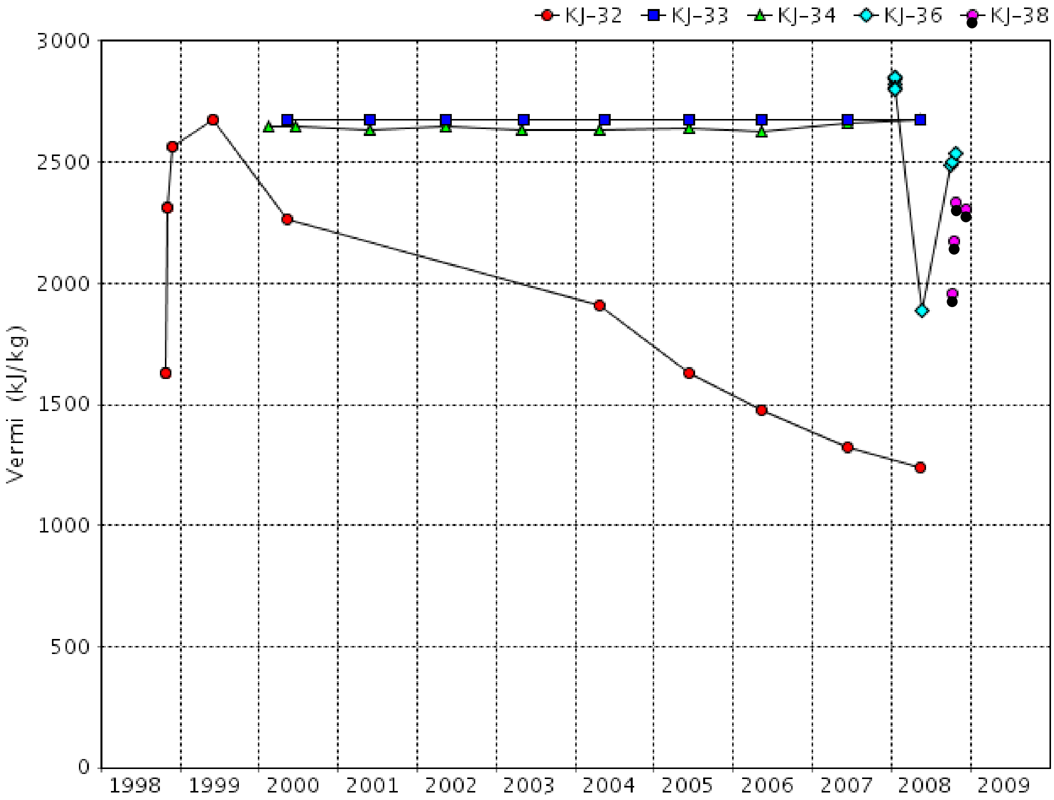


Figure 68. *Vesturhlíðar and Vítismór. Enthalpy in wells.*

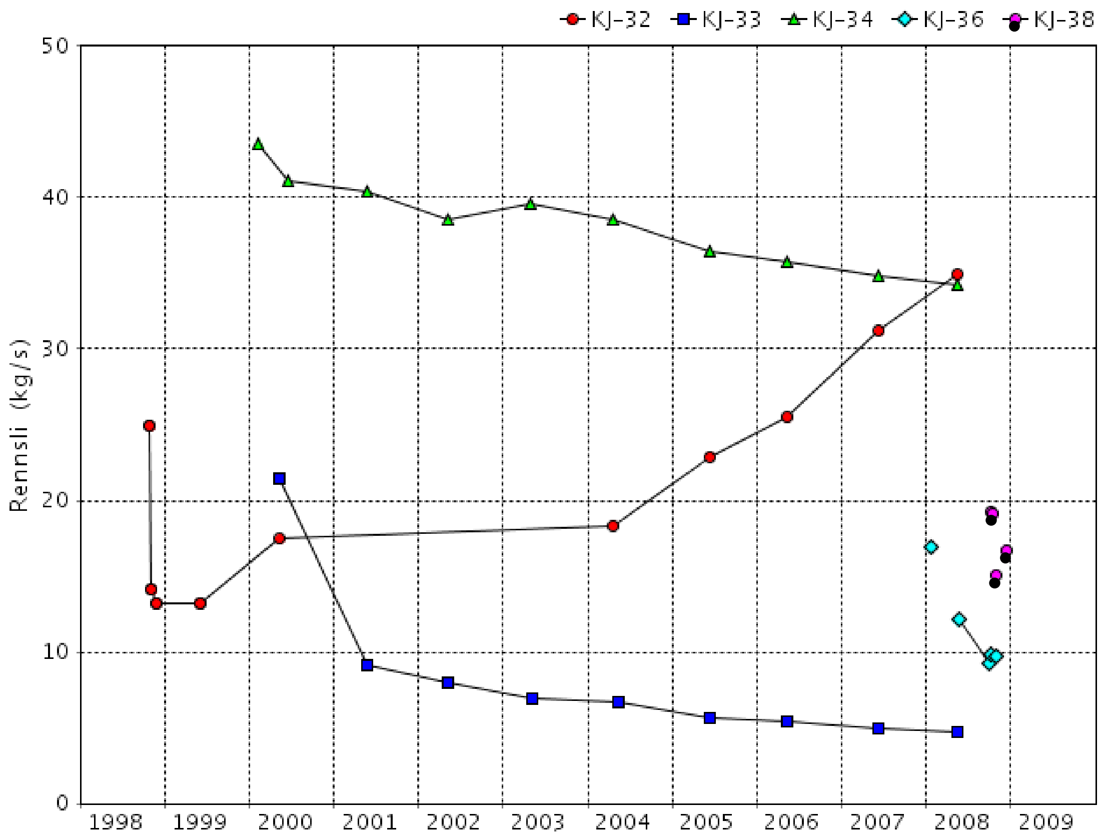


Figure 69. *Vesturhlíðar and Vítismór. Total discharge from wells*.

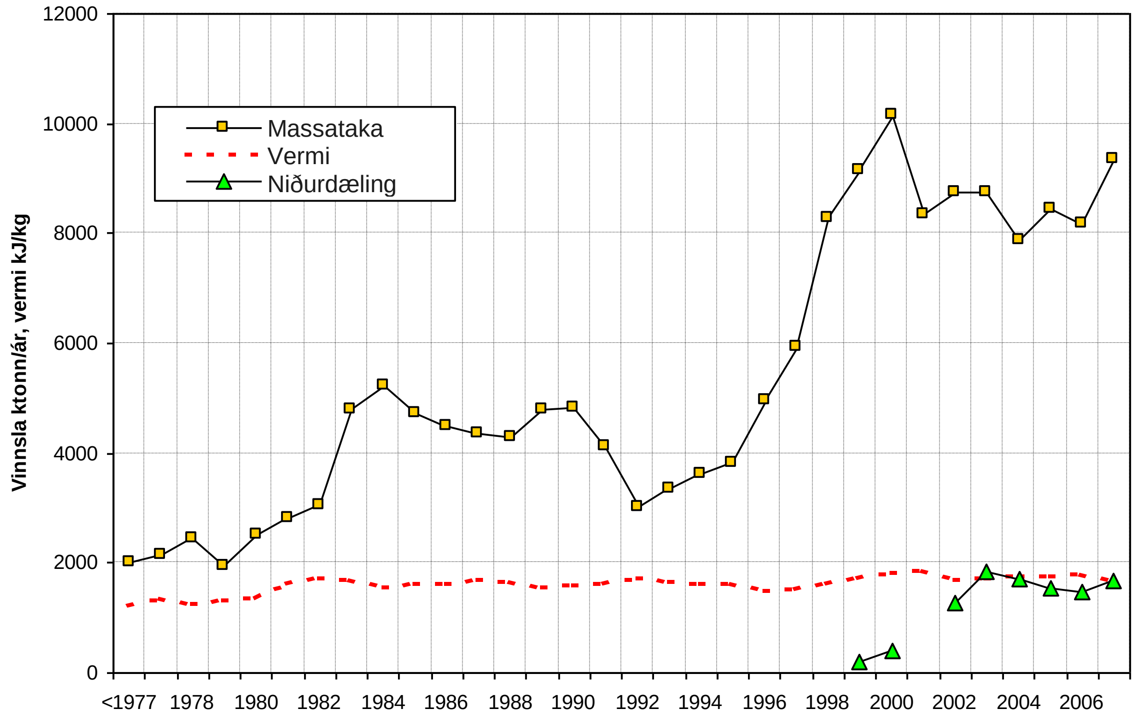


Figure 70. *Production and reinjection in the geothermal area at Krafla.*

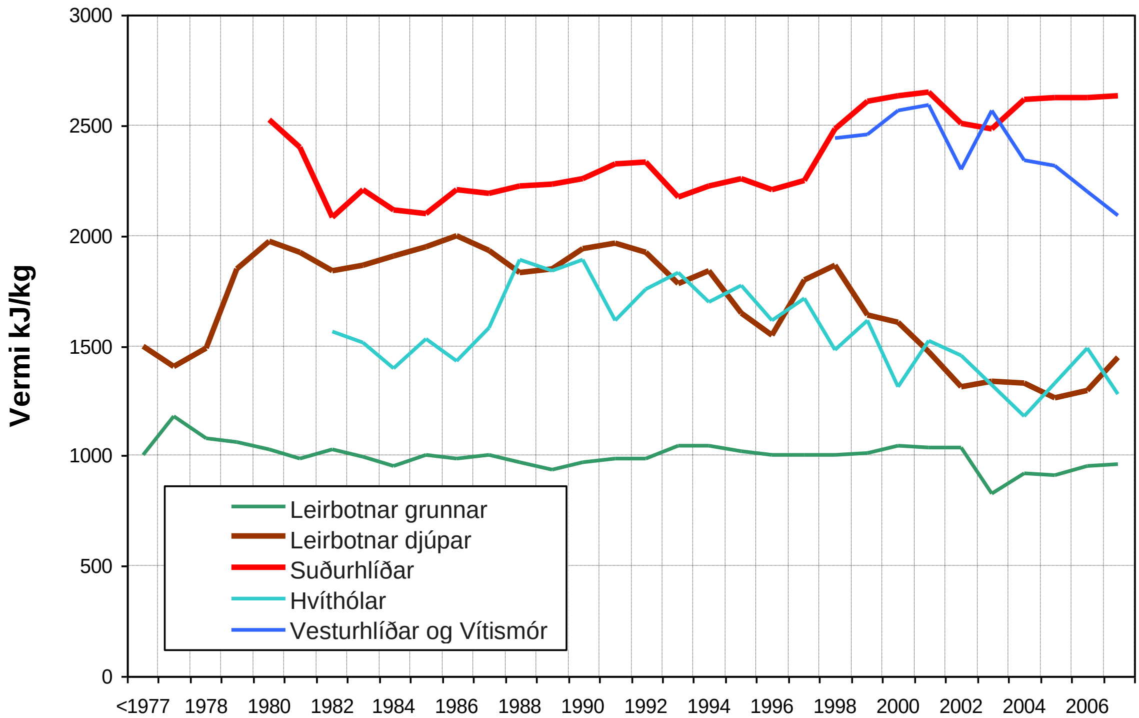


Figure 71. *Enthalpy of well fluid (by drilling area).*

9.2 Reinjection and tracer tests

The reinjection of geothermal effluent in the geothermal system at Krafla began in 1999. Initially, small quantities were reinjected in phases but reinjection has become a regular part of operations and is now quite substantial. Table 4 gives an overview of reinjection up to and including the year 2007 (see Figure 70).

Table 4. *Reinjection into the Krafla geothermal system.*

Ár	KJ-22		KJ-11		KG-26		Samtals	
	ktonn	kg/s	ktonn	kg/s	ktonn	kg/s	ktonn	kg/s
1999	207	6,6	0	0	0	0	207	6,6
2000	415	13,1	0	0	0	0	415	13,1
2001	0	0	0	0	0	0	0	0
2002	0	0	131	4,2	1147	36,4	1278	40,5
2003	0	0	257	8,1	1592	50,4	1849	58,6
2004	0	0	285	9,0	1423	45,0	1708	54,0
2005	0	0	172	5,5	1368	43,4	1540	48,8
2006	0	0	0	0	1462	46,4	1462	46,4
2007	0	0	0	0	1665	52,8	1665	52,8
2008	0	0	0	0	1880	59,1	1880	59,1

Geothermal effluent was reinjected in small amounts into well KJ-22 by Hvíthólar in 1999 and 2000 but no reinjecinjection was carried out in 2001. Reinjection measures were restarted in 2002 in wells KJ-11 and KG-26 in Leirbotnar (reinjection was discontinued in KJ-11 in 2005). Reinjection measures in well KG-26 have been substantial since 2002 and are equal to approx. 18% of the entire mass extracted from the Krafla area in 2007. Reinjection measures in well KG-26 have been successful and the well's intake capacity seems to be increasing. It has in fact increased almost tenfold since the first days of reinjection. There have been no negative effects on nearby wells.

Two tracer tests were conducted in the Krafla area, one in Hvíthólar and one in the deeper system of Leirbotnar. The first test in Hvíthólar was conducted in the autumn of 1999 when 200 kg of KI (potassium iodide) was injected into well KJ-22. Wells KJ-21, KJ-9, KJ-27, KJ-28 and KJ-29 were subsequently monitored. The material was traceable in well KJ-21 three days after the injection (the well is located 200 m to the south of the well). There was no trace of the material in other wells. This resulted in the discontinuation of reinjection in this area. Well KG-26 was injected with 450 kg of KI in December, 2005. The method and results are described in the results outlined by Halldór Ármannsson et al. (2009). Tests continued until July, 2007 (a total of 18 months) and samples were taken from 9 wells (in close proximity) throughout the process. There was no significant recovery of the potassium iodide during the testing and even if potassium iodide had been transported in significant measure below the traceable level then it would still only account for a small amount of the potassium iodide injected into the system. There are two possible explanations for this. It is possible that the boiling of water in the rock surrounding KG-26 could slow down the transport of the potassium iodide but the material seeks out water and might remain in the stagnant water despite the steam being distributed throughout the system. The second explanation is the possibility that the connection between well KG-26 and the other wells is simply not that significant. However, it is clear that insignificant recovery shows that the Krafla system is able to cope with reinjection in well KG-26 and that there is no reason to worry about the potential cooling of the system as a result of reinjection in the coming years.

10 Chemical composition of geothermal fluid and steam from boreholes

The chemical composition of water and steam from wells has been monitored since exploratory drilling began in Krafla in 1974. The frequency of the collection of samples has varied, mostly collected at the onset of discharge but then generally collected on an annual basis. The results are published annually in monitoring reports (Trausti Hauksson and Jón Benjamínsson, 2008). The location of wells at Krafla is shown in Figure 72. Drilling fields that have been utilised are also shown. The chemical characteristics of wells can differ significantly according to location and depth and there have been substantial changes in chemical composition since production began.

The geothermal system under Leirbotnar and Vítismó is twofold (a dual system). The shallow system is at a temperature of 18 - 220°C and a water phase fluid flows into the wells. The area is not rich in gases but is mineral rich. Silica and other materials are in equilibrium with minerals in the reservoir at formation temperature. The concentration of gases is greater in shallow wells located in the eastside of the area (Gestur Gíslason et al.1978). Wells close to Hveragil are warmer (KJ-09 and KJ-28). This causes calcite deposits to be released when the water begins to boil in these wells. Well KG-24, which is further west, has less concentrations of gas and there have been no signs of calcite deposits.

The chemical composition has not altered significantly in the wells at Leirbotnar with the exception of well KJ-09. Warmer water flowed into the well from deep-set aquifers but the percentage has decreased with the years and the concentration of silicon has decreased (Figure 73). There are indications that an upflow flow channel can be found below Hveragil and that the temperature follows the boiling point depth curve. The deeper wells drilled at Leirbotnar were initially lined to a depth of 300 - 600 metres. Water flowed into the wells from the shallower depths of the system. The temperature of deep-set aquifers in the wells was measured at 300- 340°C. Water and steam flowed from them, even dry steam.

Volcanic activity began at Leirhnjúkar shortly after the construction of the Krafla Geothermal Power Station began. Only three wells had been tested at this stage. Well KG-03 proved average and the gas concentration in steam was low. An increase in gas concentration was detected shortly after the volcanic activity began. The capacity of the well decreased and the well became useless within a few months (Gestur Gíslason & Stefán Arnórsson, 1976).

Drilling work on well KG-04 had just reached completion when the volcanic activity began. High pressure steam from deep-set aquifers flowed up through the well and into the shallow aquifers of the shallow system. The well-head equipment was not designed to withstand such high pressure and began to leak. The steam also became acidic and corroded a hole into the well-head resulting in well failure. A water rich crater was formed and was given the name Sjálfskaparvíti. The acidity of the water discharged from the spring measured pH 1.8 (Gestur Gíslason & Stefán Arnórsson, 1976). Subsequently drilling at well KG-05 was discontinued and the well–heads of new wells were reinforced and the liner/casing deepened to 800 m. The next wells to be drilled at Leirbotnar penetrated deep-set and high temperature aquifers which discharged gas-rich steam (Figure 74). The water discharged from them turned black once they became active and production diminished rapidly. This was given the name Black Death.

The black colour was caused by suspended solids of iron-sulphide, formed when iron from the liner corroded as a result of acidic steam from deep-set aquifers merging with alkaline water and flowing into the wells from shallow aquifers. The deposits blocked the well and the problem re-occurred after the wells (KJ-07 and KG-10) had been cleaned. A number of deep wells were drilled late on in Leirbotnar and lined with a liner to a depth of 1200 m to cut off the shallow aquifers. Super-heated, dry steam flowed from well KG-12 and contained HCI and iron ($FeCl_2$) (Trausti Hauksson, 1979). Well KJ-15 was drilled by Hveragil and proved to be gas-rich and non-acidic. These wells lasted better than the other wells. Gas-concentrations in the steam were closely monitored (Figure 75).

The concentration of carbon dioxide dwindled with the passing years and in 1999 a decision was made to investigate Vítismó and its suitability for production by drilling well KG-25. Acidic gas was detected although the concentration of carbon dioxide had decreased since the eruption period. Gas concentrations were low in well KJ-29 (Leirbotnar) when it was drilled in 1997 but the well discharged acidic fluid (Figure 76).

The concentration of sulphide in water from deep-set aquifers was initially low but much higher in shallow wells. This has changed alongside utilisation, particularly in wells in or by Hveragil (Figure 77). This indicates that cold water flows into the system and releases sulphate from the rock. It became clear that Leirbotnar and Vítismó would not be a viable sources for the station and new areas were explored. Drilling was carried out in the Suðurhlíðar area of the Krafla Mountain but the gas composition in the fumaroles indicated less effects from magmatic gases in this area than in Leirbotnar (Halldór Ármannsson & Trausti Hauksson, 1980). The gas concentration in the steam increased almost immediately after utilisation began in Suðurhlíðar. Gas concentrations were stable in most wells but varied between wells (Figure 78). Well KJ-20 (drilled under the Krafla Mountain) had the highest concentration. However, the well did not seem to contain corrosive fluid like that found in Leirbotnar, despite high gas concentrations and chloride concentrations. The wells retained power but were under-average in production despite the fact that the quality of gas was better in Suðurhlíðar than that found in Leirbotnar. Only well KJ-14 was above average. Wells KJ-16 and KJ-17 were reversed in temperature and their capacity fluctuated as a result of the interaction between water-rich but weak, deep-set aquifers and high enthalpy aquifers at a higher level.

The steam flow from fumaroles in the Hvíthólar area increased in 1978. The steam was gas-poor and therefore potentially suitable for production. Three wells were drilled in the area. Well KJ-21 was high in capacity and discharged steam from a steam pillow which had been formed at a depth of 600 m. The deeper aquifers were colder and difficult. Gas concentrations in the steam were low but stable. Well KJ-22 was directionally drilled in a western direction. The well was reversed and fluctuated in capacity as a result of the interaction between the steam aquifer at 600 m and the colder aquifer in the well. Wells were directionally drilled or drilled into the western slopes of the Krafla Mountain when the Krafla Geothermal Power Station was reaching completion. The gas from these wells was gas-rich (Figure 79). Gas levels have decreased since well KJ-34 became active and gas levels also began to decrease in well KJ-20 in Suðurhlíðar (the well was directionally drilled beneath Krafla). The wells are high in capacity and the gas flow increased from the system when they became active (Figure 80). The concentration of hydrogen sulphide was also quite high in gases from the Vesturhlíðar wells.

Well KJ-16 was directionally drilled in a north-westerly direction (well KJ-16A). The well was not high in capacity, was gas-rich and has the highest concentration of hydrogen of all the wells. This indicates that the steam utilised by the well is sourced from deep within the system. Other wells have been drilled to source steam for the next phase of the Krafla Geothermal Power Station. Well KJ-35 was drilled in a new area to the west of Leirbotnar and was directionally drilled in the direction of Leirhnjúkar. The well was initially average in capacity but diminished rapidly. The reason is mainly thought to be the iron-silica deposits/precipitation found in the well below a depth of 2000 m which is thought to have been formed as a result of corrosive deep-set fluid although there were only small amounts traceable in samples retrieved from the well head (Anette K. Mortensen et al.2008).

Well KJ-36, located to the south east of Víti was high in capacity. The well was directionally drilled beneath Víti and outward towards Vítismó. Super-heated steam discharged from the well and contained HC1. The lower section of the well was closed off and the well is now utilisable (Trausti Hauksson 2008a, b).

Well KJ-38 was drilled northward from the same drilling platform as well KJ-36. The well penetrated acidic aquifers at the wellbottom. The percentage of deep-set and shallow aquifers could be influenced by altering the opening of the well and peak pressure. This was done to attempt to steer the acidity of the water flowing around the well-head and to prevent corrosion. However, this did not affect corrosion deep down in the well. The well was therefore shut down and water was injected into it to prevent any further damage (Trausti Hauksson, 2009). Well KJ-39 was drilled eastward from the drilling platform for KJ-29 in Leirbotnar and beneath well KJ-17 in Suðurhlíðar. The well was 2,865 m long and penetrated magma at the wellbottom. The wellbottom was concreted to avoid acidity which would have accompanied the magma. However, the steam from the well proved to be acidic and very corrosive, especially when it mixed with water from the shallow aquifers in the well. The liner was partially retrieved from the well but was highly corroded and significantly damaged. Possible options for utilising the acidic well are being developed but they remain closed in the meantime.

