Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Nature and Properties of Recently Discovered Hidden Low-Temperature Geothermal Reservoirs in Iceland

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Keywords: low-temperature, surface manifestations, reservoir characteristics

ABSTRACT

Low-temperature geothermal resources play a major role in the energy economy of Iceland, in particular for space-heating. The low-temperature systems are normally characterized by warm or hot springs and/or altered ground. A number of such systems have been discovered in recent years in areas devoid of these surface manifestations, many already in use for space heating in nearby towns and villages. They were all discovered after intense surface exploration, with the key to their discovery being exploration through temperature field mapping by the drilling of shallow temperature gradient wells. Because these areas are devoid of surface manifestations the question has arisen whether their nature and properties are in some ways different from those of other low-temperature systems in Iceland. The nature and properties of some of these systems have been studied on the basis of comprehensive reservoir engineering data, as well as chemical data, and the results compared with such information for other low-temperature systems in Iceland, which have surface manifestations. The purpose was to identify inherent differences between the two kinds of systems. Three of these systems are presented as examples; Hofsstadir in W-Iceland, Hjalteyri in N-Iceland and Eskifjordur in E-Iceland. The results indicate that the characteristics of these systems fall within the range observed for other systems, except perhaps for the Hofsstadir system, which appears to have abnormally closed boundaries and limited recharge, as well as different chemical characteristics. This is attributed to the tectonic setting of the field in W-Iceland. The Eskifjordur field also appears markedly different.

1. INTRODUCTION

Geothermal energy plays a major role in the energy economy of Iceland. At present it provides about 54 % of the primary energy supply for the 290,000 inhabitants, or about 77 PJ (numbers for 2003). The principal use of geothermal energy in Iceland is for space heating. Currently about 87 % of the space heating is by geothermal energy, having increased from about 45 % in 1970. Other uses of geothermal energy in Iceland include direct uses such as for industrial applications, swimming pools, snow melting, greenhouses and fish farming as well as indirect electricity generation (Ragnarsson, 2003).

The majority of the almost thirty public district heating services (*hitaveita* in the singular and *hitaveitur* in the plural) in Iceland use energy from some of the numerous low-temperature geothermal systems found in Iceland. A number of low-temperature geothermal systems have been discovered in recent years in areas devoid of the surface manifestations, which normally characterize the low-temperature areas. They were all discovered after intense geological and geophysical exploration. Many of these systems are already in use for space heating in nearby towns and villages. Because these areas were devoid of surface manifestations the question has arisen whether their nature and/or properties are in some ways different from the nature and properties of other low-temperature systems in Iceland.

The purpose of this paper is to address this question. Three of the recently discovered systems are presented as examples; Hofsstadir in W-Iceland, Hjalteyri in N-Iceland and Eskifjordur in E-Iceland. Their locations are presented in Fig. 1. The nature and properties of these systems has been studied on the basis of comprehensive reservoir engineering data, mostly production testing data as well as some longer-term production- and pressure response data. These systems are compared with other low-temperature systems in Iceland, which have surface manifestations, with the purpose of identifying inherent differences between the two kinds of systems. The chemical composition of water from the systems has also been compared.

At first the current understanding of the nature of the low-temperature activity is reviewed as well as the methods currently employed for low-temperature geothermal resource exploration and assessment. Following that each of the three systems is described and their reservoir and chemical characteristics presented. The paper is concluded by a comparison with other low-temperature systems in Iceland and some concluding remarks.

2. THE NATURE OF LOW-TEMPERATURE ACTIVITY IN ICELAND

The low-temperature systems, which by definition have a reservoir temperature below 150°C, are all located outside the volcanic zone passing through Iceland (see Fig. 1). The largest such systems are located in SW-Iceland on the flanks of the volcanic zone, but smaller systems are found throughout the country. The surface manifestations of the low-temperature activity are in most cases hot or boiling springs, while a few such systems have no surface manifestations. Spring flow rates range from almost zero to a maximum of 180 L/s from a single spring.

The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by the continuously ongoing tectonic activity also play an essential role by providing the channels for the water circulating through the systems and mining the heat. The geothermal gradient in Iceland varies from about 50°C/km to about 150°C/km, outside the volcanic zone. The nature of the low-temperature activity has been discussed by several authors during this century (Einarsson, 1942; Arnason, 1976; Bodvarsson, 1982; Bjornsson *et al.*, 1990; Arnorsson, 1995). A highly simplified conceptual model may be described as follows: Precipitation, mostly falling in the highlands, percolates down into the bedrock to a depth of a few km (1-3) where it takes up heat from the hot rock and ascends subsequently, towards the surface, because of reduced density. Some of the systems may simply be deep-rooted ground-water systems, of great horizontal extent, but most of the systems are believed to be more localized convection systems, wherein heat is transported from depth to shallower formations (Bodvarsson, 1982; Bjornsson *et al.*, 1990). The former may constitute practically steady-state phenomena, whereas the latter must in essence be transient.

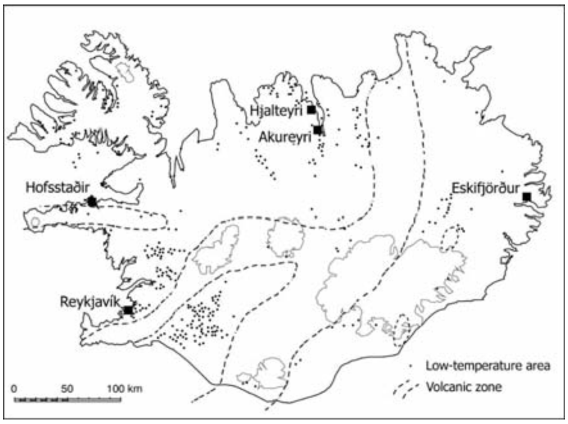

Figure 1: Locations of low-temperature areas in Iceland. Areas discussed here are indicated.

