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Low-temperature geothermal utilization in Iceland – Decades of experience

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ABSTRACT

Geothermal energy plays a key role in the economy of Iceland and it supplies about 89% of the space heating requirements. A large fraction of the country's district heating services (hitaveitas) use energy from low-temperature geothermal systems, which are mostly located outside the volcanic zone. Many of the geothermal district heating services have been in operation for several decades and much can be learned from their operation, in particular regarding long-term management of low-temperature geothermal resources. In most cases down-hole pumps are used, but there are examples of large-scale artesian flow still being maintained. The Reykjavík geothermal district heating service is the world's largest such service. It started operation on a small scale in 1930, and today it serves Reykjavík and surrounding communities, about 58% of the total population of Iceland. The Reykjavík district heating service utilizes three low-temperature systems. The production and response (pressure, chemistry, and temperature) histories of these systems and six other low-temperature geothermal systems are discussed. Four of the systems are very productive and reach equilibrium at constant production. Two are much less productive and do not attain equilibrium, while three are of intermediate productivity. Groundwater inflow has caused temperature decline and chemical changes in two of the systems. Several problems have faced the Icelandic low-temperature operations, such as excessive pressure drawdown caused by overexploitation, colder water inflow, and sea water incursion. None of the district heating systems has ceased operation and solutions have been found to these problems. The solutions include improving the energy efficiency of the associated heating systems, deeper and more focussed drilling (e.g., directional drilling), finding new drilling targets (even new drilling areas), and injection, as well as technical solutions on the surface. The long utilization case histories provide important information pertaining to sustainable management of geothermal resources.

1. Introduction

Geothermal energy plays a major role in the economy of Iceland. At present, high- and low-temperature resources provide about 66% of the primary energy supply for the almost 320,000 inhabitants, or about 135 PJ (1 PJ = 10^{15} J; data for 2007). The principal use of geothermal energy in Iceland is for space heating. Currently, about 89% of the space heating is by geothermal energy, having increased from about 45% in 1970 (see Fig. 1). 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 electricity generation (Ragnarsson, 2008).

At present, there are 22 public, or municipally owned, geothermal heating companies in Iceland operating 62 separate district heating systems or networks. In Icelandic these are called *hitaveita* (in the singular). By far, the largest is the heating company serving the capital city of Reykjavik and five neighbouring communities. It is operated by Reykjavík Energy and serves more than 180,000 inhabitants. Its geothermal energy use currently amounts to about 12 PJ/year. Another two hitaveitas serve 18,000–20,000 inhabitants while the remaining 59 public hitaveitas are relatively small, serving communities with only a few households to a few thousand inhabitants each. Their annual energy use ranges from 5 to 500 TJ/year (1 TJ = 1012 J). In addition, numerous small private hitaveitas exist in rural areas, each typically serving ten to twenty farms. These systems presently serve about 4000 inhabitants. Fig. 2 shows the 15 largest hitaveitas in Iceland ranked according to the hot water production.

Fifty-four of the public hitaveitas, and all of the private ones, use energy from some of the numerous low-temperature geother-

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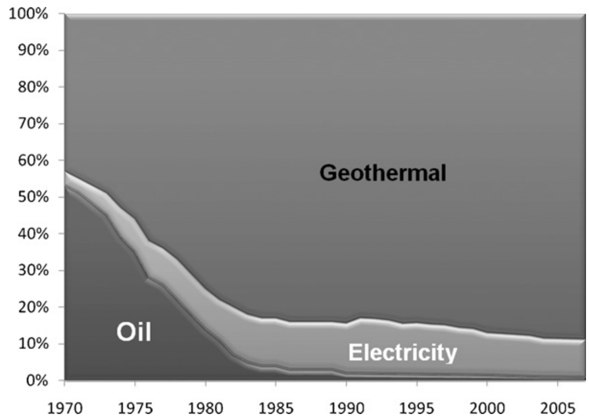

Fig. 1. Energy sources used for space heating in Iceland 1970–2007 (Ragnarsson, 2008). About 25% of the electricity is geothermal in origin while the rest is from hydropower.

mal systems found in Iceland. The low-temperature systems, which by definition have a reservoir temperature below 150 °C, are all located outside the Icelandic volcanic zone. The Reykjavík hitaveita, mentioned above, utilizes five separate geothermal areas; three low-temperature and two high-temperature (Gunnlaugsson and Ívarsson, 2010). Most of the hitaveitas use the geothermal water directly within the distribution systems.

Many hitaveitas have been in operation for several decades, the oldest ones for more than 80 years and several others for 30–60 years. Much can be learned from their operation, in particular regarding long-term management of low-temperature geothermal resources. This experience also provides valuable input into discussions and studies related to the renewability of geothermal energy and the possible contribution of geothermal energy to sustainable development (Axelsson et al., 2005a). Several problems have faced these operations, however, such as excessive pressure drawdown due to overexploitation, cold water inflow, and sea water incursion. None of the hitaveitas have ceased operation and solutions have been found to all of these problems.

The purpose of this paper is to present some of the longest Icelandic low-temperature utilization case histories and to summarize the lessons learned from the long operational experience. To begin, the current understanding of the nature of the low-temperature activity is reviewed along with a brief historical overview. Next, the overall experience is reviewed along with the presentation of nine long and well-documented case histories, including those of three low-temperature systems utilized by Reykjavík Energy. Some of the problems encountered are then discussed along with the solutions applied. Finally some general observations and recommendations are presented.

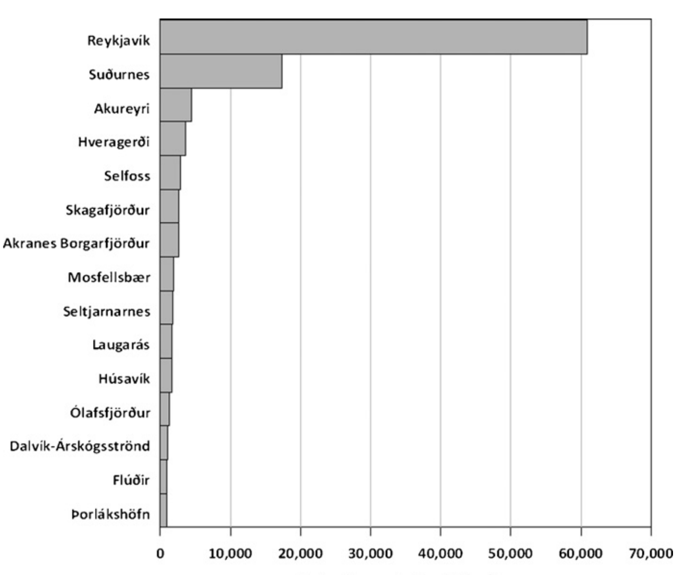

Fig. 2. Yearly hot water production of the 15 largest hitaveitas (geothermal district heating services) in Iceland (Gunnlaugsson and Ívarsson, 2010), both from high- and low-temperature resources.

2. Nature of low-temperature systems in Iceland

The low-temperature systems, which by definition have a reservoir temperature below 150 °C at 1 km depth, are mainly located outside the volcanic zone that passes through Iceland (see Fig. 3). 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 flows range from almost zero to a maximum of 180 l/s for a single spring.

The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland. Faults and fractures, which, are kept open by the continuously ongoing tectonic activity, play an essential role by providing the channels for the water circulating through the system and mining the heat. The geothermal gradient in Iceland varies from about 50 °C/km to about 150 °C/km, outside the volcanic zone (Flóvenz and Saemundsson, 1993). Inside the volcanic zone the gradient is poorly defined because of high permeability and water circulation, but the average heat-flow is of course correspondingly greater. The nature of the low-temperature activity has been discussed by several authors (Einarsson, 1942; Árnason, 1976; Bödvarsson, 1982; Björnsson et al., 1990; Arnórsson, 1995; Arnórsson et al., 2008). 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 where it takes up heat from the hot rock and subsequently ascends towards the surface because of reduced density. Some of the systems may simply be deep-rooted groundwater 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 (Bödvarsson, 1982; Björnsson et al., 1990). The former may be practically steady-state systems, whereas the latter must in essence be transient.

