Presented at SDG Short Course II on Exploration and Development of Geothermal Resources,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 9-29, 2017.

GDC Geothermal Development Company
Powering the Vision

UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

KenGen
Kenya Electricity Generating Co., Ltd.

EXPLORATION AND DEVELOPMENT OF A CONCEPTUAL MODEL FOR THE THEISTAREYKIR GEOTHERMAL FIELD, NE-ICELAND

Finnbogi Óskarsson
ÍSOR – Iceland GeoSurvey
Grensásvegur 9, 108 Reykjavík
ICELAND
finnbogi.oskarsson@isor.is

ABSTRACT

Surface exploration of the Theistareykir high-temperature geothermal field was carried out in 1972-74 and 1981-84. The results suggested reservoir temperatures in excess of 280°C, that the fluids were dilute and their origin far inland. On basis of geothermometry, the field was divided into five subfields, three of which were considered productive. The areal extent of surface manifestations is 11-15 km^2. In the years 2002-2012, 10 deep wells were sunk into the geothermal field, largely confirming the findings of surface exploration. The natural heat output of the system has been estimated at 350 MW, from measurements of groundwater and soil temperatures. The electricity generation capacity of the system has been estimated at 104 MW for 100 years or 348 MW for 30 years.

1. INTRODUCTION

The Theistareykir geothermal field lies in the Theistareykir fissure swarm in NE-Iceland, which is the westernmost of the five NNE striking left-stepping *en échelon* volcanic systems that constitute the Northern Volcanic Zone (Figure 1). The field lies about 25 km southeast of Húsavík town at an elevation of 320-370 m a.sl. For centuries it hosted the main sulphur mine in Iceland, providing the Danish king with raw material for gun powder, and indeed the earliest mapping of geothermal activity was due to sulphur mining. Both sulphur mining and farming in the area was abandoned in the late 19th century. The abandoned farm site is nestled under the hyaloclastite table-mountain Bæjarfjall, adjacent to a field of boiling mud-pools and fumaroles.

Thorough geological, geochemical and geophysical mapping of the area was conducted in the 1970s and 1980s (Grönvold and Karlsdóttir, 1975; Gíslason et al., 1984; Ármannsson et al., 1986; Darling and Ármannsson, 1989), after which the area was monitored intermittently in the 1990s (Ármannsson et al., 2000). Gautason et al. (2000) suggested drill sites based on available knowledge. The first two wells, ThG-1 and ThG-2, were drilled in 2002 and 2003, and since then 7 more wells have been drilled, and one well redrilled. Further resistivity measurements were carried out in 2004–2006 (Karlsdóttir et al., 2006), a new geological map was prepared in 2007 (Sæmundsson, 2007), and soil gas flux measurements and fumarole sampling were conducted in 2012 (Kristinsson et al., 2013a).

The purpose of this paper is to outline the major results of surface exploration and drilling and to combine all findings into one conceptual model for the area. It is mainly based on a report by Gudmundsson et al. (2008) and a review by Ármannsson (2011), but also takes into account later findings, e.g. by Kristinsson et al. (2013a, 2013b), Óskarsson et al. (2013) and Sveinbjörnsdóttir et al. (2013).

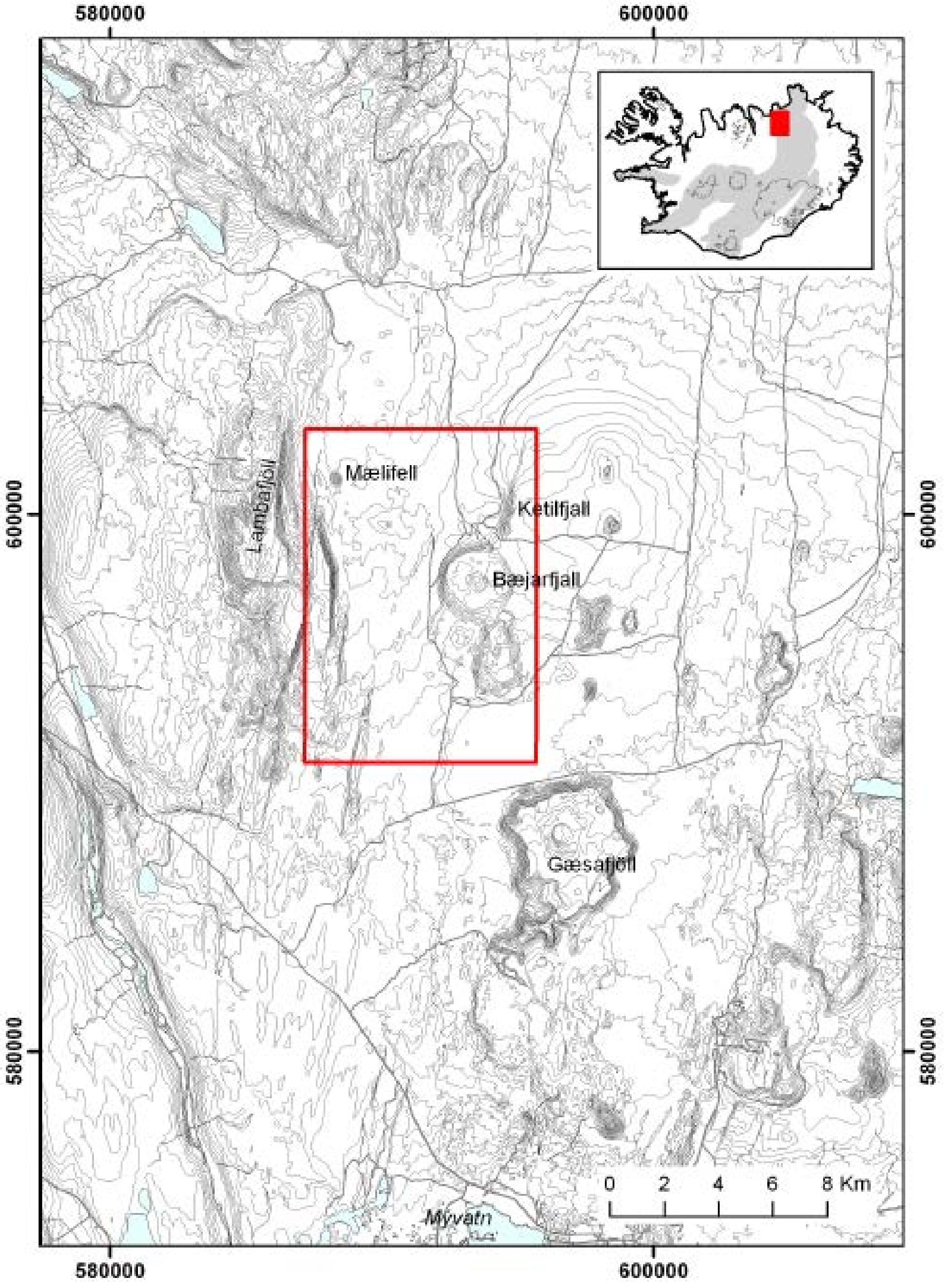

FIGURE 1: Location of the Theistareykir geothermal field, NE Iceland

2. SURFACE EXPLORATION

2.1 Geology

The geological map of the Theistareykir area (Figure 2) and accompanying discussion are from Sæmundsson (2007). His main findings are outlined below.

