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Discovery and Development of the Low-Temperature Geothermal Field at Hjalteyri, Eyjafjördur, in Northern Iceland. A Highly Productive System Apparently Lacking Surface Expression.

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ABSTRACT

Geothermal prospecting in the vicinity of Hjalteyri was initiated in 1999. During the following 3 years, it involved among other, the drilling of 16 shallow wells for temperature logging. A ground magnetic survey was carried out near the centre of the thermal anomaly, established by logging the shallow wells. The composition of thermal water from wells with artesian flow indicated system temperatures in excess of 70°C. Selected wells were subjected to wire-line logging, including logging by televiewer.

The results suggested a significant geothermal resource and drilling of well HJ-19 to 1450 m, yielded by far the most productive well in the Eyjafjördur region. The Hjalteyri low temperature area is in fact among the most productive in Iceland, capable of yielding around 200 L/s of 90°C hot water at moderate drawdown rates over extended periods of time.

1. INTRODUCTION

Hjalteyri is a small fishing village located on the western shore of Eyjafjördur some 20 km north of the town of Akureyri in north central Iceland (Fig. 1). The village is nested on a small spit sheltered to the west by a minor NW-SE trending ridge that rises some 75 m above sea-level (Fig. 2). The village Hjalteyri and the farming areas to the south collectively comprise the municipality of Arnarnehreppur with approximately 200 inhabitants

This village was one of several busy centres in Eyjafjördur during the lucrative Herring-years in the first half of the 20th century. The economy still depends on fisheries and farming. However, the facilities formerly used for processing herring, now house, among other, a flatfish “hatching and nursery” facility. These changes reflect the increasing emphasis in Iceland on fish-farming as a viable alternative to harvesting wild fish stocks.

Geothermal prospecting at Hjalteyri commenced after a well, originally drilled to obtain sediment-filtered seawater for flatfish-farming practises, indicated a thermal anomaly in the vicinity. Temperature logging of this shallow well showed a geothermal gradient of 100 to 110°C/km. This is markedly above the expected 50 to 60°C/km expected in this region (Flóvenz and Saemundsson 2002). Since the first well HJ-1 did not penetrate bedrock a second well was drilled by the municipality to confirm the findings of the first well. Following positive results, a systematic search for

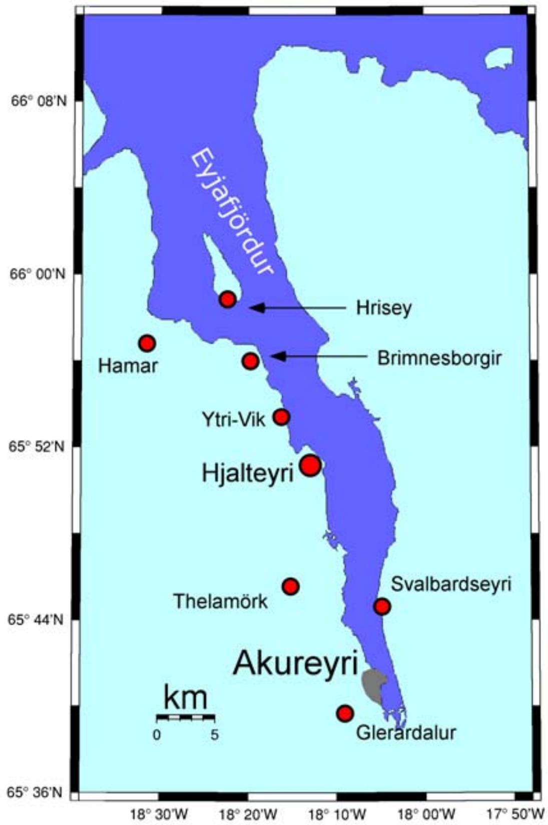

Figure 1. Map showing the location of the low temperature area at Hjalteyri in Eyjafjördur. Also shown are several other low temperature areas, currently in production. The town of Akureyri (population 16,000) is located at the head of the fjord.

the origin of the thermal anomaly was initiated. The prospect of a possible geothermal resource in the immediate vicinity generated considerable interest as there are no surface manifestations of geothermal activity in the area.

Further north in Eyjafjördur, three geothermal fields have been developed within the last 10 years or so. These are the fields at Hrisey, Brimnesborgir and Ytri-Vík (Fig. 1). A fourth system at Hamar has been utilized by the municipality of Dalvik for more than 20 years.

