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Geothermal Activity in Borgarfjordur, W-Iceland, and the Exploration, Development and Utilization of the Varmaland/Laugaland Geothermal Field

Ludvik S. Georgsson[1], Haukur Johannesson[2] and Thorhallur Bjarnason[3]

[1]UNU Geothermal Training Programme, Orkustofnun, Grensasvegi 9, IS-108 Reykjavik, ICELAND
[2] ISOR – Iceland GeoSurvey, Grensasvegi 9, IS-108 Reykjavik, ICELAND

[3]Laugaland Ltd., Laugaland, IS-311, Borgarnes, ICELAND

[1] lsg@os.is, [2] hjo@isor.is, [3] laugaland@emax.is

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ABSTRACT

The upper Borgarfjordur area in W-Iceland is the largest low-temperature region in Iceland, comprising five major low-temperature geothermal systems with a total natural discharge equivalent to about 450 l/s of boiling water, distributed between many geothermal fields. The basement rocks consist of late Tertiary lava flows. The upflow of hot water is usually structurally controlled, often through intersection of northeasterly fractures and faults, acting as flow channels of recharge water from the highlands in the northeast, and young northwesterly to northerly fractures, associated with the active Snaefellsnes fracture zone. The Varmaland/Laugaland geothermal field is located at the western margin of the Borgarfjordur thermal region and belongs to the Baer geothermal system. The natural manifestations consisted of small hot springs at 80-97°C yielding 5-10 l/s. Geothermal exploration indicates that the upflow is associated with a west-northwesterly fracture with the hot springs at its intersection with a north-northeasterly trending fault. Production drilling down to 671 m in the early 1980’s increased the availability of hot water for 15-30 l/s at 105°C and revealed the reservoir temperature in the geothermal system to be about 113°C.

Varmaland/Laugaland in W-Iceland is a good example of a community centre that developed around a geothermal site. A swimming pool was the first construction at the site. In 1942, the Laugaland greenhouse farm was established, utilizing the hot springs for heating. Soon afterwards, the Varmaland household school for young women was founded. Later, a primary school, a new public swimming pool, and a community hall were built. Thus, gradually a small village was formed, usually called Varmaland. The increased access to hot water after the drilling of the production well opened up new possibilities such as allowing piping of hot water to neighbouring farms over considerable distances. The Laugaland farm is a good example of a successful greenhouse farm in Iceland based on the benefits of geothermal energy, technical novelties and strong family traditions. It has now about 3600 m^2 under glass and produces cucumbers through 12 months of the year with electric lighting, as necessary, the year round.

1. INTRODUCTION

The upper Borgarfjordur area is the largest low-temperature region in Iceland. It is located in W-Iceland. To the east it borders the western flank of the active Reykjanes-Langjokull volcanic rift zone (Figure 1). To the west is the active Snaefellsnes volcanic zone with an associated fracture zone, continuing east across the main hot spring area. The natural discharge of the hot springs in the Borgarfjordur region can be estimated to be equivalent to more than 450 l/s of boiling water. The geothermal activity in the Borgarfjordur area has been divided into five separate geothermal systems. The different systems include geothermal fields with a few to numerous thermal springs or clusters of springs. The geothermal manifestations are usually distributed along lines related to tectonic features. Most of the major hot springs are boiling and many have a considerable discharge. The Reykholt system is by far the largest system with some of the most powerful low-temperature geothermal fields in Iceland, most notably the Deildartunga-Kleppjarnsreykir field with two of the largest low-temperature hot springs in the world. The intense geothermal activity in the Borgarfjordur area and its large hot springs has through the years attracted attention; see e.g. Georgsson et al., 1984a.

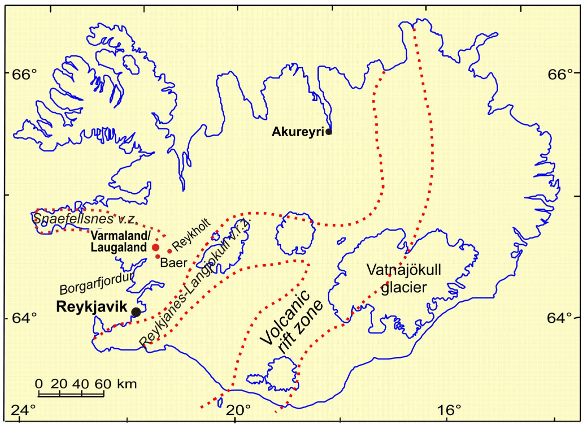

Figure 1: Location of the Varmaland/Laugaland geothermal field in Borgarfjordur, W-Iceland

Utilization of the waters has in most cases been limited to the close vicinity of the geothermal fields. House heating includes the local farms, schoolhouses, summer houses, and also commercial greenhouse farms and two fish farms. The main exception is the Deildartunga-Kleppjarnsreykir field which together with the Baer field supplies the Akranes and Borgarfjordur District Heating System with hot water, from the great Deildartunga hot spring and two production wells at Baer. The water is used for heating of the towns of Akranes and Borgarnes at the coastline with a current population of about 10,000 people. The geothermal pipeline from Deildartunga to Akranes is the longest in the world, 64 km in total and has been used since 1980-1981.

The Varmaland/Laugaland field (Figure 1) belongs to the Baer system, bordering the Reykholt system to the west. Utilization of the geothermal water at Varmaland/Laugaland for swimming dates back to the late 19th century, but in the 1940's the Laugaland greenhouse farm and the Varmaland school were established at the site. Since then the Varmaland/Laugaland area has developed into a small community centre for the rural part of the N-Borgarfjordur area. Abundance of cheap geothermal water for heating and bathing has been instrumental in this.

Georgsson (2004) discussed the Varmaland/Laugaland geothermal field as a case example for geothermal development in rural areas. Here the geothermal activity is put in context with the geothermal activity in the Borgarfjordur area and the main structures controlling it. An overview is given of the geothermal exploration, drilling, and utilization of the Varmaland/Laugaland geothermal field to date.