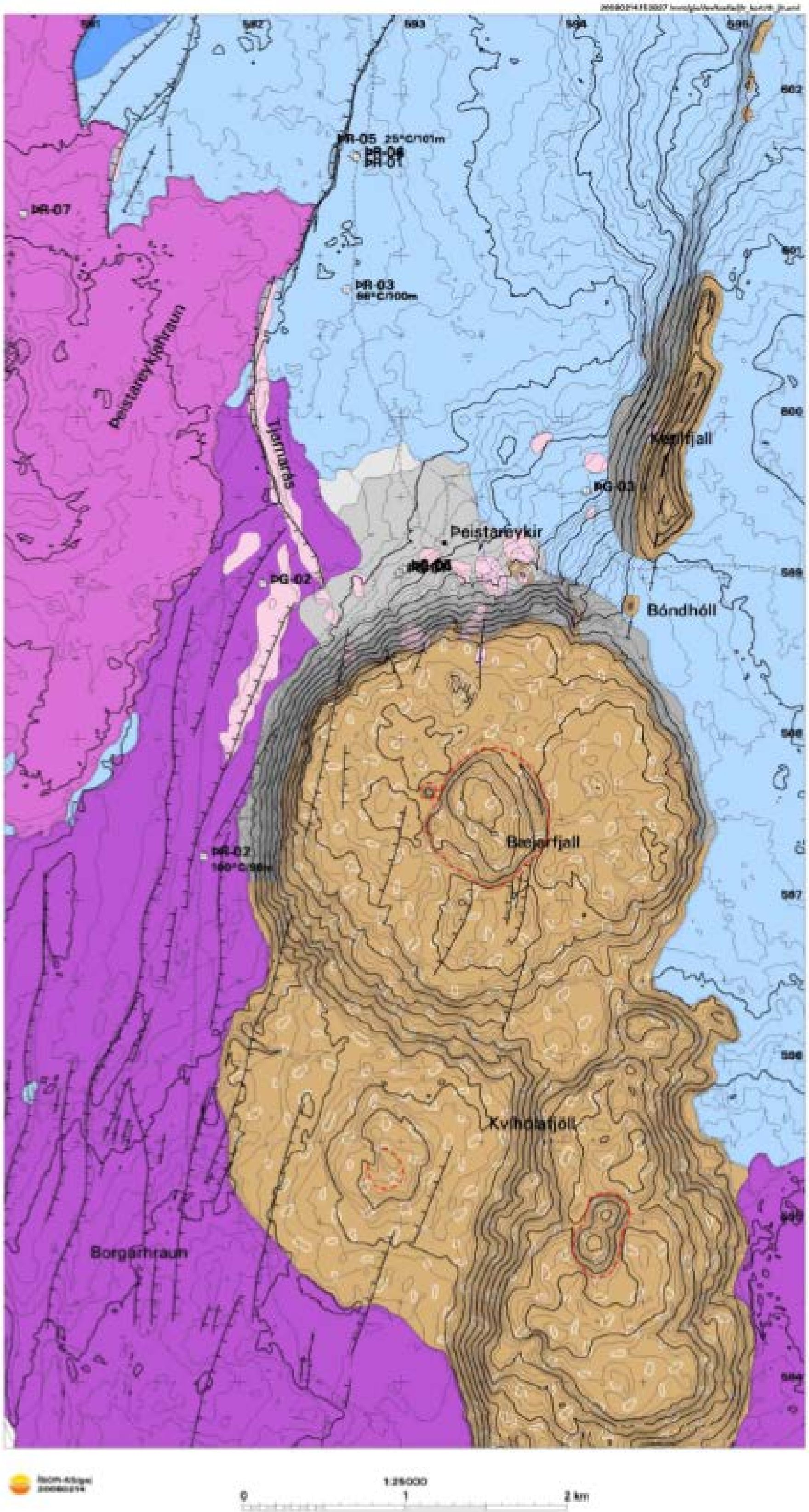

FIGURE 2: Geological map of Theistareykir. Hyaloclastites are brown, Borgarhraun dark purple, Theistareykjahraun light purple, Stóravítishraun light blue and Skildingahraun darker blue. Rock slides and surface deposits are grey. Wells marked ÞG on this and later figures are referred to with ThG in the text. From Sæmundsson (2007)

The Theistareykir geothermal field lies in the centre of one of the five volcanic systems that form Iceland's North Volcanic Zone (NVZ). It consists of an E-W tending heat source astride a N-S tectonic structure. The associated fissure swarm is about 7-8 km wide and extends 70-80 km from south of Lake Mývatn to Öxarfjördur in the north.

The area exhibits most of the features of a central volcano, except the topographical ones; volcanic productivity has been greatest near the centre of the system where siliceous rocks are found, but a true caldera structure has not developed. The surface is mostly covered in lava flows, all but one of which date from shortly before and after the end of the latest glaciation period. All are shield lavas, but of various size and composition. Older formations are generally hyaloclastites and pillow lavas. The most recent volcanic activity in the area occurred about 2,400 years ago and the high temperature geothermal activity is connected to recent magma intrusions.

The most relevant lava flows in the area are Stóravítishraun (11-12,000 y) which is a lava shield with a volume of about 20 km^3 and covers most of the eastern part of Theistareykir; Skildingahraun (>14,500 y) is a lava shield which lies to the north of Theistareykir; Borgarhraun (8-10,000 y) is a picrite basalt lava which has spread out to the southeast, south and west of Mt. Bæjarfjall; and finally Theistareykjahraun (2,400 y) which flowed from Stórihver to the north covering parts of Skildingahraun.

The geothermal surface activity is confined to the eastern part of the fissure swarm, more specifically to the the area northwest and north of Mt. Bæjarfjall which is bounded by Theistareykjahraun to the west and Mt. Ketilfjall to the east. The total areal extent of surface activity is 11 km^2. The geothermal manifestations comprise warm soil, mud-pools, fumaroles and solfataras as well as steam areas, where steam rises from the lava and fractures. Cold alteration (clay) is found in the western part of the fissure swarm, mainly south of the rhyolitic Mt. Mælifell. Geothermal activity appears to have been extinct there for at least 3,000 years. A clear division is seen in the ridge Tjarnarás, along which a fault stretches NNW from Mt. Bæjarfell. On the west side of Tjarnarás lies Borgarhraun where a number fo faults are seen, with dips of a few m to the west. Considerable geothermal activity is observed along these faults. On the east side of Tjarnarás, lies Stóravítishraun, which being closest to Mt. Bæjarfjall, has been covered with rock slides and other deposits from the mountain. No faults are observed east of Tjarnarás. On the western slopes of the hyoloclastite ridge Mt. Ketilfjall, warm springs and fumaroles are found.

2.2 Geophysics

Karlsdóttir et al. (2006) reported on TEM measurements carried out in Theistareykir in 2004-2006 (Figure 3), and Karlsdóttir and Vilhjálmsson (2011) on MT measurements from 2009. Their main findings are recapitulated below.

The TEM measurements indicate that there is a low-resistivity shell with a high-resistivity core underlying the Theistareykir area. North of Mt. Bæjarfjall, where surface activity is most abundant, the low-resistivity (smectite) zone reaches the surface and the shallowest depth to the high-resistivity core is about 200 m. In the area around Stórihver, the low-resistivity zone is at a depth of about 200 m and higher resistivity is found at about 300-400 m depth. There is currently no significant surface activity in the area, but the resistivity indicates that the temperature at this depth has at some point in time reached 230°C. South of Mælifell, a low-resistivity zone is found at 100-200 m depth. Cold surface alteration is found in the area, indicating that the low resistivity is due to an extinct geothermal system.