A steady-state process cannot explain the high natural heat output of the largest low-temperature systems in Iceland, which may be of the order of 200 MW_t. Bödvarsson (1982, 1983) proposed a model that appears to be consistent with the data now available on most of the major low-temperature systems (Björnsson et al., 1990). According to this model, presented in Fig. 4, the recharge to a low-temperature system is shallow groundwater flow from the highlands to the lowlands. Inside a geothermal area the water descends 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 assumed to be closed at depth, but it opens up and continuously migrates downward during the heat mining process by cooling and contraction of the adjacent rock.

Theoretical calculations based on Bödvarsson'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. Of particular importance is 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

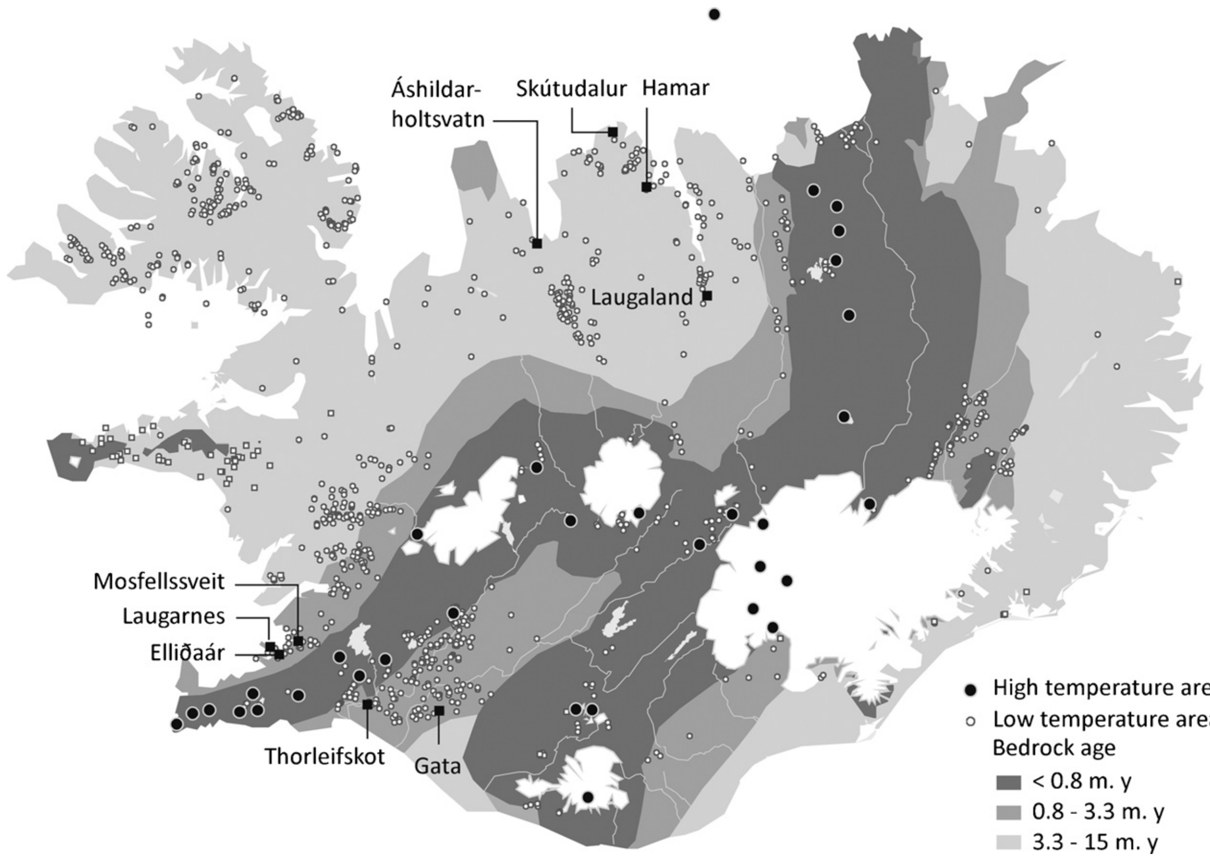

Fig. 3. Map of Iceland showing the distribution of low-temperature and high-temperature systems relative to the volcanic zone (<0.8 Myear in age). The locations of the nine low-temperature geothermal systems presented in the paper are shown on the map.

tectonics and the resulting local stress field are the main factors controlling the low-temperature activity.

A number of low-temperature systems have been discovered in recent years in areas devoid of surface manifestations, with many already in use for space heating in nearby towns and villages. They were all discovered after surface exploration, mostly shallow gradient well drilling, but also some resistivity surveying. The nature and properties of some of these systems have been studied and compared with those of other low-temperature systems in Iceland having surface manifestations. The characteristics of these systems fall within the range observed for other systems, except perhaps for systems that appear to have closed boundaries and limited recharge (Axelsson et al., 2005b).

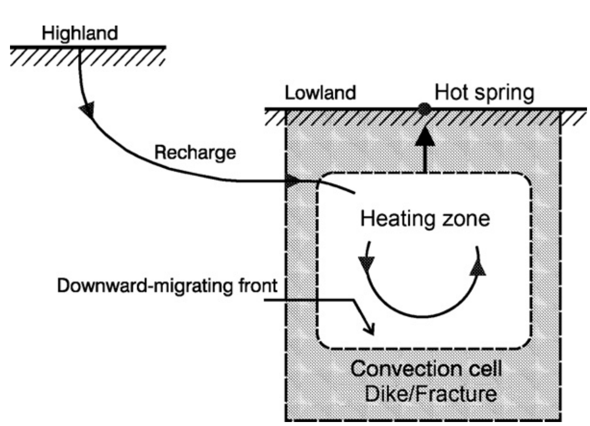

Fig. 4. Model of the heat-source mechanism of the more energetic low-temperature systems in Iceland. Based on Bödvarsson (1983).

The low-temperature systems in Iceland have been studied extensively during the last half century or so. This was done first through resource exploration, and later through reservoir engineering studies, resource assessment, and monitoring. Axelsson and Gunnlaugsson (2000) and Axelsson et al. (2005b) review the associated research and experience. Axelsson (2008) discusses the factors that control the production capacity of geothermal systems and presents Icelandic, as well as worldwide examples. Axelsson et al. (2005c) discuss lumped parameter modelling which has been used successfully to simulate the pressure changes in the Icelandic low-temperature geothermal systems during production.

3. History of low-temperature utilization in Iceland

In a cold country like Iceland, home heating needs are greater than in most countries. The average temperature in Reykjavík is −1 °C in January and 11 °C in July. Due to low summer temperatures, the heating season lasts throughout the year. Iceland is therefore suitable for localized hitaveitas and they tend to be profitable both on a national and local level.

In the Icelandic sagas, which were written in the 12–13th century A.D., bathing in hot springs is often mentioned. Commonly, baths were taken in small pools where hot water from boiling springs would often be mixed with cold water. The famous saga writer Snorri Sturluson lived at Reykholt in west Iceland in the 13th century. At that time, there was a geothermal bath at his manor, but no information is available on its age, size, or structure. There are also indications that geothermal water or steam was directed to his dwelling for heating (Sveinbjarnardóttir, 2005).