2. GEOLOGICAL SETTINGS

The Borgarfjordur region is located on the western flank of the Reykjanes-Langjokull active rift zone (Figure 1). Figure 2 shows the main geological features in the area. The basement is made of southeasterly dipping basaltic lava succession. The dip is 8-10°. Two extinct central volcanoes are found in the region, the Hallarmuli and Husafell volcanoes. A major unconformity is within the lava succession in the western part of the area, named the Hredavatn unconformity. The basement below the unconformity is about 13 m.y. old, but above 6.5-7 m.y. The unconformity separates the older lava succession from the extinct Snaefellsnes volcanic rift zone and the younger succession formed in the Reykjanes-Langjokull volcanic rift zone (Johannesson, 1980). Within the unconformity are thick fossil bearing sediments. The lava succession comprises basaltic lava flows which are 3-15 m thick, intercalated with thin sedimentary layers. At 3.3 m.y., the first extensive glaciations took place and from then onwards the succession is characterized by hyaloclastites/pillow lavas from glacial periods and interglacial lava flows from interglacial periods. Andesites and rhyolites are found within the periphery of the central volcanoes.

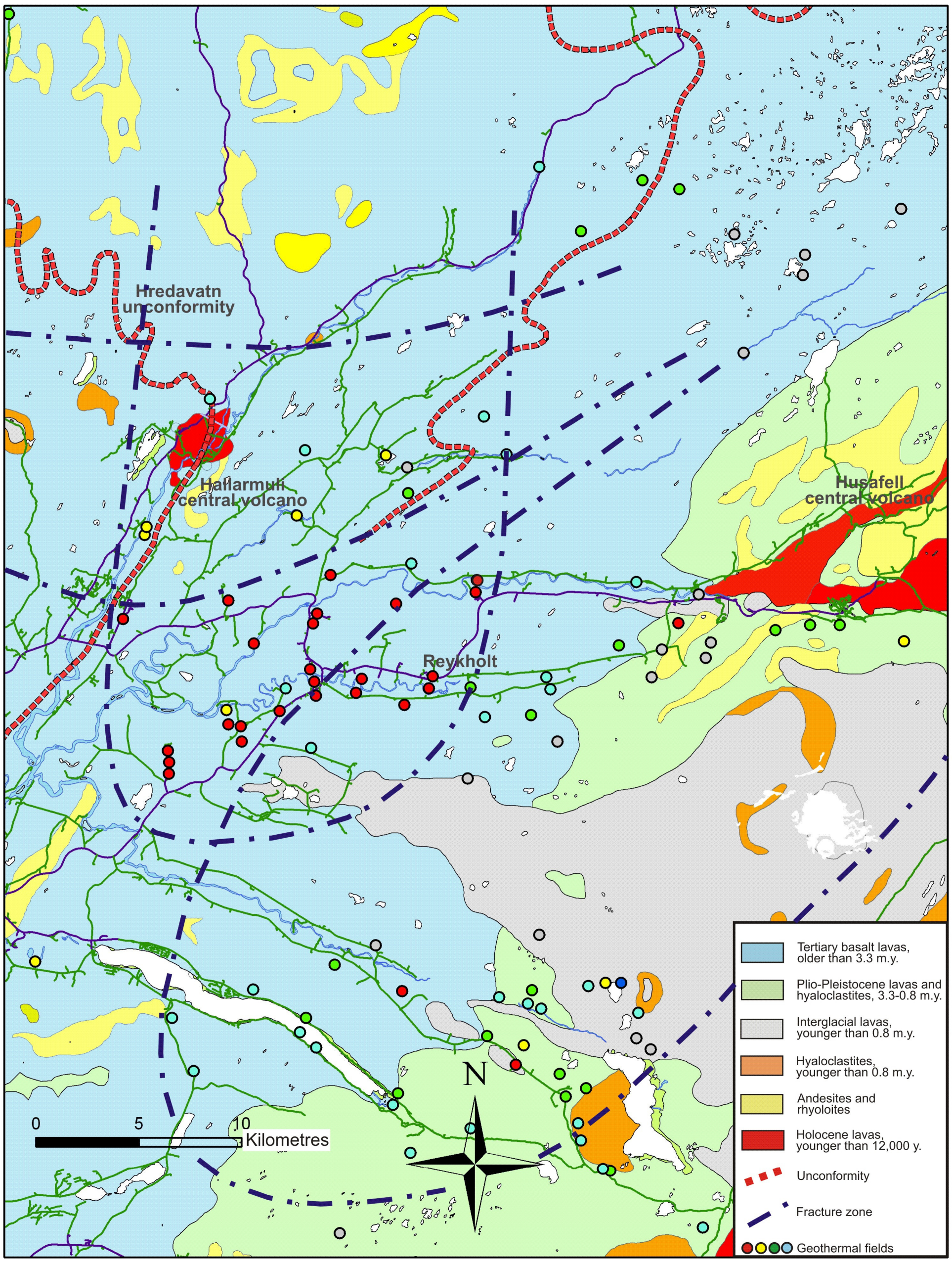

Figure 2: Geological map of the Borgarfjordur region showing the main stratigraphic units in the area and fracture zones

The tectonics of the area is a complicated pattern of NE-SW, N-S and NW-SE trending faults and fractures. All these fault systems influence the geographical distribution of the thermal surface manifestations. In the eastern and southern part of the area NE-SW trending faults and fractures control ascend of the thermal waters. The N-S trending faults and fractures have greatest influence in the central and western part of the region while the NW-SE trending faults/fractures control some of the most northerly and westerly springs. The fracture zones in Figure 2 reflect this main zonation of the active faults and fractures.

3. GEOTHERMAL ACTIVITY IN THE BORGARFJORDUR REGION

3.1 The Geothermal Fields and Their Structure

The geothermal fields in the Borgarfjordur area are mainly found in the inner parts of the region (Figure 3). They are concentrated in the Reykholtsdalur valley and surroundings, the inner part of the Lundarreykjadalur valley, and in the Husafell area. The geothermal fields have been divided into five separate geothermal systems (Figure 3) based on the distribution of resistivity and the chemical characteristics of the geothermal waters (Johannesson et al., 1980; Gunnlaugsson, 1980; Georgsson et al., 1984a). The systems are named after their thermal centres: Reykholt, Baer, Brautartunga, England and Husafell. Each geothermal field may include a few to numerous thermal springs or groups of springs, usually showing linear distribution related to tectonic features, usually faults or fractures but sometimes dykes.

