Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOTHERMAL EXPLORATION IN ARSKOGSSTROND, N-ICELAND

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Keywords: Exploration, seismicity, fracture mapping, magnetic measurements, temperature gradient.

ABSTRACT
Arskogsstrond is a small fishing society in N-Iceland, consisting of two small villages and a service centre. The distance between these places is 2-4 km. No known geothermal resource was sufficiently close to the villages to allow for the building of an economical geothermal district heating service. In 1996-97 geothermal prospecting was carried out within 5 km radius of the villages. Analysis of microseismic activity in the area and lineaments on aerial photos, led to the discovery of an active NNW trending fracture system crossing the prospect area. Furthermore, shallow geothermal gradient wells and a ground magnetic survey indicated a geothermal system, where a NNE trending dyke swarm intersects with the NNW striking fracture system. Drilling of a 430m deep well, reached a feed zone below 400m depth which yields about 40 l/s of 74°C water, suitable for direct use, with few meters drawdown and in aquifer pressure.

1. INTRODUCTION

Arskogsstrond is a small community of 300 people, at the western coast of Eyjafjordur in N-Iceland. It consists mainly of three cores of buildings, two small fishing villages and an inland located service centre. The spacing between these three cores is approximately 3 km (figure 1). The villages have been heated oil and electricity but the energy price was considerable higher than in the nearby villages which are geothermally heated. The price difference was the driving force for exploration of geothermal fields, close enough to allow construction of an economically feasible geothermal district heating service.

2. EXPLORATION

2.1 Geological settings

The Eyjafjordur area is made of sequences of tertiary flood basalts, 6-10 my. old, interbedded with thin layers of scoria and soil remainders. Around Arskogsstrond, the lava pile has a southward dip of 5-6° (Bjornsson and Saemundsson, 1975). It is intersected by dykes and normal faults, which were mainly formed by intrusions and faulting during rifting periods in nearby volcanic centres at the time of the formation of the crust.

The lava pile is relatively deeply eroded by glacial erosion, so that the bedrocks at sea level are belonging to the mesolite/scolesite alteration zone (Palmason et al. 1978), with the lamontite zone starting at a depth of approximately 500m. The primary permeability of the mesolite/scolestie zone is generally very low, and decreases with depth. Therefore, all geothermal fields occuring in such low permeability environment owe their existance to tectonically induced fracturing which creates secondary permeability.

Two highly seismically active zones are north of Arskogsstrond, the Tjornes fracture zone and the Dalvik lineament (figure 2). The Tjornes fracture zone is a WNW striking right lateral transform fault, connecting the volcanic axial rift zone in N-Iceland with the Kolbeinsey ridge, north of Iceland. The Dalvik lineament is 5-10km north of Arskogsstrond, parallel to the Tjornes fracture zone, but has not developed into a transform fault. It is seismically active, mainly on short parallel N-S striking faults (Rognvaldsson et al., 1998), which probably reflect a sort of a "bookshelf" fracturing.

Small hot springs are common in the vicinity of the villages, but none is close enough to Arskogsstrond to allow feasible harnessing. The location of the nearest hot springs is shown in figure 1.

2.2 Exploration strategy

To explore for exploitable geothermal fields close to Arskogsstrond, several different exploration methods were applied. Firstly, a map was made of possible fractures by analysing aerial photos and geological openings at the coast; secondly, the seismic activity in the area was analized in order to get information on tectonically active fractures; thirdly, shallow boreholes (50-100m deep) were drilled to look for anomalies in heat flow. Since the thermal conductivity of the lava pile in Iceland only shows very low spatial variations, it is possible to use the temperature gradient instead of the heat flow (Flovenz and Saemundsson, 1993) and omit measurements of the thermal conductivity in cores or cuttings from the boreholes.

2.3 Reconnaissance surveys

2.3.1 Seismicity

Installation of the automatically seismic SIL network was initiated in 1994 (Stefansson et al. 1993, Bodvarsson et al. 1999) following a magnitude 4 earthquake on the Dalvik lineament. One of the seismic stations is located at Arskogsstrond, yielding relatively accurate location of the hypocenters in that area. All recorded seismic events in the vicinity of the Dalvik lineament were extracted from the database of the Icelandic Meteorological Service for the period 1994 to 1996 to look for hypocentres that might be on fractures that extend to the exploration area. The resulting epicentres are marked on figure 1. They indicate a NNW-SSE lineament that also connects three known geothermal fields, in Hrisey, at Ytri-Vik and in the sea north of Arnarnes. It is therefore concluded that this lineament is an active fracture with secondary permeability that opens the way for the formation of geothermal fields.