The prospecting effort at Brimnesborgir utilized, among other methods, micro-seismic activity and relative positioning of seismic sources to map an active NNV trending lineament. The three aforementioned systems lie on this lineament and it may extend further south, towards

Arnarnes (Flóvenz et al. 2000). Of interest at this time were reports by local fishermen that gas bubbles were occasionally seen on echo sounders of small boats operating north of Arnarnes indicating hot spring on the seafloor.

This paper describes the discovery and development of the low-temperature field at Hjalteyri. An account of the methods and results of the prospecting effort and the drilling of the production well HJ-19 is given. Finally the results of production testing are presented.

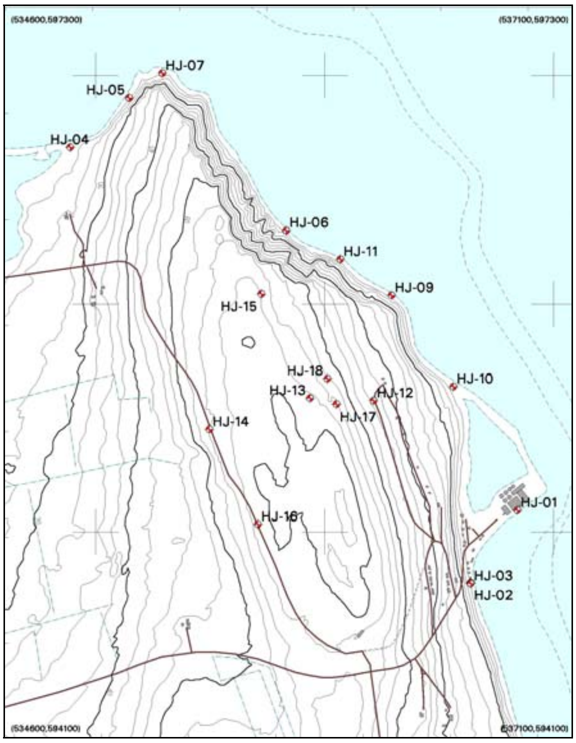

Figure 2. Map showing the topography on Arnarnes and the location of shallow wells drilled during the geothermal prospecting effort.

2. MAPPING THE GEOTHERMAL RESOURCE

2.1 Geology

Bedrock in the Eyjafjördur region close to Hjalteyri is composed of late tertiary (~10 Ma) basalt flows intercalated with thin sediments. The lava pile dips 6° to the south and is cut by basaltic dikes, believed to be feeder dikes for lava flows in many cases. Based on plate cooling models and logging of several wells a regional background temperature gradient of 50 to 60°C/km is expected in the region (Flóvenz and Saemundsson 2002).

Locally bedrock only crops out in a small area at the north end of Arrnarnes. There, bedrock is exposed at sea level and up to approximately 8 m above sea level. From the tip of Arnarnes bedrock is exposed continuously for about 1 km along the coast on the east side of the Arnarnes-ridge and for about 200 m along the west side. Depth to bedrock then increases southwards along the coast. Bedrock is composed of basaltic lavas, classified as tholeiite-basalt based on field characteristics. Vugs and fractures are commonly filled with secondary minerals such as quartz, stilbite and mordenite. At sea level the alteration of the lava pile corresponds to the mesolite-scolecite zeolite zone (Pálmason et al, 1979) with very low permeability.

In these limited exposures 3 dikes and several zeolite filled fractures and fracture-sets were mapped. The dikes trend between N10°E and N20°E. Several of the zeolite-filled fractures and fracture-sets are parallel or sub-parallel to the trend of the dikes and are thought to be similar in age to the dikes (Flóvenz and Saemundsson 1999). A set of NV-SE and NNW-SSE trending fractures are probably considerably younger, reflecting a reorientation of the crustal stress-field.

Prior to the commencing of the drilling program it was expected that the thickness of glacial sediments covering bedrock at Arnarnes might reach of 60 m to 70 m, based on exposures along the coast.

2.2 Shallow T-wells

It has become common practise to utilize drilling of shallow wells to map the thermal structure of the uppermost crust when prospecting for a potentially useful geothermal resource (Björnsson and Saemundsson 1998). Typically wells are 60 to a 100 m deep and preferably at least 60 m are within bedrock. The cost of drilling shallow wells is reasonable, particularly if surface casings can be kept to a minimum.