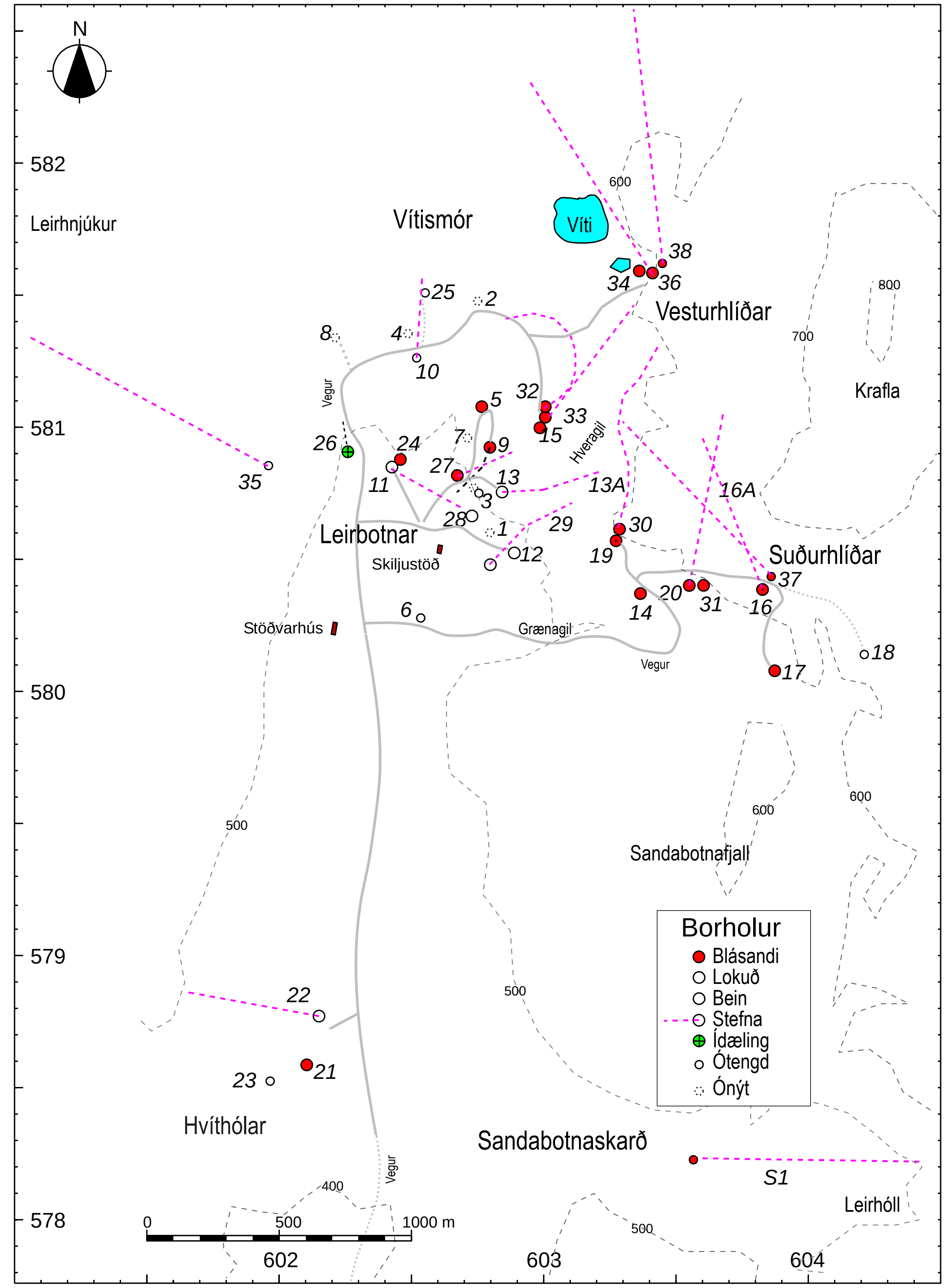


Figure 72. *Production area at Krafla in 2008..*

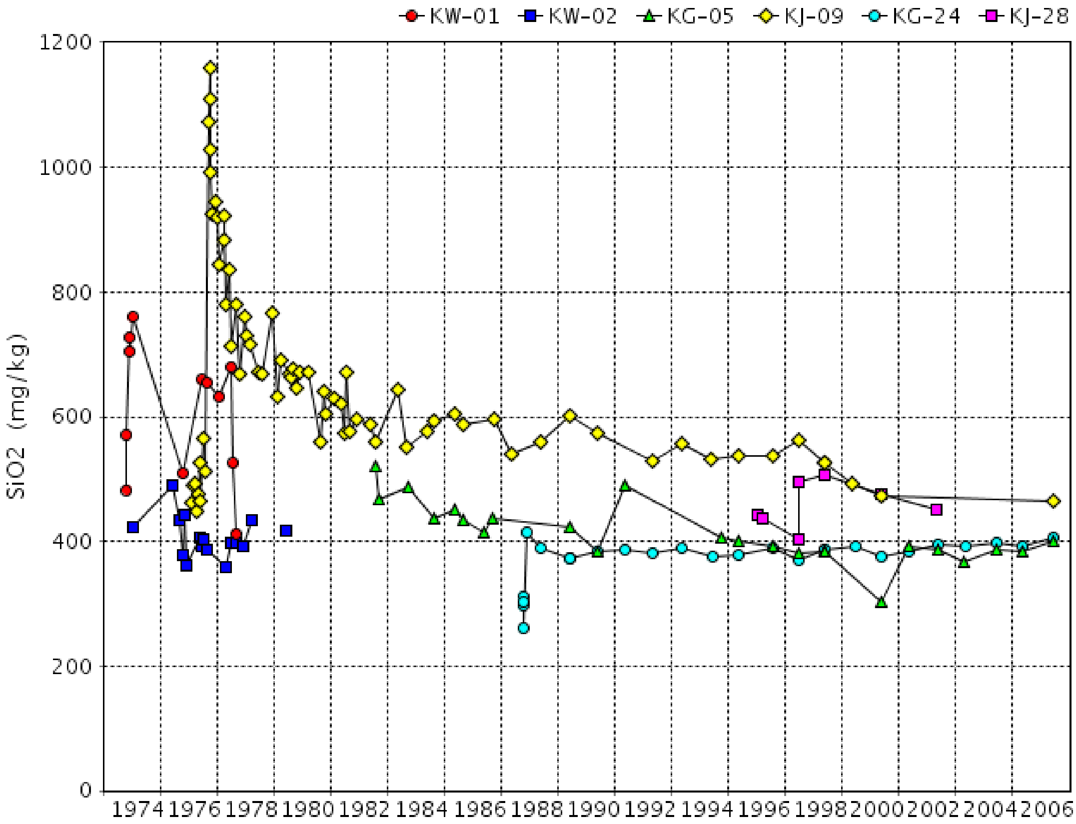


Figure 73. *Silicon in fluid from shallow wells in Leirbotnar.*

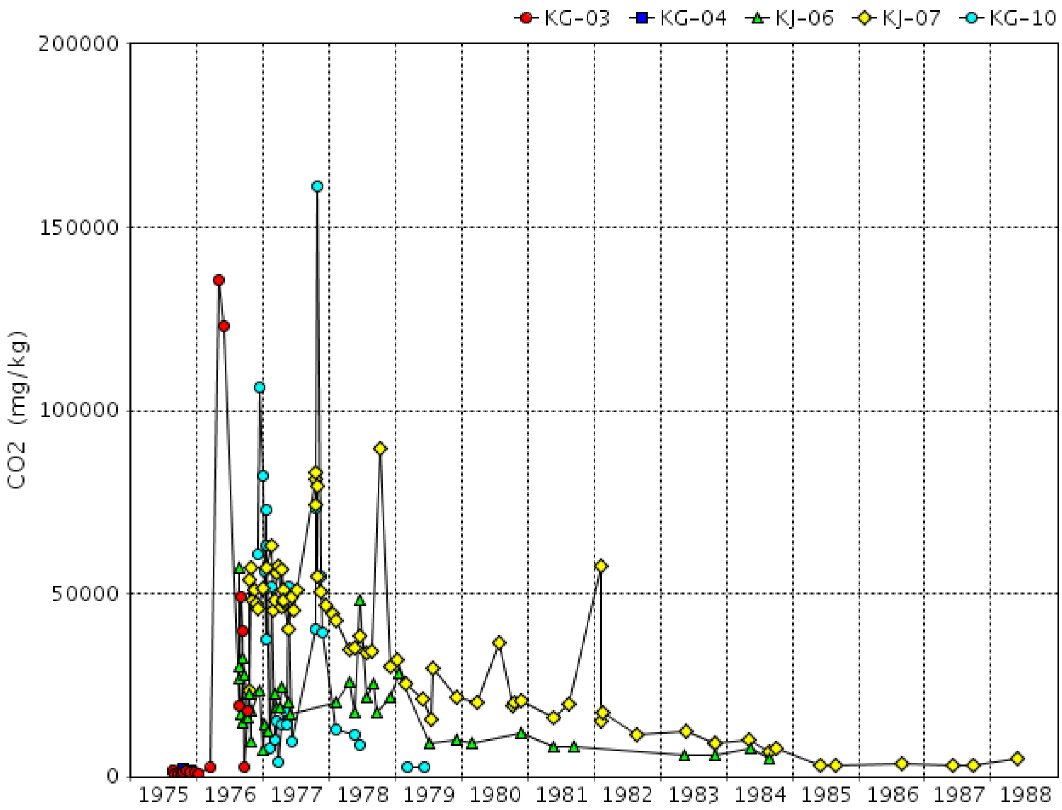


Figure 74. *Carbon dioxide in steam from deep wells in Leirbotnar.*

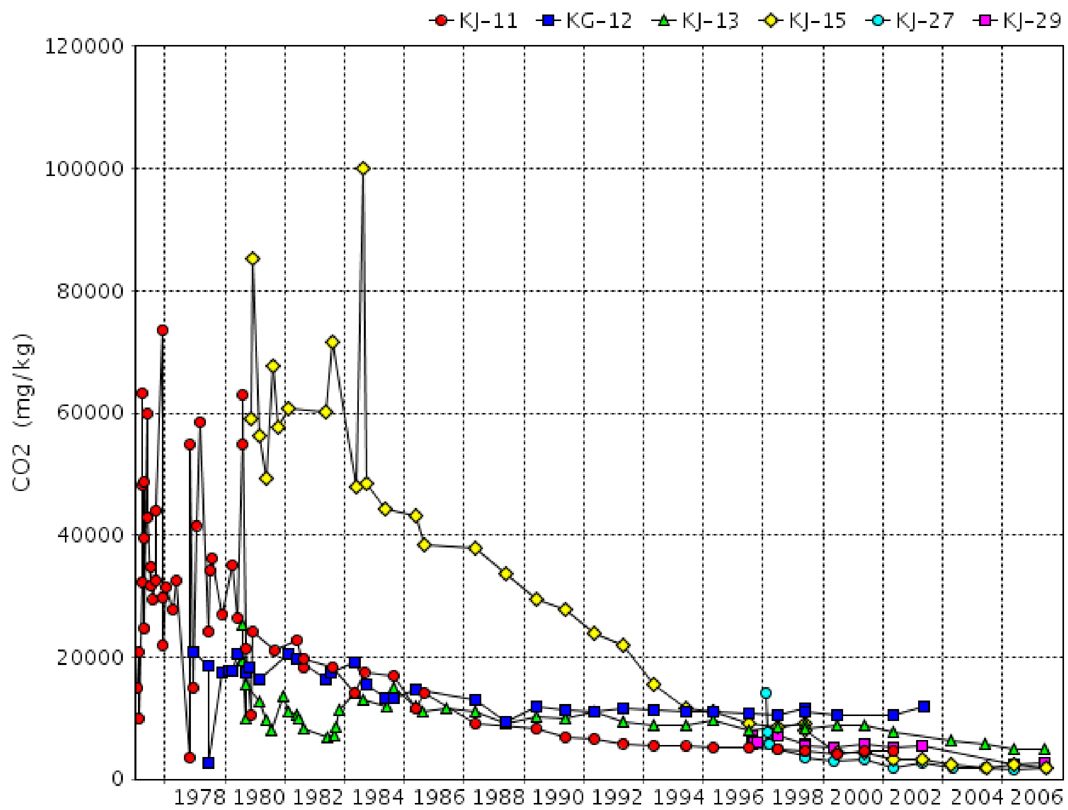


Figure 75. *Carbon dioxide in total flow from deep wells in Leirbotnar.*

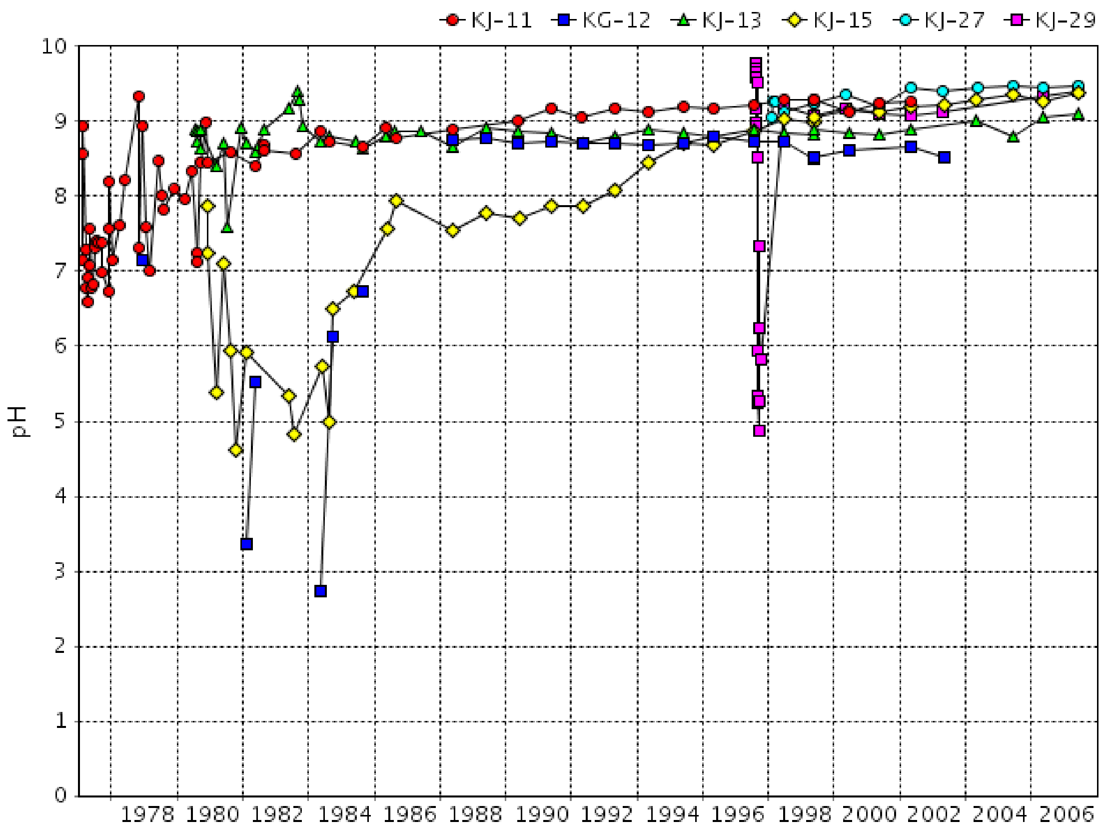


Figure 76. *Acidity levels in fluid from deep wells in Leirbotnar.*

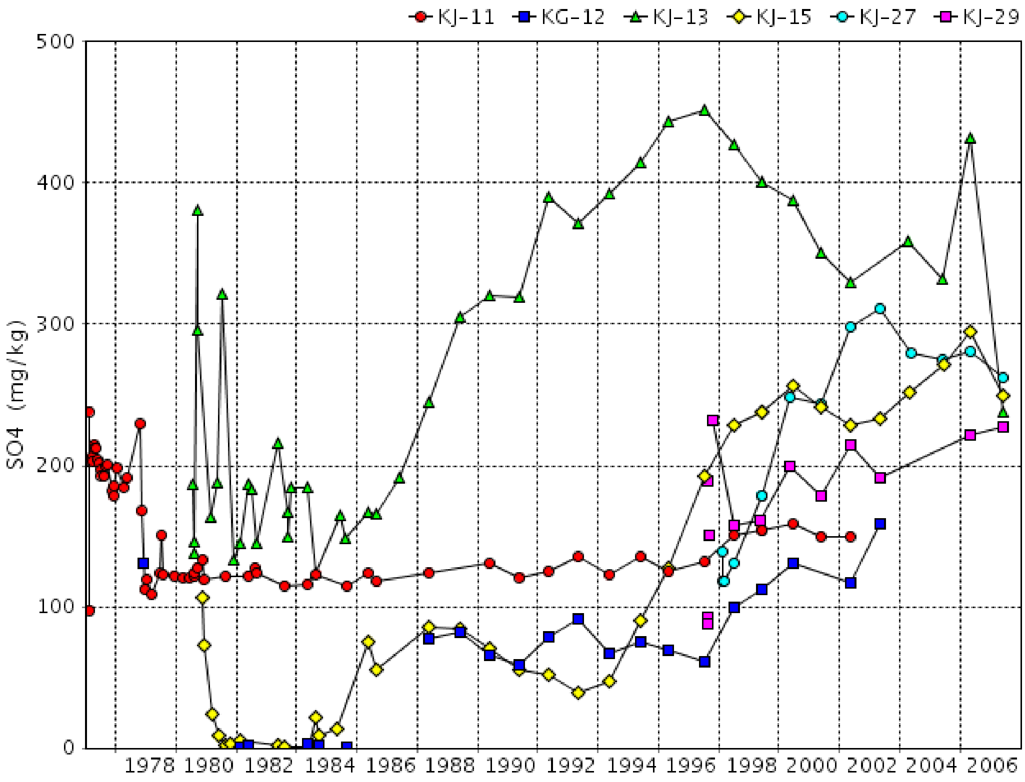


Figure 77. *Sulphide levels in fluid from deep wells in Leirbotnar.*

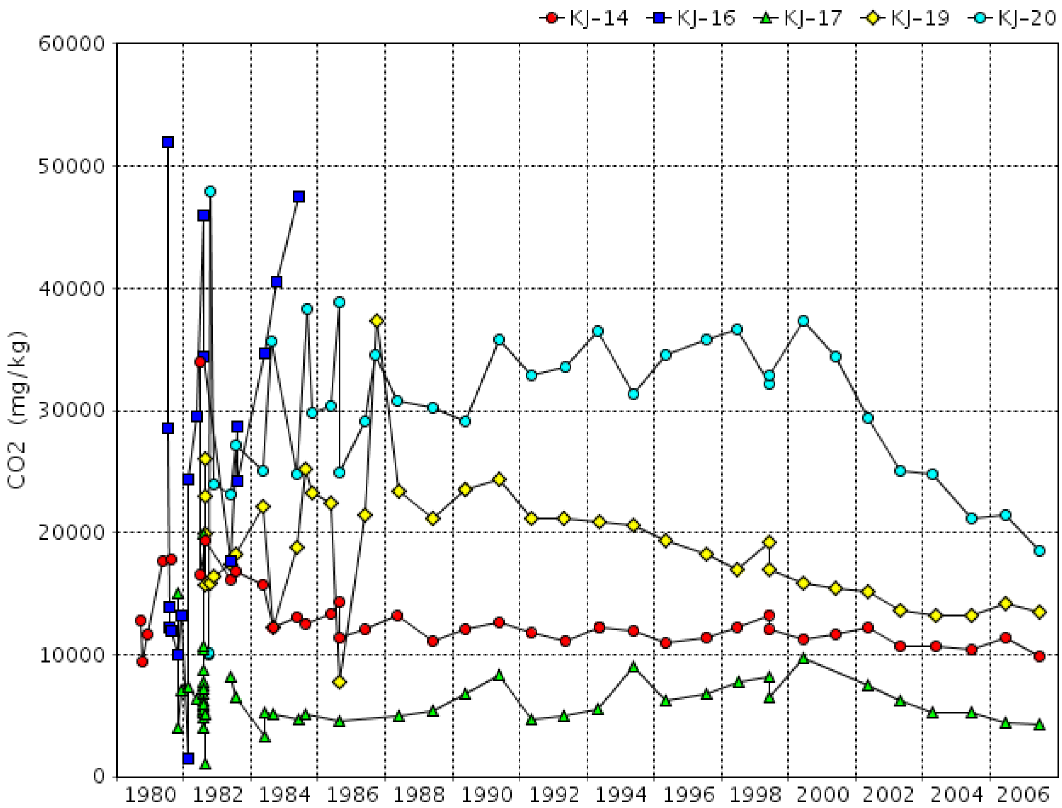


Figure 78. *Carbon dioxide levels in steam from wells in Suðurhlíðar.*

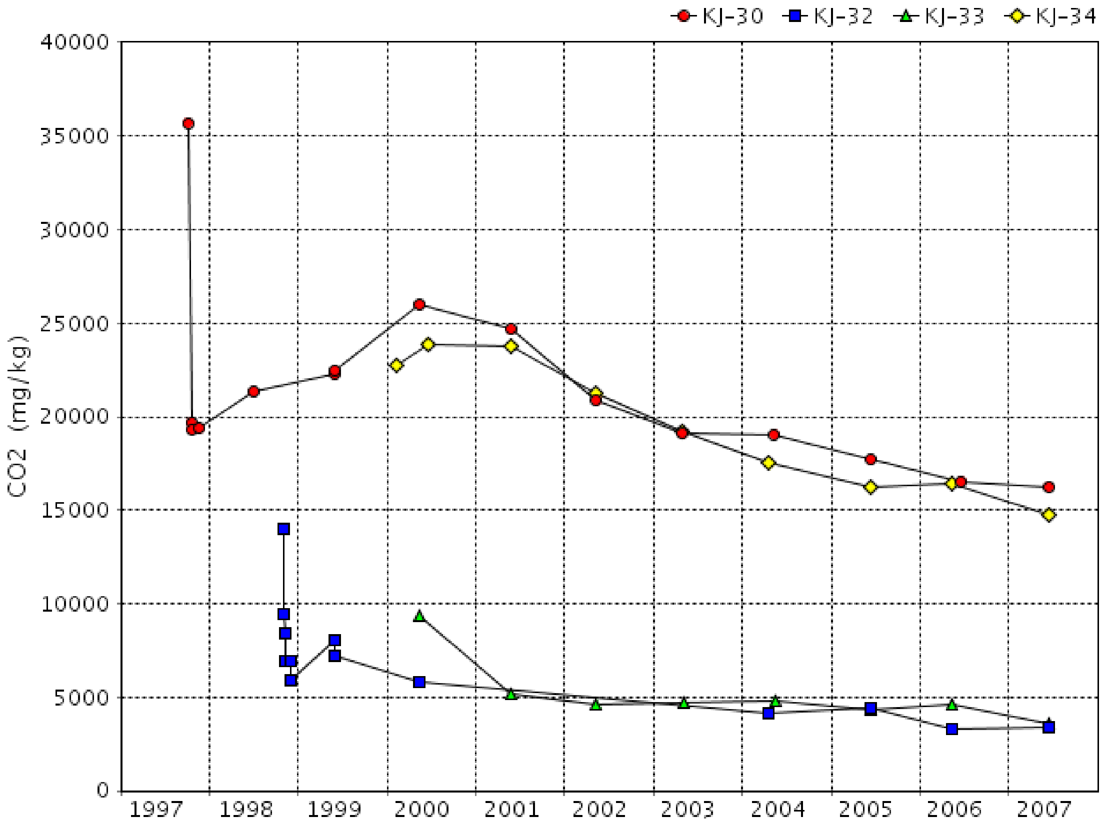


Figure 79. *Carbon dioxide levels in steam from wells in Vesturhlíðar and Vítismó.*

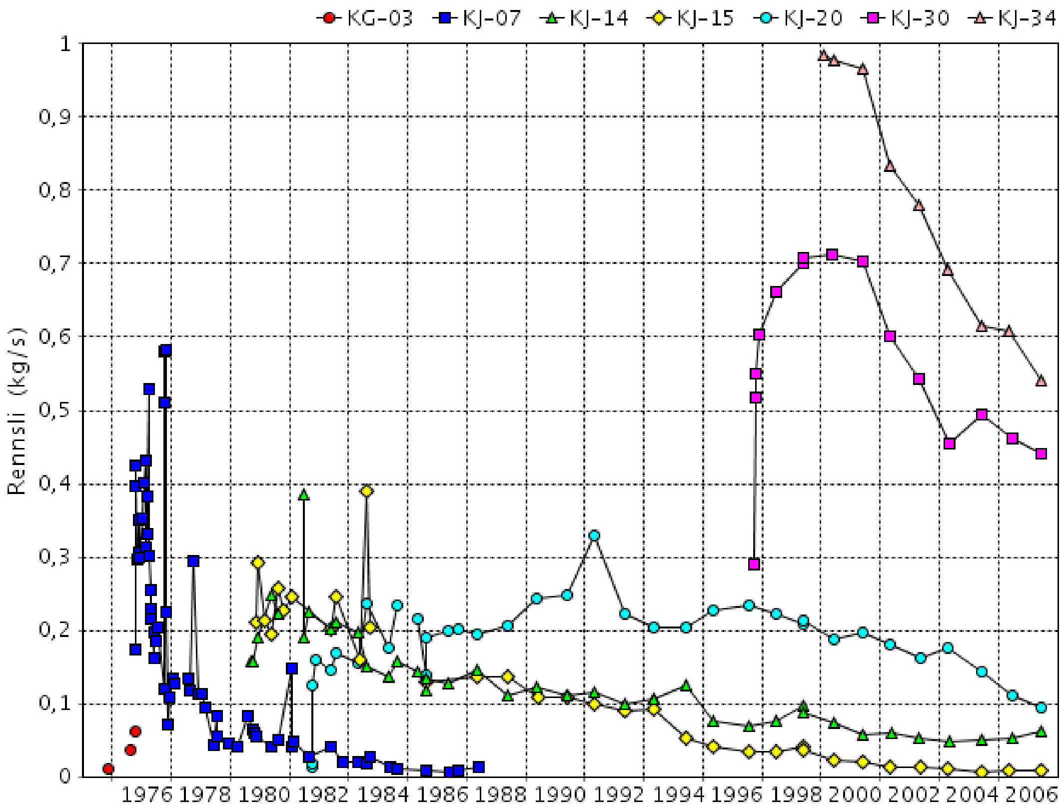


Figure 80. *Gas flow from wells in Krafla.*

10.1 Categorisation of wells based on concentration of SO4-2 and Cl- ions

Attempts have been made to categorise the chemical composition of well fluids at Krafla and the main difference has been found in the related concentration of the anions Cl^- and SO_4^{-2} (Figure 5). Sulphate is mostly found in the colder parts of the system, in the upper section of the Leirbotnar system and in substantial amounts in some warmer wells (KJ-13 and KJ-15: Category A). The concentration of both ions is low in some of the wells in Suðurhlíðar (Category C) as would be the case in boiling water. The concentration of chloride ions is more than the concentration of sulphate ions (Category B) in fluid in the Vesturhlíðar wells and in one of the Suðurhlíðar wells. These characteristics could have an effect on acidity levels. It is unlikely that high acidity levels could be found in fluid from Category C but acidic fluid should be expected in both the other categories (sulphuric acid being the dominant acid in Category A and hydrochloric acid in Category B). Attempts have also been made in categorising wells according to the effects of magmatic gases and acidity in their fluid (the four categories are shown in table 6). The increase in gas levels as a result of the magma in Leirbotnar and Vítismó was conclusive and the same can be said of the sulphide deposits/precipitation (Black Death). Sulphuric acid is present in the northern part of Leirbotnar and hydrochloric acid is more likely to be found by Hveragil and in Vítismó, to the north of Víti.

Magmatic gases slowly began to diminish within the system after the Krafla Fires with the exception of HC1. Drilling in the last few years has shown magmatic gases (particularly HC1) to be more widespread within the geothermal system than previously thought. Wells have been invaded by these gases in Suðurhlíðar (KJ-39, ~1850 m.b.s.l) to the north of Víti in KJ-38 (RD ~1600 m.b.s.l), in Vesturhlíðar in Krafla in KJ-33 (~1300 m.b.s.l) and south of Leirhnjúkar in well KJ-35 (~1600 m.b.s.l). A connection can often be made between the invasion of HC1-rich steam and aquifers at a depth of ≥1500 m.b.s.l (Figure 81) in wells drilled in recent years. The invasion of magmatic gases in Leirbotnar can be connected at a depth of 1100–1300 m.b.s.l (in KG-03, KJ-06, KG-12 and KJ-15). See Figure **Error! Reference source not found.**. This could possibly be connected to shallow intrusions in the Leirbotnar system in connection with the Krafla Fires. The presence of fresh basalt and basalt glass (similar to pillow lava) found in calcite deposits during the cleaning of HJ´9 in 1979 should also be mentioned (Ásgrímur Guðmundsson, 1983d).

Table 5. *Relative concentration of Cl^- og SO_4^{-2} in geothermal fluid in the Krafla wells.*

Flokkur	Einkenni	Holunr.	Staðsetning
A	SO_4>Cl; Cl 20-80 ppm	1-11b; 13; 13a; 15; 22; 24-26a; 27-29;32, 37	Leirbotnar; Norður-Hvíthólar
B	SO_4<Cl; Cl 55-700 ppm	12; 16; 16a; 20; 21; 26b; 33-36; 38; 39; KS-01	Vesturhlíðar; Suður-Hvíthólar; Sandabotnar, KG-26, Leirbotnum, neðri hluti
C	SO_4~Cl; Cl <20 ppm	14; 17; 30; 31	SV-Suðurhlíðar

Table 6. *Effects of magmatic gases and acid in geothermal fluid in various Krafla wells.*

Flokkur	Áhrif	Holurnr.	Staðsetning
I	Gasaukning vegna kvikugass	3; 4; 6; 7; 10; 11b; 13; 15	Leirbotnar
II	Súlfíðútfellingar	6; 7; 10; 13; 25; 26	Leirbotnar
III	Sýra (HCl + H_2SO_4)	4; 10; 25; 35	Vítismór
IV	Sýra (HCl yfirgnæfandi)	7; 12; 36; 38; 39	Hveragil; Suðurhlíðar, Vítismór

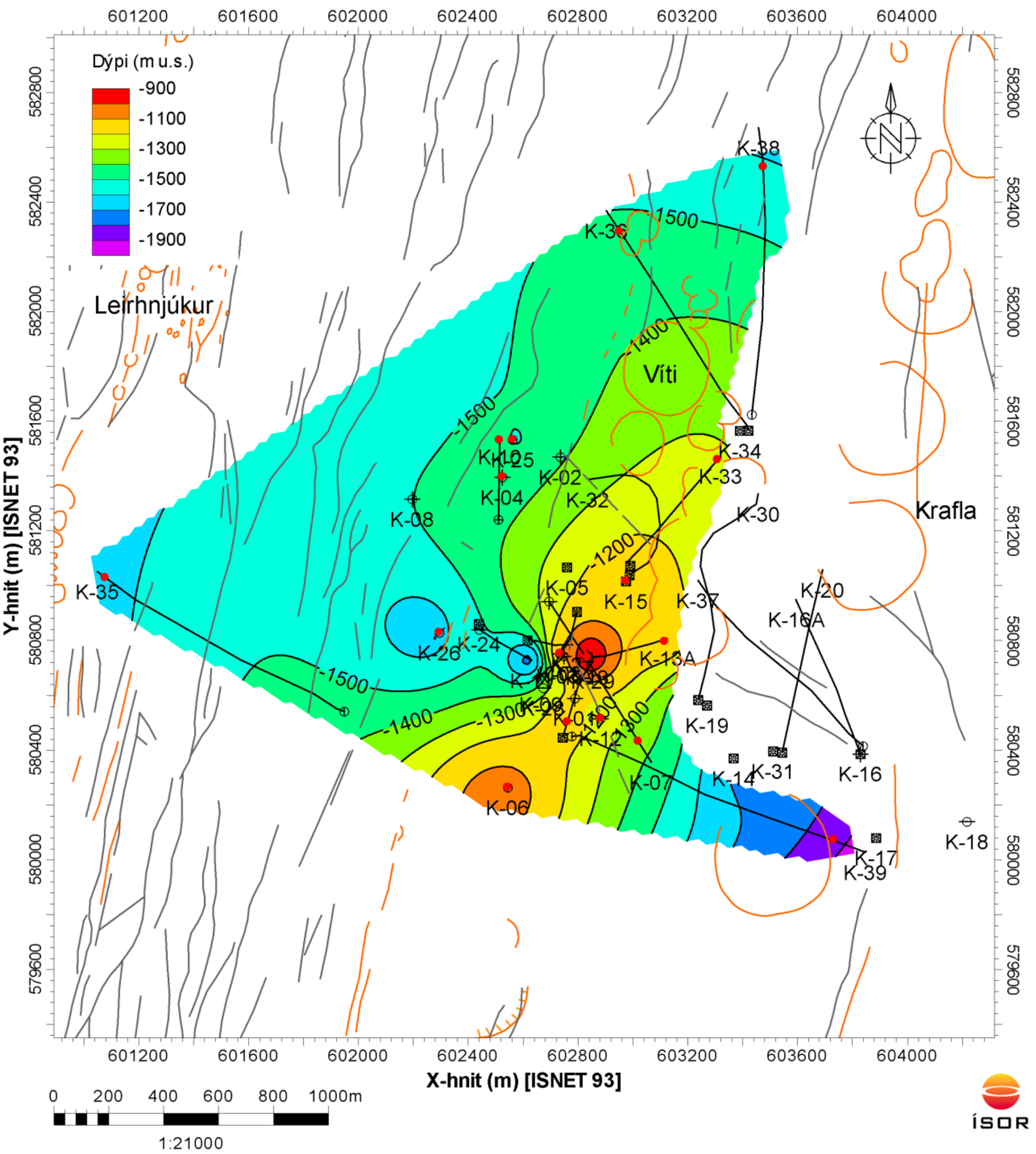


Figure 81. *Map showing the distribution of magmatic gases, including depth according to the location of feed zones thought to be connected to the inflow of magmatic gases in wells during and after the Krafla Fires*

11 Monitoring in the Krafla area

Production began at Krafla in the autumn of 1974 when well KW-1 was well tested. Drilling continued in the next few years and wells were flow tested for longer and shorter periods. Actual production from the area began when the Krafla Geothermal Power Station became fully operational in 1978. Monitoring on the development of temperature and pressure levels within the utilised area has been a main focus since the beginning and three wells have played a key role in this: wells KJ-6 in the Leirbotnar area, KG-10 by Vítismó and KJ-18 in the Suðurhlíðar area of Krafla (Arnar Hjartarson, 2006). These wells have been closed for the last 20–30 years and have been monitored on an almost annual basis during this period.