The TEM results suggest that two areas are of greatest interest; Theistareykjagrundir north of Mt. Bæjarfjall and the area around Stórihver. The total areal extent of the geothermal system according to the TEM results is about 45 km^2 (Figure 4).

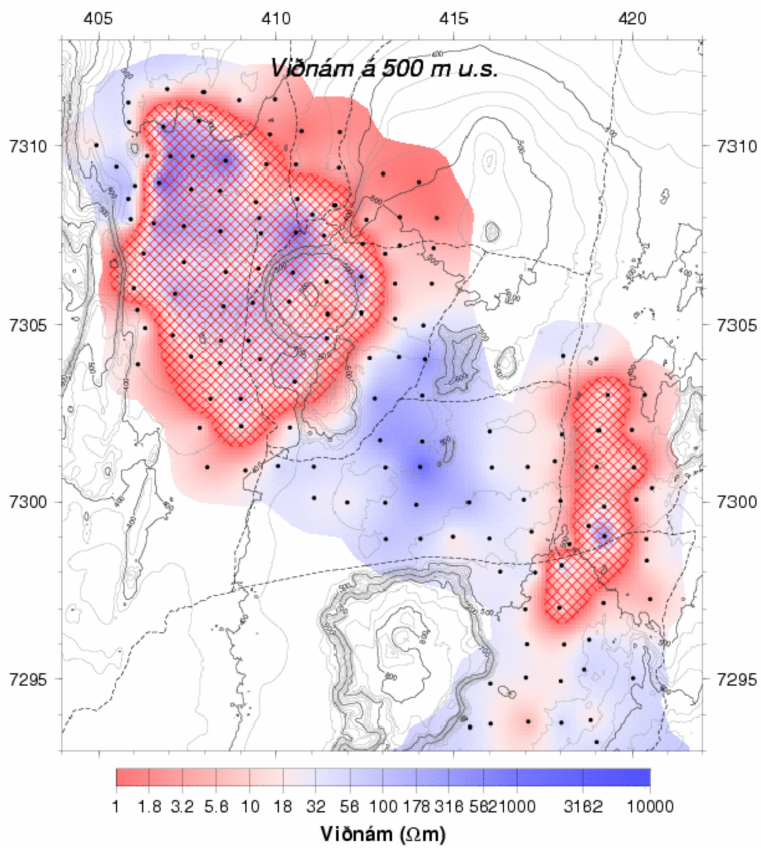

FIGURE 3: Resistivity at 500 m b.sl. in the Theistareykir-Gjástykki area, according to the TEM measurements of Karlsdóttir et al. (2006)

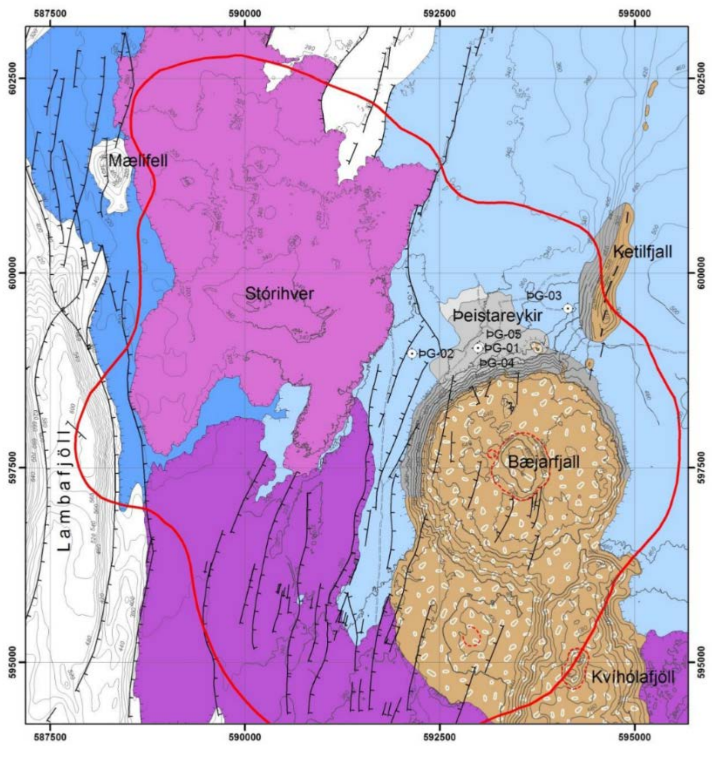

FIGURE 4: Size of the geothermal system according to results of resistivity soundings, 45 km^2 in total. The red line denotes the boundary of the high-resistivity core at 1 km depth. Wells marked ÞG are referred to with ThG in the text. From Saemundsson (2007)

The results of the MT measurements show a similar resistivity structure as those of the TEM measurements, in the depth range where both apply. According to the MT results the main heat upflow in Theistareykir is found in NNE-SSW fissures which cross Theistareykjagrundir from Mt. Bæjarfjall to Mt. Ketilfjall. Another heat upflow zone is postulated in parallel fissures further to the west, trending NNE from Stórihver. Yet another, smaller, upflow appears to exist below Mt. Ketilfjall. The results furthermore indicate that the system has a sharp border to the south, where the high-resistivity zone appears to reach much further down.

Gíslason et al. (1984) reported gravity measurements conducted in the years 1981-83 and produced a Bouguer-map of the area (Figure 5). The most striking features are a large gravity depression stretching from NW of Mt. Bæjarfjall to NE of Lambafjöll. A closer look indicates that this large depression is where two low-gravity structures meet; one N-S trending which appears to follow the Theistareykir fissure swarm and another NW-SE trending (north of Lambafjöll) which is likely to be connected to the Húsavík Fracture Zone.