When Icelanders started moving from turf cottages into houses made of wood and concrete, at the end of the nineteenth and begin-

Table 1
Low-temperature geothermal areas in Iceland utilized by some of the oldest public hitaveitas (geothermal district heating services). The areas are listed in a clockwise manner around the country (see Fig. 3). Areas in bold are discussed in the paper.

Area	In service since	Reservoir temperature (°C)	Number of prod. wells	Average prod. 2005–2008 (l/s)	Inhabitants served	Total volume extracted (km^3)
Laugarnes (SW-Iceland)	1930	120–140	10	156	183,000[a]	0.25
Ellidaár (SW-Iceland)	1968	70-90	8	65	183,000[a]	0.13
Mosfellssveit (SW-Iceland)	1943	80-90	34	877	183,000[a]	1.1[b]
Áshildarholtsvatn (N-Iceland)	1953	70	4	71	2600	0.11
Skútudalur (N-Iceland)	1975	70	2	26	1200	0.024
Hamar (N-Iceland)	1969	65	2	38	1400	0.039
Laugaland (N-Iceland)	1977	90–100	3	36	18,000[c]	0.046
Laugar/Reykjadalur (N-Iceland)	1924	65	1	<10	300	–
Gata (S-Iceland)	1946	90–100	1	15	1900[d]	0.014
Brautarholt (S-Iceland)	1950	75	1	3	40	–
Laugarvatn (S-Iceland)	1928	100	Spring	–	200	–[e]
Thorleifskot (S-Iceland)	1948	60–130	4	76	7300[c]	–

[a] One of three low-temperature areas, and two high-temperature areas, serving the corresponding hitaveita.
[b] Since 1971.
[c] One of six low-temperature areas serving the corresponding hitaveita.
[d] One of two low-temperature areas serving the corresponding hitaveita.
[e] Data not available.

ning of the twentieth century, they needed some kind of space heating. Coal import for space heating began around 1870, and the use of coal increased continuously up to the beginning of the twentieth century. The use of oil for heating first became significant after World War II.

Using geothermal energy for house heating was first attempted in 1907, but large scale distribution of hot water for space heating did not begin until 1930, with the onset of district heating in Reykjavík, utilizing water from boreholes in the Laugarnes field. The boreholes had been drilled close to thermal springs in the area. The water was piped 3 km to a primary school in the eastern part of Reykjavík, which thereby became the first building in Reykjavík to be supplied with geothermal hot water. Soon more public buildings, including the national hospital, a swimming pool, as well as about 60 private houses were connected to the hot water supply. But more water was needed to fulfill the heating requirements of Reykjavík. A large geothermal area 17 km east of Reykjavík, the Reykir/Reykjahlíd (Mosfellssveit) field, was considered to be ideal because of its proximity and its capability to produce large quantities of geothermal water. Shallow wells were drilled in this area and a pipeline built to Reykjavík. The first house was connected to the distribution system from this area in 1943. It has been estimated that by using geothermal water for house heating in Reykjavík instead of fossil fuel, emission of about 100 million tonnes of CO_2 has been avoided (Gunnlaugsson and Ívarsson, 2010). Annually, the avoided emission is in the range of 2–4 million tonnes, which is comparable to the total release of CO_2 in Iceland today. Gunnlaugsson (2008) presents the history of the Reykjavík Energy low-temperature geothermal systems in more detail.

Some other low-temperature hitaveitas in Iceland have been in operation for more than half a century and several others for more than three decades. A number of the associated low-temperature systems are listed in Table 1. Nine of these, distributed throughout the country, are discussed briefly below, including the three low-temperature systems utilized by the hitaveita operated by Reykjavík Energy; the Laugarnes, Mosfellssveit, and Ellidaár systems (see Fig. 3).

In addition, Table 1 lists the geothermal systems utilized by two of the oldest hitaveitas in Iceland. These are the Laugar (in Reykjadalur) and Laugavatn low-temperature systems, in N-Iceland and S-Iceland, respectively, serving the relatively small communities with the same names. The utilization of both systems started more than 80 years ago and is still continuing. Fig. 5 shows the schoolhouse at Laugar, which is believed to be the first large official building in

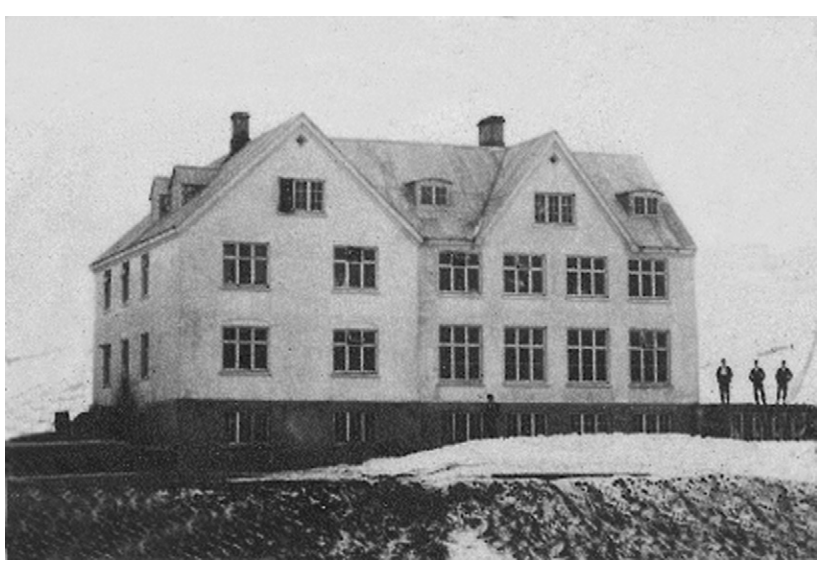

Fig. 5. The schoolhouse at Laugar in Reykjadalur in northeastern Iceland during the final stage of construction in 1927. It is believed to be the first large official building in Iceland to be heated with geothermal energy. From Thráinsson (2005).

Iceland to be heated with geothermal energy. Also included in the table is the tiny Brautarholt hitaveita in S-Iceland, which has been in operation since 1950.

Initially (from the 1930s through the 1960s), the utilization of many of these systems was through artesian flow from relatively shallow wells and in some cases from hot springs. Today in most cases down-hole pumps are used, which has enabled production at rates considerably greater than the artesian flow rates (see the Laugarnes case below). There are still examples, however, of large-scale artesian flow being maintained for more than half a century (see the Áshildarholtsvatn case below).

4. Long case histories

4.1. General

In most of the Icelandic low-temperature systems under exploitation, a quasi-equilibrium state between mass extraction and pressure decline has been reached. In a few systems, however, a continuously increasing pressure draw-down has been observed at constant yearly production. This has been attributed to more limited recharge than in the systems where quasi-equilibrium has been reached. In most cases reservoir pressure changes are monitored through water level changes in production wells or specific monitoring wells. Changes in temperature and chemistry have, furthermore, been minimal, except in a few exceptional cases, such as in the Ellidaár and Thorleifskot systems discussed below.

4.2. Laugarnes in Reykjavík

The Laugarnes geothermal system is located near the center of Reykjavík. The system is hosted by relatively young and hot crust about 20 km NW of the active zone of spreading. It is believed to be associated with the intersection of SW–NE trending faults and fractures, and the caldera rim of an extinct central volcano (Gunnlaugsson et al., 2000). Exploitation for space heating started in 1930 with the utilization of free-flowing 87 °C water from a number of shallow wells (the deepest being 246 m). In 1958, drilling of both deeper and larger diameter wells commenced in the field. These large wells, together with the introduction of large capacity down-hole pumps, enabled the hot water production in Laugarnes to be increased by an order of magnitude (Axelsson and Gunnlaugsson, 2000). Ten production wells are in operation today with the deepest extending down to 2700 m. The reservoir temperature in the Laugarnes system is about 120–140 °C. Over the last four years the average, total production from the system has been more than 150 l/s (Gunnlaugsson and Ívarsson, 2010).

