SUCCESSFUL EXPLORATION OF A FRACTURE DOMINATED GEOTHERMAL SYSTEM AT THELAMÖRK, NORTH-ICELAND

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ABSTRACT

The town of Akureyri in N-Iceland has been heated by geothermal energy since 1979 which is exploited at four geothermalfields, located 2-13 km south and west from Akureyri. Due to an increasing energy demand, detailed exploration was carried out during 1983-1993 at the Thelamörk geothermal field, located 13 km north of Akureyri. The exploration involved a ground magnetic survey to map near vertical dykes, head on resistivity prof ling to map conducting vertical fractures, drilling of shallow exploration wells, and modelling of the temperature distribution. The exploration was concluded by successful well which intersected a fracture producing 90°C hot water. A full scale production test was carried out over aperiod of 9 months including a 3 month reinjection test. The results showed that it was economicallyfeasible to use the Thelamdrk field for space heating in Akureyri.

1. INTRODUCTION

The Thelamork geothermal field is approximately 13 km north-west of Akureyri, a town of 15,000 inhabitants in central North Iceland (Figure 1). Drilling of a 380 m deep borehole in 1941 showed a temperature of 77°C at only 100 m depth. In the sixties drilling of three 650-1100 m deep boreholes supported by mapping of dykes by magnetic measurements and resistivity mapping by, Schlumberger profiling revealed a hydrothermal system with a reservoir temperature of 91°C. However, no major feedzones were intersected by these wells, the best one yielding only 3 l/s of 90°C water from 600-650 m depth in well 2. This water has been used locally for space heating and a swimming pool. Below this aquifer there is a slight temperature inversion down to 1100 m, indicating a lateral component in the hot water flow. In the eighties exploration was continued in order to get more hot water which could be piped to Akureyri at a reasonable cost.

2. GEOLOGICAL DESCRIPTION

The Thelamork geothermal field is located in a valley approximately 60 km from the present rift axis of North-Iceland in 6-10 m.y. old crust of flood basalt that generally dips 3-10" toward the spreading axis (Fig. 1). The basalt lavas are of tholeiitic composition and some are porphyritic. The lava thickness varies from a few meters to 30 m and the flows are interbedded by very thin layers of scoria and sediments. The lava pile is intersected by numerous near vertical dykes and normal faults which probably are a part of a fissure swarm belonging to a ancient and extinct central volcano 10-20 km away from Thelamork. The regional temperature gradient outside hydrothermal areas is close to 60°C/km. It reflects the heat conducted through the crust from the underlying mantle.

The only signs of geothermal activity at Thelamork were a small hot spring yielding 0.3 l/s of 45°C hot water, and ancient silica precipitation at 500-600 m distance from the hot spring, indicating boiling hot springs sometime in the past. This precipitation is found below a 4500 old tephra layer from Mt. Hekla, which gives a minimum age of the Thelamork geothermal system.

Crustal alteration studies (Pálmason et al. 1979) show that glacial erosion has removed approximately 1-1.5 km of the original crust at Thelamork. A lava unit, which is now at the surface at Thelamork, has been brought to a depth of 1-1.5 km during the spreading process (Pálmason 1973), where it was reheated to approximately

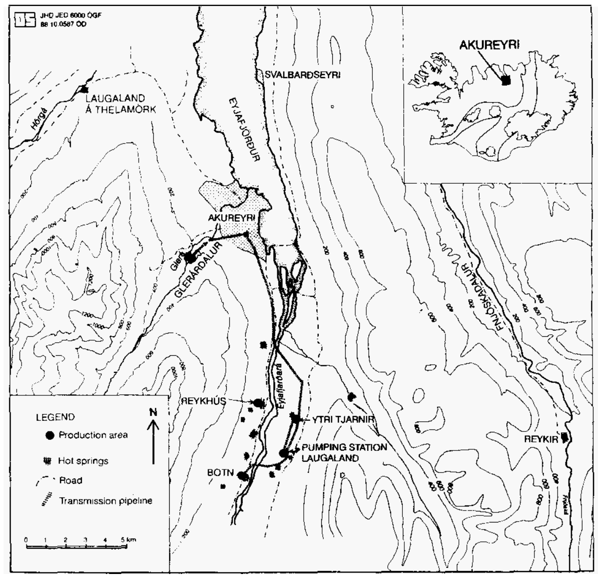

Figure 1. Locations of geothermal fields in the vicinity of Akureyri

100°C, before it was elevated to the surface due to erosion during the glaciation. During this process the lava suffered alteration; most of the open pores were filled by secondary minerals and the primary permeability greatly reduced.

