PROCEEDINGS, Twenty-fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

TEMPERATURE DISTRIBUTION AND CONCEPTUAL RESERVOIR MODEL FOR GEOTHERMAL FIELDS IN AND AROUND THE CITY OF REYKJAVÍK, ICELAND

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ABSTRACT

A 70-year history of continuous hot water production from low temperature fields within and around the city of Reykjavík, has resulted in a vast database of downhole temperature data. Systematic analysis of this database, containing around 200 deep wells which yield 30-50 million tons of hot water annually, provides valuable information on the subsurface temperature distribution in an area covering some 500 km^2. A dominant feature is vertical fracture permeability and fluid convection, where the fracture strike is between N and NE. The fracturing is associated with an active fissure swarm of the Krýsuvík volcanic center in the south. Temperatures of the fracture systems range 20ºC to 140ºC, depending on recharge mechanism and length/depth of the convection cells. The same fracture system may thus have two separate inflows, consisting of a hot recharge, coming from the north and rising to shallow depths, and deep and cold underlying recharge coming from the south. Hot springs are commonly found on surface above such mixing areas. It appears that maximum depth of vertical convection cells increases with distance from the mountain Esja, from 600 to more than 2500 m. Two of the fractured geothermal reservoir systems extend laterally over 15-20 km distance.

INTRODUCTION

The city of Reykjavik has a long and successful history of geothermal utilization. Drilling operations were initiated in 1928, and two years later the Reykjavik District Heating Company was established (now Orkuveita Reykjavíkur). At present all houses within and around the city of Reykjavík are geothermally heated, mostly with direct pumping of 80 to 130°C water from deep wells. The annual production in 1998 cumulated to 50 million cubic meters, which, assuming discharge water temperature of 40°C, is equivalent to 330 MW thermal. Maximum generating capacity of the low temperature resources presently utilized is estimated 490 MW_t. In addition, Orkuveita Reykjavíkur operates the Nesjavellir high temperature, co-generation power plant. Its production is at present 60 MW_e and 150 MW_t (Gunnarsson et al., 1992).

As a part of a reservoir management strategy, Orkuveita Reykjavíkur contracted Orkustofnun in 1992 to carry out a detailed analysis of formation temperatures in all wells within and around the city limits. Based on this analysis a conceptual model of the geothermal reservoirs involved should be defined. The project work was carried out in several phases and intermediate reports submitted during the process (Grímur Björnsson and Benedikt Steingrímsson, 1995). A final report is now in publication and the present paper is a summary thereof (Grímur Björnsson et al., 1999).

In the following, the database behind the study is introduced briefly. Formation temperature profiles in the productive reservoirs are shown and discussed in terms of heat transport mechanisms. Temperature distributions at few depths and in cross sections are presented. Special attention is drawn to vertical fluid convection in fractures and possible correlation to the vertical stress. Finally, a conceptual reservoir model is put forward for the whole Reykjavík area.

We feel that the study material may be of interest to the international geothermal community, due to the large volume of data available and due to the strong influence of fracture flow observed. The numerous publications used for the study are mostly published in our less than easily learned Icelandic. These are therefore not cited in the reference list unless an English abstract is available.

Figure 1 shows the area covered, location of wells and temperature cross sections. Two geothermal fields are within the city limits of Reykjavik, Laugarnes and Elliðaár and one, the Reykir system, is located to the NE of Reykjavik. These fields are operated by Orkuveita Reykjavíkur. Also in production is the Seltjarnarnes field, operated by the local community.