2.3.2 Fracture analysis

Figure 3 shows an aerial photo of Arskogsstrond where lineaments from stereographic examination have been inferred. The lineaments form a complex pattern of different tectonic origin. By looking at geological exposures of some of the lineaments the following main trends are observed:

1. Lineaments striking N-S (+/- 10°): Common lineament in Eyjafjordur. These are mainly dykes and normal faults.
2. Lineaments striking NNE (20-30°) : These are mainly dykes which are exposed at the coast. Common dyke direction in Eyjafjordur. A low resistivity lineament at the Hrisey hot spring has this direction according to a head-on resistivity survey (Bjornsson and Flovenz, 1985).
3. Lineaments striking ENE (50-60°): These are dykes and some of them are exposed at sea level. It is a rare direction of dykes in Eyjafjordur. However, low resistivity lineament at the hot spring in Merkisvik has this direction.
4. Lineaments striking E-W (90°): Few lineaments of unknown origin observed on the southern part of the research area. Similar tectonic lineaments hardly known in Eyjafjordur.
5. Lineaments striking NNW (330-340°): Few lineaments are observed on the aerial photos. Almost the same direction as revealed by the epicentre distribution.

In order to look for surface evidence of the NNW lineament revealed by the epicentre distribution and the aerial photos we did look very carefully at all exposed rocks at the coast where this lineament is supposed to be. At the coast the island of Hrisey this lineament is seen as an open fracture without any observable movement. At the coast close to Litli Arskogssandur the lineament is found as a series of NNW fractures in the basaltic bedrock, filled with secondary minerals (figure 4). Furthermore a NNW fracture is observed in a 50 years old concrete bridge at the Hauganes village but it might rather be a sign of poor foundation of the bridge than a tectonic movement. It is interesting that the hot springs in Hrisey are close to the intersection of this NNW fracture and a low resistivity lineament striking 20-30°.

2.3.3 Temperature gradient

The temperature gradient was mapped by drilling shallow boreholes into the poorly permeable basaltic bedrock. For satisfactory determination of the temperature gradient it is necessary to drill 50-60 m into the impermeable bedrock. Since the surface is frequently covered with soil or glacial deposits the depth of the wells ranged from 50- 100m. Due to the homogeneity of the bedrock, variations in thermal conductivity can be neglected so temperature gradient can be used to represent the heat flow.

The exploration area was surveyed with 16 boreholes, with average spacing of approximately 1 km. The spacing between holes, in a temperature gradient survey in Iceland, is selected according to the size of the expected anomalies, which in most cases are of the order of 1 km^2. They are usually elongated along the strike direction of the fractures. Therefore the density of boreholes should be of the order of one hole/km^2 or less, to avoid overlook a geothermal field, due to sparse data coverage. However economical reasons sometimes prevent so high data density.

Our exploration area, which is approximately 16km^2, was covered by 1 hole/km^2. In addition to distributing the boreholes over the whole exploration area the sites of the boreholes were selected with the aid of the lineament map and with respect to the suspected NNW striking fracture.

The result of the temperature gradient reconnaissance survey showed a background value of 50 - 60°C/km but revealed in addition an area with increased heat flow and temperature gradient of more than 200°C/km. This area was over the NNW fracture at almost equal distance between the three small villages. A geothermal field in that particular area would be at the most feasible location for a production field. A further investigation was therefore carried out in that area, including a ground magnetic survey and a further temperature gradient survey by shallow exploratory wells.

2.4 Local exploration

2.4.1 Ground magnetic survey

A ground magnetic survey was carried out in the area of the anomalous high temperature gradient. The total magnetic field was measured at 5 meters intervals along parallel lines with 25 meters spacing using a proton precession magnetometer. The resulting magnetic map revealed two groups of almost N-S striking dykes, one of the group being intersected by a NNE striking dyke. No signs of the NNW striking fracture were observed. According to the local geology, the dykes can be expected to dip few degrees towards the west from vertical. Therefore in general a borehole which aims at intersecting a dyke should be sited west of the surface intersection of the dyke, the distance depending on the planned intersection depth.