The Reykholt system is by far the largest geothermal system. During the 1970's and 1980's, the total natural discharge was measured to be about 450 l/s and the thermal output is assessed to be equivalent to more than 400 l/s of boiling water. Of its many geothermal fields the most notable is the Deildartunga-Kleppjarnsreykir field with the great Deildartunga hot spring discharging 180 l/s of boiling water and the Kleppjarnsreykir hot spring with 70 l/s. Others include the Hurdarbak-Sidumuli field, the Vellir field, the Reykholt-Haegindi-Kopareykir field and the Nordur-Reykir field, all with large boiling hot springs and a total natural discharge in the range of 15-45 l/s each, and many smaller fields. Detailed mapping of the geothermal manifestations at most of the main geothermal fields was done in the late 1970s and early 1980s with the locations tied into rectangular measuring grids surrounding the individual fields (see e.g. Georgsson et al., 1978 and 1985). Some of these fields have more recently been mapped again, using GPS technogy (Khodayar and Bjornsson, 2005).

The Varmaland/Laugaland field is a part of the Baer system, which borders the Reykholt system on the western side. It is distinguished from the Reykholt system by slightly different chemistry (mainly higher salinity), and a resistivity distribution that indicates a more westerly origin of the water (Georgsson et al., 1984a). The system includes the Varmaland/Laugaland field (maximum surface temperature 96-97°C, natural discharge approx. 9 l/s), the Baer field (95°C and approx. 8 l/s) (Georgsson et al., 1981), the Einifellshver field (71°C and 11 l/s) and some small springs.

The distribution of the hot springs in Borgarfjordur is mainly controlled by tectonic structures, often an interplay between west-northwesterly to north-northwesterly (even northerly) fractures with little or no displacement and north-northeasterly to northeasterly faults/fractures or, in some cases, dykes. The larger hot springs are found at the intersection between the main structures of the different trends, while smaller springs can be found along either one. This pattern has been revealed in most of the main geothermal fields within the Reykholt and Baer geothermal systems where detailed geothermal exploration has been carried out, such as at the Deildartunga-Kleppjarnsreykir (Georgsson et al., 1978), Baer (Georgsson et al., 1981), Vellir (Georgsson et al., 1985), Asgardur (Ganbat, 2004) and at the Hurdarbak-Sidumuli fields (unpublished data). The best example is the great Deildartunga hot spring, located at the intersection of a fracture trending N20°W and a dyke combined with a fault trending N30°E (Georgsson et al., 1978). Chemical data seem to indicate that the northeasterly structures are the main aquifers carrying the water to the geothermal fields while the active northwesterly to northerly fractures are more prominent in the distribution of the geothermal manifestations on the surface. This is very well manifested in the Baer area (Georgsson et al., 1981).

The Brautartunga and England systems are centred in the mid and inner part of the Lundarreykjadalur valley, some 20-25 km south of the Reykholt system. In the Lundarreykjadalur valley the distribution of hot springs is usually controlled by north-northeasterly to northeasterly trending faults. Here, the dual nature of the tectonic structures is not as well manifested. In the Husafell area, upflow of hot water is both associated with tectonic features and geological layers relating to the extinct Husafell central volcano. The small Husafell system is also much colder than the others.

The northern part of the upper Borgarfjordur area experienced a tectonic episode in 1974 with the main earthquake 6.4 on Richter scale (Einarsson et al., 1977). The active area was 15-20 km north of the Reykholtsdalur valley. The earthquakes had considerable effect on some of the geothermal fields, lying closest to the epicentral area. This was most profoundly felt at Helgavatn, the main geothermal field located in the immediate vicinity of the active area. Here the upflow of water ceased for three weeks but then returned in force. A slight increase was noted in maximum temperatures, from 71 to 74°C, but more importantly, discharge measurements done in 1989 showed a discharge of 30 l/s from the hot springs, or about three times the 10 l/s assessed to be there before the earthquakes (Rannsoknarad rikisins, 1944). A marked increase of discharge was also noted at Varmaland/Laugaland, Lundar and Sidumuli after the earthquakes, but some of this may have been temporary.

Another interesting aspect of the 1974 earthquakes was the distribution of the epicentres. The main epicentral zone showed a westerly trend but it was intersected by a secondary zone with a northeasterly trend (Einarsson et al., 1977). The dual trends seen in the distribution of the earthquakes coincide well with two main trends seen in the tectonic structures controlling the distribution of the hot springs within the Reykholt and Baer systems (Figure 2). Actually, the northeasterly epicentral zone in 1974 coincides exactly with the northern part of the northeasterly trending low-resistivity anomaly that stretches from the outer Reykholtsdalur valley to the Arnarvatnsheidi highlands, further supporting the importance of the northeasterly structures as recharge channels for the Reykholt system (Georgsson et al., 1984a). Combining studies of tectonics and the resistivity distribution in the region with results from deuterium measurements of water samples (Arnason, 1976, Kristmannsdottir, 2005), it can be inferred that the Arnarvatnsheidi highlands, is the probable recharge area for the Reykholt system, while the Snjofjoll area may be the recharge area for the Baer system.