Fig. 6 shows the production and water level history of the field. Production increased quickly in the 1960s, when down-hole pumps were installed in production wells, resulting in a reservoir pressure decline corresponding to about 120 m water level drop. Production and water level have, however, remained relatively stable during the last four decades. This indicates the reservoir has found a new quasi-equilibrium, with about ten times the natural recharge (assuming the artesian flow up to the middle 1950s to approximately equal the recharge). Laugarnes is among the more productive low-temperature systems utilized in Iceland. Fig. 8 shows the total yearly production from the three, low-temperature systems utilized by the Reykjavík hitaveita since the introduction of down-hole pumps.

During the mid 1980s, increased hot water extraction caused an additional pressure decline in the system, and a corresponding drop in water level (see Figs. 6 and 7). Consequently, fresh and slightly saline groundwater flowed into the pressure depression, and mixed with the geothermal water. A slight change in chemical content was noticed in some wells without noticeable changes in fluid temperature. The mixing of different water types resulted in disequilibrium of calcite and formation of the calcite scales. Reduced pumping after 1990 lessened the pressure decline and the groundwater inflow, easing the calcite scaling problem.

It is of interest to compare the total water volume produced from the Laugarnes system since 1930, presented in Table 1, with the pore-space volume of the system as estimated from the presently available knowledge of the system. It is of particular interest to determine whether the extracted volume is less than, comparable to, or more than the pore-space volume. The same applies of

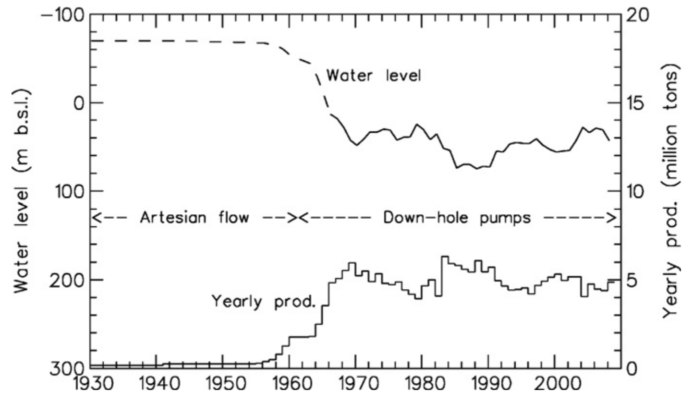

Fig. 6. Production and water level (winter minima) history of the Laugarnes low-temperature geothermal system within Reykjavík, SW-Iceland, from 1930 to 2009. The broken line indicates estimated water level. More details presented in Fig. 7.

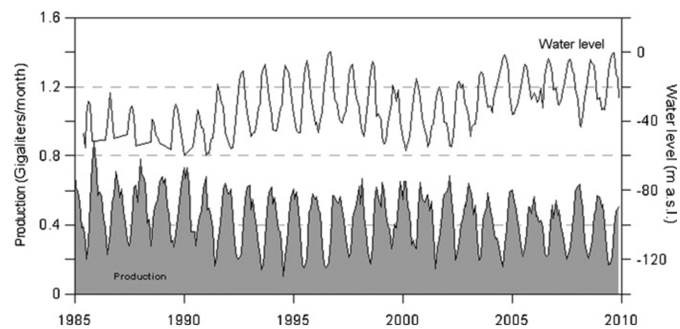

Fig. 7. Production and water level history of the Laugarnes system from 1985 to 2009 in more (detail yearly variations) than shown in Fig. 6.

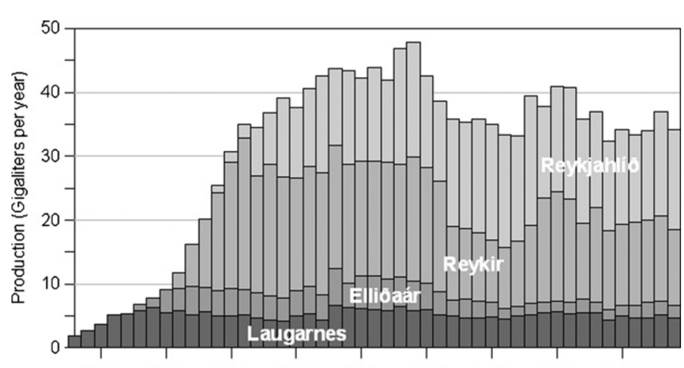

Fig. 8. Total yearly hot water production, since the introduction of down-hole pumps, from the three low-temperature geothermal systems utilized for space heating in Reykjavík. The Reykir and Reykjahlíd fields are parts of the Mosfellssveit geothermal system.

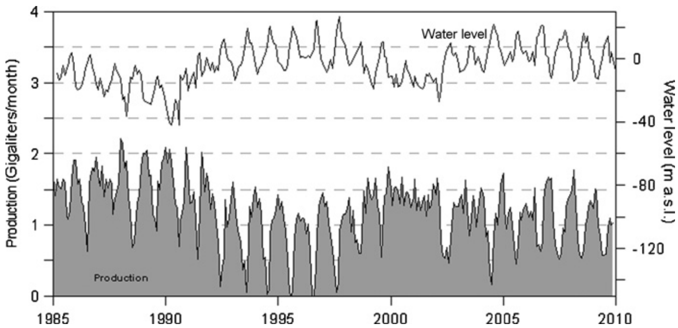

Fig. 9. Production and water level (observation wells) history of the Reykir field in Mosfellssveit from 1985 to 2009.

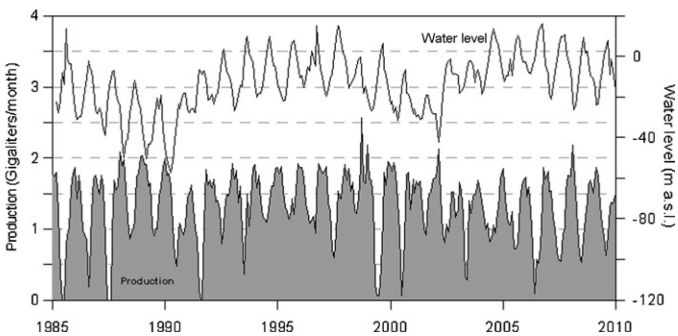

Fig. 10. Production and water level (observation well) history of the Reykjahlíd field in Mosfellssveit from 1985 to 2009.

course to the other systems discussed here, but such a comprehensive study is beyond the scope of this paper, but of interest as future research. The results of simple calculations for the Laugarnes and Hamar systems are presented with the conclusions of this paper. The Laugarnes system is believed to be one of the larger low-temperature systems in Iceland, while the Hamar system is among the smaller systems.

4.3. Reykir/Reykjahlíd in Mosfellsveit

The Reykir/Reykjahlíd geothermal field is located in Mosfellssveit about 17 km east of Reykjavík. Feed-zones in geothermal wells in the geothermal field can generally be correlated with regional faults and fractures. Prior to drilling, the artesian flow of thermal water through hot springs was estimated to be about 120 l/s of 70–83 °C water. After redeveloping the field by extensive drilling and installation of down-hole pumps in 34 production wells, the yield of the field increased to about 2000 l/s of 85–100 °C water. Figs. 9 and 10 show the total production and water level changes in observation wells in both parts of the field, Reykir and Reykjahlíd, from 1985 to 2009.

The water level steadily decreased in both fields until 1990, when it became possible to reduce pumping from the fields, once a new power plant at Nesjavellir started operation. Within a year of the reduced production, the pressure had recovered significantly and the water level rose again. Only slight changes in chemistry and temperature of the fluid have been observed near the south-eastern boundary of the field (Gunnlaugsson et al., 2000). In 2008, the combined total production from the Reykir/Reykjahlíd field amounted to 29.6 million tonnes, corresponding to an average of 936 l/s, which was almost 44% of the hot water volume required for the Reykjavík area (Ívarsson, 2009). The Reykir/Reykjahlíd field is considered to be the most productive low-temperature system utilized in Iceland.