The temperature and pressure levels have also been monitored in production well KJ-21 by Hvíthólar. The well has been utilised since 1984 but has been rested for long and short periods during the summer period. KJ-21 seems to recover well during rest periods and the temperature and pressure levels measured at the well after these periods reflect the temperature and pressure status of the Hvíthólar system. Well KG-26 (in the Leirbotnar area) has also been monitored and has also served as a main reinjecinjection well for the Krafla area in the last few years. The well is connected to the deeper system at Leirbotnar. Measurements from KG-26 are more indicative of the status of the well rather than the status of the system as a result of reinjecinjection. The location of monitoring wells can be seen in Figure 19.

The development of temperature and pressure levels in the aforementioned wells at differing depths (according to monitoring measurements) will be explicated hereafter. Temperature and pressure data is taken from the database of ÍSOR and includes all measurements in wells defined as monitoring measurements and where no reinjecinjection or production is registered. Water level data (shown here) includes all data of this kind found in the ÍSOR database. Data from well KG-26 will not be included in the discussion as the data does not fulfil the criteria for standard monitoring. An analysis of how the predicted, initial pressure of newly drilled wells in the Krafla area has changed over time. This should provide important additional information on pressure changes within the geothermal system in the last thirty five years.

11.1 KJ-6 in the Leirbotnar area

Well KJ-6 was drilled down to a depth of 2000 m in the summer of 1976 and was cleaned a few years later. The well is thought to be open to a depth of 1600 m but damage to the liner and the loss of the wire into the well means that the well can only be measured to a depth of 1200 m (Benedikt Steingrímsson & Grímur Björnsson, 1996). The well is connected to both of the systems in the Leirbotnar area and therefore adjusts to changes within both. The well was mostly active in the first few years after drilling took place. The well was low in capacity but was utilised as a production well for some time. The well continued to diminish in capacity and had become useless by 1985. The well has since been pressure-free and is used as a monitoring well.

Temperature and pressure levels have been measured annually in the well since 1986 as well as the water level in the well. Figure 82 shows the development of temperature levels at 400, 800 and 1,150 m and Figure **Error! Reference source not found.** shows the development of pressure levels at the same depths, as well as water level data from the well. These figures (as well as other figures) show changes from the predicted initial status since 1976 when the well was drilled (Chapter 7). Figure 83 also shows the production history of Leirbotnar for comparison purposes.

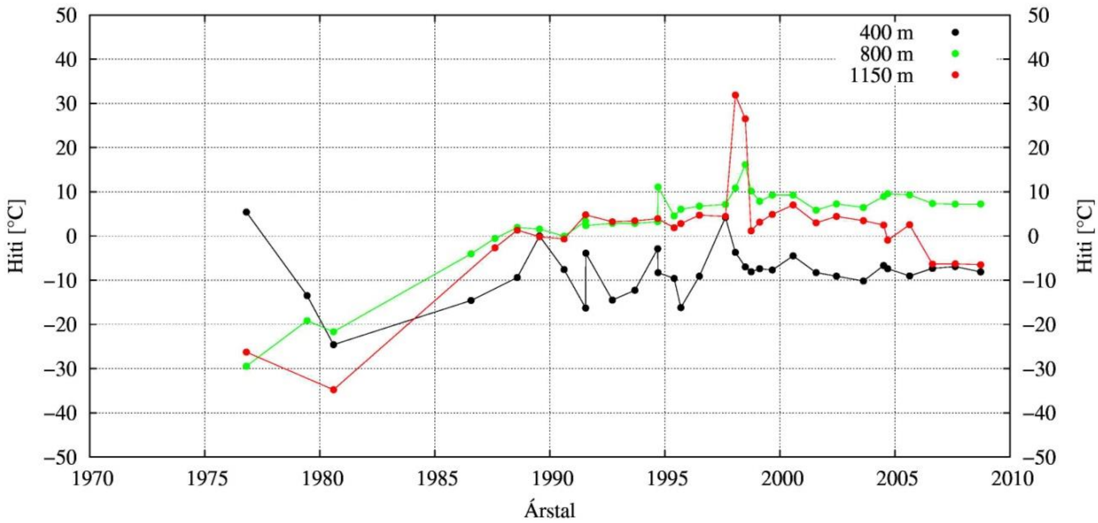


Figure 82. *Development of temperature levels by KJ-6 from 1976–2008, according to monitoring results*

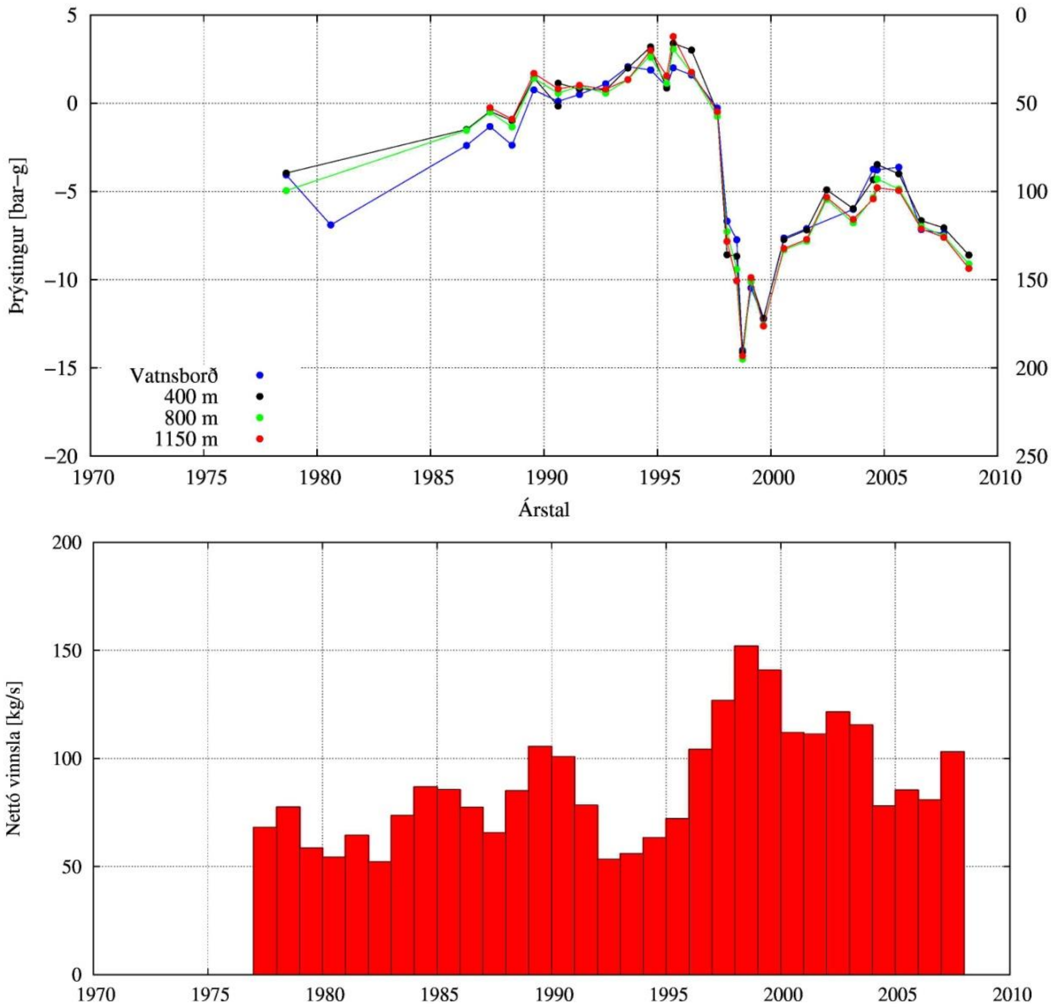


Figure 83. *Development of temperature levels by KJ-6 from 1976–2008, according to monitoring results and compared with watersurface levels.*

The pressure at these depths obviously responds and adjusts according to the water level. The oldest measurements are from the period when the well was mostly active and show a 4-7 bar drawdown in the well as a result of active discharge. The pressure was measured at a few bars below the initial pressure after the well was no longer utilised and increased from year to year with some fluctuations. These fluctuations can all be attributed to production in nearby wells, all of which are connected to the shallow system at Leirbotnar (KJ-3A, KJ-27 before they were deepened and other wells). In 1996, the pressure was measured a few bars over the predicted initial pressure but decreases in the next few years by 17 bar. This extensive drawdown in KJ-6 comes as a result of the active discharge of well KJ-28 which was drilled in 1996 (see Figure 61). This well is connected to the shallow system at Leirbotnar. The well is powerful and caused a substantial drawdown in the system when active. The increase in pressure in KJ-6 (since 2000) comes as a result of less production in K28 and reinjecinjection in KG-26. The temperature development in KJ-6 has been varied at various depths. Initial measurements would have been disturbed by activity but temperature levels since 1986 mostly show rock temperature. The temperature at a depth of 400 m has fluctuated somewhat, usually by 10°C under the predicted rock temperature since 1986. The temperature at a depth of 800 m has increased at a stable rate since 1986 to approx. 10°C above rock temperature. The temperature at 1500 m is more stable after 1986 and is closer to predicted rock temperature if the years 1997 and 1998 are not included when the temperature at 1,150m is approx. 25°C above predicted rock temperature. This is the result of an increase in pressure which has increased boiling deep in well KJ-6 and the steam below has disturbed the well. The boiling ceased deep in well KJ-6 when production levels dropped at KJ-28 and pressure levels increased once again. The temperature at 1,150 m dropped again and is below rock temperature (according to the last measurements).

11.2 KG-10 by Vítismór

Well KG-10 was drilled to a depth of 2,082 m in 1976. It was connected to both the shallow and deeper system, proving powerful at first but became blocked within a few weeks. The well was cleaned and re-activated in 1977 but became blocked again in a matter of weeks. The well has since been blocked at a depth of 850 m and is only pressure-connected to the shallow system (Benedikt Steingrímsson & Grímur Björnsson, 1996). Well KG-10 discharged as a shallow system well for a number of years around 1980 but has closed since then and has been temperature and pressure logged on an annual basis since 1985. Figure 84 shows how temperature levels have developed at a depth of 400 and 800 m and Figure 85 shows the development of drawdown in the well. Figure 85 also shows production at Vítismó, for comparison purposes.

Older measurements were disturbed by production from the well and the water level peak in 1977 is due to a pressure pulse in the shallow system after a volcanic eruption. We will therefore discuss measurements from 1985. Figure 84 shows temperature fluctuations between years at a depth of 400 and 800 m in KG-10 but decreases nonetheless. The decrease during these 25 years has been approx. 10°C. The development of drawdown in KG-10 after 1985 (Figure 85) is similar to the development in KJ-6. The pressure increases until 1996 but drops by approx. 5 bar in the following years when production levels increase as a result of the expansion of the station. The pressure has remained stable in KG-10 since 1998 and has not increased again, as is the case in well KJ-6. This is due to the fact that well KJ-28 is further away from KG-10 and therefore has less effect on its pressure than it does in KJ-6.

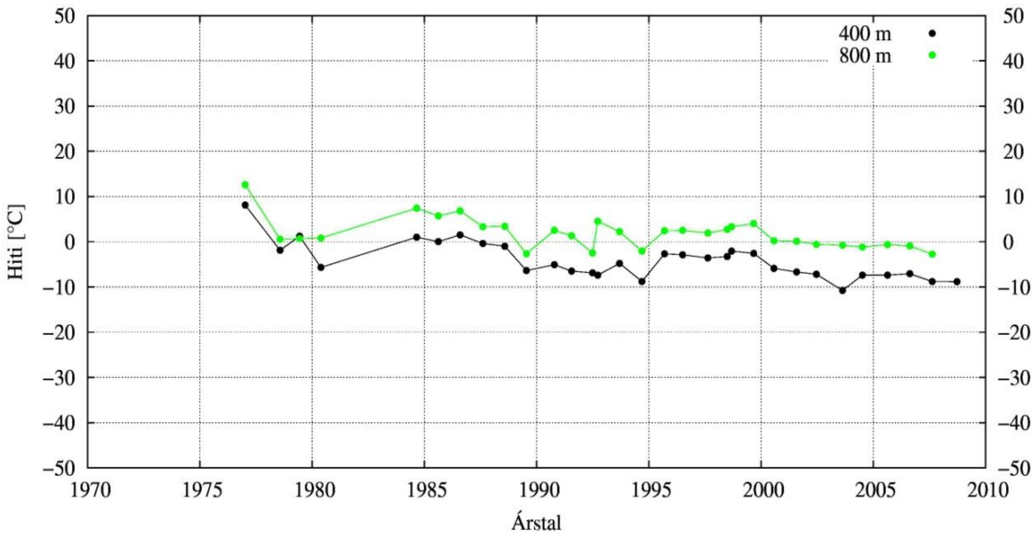


Figure 84. *Development of temperature levels in KG-10 from 1976 - 2007, according to monitoring results.*

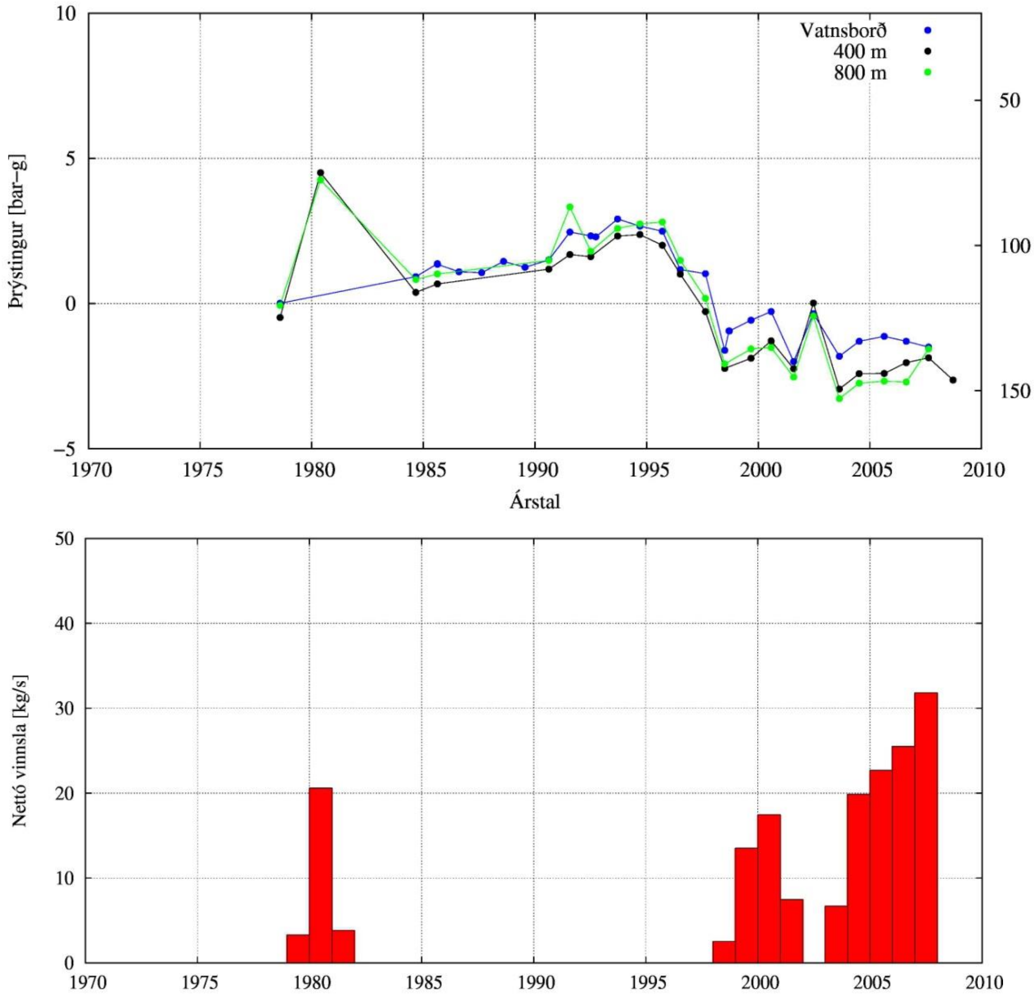


Figure 85. *Development of drawdown in KG-10, according to monitoring results and compared with water surface levels*

11.3 KJ-18 in the Suðurhlíðar area of Krafla

Well KJ-18 was drilled in the easternmost part of the Suðurhlíðar area of Krafla in the autumn of 1981. The well was 2,215 m in depth and production casing reached a depth of 663 m. Well KJ-18 was without circulation losses during drilling and a liner was not installed as a result. The well proved to be much colder than wells further west in the area and the well has never discharged (Benedikt Steingrímsson & Grímur Björnsson, 1996). The well is connected to the geothermal system in the Suðurhlíðar area of Krafla and is successfully utilised as a monitoring well for the Suðurhlíðar area (including the pressure of drawdown). Figure 86 shows the development of temperature levels from 1981 until 2007 at a depth of 500, 1000, 1500, 2000 and 2,187 m. Figure 87 shows the development of drawdown in the well. Figure 87 also shows production in the Suðurhlíðar area for comparison purposes as well as production in the Vesturhlíðar area. Temperature measurements during warm-up and after drilling quickly showed that the rock temperature above 1000 m was approx. 150°C or approx. 100°C lower than in neighbouring wells (KJ-16 and KJ-17). Measurements also showed that water from cold, small aquifers above 1000 m seeped down to the wellbottom. The flow was so slow initially that the temperature at the wellbottom increased for the first few months and the highest temperature recorded below 2000 m was approx. 280°C. The downflow from above then became dominant and the lower section of the well cooled with time. Figure 86 shows how temperature levels have developed at various depths. The temperature has remained stable above 1500 m but the temperature at wellbottom has dropped by 40°C at 2000 m and by approx. 100°C at 2,187 m. The cooling mostly became apparent in the first five years (as shown in Figure 86). The development of pressure in KJ-18 since 1981 is shown in Figure 87 as well as the results of water level measurements. The water and pressure levels in the well decreased rapidly between 1981 and 1987 when production began in the area, but slowed down after that by approx. 5 bar between 1990 and 2008 (on average). The well showed little reaction to increased production in 1997 but the pressure change gradient seemed to have increased. Monitoring during the summer showed the water level and pressure level to be substantially lower than the year before but this has since been reversed. There has been no feasible explanation for this anomaly.

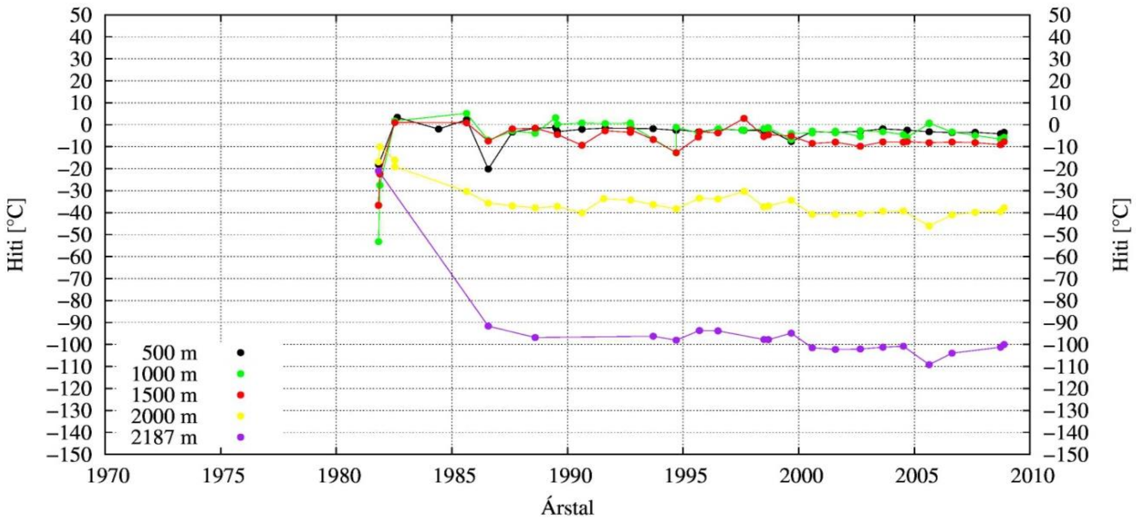


Figure 86. *Development of temperature levels in KJ-18 from 1981– 2007, according to monitoring results*

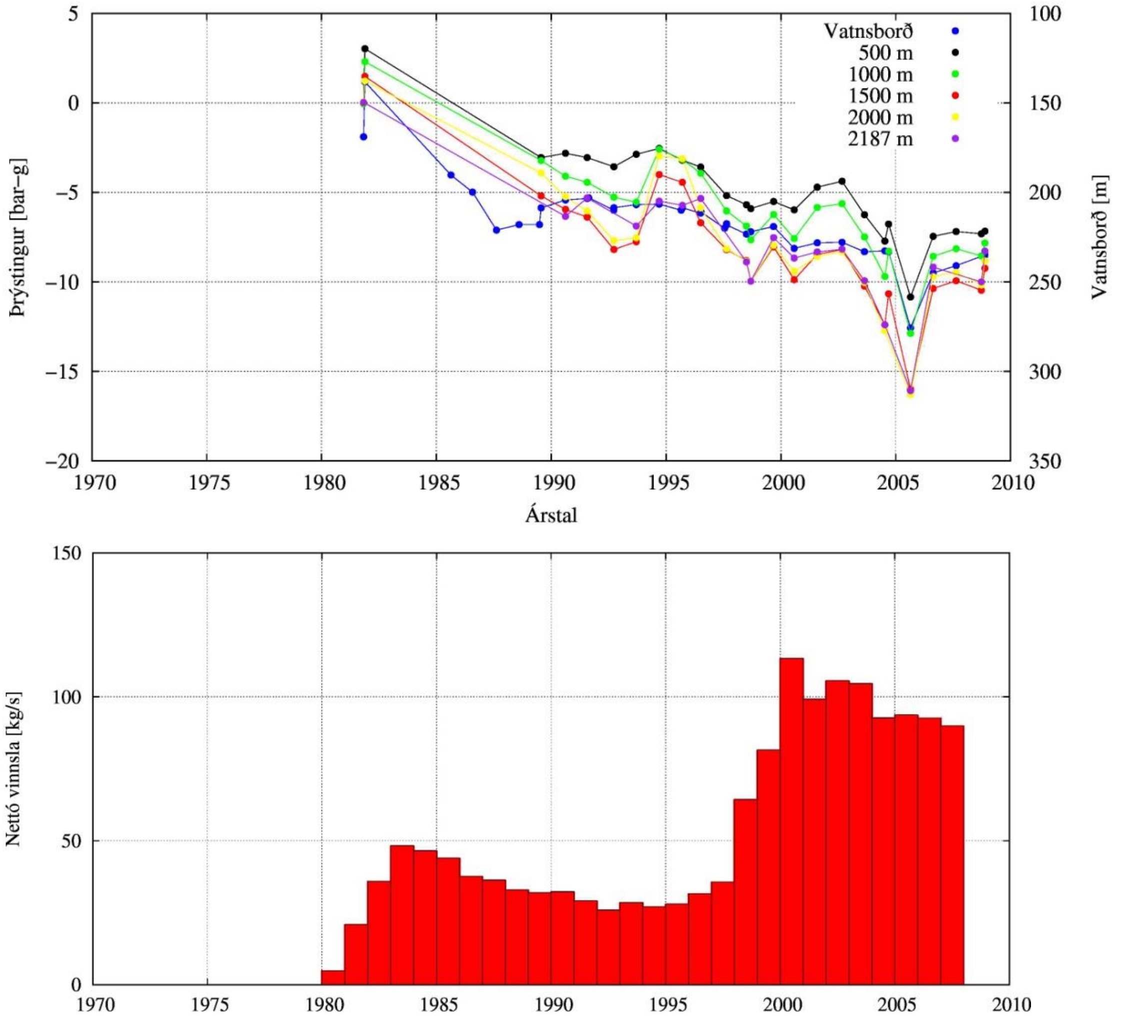


Figure 87. *Pressure development according to monitoring results from KJ-18 and compared with water surface levels*

11.4 KJ-21 by Hvíthólar

Well KJ-21 was drilled to a depth of 1200 m in 1982. The production section was drilled with a 12¼" drill bit and lined with a 7" liner with a view to concreting production casing at a later date and deepening the well if it proved to be low in capacity. However, well KJ-21 proved to be high in capacity and the 7" liner was removed from the well in 1984 and 9⅝" production casing was used to line the well. The casing was concreted to a depth of 280 m but was not concreted below 300 m and was slotted like the liner. The liner/casing reaches 1,035 m but the well is blocked below this depth and the well depth is therefore measured at 1000 m. The well is connected to the geothermal system by Hvíthólar but other wells connected to this system include KJ-22 and KJ-23 but well KJ-23 was used for monitoring purposes between the winter of 1991 and 1992 when it became blocked. Well KJ-21 is a production well and was connected to the power station in 1985. It has been utilised ever since. However, the well is rested most summers for a few weeks (sometimes months). Well KJ-21 has been temperature and pressure level monitored during summer rest periods to analyse developments within the area as there is no designated monitoring well for the Hvíthólar area. The well is pressurised when closed and gas and steam is present from the top of the well and down to a depth of 700 m (water is present below this level).

The pressure level in the well (when closed) has decreased somewhat during the years, generally approx. 35 bar but was last recorded at 30 bar. Figure 88 shows the development of temperature levels at a depth of 800 and 1000 m and Figure 89 shows the development of pressure levels at the same points. Production is also shown in Figure 89.