A steady-state process can not explain the high natural heat output of the largest low-temperature systems in Iceland, which may be of the order of 200 MW_t. Therefore, Bodvarsson (1982, 1983) proposed a model for the heat-source mechanism of the activity, which can explain the high heat output. This model appears to be consistent with the data now available on most of the major low-temperature systems (Bjornsson *et al.*, 1990). According to his model, presented in Fig. 2, the recharge to a low-temperature system is shallow ground water flow from the highlands to the lowlands. Inside a geothermal area the water sinks through an open fracture, or along a dike, to a depth of a few km where it takes up heat and ascends. In the model the fracture is closed at depth, but opens up and continuously migrates downward during the heat mining process by cooling and contraction of the adjacent rock.

Theoretical calculations based on Bodvarsson's model (Axelsson, 1985) indicate that the existence and heat output of such low-temperature systems is controlled by the temperature and stress conditions in the crust. In particular, the local stress field, which controls whether open fractures are available for the heat mining process and how fast these fractures can migrate downward. Given the abnormal thermal conditions in the crust of Iceland it appears, therefore, that the regional tectonics and the resulting local stress field are the main factors controlling the low-temperature activity.

2. LOW-TEMPERATURE RESOURCE EXPLORATION AND ASSESSMENT IN ICELAND

Exploration for exploitable low-temperature geothermal resources has been ongoing in Iceland since the middle of last century. The methods used involve various geological and geophysical methods. Some of the methods used half a century ago are still valid but the methods have evolved and new methods have been developed. The principal methods used today are the following:

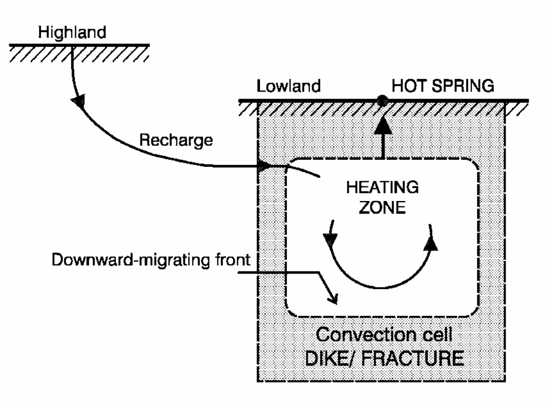

Figure 2: Model of the heat-source mechanism of the more powerful low-temperature systems in Iceland. Based on Bodvarsson (1983).

(A) Geological mapping: Geological mapping plays a key role in low-temperature exploration in Iceland. Particular emphasis is normally placed on mapping faults, fractures and dykes. Fracture analysis takes place in the field as well as through detailed studying of aerial photos.

(B) Resistivity surveying: Various methods of resistivity surveying have been used in low-temperature exploration in Iceland. These include Schlumberger, Head-on and TEM soundings.

(C) Magnetic surveying: Ground magnetic surveys are often conducted during low-temperature exploration. Their main purpose is to locate basaltic dykes and to delineate major faults.

(D) Temperature gradient surveying: This has turned out to be a very successful method of exploration. Shallow exploration wells are drilled into the poorly permeable basaltic bedrock and the temperature gradient measured in the wells directly infers the local heat-flow. This is because variations in thermal conductivity are quite small due to the homogeneity of the basaltic bedrock. Drilling about 50 m into the bedrock usually suffices so temperature gradient wells may be of the order of 50 – 100 m in depth.

(E) Geochemical surveying: Hydrochemistry surveys are conducted to estimate reservoir temperatures, delineate regional ground-water movement and to map the areal extent of geothermal systems.

Eysteinsson *et al.* (1994) discuss the resistivity methods employed in Iceland while Flovenz *et al.*, 2000 discuss the other methods, with reference to a specific case study at Arsskogsstrond in N-Iceland.

Low-temperature exploration usually starts with regional reconnaissance, which may involve all of the methods above, except ground magnetic surveys. Such regional studies may e.g. involve one temperature gradient well or one resistivity sounding per km^2 or so. When promising (low-resistivity and/or high temperature gradient) locations have been found these are studied in more detail with some or all of the methods listed above. This may also involve drilling of deeper wells, perhaps as deep as 500 m, when a specific target is being approached.

The low-temperature systems in areas devoid of surface manifestations discussed in this paper were all discovered after intense surface exploration involving these geological and geophysical methods. The key to the discovery of all the fields has, however, been temperature gradient exploration through the drilling of shallow temperature surveying wells, both during regional reconnaissance and local studies. During the last one or two decades increased emphasis has been placed on temperature gradient surveying in low-temperature geothermal exploration, while the importance of resistivity surveying has decreased. This is partly because such shallow drilling has become relatively inexpensive but also because this method involves direct measurements in contrast to the indirect nature of resistivity surveying. In fact temperature gradient surveying has replaced resistivity surveying as the principal tool of low-temperature geothermal exploration in Iceland.

More than 20 low-temperature systems, devoid of surface manifestations, have been discovered in Iceland during the last two decades. This includes the three systems discussed here; Hofsstadir, Hjalteyri and Eskifjördur. Most of these systems are located in W-Iceland and in central N-Iceland, while a few are also located in S and E-Iceland. Temperature gradient exploration has played an essential role in the discovery of all these systems.

Axelsson and Gunnlaugsson (2000) describe the monitoring and reservoir engineering work carried out in conjunction with the utilization of the low-temperature systems in Iceland, in particular the methods employed to model low-temperature reservoirs and to assess their energy production potential. The principal tools are various simple modeling methods, in particular lumped parameter modeling. The methods selected are primarily determined by the purpose of a study, available data and available funds. Lumped parameter models have been used to simulate the three systems studied here, to estimate their properties, calculate future predictions and estimate their energy production capacity.

Lumped models have been used extensively to simulate data on water level and pressure changes in geothermal systems in Iceland, as well as in other parts of the world (Axelsson *et al.*, 2005; Axelsson and Gunnlaugsson, 2000). Axelsson (1989) has described an efficient method that tackles the simulation as an inverse problem and can simulate such data very accurately, even very long data sets (several decades). It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters.

The theoretical basis of this automatic method of lumped parameter modeling is presented by Axelsson (1985 and 1989). The *LUMPFIT* computer code has been used since 1986 in the lumped modeling studies carried out in Iceland (Axelsson and Arason, 1992).