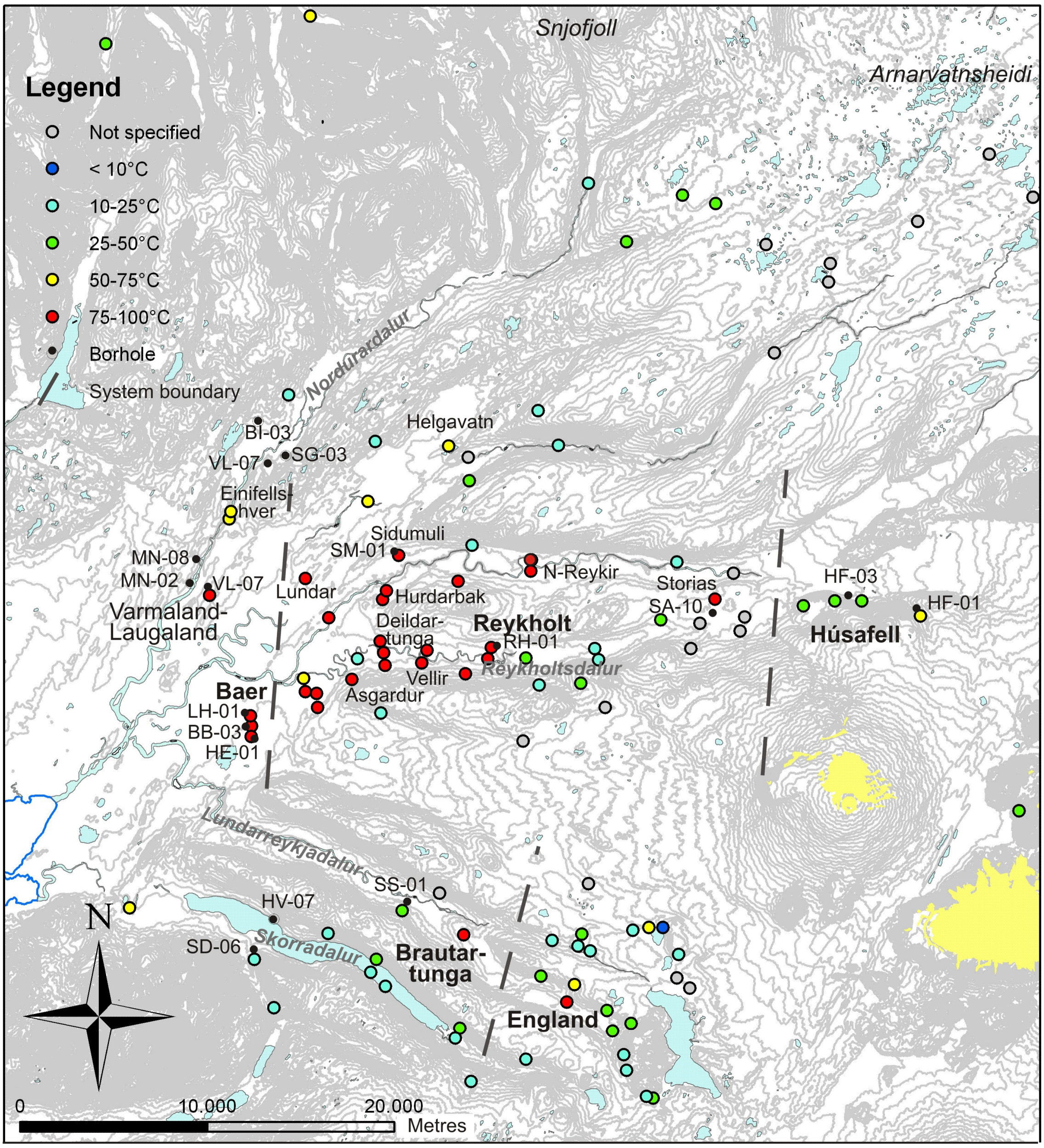

Figure 3: The main hot springs of the Borgarfjordur area and the five geothermal systems; also shown are the locations of the main production wells in the area

The chemical characteristics of the small Brautartunga system are similar to that of the Reykholt system and it is only separated from it on geographical grounds (Figure 3), and has probably the same recharge area. On the other hand, resistivity distribution and lower deuterium values of the England system indicate a different origin of the water coming from the area bordering the southern part of the Langjokull glacier. The Husafell system is located east of the Reykholt system and has quite different characteristics through its association with the extinct Husafell central volcano (Saemundsson and Noll, 1975). It has lower surface temperatures and the origin of the water is from the central part of the Langjokull glacier, as seen from deuterium values (Johannesson et al., 1980; Kristmannsdottir et al., 2005).

The Borgarfjordur area is the largest low-temperature region in Iceland, but most of the upflow is limited to a fairly small area (~100 km^2). The thermal fluid is of meteoric origin. The old accepted model was that the heat was transferred to the water by thermal conduction within the upper crust. Thus, the precipitation percolated to depths of perhaps 1-3 km on its way to the lowlands where it heated up and subsequently ascended to the surface through structural weaknesses at lower elevation (e.g. Arnason 1976). In the 1980's new ideas on a more transient nature of the low-temperature areas came forward, where the flow of the recharge water is believed to be more shallow and that the main heat transfer takes place locally inside the geothermal systems (Bodvarsson, 1982; 1983; Bjornsson et al., 1990). According to this model, the recharge to the low-temperature systems is shallow groundwater flow from the highlands to the lowlands, possibly heated somewhat along the way. Inside the geothermal field, the water sinks through an open fracture to depths of a few kilometres where it takes heat from the hot adjacent rock and returns to the surface because of reduced density. This convection transfers heat from the deeper parts of the system to the more shallow part. The fracture is closed at depth, but opens up and continuously migrates downward during the heat mining process by cooling and contraction of the host rock

(Bjornsson et al., 1990). This model seems consistent with many low-temperature systems in Iceland, at least the smaller ones.

Gunnlaugsson (1980) published a survey of the water chemistry in the region. There he calculates the silica-temperature for numerous fields in the region. His results indicate that the temperature at depth is about 150°C in centre of the Reykholt system and 130°C in the Brautartunga and England systems. The Baer system reaches 120°C. These are high values for low-temperature fields in Iceland. The apparent zonation of the silica temperature values within each system also suggests a local heat source. The natural thermal output in the Reykholtsdalur valley and its immediate vicinity is very high and even comparable to some high-temperature areas. Sustaining this for a long time is though difficult to envisage without some extra heat source. Arnorsson and Olafsson (1986) have proposed that the unusually high temperature and output in the Reykholtsdalur valley is caused by magma intrusions into the crust adjacent to the Reykjanes-Langjokull active rift zone, due to vanishing dilation in the northern part of the Reykjanes-Langjokull rift zone. Thus, the active fracture zones in the otherwise quite impermeable Tertiary crust of the area provide good conditions for both recharge and heat mining, and this high thermal output can be sustained with the help of deep-seated local intrusions.