Temperature levels shown in Figure **Error! Reference source not found.** show that the temperature at 800 and 1000 m is variable but decreases with time. Temperature fluctuations are due to the fact that the wellbottom is boiling during production and the temperature at wellbottom changes rapidly when production ceases and the well is shut off. The length of time since the well was shut off is therefore relevant to subsequent measurements. The overall picture is therefore clear. Temperature levels decrease deep in the well and the change since 1982 is approx. 25°C. The cooling can probably be explained by boiling in the system as a result of lowering pressure.

Figure 89 shows the development of drawdown in well KJ-21 since 1982. Fluctuations in drawdown can be explained by how much time has passed since the well was closed and measurements took place. The overall picture is also clear in this case. The pressure level drops rapidly when the well is put into production in 1984 and the drawdown at 800 and 1000 m is already 12-13 bar in 1986. The pressure falls at a slower rate throughout the next decade but increases again rapidly with the expansion of the power station from 30 MWe to 60 MWe. Levels are at their lowest between 2000 and 2001 and is then measured at 30 bar. This substantial drawdown can be explained by increased production in the area after the expansion. Production decreased in the area between 2001 and 2005 and the drawdown was reversed, measuring 23 bar in the summer of 2005. However, drawdown has increased once again after production was increased in 2005.

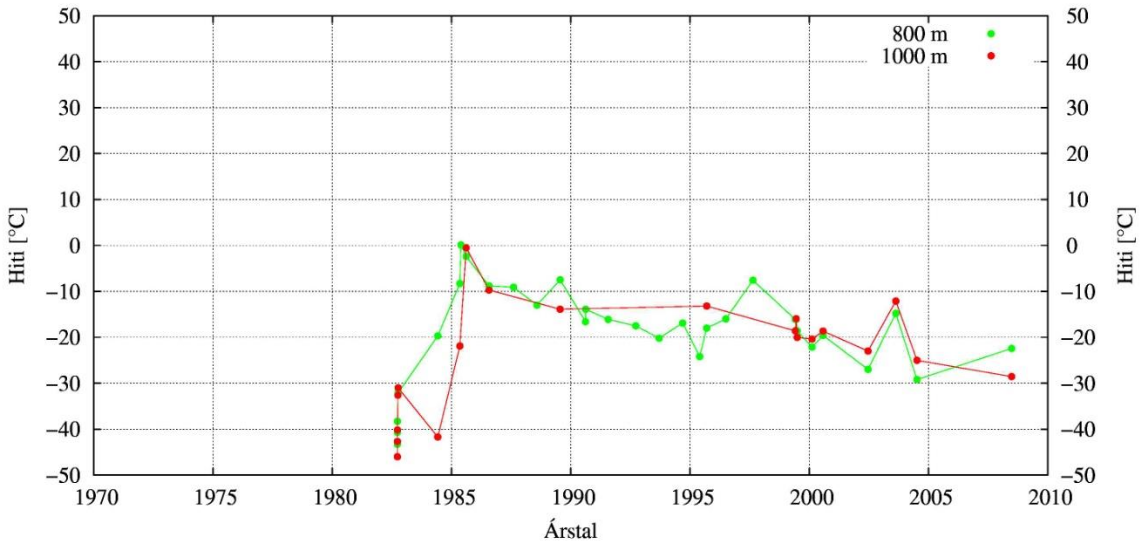


Figure 88. *Development of temperature levels in KJ-21 between 1982–2005, according to monitoring results*

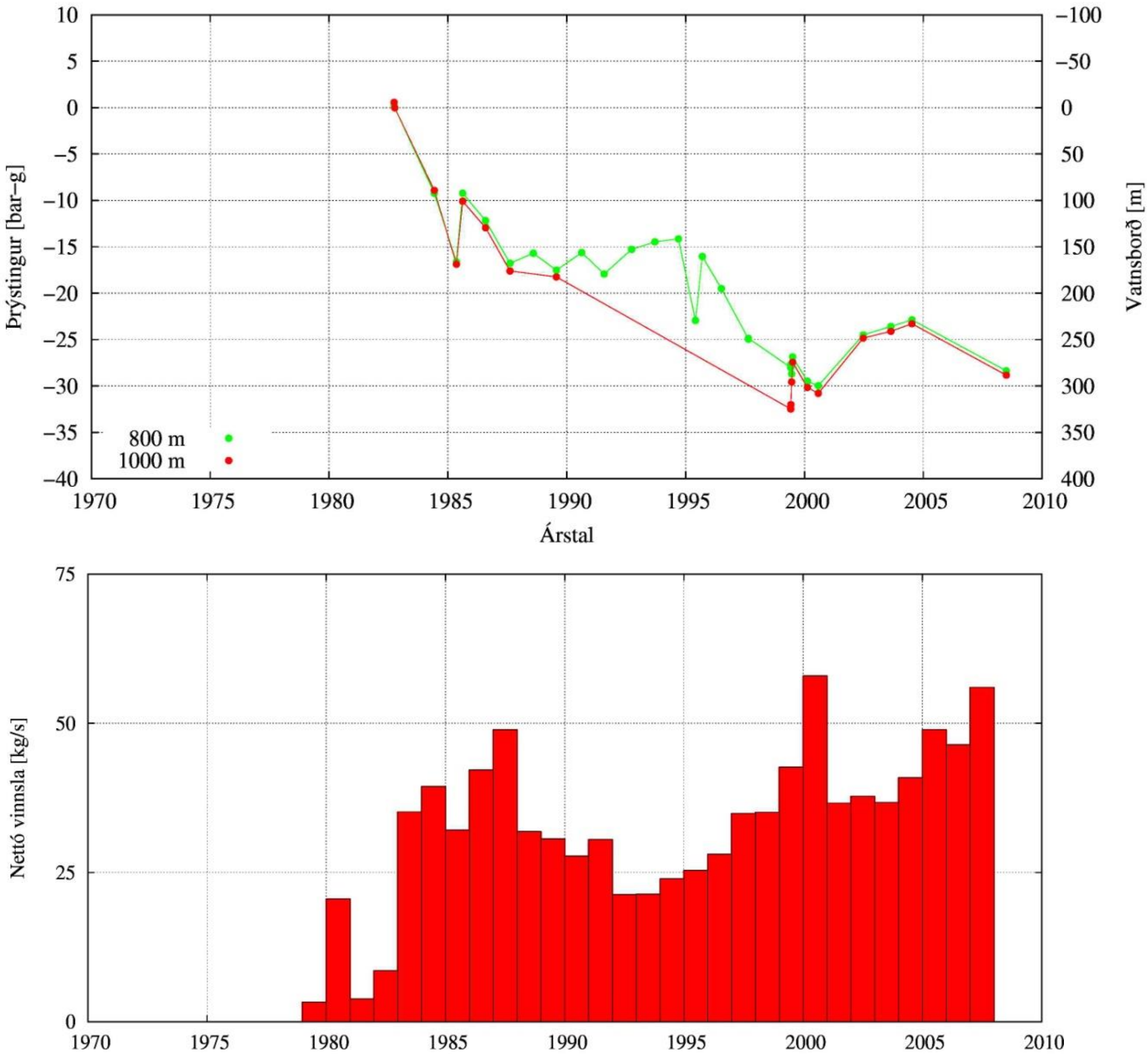


Figure 89. *Development of drawdown in KJ-21 between 1982-2005, according to monitoring results*

11.5 Discussion and summary

Information on temperature and pressure levels is the key to understanding the reaction of the Krafla geothermal system to utilisation and the basis for any attempts to assess the capacity of the geothermal system.

The geothermal system is divided into various sub-regions utilised by the power station. They are Leirbotnar (upper and lower section), Vítismór (upper and lower section), Suðurhlíðar, Vesturhlíðar and Hvíthólar. Extensive information is available on temperature and pressure level changes as a result of utilisation (in some areas) from the last few decades. Additional information on temperature and pressure levels has also been acquired when new wells have been drilled in the Krafla area or when older wells have been cleaned. The initial pressure of wells drilled over a period of 35 years tells us a great deal about the pressure changes that have occurred in different parts of the geothermal system. Figures 90-92 show the predicted initial pressure of the wells in four sub-surface areas of the geothermal area, the changes to this over the years as well as the production history of that particular area. The figures show the predicted pressure at a depth of 500 m.b.s.l (to facilitate a comparison) but not at the depth of dominant feedzones in particular wells. They are intended to show general changes but cannot be used to determine accurate pressure changes.

The following is a summary of the main changes within each area as a result of utilisation:

Leirbotnar, upper system (shallow system). Temperature and pressure logs in well KJ-6 successfully show the development within the area after 1986. Temperatures above 1200 m have increased during this period. There is a 10°C increase at 900 m but less at 1,150 and the temperature has not changed significantly at a depth of 400 m. Pressure in the upper system (shallow system) of Leirbotnar fluctuates alongside production in the area. Pressure logs in well KJ-6 show rising pressure levels between 1986 and 1996, which correlate with a decrease in production levels in the area. The increase over the ten year period is approx. 3 bar. Production levels increased in the upper system (shallow system) of the Leirbotnar area during the expansion of the Krafla Geothermal Power Station and the pressure in well KJ-6 dropped by 17 bar over a two year period. Well KJ-28 had the greatest effect on the pressure level in well KJ-6. KJ-28 is a high capacity well and there seems to be a strong connection between KJ-28 and KJ-6. Well KJ-28 has been used less since 2000 and this has meant an increase in the pressure level in KJ-6. The drawdown in the upper system (shallow system) of the Leirbotnar area since 1976 is estimated to be 7 bar.

Leirbotnar, lower system (deeper system). Most of the wells connected to the lower system (deeper system) of the Leirbotnar area are either used for production or are blocked. The wells boil to the wellbottom level during production and temperature and pressure logs recorded during discharge are not a basis for measuring undisturbed temperature and pressure in the geothermal system surrounding them. There is no designated monitoring well for the lower system (deeper system) of the Leirbotnar area. However, some indirect indicators on temperature and pressure have been acquired over time. This information has been collected when new wells have been drilled in Leirbotnar or when older wells have been cleaned and the temperature and pressure has then been measured. The temperature and pressure level is bound to the boiling point depth curve (of water) as the lower system (deeper system) is boiling.

Figure 90 shows the initial pressure at a depth of 500 m.b.s.l in all wells connected to the lower system (deeper system) in Leirbotnar. The oldest well is KW-1 (since 1974), followed by KG-3 and KG-5 (since 1975) etc. Wells KJ-27, KJ-28 and KJ-29 were drilled in 1996 and 1997 and well KJ-35 was drilled in 2007. these were the last wells to be drilled within this system. According to Figure 92, the predicted initial pressure in wells at a depth of 500 m.b.s.l is in most cases under 80 bar, irrespective of when they were drilled. The pressure is lowest (approx. 73 bar) in well KJ-29 which was drilled in 1997 but is highest in well KJ-35 which was drilled in 2007 (approx. 87 bar). Figure 92 shows that the pressure drawdown in the lower system (deeper system) in Leirbotnar since 1974 is insignificant (at the most; 5 bar). The high pressure in KJ-35 could indicate that this particular well is in fact connected to another sub-system in the lower system (deeper system) of Leirbotnar. KJ-35 is located to the west of Rauðhól in the westernmost part of the drilling area and is directionally drilled towards Leirhnjúkar. It could be said that this well is more connected to the system at Leirhnjúkar than it is to the system in Leirbotnar. The temperature decreases within the system when the pressure drops because the initial temperature in the lower system in Leirbotnar follows the boiling point. A 3°C drop in temperature can be expected at a depth of 1500 m if a 5 bar pressure drawdown occurs within the system.

Vítismór, upper system (shallow system). Well KG-10 is a good example of the changes that have occurred in Vítismó after 1985. The temperature of the well above 800 m has decreased by a few degrees centigrade in the last 25 years and the change is 5–10°C. This is unlike well KJ-6 in Leirbotnar which has increased in temperature. Pressure in KG-10 increases until 1996 by 3 bar which is similar to that of KJ-6. The increase is probably due to a decrease in production from the upper system (shallow). The pressure level in well KG-10 dropped by 5-6 bar within two years, when production was increased during the expansion of the Krafla Geothermal Power Station (to 60 MW) but has stabilised since then.

Vítismór, lower system (deeper system). There is no available monitoring well for the lower system in Vítismó. However, indirect information on temperature and pressure changes have been collected for both the Vítismó and Leirbotnar areas by comparing the initial temperature and pressure levels in wells drilled during differing periods. Figure 91 shows the predicted initial pressure at a depth of 500 m.b.s.l in all wells at Vítismó. The oldest well is KW-2 which was drilled in 1974, but is only connected to the upper system (shallow system). Well KG-10 was drilled in 1975 and KG-25 in 1990. The youngest wells include KJ-36 and KJ-38 from 2007 and 2008. Figure 91 shows a similar initial pressure in wells in Vítismó and Leirbotnar. The initial pressure in KG-10, KG-25, KJ-36 and KJ-38 at a depth of 500 m.b.s.l is approx. 80 bar which indicates minimal drawdown in the lower system (deeper system) in Vítismó throughout this period. Well KJ-32 shows a significantly lower pressure level of approx. 72 bar in 1998. This pressure level is similar to that measured in the Suðurhlíðar area of Krafla during these years which indicates that these wells are connected to the system there. The temperature follows the boiling point in the lower system (deeper system) in Vítismó and drawdown is minimal, which means that there have been no significant changes to wells KG-10, KG-25 and KG-36 since 1976.

Suðurhlíðar. Well KJ-18, to the east of the production area shows an increase in drawdown since 1981 (approx. 10 bar). The drawdown is probably more prominent in the production area in the Suðurhlíðar area, but there is no concrete information on this as most of the wells are in constant production. Indirect information can be gathered on changes over time if the initial pressure and rock temperature in wells, drilled during differing periods, are analysed. Figure **Error! Reference source not found.** shows the predicted initial pressure in wells in the Suðurhlíðar area and in the Vesturhlíðar area of Krafla. Drilling began on the oldest wells in Suðurhlíðar in 1980. The pressure levels are shown to be 84–90 bar at a depth of 500 m.b.s.l. Well KJ-16 was recycled in 1997 and wells KJ-30 and KJ-31 were drilled in the Suðurhlíðar area. According to Figure **Error! Reference source not found.**, the initial pressure in KJ-30 and 16A was lower than in 1980 and approx. 15 bars lower in KJ-31. The initial pressure in well KJ-37 (since 2008) at a depth of 500 m.b.s.l is only 60 bar, or approx. 25 bar under the prediction for 1980. This indicates that the pressure within the middle of the production area in Suðurhlíðar has decreased by 20–30 bar since production began. The temperature in the Suðurhlíðar area follows the boiling point depth curve which means that a drop in pressure causes an increase in boiling and a decrease in temperature. A pressure drop of 20–30 bar causes a drop of between 15–20°C at a depth of 1500 m within the Suðurhlíðar system.

Hvíthólar. Well KJ-21 is the only production well in Hvíthólar and is also the only monitoring well. Temperature and pressure logs recorded during the summer rest period show a decrease in pressure and temperature in the area since 1982. The pressure drawdown during the summer of 2000 reached 30 bar, but does not seem to have increased since then. The temperature change throughout this period is approx. 20–25°C and can be explained by subsequent cooling as a result of boiling from a drop in pressure in the area.

Vesturhlíðar. The first production wells in the Vesturhlíðar area were drilled ten years ago. Most of the wells are connected to steam production and utilised by the power station. None of the wells can be used for monitoring purposes and there is limited information on any temperature or pressure changes in the Vesturhlíðar area. Indirect information shows a lower initial pressure in the Vesturhlíðar area than in the Suðurhlíðar area which could indicate a connection between the systems (Figure 92). Figure 92 shows the initial pressure in the wells in Vesturhlíðar alongside the wells at Suðurhlíðar. Drilling started in the Vesturhlíðar area in 1997 (KJ-30) and KJ-33 and KJ-34 were drilled two years later. The pressure level at 500 m.b.s.l in well 30 is shown to be 85 bar but is only 50-55 bar in wells KJ-33 and KJ-34. This could indicate that the drawdown in the Vesturhlíðar area since 1997 could be anything between 20 and 25 bar. This could be due to boiling in areas close to well KJ-30.

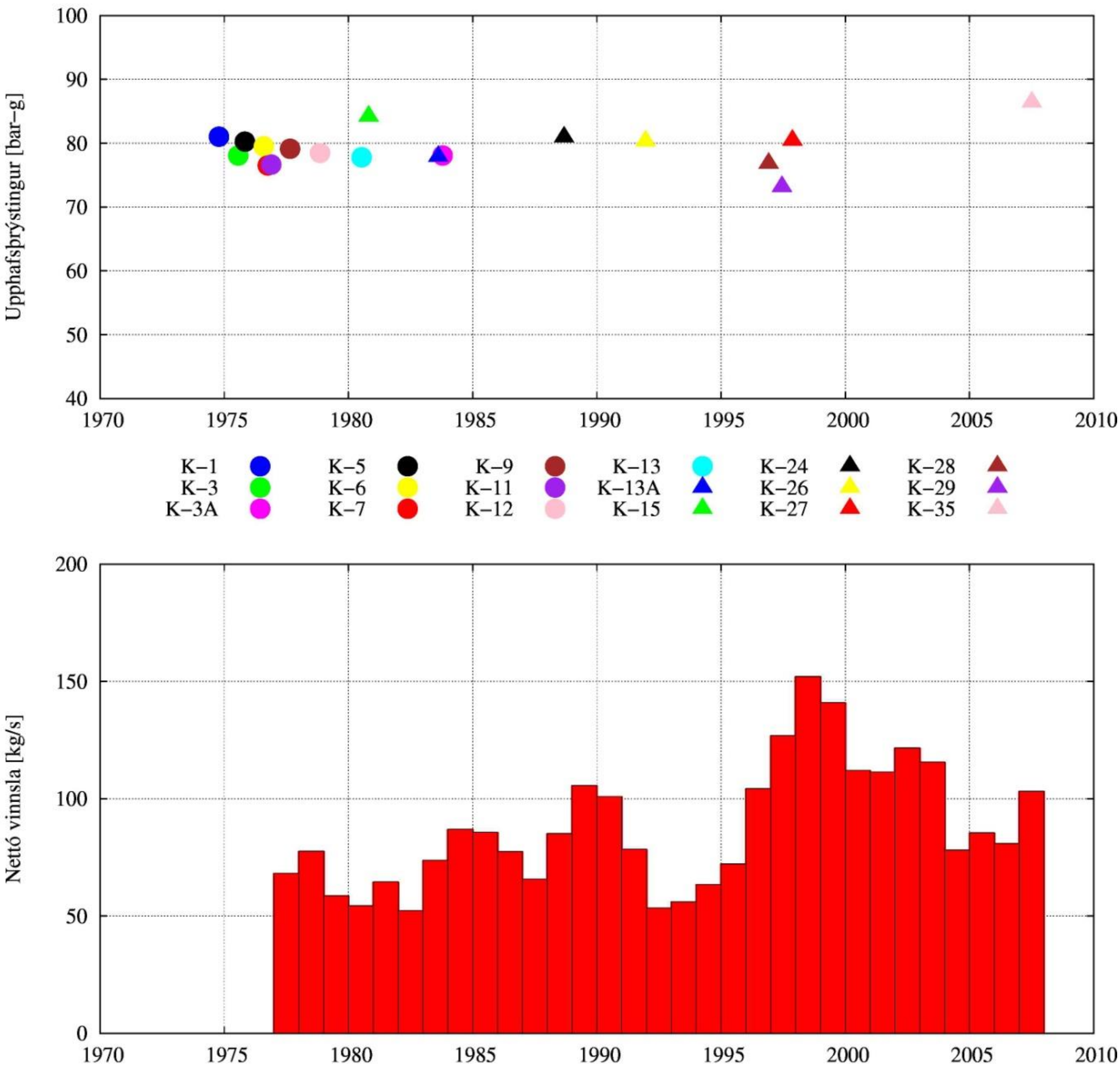


Figure 90. *Changes to the initial pressure at a depth of 500 m.b.s.l in all wells connected to the lower system (deeper system) in Leirbotnar as well as mass extraction from Leirbotnar, between 1977–2008*.

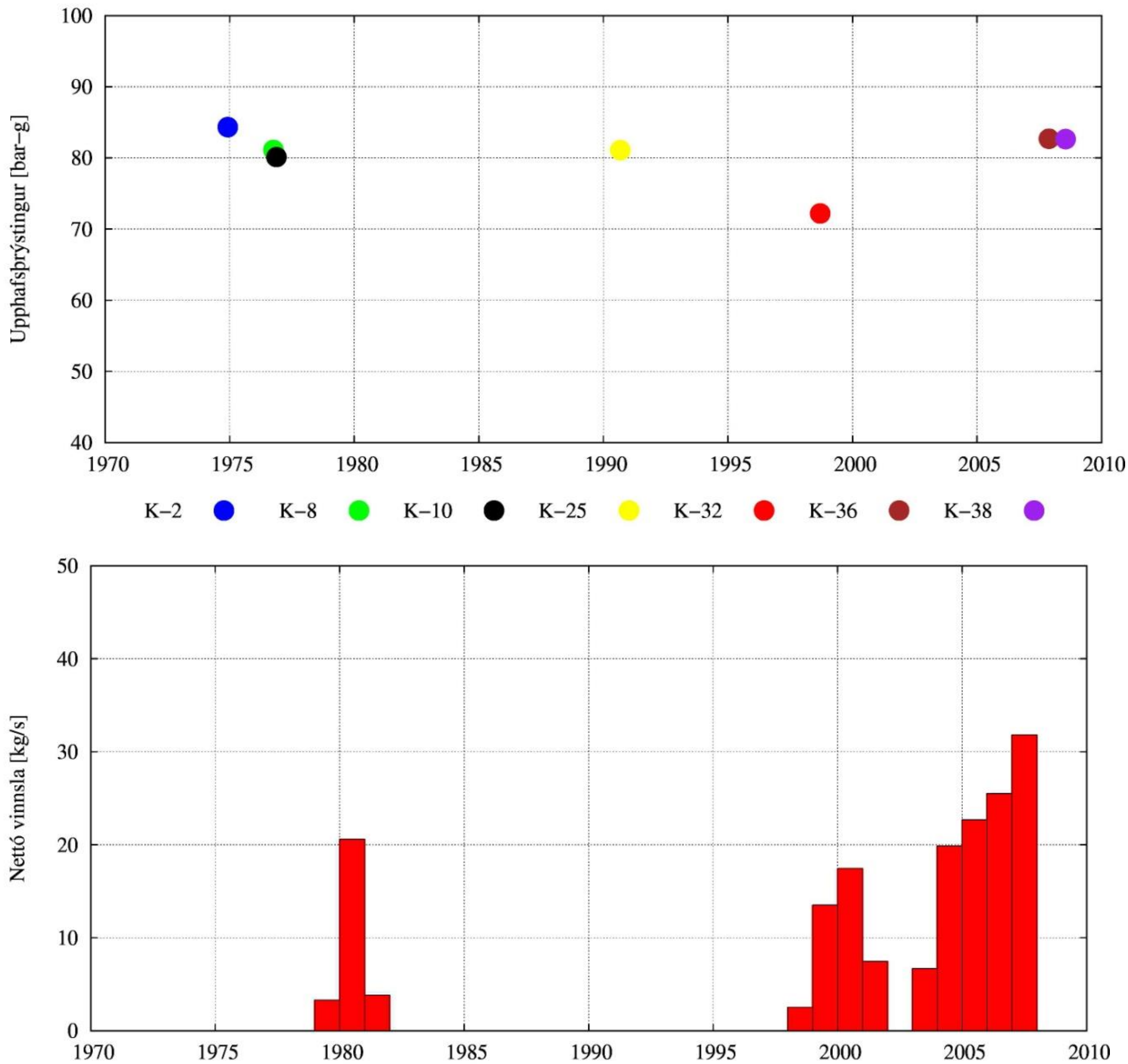


Figure 91. *Changes to the initial pressure at a depth of 500 m.b.s.l in wells in Vítismó as well as mass extraction from Vítismó between 1977–2008.*

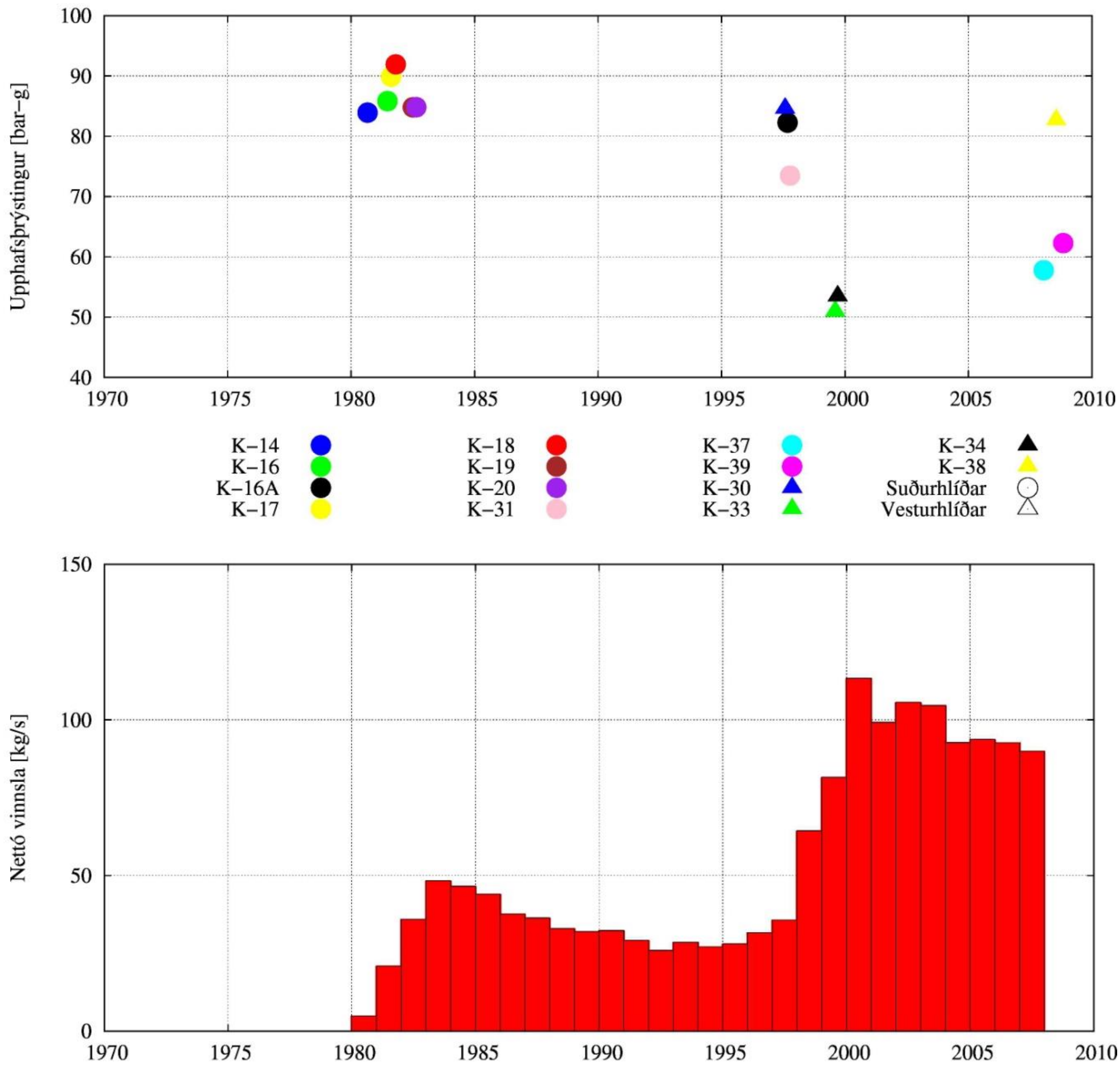


Figure 92. *Changes to the initial pressure at a depth of 500 m.b.s.l in wells in the Southern and western slopes (Suður og Vesturhlíðum) as well as mass extraction from the Southern and western slopes (Suður og Vesturhlíðum), between 1980–2008.*

12 Development of numerical modeling for the Krafla area

The numerical model for the Krafla area has developed over a period of 35 years by taking advantage of increased measurements/monitoring, increased expertise on the geothermal area and improved calculation methods, as well as developments in numerical modeling for geothermal systems. Many earlier models are therefore outdated but their predictive value gives a good picture of the substantial changes needed to create a model that mimics the geothermal system. They also give an indication of just how much we can trust the results of new numerical models.