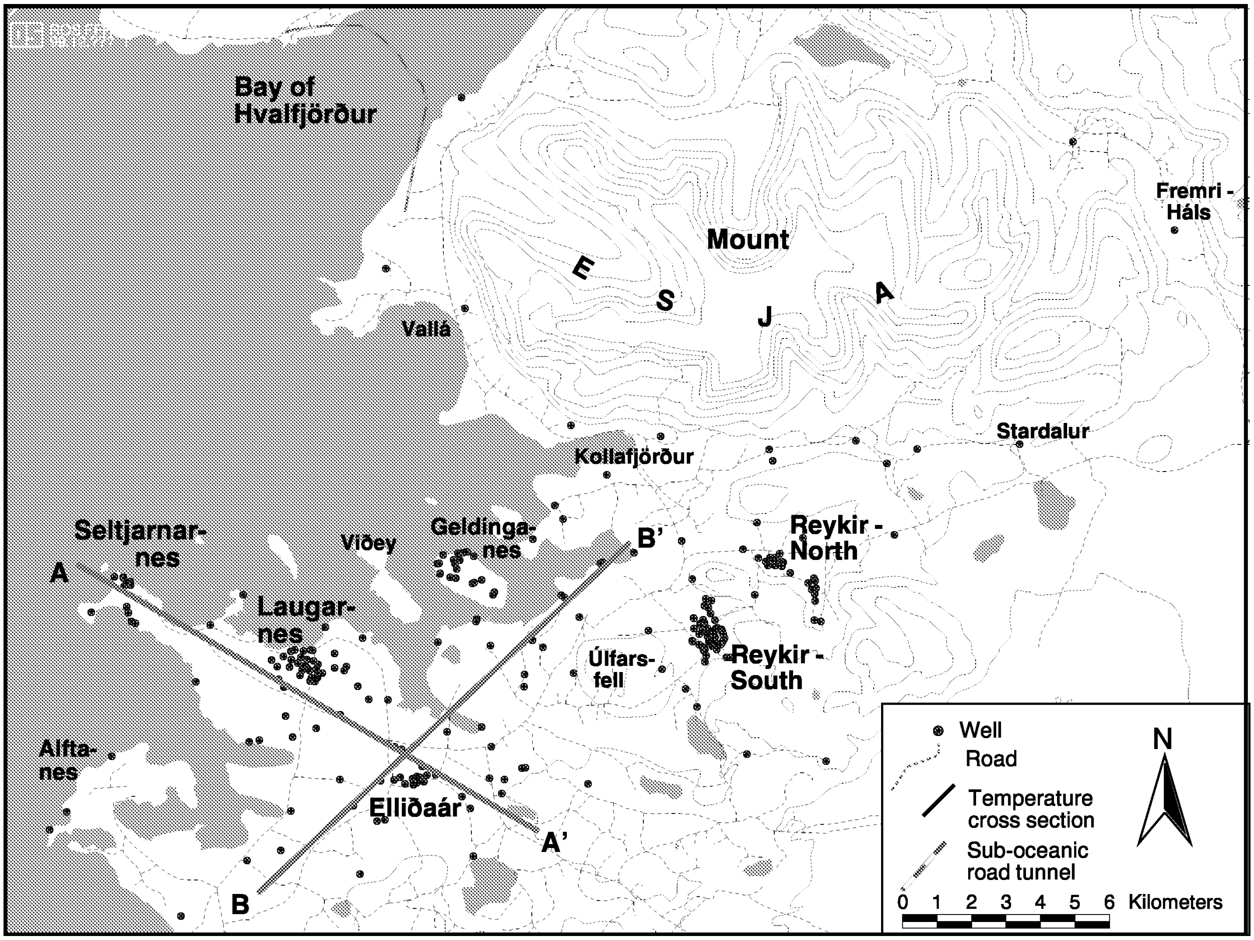

Figure 1: Location of wells and geothermal fields in and around the city of Reykjavik. Also shown is the location of temperature cross sections. Elevation contours are 100 meters apart.

DATA SOURCES AND PROCESSING

In the present study, around 1500 downhole temperature profiles in some 200 geothermal wells are considered. These data are stored and can be easily retrieved from an Oracle relational database of Orkustofnun. The oldest measurements were collected in 1929 and the most recent one in December 1999. The 200 wells analyzed cumulate to 200 km of drilled distance and the sum of all the temperature logs amounts to approximately 1500 km. This means that the average well has only been logged 7 to 8 times, mostly in connection with drilling operations. Later in the history of an average well, submersible pump have been installed and operated without interruption for tens of years, underlining the quality of the produced fluid and reliability of the resource. This means that stable well temperatures are exceptional at the time of measurement.

In addition to the downhole logs, drilling reports and production histories of most wells were available for the study. Precise geographical coordinates for most of the wells had, or were, specially measured. Several maps belonging to the ArcInfo geographical information system of Orkustofnun and the city of Reykjavík proved to be of value, such as location of hot springs, houses and roads.