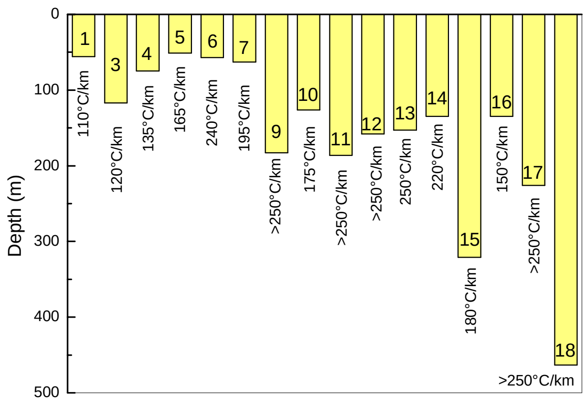

Figure 3. Well number and depth of all successful exploratory wells. The estimated temperature gradient in each well is indicated.

A total of 16 successful exploratory wells were drilled to map out the thermal anomaly (Fig 3). Two wells (HJ-2 and HJ-8) were abandoned due to technical problems during drilling. Most of the wells were originally close to 100 m deep, a few wells were further deepened to 150 to 200 m in order to map in more detail the temperature structure at depth. The last of the exploratory wells HJ-18 was drilled to a depth of 452 m. HJ-18 now serves as a monitoring well.

The first four wells (HJ-4 to HJ-7) were drilled at or close to the tip of Arnarnes (Fig. 2). This was in part due to the purported geothermal activity in the fjord north of Arnarnes. In addition, recent work had suggested the alignment of three established geothermal fields on an apparent lineament, which is in part defined by recent seismic activity (Flóvenz et al. 2000). This lineament could be extended southwards toward the tip of Arnarnes. In addition casing-costs in this area would clearly be insignificant.

Wells HJ-9 and HJ-10 were situated further south along the coastline and as expected the thickness of sediments increased substantially. Finally, well HJ-11 was drilled between wells HJ-6 and HJ-9 to pinpoint the temperature maximum along the coast (Fig. 2). Two of the wells (HJ-9 and HJ-11) yielded a small artesian flow of about 1 to 2 L/s of approximately 30°C water.

The next wells (HJ-12 to HJ-14) were placed approximately on a line transecting the Arnarnes ridge (Fig 2). Well HJ-12 was drilled to 158 m after it intersected a thermal aquifer at 120 m which yielded an artesian flow of 7 L/s of 40°C hot water. Chemical analysis of the discharged fluid indicated subsurface temperatures in excess of 70°C. Furthermore it was established the chemistry of the geothermal fluid is similar to fluids in other geothermal system in the Eyjafjördur region and suitable for direct use in space heating.

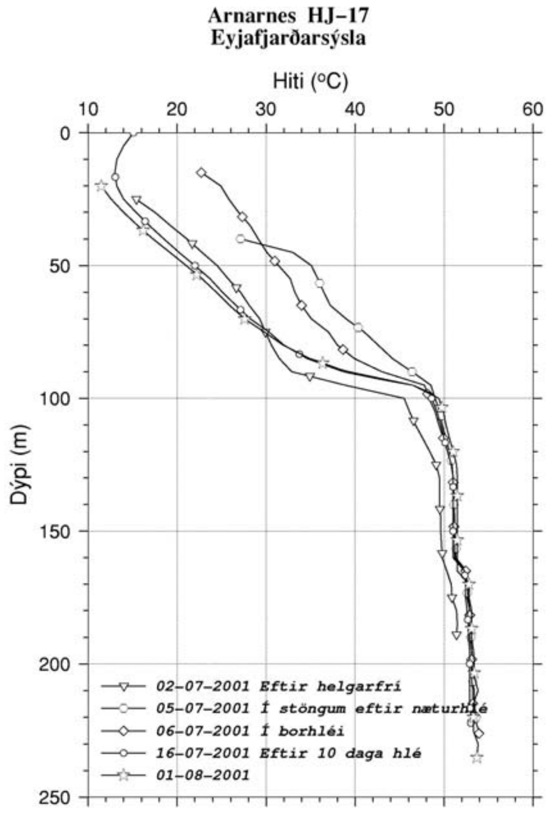

Figure 4. Temperature measurements displayed as a function of depth in well HJ-17.