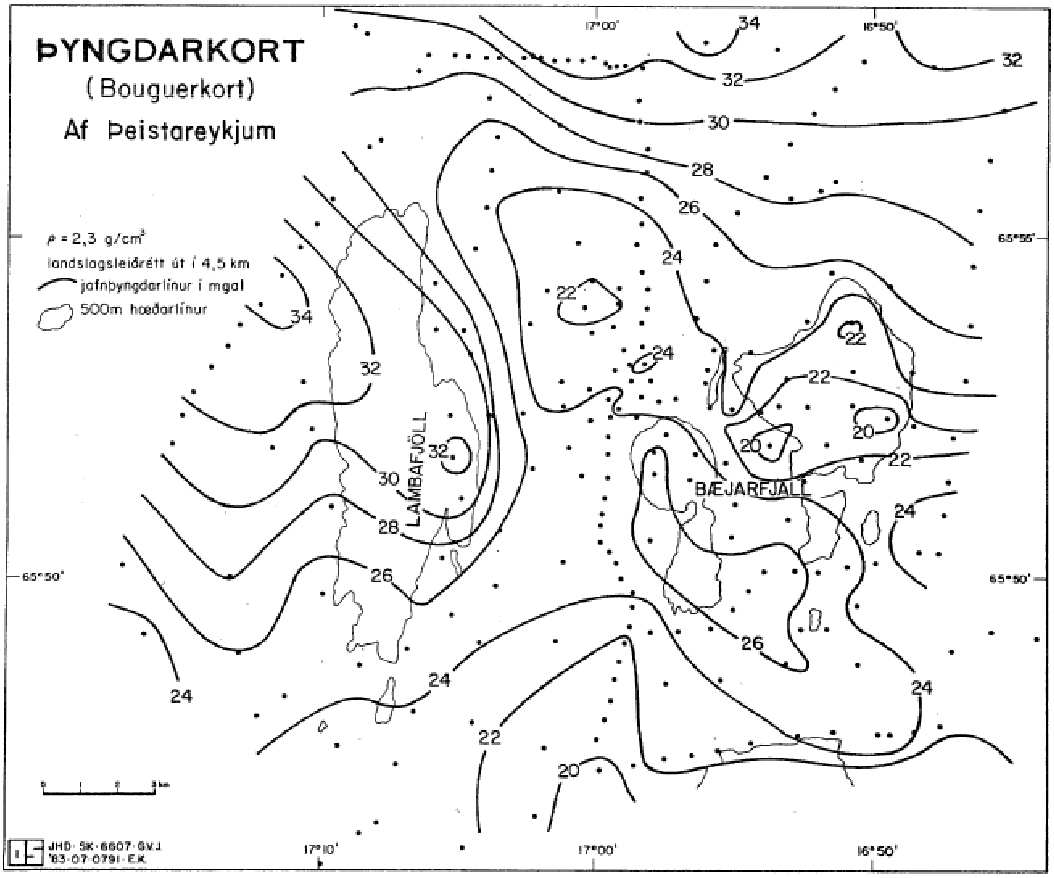

FIGURE 5: Bouguer map of Theistareykir. Values for iso-gravity lines are given as mgal. From Gíslason et al. (1984)

2.3 Geochemistry

The first few steam sample analyses from Theistareykir date from about 1950, but a comprehensive geochemical study was conducted in the 1970s and 1980s and reported by Grönvold and Karlsdóttir (1975) and Gíslason et al. (1984). The latter collected samples from 34 fumaroles and estimated reservoir temperatures by gas geothermometry, with results ranging from 230 to 315°C. Their results were further refined by Ármannsson et al. (1986) who divided the active surface area into five sub-areas (Theistareykjahraun (E), Tjarnarás (D), Theistareykjagrundir (C), Bóndhólsskard (B) and Ketilfjall (A); Figure 6), out of which Tjarnarás, Theistareykjagrundir and Ketilfjall appeared promising for drilling.

Theistareykjahraun appeared to be cold, and a relatively large, cool, shallow flow was predicted through Bóndhólsskard, preventing primary steam from rising to the surface. From the distribution of gas temperatures and concentrations of radon and solutes in condensate, it was suggested that the direction of the heat source was E-W.

Darling and Ármannsson (1989) concluded from isotope values for fumarole steam that in Tjarnarás, the steam had been condensed by a fraction of 0.15 to 0.25 of the original steam at temperatures of 130-200°C, resulting in too high geothermometer temperatures. On the other hand, they found that the steam at Theistareykjagrundir was mainly secondary steam and that the geothermometer temperatures were probably too low. They concluded, however, that the steam rising from Ketilfjall was undisturbed and that the geothermometer temperature values were probably close to true ones. They also found that the stable isotope signature of the deep inflow to the system was about -100‰ and -12‰ for δD and $\delta^{18}O$, respectively, suggesting that the origin of the reservoir fluid is far to the south of Theistareykir and that it may have fallen as precipitation during a colder climate regime. Water from warm springs in the area was found to have a local origin.

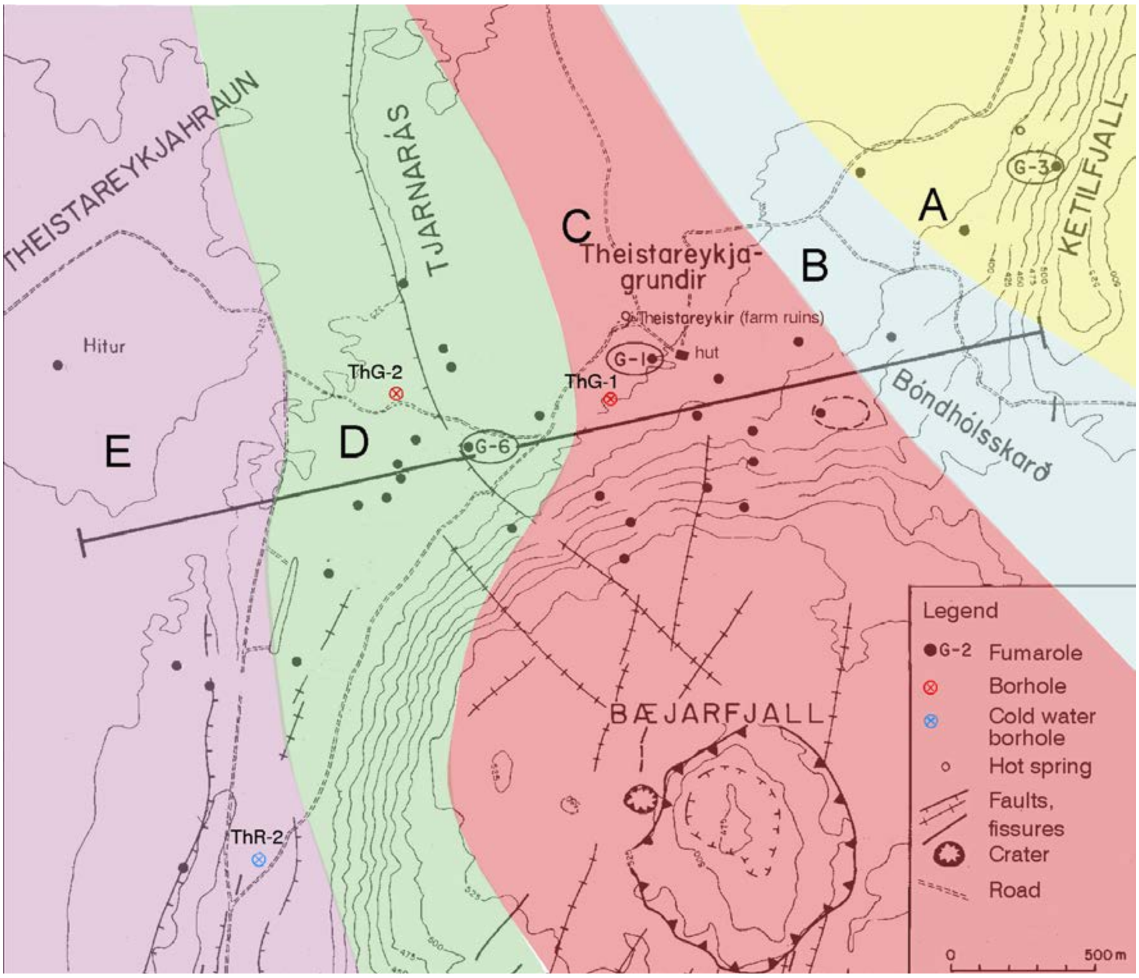

FIGURE 6: Division of the Theistareykir area into five sub-areas, based on chemical and isotope data (Ármannsson et al., 1986)

Ármannsson et al. (1986) proposed a deep inflow to the area from the southeast with Theistareykjagrundir closest to the source. Thus, that area was considered most promising even though the gas geothermometer values obtained seemed rather low. Tjarnarás and Ketilfjall were also considered intersting drilling targets. The Tjarnarás and Theistareykjagrundir areas are more accessible than Ketilfjall, and therefore the suggestion was that the first exploration wells be situated in these two subareas. The dissolved solids concentration of the steam was very low suggesting that the reservoir fluid was dilute. Low radon concentrations in fumarole samples were interpreted to suggest good permeability, especially in the Tjarnarás area.