12.1 Observations before utilisation

The National Energy Authority assessed the cost of various power projects in 1972 and 1973 and the following options were explored: an 8, 12, 16 or 55 MW_e power station (the geothermal department of the National Energy Authority and the engineering consultancy services of the engineering consultancy Guðmundur & Kristján, 1973). There was no actual numerical model of the area but it was assumed that the steam collected from wells 4, 5 and 9 in Bjarnarflag were typical of the area.

12.2 Early developments in geothermal reservoir modeling in the Krafla area

Valdimar Kr. Jónsson (1978) was responsible for the first simulation model for the Krafla system. The model was created using the SHAFT-78 program which offered the possibility of simulating a two-phase geothermal system. The reaction of the geothermal system to utilisation over a 33 year period was analysed using the simulation model based on production levels of 50 kg/s from a dual system (20 kg/s from the shallow, liquid dominated system and 30 kg/s from the lower two-phase system).

In 1981 and 1982, Guðmundur S. Böðvarsson et al. (1982) created a summary of the research in the Krafla area using the conceptual model of the area which has since then been the basis for all conceptual models in the area (Figure 93). They created a geothermal model of the Krafla area using the MULKOM-simulator. The results are outlined in articles in Water Resource Research (Guðmundur S. Böðvarsson et al.1984a, b, c; Pruess et al.1984).

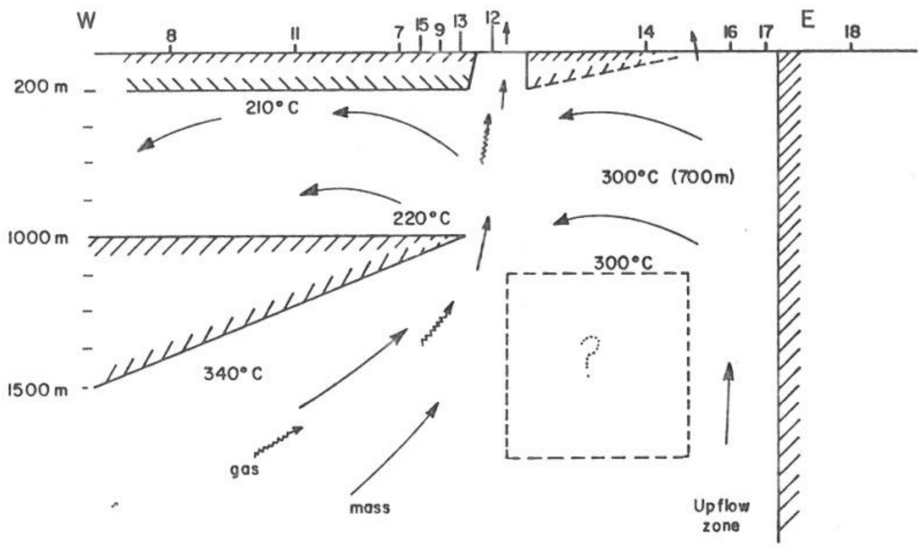


Figure 93. *Conceptual model 1977 (Valgarður Stefánsson et.al.1977)*

The first model was two-dimensional and was comprised of 100 blocks and 8 types of rock.The model simulated the initial state quite successfully and simulations were used to predict the reaction to different types of production. The results of the simulation showed the capacity of the Krafla area to sustain 30 MW_e, over a thirty year period in Leirbotnar and 20 MW_e in the Suðurhlíðar area. The second model was “two and a half”-dimensional i.e. it did not consider the flow between layers. Each layer was comprised of 115 blocks and ten of these represented wells. The upper layer had six types of rock and the lower layer had 23 rock typeslayers. Developments in the “well blocks” were then compared with the development of enthalpy and production in wells (the simulation of wells was quite successful). The reaction to an increase in wells, the reinjection of fluid at pressure, production and enthalpy, were also analysed.

12.3 Smaller geothermal reservoir models in SHAFT-79 and TOUGH

The SHAFT-79 model of Hvíthólar in the Krafla area which includes wells KJ-21, KJ-22 and KJ--23 (Helga Tulinius and Ómar Sigurðsson, 1988) was developed in 1988. One of the main objectives of the project was to train staff in the geothermal department of the National Energy Authority to use a program that could simulate a two-phase geothermal system. The model was two-dimensional and separated the area into 85 blocks and included 6 types of rock. The model struggled to simulate the initial state and did not fully consider the inflow from the north and south. A three dimensional TOUGH model for the same area was developed in 1990 and 1991 (Helga Tulinius and Ómar Sigurðsson, 1991). The model included 414 blocks, divided into three layers and five types of rock and was more successful in simulating the area.

A three-dimensional TOUGH model was developed for the Bjarnarflag area in 1993 (Ómar Sigurðsson, 1993). The model used 93 blocks in three layers and three types of rock. The model was able to successfully simulate the discharge history of wells BJ-11 and BJ-12 and predicted that the area could withstand 20 MW_e of production over a thirty year period.

12.4 TOUGH2-model

A three-dimensional model of the entire Krafla area was developed over a number of years following the decision to expand the Krafla Geothermal Power Station in 1996. The model was based on a new conceptual model (Figure 94) and was comprised of 5500 blocks in ten layers and divided into twenty six types of rock. The model was still being developed when the progress report was written and it was difficult to simulate capacity measurements (Grímur Björnsson et al.1997a). Three reports have been written on the status of the project since then (Grímur Björnsson et al.1997b; Grímur Björnsson & Ómar Sigurðsson, 1999; Ómar Sigurðsson, 2001). The reports outline advancements in simulations of the area but a final report has not been released on the project. Arnar Hjartarson et al. (2005) developed a TOUGH2 model for Bjarnarflag in 2004 using the program iTOUGH2 to calibrate the model.

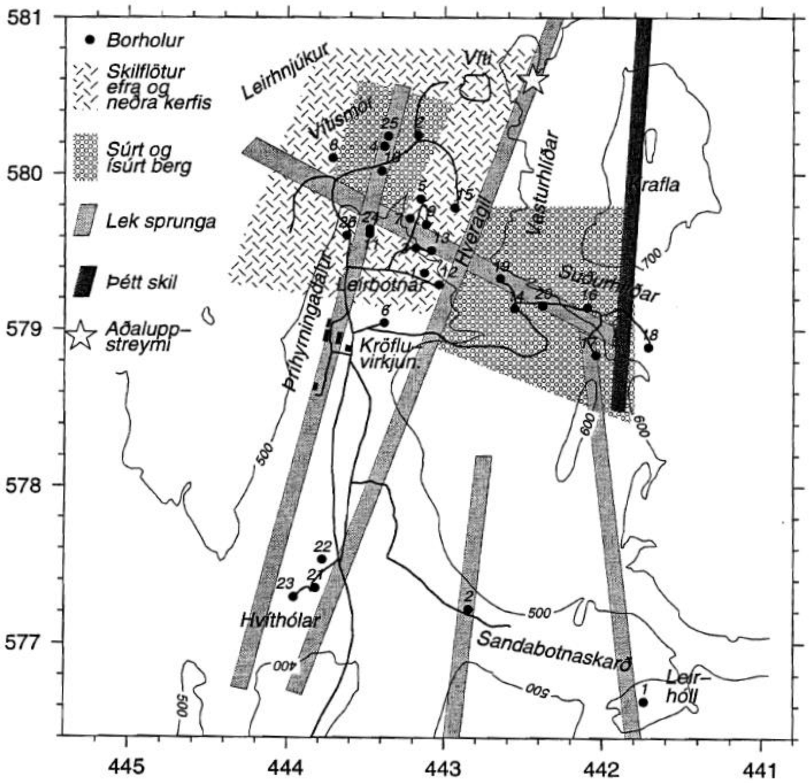


Figure 94. *Conceptual model 1997 (Grímur Björnsson et.al., 1997).*

12.5 Summary and continuation

A numerical reservoir model is a simplification of reality to give us an idea of the reaction of geothermal areas to production and is an invaluable contribution to the decision process on increasing production. Numerical modeling of the Krafla area has moved towards ever more complicated models, using more blocks and rock types. This has improved the ability to simulate the initial state and a lengthening production history. These advancements are also the result of the development of equipment but the situation is now threatened by over parameterisation which could degrade the model's predictive capacity, despite the ability to successfully simulate the available production historydata. The success rate of simulating data collected since the last model was developed should be assessed and a decision should then be made on the need for any improvements to the current numerical smodels.

The Krafla area has so far been simulated without considering production in the Námafjall (a.k.a. Bjarnarflag) area. However, plans for an increase in production in the Krafla area, in conjunction with plans for a 90 MW_e development by Mt. Námafjall, calls for a reassessment of the model. The question remains about whether production in both areas need to be simulated using one model for both areas.

13 Conceptual model of Krafla

The results of geothermal research conducted over the last few decades in the Krafla area have been outlined above. The objective is to collect and integrate the results into a comprehensive conceptual model of the geothermal system in Krafla which will then serve as the basis for the re-development of a numerical model of the system as the premise for further drilling in the area.

The main features of conceptual models are built on the following aspects:

- Geological structure

- Size of area according to external features/surface markings
- Size of area according to resistivity measurements
- Resistivity deviations indicating higher temperatures and/or upflow
- Deep-set thermal source and/or upflow of geothermal fluid according to MT-resistivity measurements
- Upflow of geothermal fluid according to temperature logs
- Recognised fault systems and fault permeability
- Connection between powerful wells and fractures as well as temperature and low-resistivity
- Connection between magma chambers and intrusion swarms in upflow areas and their role as geothermal sources
- Connection between acidic fluid and magma chamber/fault systems
- Origin and inflow of fluid in the system
- Reaction of the geothermal system to production
- Assessment on the effect of reinjecinjection

Figures **Error! Reference source not found.**–**Error! Reference source not found.** show the results of various research aspects combined in an effort to integrate them.

Krafla is a mature central volcano with a 8x10 km caldera and an active geothermal system. A fissure swarm traverses the caldera but the swarm can be divided into the east and west swarms. Volcanic activity has switched between the east and west swarms since the end of the Ice Age but activity has remained in the east fissure swarm for the last 3000 years. The magma chamber beneath Krafla is approx. 3-7 km in depth and is the main heat source for the geothermal system. Swarms of intrusions from the magma chamber and alongside the fissure swarm are also important heat sources as intrusions form most of the rock matter below a depth of 1500-2000 m within the system. Earthquake analyses beneath the central volcano show the presence of a magma chamber in the east-west belt of the caldera which correlates with surface manifestations, active geothermal areas and alteration. Alteration is widespread in the Krafla area and covers an area of 30 km^2, extending from Hvannastöð and Krókóttuvötnum, westward across Leirhnjúkar, Hveragil and Krafla, to the east of Hrafntinnuhryggur in the east.

Geothermal alteration can be found to the south of the caldera edge in Sandabotnaskarð and by Hvíthólar. Geothermal activity is highest along the mid-section of the Leirhnjúkar area and towards the east-west by Víti and Hveragil. The size of the geothermal area has been mapped out using the Schlumberger method and TEM and MT resistivity measurements. Basic resistivity deviation can be found in four areas: between Krafla and Leirhnjúkar, in the western area below the Leirhnjúkar lava field, by Hágöngur (close to the eastern periphery of the caldera) and in Sanbotnaskarð (by the south-western periphery of the caldera). Resistivity deviations were not detected in measurements conducted by Hvannstöð and Krókóttuvötn on the western side of the caldera where geothermal alteration can be seen at the surface. TEM and MT measurements show that the geothermal system in Krafla is large-scale or anything up to 48 km^2. The MT-measurements show low-resistivity deviation at a depth of 2 km (below sea level) beneath Leirhnjúkar and to the west of the Krafla Mountain and at a depth of 4–5 km (below sea level) beneath Sandabotnaskarð. Low-resistivity deviation can indicate geothermal heat sources and high temperature upflow. These deviations are not found beneath Hágöngur and the area beneath the Vestursvæði area does not show obvious signs of deep resistivity deviations. Drilling has revealed cooling in the geothermal system in the Vestursvæði area and by Hágöngur. The Krafla area is estimated to have a total surface area of approx. 40 km^2 if these two areas are not included.

A total of 43 high temperature wells have been drilled at Krafla. Most of the wells are located in the area by Vítismó and Leirbotnar and to the west and south of the Krafla Mountain. A number of wells have also been drilled by the southern periphery of the caldera, by Hvíthólar, in Sandbotnaskarð and in the Vestursvæði area in the Leirhnjúkar lava field.

The stratigraphy of the uppermost 1000-1200 m of the west to east section between Leirhnjúkar and Suðurhlíðar is dominated by a pile of surface formations but intrusions are almost completely dominant below this layer and permeability is connected to fissures. However, the intrusion rate is lower to the north and the caldera edge and piles of surface formations are dominant to a depth of 1800-2000 m.

The main fracture pattern at Krafla is parallel to the active fissure swarm taversing the central volcano which trends N5°–15°E. The tension area within the Krafla caldera is the result of the interplay between expansion as a result of divergence in the fracture zone and movement and tension shifts above the shallow magma chambers. Fractures and intrusions have subsequently formed (both parallel and perpendicular) in the same direction to the fissure swarm, as well as layered intrusions and inclined intrusions

The most powerful feedzones in the wells at Leirbotnar, Vítismó, the Vesturhlíðar area and the Suðurhlíðar area are connected to eruptive faults trending NNE- SSW (the Hveragil and Vítissprungu system, as well as the Hólselda and Dalelda eruptive fissures). Alteration and geothermal activity at the surface is also connected to these faults. Acidic intrusions, including horizontal intrusions, are found at differing depths in the area but powerful aquifers are generally connected to them (particularly beneath Vítismó). Faults trending WNW-ESE are found in the Suðurhlíðar area and Leirbotnar. Warm ground at the surface, CO_2 flux through the soil and the hypocenter indicate that a NNW-SSE structure is present. Drilling has also shown that permeability is connected to the NNW-SSE faults. The geothermal source in Hvíthólar can be seen at the intersection of the southern end of the Dalelelda Fire fracture and the caldera fault, whereas geothermal energy in Sandbotnaskarð can be seen at the intersection of the graben trending NNE-SSW and caldera fault. Permeability can be connected with these structures.

The most powerful wells at Krafla, apart from KJ-21 in Hvíthólar, are by Hveragil and in the Vesturhlíðar area, which correlates with indications of a powerful upflow from active geothermal manifestations at the surface, MT measurements and temperature logs.

MT measurements show another powerful upflow beneath Leirhnjúkar and this is confirmed by surface manifestations. Well KJ-35 was drilled towards Leirhnjúkar and temperature logs from the well indicate that the well has penetrated a powerful geothermal system.

The predicted initial temperature of this drilled section of the geothermal system indicates substantial upflow beneath Víti and Hveragil. This mostly correlates with TEM and MT resistivity measurements. The other main upflow area beneath Leirhnjúkar (based on resistivity measurements and surface manifestations) was confirmed when well KJ-35 was drilled. Temperature logs from the wells indicate a particular upflow channel in the direction of Suðurhlíðar but other indications show that Suðurhlíðar (and to some degree, Vesturhlíðar) are not easily connected to Hveragil and Leirbotnar; the initial pressure seems to have been higher there than in Hveragil and Leirbotnar and the pressure has dropped more in this area than elsewhere in the geothermal system. Temperature logs also indicate a thermal upflow in Sandbotnaskarð which correlates with resistivity measurements. TEM measurements show a connection between this area northward along the graben and towards the Suðurhlíðar. There is no available information to assess where the inflow to Hvíthólar originates from. It could possible originate from the east of Sandabotnaskarð along fissures connected to the caldera fault or from the north from Leirbotnar.

The isotopic properties of the geothermal fluid indicate that the water in Leirbotnar and Vítismó is originally local rainwater, but the water in the the Suðurhlíðar area and Hvíthólar originates from the Vatnajökull Glacier. This indicates that the cycle of water in the Krafla system is more complicated than the idea that there is a single main upflow beneath Víti and Hveragil. The state of the geothermal system also varies from one area to another. The Suðurhlíðar area follow the boiling point depth curve, whereas the system in Leirbotnar is twofold (dual). It is separated into an upper system (shallow system) which has a temperature of between 180–220°C (which indicates convection and the lower system (deeper system), which follows the boiling point depth curve. Alteration indicates that the upper system in Leirbotnar has cooled considerably and that the temperature in the area was previously close to boiling point right up to the surface (Figures 5 and 96). Cooling seems to be the result of the inflow of local groundwater. The upper system is shallowest in Leirbotnar but deepens both to the west from Hveragil and to the north. The temperature below a depth of between 1000 and 1500 m follows the boiling point depth curve in all these areas with the exception of Hvíthólar (Figure 97).

The concentration of sulphate was initially low in water from the deeper wells at Leirbotnar but was higher in the shallow wells. Concentration levels have increased alongside production levels, particularly in wells located by or in Hveragil. This indicates that cold water is entering the system and releases sulphate from dissolution of minerals. Enthalpy has also decreased in the deeper wells in Leirbotnar.

The magma chamber in Krafla is 3 to 7 km deep and is the main energy source for the geothermal system. Intrusions distribute heat in the Krafla caldera via thermal conductivity and convection of water from these thermal sources to the surface along the fissure system.

Thermal conductivity probably only covers a short distance but it is difficult to explain high temperature and enthalpy (biphasic to a degree) in some areas of the geothermal system (Vítismó, Leirbotnar, the Vesturhlíðar area and the Suðurhlíðar area. In other words, the conductivity layer needs to relativitly small and in ashort distance from magma or hot intrutions over to the convection to account for enough heatflow

Acidic rock can be seen at the surface and in wells at Krafla and is thought to be formed by the partial melting of basalt or altered basalt. The conditions needed for this type of melting include high temperatures in close proximity to hot intrusions or a magma chamber. These types of conditions are present at a shallow depth in Krafla and have been confirmed twice during drillling when acidic magma was penetrated at a depth of between 2100 and 2500 m in the geothermal system.

Magma activity is a powerful source of convective heat transfer but volcanic activity can also cause the inflow of magmatic gases (CO_2, HCl, SO_2) in the geothermal system. This became clear during the Krafla Fires when the lower system in Vítismó and Leirbotnar was affected by these gases. It became difficult to utilise the deeper system and production was almost impossible. CO_2, H_2S and H_2 gases have decreased over the years, particularly in wells in Leirbotnar and Vítismó but gas levels have decreased at a slower rate in the Suðurhlíðar area. Wells that cut through super-heated, acidic feedzones in the deeper system are still adversely affected by HCl gases. Super-heating and corrosion, caused by HCl rich fluid, was initially only thought to have affected Leirbotnar and Vítismó (to the west of the Hveragil fracture) but recent drilling has shown that the Suðurhlíðar area and the Vesturhlíðar area are also affected at a depth of below 2000 m.

Drilling in these areas has revealed that the temperature in an area up to one kilometre above the magma chamber is so high, as a result of intrusions, that it can cause localised melting of altered basalt, the accumulation of acidic magma and super-heated steam and acidic gases. Powerful aquifers in the deeper system in Vítismó can either be connected to the eruptive fissure from the Hólselda Fires or acidic intrusions.

The changes to pressure, chemical composition and temperature, which have occurred within the Krafla system since production began, reveal a great deal on the nature of the system and its capacity. Pressure changes within the system are particularly relevant, especially those that have occurred after the expansion of the power station. There has been some decrease in pressure in Leirbotnar and Vítismó, or approx. 5 bar since 1976. However, a more substantial pressure decrease seems to have occurred in the Suðurhlíðar area and to some degree in the Vesturhlíðar area. The initial pressure of the wells, drilled in the area during various time periods, indicates a decrease in pressure of anything between 20 to 30 bar. This indicates that these areas are poorly connected to the powerful inflow compared with other production areas within the Krafla system.

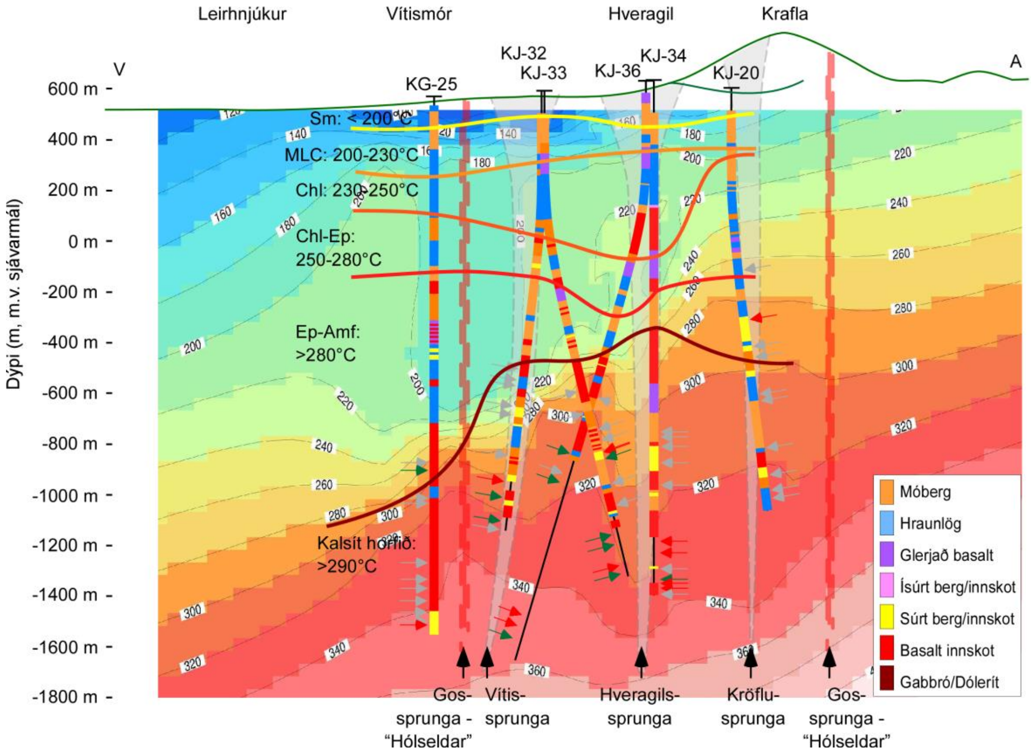


Figure 95. *East- west strata layer, alteration and temperature cross-section in Víti.*

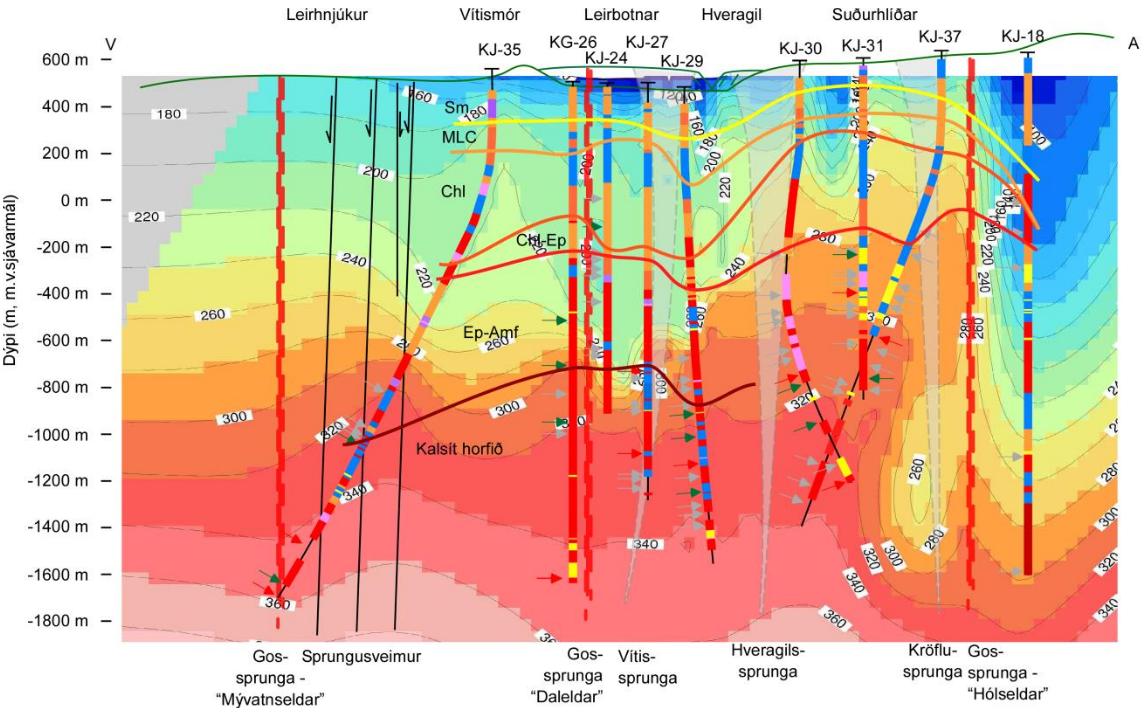


Figure 96. *East- west strata layer, alteration and temperature cross-section in Suðurhlíðar, Leirbotnar and Leirhnjúkar.*

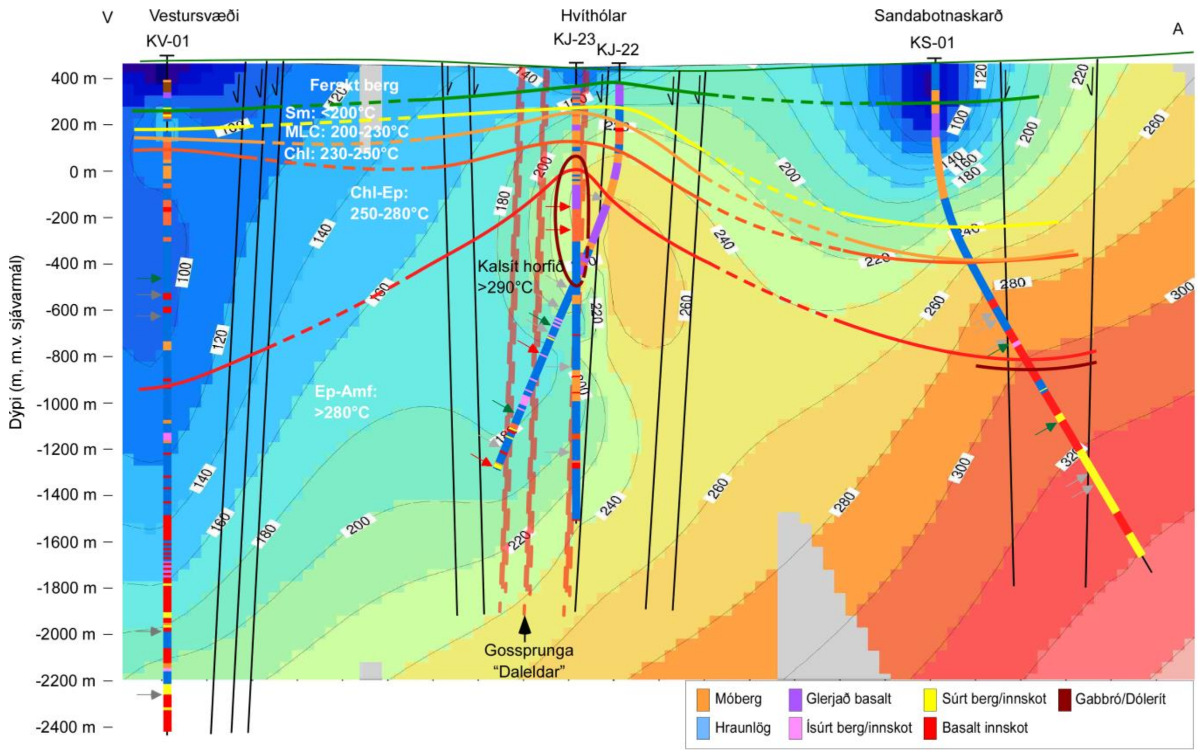


Figure 97. *East- west strata layer, alteration and temperature cross-section in Sandabotnaskarð, Hvíthólar and the Vestursvæði area.*

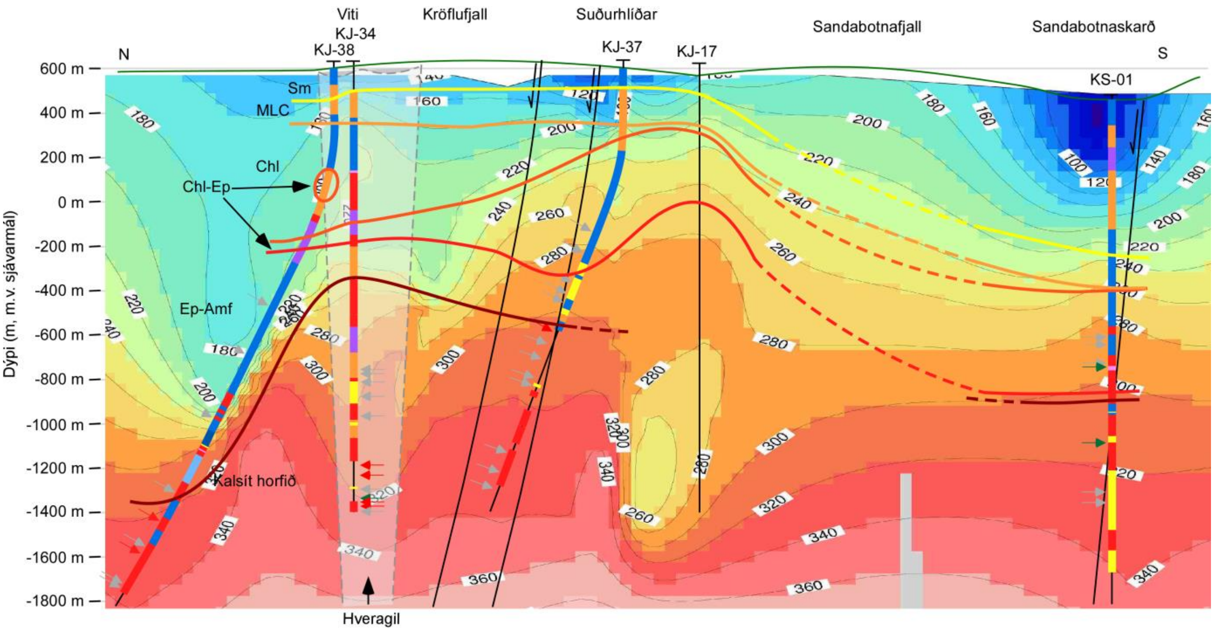


Figure 98. *North- south strata layer, alteration and temperature cross-section in Víti, Suðurhlíðar and Sandabotnaskarð.*

13.1 Subregions in the Krafla system

Steam for the Krafla Geothermal Power Station has up until now been extracted from four sub-regions: Leirbotnar and Vítismór, Vesturhlíðar, Suðurhlíðar and Hvíthólar. The Vestursvæði and Sandabotnaskarð (described hereafter alongside Hvíthólar as they are most similar in nature) area remain unutilised. Each subregion has its own particular characteristics (Figures **Error! Reference source not found.**–**Error! Reference source not found.**) and these will be described hereafter.