There are indications that most of the present low-temperature geothermal fields in Iceland were formed by crustal movements during the last deglaciation and are therefore about 10000 years old (Bödvarsson 1982). It has been proposed that tectonic movements, that followed the deglaciation, formed macroscopic fractures in which convection started and formed a geothermal system. Once the convection is initiated it is a self-renewable process, contraction in the deepest part of the fracture due to heat-mining extends the fracture to greater and greater depth and the convecting liquid comes continuously in contact with new hot rock (Axelsson 1985). The heat is therefore mined from the hot crust that is heated by relatively high heat flow from the underlying mantle. Since the regional heat flow around Thelamork is 60°C/km the convection system has to reach nearly 2 km depth to reach the 100°C indicated by geothermometers. Therefore the most active part of the geothermal system at Thelamork, where the heat mining takes place, is considered to be below 2 km depth.

Since the low-temperature geothermal fields in Iceland are characterised by secondary permeability in young fractures surrounded by low permeability rocks, prospecting for these fractures is of utmost importance in geothermal exploration. The methodology used in Iceland in prospecting for such vertical aquifers involves ground magnetic surveys, head-on resistivity profiling, temperature measurements in shallow boreholes and geological investigations (Flovenz and Georgsson, 1982)

3. MAGNETIC MEASUREMENTS

Dykes and in some cases faults are easily recognisable as narrow linear anomalies in the magnetic field, especially when the overburden is less than 20 m thick, as is generally the case in the Thelamork field. The total magnetic field intensity was measured by using a proton-precession magnetometer. The sensor was kept at 2.5 m elevation above the ground and the total intensity of the magnetic field was measured with 5 m sampling interval, along lines with 20-25 m spacing, perpendicular to the expected strike of the dykes. The results are shown on Fig. **2** as magnetic profiles along with the interpretations in terms of normal and reverse magnetised dykes.

The map shows that two systems of dykes intersects close to the hot springs, two **or** three normal dykes striking NS (A-1 and A-2 on fig. **2)** and two reverse dykes striking *NW* (A-8 and A-9). The feed zones in well 2 are within the dyke A-1 on Fig. 2. This is a very common situation in Iceland, a hot spring located at the intersection of two vertical structures. The magnetic measurements show however only the location of the dykes but not whether they are permeable or not. For that purpose, resistivity profiling and temperature measurements in shallow boreholes are important.

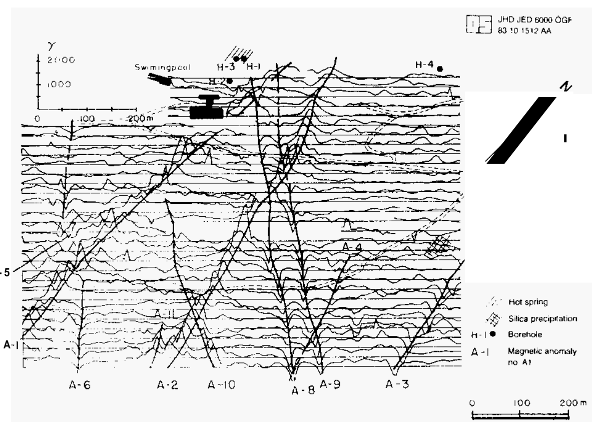

Figure 2. *A magnetic map of the Thelamörk geothermal field.*

4. HEAD-ON RESISTIVITY PROFILING

Since head-on resistivity profiling has been one of the most powerful tools in prospecting for subvertical aquifers in Iceland (Flovenz, 1984) it was decided to carry out such survey at Thelamork. Since fractures filled with hot geothermal water, or hydrothermally formed alteration minerals, are highly conductive, they are easy to locate by the head-on profiling method. Fig. 3 shows the results of 9 resistivity profiles combined with the results of the magnetic measurements. Each profile was made measured with AB/2 = 500m and 300m and the MN spacing was 50m. Figure 4 shows an example of one of these profiles together with the corresponding model. The regional resistivity is 150-200 Ωm but the low resistivity fracture is modelled as a narrow zone of 10 Ωm. The spatial distribution of the low resistivity fractures came as a surprise as they do not follow the dykes but show a pattern of two *NW* trending fractures connected by a **NE** trending one, almost parallel to the Horga river. The hot spring is located at the centre of the NE striking fracture, where it intersects the dykes A-1, A-8 and A-9, but the ancient silica precipitation is at the southern end of one of the *NW* striking fracture, which strongly indicate a relation between the low resistivity fractures and extinct as well as existent hot springs.