3.2 Geothermal Wells in the Region

Quite many shallow wells were drilled in the Borgarfjordur area in the 1950’s and 1960’s, most less than 100 m deep. Some of them were successful, and have, in a few cases, been used to date. However, usually they were connected to the local hot springs, and thus influenced their flow, sometimes not adding much to it. Since the 1970’s, deeper production wells have been drilled with good results at several geothermal fields, often considerably increasing the total discharge from the geothermal fields. Also, good production wells have been drilled in areas with no surface manifestations of geothermal activity, most of them west and north of the Baer system Locations of the most important production wells are shown in Figure 3 and Table 1 summarizes some key data on these.

The first really successful production well, RH-01, was drilled at Reykholt in 1974. It is 251 m deep and produces about 20 l/s in free flow with a temperature of 124°C, but has a maximum temperature of 127°C. It is still the hottest producing well in the region. The well is now the main supplier of hot water for the small Reykholt village, but it is used under pressure as 8 l/s have sufficed for the village. RH-01 proved to be well connected to the hot spring Skrifla, one of the two main hot springs at Reykholt.

Three deep wells are found at the Baer field, two of which are producing, and four additional exploration wells, all dating from 1976 and 1977. Well BB-03 gives 110-115°C hot water from rather shallow aquifers, while LH-01 was a real success giving 28 l/s of 93°C water in free flow from two main aquifers at 323 and 580 m depth (Georgsson et al., 1981). Both wells are now used by the Akranes and Borgarfjordur District Heating System through downhole pumping during the coldest season, when water from the Deildartunga hot spring is not sufficient to fulfil the needs of the system. The successful production well VL-07 drilled at Varmaland/Laugaland in 1983 is discussed in next section. Good production wells have later been drilled at Sidumuli, and at Storias in the innermost part of Reykholtsdalur valley. To this can be added shallow wells at Haafell and Kjalvararstadir. All are utilized for heating purposes today, and the well at Storias for a fish farm as well.

Exploration for hot water outside known geothermal fields has also been quite successful in the upper Borgarfjordur area. Five production wells have been drilled at the northwestern margin of the geothermal systems where no surface geothermal manifestations are known. Three of them are in the Nordurardalur valley, north of the Baer system, and two at Munadarnes, just west of Varmaland/Laugaland. All are productive. The location indicates that they are within the Baer geothermal system. They are used for local rural heating systems, most importantly for the Bifrost University centre (BI-03 and SG-03), and a large number of summer houses (MN-08) (courtesy of Reykjavik Energy, unpublished data).

Table 1. Production Wells in the Borgarfjordur Area Deeper than 100 m.

Well no.	Location	Geothermal field	Year drilled	Depth (m)	Temp. (°C)	Productive	Flow	Heating system
Reykholt system								
RH-01	Reykholt	Reykholt	1974	251	128	Yes	Free flow	Reykholt village district heating
SM-01	Sidumuli	Hurdarbak-Sidumuli	1993	324	90	Yes	Pumping	Local use
SA-10	Storias	Storias	2003	203	76	Yes	Free flow	Rural district heat. and fish farm
Baer system								
BB-03	Baer	Baer	1976	1151	115	Yes	Pumping	Akranes and Borgarfj. distr. heat.
HE-01	Hellur	Baer	1976	1104	~110	No	-	Not useable
LH-01	Laugarholt	Baer	1977	1013	98	Yes	Pumping	Akranes and Borgarfj. distr. heat.
VL-07	Varmaland	Varmal./Laul.	1983	671	113	Yes	Free flow	Varmaland and rural distr. heating
BI-03	Bifrost		1991	409	68	Yes	Pumping	Nordurardalur district heating
SG-03	Svartagil		1992	751	74	Yes	Pumping	Nordurardalur district heating
MN-02	Munadarnes		1992	969	86	Yes	Free flow	Local use
MN-08	Munadarnes		2002	900	85	Yes	Pumping	Munadarnes district heating
VL-07	Veidilaekur		2007	244	61	Yes	Pumping	Not yet used
Husafell system								
HF-01	Husafell	Husafell	1986	397	80	Yes	Free flow	Husafell district heating
HF-03	Husafell	Husafell	2002	606	62	Yes	Free flow	Husafell district heating
Brautartunga system								
SS-05	Snartarstadir	Snartarstadir	1991	309	~100	Yes	Free flow	Rural district heating system
SD-06	Stora-Drageyri		1996	836	98	Yes	Pumping	District heating for summerhouses
HV-07	Hvammur		2002	1237	120	Yes	Pumping	Not used

A few wells have also been drilled in the eastern and southern part of the Borgarfjordur region. Two wells are in production at Husafell, supplying the large, local summerhouse area with hot water for heating and bathing, and a fish farm. Well SS-05 at Snartarstadir within the Brautartunga system supplies a quite extensive rural system with hot water. Finally, two deep wells have been drilled at the southern margin of the Borgarfjordur region in the Skorradalur valley, at locations where no surface manifestations were known. Well SD-06 at Stora-Drageyri, is a quite good producer. Well HV-07 at Hvammur is the deepest well in the Borgarfjordur area, 1237 m deep. The well has a bottom temperature of 120°C hot water, and has some producing aquifers.