It would be a topic for a special report to describe the techniques applied in analyzing the temperature profiles collected in a well, and how they resulted in a formation temperature profile. In short, we based the work on drawing several plots of all available logs in a well with different depth and temperature scales. A special effort was made in studying bottom hole temperatures, collected during drilling interruptions, and inflow temperatures at feedzones. Temperature gradients in well sections dominated by internal flow were checked for indicators of stable, rising or reversed formation temperature in that same interval. Temperature data from two or more adjacent wells were in few cases combined to obtain a single formation temperature profile. Finally the temperature of produced fluids were compared with feedzone depths to double-check the suggested formation temperature. At completion, all the formation temperature profiles were stored in our database and accessed from there when drawing temperature maps or cross sections. Such a database turned out to be essential in our work and is strongly recommended.

Note that the authors are all trained well loggers and rely extensively on temperature data in their daily work. This experience has developed into a “feeling” for this reservoir parameter, a feeling which often proved essential when minimal or only badly disturbed downhole data were available for a well.

VERTICAL TEMPERATURE DISTRIBUTION

Figures 2, 3 and 4 show formation temperature profiles within the Laugarnes, Elliðaár and Seltjarnarnes fields. In the former two fields, vertical convection is the dominant way of heat transport, whereas in the Seltjarnarnes field conductive heat flow appears significant. All the reservoirs are characterized by very high temperature gradients in the uppermost 500 m, a common value is 200 to 450 °C/km. This may indicate the existence of a caprock.

In the Laugarnes reservoir, a 120 to 140°C convection cell resides in the depth interval of 500 to 2200 m (Figure 2). At greater depths the temperature profiles become of the gradient type again (40°C/km) although this value is substantially lower than the regional 80-100 °C/km (Flóvenz and Sæmundsson, 1993). The change in slope at 2200 m in the deepest well is taken as the lower end of the convective geothermal system. The system’s production capacity is estimated as 280 kg/s of 128°C mean fluid temperature.

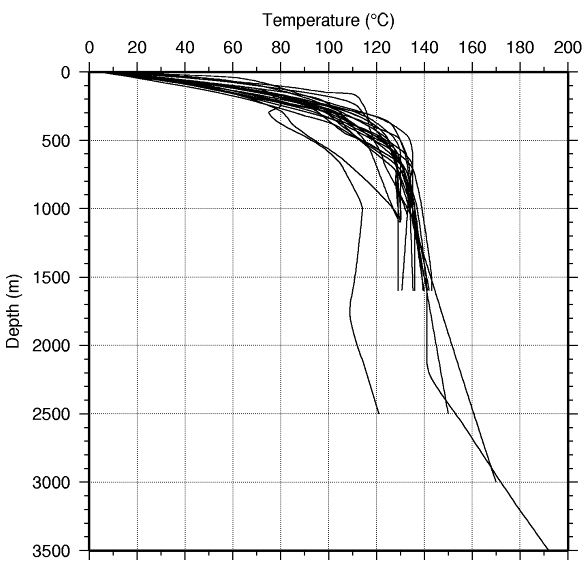

Figure 2: Formation temperature profiles for deeper wells of the Laugarnes system.

The Elliðaár system is characterized by reversed temperatures at depths greater than 1000 m. The 90 to 110°C reservoir temperature is considerable lower than in the Laugarnes field. This system is hosted by a fracture system of both hot and cold recharge, as will be discussed in later sections. Very similar shape and value of the formation temperature is found in the Reykir systems, indicating that these two reservoirs are of similar nature. Their production capacity is, however, quite different or 220 kg/s at 89ºC in Elliðaár and around 1550 kg/s at 87°C for the Reykir systems. Note that the formation temperature is convection shape beyond the depth of 2500 m, which is few hundred of meters deeper than observed in Laugarnes.