5. EXPLORATORY DRILLING

In order to get a clear picture of the temperature distribution around the aquifers five additional shallow (200-390m) boreholes were drilled. Their locations are shown on Fig. 3. Well 5 intersected a feed zone within dyke A-1 at a depth of 160m. The temperature of the water at that depth was 80°C and the well discharged 16 l/s by air lifting during the drilling. Below that depth the temperature

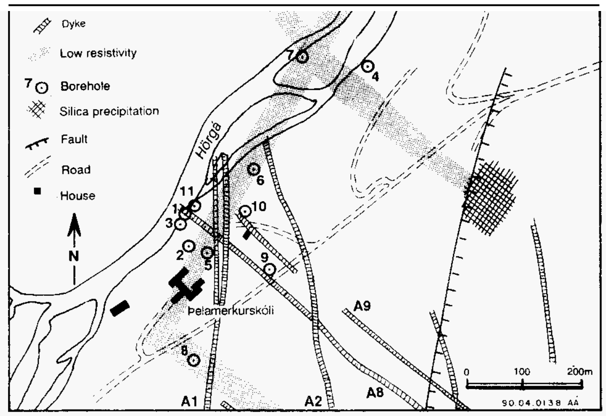

Figure* 3. *Results of head-on resistivity profiling and magnetic measurements. The hot springs were located along the river bank between wells 1 and 11.

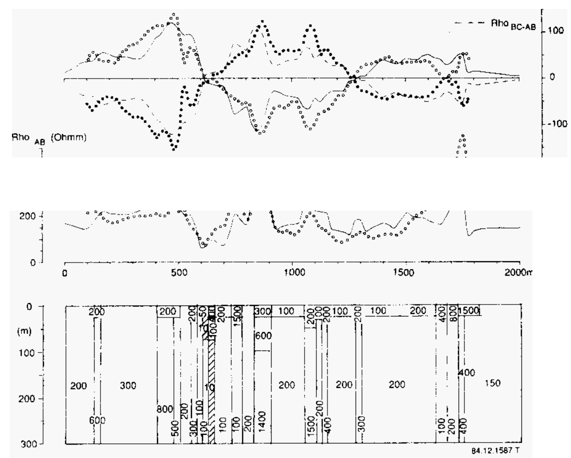

Figure 4. Data and model for line 6 of the head on resistivity survey

decreased. Well 6 intersected a feed zone at 150 m depth which yielded 12 l/s during drilling. The temperature of the feed zone was 75°C, with a minor inversion of temperature below. This feed zone was found to be associated with an interbedded sedimentary layer in the lava pile. The same applies to other small aquifers found in the exploratory boreholes. Well 7 and 8 were drilled to investigate the *NW* striking part of the low resistivity fracture system but well 9 was drilled to check the temperature distribution around the dykes A-8 and A-9. No considerable feed zones were found in these three wells, only small ones related to the interbedded layers. Fig. 5 shows temperature logs from the boreholes at Thelamork and Fig. 6 shows the temperature distribution at 400 m depths along with the location of dykes and low resistivity fractures. It seems evident that the temperature distribution at 400 m depth follows the NE-fracture. At very shallow depth, the isolines are, however, strongly affected by the dyke A-1. It was concluded at this point in time that the upflow of hot water from depths is mainly associated with the NE-striking fracture but at shallow depth the hot water flows into the dyke A-1 and some of the thin sedimentary layers in the vicinity of the fracture.

6. BOREHOLE GEOLOGY

Drill cuttings collected from all the boreholes during drilling were analysed. In addition neutron-neutron, resistivity, natural gamma ray emission, caliper and temperature logs were measured in the wells. Comparison between logs and drill cutting analysis shows that the neutron and natural gamma ray logs are extremely useful to identify individual lava flows and sedimentary layers. By careful comparison of the logs from one well to another individual layers can be traced over the whole well field. The strata turned out to be very homogeneous and only few meter variations in thickness of individual lava flows were observed. No sign of faults were found in between the boreholes. By least square fitting of a plane surface to several of the most easily identified interfaces in the lava pile, the strike was calculated to be N60-70°E and the dip to be 5-7° towards SE.