Leirbotnar and Vítismór – Vesturhlíðar – Suðurhlíðar

The Suðurhlíðar area follows the boiling point depth curve, contrary to Leirbotnar and Vítismó, which are divided into an upper and lower system. The temperature in the upper system is between 180 and 220°C down to a depth of 1000 to 1500 m but the temperature in the lower system follows the boiling point depth curve. The upper system thickens and the temperature within the system decreases northward and to the west from Hveragil. One of the main upflow areas of the Krafla system is thought to be beneath the Hveragil/Víti fracture zone. The division between Leirbotnar/Vítismó and Suðurhlíðar can be found in and around Hveragil. The first conceptual model of the geothermal system has endured time. According to the model, fluid flows from the Hveragil fracture zone, traveling west, also flowing to the surface and from Suðurhlíðar into Hveragil. However, recent opinion does not consider the flow from Suðurhlíðar westward into Hveragil. However, the idea that the fluid from the west flows into the upper system of Leirbotnar and Vítismó and contribute to the convection is still valid, as the high temperature suggests. High pressure to the east of Hveragil is probably the reason why there is no flow from the deeper system in Leirbotnar into the southern and western slopes of Krafla. The older model also considered high pressure levels in Suðurhlíðar which could explain why acidic fluid is nearly only found to the west of Hveragil. One explanation for the existence of the powerful upflow by Hveragil-Víti is that the NNE-SSW and E-W fracture zones intersect with each other, which could mean an increase in permeability as a result of multi-fractured formations. There is a 200 to 400 m series of acidic intrusions at a depth of between 200 and 600 m.b.s.l in Suðurhlíðar and substantial permeability is connected to them. The main research data indicates that ESE-WNW trending faults in Suðurhlíðar control permeability in this area and that a cold stream enters the lower section of acidic intrusions from the east (which does not reach Hveragil). This causes a reversal in temperature at a depth of between 1400 and 1800 m.

Substantial cooling has occurred in well KJ-18, in the easternmost part of Krafla, as a result of the cold downflow of groundwater down into the bedrock. The alteration temperature decreases at a slower rate (down to 800 m) than that found in nearby wells. The alteration pattern below this is similar to that found in other wells in Suðurhlíðar. The rock temperature is therefore lower in the upper section than that found in wells KJ-16 and KJ-17, according to alteration and temperature logs. This indicates a substantial deepening of the geothermal system by well KJ-18, possibly reaching the eastern periphery of the geothermal system in Suðurhlíðar. However, a steam discharge and alteration is visible at the surface to the east of this area, in Hrafntinnuhryggur.

Permeability in the wells in the Leirbotnar and Vítismó area is connected to acidic intrusions, on the one hand (the most powerful aquifers are acidic at a depth of 2000 m in Vítismó), and NNE-SSW faults and eruptive fissures that have been recently active, on the other. The upper system in Leirbotnar and Vítismó can be explained by its close proximity and connection with the mid-section of the rift zone where the flow of colder water could have easier access to the geothermal system. The water is thought to originate from the highland area of Krafla or from the fracture zone of the Krafla Fires further away. Investigations on the homogenization temperatures of fluid inclusions indicate that the temperature in the upper system was previously similar to that currently found in Suðurhlíðar. Temperatures were probably higher within the system during the last Ice Age when the glacier covered the highland areas of Krafla. The water level in the glacier was higher than the surface of the land is today thus affecting the temperature and pressure levels within the geothermal system.

The distance to the lower system in the Leirbotnar and Vítismó area varies. The thickness of the upper system to the northwest by Vítismó and northward to Víti can be anything up to 1200-1500 m. Drilling has shown that the thickness of the upper level in the area to the north of Víti can be anything up to 1600 m (as is evident in well KJ-38). The area has obviously cooled, despite tha fact that it is well within an area of low-resistivity, which could be the result of the inflow of cold water from the north of the fracture zone. Enthalpy in the wells in Vesturhlíðar has decreased in the last few years and the concentration of sulphate has increased. This could be the sign of increased inflow from colder water. The geothermal system is delineated to the north approx. 2 km to the north of Hveragil and to the east by the Krafla Mountain (in accordance with low-resistivity).

The upper system becomes thinner to the south of Leirbotnar, measuring 800-1000 m in thickness, which correlates with various observations. The earthquake frequency is highest in Leirbotnar and tremors follow the ESE-WNW belt, which in turn follows the magma chamber beneath it. There is an increased fluxof CO_2 in soil, at the surface following an ESE-WNW line. ESE-WNW deviations can be seen in resistivity, aeromagnaetic and gravity surveys and the Hólselda and Dalelda volcanic craters end where these structures begin. This could be some sort of barrier to the flow caused by tension changes in the litosphere. There is a hypothesis that the ESE-WNW faults are in fact the barrier; there is evidence of a NNW-SSE ridge transecting the main fault direction across Leirbotnar. There is also a correlation with the magma chamber at Krafla and intrusions are more prevalent above this (there is some sort of connection to the intrusion structure). The other main upflow zone for the Krafla system is believed to be underneath Leirhnjúkar. The area was explored by drilling KJ-35. The deeper system seems to be characterised by corrosive HCl rich fluid which corroded the liner and blocked the well with iron-silica deposits. The invasion of acidic fluid from the deepest aquifers in the wells has been problematic in the Leirbotnar and Vítismó areas and all the way to the north of Víti. Subsequently, a large portion of the lower system has proved unsuitable for production. Magmatic gases invaded the Leirbotnar and Vítismó areas after the Krafla Fires and production from the lower system has been limited due to acidic fluid. The acidic fluid has not disappeared despite the fact that CO_2 levels have returned to previous levels. It should also be noted that other wells in the Leirbotnar and Vítismó area have been drilled into areas where there is evidence of super-heated conditions. Wells KG-04, KG-25, KJ-36, KJ-39 (Suðurhlíðar) and IDDP-01 (Vítismó) are prime examples of this. Super-heated conditions can occur in close proximity to magma and drill cuttings from wells KJ-39 and IDDP-1 showed that magma had been penetrated at a depth of approx. 2100 m.b.s.l and 1,550 m.b.s.l in these wells.

Vestursvæði – Hvíthólar – Sandabotnaskarð

Three sub-regions have been drilled on the southern periphery of the caldera alongside the caldera fault. The Vestursvæði area in the Leirhnjúkar lava field is located by the caldera fault where the most active part of the NNE-SSW fissure swarms transect it. The Hvíthólar area is located where the Daleldar fracture transects the caldera fault and where steam extraction for the Krafla Geothermal Power Station has taken place since 1985. Well KS-01 in Sandabotnaskarð is approx. 2 km to the east of the fissure swarm just inside the caldera fault.

The layout of the area (considering fissure swarms and well data) shows how the geothermal system has developed. Drilling in well KV-01 revealed that the Vestursvæði had cooled and that there is a temperature reversal in in Hvíthólar below a depth of 400–500 m.b.s.l. The temperature in Sandabotnaskarð is well above 250°C below a depth of 400 m.b.s.l and there is no evidence of temperature reversal.

The Vestursvæði area is located in a large resistivity deviation area and stretches north to south. The resistivity deviation indicates that a powerful geothermal system was once active in the area and the upflow zone for the system probably transected the caldera fault and fissure swarms. The north to south feature of the resistivity deviation indicates that the upflow would have travelled north and south alongside the fissure swarm where there is high permeability. Alteration indicates that the system was characterised by convection down to a depth of 1000- 1200 m (much like that in Leirbotnar). It is difficult to estimate when activity was at its highest in the Vestursvæði area but it is likely to have been during the Ice Age when permeability in the fissure swarm was different as the glacier covered the area and there was also a different pressure status in the geothermal system.

The Vestursvæði has cooled significantly (temperatures are beneath 120°C at a depth of 1000 m.b.s.l) but fractures and continuous divergence in the area has facilitated active and deep cooling within the system. Temperature reversal in the Hvíthóla system can possibly be explained by flow from the geothermal upflow in a narrow channel a short distance from the Hvíthólar wells.

Sandabotnaskarð lies in an approx. 2 km section to the east of the fissure swarm but the area has not experienced any obvious cooling. MT and TEM measurements show the heat source to be deep-seated or at a depth of approx. 4–5 km. The Sandabotnaskarð system is by the intersection between the graben (trending N-S) and the caldera fault (trending E-W). This could explain the geothermal upflow to the surface and into the caldera fault and fractures in the graben.

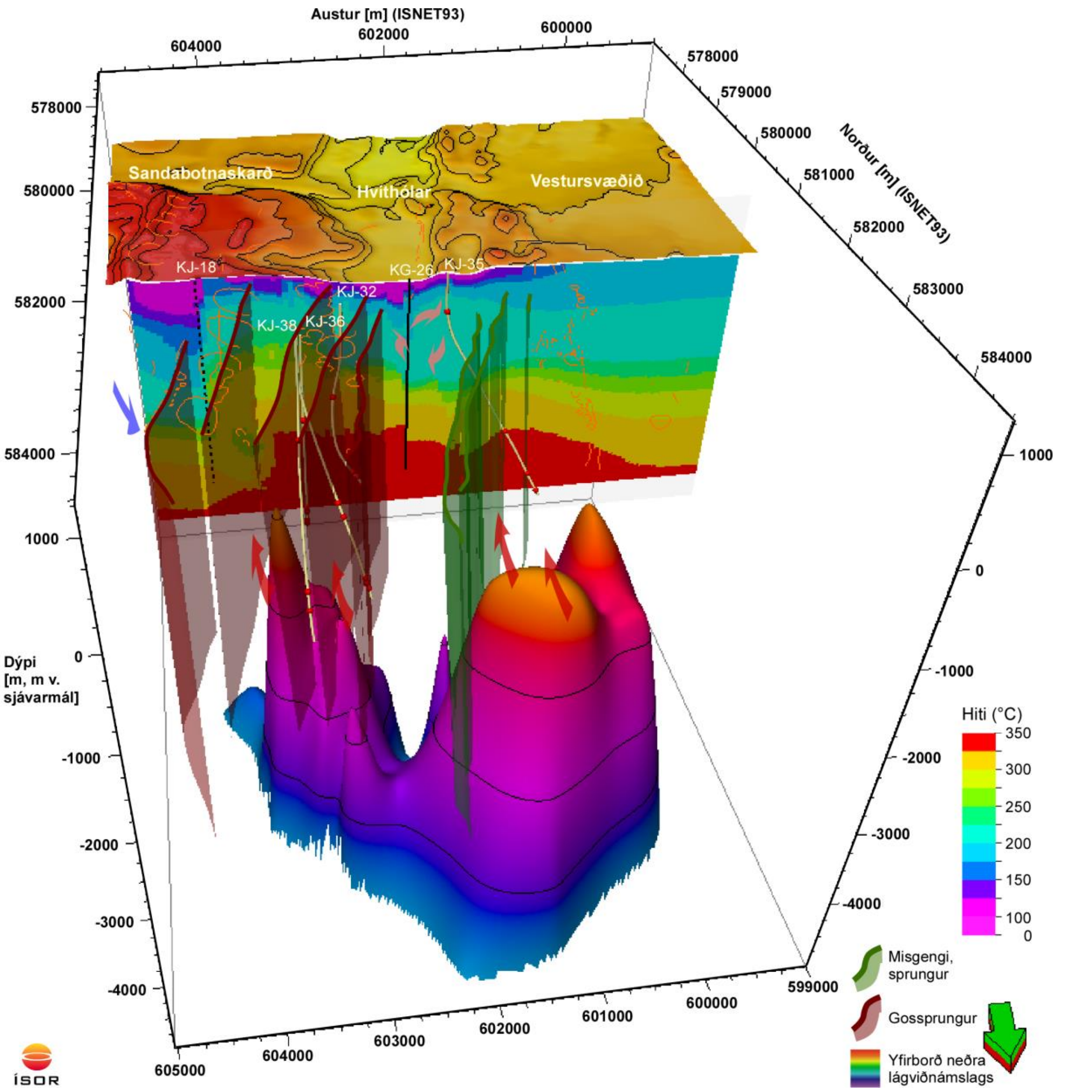


Figure 99. *Simplified diagram of the internal geothermal system in Krafla, southward in an east-west profile, traversing the mid-section of the Krafla caldera from the southern slopes (Suðurhlíðum), across Leirbotnar and westward to Vítismó.*

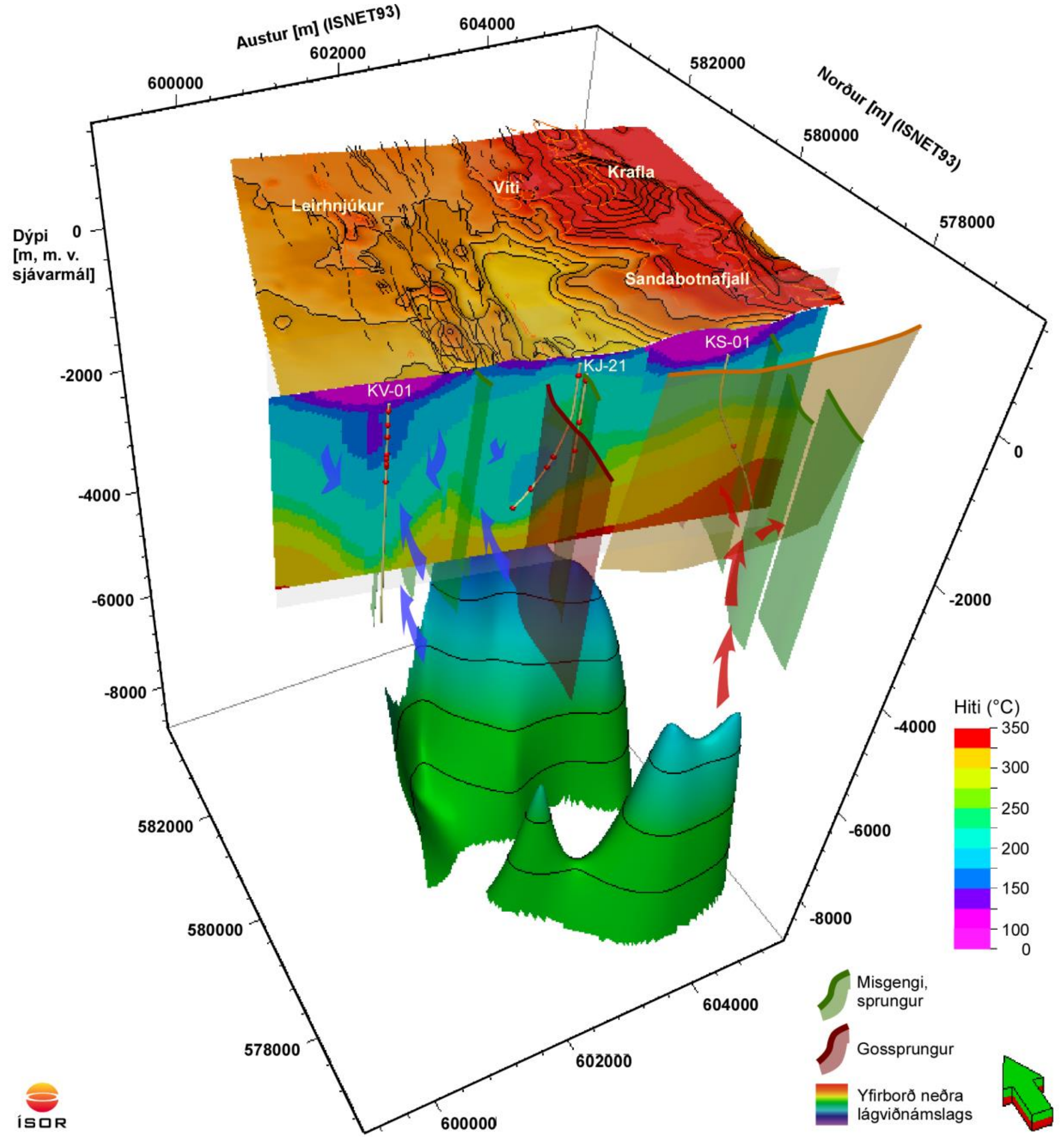


Figure 100. *Simplified diagram of the structure of the Krafla geothermal system*

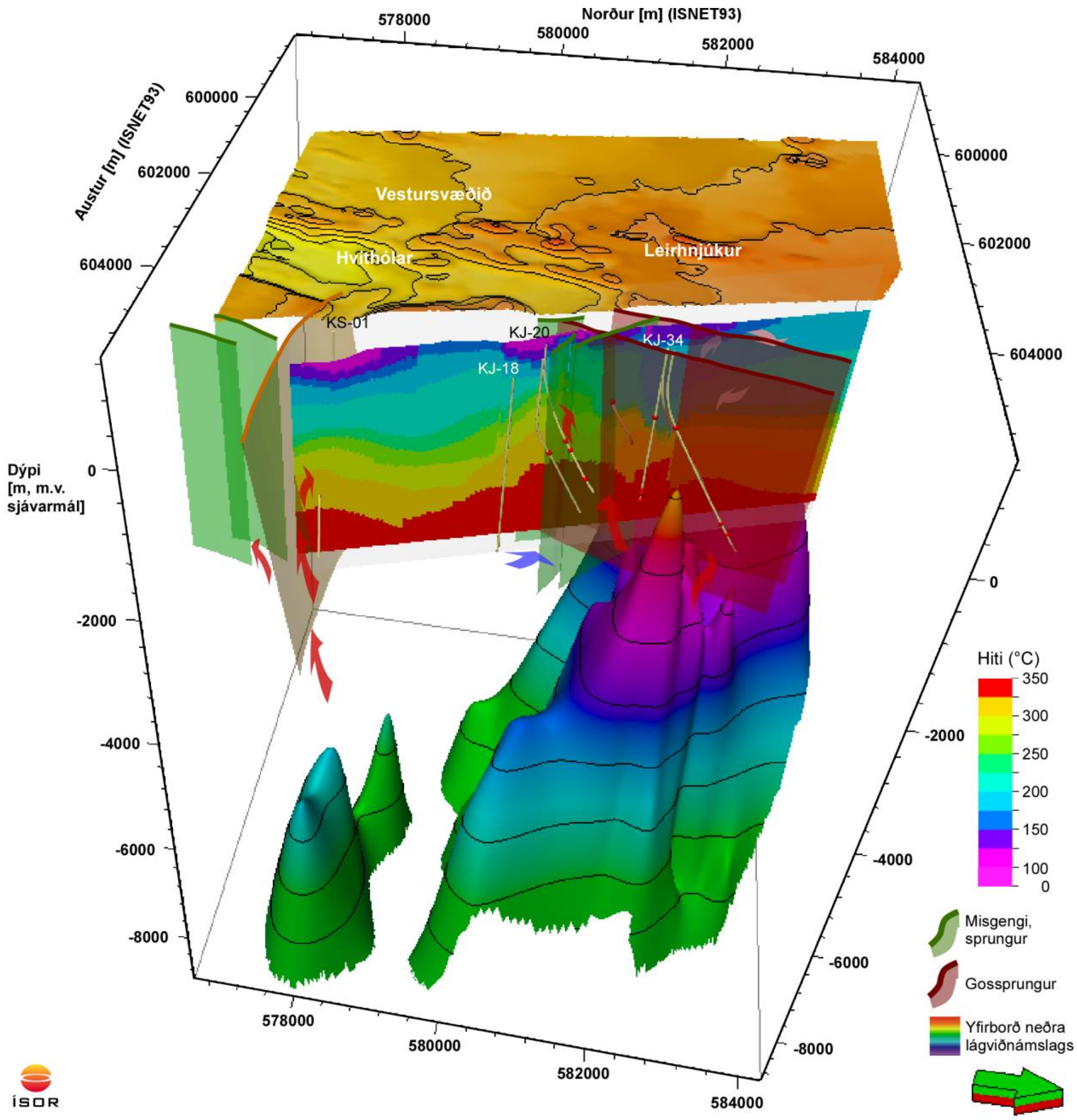


Figure 101. *A simplified figure of the structure of the Krafla geothermal system westward in a north-south profile, in the eastern area of the drilling area from Vítismó, accross Vesturhlíðar, Suðurhlíðar and southward across Sandabotnaskarð.*

14 Volumetric assessment

14.1 Geothermal resource assessment using the volumetric method

14.1.1 Theoretical foundation/basis

The most important factor in geothermal resource assessment, when using the volumetric method, is determining the volume of the geothermal system in question. The volume is calculated by assuming that the area is a box with a surface area *F* in the *xy plane* and a height (thickness) $z_1 - z_0$, along a z-axis, where z_1 and z_0 are the upper and lower depth limits (for the purposes of this report).

Once the volume of the geothermal reservoir has been assessed then a choice has to be made on how to calculate the utilisable heat stored within the system. This can be simplified by assuming that the heat capacity and temperature are homogenous in the x and *y* plane (volume) and only dependent on the depth in the *z* plane. The heat reserve of the reservoir can be calculated by integrating the product of the estimated heat capacity per unit-volume C(z) and the difference of the estimated temperature curve T(z) and the reference temperature (cut off temperature) T_0. The reference temperature is the state from which the heat is integrated. This could be the ambient temperature, the minimum temperature for generation, absolute zero temperature, etc. The choice of T_0 is relative to how utilisable energy can be calculated based on geothermal heat. We can therefore assume that the total heat energy content of the geothermal reservoir by:

$$\boldsymbol{Q = F \int_{z_0}^{z_1} C(z)\,[T(z) - T_0]dz} \qquad (1)$$

Only a portion of the total heat within the reservoir can be extracted and a so-called thermal recover factor is therefore defined as *R* which represents the percentage of recoverable heat from the system. The recoverable heat is therefore:

$$\boldsymbol{Q_H = RQ} \qquad (2)$$

According to Equation 1, geothermal heat can be calculated in two ways. The first method is to integrate over the temperature curve, and the other is to assume a homogenous temperature for the entire volume (providing a mean temperature for the volume). The first method of calculation will be used here. If the formation pressure with depth has been estimated for the geothermal reservoir, one can use that estimate, along with a formation temperature estimate, to find the thermal heat capacity of the water as a function of depth (The International Association for the Properties of Water and Steam, 2007). This method is more complicated. A more common method is to divide the volume into layers and to assume that the heat capacity of rock and water is fixed for each layer. For further simplification, we assume one wet layer. Heat capacity per unit volume in this layer is therefore:

$$\boldsymbol{C = s_B(1-\phi)\rho_B + s_v\phi\rho_v} \qquad (3)$$

Where s_B and s_v are the specific heat of rock and water, ρ_B *and* ρ_v are the density of rock and water and ϕ the porosity of the rock. It is convenient to assume that the temperature curve follows a curve much like the boiling point depth curve (James, 1970).

$$\boldsymbol{T(z) = x \cdot 69{,}56(z + z_{Delta})^{0{,}2085}} \qquad (4)$$

Here x is the ratio of the boiling point depth curve and z_{Delta} is the shift value which gives the heat boundary conditions T_{z_0} in z_0. We can then write the recoverable heat described in equation 2 as:

$$Q_H = RFC \int_{z_0}^{z_1} [T(z) - T_0]dz$$

$$= \boldsymbol{RFC\left[x\frac{69{,}56}{1{,}2085}\{(z_1 + z_{Delta})^{1{,}2085} - (z_0 + z_{Delta})^{1{,}2085}\} - T_0(z_1 - z_0)\right]} \qquad (5)$$

Only a small portion of the recoverable heat from the geothermal system can be used for electricity generation. We can use a number of methods to assess the size of this portion. The easiest method to define an electric utilisation constant is to assume a mean utilisation $\overline{\eta_e}$ for all the heat in geothermal fluid. This mean can be based on experience in utilising geothermal areas or by using the central limit etheorum. This gives us a total electric utilisation of:

$$Q_e = \overline{\eta_e} Q_H \quad (6)$$

And the electric power:

$$\boldsymbol{P} = \frac{\boldsymbol{Q_e}}{\boldsymbol{t}} , \quad (7)$$

Where t is the power project lifetime.