A general lumped model is shown in Fig. 3. It consists of a few tanks and flow resistors. The water level or pressure in the tanks simulates the water level or pressure in different parts of the geothermal system. The resistors simulate the flow resistance in the reservoir, controlled by the permeability of its rocks. The first tank simulates the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model in Fig. 3 is, therefore, open. Without the connection to the constant pressure source the model would be closed. An open model may be considered optimistic, since a equilibrium between production and recharge is eventually reached during long-term production, causing the water level draw-down to stabilize. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines steadily with time, during long-term production. In addition, the model presented in Fig. 3 is composed of three tanks; in many instances models with only two tanks have been used.

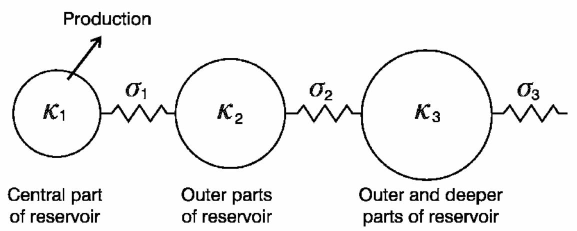

Figure 3: A general lumped parameter model used to simulate water level or pressure changes in geothermal systems.

Hot water is pumped out of the first tank, which causes the pressure and water level in the model to decline. This in turn simulates the decline of pressure and water level in the real geothermal system. When using this method of lumped parameter modeling, the data simulated are the water level data for an observation well inside the well-field, while the input for the model is the production history of the geothermal field in question.

3. HOFSSTADIR IN W-ICELAND

The Hofsstadir geothermal system was discovered during an extensive regional reconnaissance on the northern part of the Snaefellsnes peninsula in W-Iceland (Fig. 1). This reconnaissance, which was most intense in 1995 and 1996, has continued to this day. More than 120 exploration wells, mostly 50 - 100 m in depth, have been drilled in the region since 1995. The region has a surface area of approximately 800 km^2.

During the reconnaissance a temperature gradient anomaly was discovered at Hofsstaðir about 5 km south of the town of Stykkisholmur (1500 inhabitants). This was followed up by more localized geological-, magnetic- and temperature gradient surveying, which confirmed a pronounced temperature gradient anomaly of up to 400°C/km shown in Fig. 4 (Olafsson *et al.*, 2004). For comparison the regional temperature gradient is of the order of 70°C/km.

The bedrock in the Hofsstadir area is mainly composed of Miocene basalts from which about 1000 m have been eroded. Alteration indicating a fossil temperature of 260 - 300°C has been found in the reservoir. The dominant structural grain of the area is NE-SW as defined by basaltic dykes, faults and the strike of the basalts. A more recent tectonic pattern of east-west faults and rare NW-SE dykes is less conspicuous. This is interpreted as a conjugate set in response to maximum WNW-ESE horizontal compression. The geothermal system at Hofsstadir is related to dykes trending NW-SE. Although of Miocene age they form a plane of weakness, which breaks up under the present stress field.

During the autumn of 1996 a production well, HO-1, was drilled to a depth of 855 m in the center of the main anomaly. The well was cased to a depth of 156 m and intersected two main aquifers with water at a temperature between 86 and 88°C. Air-lift testing at the end of drilling indicated that well was quite productive (~40 L/s).

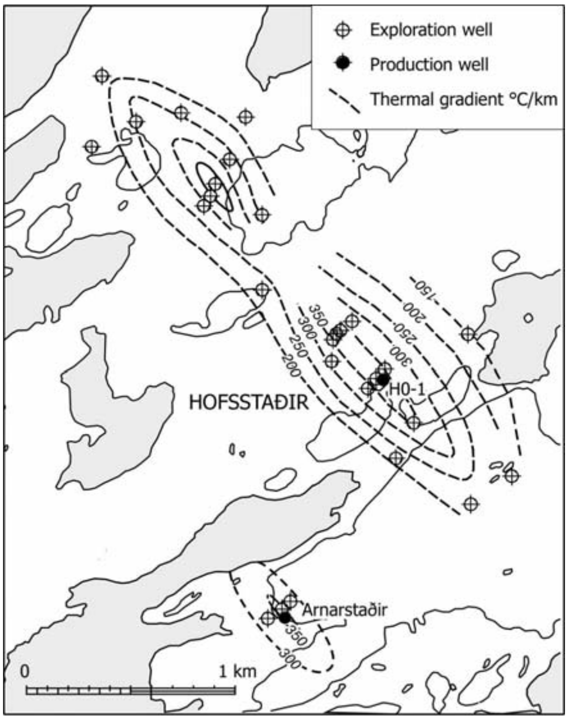

Figure 4: Map of the Hofsstadir area showing exploration wells, temperature gradient contours and well HO-1.

In order to evaluate the feasibility of constructing a *hitaveita* from Hofsstadir to Stykkisholmur well HO-1 and geothermal reservoir were tested for a period of 4 months in 1997 by pumping 15 – 20 L/s from the well. The purpose of the test was twofold. Firstly, to assess the production potential of the well and reservoir and, consequently, decide whether well HO-1 could sustain the hot water production required for heating Stykkisholmur and the closest vicinity, and secondly, to test scaling and corrosion characteristics of the geothermal fluid.

The principal results of the production test were that well HO-1 should most likely be able to sustain an average production of 15 – 20 l/s (Bjornsson *et al*., 1997). Through a comparison with other comparable communities in Iceland, heated by geothermal, it was estimated that Stykkisholmur would require an average flow rate between 12 and 20 l/s. Thus it was concluded that well HO-1 would sustain the hot water production required to fulfill the requirements of the Stykkishólmur community. It should be mentioned that considerable uncertainty was inherent in the production capacity estimate, which was reflected in the fact that a closed (pessimistic) model predicted a rapidly increasing draw-down at these production rates. It was assumed, however, if this turned out to be the case that reinjection could be applied for pressure support in the long run.