The dip of the dykes can be calculated by identifying them within the boreholes and measuring the horizontal distance from the borehole to the dykes at the surface. It was found that dyke A-1 and A-2 dip 4-7° towards west.

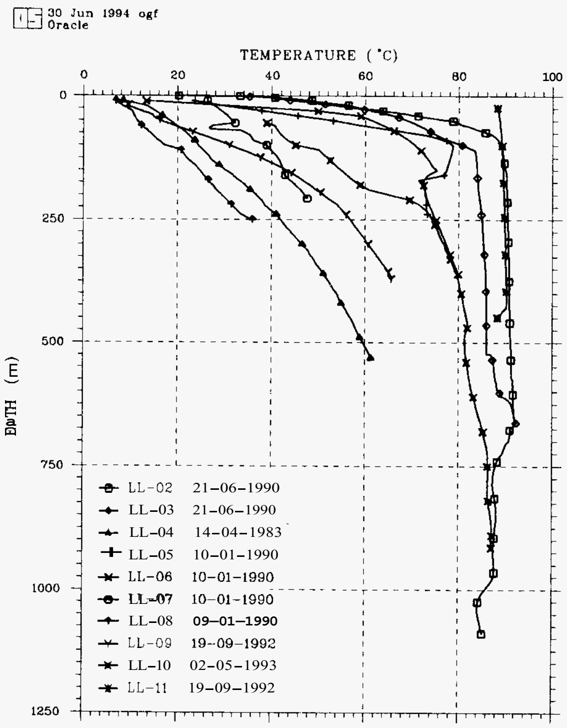

Figure 5. Representative temperature logs. Post-drilling equilibrium has been reached but water is flowing within in some of the wells.

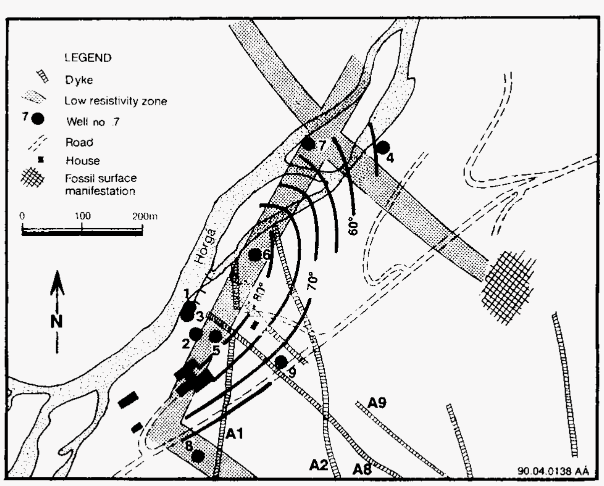

Figure 6. Isolines for temperature at 400 m depth.

Well	Apparent porosity %	Estimated effective porosity %	Well	Apparent porosity %	Estimated effective porosity %
2	6.5	3-4	7	12.8	6-7
3	14.4	7-8	8	14.2	6-8
4	18.5	8-9	9	15.1	7-8
5	12.4	5-7	10	16.5	7-8
6	13.0	6-7	11	7.2	3-4

Table 1 shows a relatively wide range for the porosity over the research area although the strata are the same. It appears that there is a systematic spatial variation in the porosity values. The values become lower as the temperature increases and the closer the wells are to the upflow zone. The most likely explanation is that the porosity around the upflow zone is reduced due to precipitation of secondary minerals. This reflects the self-sealing process that takes place around geothermal upflow zones.

8. TEMPERATURE MODELLING

The next step in the investigation of the Thelamork field was use the temperature logs to further constrain on the location of the upflow zone, i.e. its location and dip. This was done by two dimensional modelling of the temperature distribution perpendicular to proposed aquifers (Milicevic, 1990). The location of the aquifers, their dip and temperature were varied to fit the temperature logs. The method used assumes steady state conditions, fixed temperatures in the aquifers and that outside the aquifers heat is transported by conduction. (Flovenz, 1984). Boundary conditions are provided by the regional temperature gradient and the average surface temperature. A finite element solution of the Laplace equation is used to calculate the temperature distribution.