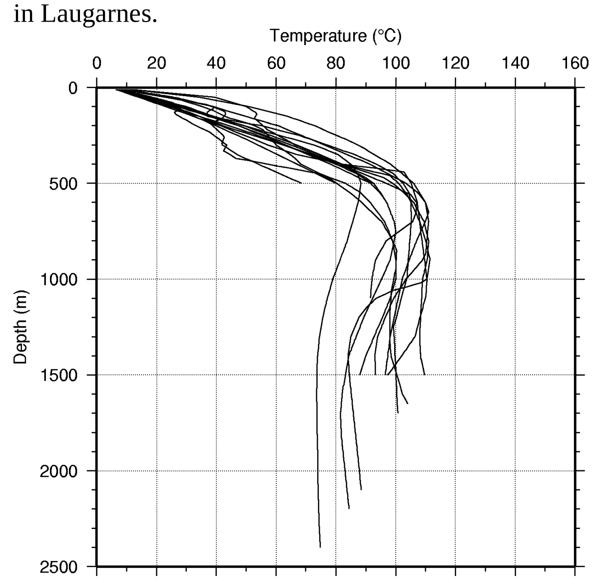

Figure 3: Formation temperature profiles for wells in the Elliðaár field.

Formation temperature profiles of wells in the Seltjarnarnes field are shown on Figure 4. The steep, cap rock like temperature gradient in the uppermost 300 meters, is followed by a 30°C/km gradient, much lower than the regional 80-100°C/km. Convective and conductive heat flow processes may therefore be equally important. Several wells have been stimulated successfully in Seltjarnarnes to obtain the present production capacity of at least 50 l/s, in contrary to what might be expected from the gradient looking temperature profiles (Tulinius et.al. 1996). Vertical fracture permeability is most likely less developed here than in the Laugarnes and Elliðaár fields. Orientation and strength of principal rock stresses are, fortunately, optimal to hydrofracture permeable paths from new wells to this semi passive fracture network.

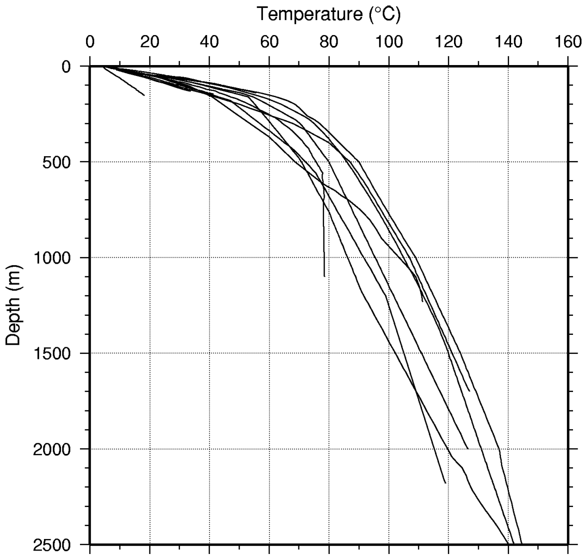

Figure 4: Formation temperature profiles in the Seltjarnarnes geothermal field.

TEMPERATURE DISTRIBUTION AT 200 M

Figure 5 presents a map of temperature distribution at 200 meters under sea level (200 m b.s.l.). It covers the two production fields in Laugarnes and Elliðaár, which are located inside the city limits. The temperature distribution is dominated by vertical discharge of water to the hot springs that were active before pumping was initiated in 1965. Also noticeable is the elongated shape of the Elliðaár anomaly, suggesting vertical fracture permeability. This feature is not as clear in the case of the Laugarnes system, where the upflow looks more of a point source type. A set of parallel fractures might explain the shape of the temperature anomaly, as suggested by bold lines on the figure.

Of particular interest is a NNE striking, colder structure, which separates the two geothermal fields. The shape of the temperature contours also suggests fracture permeability, but this time dominated by cold water recharge. The recharge then comes from south, where an active fissure swarm of the Krýsuvík volcanic center is encountered. It is presumed responsible for the temperature reversal in the Elliðaár and the Reykir fields and may, furthermore, contribute substantially to the present production rates.

The third, fracture dominated upflow zone is found in Geldinganes, shown at the top of Figure 5. No hot springs are visible in this location, the field was actually discovered during an exploration project which consisted of drilling shallow, thermal gradient wells. A 1300 m deep well has proved the existence of a 100-110°C temperature convective system. Note that the cold structure between the Laugarnes and the Elliðaár fields, and the Geldinganes upflow zone, may share the same fracture system.