2.4.2 Gradient survey

In order to map the temperature gradient anomaly in more details, its size, and strike, 13 more gradient wells were added. They revealed a geothermal gradient anomaly by the size of 250x350 meters with geothermal gradient exceeding 200°C/km and peak value of 238°C/km. The maximum values seem to be close to the intersection of the NNE striking dyke and the one of the N-S striking dyke groups. The temperature gradient survey also confirmed that the temperature gradient anomaly appears close to the intersection off the NNE dyke group and the NNW lineament as defined by the epicentres. Figure 5 shows the map of the temperature gradient anomaly together with the result from the ground magnetic survey and the approximate location of the NNW fracture.

3. DEEP DRILLING

3.1 Selection of drillsite

The above result was used in siting a deeper exploratory well. The drillsite was selected close to the maximum value of the geothermal gradient anomaly, and at the intersection between the N-S dyke group and the NNE striking dyke. (figure 5).

3.2 Result of the drilling

The drillhole, ARS-29, was 200mm wide and drilled to the depth of 440 meters. It was cased down to 191m with 200", cemented steel casing. Only small feedzones were observed until a major feedzone was observed at 428m depth. The initial pressure within the aquifer was low, the water level in open hole was at 25m depth while the well head is at 50m elevation above the sea level. During the drilling temperature logs were run during drilling stops. Figure 6 shows these temperature logs.

Analysis of drill cuttings and well logging data showed as expected typical sequences of basaltic lava flows (figure 7) with interbedded layers of scoria and sediments. In addition dykes are observed at 4 or 5 places. Two of the five small feedzones appear where the borehole enters a dyke and the big one is associated with a thin dyke. Because the borehole is located just outside the magnetic map it is not possible to correlate the dykes in the boreholes to the dykes mapped at the surface.

3.3 Well test

After the drilling was completed it was obvious that the well could provide sufficient hot water for house heating in the community of Arskogsstrond. However, the experience shows that short time flow test during or at the end of drilling operations can be misleading and give over-estimate of the capacity. Furthermore, since the initial pressure is rather low, it could indicate that the geothermal fracture system is in pressure balance with the sea level. Therefore, there could be some risk of seawater contamination of the reservoir especially after long time production and pressure drop due to pumping.

A pump was installed in the well in early January 1998 and a long time pumping test was initiated. 16-17 l/s of hot water were pumped from the well and during the first 16 days the water level fell from 24 to 26 m below the well head but the temperature of the water kept constant. Figure 8 shows the water level change on a logarithmic scale. The water level is almost constant over the first four days, but then it started to decline linearly on the logarithmic scale. By extrapolating the draw down curve, the water level can be expected to fall down to approximately 35m after 3 years of pumping at the rate of 16 l/s, provided that all limits of the geothermal system had already appeared in the data. Based on this extrapolation, it was decided to build the district heating system for the community.

3.4 Chemical composition

Sample for chemical analysis was taken after few days of the pumping test. The result is shown in table 1. The total dissolved solids are quite low, only 150ppm. The silica content is close to 100ppm and corresponds to chalcedony temperature of 70°C which is slightly lower than the measured temperature of 73,5°C, similar to the result from other geothermal systems in Eyjafjordur (Kristmannsdottir and Johnsen, 1981). Small amount of H_2S is observed which is an advantage because it eats up possible oxygen contamination and thus prevents corrosion.