Several models with different orientation and dip of the up-flow fracture were tried but none of these could explain all the observed temperature logs, probably because of three dimensional effects. It was especially difficult to model the temperature inversion in well 2. From the modelling work several conclusions were however drawn:

- The inversion in temperature in wells 2 and 5 can only be explained by horizontal flow along the dyke A-1, from a upflow zone located at least 50 m away from these wells.
- The temperature distribution suggest that the upflow zone is limited to a very narrow part of the low resistivity fracture or of the dyke A-1. It could even be limited to the intersection of these structures.
- It is likely that the upflow zone dips away from well 2 .

9. FURTHER DRILLING

Well 10 was drilled during the summer 1992 to a depth of 914 m. It cut no major feed zones. Since there is no flow from the well, the temperature profile on Fig. 5 is close to the formation temperature. The temperature log show rapidly increasing temperature down to approximately 200 m where the gradient decreases substantially. At the bottom of the well the temperature is only 86°C or 5°C lower than in the aquifer at 600 m depth in wells 2. It is therefore evident that the fracture does not dip towards the east.

The next step was therefore to drill well 11 on the western side of the fracture. It was sited such that it would intersect the dyke A-1 between 400 and 500 m depth. This well was successful. The dyke was entered at 370 m depth and at a depth of 430 m a major feed zone was intersected. There was a total circulation loss and a brief air lift test during drilling gave 40-60/s of 90°C hot water. Due to total circulation loss further drilling was not possible in spite of several attempts. The temperature logs from wells 10 and 11 are shown on Fig. 5.

10. CHEMICAL COMPOSITION

Table 2 shows the chemical composition of the hot water from the Thelamork field, which is very low in chemical content. The water is suitable for direct use and there is low risk for scaling or corrosion. The water contains a small amount of hydrogen sulphide which helps to deplete it of minor oxygen contamination which may occur in the degasser and the distribution system.

The equilibrium between the fluid and several minerals has been calculated in order to estimate the temperature of the water deeper in the reservoir. This was done by the program WATCH (Arnorsson et al. 1983). The equilibrium of chalcedony, albite and calcite indicate an equilibrium temperature of 100°C, while slightly higher values are obtained by the equilibrium of microcline, chrysotile and laumontite. It is therefore concluded that the temperature of the water is at least 100°C deeper in the geothermal system.

Table 2. Chemical composition of water from well 11 (ppm).

pH/°C	9.72/15	Hydrogen sulphide, H_2S	0.24
Silica, SiO_2	129.8	Chloride, Cl^-	13.2
Sodium, Na^+	59.0	Fluoride, F^-	0.83
Potassium, K^+	1.4	Bromide, Br^-	0.03
Calcium, Ca^{+2}	2,2	Boron, B	0.27
Magnesium, Mg^{+2}	0.002	Aluminium, Al^{+3}	0.086
Carbonate, CO_2	23.7	Dissolved solids (TDS)	285
Sulphate, SO_4^{-2}	31.5	Oxygen, O_2	0.003
		δO^{18} (‰ SMOW)	-14.16

11. RESERVOIR MODELLING

After completion of well 11, a rotary shaft pump was installed at 200 m depth in the well. In September 1992 a pumping test started which lasted for nine months. It was interrupted once for a few days because of pump failure and the last 2.5 months a part of the water was reinjected into wells 6 and 8. The pumping test, together with data processing and interpretation is described in detail in Flovenz et al. (1994) and Bjornsson et al. (1994). Figure 7 shows the pumping and draw down data. The discharge during these nine months varied from 15 to 20 l/s of 91.5°C hot water and the maximum reinjection was 6 l/s. The purpose of the injection test was to investigate the effect of a proposed reinjection of 3 l/s of return water fiom the local buildings at Thelamork.

11.1 Water level predictions

The water level data were simulated by lumped reservoir modelling (Axelsson, 1989) to predict the draw down due to long term production from well 11. The lumped model simulates the reservoir by three tanks, each characterised by a mass storage coefficient, connected to each other by conductors representing the fluid conductivity between the tanks. The innermost tank represents the production part of the system, the second one simulates the outer and