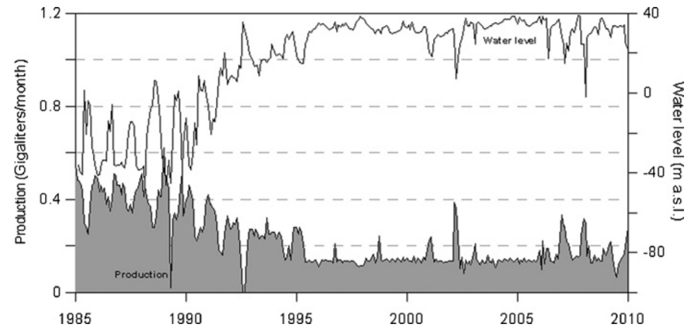

Fig. 11. Production and water level (observation well) history of the Ellidaár field in Reykjavík from 1985 to 2009.

4.4. Ellidaár in Reykjavík

The Ellidaár field is the smallest of the three low-temperature geothermal fields used for district heating in Reykjavík. Production from the field started in 1968. Eight production wells are located in the area. When exploitation first started in the Ellidaár field, the water temperature was in the range of 95–110 °C. Production caused a pressure drop in the system and consequent cooling of the production wells. Cold groundwater from the surroundings mixed with the geothermal water, causing the water chemistry to change and later a considerable temperature decline. This demonstrated that chemical changes can often be seen before noticeable changes in temperature are observed. Reduced production in 1990 resulted in higher water levels in the area (Fig. 11) and a decrease in the cold water inflow and mixing, as observed through chemical monitoring. In 2008, the Ellidaár geothermal field produced 2.1 million tonnes, corresponding to 66 l/s average production.

4.5. Áshildarholtsvatn in Skagafjördur

The Áshildarholtsvatn low-temperature geothermal system is located in the Skagafjördur region in north-central Iceland. This region is geothermally quite active because of its proximity to an extinct segment of the northern Iceland spreading axis and considerable tectonic activity. The Áshildarholtvatn area is a few km southeast of the town of Saudárkrókur and geothermal energy from the system is used for space heating of the town and neighbouring farms. Today this hitaveita is connected to a smaller hitaveita from Varmahlíd, located further south, resulting in an integrated system extending about 30 km.

The Áshildarholtsvatn system has been utilized since 1948 by artesian flow from a number of wells. Today four production wells, ranging in depth from 520 to 670 m, are utilized. The reservoir temperature is approximately 70 °C and the average production has been about 70 l/s during the last few years. Fig. 12 shows the production and pressure change history of the system, the pressure changes being monitored as well-head pressure changes in a special observation well.

Like the Laugarnes system in Reykjavík, the Áshildarholtsvatn system is one of the more prolific low-temperature systems in Iceland, even though the reservoir temperature is considerably lower than in Laugarnes. This is reflected in relatively small pressure changes, both annually and long-term. The Áshildarholtvatn system appears to have found a new quasi-equilibrium just as has occurred within the Laugarnes system. The Áshildarholtvatn system is, furthermore, one of a very few Icelandic low-temperature systems where all the production is by artesian flow.

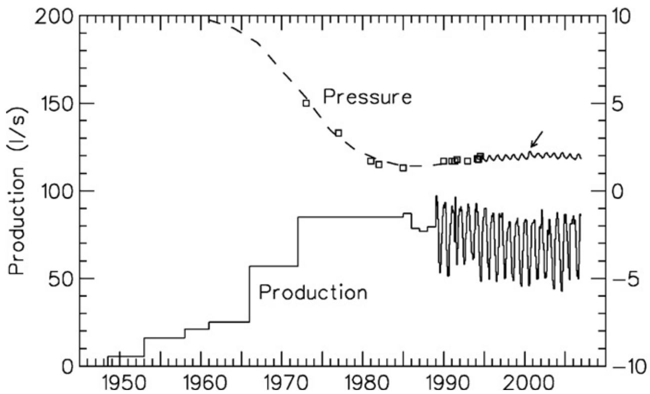

Fig. 12. Production and pressure history of the Áshildarholtsvatn low-temperature geothermal system near the town of Saudárkrókur in northern Iceland from 1948 (the hitaveita started operation in 1953) to 2006. The figure shows yearly average production up to 1989. The broken line indicates estimated reservoir pressure and the boxes isolated pressure readings. The arrow points to a temporary peak in reservoir pressure following two major earthquakes in southern Iceland in the summer of 2000.

It is of interest to note a relatively pronounced peak in wellhead pressure in the summer of 2000 is not only due to the annual production minimum, but to the pressure increase effect of two major (both M_S = 6.6) earthquakes that occurred in southern Iceland at a distance of about 200 km from the field.

4.6. Skútudalur in Siglufjördur

The Skútudalur low-temperature system is located on the east side of the Siglufjördur fjord in north-central Iceland and serves the town of Siglufjördur on the west side of the fjord. It is in a region of relatively old crust that is tectonically quite active, explaining the low-temperature geothermal activity in the region. The system has a reservoir temperature of approximately 70 °C and has been utilized since 1975. Fig. 13 shows the production and water level history of the Skútudalur system.

The Skútudalur system is not highly productive, but it does reach a quasi-equilibrium during constant production as Fig. 13 shows. The water level appears to drop more over the last few years than would be expected on the basis of the production. It has been speculated this may be due to a recently constructed road-tunnel through the mountains above Skútudalur. This is being studied, but would not be surprising since the road-tunnel drains water from, and lowers pressure in, the groundwater system in the mountains, which is thought to provide recharge for the Skútudalur geothermal system.

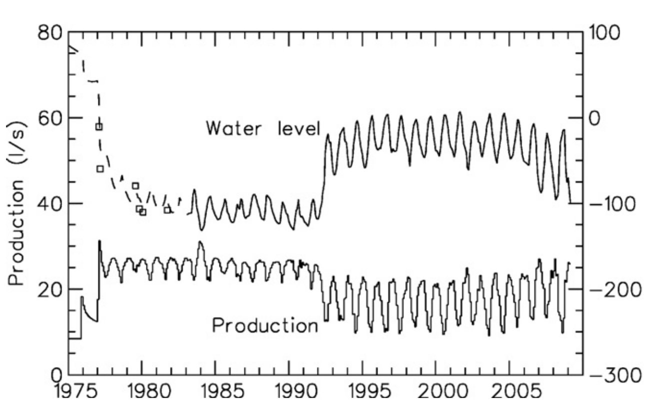

Fig. 13. Production and water level history of the Skútudalur low-temperature geothermal system in Siglufjördur, N-Iceland, from 1975 to 2008. The broken line indicates estimated water level and the boxes isolated water level readings.

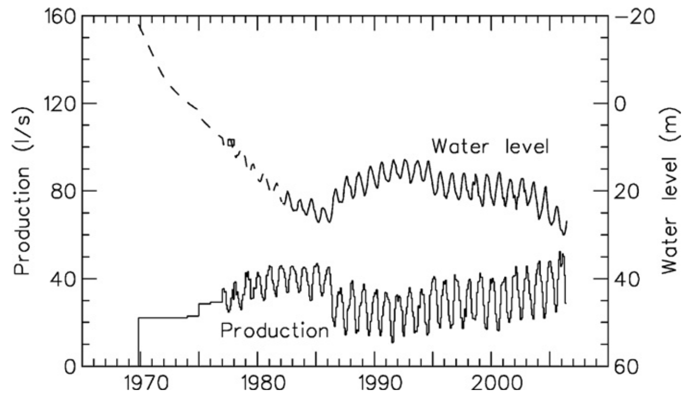

Fig. 14. Production and water level history of the Hamar low-temperature geothermal system near the town of Dalvík in N-Iceland from 1969 to 2006. The broken line indicates estimated water level and the box an isolated water level reading.