14.1.2 Monte Carlo calculations

The variables used in the volumetric method are often shrouded with uncertainty and therefore it is necessary to define a probability distribution for these variables. By choosing one random value for each variable out of that probability distribution, one possible outcome of the volumetric method can be calculated. If this process is then repeated several times a discrete probability distribution for the outcome begins to form. This method of calculation is often named the Monte Carlo calculation after the Monte Carlo casino where a similar method is used for wealth distribution. To form the discrete distribution for the outcome we divide the interval of possible outcomes into equally long subintervals (Hjartarson et al., 2008). The probability that the real outcome is in a particular subinterval is the ratio of possible outcomes that fall in that subinterval to the total number of possible outcomes that have been calculated. With the discrete probability distribution an opportunity emerges to evaluate the probability for the outcome to fall into a particular interval.

14.2 Assumptions about variables for calculations

In order to calculate the geothermal reserves and potential electrical generation for the Krafla area (using the methods described in Chapter 14.1) we must determine the following parameters and variables:

Surface area of the geothermal system: F

Thickness of the system: $Þ = z_1 - z_0$

Porosity of the rock: ϕ

Heat capacity of the geothermal reservoirs: C

Rock temperature in the geothermal reservoir: $T(z)$

Thermal recovery factor: R

Reference temperature/ cut off temperature: T_0

Electric conversion coefficient: $\overline{\eta_e}$

14.2.1 Surface area

TEM-resistivity measurements effectively show the resistivity of rock and this is often used to estimate the size of a high temperature system. This is usually based on areas where a low-resistivity cap envelops the high-resistivity core at a depth of 800-1000 m. The temperature of the rock within such an area is at least 240°C. A correlation between resistivity and current rock temperature can only be confirmed by drilling. Resistivity at 600 m.b.s.l, approx. 1000-1100 m in depth, according to TEM measurements, is shown in Figure 2. The low resistivity cap covers an area of 48 km^2. Core wells drilled on the easternmost side of the area (to the north of Mt. Jörundar) proved to be cold. The cold area within the low-resistivity cap is identified with green in the Figure and the remaining area is 40 km^2 in size. It could therefore be assumed that the geothermal system in Krafla is anything up to 40 km^2. The existence of the high temperature system has been confirmed for the current utilisation areas, i.e.

Leirbotnar, Vítismó, Suðurhlíðar, Hvíthólar and Vesturhlíðar. A well has also been drilled by Sandabotnaskarð and temperatures reach above 260°C at a depth of 400 m.b.s.l and over 300°C when the depth reaches 800 m.b.s.l. The size of each area is approximated as:

Leirbotnar	3 km^2
Suðurhlíðar	3 km^2
Vítismór	3 km^2
Vesturhlíðar	3 km^2
Hvíthólar	2 km^2
Sandabotnaskarð	2 km^2

Geothermal heat has been confirmed via drilling in an area covering 16 km^2. However, it is likely that the geothermal system covers a larger area of the resistivity deviation. Calculations show a maximum area size of 40 km^2 and a minimum size of 16 km^2 but the most likely value is the mean of the two, 28 km^2. For comparison purposes, the size of the area is estimated to be 30 km^2 according to a geothermal assessment carried out in 1985 (Guðmundur Pálmason et al.1985). The probability distribution for the surface area which can be calculated using these values can be seen in Figure.

14.2.2 Thickness

Production wells in high temperature areas in Iceland are often 2–2.5 km in depth. The deepest wells in Krafla are over 2500 m in depth. Calculations only allow for one layer and the thickness of the geothermal reservoir is said to be 3000 m, or the same thickness identified in the geothermal resource assessment since 1985.

14.2.3 Rock porosity

Drill cuttings from the wells at Krafla show a division between lava layers and hyaloclastite(s)/ palagonite(s) series in stratigraphic formations. The porosity of the lava layers is assumed to be between 5–15% (Svanur Pálsson et al. 1984). There is more variability in hyaloclastite(s)/ palagonite(s) where porosity can vary from 15% and anything up to 45% in fresh hyaloclastite(s)/ palagonite(s). The frequency of intrusions increases below 900-1200 m (they typically have a low porosity). Calculations assume that porosity alters according to a triangular distribution where the minimum value is 5%, the maximum value is 20% and the most likely value is 10%. The geothermal resource assessment carried out in 1985 shows a porosity value of 10%. The probability distribution for porosity from these values is shown in Figure **Error! Reference source not found.**.

14.2.4 Heat capacity

Heat capacity is generally calculated using the equation $c = s\rho$, where s is the specific heat and ρ is the density. Calculations are made on the basis of utilisable heat from the layer where fluid can be extracted. The heat capacity in this layer is shown with Equation 3.

$$C = s_B(1-\phi)\rho_B + s_v\phi\rho_v$$

Where s_B *and* s_v is the specific heat of rock and water and ρ_B *and* ρ_v is the density of rock and water and φ is the porosity of rock. For further simplification, porosity is assumed to be probability distributed but other parameters are fixed. The probability distribution for porosity can be seen in Figure **Error! eference source not found.**. The specific heat of rock is assumed to be 880 kJ/(kg °C) and the density of rock 3000 kg/m^3. The specific heat of water is 5200 J/(kg °C), at a temperature of 280°C and 100 bar in pressure and the density is approx. 760 kg/m^3. These are the values of rock temperature and initial pressure curves in wells at Krafla, at a depth of 1000–1500 m. The same values are used for rock in the geothermal resource assessment from 1985, but the values for water is 4190 J/(kg °C) and 1000 kg/m^3. The variable $s_v\rho_v$ is similar in both instances.

14.2.5 Rock temperature

Calculations are made on the basis of utilisable heat from the layer where fluid can be extracted. The temperature in this layer can be calculated by using an equation that describes the boiling point curve. Rock temperature in the layer is described using equation 4 (James, 1970).

$$T(z) = x \cdot 69{,}65(z + z_{delta})^{0{,}2085}$$

Where x symbolises the ratio of rock temperature and the boiling process or how close the temperature is to the boiling point curve.

If x = 1 then the profile follows the boiling point curve whereas if x = 0.8 then the profile is 80% of the boiling point curve.

Figures**Error! Reference source not found.**–**Error! Reference source not found.** in Chapter 7 show the rock temperature in wells at Krafla. Figure **Error! Reference source not found.** shows typical rock temperature profiles for Leirbotnar, Vítismó, Suðurhlíðar, Vesturhlíðar and Hvíthólar, as well as rock temperatures in KS-01 and KV-01. The Figure also shows $T(z)$ for a number of values on x and an initial temperature of 5°C. Leirbotnar and Vítismó are dual areas (this is clearly shown in Figures**Error! Reference source not found.**–**Error! Reference source not found.**. Rock temperature follows the boiling point curve above a depth of 200-300 m and below a depth of 1000–1500 m in wells but the temperature is 180–220°C between the two depths. Rock temperature profiles are between the profiles for $T(z)$ where x = 0.6 and x = 1.0.

The rock temperature in most wells in Suðurhlíðar is at the boiling point curve (see Figure 38). Wells KJ-16 and KJ-17 are reversed and KJ-18, which is located in the easternmost part of the area, is the coldest well. If these three wells are not included then the rock temperature profiles are between the profiles for $T(z)$ where x = 0.9 and x = 1.0.

The three wells in Hvíthólar are reversed (see Figure 39). Rock temperature profiles are between the profiles for $T(z)$ where x = 0.6 and x = 1.0.

Three wells are associated with Vesturhlíðar: KJ-30, KJ-33 and KJ-34. KJ-33 is located between the Leirbotnar and Vesturhlíðar whereas well KJ-34 is in Vesturhlíðar. Both wells have a dual system similar to that found in the Leirbotnar system. KJ-30 is located between Suðurhlíðar and Vesturhlíðar and the temperature follows the boiling point curve (like all other wells in Suðurhlíðar). Rock temperature profiles are between the profiles for $T(z)$ where x = 0.8 and x = 1.0.

Two wells have been drilled outside the aforementioned five areas. They include well KS-01 by Sandabotnaskarð and well KV-01 to the west of Hvíthólar in the so-called Vestursvæði. Well KS-01 is rather cold above a depth of 500 m but rapidly increases in temperature below this depth, reaching boiling point at a depth of 1000 m. The temperature below this depth follows the boiling point curve down to the bottom (see Figure **Error! Reference source not found.**). Well KV-01 is cold (see Figure 102). Chapter 7 discusses rock temperature and initial pressure in more detail.

When well data is considered, it seems pertinent to allow x to begin from 0.7 and up to 1.0 in the calculations. The most likely value is assumed to be 0.9 because a part of Vesturhlíðar and the area to the east of Suðurhlíðar were excluded when determining the maximum surface area. The remaining area is assumed to be higher in temperature. The probability distribution for x which can be obtained using these values can be seen in Figure 105. The geothermal resource assessment from 1985 was based on a temperature status where x = 0.9 (Guðmundur Pálmason, 1985).

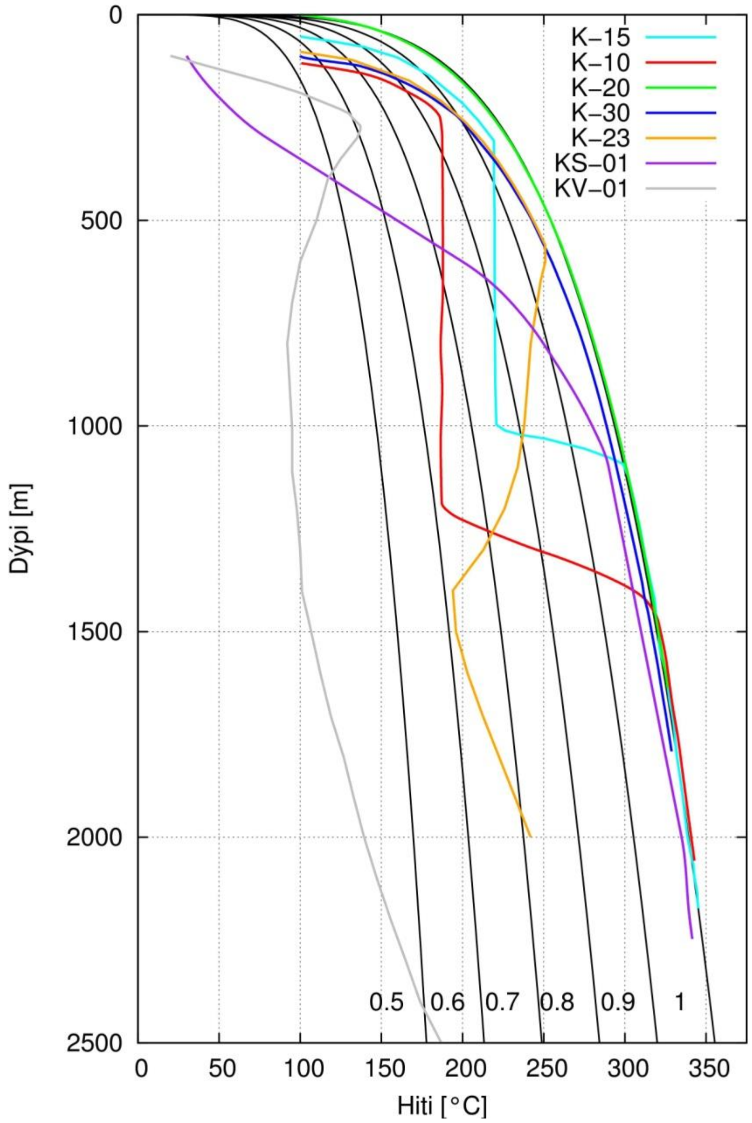


Figure 102. *Rock temperature profiles in wells at Krafla*

14.2.6 Thermal recovery factor

The thermal recovery factor is defined as the ratio of retrievable heat from wells and the heat capacity of the geothermal system. Porosity, permeability and inflow have the greatest influence on the thermal recovery factor. This coefficient is often given a value from 10 and up to 25%. Muffler (1977; 1979) introduced a linear relationship between the thermal recovery factor and porosity which would mean that porosity would be equivalent to 10%, which is often assessed to be the mean porosity of extrusive rock in Iceland to a thermal recovery factor of 25%. Permeability is usually related to the number and distribution of fractures rather than rock porosity. Two models of fracture distribution are compared in a new article by Williams (2007). One model shows regularly distributed fractures and the other model shows irregularly distributed fractures (*self-similar distribution*). The models give a thermal recovery factor of between 2 and 25% (in the case of regular distribution) and between 8 and 20% (in the case of self-similar distribution) for a distance between fractures from 250 m and down to 30 m.

It is unlikely that the fracture distribution is completely regular and calculations assume the thermal recovery factor to be between 10-20%, with the most likely value being 15%. The probability distribution for the thermal recovery factor using these values can be seen in Figure **Error! Reference ource not found.**.

For comparison purposes, the thermal recovery factor was 20% in the geothermal resource assessment from 1985. A comparison of the results of numerical modeling for a number of high temperature areas, conducted in 1990, revealed that the thermal recovery factor simulation could be 5–10% (Benedikt Steingrímsson et al. 1991). A comparison of numerical modeling from the period after 1990 indicates that the previous model had somewhat underestimated the capacity of the areas (Sarmiento & Björnsson, 2007). This would indicate that the thermal recovery factor simulation calculations are higher than those shown in older comparisons.

14.2.7 Reference temperature and utilisation efficiency

Heat can be extracted from fluid above a certain reference temperature T_0. The average temperature in Iceland, at a height of 2 m from the surface, is 3–5°C and the recoverable heat is calculated from the higher value as well as a value that is obtained by assuming a peak pressure in production wells. Geothermal power stations operate at a particular steam separation pressure and this value can vary according to the technology used at the station. The pressure in the high-pressure separator at the Krafla Geothermal Power Station is 7.7 bar-a, i.e. at a temperature of approximately 170°C. The calculation for technically utilisable heat uses this value. Only a portion of the thermal energy available within the temperature range $T - T_0$ can be used for electricity generation. The efficiency of power stations is generally assumed to be 10–15%, according to where the temperature range $T - T_0$ is. A reference temperature of 170°C would assume an efficiency rate of 12% (Wilcox, 2006). The efficiency rate is estimated to be 8% in the geothermal resource assessment from 1985 when the reference temperature is 130°C.

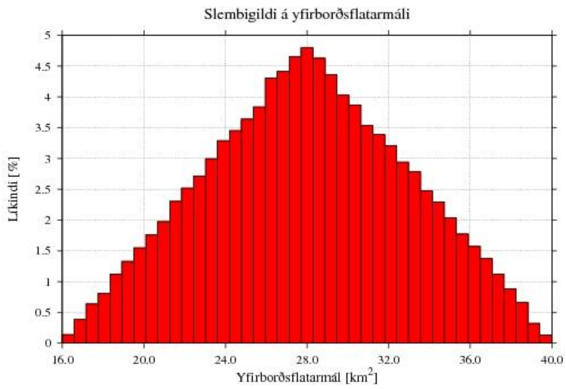


Figure 103. *Random values from the probability distribution of the surface area collected in 40 subintervals*

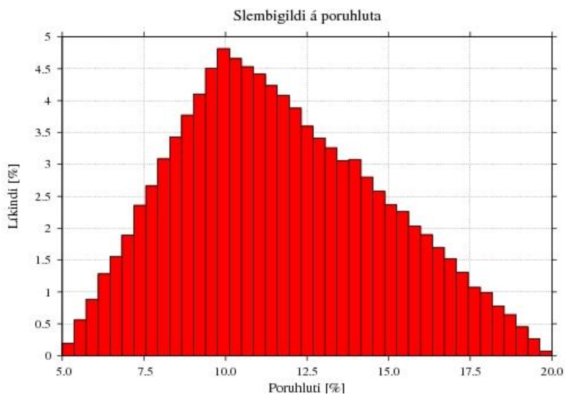


Figure 104. *Random values from the probability distribution of porosity collected in 40 subintervals*

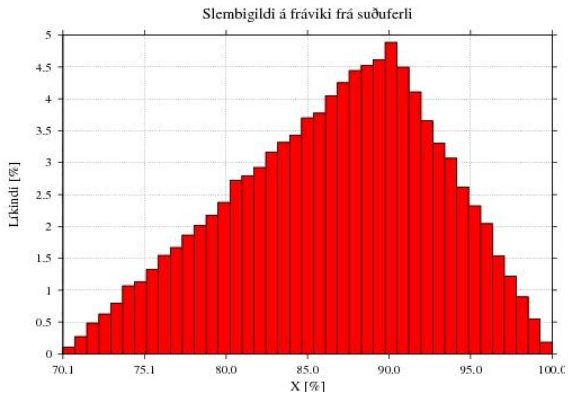


Figure 105. *Random values from the probability distribution of deviations from the boiling point curve collected in 40 subintervals*

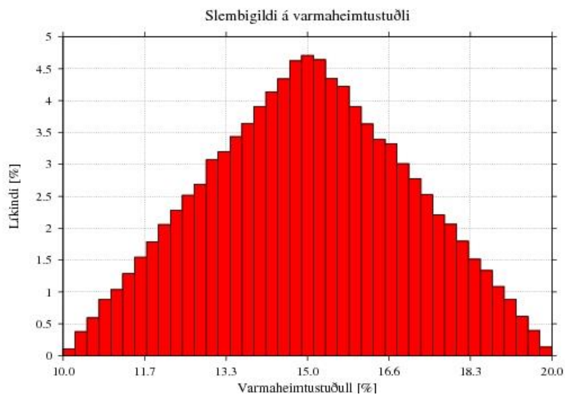


Figure 106. *Random values from the probability distribution of the thermal recovery factor collected in 40 subintervals.*

Table 7. *Overview of variables used for calculations on geothermal reserves and wattage at Krafla*

Nafn breytu	Breyta	Teg.	Minnsta gildi	Líklegasta gildi	Mesta gildi	Mat 1985
Heildarvarmi	Q	jafna 1				jafna 1
Yfirborðsflatarmál	F	líkindadreifing	16 km²	28 km²	40 km²	30 km²
Varmarýmd	C	jafna 3				jafna3
Eðlisvarmi vatns	s_v	fasti		5200 J/(kg°C)		4190 J/(kg°C)
Eðlisvarmi bergs	s_B	fasti		880 J/(kg°C)		880 J/(kg°C)
Eðlismassi vatns	ρ_v	fasti		760 kg/m³		1000 kg/m³
Eðlismassi bergs	ρ_B	fasti		3000 kg/m³		3000 kg/m³
Poruhluti	φ	líkindadreifing	5%	10%	20%	10%
Hitastig	$T(z)$	jafna 4				jafna 4
Viðmiðunarhiti	T_{Ref}	fasti		5°C, 170°C		130°C
Hlutfall af suðuferli	x	líkindadreifing	0,7	0,9	1,0	0,9
Dýptarmörk	$z_0, z_1 = z_2$	fastar		0,3000 m		0,3000 m
Rafafl	P_e	jafna 7				jafna 7
Varmaheimtustuðull	R	líkindadreifing	10%	15%	20%	20%
Nýtingarstuðull	η_e	fasti		12%		8%
Nýtingartími	t	fasti		30,50,100 ár		50 ár

14.3 Results

A geothermal resource assessment was calculated for recoverable heat (Equation 5 on page 135) from the geothermal system in Krafla. This assessment includes the results for recoverable heat from this section of the system, which is on the one hand warmer than 5°C, and on the other hand, warmer than 170°C. The electric production capacity of the system is calculated for the next 30, 50 and 100 years using results were temperatures are shown to be above 170°C (Equation 7 on page 141). The results are shown as a probability curve, comprised of 100,000 randomly generated results collected in 40 sub-intervals. Varied statistical information can be acquired from these results. Amongst these is the most probable value of each curve, 90% confidence interval, 90% cumulative probability, the average cumulative probability, the median for the results and their standard deviations. The 90% confidence interval should be considered the most important result as it tells us that there is a 90% probability that the actual outcome will lie within that confidence interval. Other important information includes the 90% cumulative probabiliy as it indicatesthat there is a 90% likelihood that the actual outcome will be above the limit.

Figure**Error! Reference source not found.** and Table**Error! Reference source not found.** should be nsidered when assessing the potential recoverable heat from this section of the geothermal reservoir which is warmer than 5°C. This shows a 90% likelihood that this section of the geothermal reservoir is between 4.7 EJ (exaJouleJoueexajúl=10^{18} J) and 11 EJ. The most likely value is 7 EJ with a probability of around 7%. The section of the geothermal reservoir that is warmer than 170°C has (according to the results shown in Figure**Error! Reference source not found.** and in Table**Error! Reference source not found.**) a 90% likelihood of being between 1.5 EJ and 4.5 EJ. The most likely value is 3 EJ with over 7% probability.

Figures **Error! Reference source not found.** and **Error! Reference source not found.** and Table**Error! erence source not found.** show how much electric energy could be generated from utilising this section of the geothermal reservoir, which is warmer than 170°C, based on 12% electricity utilisation. Generation over a period of 30, 50 and 100 years is considered. If geothermal energy is utilised over a 30 year period then there is a 90% confidence interval that the electrical energy is between 190 MWe and 580 Mwe and a 90% probability that the electrical energy is at least (or more than) 250 MWe. If geothermal energy is utilised over a 50 year period then the confidence interval is between 120 MWe and 350 MWe, and there is a 90% probability that electrical energy is more than 150 MWe. Finally, if geothermal energy is utilised over a 100 year period then the 90% confidence interval is between 60 MWe and 180 MWe and there is a 90% probability that the electrical energy is more than 70 MWe.

The geothermal resource assessment from 1985 shows the recoverable heat from this section of the geothermal reservoir at temperatures above 130°C J. Access to the area was included in these estimates (up to 90% of the geothermal area) as well as a thermal recovery factor of up to 20%. Electrical energy is based on a utilisation period of 50 years, assessed to be 380 WMwe, based on utilisation levels of 8% at the power station.

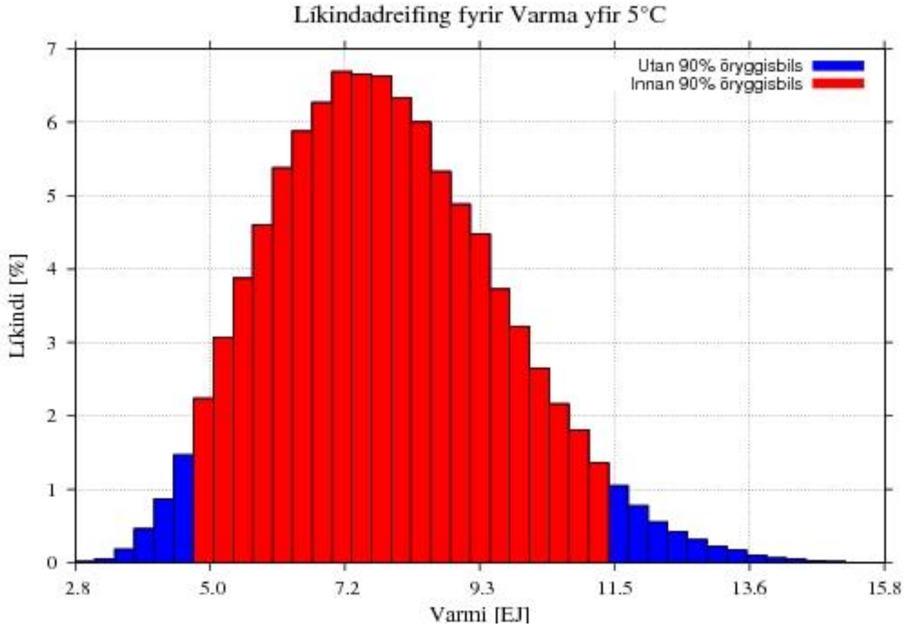


Figure 107. *Probability distribution for potential recoverable heat in areas of the geothermal reservoir where the tempereature is above 5°C.*

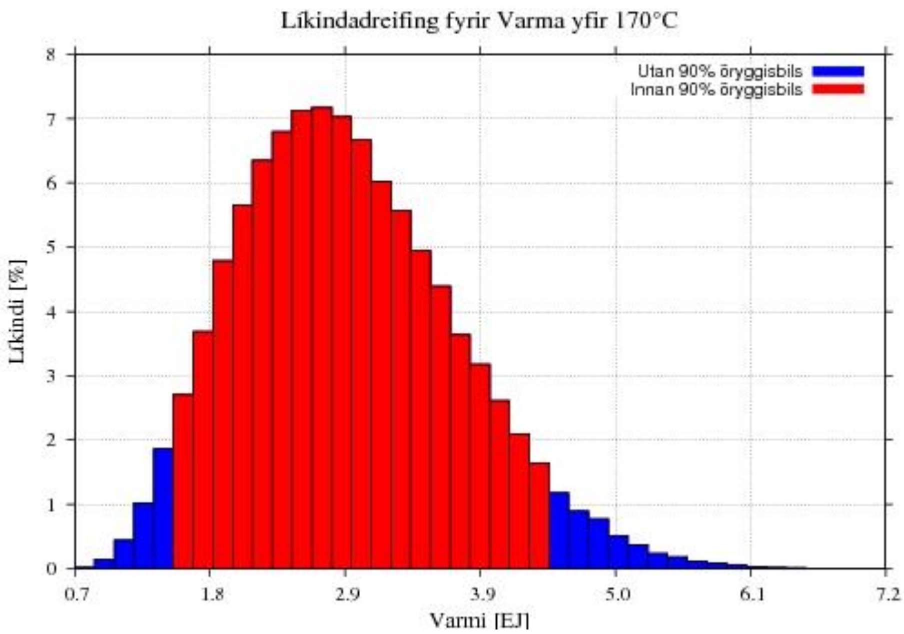


Figure 108. *Probability distribution for potential recoverable heat in areas of the geothermal reservoir where the tempereature is above 170°C.*

Table 8. *Probability distribution for potential recoverable heat over 5°C and over 170°C).*

Tölfræðistærðir	**Gildi [EJ] (yfir 5°C)**	**Gildi [EJ] (yfir 170°C)**
Líklegasta gildið	7,1 (7% líkur)	2,7 (7% líkur)
90% öryggisbil	4,7–11	1,5–4,5
Meðaltal	7,8	2,9
Miðgildi	7,7	2,8
Staðalfrávik	1,9	0,86