Utilization of well HO-1 started during middle to late 1999. Since that time the hot water production, as well as the response of the well and geothermal reservoir, has been monitored carefully through a computerized monitoring system (Kristmannsdóttir *et al.*, 2002). The average yearly production since that time has been of the order of 19 L/s. The production response of well HO-1 has been accurately simulated by a lumped parameter model. The results of the simulation are presented in Fig. 5 and the principal properties and characteristics of the reservoir, deduced from this modeling, are presented in Table 1 below. Fig. 5 shows that water level has, in fact, declined rapidly. The Hofsstadir reservoir has fairly good internal permeability, or a permeability-thickness of the order of 15 Darcy-m. This explains the wells high short term productivity. In contrast the reservoir appears to have very low external permeability, or behave as almost closed, which explains the continuously increasing draw-down.

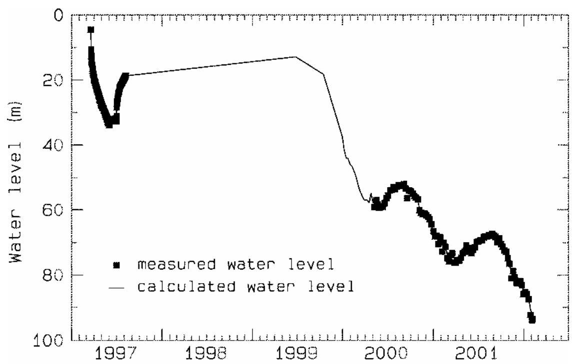

Figure 5: Water level data from well HO-1 at Hofsstadir simulated by a lumped parameter model. The data set used includes data from the production test in 1997 and the first two years of the production history of the well.

Predictions have been calculated for various future production scenarios, which will not be discussed here. Fig. 6 shows predictions for one of the scenarios as an example. The small difference between the predictions of the open and closed models is noteworthy, it probably reflects the closed nature of the Hofsstadir reservoir.

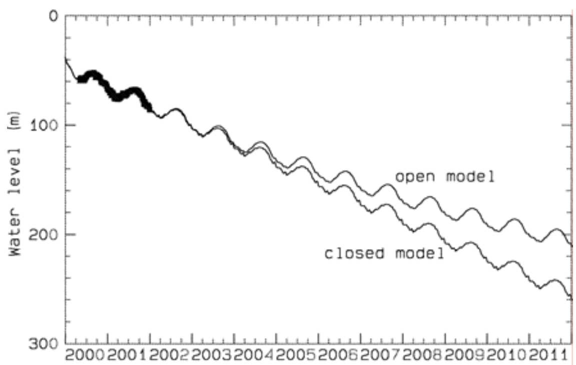

Figure 6: Predicted water level changes in well HO-1 at Hofsstadir until 2012 for a production scenario assuming the same production as in 2001, calculated by a closed and open version of a lumped parameter model.

The water from well HO-1 is relatively mineral-rich compared to most low-temperature water in Iceland (see Table 2). Chlorine (Cl) is the main anion (~3000 mg/L) while calcium (Ca) is the main cation (~1200 mg/L) instead of potassium (Na), which normally is the main cation (Kania and Olafsson, 2005). Chemical geothermometers reflect a reservoir temperature of 90-95°C while the stable isotopic ratio indicates that the water is very old (since last ice-age).

4. HJALTEYRI IN N-ICELAND

The Hjalteyri geothermal system is located on the western shore of the Eyjafjordur fjord in central N-Iceland (Fig. 1). It was discovered after an unsuccessful seawater well, to be used by a near-by fish farm, revealed an above average temperature gradient. Following this extensive and detailed geothermal prospecting was conducted in the area, which culminated by the drilling of a highly productive production well during the summer of 2002 (Gautason *et al.*, 2005).

The geothermal prospecting in the Hjalteyri area is described in detail by Gautason *et al.* (2005). It involved the conventional geological, magnetic and temperature gradient surveying. A total of 15 temperature gradient wells were drilled, ranging in depth from 60 to 200 m, with one well extending down to 450 m depth. The temperature gradient mapping revealed a clear anomaly of up to 300 °C/km in an area where the regional gradient is of the order of 60 °C/km (Fig. 7). The magnetic mapping indicated the presence of a dyke trending N14°E, coinciding with the temperature anomaly. In addition to this conventional surveying drill cut analysis, lithological logging as well as televiewer logging aided in delineating the geothermal system (Gautason *et al.*, 2005).

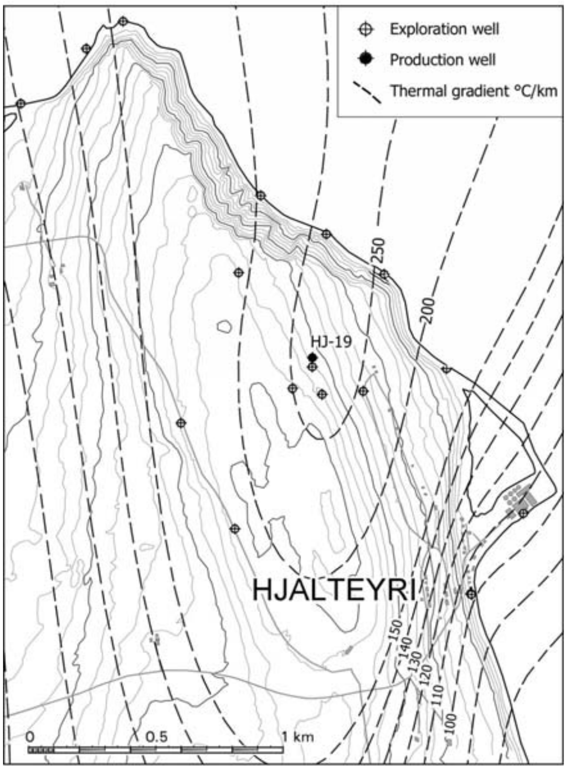

Figure 7: Map of the Hjalteyri area showing exploration wells, temperature gradient contours, a basaltic dyke believed to play a key role and well HJ-19.

The bedrock in the Hjalteyri area is composed of late Tertiary basalt flows intercalated with thin sediments. The lava pile dips 6° to the south and is cut by basaltic dykes, faults and fractures. Some recent faulting trending N-S is evident in the area. The Hjalteyri anomaly is, furthermore, aligned with three other N-S trending anomalies along the western shore of Eyjafjordur, namely Ytrivik, Brimnes-borgir and Hrisey.