Ármannsson et al. (2000) reported on a few samples that were collected in the 1990s from three of the fumaroles located by Gíslason et al. (1984) and in 2012 and 2013, Kristinsson et al. (2013a, 2013b) collected samples from the same three fumaroles, and added samples from another three. The locations of all fumaroles are shown in Figure 7 and the temporal development of gas concentrations and stable isotope values is shown in Figure 8.

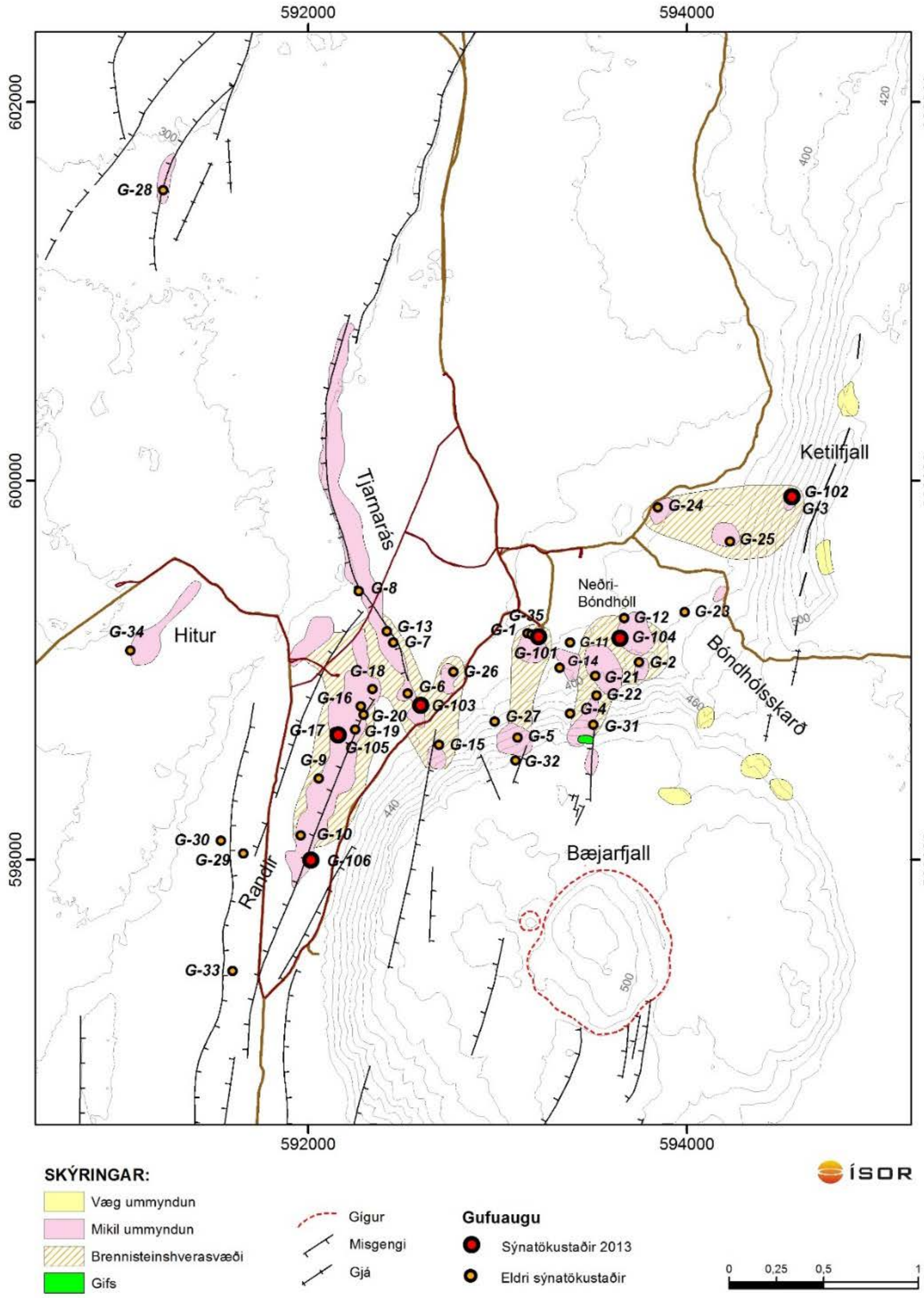

FIGURE 7: Locations of fumaroles sampled in Theistareykir. Names according to Gíslason et al. (1984) and Kristinsson et al. (2013a). Yellow areas denote some alteration on surface whereas pink areas show intense alteration

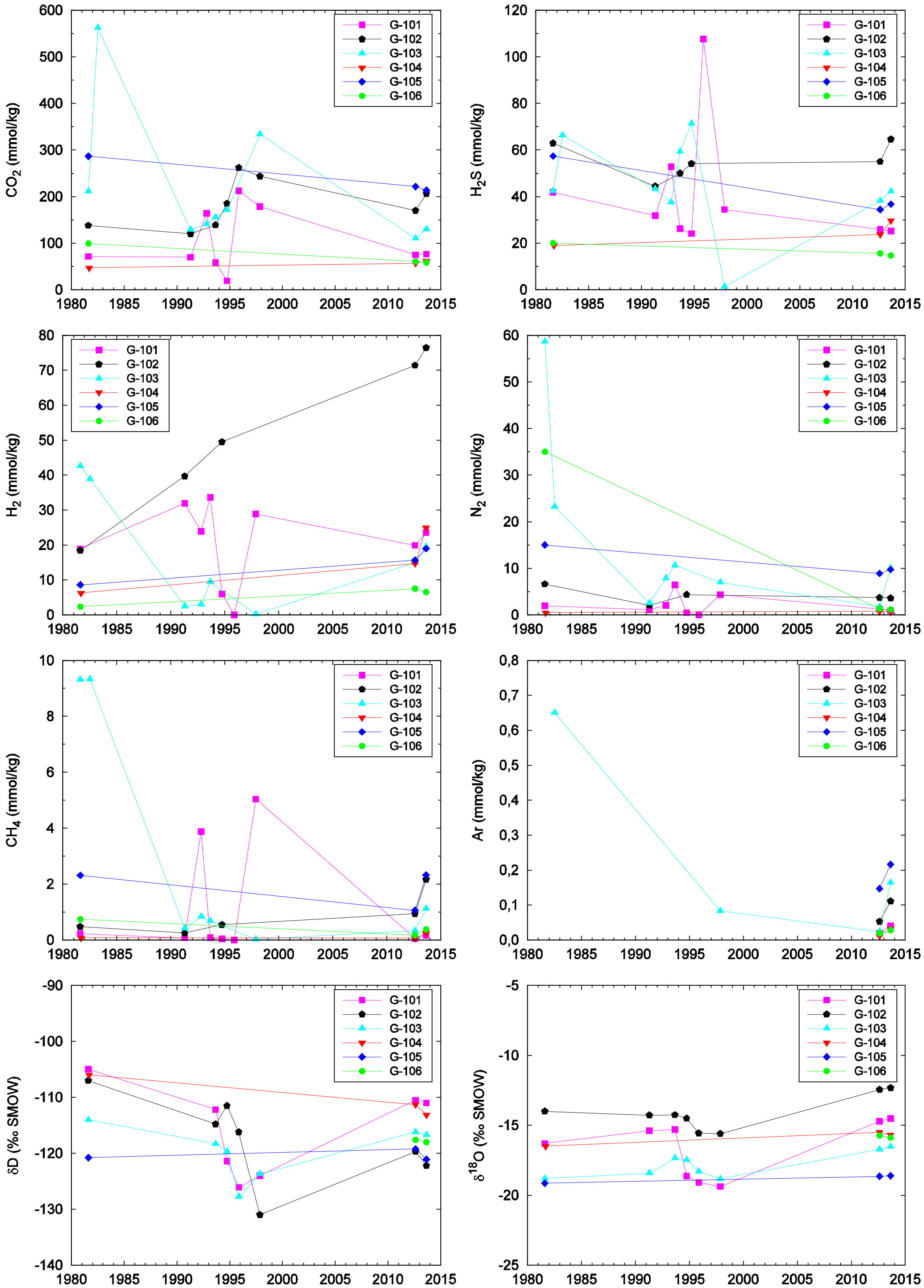

FIGURE 8: Gas concentrations and stable isotope values for fumaroles in Theistareykir (from Kristinsson et al., 2013b)