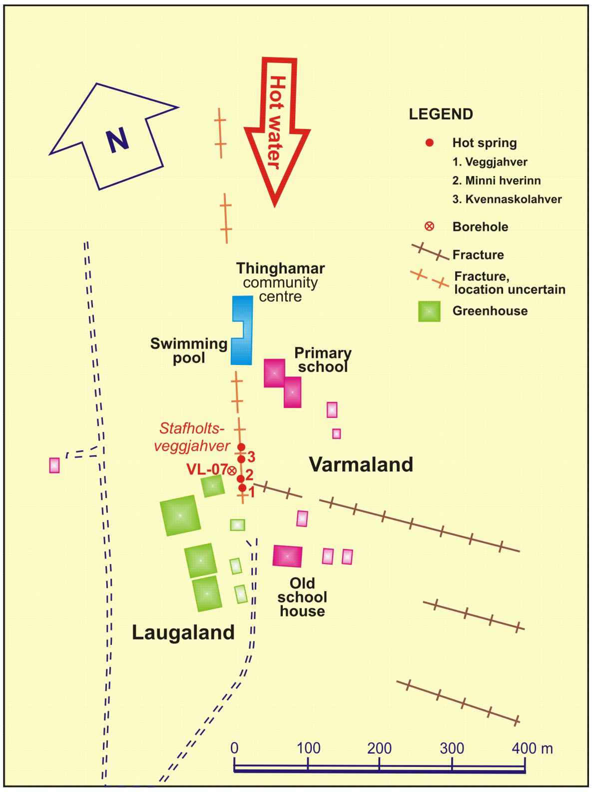

Figure 4: The Varmaland/Laugaland geothermal field and its main structures

4. THE GEOTHERMAL FIELD AT VARMALAND/LAUGALAND

The Varmaland/Laugaland geothermal field is located at the western margin of the Borgarfjordur thermal region. The hot springs are in a tiny shallow valley about 1 km north of the farm Stafholtsveggir, and the discharge comes from a low mound in an otherwise boggy area. The geothermal field belonged to the Stafholtsveggir farm, and was usually referred to as Stafholtsveggjahver, meaning the hot spring of Stafholtsveggir.

The main hot springs are in fact three (Figure 4), now called Veggjahver, Minni hverinn and Kvennaskolahver, with a few smaller springs around. Figure 4 shows the geothermal field and related structures, while Figure 5 is a photo of the geothermal field in its present state. The highest surface temperature was measured to be 96-97°C and the total free flow assessed to be 10 l/s in 1935-36 (Sonder, 1941), a figure confirmed by measurements in 1944 (Rannsoknarad rikisins, 1944). Through the fifties and sixties, the flow seemed to decline. This was counteracted in the late fifties by the drilling of six shallow wells (60-105 m deep) into the shallow local sedimentary formations, associated with the Hredavatn unconformity, three of which were productive and gave 97-100°C hot water. However, the wells and the hot springs were well connected and the overall flow continued to decline. In the 1960's and early 1970's the total discharge was measured to be 5-7 l/s. The Borgarfjordur earthquakes in 1974 seemed to have a reviving effect on the hot springs and wells at Varmaland/Laugaland with the flow increasing to about 9.0 l/s of 90-100°C water (Johannesson et al., 1979; Georgsson et al., 1984b).

Increased development at Varmaland/Laugaland from the 1940's to the 1970's meant that gradually more water was needed despite the positive effect of the 1974 earthquakes. Exploration work was done in 1974/75, and again in 1978 (Johannesson et al., 1979), including chemical sampling, detailed geothermal and geological mapping of the surroundings, and magnetic measurements of the area for structural exploration. Figure 4 shows the details of the geothermal field and the main geological structures associated with upflow of water (Georgsson et al., 1984b).

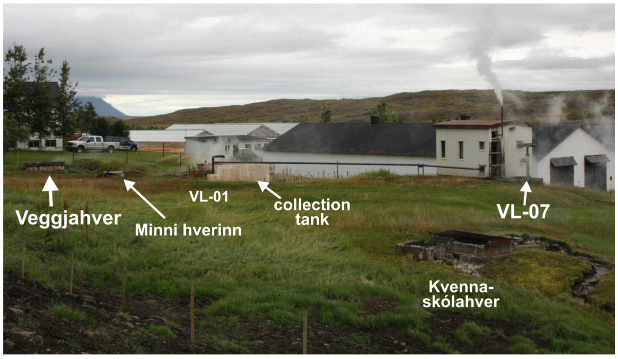

Figure 5: Photo showing the geothermal field. The hot springs are now inside old covered concrete cisterns and are still discharging. The production well VL-07 is also seen together with one of the old wells

The system is fracture-controlled with the main upflow appearing to be associated with a north-northeasterly trending fault or fracture, and the hot springs located at its intersection with an active west-northwesterly trending fracture, close to the largest hot spring Veggjahver. This is very much a similar picture to what has been seen in many other geothermal fields in Borgarfjordur. No vertical movement is seen on the westerly trending fracture, which is typical for westerly to northerly trending fractures associated with upflow of hot water in the Borgarfjordur area. Chemical analysis of the samples and chemical geothermometry showed the reservoir temperature of the geothermal system to be 100-110°C (Georgsson et al., 1984b).

Well VL-07 was located 15 m to the west of the line of hot springs, meant to cut the NNE-SSW trending fault at 300-500 m depth close to where it intersects the E-W trending fracture (Figure 4). It was drilled in late 1983 to a depth of 671 m and was a major success, even though the hot water came at deeper level than planned. At 661 m depth a large aquifer was struck, and continued drilling revealed an open fracture in the interval 667-671. Consequently drilling was stopped with the drill rig also having reached its maximum depth capacity. In free flow the well gave 41.5 l/s of 105°C water at the top, but temperature logging showed the temperature in the geothermal system to be 113°C (Figure 6), which is somewhat higher than predicted by geothermometry. Production tests showed that the well could be expected to sustain at least a production of 15 l/s in free flow, and more with pumping if necessary (Georgsson et al., 1984b). With the well producing under slight wellhead pressure, it has so far not had much effect on flow from the hot springs and the old wells. With the drilling of this well the continued development of the Varmaland/ Laugaland area was assured, and to date it has provided enough hot water for the Varmaland/Laugaland area and its rural surroundings.