After establishing broadly the shape of the temperature anomaly along a line from HJ-10 to HJ-14, the next wells were aimed at determining better the outer fringes of the anomaly. Well HJ-17 was intended to pinpoint the location of the temperature maximum between wells HJ-10 and HJ-14. Results of several temperature measurements from HJ-17 are shown in Fig. 4. Finally, well HJ-18 was located close to the suspected centre of the anomaly. It was drilled to a depth of 453 m to study in detail the temperature structure at depth. Analysis of temperature data from all the wells reveals a temperature anomaly striking N35°E.

2.3 Magnetic survey

At this point a ground magnetic survey was carried out. Such surveys have proved useful in delineating near vertical dikes and faults (Flóvenz and Georgsson 1982). Three profiles were taken nearly perpendicular to the axis of the temperature anomaly. In spite of the thick glacial sediments on Arnarnes ridge the profiles produced useful data. A simple 3D graph displaying the results is shown in Fig. 5. The vertical axis shows the absolute strength of the magnetic field. The two horizontal axes show distance in meters (Northing and Easting). A distinct low occurs in all three profiles. They all fall on a line sub-parallel to the axis of the thermal anomaly (Fig. 6). This low is interpreted as the trace of a reverse magnetized dike (or dikes) striking N10A. The dip of the dike is not known but in general they tend to be almost perpendicular to the layering of the lava pile. A slight westward dip of the dikes is therefore anticipated.

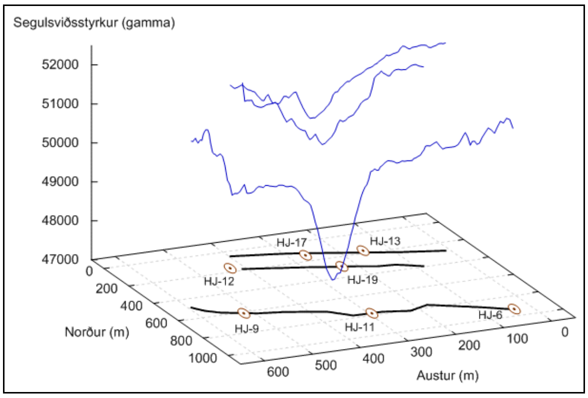

Figure 5. A simple 3D graph, showing the results of a ground magnetic survey. The view is to the SSW along the trace of the dike (see text).

2.4 Televiewer logging

Several of the shallow boreholes were logged with a borehole televiewer in order to determine the strike and dip of the lavas and fractures. In well HJ-13 the average dip of the lava interfaces turned out to be 3° striking 170° which is in agreement with measurements from nearby exposures. In addition fractures striking N38°V and dipping 7° to the west were observed. These fractures were close to the main feed zone of well HJ-13. They might be a part of the proposed NV striking system extending through Brimnesborgir.

2.5. Microseismicity

A major right lateral transform fault, trending WNW, is located just north of Eyjafjördur. It connects the spreading axis in NE-Iceland to the central valley of the Kolbeinsey Ridge, which is a part of the Mid-Atlantic Ridge. The transform shift is of the order of 80 km. The transform fault is highly active seismically. Associated with the transform, are NNE striking, left lateral, fault systems that go from the fault into the Eyjafjordur area. Earthquakes, up to magnitude 6, occurred on one of these faults in 1934. The microseismicity along these faults extends almost to Hjalteyri in the south. A cluster of earthquakes have recently occurred NE of Hjalteyri. Their epicentres form a line striking N30E or very close to the strike of the temperature anomaly at Arnarnes. This suggests the geothermal fracture observed in the temperature measurements may indeed be the southernmost part of a presently active fault zone.

3. SITING OF PRODUCTION WELL HJ-19

Figure 6 shows an aerial photo of the research area where locations of the boreholes and the dyke are shown, as well as isothermal contours at 150 m depth. The temperature contours indicate an underlying fracture striking N35°E that intersects the dike in the middle of the geothermal field. The isothermal contours are closed toward south, but are open to the north, toward the sea. This may indicate that the upflow of the geothermal fluid is related to the intersection of two, or even three, fracture systems; the dike detected by the magnetic measurements, an earthquake fracture derived from the isothermal contours and possibly also the N38°V trending fracture that appears in the televiewer logs.

Well HJ-19 was located (Fig. 6) close to the centre of the thermal anomaly, just northwest of the magnetic trace of the supposed dike. Given the strike and dip of the lava pile the well was expected to intersect the dike of depths of 1000 to 1500 m.