4. DISTRICT HEATING

Based on the pumping test it was decided to start the design and construction of the district heating service. The material and the construction vent out for tender in May and June 1998. Construction work started in late August and was completed in late November. The district heating service was formally opened in December 1998. The highlights of the district heating system are as follows:

1. A single borehole equipped with a five step Floway downhole pump located at 43m depth which can yield 70 m^3/h . The water level was originally at 27m depth but drops by 2m at maximum pumping rate. The water is pumped directly to a storage tank.
2. A 305m^3 storage and degassing tank. The tank is designed for keeping a 10 hours of water supply for the villages, which is approximately the time it would take to replace the downhole pump in case of failure. This made it possible to postpone the drilling of a reserve well and thus save investment costs at the beginning. The waterlevel in the storage tank is kept at a constant level within the limits of 10cm. This is done by frequency regulation of the downhole pump.
3. From the storage tank there is a free flow to the villages at Litli-Arskogssandur and Hauganes, but a frequency regulated pump is used to increase the water pressure at the Arskogur service centre. The main pipeline from the storage tank to the three villages is made of pre-insulated 200mm steel pipe, DN 100, which complies to the standards ISO 9001 and EN 253. The total length of these three main pipelines is 5 km.
4. A non-return distribution network is used within the villages, which means that the return water is disposed of, at the individual houses. The water is for direct use and no heat exchangers are required.

A total of 87000 m^3 of houses are connected to the service and estimated consumption is 120000m^3 /year. Based on 71-72°C inlet temperature at the consumer side, it equals 18 TJ/year (or 5 GWh/year) in annual energy consumption. However the actual temperature from the borehole is 73°C, the energy loss in the storage tank is 0.5-1.0°C, and the inlet temperature is 67-70°C depending on the flow rate and the distance from the storage tank. The total cost of the project is approximately 1 million Euro and the energy price to the consumers is 0.015 Euro/kWh.

The district heating service was formally opened just before Christmas 1998, and all the inhabitants were invited to a formal opening session in the cultural hall of the community. The children at the primary school had decorated the building by an artistic picture of the new, and very welcome district heating service, which will improve the living conditions in the villages in future, by a surplus of convenient end environmental friendly geothermal heating at much lower cost than before. This picture is shown in figure 9.

5. SUMMARY AND CONCLUSIONS

This successful example of geothermal exploration shows how important it is to select carefully the methods used for the prospecting. We have described one of the first cases where the use of the highly sensitive seismic network in Iceland has delineated a fracture, which clearly has geothermal potential. It shows how the combined use of the seismic result, tectonic mapping, geothermal gradient observations and ground magnetic survey has led to the discovery of a productive geothermal field where no surface manifestations of geothermal activity were found.

6. ACKNOWLEDGEMENT

The authors express their gratitude to all those who contributed to the progress of this work. We would especially like to thank Wilhelm Steindorsson, civil engineer and Kristjan Snorrason, mayor of Arskogsstrond for their enthusiasm in initiating the exploration survey; the Meteorological Office in Iceland for providing the seismic data; Helga Sveinbjornsdottir for technical drawing and the children and the staff of the primary school in Arskogsstrond for allowing publication of their drawing.

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Table 1. The chemical contents of the geothermal water in well ARS-29. The units are in mg/l (ppm).

Tem.(°C)	73,5	H_2S	0,18
pH/°C	10,1/21	Cl^-	13,7
SiO_2	104,9	F	0,86
B^-	0,15	Al^{+3}	0,073
Na^+	55,4	Fe	0,003
K^+	0,9	Mn	0,003
Ca^{+2}	2,1	Total diss. solids	150
Mg^{+2}	0,01	∂D (‰ SMOW)	-109,1
CO_2	16,0	$\partial^{18}O$ (‰ SMOW)	-14,96
SO_4^{-2}	15,7	Silica temp (°C)	70