During the summer of 2002 a production well, HJ-19, was drilled into the anomaly to a depth of 1450 m with the intention of intersecting target dykes between 1000 and 1500 m depth. The well was cased to a depth of 400 m. It intersected productive aquifers at 1170 and 1250 m depth, associated with one of the dykes. At that depth temperature is about 90°C. At the end of drilling the well yielded about 45 L/s by free-flow and more than 100 L/s through air-lift testing.

In order to estimate the production capacity of this newly discovered Hjalteyri geothermal system, well HJ-19 was tested for a period of 13½ months. First for a little over 9 months at about 20 L/s and, consequently, for about 4 months at 3 L/s. During the testing comprehensive data were collected by a computerized monitoring systems, water level in nearby wells was observed manually and changes in chemical content monitored. The test and consequent data interpretation and modeling are described by Axelsson *et al.* (2003) and Gautason (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 and the principal properties and characteristics of the Hjalteyri reservoir, deduced from the modeling, are presented in Table 1 below. The Hjalteyri reservoir appears to be 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. It also appears large in size, i.e. with a great volumetric storage.

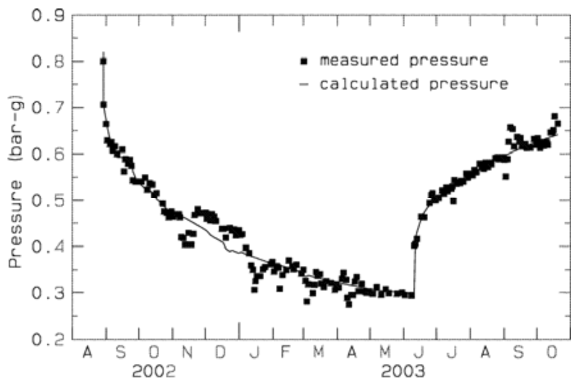

Figure 8: Pressure change data from well HJ-19 collected during production testing of the Hjalteyri geothermal system simulated by a lumped parameter model. Production was about 20 L/s until early June 2003, but about 3 L/S during the following recovery period.

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.

The water from well HJ-19 has low chemical content and is similar to water from geothermal areas in the region (see Table 2). At the wellhead, the measured temperature (~86-90°C) is higher than indicated by deep-water temperature estimates based on mineral equilibria of calcedony (81°C) as a result of the high pH value of the water. During the well-testing period samples from the well were collected regularly and they analyzed for selected elements. To date there have been no changes in chemical content or isotope ratios to indicate any inflow of colder groundwater or seawater.

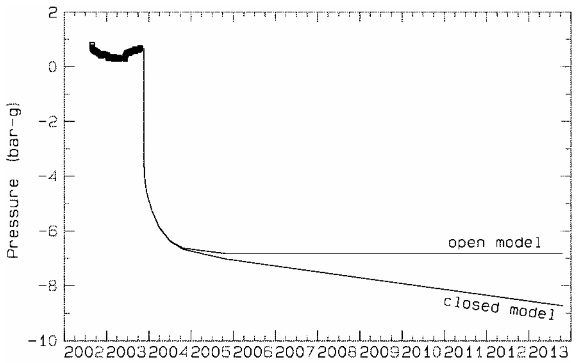

Figure 9: Predicted pressure changes for well HJ-19 at Hjalteyri until 2013 for a production scenario assuming a constant production of 150 L/s, calculated by a closed and open version of a lumped parameter model. Negative pressure indicates pressure draw-down.

A 19 km pipeline has now been installed, connecting well HJ-19 at Hjalteyri to the *hitaveita* for the city of Akureyri (16000 inhabitants) to the south (Flovenz *et al.*, 2005). 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.

It is noteworthy that the Hjalteyri geothermal system appears to be about an order of magnitude more productive than several other geothermal system closer to Akureyri, also utilized by the Akureyri *hitaveita* (Flovenz *et al.*, 2005). The reason is believed to be the fact that the western shore of Eyjafjordur is much more tectonically active than the region were the other systems are located.

5. ESKIFJÖRDUR IN E-ICELAND

It has been generally accepted that the part of Iceland east of the volcanic zone is to a large extent lacking in geothermal activity (Fig. 1). This applies, at least, to geothermal systems with surface manifestations. In spite of this some extensive temperature gradient surveying has been ongoing in the neighborhood of population centers in the East during the last few years. A few anomalies have been discovered and one of these is associated with the Eskifjordur geothermal system (Fig. 1).

The discovery of the Eskifjordur anomaly was followed up by a more detailed local geological-, and temperature gradient prospecting, which was concluded by the drilling of a successful production well, ES-1. Twenty-two temperature gradient wells were drilled, ranging in depth from 36 to 132 m (Fig. 10). A few of the wells were consequently deepened to 240 – 640 m depth. The maximum temperature gradient observed was close to 150 °C/km compared to a regional gradient of about 60 °C/km.

The bedrock in the Eskifjordur area is composed of late Tertiary basalt flows intercalated with thin sediments, thick tuff layers and a group of andesite and rhyolite lavas. The fracture that is believed to control the up-flow of the geothermal water has a NNW trend and tilts 85° towards WSW. The lavas tilt about 6° towards SW and the dykes have a northerly trend and tilt about 85° towards E.

During the autumn of 2002 a production well, ES-1, was drilled into the Eskifjordur anomaly (Fig. 10). It was drilled to a depth of 1327 m and cased to a depth of 430 m. A good feed-zone, with a temperature a little over 80°C, was intersected at approximately 930 m depth. During air-lift testing at the end of drilling the well yielded up to 30 L/s with less than a 100 m water-level draw-down. In addition the well turned out to be artesian, with free-flow declining from 7 to 4.5 L/s during a four month period following the drilling operation.