The calculated gas temperatures for the three periods, 1981-82, 1991-97 and 2012-13 are given in Table 1. The temperatures given are averages for those obtained by the gas geothermometers of Arnórsson et al. (1998) and the gas ratio geothermometers of Arnórsson and Gunnlaugsson (1985). Judging by the data in Table 1, it seems that the temperature in the Ketilfjall and Theistareykjagrundir sub-areas has increased since the 1980s, and were at about 315 and 300°C, respectively, in 2012-13. On the other hand, the Tjarnarás area appears to have cooled somewhat in the 1990s but at least the northern part of Tjarnarás (where G-103 is located) shows a higher gas temperature in 2012-13 than before. At any rate, the results of gas geotermometry indicate that the reservoir temperature in Theistareykir is at least 280°C.

TABLE 1: Average gas temperatures for six Theistareykir fumaroles in three periods. Locations are drawn in Figure 7.

Fumarole	Area	1981-82	1991-97	2012-13
G-101	Theistareykjagrundir	293°C	297°C	299°C
G-102	Ketilfjall	293°C	310°C	315°C
G-103	Tjarnarás	289°C	277°C	298°C
G-104	Theistareykjagrundir	283°C	-	298°C
G-105	Tjarnarás (Randir)	289°C	-	285°C
G-106	Tjarnarás (Randir)	257°C	-	283°C

2.4 Soil gas measurements

Kristinsson et al. (2013a) reported on soil gas measurements conducted in Theistareykir in 2012. They measured CO_2 flux from soil at 374 locations and measured soil temperature at 15 cm depth at the same locations. The majority of the measurement points was at an interval of 25 m on two long profiles, one stretching eastwards from Stórihver, crossing Tjarnarás and Theistareykjagrundir and passing through Bóndhólsskard to the east side of Mt. Bæjarfjall, and the other following the surface activity in Tjarnarás and Randir from the north to the south, with a few points added west of Mt. Ketilfjall (Figure 9).

As seen in Figure 9, gas emissions through soil are generally quite low in Theistareykir. Out of the 374 locations, 192 showed either visible alteration on the surface or a soil temperature exceeding 25°C at 15 cm depth. The average CO_2 flux in these locations was 18.2 $g/m^2/day$, with values ranging from 0.2 to 820 $g/m^2/day$. For the remainder of the locations, the average CO_2 flux value was 7.5 $g/m^2/day$. Only 8 locations had CO_2 flux in excess of 50 $g/m^2/day$. The most probable explanation for this is that in the areas of surface acitity in Theistareykir, the soil is quite dense and rich in clay, and therefore it may be rather impermeable.

2.5 Heat loss from the area

Using information from Hafstad (1989, and personal communication) about the Lón estuary in Öxarfjördur, 20 km to the north of the Theistareykir area, Ármannsson (2001) calculated the heat loss from the field (Table 2). The estuary is believed to receive solely subsurface water from Theistareykir. The values are minimum values but they suggest a 300 MW heat loss to groundwater and 50 MW through surface (Ármannsson, 2001).

3. EXPLORATION WELLS

3.1 Well locations and characteristics

In the years 2002 to 2012 nine deep wells were sunk into the Theistareykir field, with depths ranging from 1723 m to 2799 m. The maximum formation temperature in 6 of the wells exceeded 300°C, with a maximum temperature of 380°C. The locations of the wells are shown in Figure 10. In addition one production section was abandoned and a new production section drilled from wellhead ThG-5, providing data from a total of 10 transects in the potential production zone. The drilling of the first 6 wells is discussed in more detail by Gautason et al. (2010).

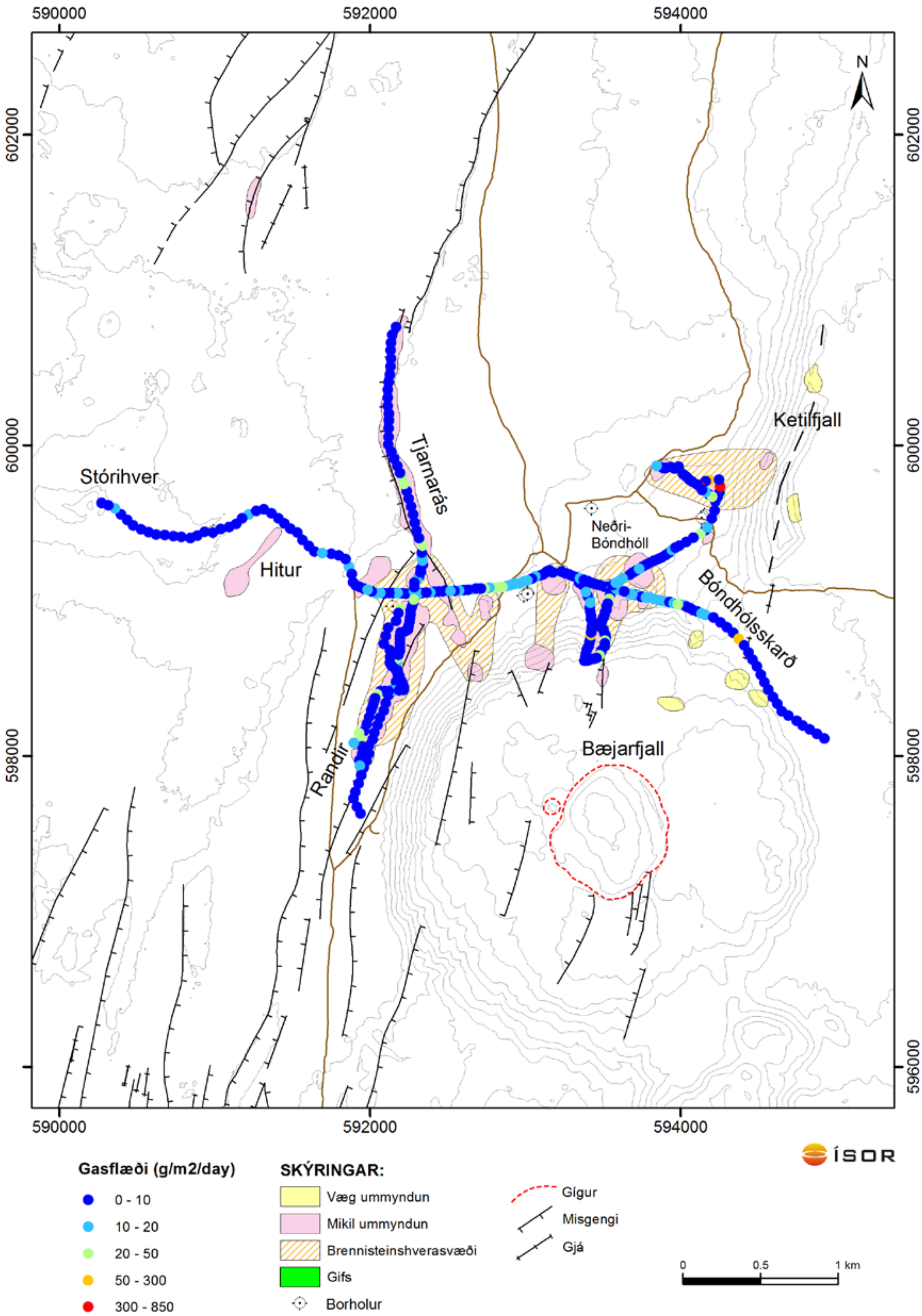

FIGURE 9: Surface activity and soil gas measurements in Theistareykir in 2012 (from Kristinsson et al., 2013a)