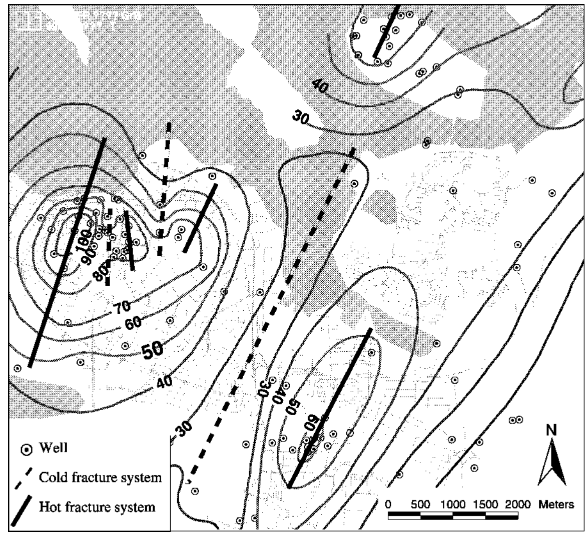

Figure 5: Temperature distribution at 200 m b.s.l. Contours are at 10°C intervals. Temperature anomalies refer to Laugarnes (center left), Elliðaár (center right) and Geldinganes (top) geothermal systems (see Figure 1).

TEMPERATURE DISTRIBUTION AT 500 M

Figure 6 shows temperature distribution at 500 m depth below sea level. Dominant thermal anomalies are, like in Figure 5, associated with hot water upflow zones of the respective geothermal reservoirs. Another striking feature is the less than 20°C volume to the south, where the Krýsuvík fissure swarm is encountered. This groundwater system is considered important pressure support for the present low temperature resources, given that production takes place at sufficient distance from it to both heat up the cold inflow and make it chemically stable. There are few cases of wells in Elliðaár and in Reykir-South where cold and oxygen rich fluid entered wells. These wells have either been cemented or re-cased by now.

The nature of the hot recharge, which feed some of the reservoirs from the north, has also been clarified in this and previous studies. As an example, production from the Reykir systems results in water level fluctuations in a well at Fremri-Háls, some 15-20 km to the NE (Figure 1). The flow channel involved was later confirmed by a new well half way between Fremri-Háls and Reykir-North. A flow channel of a similar length scale is proposed between the Laugarnes field, in the south, and Vallá and the Bay of Hvalfjörður road tunnel, in the North (Figure 1). This 20 km long connection takes support from high temperatures measured in the Laugarnes system and in a well near Vallá. High thermal gradients and permeable fractures, encountered during the tunnel construction, are also strong indicators for this hypothesis. Of the three fractures intersected in the tunnel, the outer two are hot and fresh (>60°C) whereas the center one has cooled recently to 35°C and is saline. We suggest that the Laugarnes and the tunnel hydrothermal systems are of the same root. Pumping from the Laugarnes system has led to pressure drawdown after 1970 and a reversed flow direction in the vertical tunnel fracture, which formerly served as a supply channel to a sub oceanic hot spring area in Hvalfjörður.