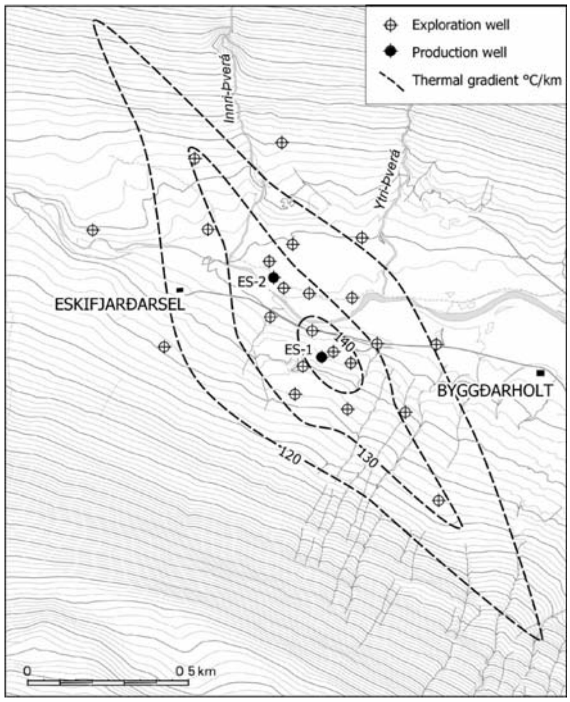

Figure 10: Map of the Eskifjordur area showing exploration wells, temperature gradient contours and wells ES-1 and ES-2.

Following the successful drilling of well ES-1 the possibility of utilizing water from the well for space-heating the Eskifjordur community (about 1000 inhabitants) has been evaluated. Part of that involved production testing the well for an extended period, just as in the cases of Hofsstadir and Hjalteyri. Therefore, the well was tested from the middle of February 2003 till the middle of July the same year, or for a period of 5 months. During the test production from well ES-1 declined from 20 L/s initially to about 16 L/s towards the end of the test. Comprehensive data were collected during the test, including water level data for well ES-1 and a few other wells in the area. The pressure recovery following the test was also carefully monitored. Water samples for chemical analyses were also collected during the test.

The water level transients observed in well ES-1 during the test were accurately simulated by a lumped parameter model. The results are presented in Fig. 11 and the principal properties and characteristics, deduced from the modeling, are presented in Table 1 where they can be compared with the same parameters for Hofsstadir and Hjalteyri. The Eskifjordur geothermal system appears to be rather poorly permeable, or with an internal permeability thickness of the order of 3 Darcy-m. This is comparable to the permeability thickness of the less productive low-temperature geothermal systems in Iceland, which are generally located in the older and less tectonically active areas of the country.

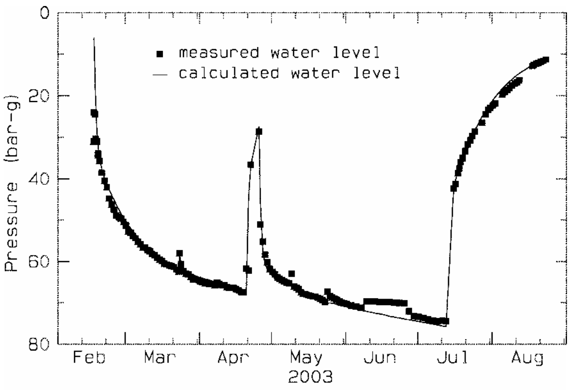

Figure 11: Water level data from well ES-1, during the production test in 2003, simulated by a lumped parameter model.

The lumped parameter model was, consequently, used to calculate water level predictions for well ES-1 during long-term water production. An example of the results is presented in Fig. 12, which clearly demonstrates the uncertainty in such predictions based on short data sets. The results indicate that it's likely that after 5 years of a constant 15 l/s production the water level in the well may have declined to 130 – 170 m depth. A conservative prediction by a closed version of the lumped parameter model indicates that the water level will have dropped to a depth below 250 m, which is the maximum operating depth of hot water pumps presently used in Iceland. If this turns out to be the case reinjection may be applied in the Eskifjordur field to counteract the pressure draw-down. This need further study, as well as drilling of a specific reinjection well.

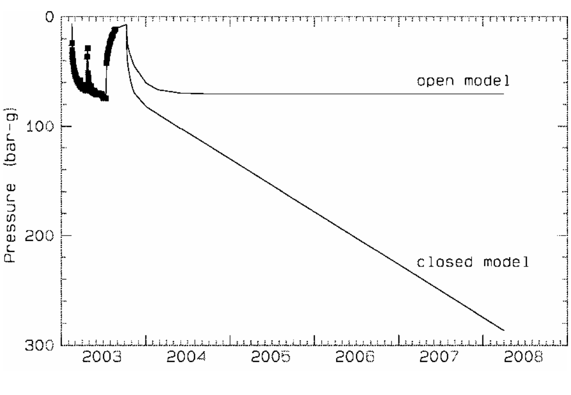

Figure 12: Predicted water level changes for well ES-1 in Eskifjordur until 2008 for a production scenario assuming a constant production of 15 L/s, calculated by a closed and open version of a lumped parameter model.

The water from well ES-1 has relatively high mineral content compared to most low temperature area in Iceland (Table 2). The chlorine content is about 400 mg/L and TDS are about 1200 mg/L. Water chemistry was monitored during the production testing of well ES-01, but significant changes were not detected. Calculations show that the water is slightly supersaturated with respect to calcite, as is the case for most low temperature geothermal waters in Iceland. However, the scaling potential for calcite is believed to be low. Chemical geothermometers indicate a reservoir temperature of 75-80°C, similar to the water temperature at wellhead.

Following the successful drilling of well ES-1 a second production well, ES-2, was drilled in Eskifjordur in early 2004 (see Fig. 10). It is directionally drilled about 109 m to the ESE, has a drilled depth of 1004 m as well as being cased to a depth of 470 m. It turned out to be more productive than well ES-1, according to air-lift testing at the end of drilling, most likely because of smaller turbulence pressure losses. Comprehensive testing of this new well and the interference between the two wells is planned for the summer of 2004. The results will provide the basis for the design of a *hitaveita* (district heating service) for the Eskifjordur community.