TABLE 2: Heat loss from the Theistareykir area

Inflow to Lón, Öxarfjördur	20 m^3/s
Local groundwater ambient temperature	3.7°C
Inflow to Lón, mean temperature	7.2°C
Excess temperature	3.5°C
Heat power of area	3.5°C × 20 m^3/s × 4.18 J/(g °C) ≈ 300 MW
Areal extent of Theistareykir	15 km^2
Heat loss from area	300MW / 15 km^2 =20 MW/km^2

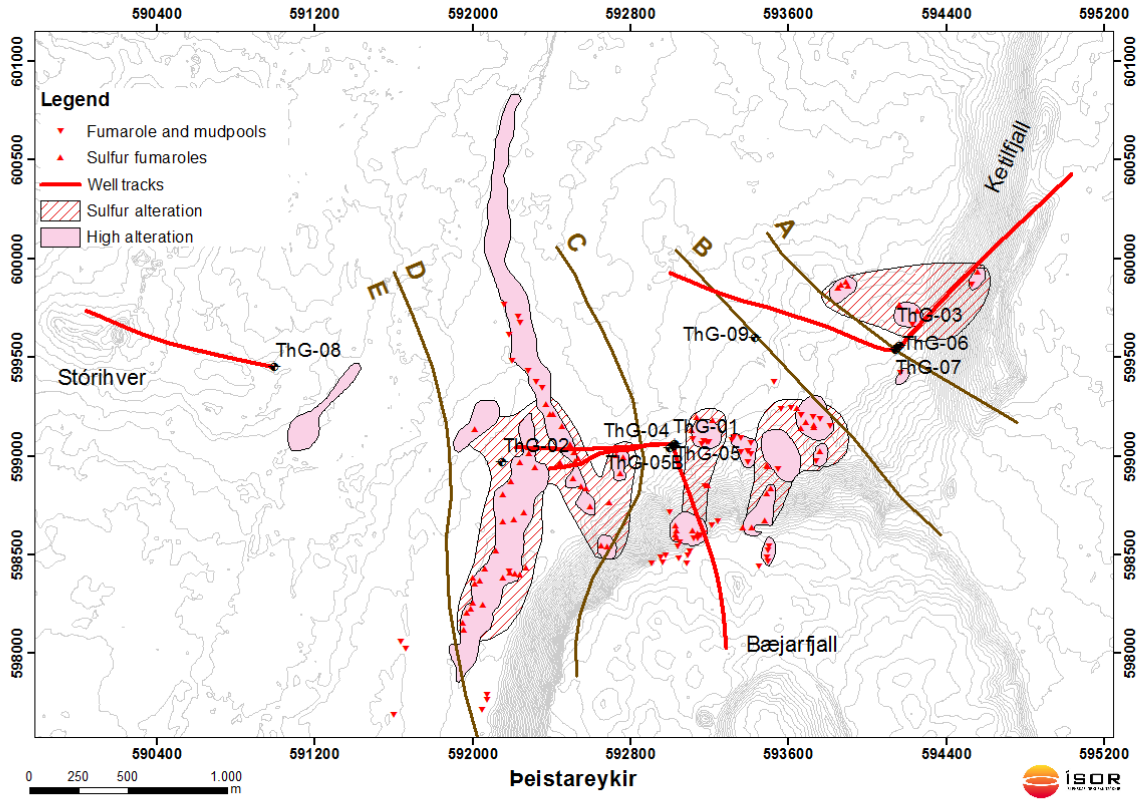

FIGURE 10: Locations and well tracks of deep geothermal wells in Theistareykir. Sub-area labels are the same as in Figure 6

An overview of the deep exploration wells in Theistareykir is given in Table 3. Six of the wells (ThG-1, -3, -4, -6, -7 and -9) have a discharge enthalpy of 2000 kJ/kg or more, three wells (ThG-2, -5 and -5b) have enthalpy corresponding to liquid enthalpy at the reservoir temperature. Well ThG-8 is cold and has never discharged.

Prior to deep drilling, four shallow “cold water” wells, ThR-1 to -4 were drilled to obtain drilling fluid. Well ThR-2, which is 102 m deep, just reached the groundwater table, and the temperature of the water proved close to boiling. In ThR-3 the groundwater table is also close to 100 m depth. The temperature was 66°C there, but 90°C at 140 m depth. The groundwater table was at about 100 m depth in wells ThR-1 and ThR-4, the former is 128 m deep and the temperature of the water was 26-28°C, but the latter is 150 m deep, with water temperature 26-35°C (Hafstad, 2000). Water from these two wells was used as drilling fluid for the deep geothermal wells.

Results of drilling largely confirm those obtained from surface exploration. Temperature and enthalpy are high on wells drilled in Theistareykjagrundir (C) and Ketilfjall (A) have high, but those drilled into or towards Tjarnarás (D) are lower enthalpy wells. Well ThG-5b which was side-tracked out of well

ThG-5 is deeper and hotter, but of liquid enthalpy. The only well drilled in Theistareykjahraun (E), well ThG-8, was found to be cool and unproductive, thus confirming that the alteration observed in the resistivity soundings is a remnant of an extinct geothermal system.

TABLE 3: Key information on deep geothermal wells in Theistareykir

Well	Area (cf. Fig. 6 and 10)	Year of completion	Depth (m)	Well type	Max. T (°C)	Enthalpy (kJ/kg)
ThG-01	C	2002	1953	Vertical	332	2000
ThG-02	D	2003	1723	Vertical	242	900
ThG-03	A	2006	2659	Vertical	380	>2600
ThG-04	C	2007	2239	Inclined	328	>2600
ThG-05	C->D	2007	1910	Inclined	261	900
ThG-05b	C->D	2008	2499	Inclined	342	1250
ThG-06	A->C	2008	2799	Inclined	311	>2600
ThG-07	A	2011	2508	Inclined	292	2500
ThG-08	E	2011	2503	Inclined	202	-
ThG-09	C	2012	2194	Vertical	339	>2600

Alteration of the bedrock is extensive and minerals indicating high temperatures are found high up in the stratigraphic column. A narrow zone of over-pressure is encountered in some wells between ~100 m and ~300 m depth. The strata observed in the wells show thick palagonite strata (tuff, breccias and pillow lavas) in the top part. The number of intrusions increases with depth. At a depth of about 1150-1300 m a change occurs and lava layers with intermediate layers become prominent. The alteration pattern suggests a steadily increasing temperature with depth.