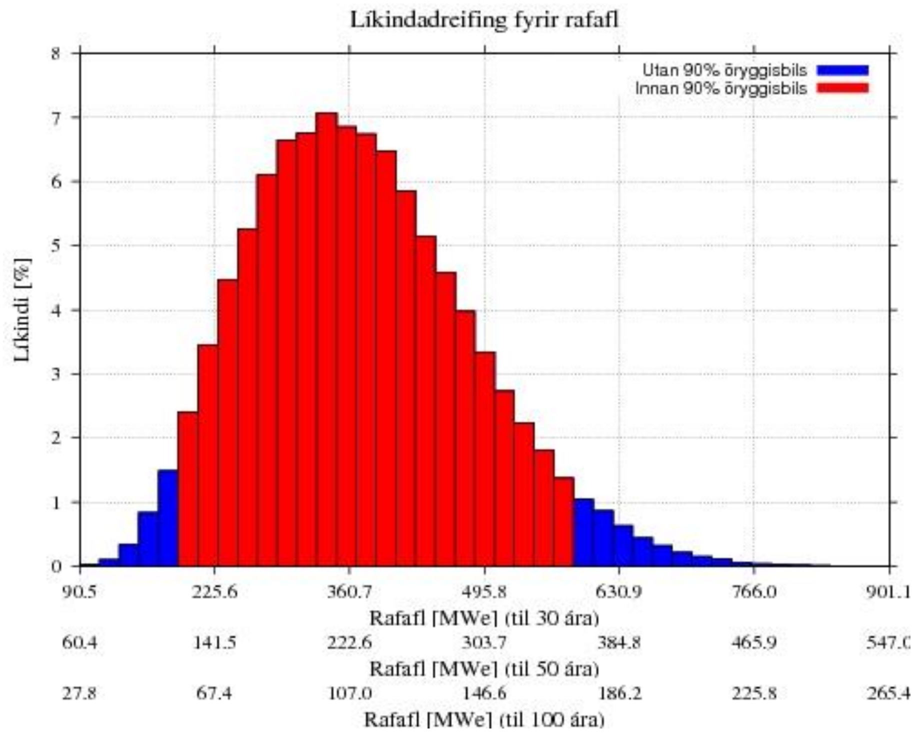


Figure 109. *Probability distribution for electrical energy from the proposed geothermal reservoir at Krafla for a 30, 50 and 100 year period.*

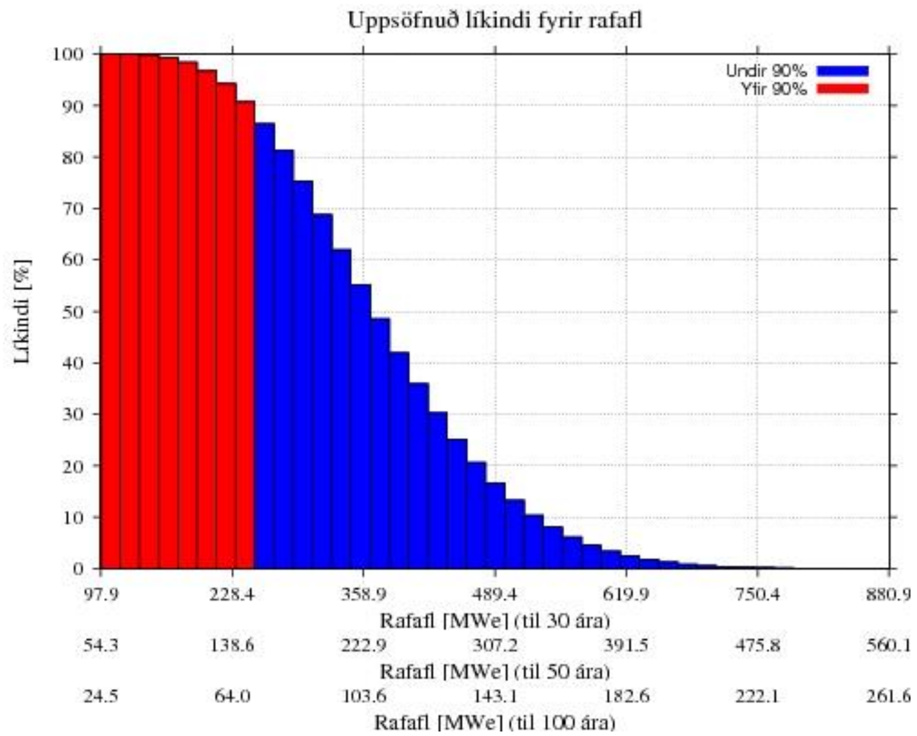


Figure 110. *Cumulative probability for electrical energy from the proposed geothermal reservoir in Krafla for a 30, 50 and 100 year period*

Table 9. *Probability distribution for electricity from the proposed geothermal reservoir at Krafla for a 30, 50 and 100 year period.*

Tölfræðistærðir	Gildi [MWe] (til 30 ára)	Gildi [MWe] (til 50 ára)	Gildi [MWe] (til 100 ára)
Líklegasta gildið	340 (7% líkur)	200 (7% líkur)	110 (7% líkur)
90% öryggisbil	190-580	120-350	60-180
Meðaltal	370	220	110
Miðgildi	360	220	110
Staðalfrávik	110	70	30
90% mörk	250	150	70

15 Concluding remarks

The Krafla area is one of the largest geothermal areas in Iceland and is located within an active central volcano, with a rather large shallow magma chamber. The last surge of volcanic activity in the area (the Krafla Fires) had a significant effect on utilisation in the area and it took twenty years for the current power station to achieve full production of/at 60 MW. The effects of the Krafla Fires and the close proximity of the magma chamber are still proving to be a challenge for the geothermal utilisation of the field. There are plans to increase production at Krafla by 150 MW_e and research and drilling has continued in the last few years to explore new production areas for this purpose. The main results of this research have been outlined in this report and the conceptual model and geothermal resource assessment have been reassessed. This last section will specifically discuss current ideas on the capacity of the Krafla system and whether the system could support the proposed expansion of the power station, as well as an analysis of which areas are most likely to support steam production in the future (potential drilling areas). The main parameters of the geothermal system have been reassessed and the older geothermal resource assessment for the Krafla system has been re-calculated. A so-called volumetric assessment is used which does not consider the effects of changing permeability and inflow as a result of pressure drawdown or the current chemical technical problems in utilising the deeper section of the system. The following main points should be observed:

- Resistivity measurements estimate the size of the geothermal area to be 48 km^2 but drilling has confirmed cooling in certain areas of the system which would bring the net total area to approx. 40 km^2.
- If the estimated size, rock temperature and various other factors are considered then the harnessable geothermal energy above 170°C and down to a depth of 3 km is 1.5 EJ (10^{18} J or 10^9 GJ) and up to 4.5 EJ (90% safety margin).
- If energy utilisation is 12% during electricity generation then there is a 90% likelihood that the capacity of the geothermal system is between 120–350 MW_e over a 50 year period.

The results of the geothermal resource assessment show that there is probably enough energy within the Krafla geothermal system to supply the expansion of the Krafla Geothermal Power Station. However, changes to production levels should be expected over a long period of operations. If high production levels are allowed short-term then they must be reduced later on in order to maintain sustainable utilisation (Guðni Axelsson et al. 2006; Guðni Axelsson, 2009).

However, the last few decades have shown that there are various limits to utilising the vast energy stores within the system and technical solutions for these have yet to be found. The effect of magmatic gases (currently mostly HC1) is the most substantial limit, but changes to permeability, variable levels of pressure drawdown and variable temperature levels are also problematic. Utilisation has so far been limited to specific areas of the geothermal system including Leirbotnar, Vítismó, Suðurhlíðar, Vesturhlíðar and Hvíthóla. Other areas have been explored in the last few years in connection with the proposed expansion of the power station. Areas of particular interest included Sandabotnaskarð, the Leirhnjúkar area and the area to the north of Víti and the Vestursvæði area. The following conclusions apply to any further utilisation of these areas:

- There has not been a significant drop in pressure in the upper system (shallow system) in Leirbotnar and Vítismó since production began (approx. 3–7). This indicates that the upper system in these areas could withstand an increase in the production of low-pressure steam.
- There has not been a significant drop in pressure in the lower system (deeper system) in Leirbotnar and Vítismó since production began at Krafla. The area is not thought to have reached full utilisation. However, mixing between systems during production (wells KJ-27 and KJ-32) and deep-set magmatic gases should be considered. Drilling during the last few years has shown that magmatic gases (mainly HC1) are still, to some extent, responsible for preventing further utilisation of the geothermal system, below a depth of 2000 m, in these areas. A technical solution for the utilisation of super-heated, HCl rich steam is also urgently needed. Magma has been penetrated at a depth of ~2100 m (based on surface level) in two wells (KJ-39 and IDDP-1) in Vítismó and at a depth of ~2500 m (based on surface level) beneath the Sandbotnar Mountain. This would indicate a certain risk, but over 22 wells have so far been drilled below 2000 m.
- The pressure has dropped significantly in the Suðurhlíðar area or by approx. 20–30 bar in the mid-section of the area. This correlates with the diminishing capacity of production wells over time and the production levels of new wells has been less than the permeability of the wells would have indicated (KJ-31 and KJ-37). Limited inflow in this area of the geothermal system is thought to be the cause. Increased production in the area does not seem possible unless reinjecinjection measures which could replace some of the natural inflow to the area were introduced. Drilling has also shown that there is a risk of penetrating magma deep within the system (below a depth of 2500 m) and that this part of the system is also affected by HCl-magmatic gases. There are therefore limits to collecting steam at particular depths in the Suðurhlíðar area until a technical solution is found.
- Vesturhlíðar has become one of the main production areas utilised by the Krafla Geothermal Power Station in the last decade. There is limited knowledge on pressure changes in the area except for the fact that the capacity of well KJ-34 has decreased, indicating a pressure decrease. Opportunities for further utilisation could be found beneath the Krafla Mountain (east and northeast) but the possibilities for further drilling in the Hveragil area should also be explored. The Vesturhlíðar area is probably to some extent connected to the Suðurhlíðar area and reinjecinjection measures in the Suðurhlíðar area could therefore have a positive effect on the pressure status in Vesturhlíðar.

The Hvíthólar area is limited in size and capacity. Pressure levels have dropped by approx. 20–25 bar. An extensive increase in production is therefore unlikely unless a possible connection is found in the east in Sandabotnaskarð or to other areas.

- The existence of a geothermal system with good permeability and a fluid suitable for production has been confirmed in Sandabotnaskarð, where MT measurements indicate the presence of a geothermal heat source and/or upflow. This system, or sub-system, seems to stretch northward along fissures in a graben (according to surface manifestations and TEM-resistivity measurements). It would therefore be appropriate to thoroughly explore the possibility of drilling utilisable wells in the area. The fluid is probably suitable for production as the area is further away from the Krafla magma chamber. Hence there is less risk associated with magmatic gases. A possible connection between Sandbotnaskarð, westward to Hvíthólar, along the caldera fault in the Krafla caldera should be noted.

- The possibility of widening the production area on the Norðursvæði area should be explored (the area to the north of Víti and between Krafla and Graddabungu). The results of a chemical analysis of fluid from well KJ-38 shows that magmatic gases are still affecting the area and that the lower system is deep-set. The permeability of the fissure swarm and eruptive fissures to the north of the Krafla Mountain should be investigated. The further the distance from the magma chamber, the less effect from magmatic gases.
- High temperatures and good permeability in the fracture system just to the south of Leirhnjúkar has been confirmed by drilling. The system is still affected by magmatic gases below a depth of 2000 m. There is a high likelihood of finding super-heated, HCl rich steam above the magma chamber but seeking out and following the fissure swarm to the north and south of Leirhnjúkar should reduce the effects of HCl-magmatic gases. However, the likelihood of cooling within the fissure swarm also increases to the north and south of Leirhnjúkar (this was confirmed by drilling in the Vestursvæði area). Resistivity measurements show that the area by Leirhnjúkar is another main upflow area of the geothermal system and could therefore become one of the main production areas once a technical solution has been found for utilising geothermal fluid affected by magmatic gases.
- There are indications that the area to the west of Leirhnjúkar (the area surrounding Hvannstóð and Krókóttuvötn) could also prove to be a utilisable production area although resistivity measurements indicate otherwise. There is extensive geothermal alteration at the surface in the area which has now cooled. No drilling has taken place in the area so far.
- It should be noted that reinjecinjection measures can play a key part in the utilisation of the geothermal system in Krafla. Tremendous amounts of energy are stored in the system and reinjecinjection measures could help in harnessing this energy as well as stabilising pressure levels within the system. Increased efficiency in energy utilisation is important and could be achieved by developing binary geothermal power stations instead of conventional steam turbines which would utilise the colder section of the system in a more efficient manner.

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18 Map 1: Krafla. Geological Map, 1:25000 (Kristján Sæmundsson, 2008)

19 Map 2: Krafla. Geological Map, 1:25000 (Kristján Sæmundsson, 2008)

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KRAFLA

JARÐFRÆÐIKORT / GEOLOGICAL MAP

SKÝRINGAR / *LEGEND*

LAUS JARÐLÖG / *Surface deposits*

- K — Fjallskriður / *Talus*
- E — Framhlaup / *Rock slide*
- Á — Framburður / *Stream deposits*
- J — Jökulruðningur / *Till*
- C — Vatnahjallar / *Terrace*
- F — Úrkast úr sprengigígum / *Hydrovolcanic debris*
- Gjall og kleprar / *Pyroclastics*

Nútímahraun < 11.000 ára / *Postglacial lavas < 11.000 years*

Síðara gosskeið / chron 2900 ára / *Second eruptive stage 2900 y 0 present*

Söguleg hraun / chron / *Post settlement*

- te — Kröflueldahraun 1975-1984 / *Lava of Krafla fires*
- mve — Mývatnseldahraun 1727 - 1729 / *Lava of Mývatn fires*
- dle — Daleldahraun ~900 ára / *Lava of Dal fires ~900 AD*
- hle — Hólseldahraun ~ 2200 - 2500 ára / *Lava of Hólseldar ~ 2200 - 2500 years*
- hve — Hverfellseldahraun ~2800 - 2900 ára / *Lava of Hverfell fires ~2800 - 2900 AD*
- bfh — Búrfellshraun ~ 3200 ára / *Búrfell lava ~ 3200 years*
- hse — Hvannstóðseldahraun ~ 5000 ára / *Hvannstóð lava ~ 5000 years*

Fyrra gosskeið / chron 11.000 0 8000 ára / *First eruptive stage 11.000 0 8000 years*

- ghr — Grímsstaðahraun / *Grímsstaðir lava*
- fbh — Fjárborgahraun / *Fjárborgir lava*
- llh — Litla-Leirhnjúkshraun / *Lava of Litli-Leirhnjúkur*
- khh — Kröfluhálshraun / *Lava of Kröfluháls*
- khl — Hraunlap á austursvæði / *Ultrathin lava sheet of eastern Krafla area*
- gsh — Grunnaskurðshraun / *Lava of Grunniskurður*
- bon — Bóndhólshraun 5000 - 5.500 ára / *Lava of Bóndhóll*

Gosmyndanir frá síðjökultíma / *Finiglacial lava and hyaloclastite*

- kbh — Kleprahraun / *Spatter lava*
- kbh — Kleprabrynjur / *Welded spatter*
- ath — Andesíthraun / *Andesite lava*
- atm — Andesítmóberg / *Andesitic hyaloclastite*
- grh — Hraun norðan Graddabungu / *Lava north of Graddabunga*
- grm — Móbergstúff sunnan Graddabungu / *Hyaloclastite tuff south of Graddabunga*
- Hraunjaðar / Lava margin
- Hrauntraðir / Lava channel
- Hraun undir seti / Covered lava
- Öskjurimi / Caldera fracture

Gosmyndanir fra síðasta jökulskeiði / *Weichselian volcanic succession*

- bkm — Móberg á bogsprungukerfi / *Hyaloclastite of arcuate system*
- hrr — Líparíthryggir / *Intracaldera rhyolite*
- mbm4 — Móbergshryggir og bólstraberg í miðrein / *Hyaloclastite and pillow lava of median zone*
- mbm3 — Móbergshryggir og bólstraberg í miðrein / *Hyaloclastite and pillow lava of median zone*
- mbm2 — Móbergshryggir og bólstraberg í miðrein / *Hyaloclastite and pillow lava of median zone*
- mbm1 — Móbergshryggir og bólstraberg í miðrein / *Hyaloclastite and pillow lava of median zone*
- vhm — Móbergshryggir á vestursvæði / *Hyaloclastite of western area*
- sb — Sandabotnafjall, móbergstúff / *Tuff*
- sb — Sandabotnafjall, hraunlög, skálaga móberg / *Lava, foresets*
- ige — Grágrýti / *Interstadial lavas*
- gfh — Gæsafjöll, hraunlög, skálaga móberg / *Lava, foresets*
- ahm — Móbergshryggir á austursvæði / *Hyaloclastite of eastern area*
- hli — Hlíðarfjall, líparítgúll / *Extracaldera rhyolite*
- kr — Krafla, túff / *Krafla, tuff*
- kr — Krafla, hraunlög / *Krafla, lava cover*
- kr — Krafla, móberg / *Krafla, hyaloclastite*

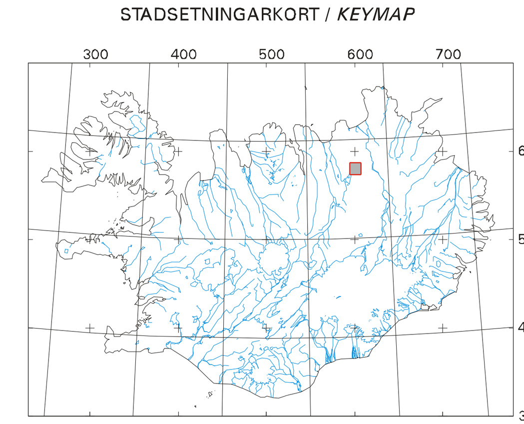
Gosmyndanir fra síðasta hlýskeiði / *Eemian volcanic succession*

- igh — Grágrýti (yngra) / *Interglacial lava*
- igh — Grágrýti (eldra) / *Interglacial lava*
- hrg — Halarauður, gjóskuberg / *Welded airfall tuff*

Gosmyndanir eldri en Eem / *Pre Eemian volcanic succession*

- hlr — Elsta líparít / *Oldest rhyolite*
- bhd — Basalthraunlög, dalfyllur / *Lavas, valley fills*
- hát — Móberg sunnan í Högöngum / *Hyaloclastite of southern Hágöng*
- hhr — Hraunlög í hlíðum Kröflueldstöðvar / *Lavas of shield building stage*
- Gígar frá Nútíma / Postglacial craters
- Sprengigígur frá Nútíma / Postglacial explosion crater
- Sprengigígur frá ísöld / Pleistocene explosion crater
- Gígrimi frá ísöld / Pleistocene crater rim
- Misgengi og gjár / Faults and fissures
- Jaðarsprungur höggunar í Kröflueldum / Boundary faults of Krafla fires
- Fallgígur / Pit crater
- Gangur / Dyke
- Gígar frá nóvember 1981 / Craters from november 1981
- Gígar frá september 1984 / Craters from september 1984

STADSETNINGARKORT / *KEYMAP*



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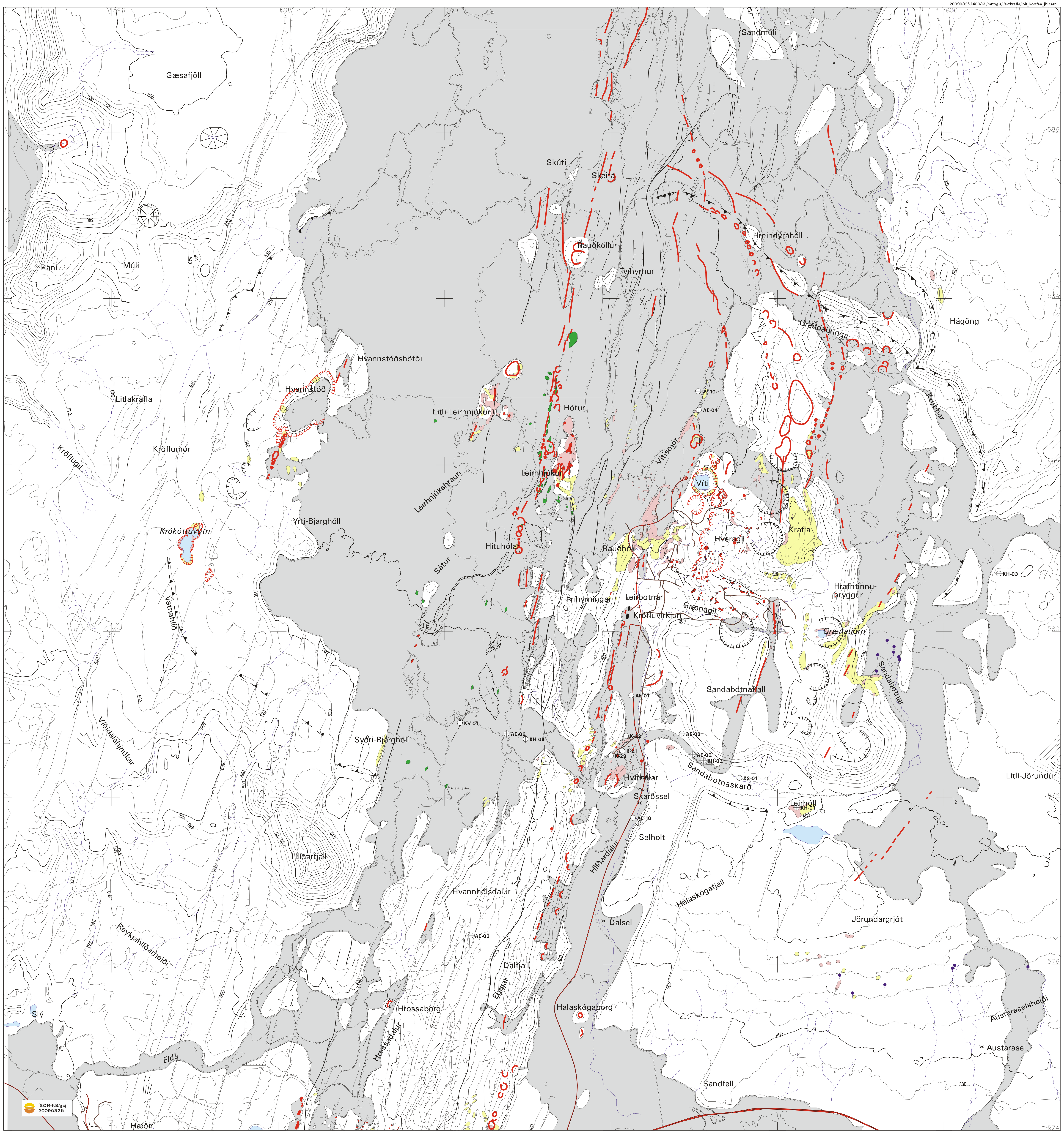
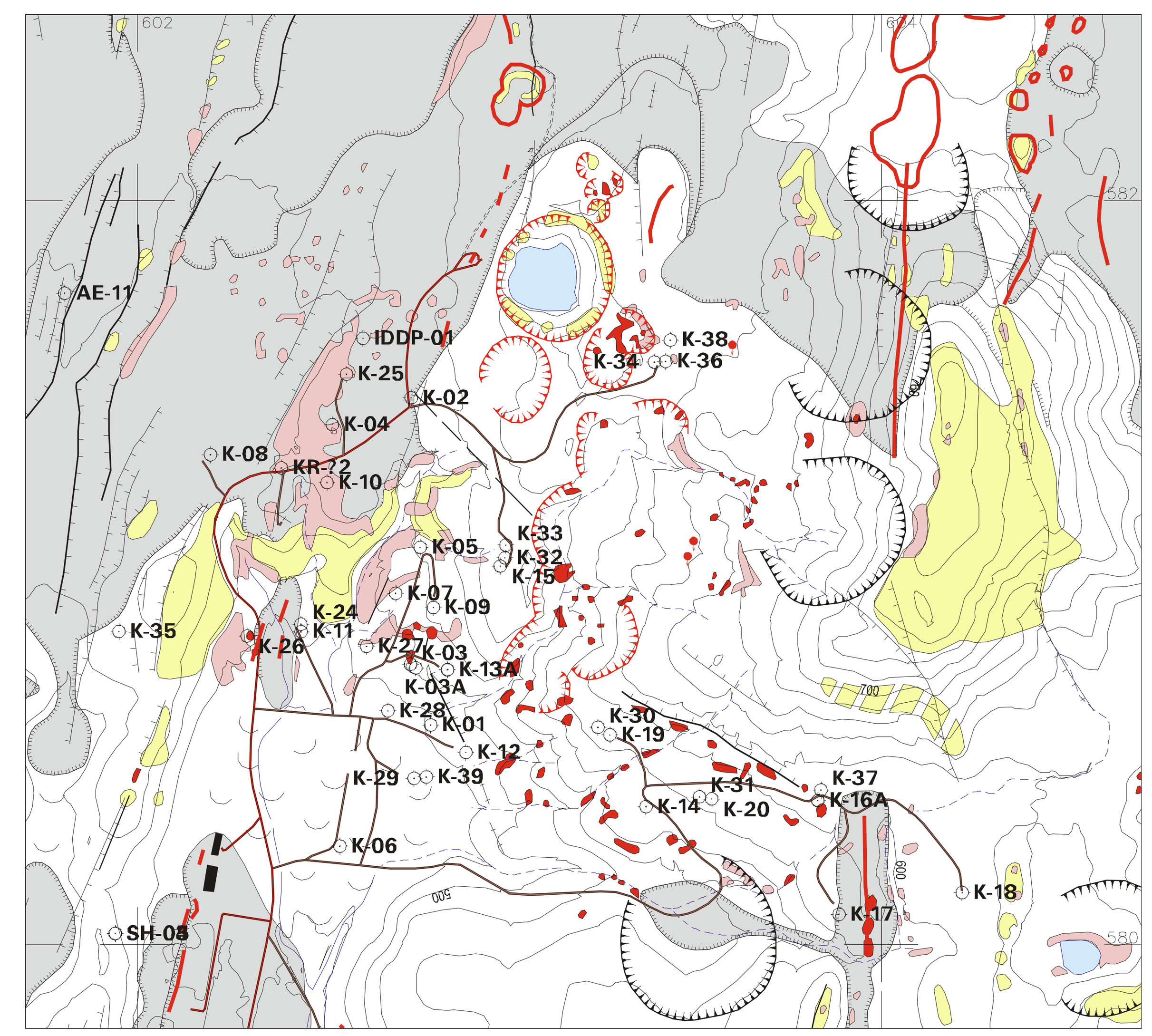
KRAFLA

JARÐHITAKORT / GEOTHERMAL MAP





SKÝRINGAR / *LEGEND*

Nútímahraun
Postglacial lava

Heit jörð, mikil ummyndun
Hot ground, clayey alteration

Væg ummyndun
Slight alteration

Nýjar gufur í Kröflueldum
Steam emanations related to Krafla fires

Hverir
Fumarole, mud pool

Lind
Cold spring

Laug
Warm spring

Hraunjaðar
Lava margin

Hrauntraðir
Lava channel

Hraun undir seti
Covered lava

Öskjurimi
Caldera fracture

Gígar frá Nútíma
Postglacial craters

Sprengigígur frá Nútíma
Postglacial explosion crater

Sprengigígur frá ísöld
Pleistocene explosion crater

Gígrimi frá ísöld
Pleistocene crater rim

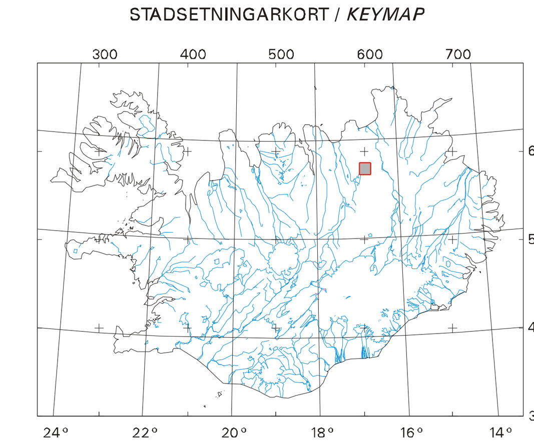
Misgengi og gjár
Faults and fissures

Jaðarsprungur höggunar í Kröflueldum
Boundary faults of Krafla fires

Fallgígur
Pit crater

Gangur
Dyke

STAÐSETNINGARKORT / *KEYMAP*



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