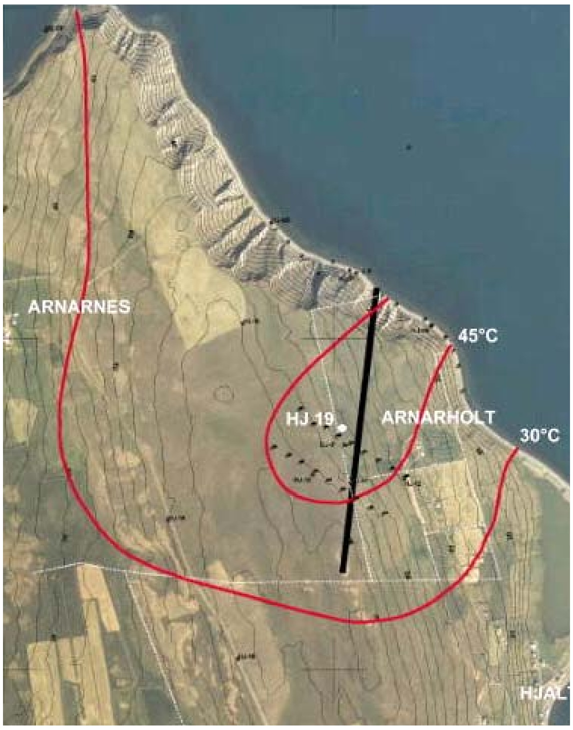

Figure 6. An aerial photograph of Arnarnes, showing the results of the thermal and magnetic mapping and the location of well HJ-19.

4. DRILLING OF THE PRODUCTION WELL

Drilling commenced in May of 2002. The well design called for a vertical well-bore to 1500 m. The drilling of well HJ-19 took, in all, less than 40 days, including logging and airlift tests. The well was cased with a 50 m (14") surface casing and a 400 m (10¾") production casing.

At a depth of roughly 840 m, a test to estimate the undisturbed bedrock temperature test was carried out. This involves measuring temperature as a function of time, for several hours, at a fixed depth. The resulting temperature data may be used to evaluate the undisturbed bedrock temperature using Albright's method or the Horner plot (Arason and Björnsson 1994). Projected bedrock temperatures at this depth were 85 ± 3°C, confirming expectations and indicating a nearby thermal source.

At depth of 1169 m a partial loss of circulation occurred. At this point an additional casing, to a depth of 192 m, was emplaced and an "air-lifting during drilling" technique employed for the remainder of the drilling effort. The aim of this technique is to decrease the fluid pressure on any potential aquifer and reduce likelihood of circulation fluid carrying drill cuttings to, and stifling the aquifers. For the remainder of the drilling, the volume of water discharged

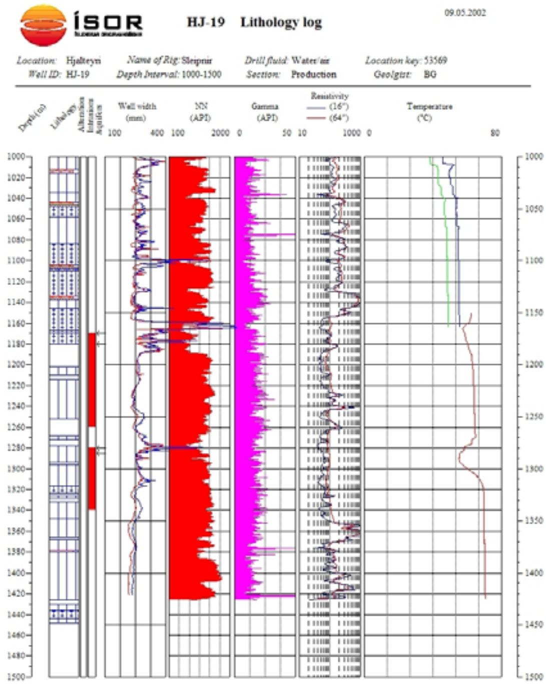

Figure 7. A stratigraphic column (below 1000 m) based on well cuttings and results of geophysical logging (from left to right width, neutron (red), gamma (purple), resistivity and temperature logs).

from the well was significantly greater than the amount of circulation fluid introduced. Variation in volume and temperature of discharge indicated the additional aquifers were intersected between 1200 m and 1300 m depth

When HJ-19 reached a depth of 1450 m it was clear that the well was already success and therefore drilling ceased at this point. A short airlift test immediately following drilling of well HJ-19 returned geothermal fluids well in excess of 100 L/s.