5. COMPARISON WITH OTHER LOW-TEMPERATURE SYSTEMS IN ICELAND

It is evident that the nature and properties of the three low-temperature geothermal systems discussed above; Hofsstadir, Hjalteyri and Eskifjordur are quite variable. They don't appear to have anything in particular in common that might explain the fact that they are without apparent surface manifestations. Therefore, their nature and properties have been compared with the nature and properties of a few other low-temperature geothermal systems in Iceland, which have/had observable surface manifestations. These systems are *Hamar* (Axelsson and Stefansson, 2003), *Thelamork* (Bjornsson *et al.*, 1994) and *Laugaland* (Axelsson *et al.*, 2001)) in the Eyjafjordur region in central N-Iceland, all relatively close to Hjalteyri, *Laugarnes* inside Reykjavik (Axelsson and Gunnlaugsson, 2000) and *Kaldarholt* (Zhang, 2003) and *Gata* (Axelsson *et al.*, 1995) in central S-Iceland.

Tables 1 and 2 present this comparison. The first table presents a simple comparison of the systems' nature and properties, mostly based on the results of lumped parameter modeling, while the second table presents a comparison of their chemical properties. The following reservoir engineering properties/conditions are presented in Table 1:

(1) Calculated unit step response of a system after 100 days of production, i.e. the response after constant production of 1 kg/s.

(2) Internal permeability-thickness of a system according to the parameters of a lumped parameter model.

(3) Minimum total storage capacity based on the sum of the storage coefficients of tanks of a closed version of a lumped parameter model of a system. This should reflect the size of a system, but is also dependent on the storage mechanisms in effect (Axelsson, 1989).

(4) A qualitative estimate of the significance of recharge to a system. Classified either as limited, small, partial or strong.

(5) Inferred boundary conditions of a system. Classified either as closed, semi-closed, semi-open or open.

The chemical composition of water samples, collected in 2003, from wells in the same areas is presented in Table 2. In general low-temperature geothermal water in Iceland has very low chemical content. This is reflected in the table where most of the systems have total dissolved solids of only 200 – 300 mg/L.

Table 1 shows that in general the variability in the nature and properties of low-temperature geothermal systems in Iceland is so great that the nature and properties of the three systems presented here fall within the range defined by the other systems. In other words they don't appear to stand out in one way or another. Hjalteyri, for example, appears to be quite similar to the Laugarnes system and Eskifjordur to the Gata system. Only the Hofsstadir system appears a little different in that it has unusually closed boundaries and limited recharge.

To study this further a few cross-plots were drawn. A plot of step response vs. permeability-thickness showed an obvious relationship, so such a plot is not presented here. Fig. 13, however, shows the relationship between total storage capacity and permeability thickness. There Hofsstadir and Eskifjordur clearly stand out in that their storage appears to be abnormally small. It should be pointed out that the minimum storage capacity estimate for Eskifjordur is based on a relatively short data set, which normally results in a somewhat smaller storage capacity estimate. Yet, the figure demonstrates clearly that these two systems have smaller storage capacity than might be expected on basis of their permeability (presented as u(100 days)) and the relationship evident for the other systems.

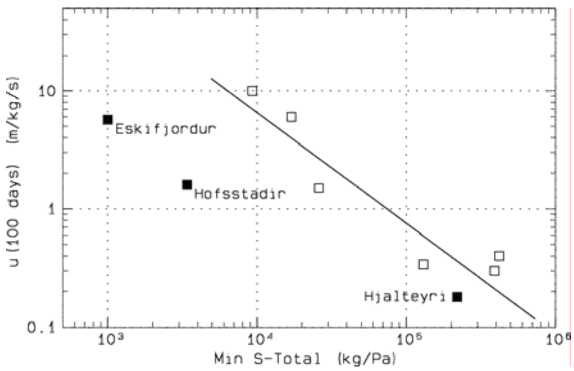

Figure 13: A cross-plot showing the relationship between total storage capacity and permeability thickness for the geothermal systems presented in Table 1.

The chemical data (Table 2) shows that the Hjalteyri fits in with the other systems selected for comparison. The chemistry of the Hofsstadir water is markedly different and the Eskifjordur water also appears somewhat different. This can be seen in Figure 14 which shows the calcium content plotted vs. the chloride content of water-samples from Table 2. The Eskifjördur reservoir and especially the Hofsstadir reservoir have water with higher salinity than the other reservoirs. Geological investigations indicate that the Hofsstadir reservoir sits within an extinct central volcano and therefore the bedrock has suffered a high degree of alteration. The chemical information indicates that the water at Hofsstadir may be very old and that it has had a long time to equilibrate with the bedrock, which could explain the high mineral content of the water. This also agrees with the fact that the Hofsstadir system has unusually closed boundaries.

The Eskifjordur reservoir is situated within a Tertiary lava pile, which has experienced low-temperature alteration. The water chemistry can most likely be explained by a mixture of dilute low-temperature water and a small amount of sea water. Yet, waters from a few other low-temperature geothermal systems in Iceland also appear to have a seawater component. Therefore, the chemical content in Eskifjordur can't be classified categorically as different from that of other low-temperature geothermal systems in the country.

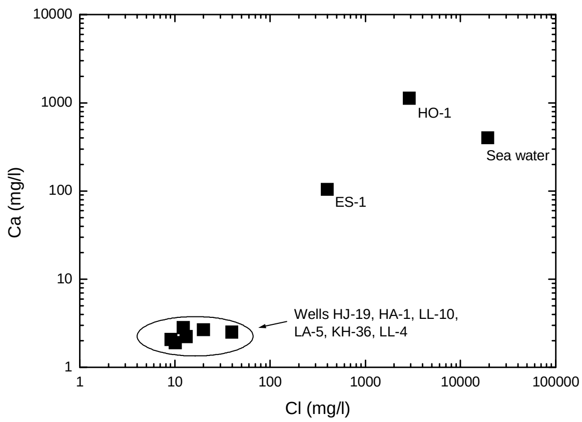

Figure 14: A cross-plot showing the relationship between chloride- and calcium content of water samples from the geothermal systems presented in Table 2.