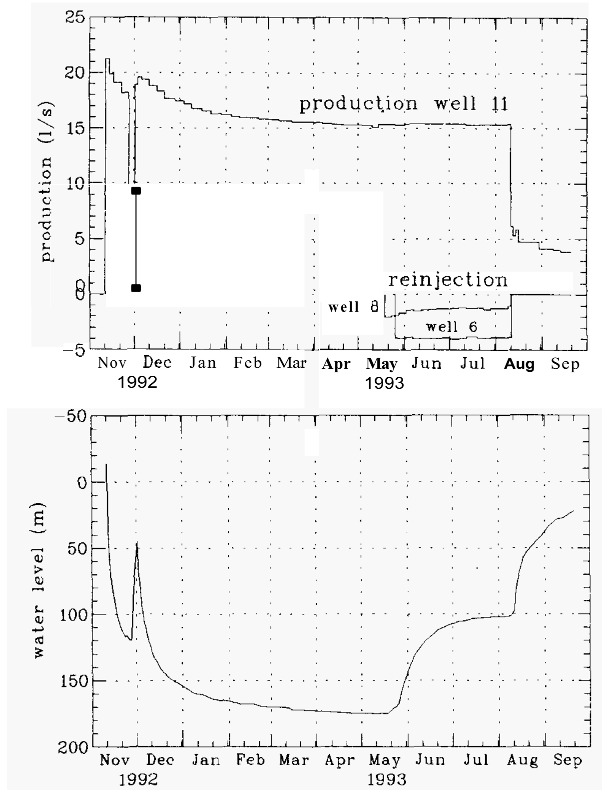

Figure 7. Production and water level during the pumping test.

deeper parts and the third one simulates the recharge part of the system, which involves the deeper parts of the system as well as the overlaying groundwater system. The results of the simulations indicate that the geothermal system is small in volume (≈1 km^3) and has low permeability thickness (≈1Dm). This leads to a great pressure draw down during production. A closed model, which gives pessimistic water level predictions, was used here mainly to be on the safe side. Figure 8 shows the predicted water level changes for different production rates. It shows that in order to keep the water level above 240 m, which is the maximum depth used for rotary shaft pumps in Iceland, the average production should not exceed 16 l/s net over the first 10 years of production. Thus if 3 l/s of the local return water can be reinjected into the reservoir the total production can be increased to 19 l/s.

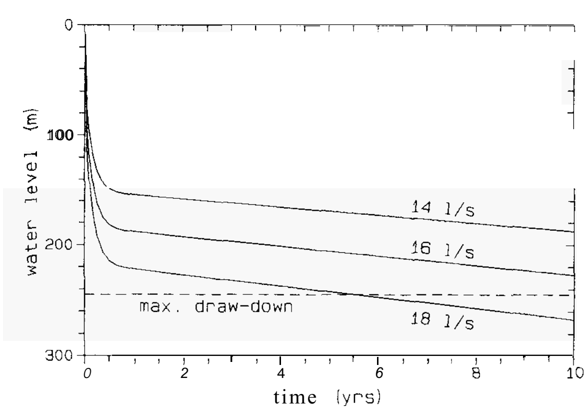

Figure 8. Predicted water level changes in well 11.

11.2 Cold water inflow

Since more than 200 m draw down in water level is expected during long term production, cold water from the overlying groundwater system may possibly leak into the reservoir. Therefore the silica content (SiO_2) and the oxygen isotope ratio (δO^{18}) of the water from the production well was monitored during the production test. Fig. 10 shows how SiO_2 concentration declined with time indicating inflow of cold water. Yet no temperature decline was observed during the same period. Figure 10 shows the relation between the oxygen isotope ratio and silica concentration during the pumping test. We observe a decline in SiO_2 content and simultaneous increase in δO^{18} ratio. The straight line on Fig.10 shows the mixing line between the geothermal water and cold groundwater. The data points follow this line fairly well which indicates that the travel time of the cold water to the production well is very short compared with the time it takes the SiO_2 to establish new equilibrium.

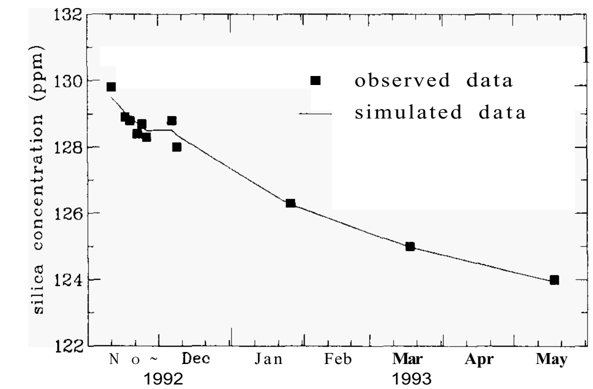

Figure 9. Measured and simulated silica content in well 11, as finction of time, during the pumping test .