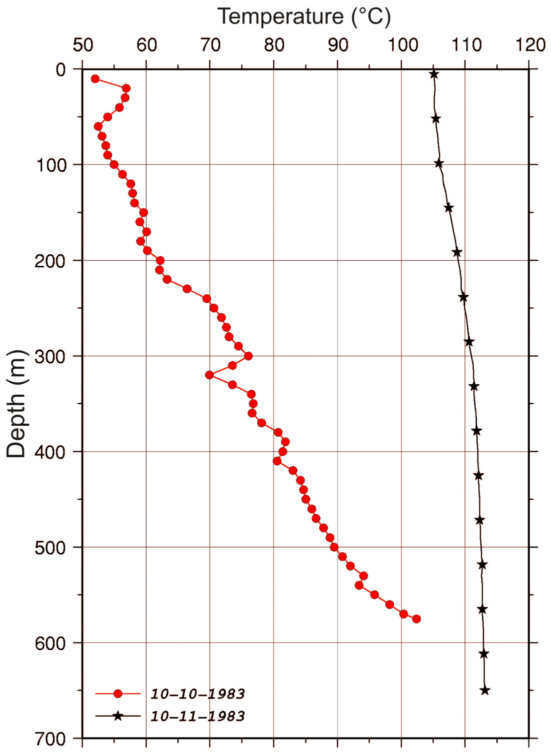

Figure 6: Temperature logs from well VL-07, one done during drilling, the other about 4 weeks after drilling ended with the well discharging

5. GEOTHERMAL UTILIZATION AT VARMALAND/LAUGALAND AND THE DEVELOPMENT OF THE SITE

5.1 Early Utilization of the Hot Water

The location of the Stafholtsveggjahver hot spring quite far from the Stafholtsveggir and other farms meant that the hot spring was not used in ancient times, except perhaps as drinking water for live stock during winter time. Probably, it was rather looked at as a nuisance that could be dangerous for the animals. The first recorded use of the hot water dates back to 1895, when a primitive pool for bathing and swimming was constructed of turf and stones at the base of the hot springs mound. This was in a period of an active movement encouraging young men to learn to swim. In 1931, the local sports club led an effort to build a new concrete swimming pool, 8×20 m which became very popular among the local residents. The pool was referred to as the Laugaland swimming pool, named after a small cottage found nearby. The name means the *land of warm springs*.

5.2 The Laugaland Greenhouse Farm

In 1942, new owners of the Stafholtsveggir farm, decided on establishing a greenhouse farm based on geothermal heating at the site, naming it Laugaland after the old cottage. Unusual for this period was the decision to establish it as a limited liability company, despite being a family business. In the first phase, 660 m^2 of greenhouses were built which was increased to 1600 m^2 in 1946. The first crops in 1943 included tomatoes and cucumbers. These continued to be the main crops with emphasis on the former, but crops also included growing of melons and grapes for several years, mainly in the 1950's. In 1960, the greenhouse area was increased to 2200 m^2. During the early years, the average annual yield was 20-25 kg/m^2 of tomatoes and 30-35 kg/m^2 of cucumbers, in a growing season extending through approximately 7 months, March-September for cucumbers and April-October for tomatoes. This was typical for greenhouses in Iceland during this period. The next step in the development was the building of a special house for mushroom growing (champignons) in 1961 that was unique in Iceland at that time. During the next 20 years, mushrooms were an important part of the production at Laugaland.

In more recent years, the greenhouse growers in Iceland have entered an era of increased competition, where specialization has replaced diversification, both due to general competition and reduction of import barriers. The mushroom growing was abandoned in 1981. About 1200 m^2 of greenhouses were added to the farm in 1991 extending the area under glass to 3600 m^2. Figure 4 shows the approximate extent of the greenhouses, still at about 3600 m^2. About 10 years ago, tomato growing was also abandoned. Thus, high quality cucumbers at competitive prices are now the speciality of the Laugaland farm.

The Laugaland farm has always been ready to adopt recent technical improvements, such as installing of automatic temperature control and window opening in the early years.

Figure 7: The Varmaland/Laugaland geothermal centre, W-Iceland

Later instalments include automatic feeding of water and fertilizers, use of artificial lighting, and automatic CO_2 enrichment for increased photosynthesis. The same applies to the growing media, where the farm has gone from earth in the first decades, where the hot water was used for sterilization once a year, to sterile inactive media such as rock wool and more recently to the environmentally friendly pumice, which allows complete control of the growth of the plants. This has included rebuilding or modernizing of old houses when necessary. An important step was the extension of lighting to "complete lighting" of the cucumbers around 1993, which allowed a lengthening of the growing season from approximately 8-9 months at that time to all year around. This was a pioneering project in Iceland, since followed by many other greenhouse farmers. The power of the lamps used is 200 W/m^2. The lighting of the crops when necessary through the whole year, and the use of CO_2 enrichment have increased the annual yield of cucumbers to the present value, 100 kg/m^2. The production is vacuum-packed at the site and sold in supermarkets mainly in the Reykjavik area. Currently, the annual production of cucumbers is about 260 tons. Use of biological control to fight insects and parasites has allowed the farm to produce without use of any chemical pesticides. With regard to this, the location of the farm has also helped, with no other greenhouse farms in the immediate vicinity.

The Laugaland family enterprise is now in the hands of the 3rd generation. Thorhallur Bjarnason has followed in the footsteps of his father Bjarni Helgason and grandfather Helgi Bjarnason. It is a fine example of successful development of greenhouse growing in Iceland based on the benefits of the geothermal energy, and strong family traditions. Thorhallur Bjarnason is now (2009) sitting as chairman of the greenhouse growers association in Iceland.

5.3 The Varmaland School and Community Centre

During the change of ownership of the Stafholtsveggir farm in 1941, the local rural community, Stafholtstungur, used their lawful option to claim some land close to the hot springs and a part of the hot water rights for a possible later development. The first step in this was a special school opened in 1946 by the Women´s Association of the Borgarfjordur Area in cooperation with the administration of the Borgarfjordur and Myrar districts. The school was named Varmaland (meaning *warm-land*), and hence the dual name of the area. This was a so-called finishing school for young women. These schools were popular in Iceland through the middle part of last century and intended for teaching young ladies cooking, handwork and arts necessary for running a home. The era of these schools was over in the last decades of last century and the Varmaland finishing school was closed in 1986.