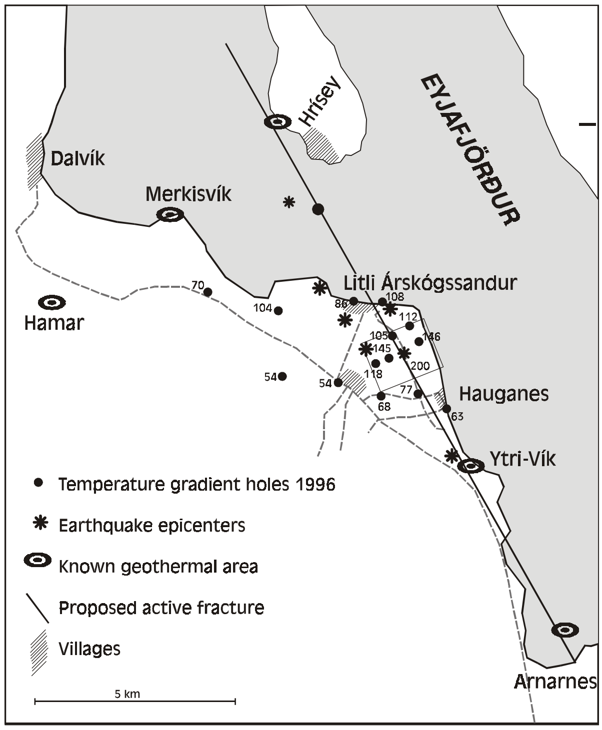

Figure 1. The figure shows the villages, the hot springs, earthquake epicentres, proposed fracture and the temperature gradient in the regional survey. The rectangle north of Hauganes shows the outline of the area in figure 5.

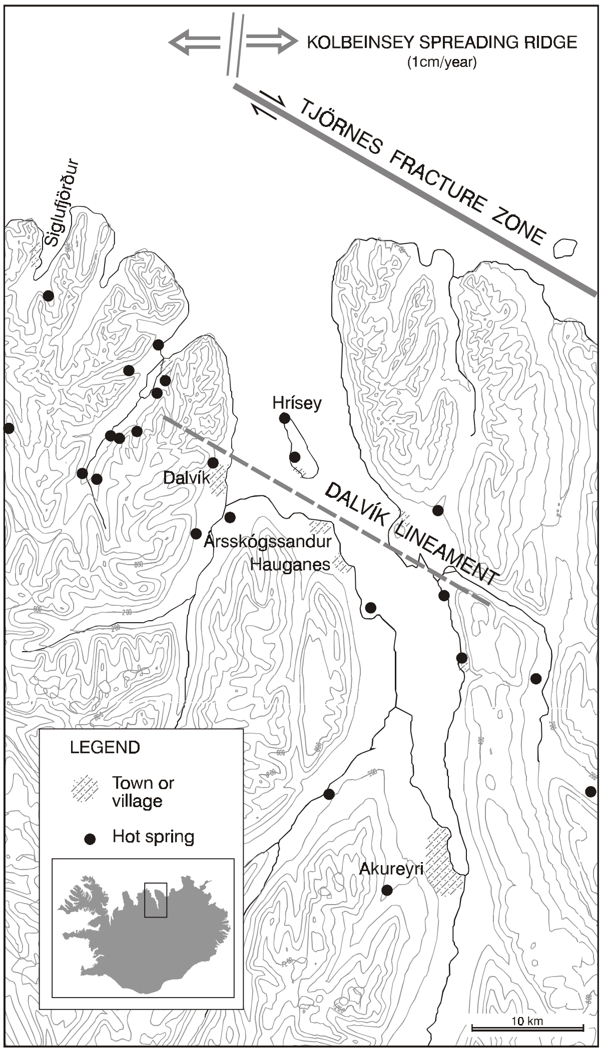

Figure 2. The figure shows hot springs in the Eyjafjordur area and the main tectonic structures.

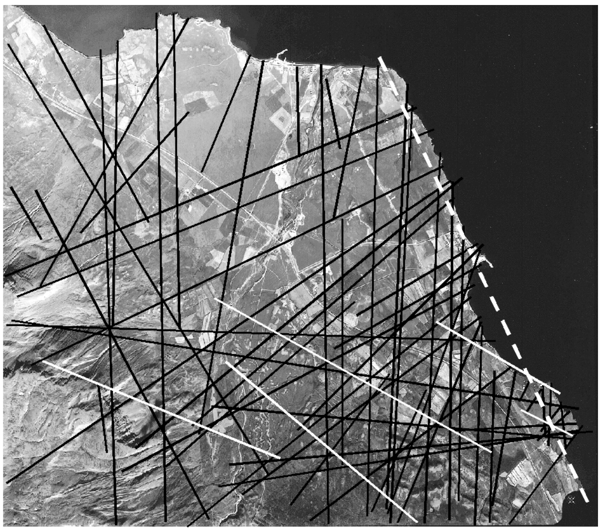

Figure 3. An aerial photograph of Arskogsstrond with the result of lineament analysis. The white stippled line is the proposed fracture from the earthquake epicentres.