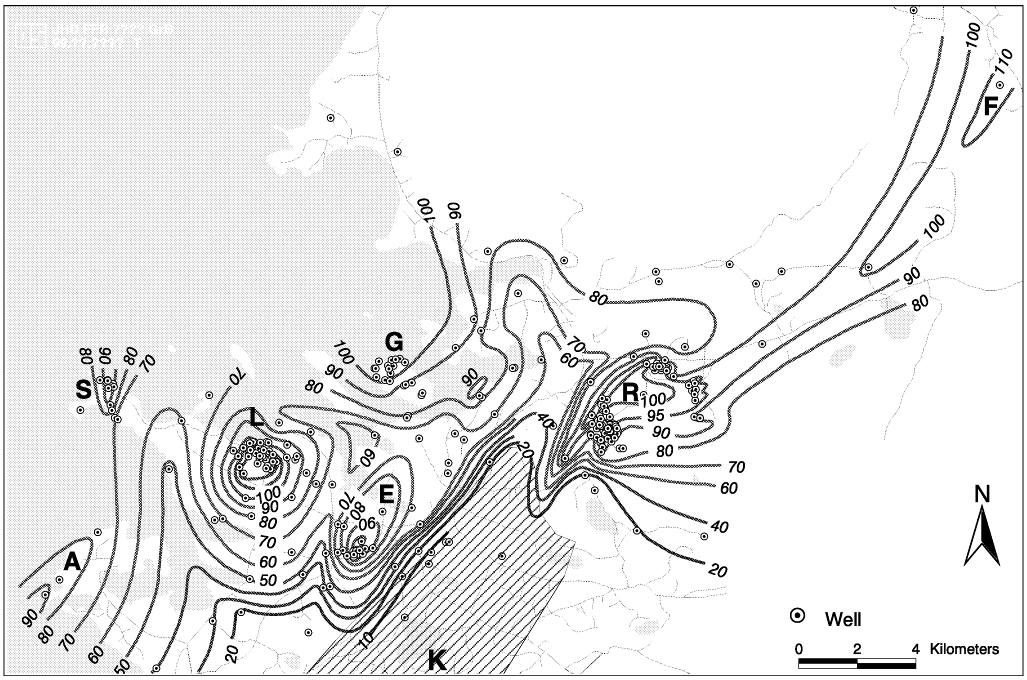

Figure 6: Temperature distribution at 500 m b.s.l.. Contours are in °C. Capital letters refer to A: Álftanes, S: Seltjarnarnes, L: Laugarnes, E: Elliðaár, G: Geldinganes, R: Reykir and F: Fremri-Háls geothermal systems. The northern end of the Krýsuvík fissure swarm is shown shaded and marked with the letter K.

Also to mention is a local temperature anomaly at Álftanes, in the SW corner of Figure 5. It suggests a classical, low temperature geothermal system, hosted in a fracture system. This system still has to be explored be deep drilling.

TEMPERATURE CROSS SECTIONS

Figure 7 and 8 present two temperature cross sections in the Reykjavík area. Their location is shown on Figure 1. Some interesting features can be seen here. As an example, Figure 7 shows that the Laugarnes system is much hotter at depth than the Seltjarnarnes and the Elliðaár systems. Another striking feature is the cold fissure swarm of the Krýsuvík volcanic center in the east and it's influence on deep temperatures in the Elliðaár system. Also worth noting is the temperature distribution between Seltjarnarnes and the Laugarnes fields. Here we assume rather low temperature, actually much lower than might be expected from the regional 80-100°C/km regional temperature gradient. This volume may be considerable hotter at depths >1 km than shown on Figure 7, due to low degree of fracturing and minor vertical fluid convection.

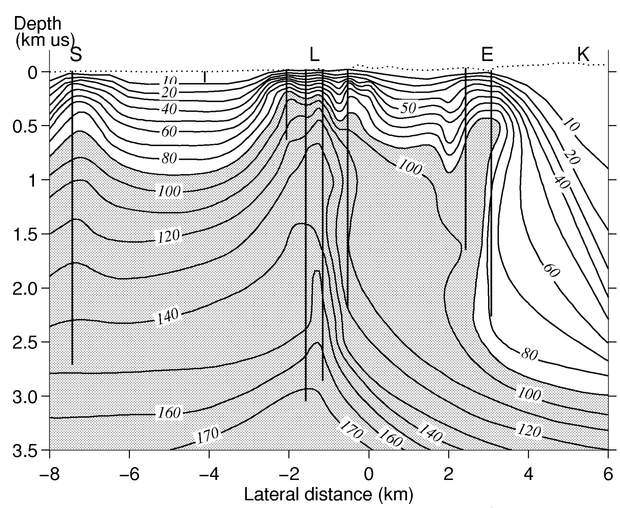

Figure 7: Temperature cross section A-A', from East to West. Contours in °C. Capital letters refer to S: Seltjarnarnes, L: Laugarnes and E: Elliðaár geothermal systems. K is the Krýsuvík fissure swarm. See Figure 1 for location.

The temperature cross section in Figure 8 shows clearly how the interaction of opposite cold and hot recharge zones characterize the Elliðaár geothermal system. The Elliðaár wells are most likely drilled peripheral to the main inflow zone, which might reach temperatures above 120°C. This hot fluid rises by density effects to surface, while the more dens and cooler recharge in the south, creeps in under this hot recharge and mixing occurs.