4.7. Hamar near Dalvík

The Hamar low-temperature geothermal system is discussed by Axelsson et al. (2005a). It is located on the western side of the Eyjafjördur fjord in north-central Iceland, a little less than 30 km southeast of Skútudalur. The basaltic lava-pile hosting this system is relatively permeable because of recent tectonic activity (Flóvenz et al., 2000). The western edge of the fjord is in fact particularly active as is demonstrated by the 6.2 (Richter-scale) Dalvík earthquake in 1932, which occurred a few kilometres east of the Hamar system.

The Hamar system has been utilized for space heating in the nearby town of Dalvík since 1969. In recent years, the average annual production from the field has been close to 40 l/s. Two production wells, with feed-zones between depths of 500 and 800 m, in the basaltic lava-pile, are currently in use and the reservoir temperature is about 65 °C. The production and water level history of the field is presented in Fig. 14. The production has caused a very modest pressure decline of about 3 bar (30 m).

The Hamar system is a small, but productive low-temperature system, as demonstrated by the modest pressure drop. It appears to reach quasi-equilibrium when production rate is constant. The reservoir pressure has been declining since 1995, however, due to constantly increasing production. Axelsson et al. (2005a) present the results of a modelling study to estimate the sustainable potential of the Hamar system. They concluded that the long-term (200 years) production potential of the system is limited by its energy-content rather than pressure decline. The sustainable rate of production at Hamar is estimated to be greater than 40 l/s, corresponding to more than 11 MW_t.

4.8. Laugaland in Eyjafjördur

The Laugaland low-temperature system is located in the Eyjafjördur valley south of the Eyjafjördur fjord in north-central Iceland. It is the second largest of six low-temperature geothermal fields utilized by Nordurorka for space heating in the town of Akureyri (Flóvenz et al., 1995, 2010). The Laugaland system has been utilized since late 1977, following a testing period in 1976. The name Laugaland actually means land, or farm, of hot-springs.

The Laugaland geothermal system is a typical fracture-controlled system, hosted by 6–10 Myears old flood basalts, wherein the hot water flows along open fractures in otherwise low-permeability rocks. Twelve wells have been drilled in the Laugland area, but only three of them are sufficiently productive to be used as production wells. The reservoir temperature at Laugaland is about 100 °C. The Laugaland system is considerably less perme-

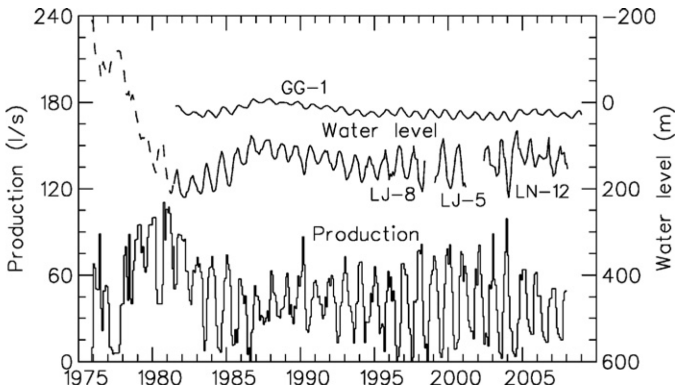

Fig. 15. Production and water level history of the Laugaland low-temperature geothermal system south of Akureyri in N-Iceland from 1976 to 2007. The broken line indicates estimated water level. Wells LJ-5, LJ-8 and LN-12 are inside the field, while well GG-1 is 2 km from the field's center.

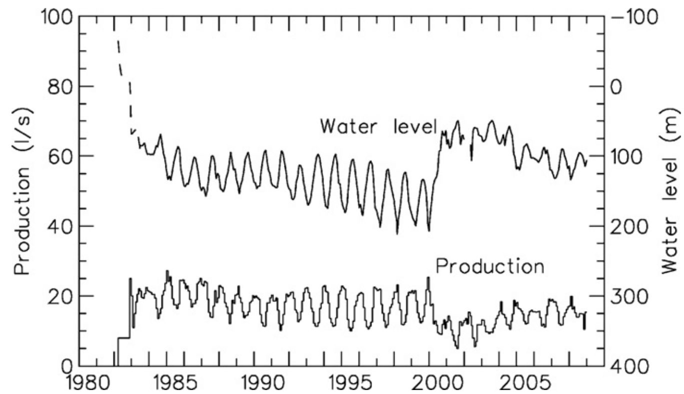

Fig. 16. Production and water level history of the Gata low-temperature geothermal system in the Holt district of southern Iceland from 1982 to 2008. The broken line indicates estimated water level.

able than the Hamar system described above, even though both systems are in the same region. The main reason is believed to be that the Eyjafjördur valley, where Laugaland is located, is much less tectonically active than the western side of the Eyjafjördur fjord, where Hamar is located. The distance between the two fields is about 50 km.

Fig. 15 shows the production and water level history of the Laugaland system. Hot water production from the field has varied between 0.9 and 2.5 million tonnes annually and today the average production from the field is around 30–40 l/s. Because of the low overall permeability, and apparently limited recharge, this modest production has lead to a great pressure drawdown. The pressure decline continues to increase with time for constant rate production. In the early 1980s, the draw-down had reached about 400 m, which forced production from the field to be reduced by about 50%.

Because of the drastic pressure draw-down and limited recharge, injection was long considered a possible way to improve the productivity of the Laugaland system. Therefore, a comprehensive 2-year re-injection experiment was conducted in the field at the end of the 20th century (Axelsson et al., 2001). Since then, re-injection corresponding to about 25% of the extracted mass has been part of the management of the Laugaland geothermal system. It has helped to stabilize the pressure decline in the system.

4.9. Gata in the Holt district

The Gata (or Laugaland) system has been discussed briefly by Axelsson et al. (1995) and Zhang (2003). It is located in the Holt district of the south Iceland lowlands, a few kilometres south of the highly active South-Iceland seismic zone. In spite of its proximity to the seismic zone, the permeability of the Gata system is unusually low and the system has poor productivity. It is noteworthy that numerous, permeable, low-temperature systems are located within, and north of, the seismic zone while hardly any systems are found south of the zone.

The Gata geothermal system has been utilized since 1946. Up to 1982, the utilization was for local heating and a swimming pool, but after 1982, a hitaveita for the towns of Hella and Hvolsvöllur, east of Gata, was added. The geothermal system has a reservoir temperature of 100–105 °C. The production and water level history of the system is presented in Fig. 16. The average yearly production rate has varied between 10 and 22 l/s and, over the last few years, it has been about 15 l/s. One primary production well, 1000 m deep, has been in use since 1982.

Fig. 16 shows that the water level declined continuously up to early 2000, indicating very limited recharge to the Gata geothermal system. Therefore, a new production area with two production wells was connected to the Hella/Hvolsvöllur hitaveita in early 2000, which enabled a drastic reduction in production from the Gata system. This is the Kaldárholt system described by Zhang (2003). It is a very productive system, but with a reservoir temperature of only 65–70 °C. At the same time, limited (10–20% of the production) re-injection was started at Gata. Over the last few years production at Gata has started to increase again causing the water level to decline once more.