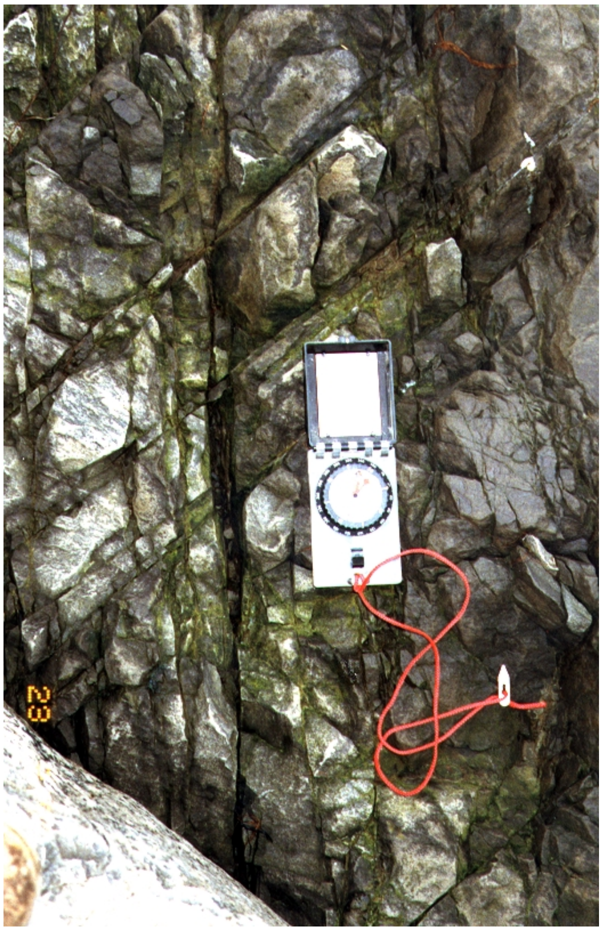

Figure 4. A close up photo of two intersecting fracture systems in bedrock, at the coast just east of Litli-Arskogssandur. The NNW striking fractureis parallel to the compass in the figure.

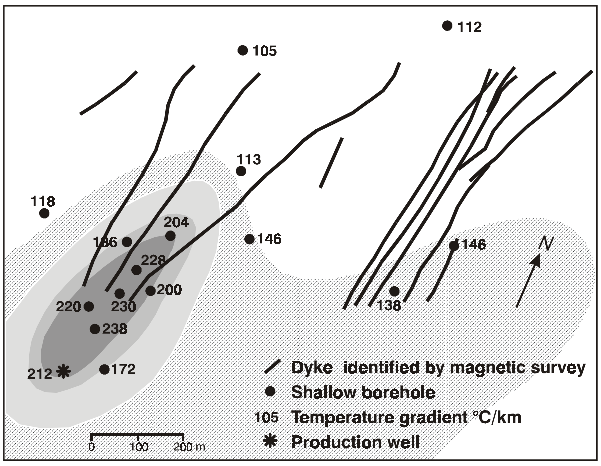

Figure 5. An area outlined in figure 1. Dykes mapped by ground magnetic surveys emplaced on a temperature gradient map. The production well ARS-29 is marked by a star. Note the two dyke swarms and that the main anomaly in the gradient is located, where three dykes are converging.

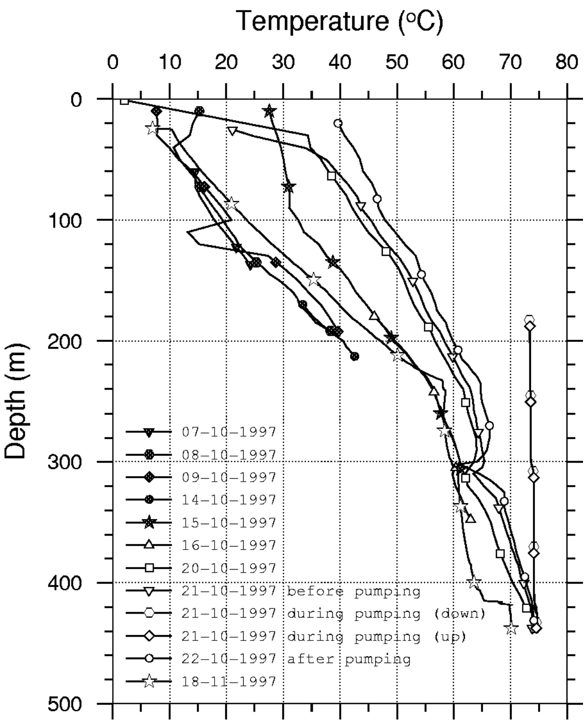

Figure 6. Temperature logs from the borehole ARS-29, measured during drilling.