Analysis of well cuttings and geophysical logging (Fig. 6) confirmed the geological model to a large extent. The well intersects a dike, or possibly two dikes, at depths between 1170 and 1350 m depth. The main aquifers are associated with this dike (dikes).

5. TESTING AND PRODUCTION CAPACITY OF WELL HJ-19

In order to estimate the production capacity of the newly discovered Hjalteyri geothermal system, well HJ-19 was tested for a period of 13½ months. During the first 9 months, about 20 L/s were discharged from the well but 3 L/s after that. During the testing comprehensive data were collected by a computerized monitoring system, water level in nearby wells was observed manually and changes in chemical content monitored. The test and consequent data interpretation and modelling are described by Axelsson *et al.* (2003) and Axelsson *et al.* (2005).

The pressure changes in well HJ-19 have been accurately simulated by a lumped parameter model. The results of the simulation are presented in Fig. 8. The Hjalteyri reservoir appears to very permeable, or with an internal permeability-thickness of 110 Darcy-m, which is comparable to that of other highly productive low-temperature geothermal systems in Iceland (Axelsson *et al.* 2005). It also appears large in size, i.e. with a great volumetric storage.

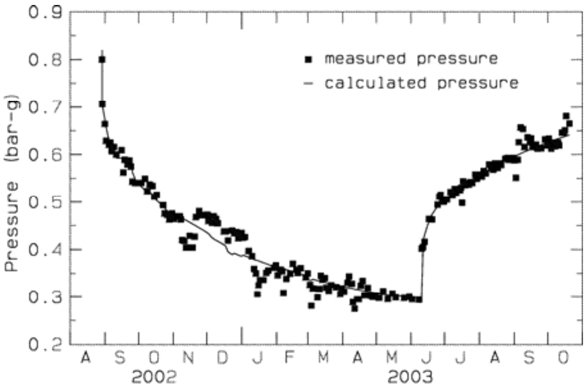

Figure 8: Pressure change data from well HJ-19 collected during production testing of the Hjalteyri geothermal system (squares) simulated by a lumped parameter model (solid line). Production was about 20 L/s until early June 2003, but about 3 L/S during the following recovery period.

The production potential of the Hjalteyri reservoir was estimated through the calculation of future predictions for various production scenarios and Fig. 9 shows an example of two such predictions. According to a conservative (pessimistic) estimate, based on predictions by a closed version of the lumped parameter model for Hjalteyri, the production potential of the reservoir is of the order of 200 L/s assuming down-hole pumps at depth above 250 m. This is comparable to the production capacity of a few of the most productive low-temperature systems in Iceland. Time will tell whether the production capacity is even greater, but it may be possible that the production capacity of Hjalteyri will be limited by energy-content rather than pressure changes. In other words, cooling due to inflow of colder ground-water, or even sea-water, may be the factor that limits the production capacity.

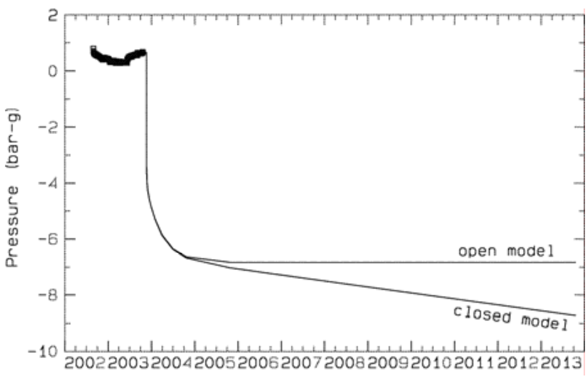

Figure 9: Predicted pressure changes for well HJ-19 at Hjalteyri until 2033 for a production scenario assuming a constant production of 150 L/s, calculated by a closed and open version of a lumped parameter model. Negative pressure indicates pressure draw-down.