A major earthquake (M_s = 6.6) shook the Holt district on 17 June 2000, only a few kilometres north of Gata, followed by another one a few days later further to the west (see discussion on Áshildarholtsvatn above). The earthquake caused drastic changes in hydrological systems all over the southern lowlands of Iceland (Jónsson et al., 2003). A modelling study of the Gata system indicates that the observed water level after the earthquake(s) is, in fact, 40–80 m higher than the modelled level (Axelsson et al., 2005c). This is believed to be the result of reservoir permeability at Gata, as well as fluid recharge, having increased considerably because of the earthquake(s).

4.10. Thorleifskot near Selfoss

The Thorleifskot low-temperature geothermal system is on the outskirts of the town of Selfoss in southern Iceland. Along with the Ósabotnar low-temperature system, it is used by the Selfossveitur hitaveita for district heating in the Árborg community, which encompasses the towns of Selfoss, Eyrarbakki, and Stokkseyri, as well as surrounding rural areas (Ólafsson et al., 2005). The Thorleifskot system has been utilized for space heating since 1948, and currently the average yearly production is 70–80 l/s.

The Thorleifskot system is inside the South-Iceland seismic zone mentioned above and is highly permeable. Initially, the hot water production was by pumping from a few shallow wells, but these had to be abandoned, one by one, because of inflow of cold groundwater through some of the open fractures. Later, deeper wells were drilled that were also cased to greater depth, but many of these have also been affected by the inflow (Tómasson and Halldórsson, 1981). Today four production wells are utilized at Thorleifskot. They were drilled from 1979 to 1999, and range in depth from about 1400 m to about 2400 m with casings that are 310–630 m deep. In the last few years, average production at Thorleifskot has been about 70–80 l/s. Reservoir temperature in the Thorleifskot system is unusually variable, ranging from about 60 °C to more than 120 °C.

Fig. 17 presents water temperature and silica content data from two of the main production wells. The figure shows that cold groundwater inflow continues to plague geothermal production at Thorleifskot in spite of the deep casings. Well 10 cooled down dra-

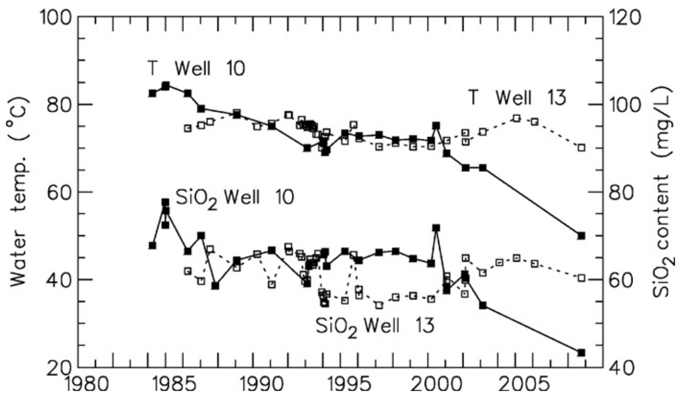

Fig. 17. Changes in water temperature and silica (SiO_2) content for two of the main production wells in the Thorleifskot field near Selfoss in S-Iceland from 1984 to 2008.

matically, in particular after the South-Iceland earthquakes, which affected the geothermal system drastically. Changes in well 13 are much less pronounced and the earthquakes even seem to have caused the production temperature of the well to increase slightly. The difference between the two wells may be attributed to different casing depths, with well 10 having a shorter casing, allowing a more direct connection to colder ground-water.

Drastic changes in production temperature, as observed at Thorleifskot, are really an exception for low-temperature systems utilized in Iceland. Changes of this magnitude have not been observed in the other systems discussed in this paper, except the Ellidaár system. Other cooling examples are limited to wells with very short casings or wells located along the outer boundaries of particular systems (Axelsson and Gunnlaugsson, 2000). In the case of the Árborg hitaveita, this problem has been resolved by adding a new low-temperature geothermal system to the hitaveita. Temperatures are quite high in the deeper parts (>1000 m) of the Thorleifskot system, being above 120 °C. However, feed-zones with sufficient permeability have not been found there in spite of several drilling attempts. It's hoped, however, that in the future, this deeper part of the system will provide more energy for the Árborg hitaveita.

5. Problems and solutions

Several problems and challenges have been faced by the district heating operations in Iceland. The most common problems are:

- Overexploitation resulting in excessive pressure draw-down.
- Problems related to colder water inflow, such as production well cooling and changes in chemical composition.
- Sea water incursion.
- Changes in reservoir conditions due to earthquake activity.
- Corrosion and scaling.
- Technical problems associated with wells (casings), pumps, etc.

Solutions have been found to these problems and none of the hitaveitas have ceased operation as yet. The solutions include:

(1) Improving the energy efficiency of the associated heating systems.
(2) Deeper and more focussed drilling (e.g., directional drilling).
(3) Finding new drilling targets or new drilling areas.
(4) Injection of return water from the hitaveitas.
(5) Use of scaling and corrosion inhibitors.
(6) Technical solutions to surface hardware problems.

Solutions (1) and (3) aim at reducing production from a given low-temperature system. Figs. 13 and 14 show examples of, reduced production and water level recovery. Solutions (2) and (4) shift a part of the production from overexploited zones.

The operational problems and solutions associated with the Reykjavík low-temperature systems are reviewed in more detail by Gunnlaugsson and Ívarsson (2010), and Thórhallsson (2005) discusses some of the technical problems and solutions.

6. Results and conclusions

This paper has reviewed the long Icelandic experience on utilizing low-temperature geothermal systems for direct use, such as space heating. The longest case histories presented span more than 80 years while the shortest history presented is 33 years. These, and other comparable histories, are useful for understanding the nature of the geothermal systems. The Icelandic experiences also provide guidance for the long-term management of other low-temperature geothermal systems, in Iceland and worldwide.

The nine low-temperature geothermal systems presented here are quite variable in terms of size, nature, and production capacity. Four of them are very productive, because of favourable permeability and boundary conditions, and reach quasi-equilibrium at constant production. Two of them are much less productive and do not attain equilibrium, while one has low permeability but favourable boundary conditions. Only two of the systems, which are albeit highly productive, are plagued by considerable cold groundwater inflow that has resulted in temperature decline and chemical changes. In spite of such inflow being deleterious, it helps extract more energy from the reservoir rocks than would otherwise be possible. Such a system classification into open or closed systems is along the lines proposed by Axelsson (2008).

Table 1 presents the total volume of water extracted from 7 of the 11 systems listed in the table during their entire production life (only since 1971 for the Mosfellssveit system). These range from 0.014 to 1.1 km^3. It is of interest to compare these volumes with the pore-space volumes of the systems involved. Though a detailed study is beyond the scope of this paper, two examples are mentioned here:

(i) The volume of the Laugarnes system is believed to be of the order of 10 km^3 and its porosity approximately 10% (partly based on Björnsson et al., 2000). A rough estimate of its pore-space volume is, therefore, about 1 km^3. The total volume extracted from the system (0.25 km^3) thus corresponds to about 25% of the total volume of water in-place prior to production.
(ii) The volume of the Dalvík system is believed to be at least 0.5 km^3 and its porosity approximately 10% (see Axelsson et al., 2005a). Its pore-space volume is, therefore, more than 0.05 km^3. The total volume extracted from the system (0.039 km^3) thus corresponds to less than 80% of the total volume of water in-place prior to production.

In both cases, the volume extracted is less than the initial water in-place in the system, in spite of the long production histories. This is important for understanding the long-term behaviour of such systems and may explain why no noticeable chemical or temperature changes have been detected during the utilization of these and most other Icelandic low-temperature systems.