In the early 1950's, all the rural communities in the Myrar district (northern part of Borgarfjordur area) joined in building a primary boarding school at Varmaland. The school opened in 1954 and was intended for all children between 7 and 12 years of age in the area. It has since been enlarged considerably, in two steps, in the 1960's and 1980's. The school has evolved through the years, along with the school system in Iceland and is now a complete primary school (children 6-15 years) for the northeastern part of the rural Borgarfjordur area, with the older classes using the old house of the finishing school (Figure 4). It has now about 150 children and more than 30 employees. Boarding is not practised anymore, but school buses operate in the region driving the children between school and home. The latest addition is a kindergarten for the youngest children established in 1992.

A new swimming pool, 12×25 m, was built in 1958, and a community hall/centre named Thinghamar including a sports hall was opened in 1981, adjacent to it. To this can be added several houses built for or by the people working in the area. Figure 7 is a photo of the Varmaland/Laugaland centre dating back to 2004, showing a prosperous centre in a rural region of beautiful surroundings.

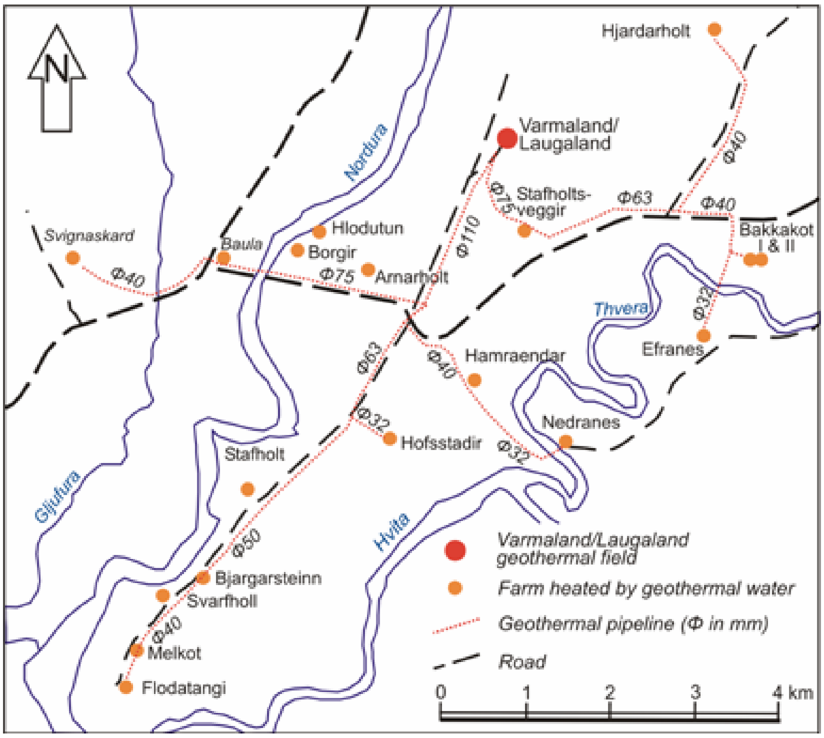

Figure 8: The rural geothermal district heating pipe system connected to well VL-7 at Varmaland/Laugaland

5.4 The Rural Heating System

Another important addition in the geothermal utilization in the area was the piping of hot water for space heating to the local surrounding farms. This became feasible with the successful drilling of well VL-7 in 1983. However, it was not until late in 1990 that the project was realised. All 17 farms within a distance of 6-8 km joined in the project, and are now connected to a geothermal pipeline from Laugaland.

In addition, a shop, a large camp of summerhouses at Svignaskard and a few summer houses at other locations are connected. Figure 8 shows the main features of the geothermal piping system, that has a total length of about 32 km. The pipeline is made of polybutylen and insulated with polyurethan. The diameter varies from 110 mm in the main pipeline, to 32 mm in the end pipelines to farms (Figure 8).

The limitation of the polybutylen is that maximum temperature should not exceed 80-85°C, which means that optimal use of the available energy cannot be attained. The design of the system includes three small pumping stations and guarantees a minimum temperature of 50-55°C for the end users. To accomplish this, the rural district heating system buys 6 l/s from well H-7. The geothermal district heating system does not only provide inexpensive hot water for heating, but also for bathing in mini pools or hot tubs, a common popular feature often accompanying the geothermal water, especially at summer or holiday houses.

CONCLUSIONS

The upper Borgarfjordur region comprises five low-temperature geothermal systems. The Reykholt system is the largest low-temperature system in Iceland, including many geothermal fields with large boiling hot springs, such as the Deildartunga and Kleppjarnsreykir hot springs. The total natural discharge of the system is about 450 l/s, most of it boiling water. The Baer system including the Varmaland/Laugaland geothermal field flanks it on the western side, while the England and Brautartunga systems are found to the south and the Husafell system to the east.

Distribution of the hot springs is structurally controlled, usually by through interplay of two active fracture trends, where the large hot springs are found at the intersection of the main structures. The active fractures zones found in the otherwise mainly impermeable Tertiary crust of the area, possibly together with deep-seated intrusions in the northern part of the region, provide good conditions for local heat mining inside the geothermal systems.

The Varmaland/Laugaland geothermal field is a good example of the geothermal activity in the Borgarfjordur region. The hot springs are found at an intersection between west-northwesterly and north-northeasterly fractures. Before drilling, the natural discharge was about 9 l/s with a maximum temperature of 96-97°. Drilling of the production well VL-7 yielded in free flow 40 l/s of hot water at a temperature of 105°C, and temperature logging indicates a reservoir temperature of 113°C. As the well is kept under some wellhead pressure to control the production, the hot springs are still producing. The well and the hot springs provides ample hot water for heating and bathing at the Varmaland/Laugaland centre and for the rural surroundings.

The Varmaland/Laugaland geothermal centre is a good example on how good access to geothermal water for heating and bathing has had a decisive effect on the rural development in Iceland. Here, a thriving regional centre has developed in a rural area at the site of the Stafholtsveggjahver hot spring, including schools, swimming pool, community hall, service centre and a prosperous greenhouse farm. The geothermal water is also piped to all neighbouring farms, within a distance of 6-8 km.

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