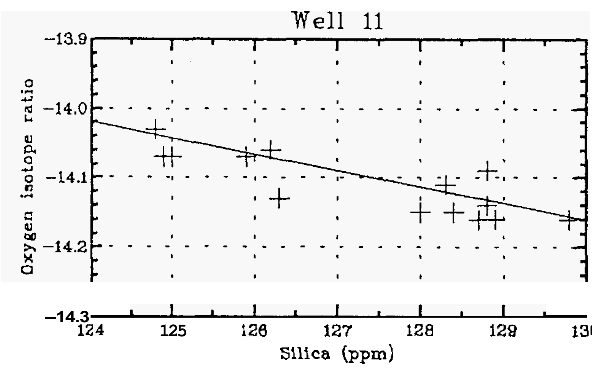

Figure 10. A plot of δO^{18} ratio versus the silica content of the water from well 11 during pumping test.

A simple model was used to simulate the data of Fig. 9. (Bjornsson et al. 1994). It consists of three parts, an infinite groundwater system and a deep reservoir system, both with fixed temperatures and solute concentrations, and a production part with varying temperature and concentration due to mixing. A fixed inflow from the deep system to the production part is assumed but variable cold water inflow. By using the laws for conservation of mass and energy the temperature and solute concentration of the production part can be calculated as a function of time and production rate from the reservoir, based on a given value of porosity. The match between the observed and calculated silica concentration is shown in Fig. 9. In the model, mixing of geothermal water and cold groundwater takes place in a small subvolume of the geothermal reservoir. The product of this volume and porosity equals 0.0007 km^3 and corresponds to a volume of 0.015 km^3 assuming an effective porosity of **5%**. In the model the base inflow from the deeper reservoir is about 83 % of the production whereas the colder down flow is about **22%** with silica concentration of 10 ppm. The predicted temperature for long term production from well 11 according to the model, is shown on Fig 1 1. A temperature decline of **7°C**, over 10 years of 16 l/s production, is predicted.

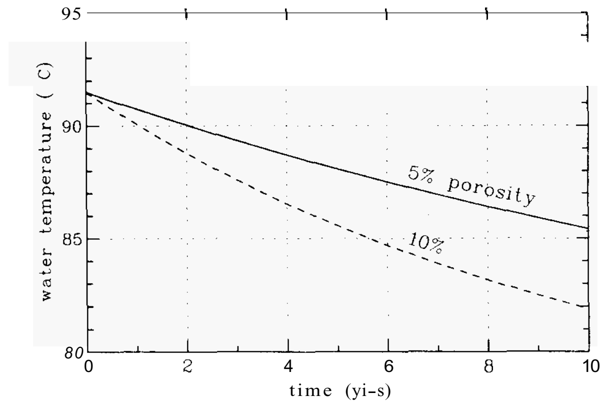

Figure 11. Predicted cooling due inflow of cold groundwater

11.3 Reinjection

Another method of producing more energy out of the reservoir, than just by pumping water from well 11, is to reinject water after it has been used to heat the local buildings and a swimming pool at Thelamork. The return water is close to 3 l/s and 30°C. In order to investigate the effect of reinjection on water level and temperature of the production well, a part of the production from well 1 1 during the pumping test was reinjected, 4 l/s into well 6 and 2 l/s into well **8.** The reinjection lasted for a period of **2.5** months. **After** approximately one week of reinjection known mass of tracer was injected instantaneously into the reinjection wells, sodium bromide into well 6 and sodium fluorescein into well *8,* and their recovery in the production well measured. The water level increase due to the reinjection is shown on Fig. 7 and observed and simulated tracer recovery curves for well 6 on Fig. 12.

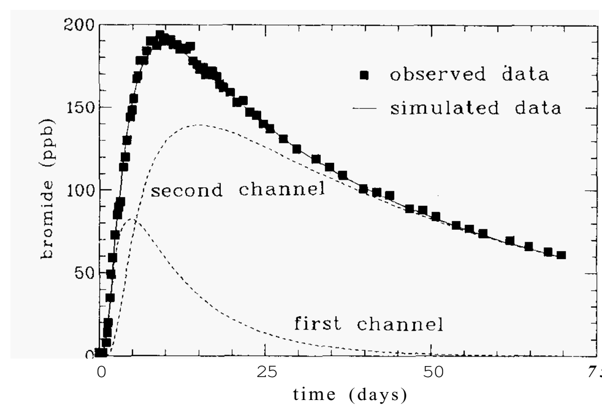

Figure 12. Observed and simulated recovery curvesfor tracer test in wells 6 and 8.