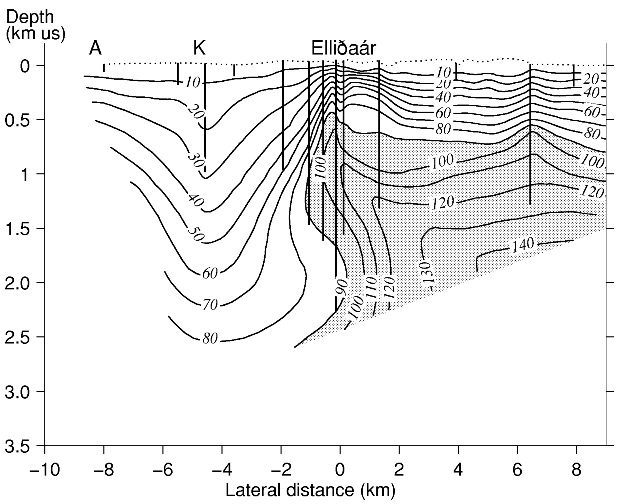

Figure 8: Temperature cross section B-B’, across the Elliðaár system, from South to North. Contours in °C. Letter A refers to the Álftanes geothermal system and K to the Krýsuvík fissure swarm. See Figure 1 for locatoin

Note that the Krýsuvík fissure swarm may have reached temperatures suitable for space heating at depths greater than 2 km, according to the cross section on Figure 8. Such reservoir volumes may thus become a valuable reserve in the future despite their “cold” looking character at shallow depths. Very little is known presently about temperature and pressure conditions in the massive fissure swarms which intersect volcanic centers in Iceland, except at the centers themselves. A growing interest in now to learn more about their potential. One of the main reasons is that environmental impact is considered low in such areas compared to what happens when drilling and production takes place at the often naturally unique volcanic centers.

VERTICAL HEAT TRANSFER AND THE LITHOLOGICAL STRESS

In Figure 9 several formation temperature profiles have been drawn to demonstrate effectiveness of vertical heat transfer in the fractured, geothermal systems in Reykjavík and vicinity. Areas of temperature higher or lower than the regional 80-100°C/km thermal gradient are shaded. Temperature profiles, drawn inside the region of temperature above the regional gradient, thus represent depths to which heat has been transmitted by convection. Similarly, when the well temperature is lower than the normal gradient, heat mining by colder fluid may have, or is, taking place.