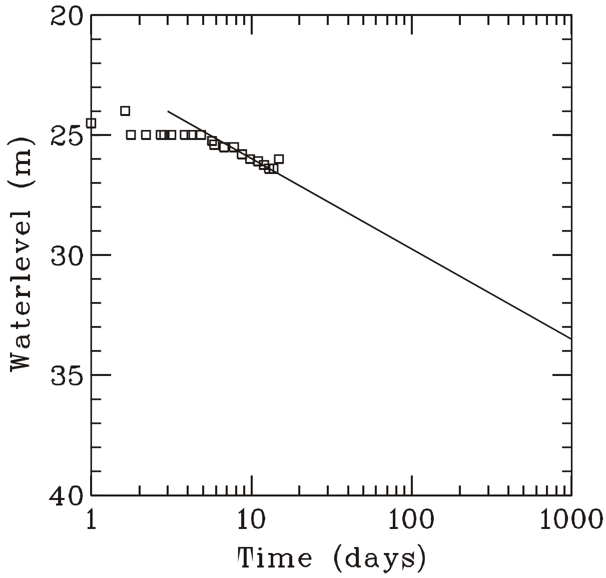

Figure 8 Waterlevel with time during the first 16 days of the pumping test. Pumping rate was 16-17 l/s.

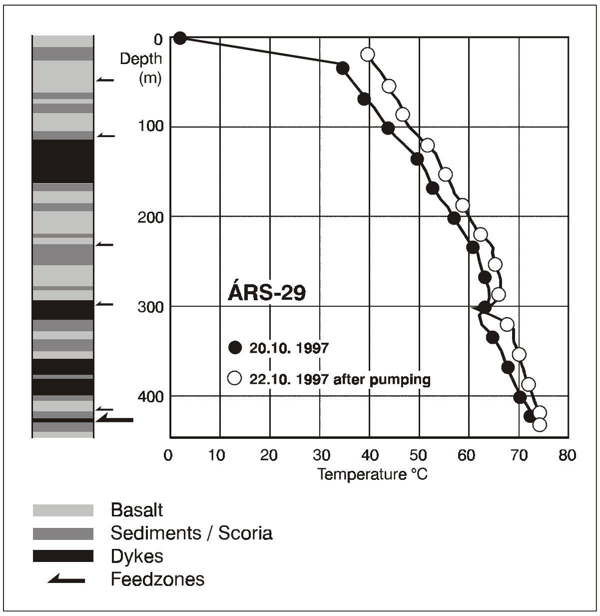

Figure 7. Simplified geological section from the borehole ARS-29 and temperature log from the well. Five small feedzones are within the well in addition to the main feedzone at 430m depth. Two of the small feedzones appear at dyke contacts but the main feedzone was reached when a thin dyke was intersected.

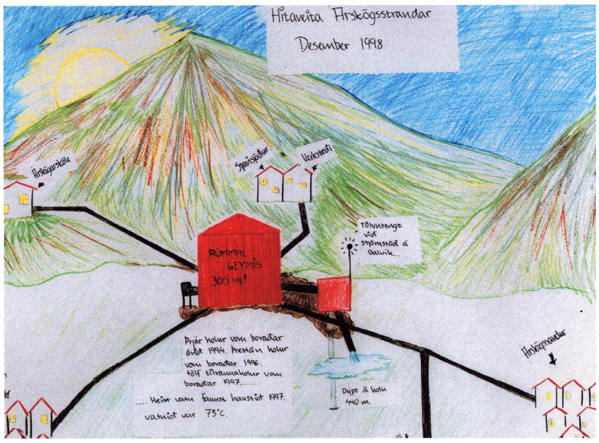

Figure 9. The sketch from the children at Arskogsstrond primary school showing a overview of the district heating survey showing the borehole, the storage tank, the pipelines and the two villages and the service centre.