The tracer recovery curves were analysed by a simple one-dimensional fracture zone model (Björnsson et al. 1994). Two channels between the injector and the producer were assumed. For the case of well 6, the first channel accounts for **15%** of the recovered tracer and is taken to be the shortest distance between the two wells (120m). The second channel, that transports ***85%*** of the recovered tracer mass, is assumed to be a fracture zone connecting the major feedzones of the two wells. According to the model a maximum recovery of 77% of the injected tracer is predicted for the two channels between wells 6 and 11, the rest diffises through a larger volume. The fracture properties that were determined by the simulation were used to estimate the heat absorbed in the fracture system by the injected fluid. The result shows that if the injection rate is kept at **1-2 l/s** per injection well, it will cause less than **2°C** cooling of the produced fluid.

12. FEASIBILITY

Once the reservoir characteristic had been estimated, the next step was to design and estimate the feasibility of building a pipeline to Akureyri. A 175 mm steel pipe was selected, insulated with 120 mm of polyurethane and covered with a thin coat of polyethylene. The pipeline is 10.1 km long and buried at 70-100 cm depth in the soil, without any expansion units. The temperature **loss** is estimated to be 6°C **on** the average. ***An*** overview of the total cost of the project, including all investment since 1941, the operating cost and the project economics is presented in table 3. The calculated energy price for the project is 7.2 mills/kWh$_t$. Approximately the same price results if we only include the exploration and drilling cost of the last exploration phase initiated in the eighties, and the energy that reaches Akureyri. This energy price can be compared to the following consumer energy prices in Iceland in 1993:

Geothermal space heating in Akureyri	29 mills/kWh$_t$
Average price for geothermal space heating	11 **mills/kWh$_t$**
Heating by oil	42 mills/kWh$_t$
Heating by electricity (government subsidised)	34 mills/kWh$_t$

This comparison shows that the energy price from Thelamork is very low compared to other alternatives .

Table 3. Economy of the Thelamorkgeothermalproject

Investment:	
Exploration, including pumping test	0.18 M$
Drilling	0.90 M$
Pumps, degasser etc.	0.15 M$
Pipeline	0.90 M$
Total investment	**2.13 M$**
Energy production:	
Production rate	19 l/s
Reinjection rate	3 l/s
Average water temperature from the well	84°C
Cooling in pipeline to Akureyri	6°C
Lower utilisation limit	27°C
Annual energy production:	**35 GWh$_t$**
Annual operating cost:	
Electricity for pumping	59,000 $
Other operating costs	22,000 $
Total operating cost:	**81,000 $**
Project lifetime	20 years
Interest rate	**6%**
Energy price	**7.2 mills/kWh$_t$**

13. SUMMARY

The highlights of the history of exploration of the Thelamork geothermal field, from the early beginning to exploitation, can be summarised as follows:

- Original manifestations of geothermal activity were a minor hot spring with a temperature of 40°C and ancient silica precipitation, a few hundred meters From the hot spring.
- Drilling of 4 wells in the period of 1941-1970 yielded only 3 **l/s** of 90°C water for local use.
- Ground magnetic measurements revealed two systems of dykes, **N-S** and **NW-SE** striking. They intersect close to the hot spring.
- Head-on resistivity profiling led to the discovery of a two NW-trending low resistivity structures connected by a NE-trending one. The third one intersects the dyke systems close to the hot spring.
- Temperature measurements in several exploration wells show that the isolines of temperature follows the NE-trending low resistivity structure.
- A productive feed zone with a temperature of 91°C was found at 430 m depth by drilling into the intersection of the dyke and the NE-fracture.
- Geothermometry indicates reservoir temperature above 100°C.
- **A** nine month pumping test indicates that the production well will yield on average 19 l/s for 10 years, if the water level is kept above 240 m depth and 3 l/s of local return water are reinjected.
- Modelling of changes in chemical content of the water during the pumping test predicts a slow cooling of the water to 85°C after 10 years. The reason is a down flow of water from the local groundwater system. Reinjection will cause 2°C additional cooling over the same period.
- The total investment in exploration, drilling and pipeline to Akureyri is 2.13 M$ and the resulting energy price is 7.2 mills/kWh$_t$ which is very low compared to other alternatives.

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