6. CONCLUSIONS

Since the drilling and testing of well HJ-19 a 19 km pipeline has been installed, connecting the well at Hjalteyri to the district heating (Nordurorka) for Akureyri (Fig. 1). The well is currently producing some 60 L/s of 90°C water fulfilling the hot-water needs of the Hjalteyri community, some 12 nearby farms and about 30% of the average hot water demand in Akureyri. A second pipeline was installed connecting HJ-19 to the Thelamörk area (Fig.1) providing an additional 15 farms with hot water. The number of new users serviced by the Hjalteyri field is relatively small. However, well HJ-19 provides much needed relief for the heavily exploited fields south of Akureyri.

It is noteworthy that the Hjalteyri geothermal system appears to be about an order of magnitude more productive than several other geothermal systems closer to Akureyri, also utilized by the Akureyri district heating service (Flóvenz *et al.*, 2005). The reason is believed to be that the northern part of Eyjafjördur is more tectonically active than the region further south were the other systems are located.

The research effort at Hjalteyri has demonstrated that geothermal resources may be located, mapped and developed in areas lacking surface manifestations of geothermal activity. During the first several decades of geothermal development in Iceland, prospecting efforts concentrated on areas with obvious surface manifestations of geothermal activity, such as active warm springs or signs recent geothermal activity. The success at Hjalteyri justifies continuing government programs that subsidize prospecting efforts, in areas apparently lacking geothermal resources. In the long run the government recovers its investment in reduced subsidies to space heating using electricity or fossil fuels. Currently, geothermal energy accounts for over 90% of space heating requirements in Iceland (Ragnarsson 2003)

REFERENCES

Arason, P. and G. Björnsson, 1994: ICEBOX, 2nd edition. Orkustofnun, Reykjavik, 38 pp.

Axelsson, G., Th. Egilson, S. Hauksdóttir and O.G. Flóvenz, 2003: Testing of the Hjalteyri geothermal system in Eyjafjördur (in Icelandic). ISOR-report ISOR-2003/017, Reykjavik, 47pp.

Axelsson, G., G. Björnsson, Th. Egilson, O.G. Flóvenz, B. Gautason, S. Hauksdóttir, M. Ólafsson, O.B. Smárason and K. Saemundsson 2004: Nature and properties of recently discovered hidden low-temperature geothermal reservoirs in Iceland. *Submitted to World Geothermal Congress 2005.*

Björnsson, A., G. Axelsson and O.G. Flóvenz, 1990: The nature of hot spring systems in Iceland (in Icelandic with an English abstract). *Natturufraedingurinn*, **60**, 15-38.

Björnsson, G., K. Saemundsson 1998: Geothermal prospecting in “cold” regions (in Icelandic) *National Energy Authority Annual Meeting, March 23, 1-18*.

Flóvenz, O.G. and L S. Georgsson 1982: Prospecting for Near Vertical Aquifers in low Temperature Geothermal Areas in Iceland, *Geothermal Resources Council, Transactions Vol. 6, 1982 6 19-22*

Flóvenz, O.G. and K. Saemundsson, 1999: A plan for geo-thermal prospecting at Hjalteyri (in Icelandic). Nat. Energy Auth. Short report OGF-KS-99/02 5 pp.

Flóvenz, O.G. and K. Saemundsson 2002: A new heat flow map of Iceland, *The 25th Nordic geological winter meeting January 6th-9th, 2002*, Reykjavík, Iceland. Abstract volume 1.

Flóvenz, O.G., R. Karlsdóttir, K. Saemundsson, O.B. Smarason, H. Eysteinsson, G. Björnsson, M. Ólafsson and Th. Björnsson, 2000: Geothermal exploration in Arskogsstrond, N-Iceland. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 1133-1138.

Flóvenz, O.G., F. Árnason, M. Finnsson and G. Axelsson 1995: Direct utilization of geothermal water for space heating in Akureyri, N-Iceland. *Proceedings of the World Geothermal Congress 2000*, Flornece, Italy, May, 2233-2238.

Ragnarsson, A., 2003: Utilization of geothermal energy in Iceland. *Proceedings of the International Geothermal Conference IGC-2003*, Reykjavik, September 2003, Session 10, 39 – 45.

Pálmason, G., S. Arnórsson, I.B. Fridleifsson, H. Kristmannsdóttir, K. Saemundsson, V. Stefánsson, B. Steingrímsson, J. Tómasson and L. Kristjánsson 1979: The Iceland Crust: Evidence from Drillhole Data on Structure and Processes. In Talwani, M., (ed), *Maurice Ewing Series II, American Geophysical Union 43-65*..