Various problems, differing in nature and severity, have been faced by many of the Icelandic low-temperature based hitaveitas. Some continue operation without any immediate action being required, while a variety of solutions have been found for other problems. One solution may involve revised, or new, drilling targets within a geothermal system, while the solutions for systems where a reduction in production has been required, may involve re-injection or transferring part of the production to other geothermal systems. None of the hitaveitas discussed here, or any other low-temperature hitaveitas in Iceland, for that matter, have ceased operation and the future of all of the operations appears bright. Due to the fact that geothermal energy supplies about 89% of the space-heating market in Iceland today, a further rapid growth is not foreseen. Yet, exploration work still continues in several regions of the country where known geothermal resources are scant, in the hope of being able to supply some of the remaining 11% of the market.

The long utilization case histories presented here are extremely valuable for the study of the renewability of geothermal resources. A comprehensive study of this aspect of low-temperature resources in Iceland has not been conducted so far, but the data presented here are available for such studies. They also demonstrate that the low-temperature resources can be utilized in a sustainable manner (Axelsson et al., 2005a), and provide important information pertaining to sustainable management of geothermal resources.

Acknowledgements

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References

Árnason, B., 1976. Groundwater systems in Iceland traced by deuterium. Societas Scientiarum Islandica 42, 236 pp.

Arnórsson, S., 1995. Geothermal systems in Iceland: structure and conceptual models. II. Low-temperature areas. Geothermics 24 (5–6), 603–629.

Arnórsson, S., Axelsson, G., Saemundsson, K., 2008. Geothermal systems in Iceland. Jökull 58, 269–302.

Axelsson, G., 2008. Production capacity of geothermal systems. In: Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia, Tianjin, China, 14 pp.

Axelsson, G., 1985. Hydrology and thermomechanics of liquid-dominated hydrothermal systems in Iceland. Ph.D. Thesis. Oregon State University, Corvallis, Oregon, USA, 291 pp.

Axelsson, G., Gunnlaugsson, E. (Convenors), 2000. Long-term Monitoring of High- and Low-enthalpy Fields Under Exploitation. International Geothermal Association, World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu, Japan, 226 pp.

Axelsson, G., Stefánsson, V., Björnsson, G., 2005a. Sustainable utilization of geothermal resources for 100–300 years. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 8 pp.

Axelsson, G., Björnsson, G., Egilsson, Th., Flóvenz, Ó.G., Gautason, B., Hauksdóttir, S., Ólafsson, M., Smárason, Ó.B., Saemundsson, K., 2005b. Nature and properties of recently discovered hidden low-temperature geothermal reservoirs in Iceland. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 10 pp.

Axelsson, G., Björnsson, G., Quijano, J.E., 2005c. Reliability of lumped parameter modelling of pressure changes in geothermal reservoirs. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 8 pp.

Axelsson, G., Flóvenz, Ó.G., Hauksdóttir, S., Hjartarson, A., Liu, J., 2001. Analysis of tracer test data, and injection-induced cooling, in the Laugaland geothermal field, N-Iceland. Geothermics 30, 697–725.

Axelsson, G., Björnsson, G., Flóvenz, Ó.G., Kristmannsdóttir, H., Sverrisdóttir, G., 1995. Injection experiments in low-temperature geothermal areas in Iceland. In: Proceedings of the World Geothermal Congress 1995, Florence, Italy, pp. 1991–1996.

Björnsson, G., Thordarson, S., Steingrímsson, B., 2000. Temperature distribution and conceptual reservoir model for geothermal fields in and around the city of Reykjavík, Iceland. In: Proceedings of the 25th Workshop on Geothermal Reservoir Engineering. Stanford University, California, USA, 7 pp.

Björnsson, A., Axelsson, G., Flóvenz, Ó.G., 1990. The nature of hot spring systems in Iceland. Náttúrufraedingurinn 60, 15–38 (in Icelandic with an English abstract).

Bödvarsson, G., 1983. Temperature/flow statistics and thermomechanics of low-temperature geothermal systems in Iceland. Journal of Volcanology and Geothermal Research 19, 255–280.

Bödvarsson, G., 1982. Glaciation and geothermal processes in Iceland. Jökull 32, 21–28.

Einarsson, T., 1942. Uber das Wesen der Heissen Quellen Islands (The nature of the hot springs in Iceland). Societas Scientiarum Islandica 42, 91 pp.

Flóvenz, Ó.G., Saemundsson, K., 1993. Heat flow and geothermal processes in Iceland. Tectonophysics 225, 123–138.

Flóvenz, Ó.G., Árnason, F., Gautason, B., Axelsson, G., Egilson, Th., Steindórsson, S.H., 2010. The district heating of the town of Akureyri, N-Iceland; 35 years of problems, solutions and success. In: Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 8 pp.

Flóvenz, Ó.G., Karlsdóttir, R., Saemundsson, K., Smárason, Ó.B., Eysteinsson, H., Björnsson, G., Ólafsson, M., Bjornsson, Th., 2000. Geothermal exploration in Arskogsstrond, N-Iceland. In: Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan, pp. 1133–1138.

Flóvenz, Ó.G., Arnason, F., Finnson, M., Axelsson, G., 1995. Direct utilization of geothermal water for space-heating in Akureyri, N-Iceland. In: Proceedings of the World Geothermal Congress 1995, Florence, Italy, pp. 2233–2238.

Gunnlaugsson, E., 2008. District heating in Reykjavík; past–present–future. In: UNU Geothermal Training Programme. 30th Anniversary Workshop, Reykjavík, Iceland, 12 pp.

Gunnlaugsson, E., Ívarsson, G., 2010. Direct use of geothermal water for district heating in Reykjavík and other towns and communities in SW-Iceland. In: Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 6 pp.

Gunnlaugsson, E., Gíslason, G., Ívarsson, G., Kjaran, S.P., 2000. Low-temperature geothermal fields utilized for district heating in Reykjavík, Iceland. In: Proceedings of the World Geothermal Congress 2000, Kyushu-Tohaka, Japan, pp. 831–835.

Ívarsson, G., 2009. The Reykjavík Hitaveita. Hot Water Production in 2008. Reykjavík Energy Report 2009-018. Reykjavík Energy, Reykjavík, Iceland, 32 pp. (in Icelandic).

Jónsson, S., Segall, P., Pedersen, R., Björnsson, G., 2003. Post-earthquake ground movements correlated to pore pressure transients. Nature 424, 179–183.

Ólafsson, M., Hauksdóttir, S., Thórhallsson, S., Snorrason, Th., 2005. Calcite scaling at Selfossveitur hitaveita, S-Iceland, when mixing waters of different chemical composition. In: Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 6 pp.

Ragnarsson, Á., 2008. Utilization of geothermal energy in Iceland. In: Proceedings of the 14th Building Services, Mechanical and Building Industry Days, Debrecen, Hungary, 9 pp.

Sveinbjarnardóttir, G., 2005. The use of geothermal resources at Reykholt in Borgarfjördur in the medieval period: some preliminary results. In: Mortensen, A., Arge, S.V. (Eds.), Viking and Norse North Atlantic. Selected Papers from the Proceedings of the Fourteenth Viking Congress. Tórshavn, Annales Societatis Scientiarum Faeroensis, Supplementum XLIV, pp. 208–216.

Thórhallsson, S., 2005. Common problems faced in geothermal generation and how to deal with them. In: Proceedings of the Workshop for Decision Makers on Geothermal Projects and Management, Naivasha, Kenya, 12 pp.

Thráinsson, S., 2005. The history of the school at Laugar 1925–1988. Framhaldsskólinn á Laugum, Laugar, Iceland, 575 pp. (in Icelandic).

Tómasson, J., Halldórsson, G.K., 1981. The cooling of the Selfoss geothermal area, S-Iceland. Geothermal Resources Council Transactions 5, 209–212.

Zhang, Y., 2003. Assessment of the Kaldárholt Geothermal System and Associated Reinjection into the Nearby Laugaland System, S-Iceland. UNU Geothermal Training Programme. Report 22, Reykjavik, Iceland, pp. 527–552.