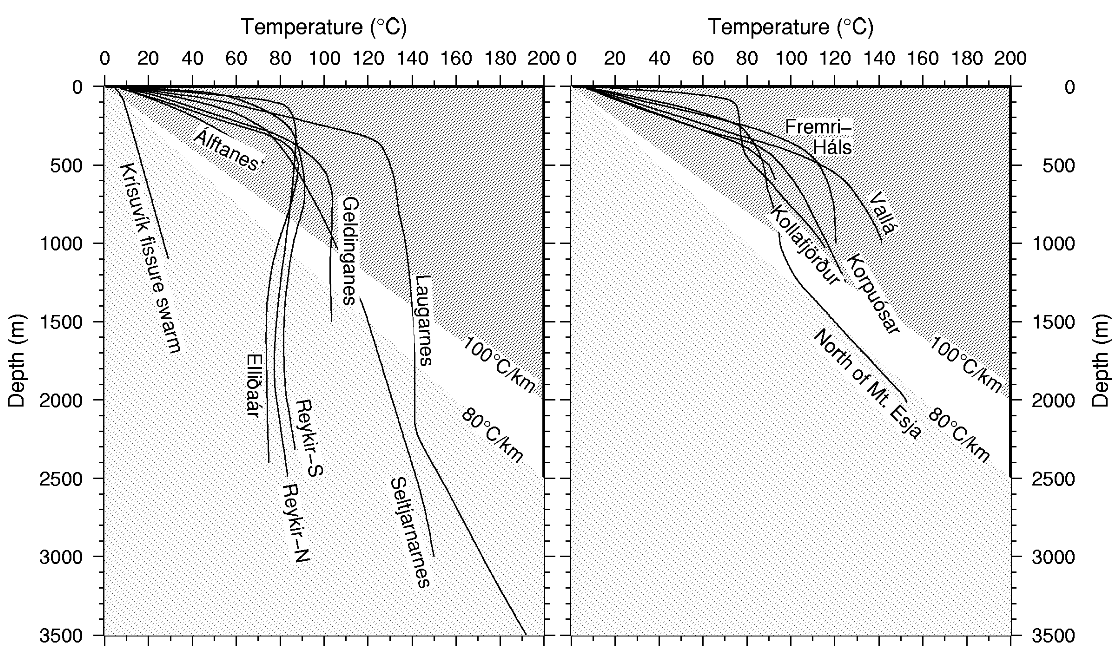

Figure 9: Formation temperatures in selected wells in and around Reykjavik. Left hand side of the figure presents wells drilled in the lowlands south of Mt. Esja, but wells on the right hand side are drilled near the mountain. Lighter shading denotes temperatures lower than to be expected from the regional gradient and the darker shading the opposite.

It is evident from Figure 9 that considerable mining of heat has taken place deep under the excellent production field at Reykir, and also in Elliðaár. Vertical transfer of heat from the roots of the Seltjarnarnes and Laugarnes fields is also observed, but not on the same scale as in the former two fields. As stated earlier, the deep temperatures of Reykir and Elliðaár are close to what could be expected from wells drilled into the cold Krýsuvík fissure swarm. Depending on the depth scale, the same system can thus be considered both abnormally hot or cold.

Also of interest is a changed character of the formation temperature profiles as we approach the slopes of the 900 m high Mt. Esja, north of Reykjavík (Figure 1). Here, well temperatures are all above the regional gradient. Vertical convection cells are observed by two wells, at Kollafjörður in the south, and in Hvammsvík, north of Mt. Esja. The maximum depth of convection is only around 600 m in Kollafjörður and 1300 m in Hvammsvík, compared to more than 2500 m in Reykjavík and at Reykir. This may suggest that lithological stress plays a role in the fracture permeability, and that the weight of Mt. Esja limits the maximum depth of vertical convection in fractures compared to wells in the south.

A CONCEPTUAL RESERVOIR MODEL AND CONCLUSIONS

The conceptual reservoir model which applies to most of the geothermal systems in the Reykjavík area can been explained as follows, making frequent reference to Figures 5 and 9:

- Fracturing, in connection with the fissure swarm of the Krýsuvík volcanic center, plays a major role for subsurface fluid flow. The fractures strike between N and NE and are near vertical.
- Geothermal systems reside within systems of vertical fractures. Formation temperature is dominated by conduction in the uppermost 500 m, reflecting caprock conditions in that depth interval. This zone is followed by 1-2 km thick interval, where temperature is steady or semi steady, suggesting rapid vertical convection.
- Temperature of these convection cells ranges from 80 to 140°C. Most of them appear in temperature contour maps as ellipsoids, striking N-NE, with characteristic lengths in the order of 5 to 20 km. The longest systems, in temperature and pressure interference range, also have the highest production capacity.
- Cold groundwater systems to the south serve as important pressure support for the geothermal reservoirs in Elliðaár and at Reykir. Fluid is recharged at depth to these systems, resulting in reversed formation temperature profiles.
- In addition to the cold recharge, a hot recharge zone is identified for the Laugarnes, Elliðaár and the Reykir systems. This recharge flows either laterally or diagonally upward, and finally towards the surface.
- Hot spring areas are found above reservoir volumes where mixing of the southerly cold water and northerly hot water takes place. Fluid density may play an important role.
- Local convection of heat, from depth to surface, appears to have a long history in the geothermal reservoirs. This is best seen at depths exceeding 1-2 km, where reservoir temperatures turn out to be 50 to 100°C lower than might be expected from the regional temperature gradient.
- Maximum depth of convecting zones appears to increase with distance from the 900 m high mountain Esja. In wells next to the mountain, convection cells reach down to 1200 m, where as in the south, a depth range of 2500-3000 m appears common. This may reflect the effect of lithostatic pressure on the least horizontal stress and, hence, the permeability.

ACKNOWLEGDEMENTS

The authors wish to thank Reykjavík District Heating Company for financing this work and for the permission to publish their data. We also thank Seltjarnarnes District Heating for permission to publish data from the Seltjarnarnes wells.

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