7. CONCLUDING REMARKS

The purpose of this paper has been to study whether the nature and properties of hidden low-temperature geothermal systems in Iceland are in any way different from the nature and properties of systems with surface manifestations. For this purpose reservoir engineering and chemical information on the recently discovered low-temperature systems at Hofsstadir in W-Iceland, at Hjalteyri in N-Iceland and in Eskifjordur in E-Iceland has been reviewed and compared with corresponding information for six other low-temperature geothermal systems in Iceland.

The comparison indicates that the reservoir- and chemical characteristics of the Hjalteyri system fall within the range observed for other low-temperature systems in Iceland. In fact it appears comparable to the powerful Laugarnes system in Reykjavik. The Hofsstadir system appears to be markedly different, however. It appears to be unusually small and have abnormally closed boundaries. This is supported by water chemistry, which indicates that the water at Hofsstadir may be very old. The Eskifjordur system also appears to be somewhat different, but can't be categorically classified as so.

But why does a powerful geothermal system like the one at Hjalteyri not have clear surface manifestations? It is possible that the outflow from the system is either directly into the ocean, on the ocean-floor, or into the ground-water system above the geothermal reservoir and through that into the ocean. This may also apply to the Hofsstadir and Eskifjordur systems, even though it may be likely, based on the discussion above, that the Hofsstadir system simply doesn't have an outflow, or perhaps has only a very minor one. The unusual characteristics of the Hofsstadir system are attributed to the tectonic setting of the Snaefellsnes-peninsula in W-Iceland.

In general it may be stated that this needs further study. On one hand the chemical characteristics of all low-temperature systems in Iceland are not fully understood. On the other hand their nature and properties are only revealed slowly as their production histories extend with time. This, in particular, applies to the Eskifjordur system, which only has a relatively short testing history.

ACKNOWLEDGEMENTS

The authors thank the following *hitaveitur* (district heating services), municipal power companies and communities for the permission to present information pertaining to geothermal systems used by them: The Stykkisholmur hitaveita, Nordurorka, Austurbyggd, the Dalvik hitaveita, Reykjavik Energy and the Rangarvellir hitaveita.

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Table 1. Summarized information on nature and properties of the Hofsstadir, Hjalteyri and Eskifjordur low-temperature geothermal systems compared with corresponding information for a few other low-temperature geothermal systems in Iceland. The information is: (1) calculated unit step response after 100 days of production (u(100 days)), (2) internal permeability thickness (kh), (3) minimum total storage capacity (S_{Total}), (4) estimated recharge and (5) inferred boundary conditions (BC).

Geothermal system	u(100 days) (m/kg/s)	kh (Darcy-m)	Min. S_{Total} (kg/Pa)	Recharge	Inferred BC
Hofsstadir	**1.6**	**15**	**3400**	**limited**	**closed**
Hjalteyri	**0.18**	**110**	**220,000**	**strong**	**open**
Eskifjordur	**5.7**	**3.0**	**1000**	**small**	**semi-closed**
Hamar (N-Iceland)	0.34	100	130,000	strong	open
Thelamork (N-Iceland)	10.0	0.85	9300	partial	semi-open
Laugaland (N-Iceland)	1.5	12	26,000	small	semi-closed
Laugarnes (Reykjavik)	0.3	140	390,000	strong	open
Kaldarholt (S-Iceland)	0.4	70	420,000	strong	open
Gata (S-Iceland)	6.0	4.6	17,000	small	semi-closed

Table 2. Information on chemical content of water produced from wells HO-1, HJ-19 and ES-1 compared with the chemical content of water from a few other low-temperature geothermal systems in Iceland. In addition to temperature (T), pH and concentration of total dissolved solids (TDS), the concentration of carbonate (CO_2(t)), hydrogen sulfide (H_2S), silica (SiO_2), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), fluoride (F), chloride (Cl), sulfate (SO_4), aluminum (Al) and iron (Fe) is presented (mg/L). The concentration of deuterium and oxygen-18 is, furthermore, presented relative to SMOW. All the data are based on samples collected in 2003.

	Geothermal system (well)								
Chemical parameter	**Hofsstadir (HO-1)**	**Hjalteyri (HJ-19)**	**Eskifjordur (ES-1)**	Hamar (HA-1)	Thelamork (LL-10)	Laugaland (LA-05)	Laugarnes (RV-05)	Kaldarholt (KH-36)	Gata (LL-04)
T (°C)	**86**	**84**	**80**	64	104	95	128	67	97
pH	**8.31**	**9.96**	**9.23**	10.2	9.68	9.79	9.40	10.23	9.87
CO_2(t)	**3.42**	**18.7**	**4.3**	15.1	25	19.8	17.1	13.1	21.7
H_2S	**0.08**	**0.15**	**0.06**	0.04	0.17	0.05	0.5	0.16	0.04
SiO_2	**70.8**	**113**	**57.1**	88.2	127	97.4	141	88	96.7
Na	**708**	**57.3**	**283**	49.4	56.2	52.8	68.7	64.5	87.8
K	**13.5**	**1.1**	**4.25**	0.55	1.5	1.14	2.6	0.65	1.62
Mg	**0.48**	**0.004**	**0.01**	0.002	0.002	0.002	0.004	0	0.002
Ca	**1130**	**1.9**	**104**	2.07	2.23	2.82	4.04	2.66	2.52
F	**1.33**	**1.65**	**2.97**	0.47	0.74	0.38	1.00	2.31	1.14
Cl	**2900**	**10.1**	**399**	9.14	13.2	12.3	53.2	20	39.7
SO_4	**328**	**16.6**	**311**	13	27.6	38.7	41.2	25.2	55.9
Al	**0.008**	**0.131**	**0.021**	0.084	0.178	0.146	0.186	0.095	0.236
Fe	**0.011**	**0.005**	**0.002**	0.001	0.017	0.01	-	0.001	0.01
TDS	**5290**	**244**	**1210**	206	267	241	329	239	322
δO^{18} (‰)	**-11.0**	**-14.1**	**-12.6**	-14.7	-14.0	-13.4	-	-9.79	-10.4
δD (‰)	**-65.5**	**-100**	**-89.6**	-105.2	-	-	-	-66.5	-73