A graphical representation of bedrock temperatures on a profile linking wells ThG-2, -1 and -3, determined by analysis of secondary minerals and temperatures from well logging, is given in Figure 11 (from Gudmundsson et al., 2008). The figure clearly shows the difference between wells ThG-1 and -3, on one hand, and well ThG-2 on the other hand, which is cool down to a depth of about 1700 m. Many aquifers are seen in the interval 200-1700 m indicating high permeability and very fractured rock. This interpretation is further corroborated by the high injectivity index of the well.

3.2 Well fluids

All wells except ThG-8 have discharged, ThG-9 only for one month but the other wells for several months each. The results of analysis of fluids extracted from the wells confirms to a large extent the findings from the exploration phase. The high enthalpy fluid in the system, which has a near-neutral pH and contains less than 1% (wt.) of gas and low TDS (~1000 ppm), is suitable for electrical production by conventional means. The calculated concentration of main components in the Theistareykir deep liquid is given in Table 4. The deep liquid composition is calculated using the speciation program WATCH (Bjarnason, 2010). The excess enthalpy of wells ThG-1, -3, -4, -6, -7 and -9 is assumed to be due to phase segregation in the reservoir, and the method of Arnórsson et al. (2007) is used to account for the excess enthalpy.

Figure 12 shows the results of geothermometry for the latest samples from each well in Theistareykir. The gas calibrations used are those by Arnórsson et al. (1998), Na/K-temperatures are calculated using the calibration of Arnórsson et al. (1983) and quartz temperatures are calculated from the calibration of Fournier and Potter (1982).

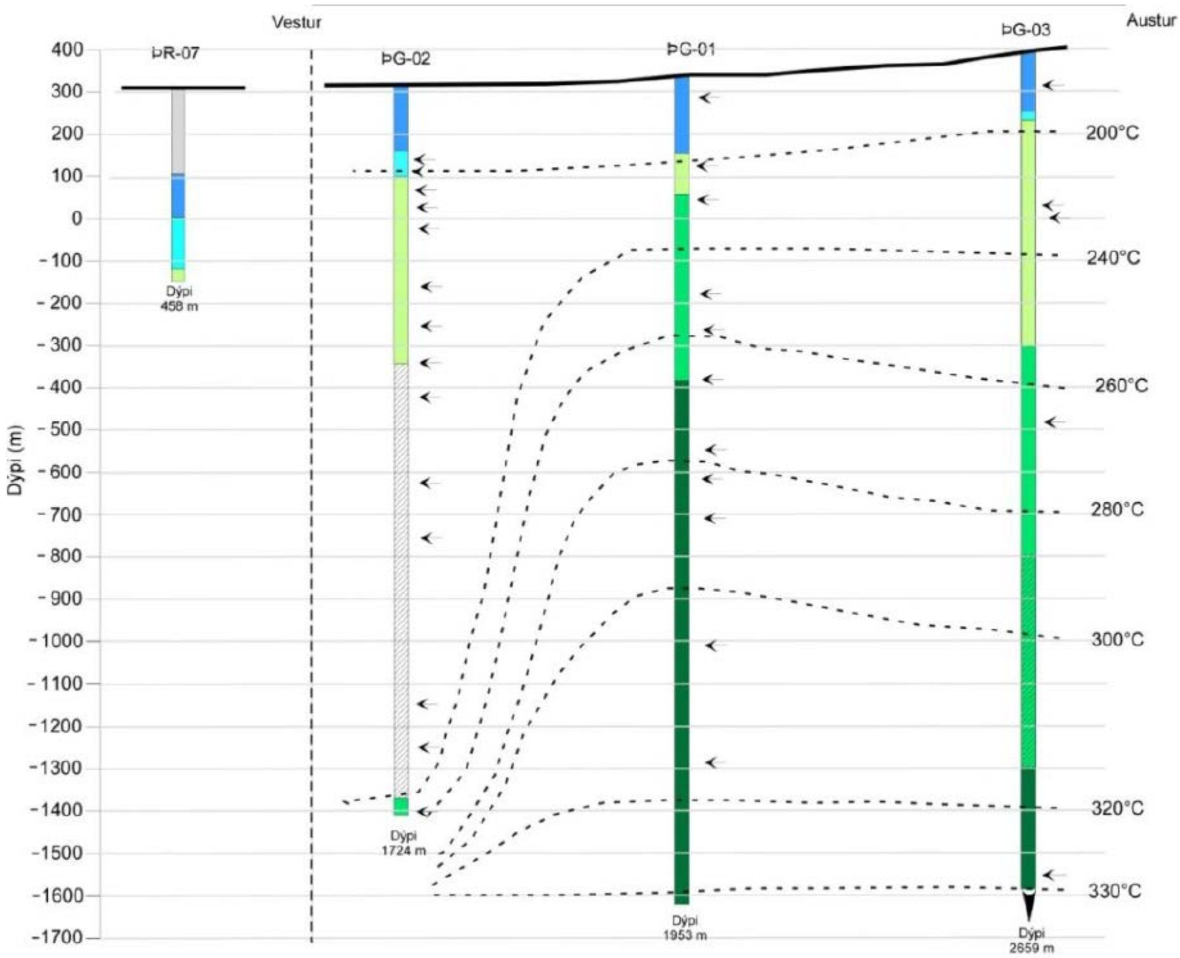

FIGURE 11: Graphical presentation of bedrock temperatures from analysis of secondary minerals and temperatures from well logging. Grey are fresh rocks, blue is the smectite-zeolite zone (< 200°C), light blue is mixed layer clays (200-230°C), light green is the chlorite zone (230-250°C), green is the chlorite-epidote zone (250-280°C) and dark green is the epidote-actinolite zone (>280°C). Wells marked ÞG are referred to with ThG in the text (from Gudmundsson et al., 2008)

TABLE 4: Chemical composition of deep liquid in high-temperature wells in Theistareykir

Well	T_{ref} (°C)	pH	B	SiO_2	Na	K	Ca	F	Cl	SO_4	CO_2	H_2S	N_2	H_2
ThG-1	280	7.32	1.35	608	81.1	16.8	0.13	1.47	83.1	10.6	99.8	48.2	4.31	1.47
ThG-2	220	7.16	0.47	351	117	12.6	0.73	0.64	38.5	35.8	353	47.2	21.9	0.09
ThG-3	290	7.49	2.86	753	101	21.1	0.67	1.03	81.8	8.28	103	94.7	3.07	2.34
ThG-4	290	7.24	3.01	506	58.0	13.0	0.17	1.08	67.3	2.46	17.0	124	2.94	3.66
ThG-5	220	7.32	1.83	366	112	15.1	0.77	0.83	40.6	31.1	274	30.7	67.2	0.08
ThG-5b	270	6.97	0.93	550	88.4	16.5	0.19	0.98	47.0	18.0	404	86.5	39.2	0.51
ThG-6	280	7.17	4.06	813	113	23.9	0.19	0.96	128	5.30	71.7	111	4.48	2.84
ThG-7	250	7.46	2.43	735	100	22.1	0.15	0.74	28.9	5.82	877	127	8.21	1.42
ThG-9	260	7.21	-	827	192	32.0	0.82	0.89	213	8.12	41.3	140	1.01	1.79

The gas geothermometers give average reservoir temperatures in the range 280-290°C for wells ThG-1, -3, -4, -6 and -7, but 200-210°C for wells ThG-2 and -5. Na/K temperatures generally agree with the average gas temperatures, but quartz temperatures are systematically higher in wells in the Ketilfjall area (ThG-3, -6, -7 and -9).

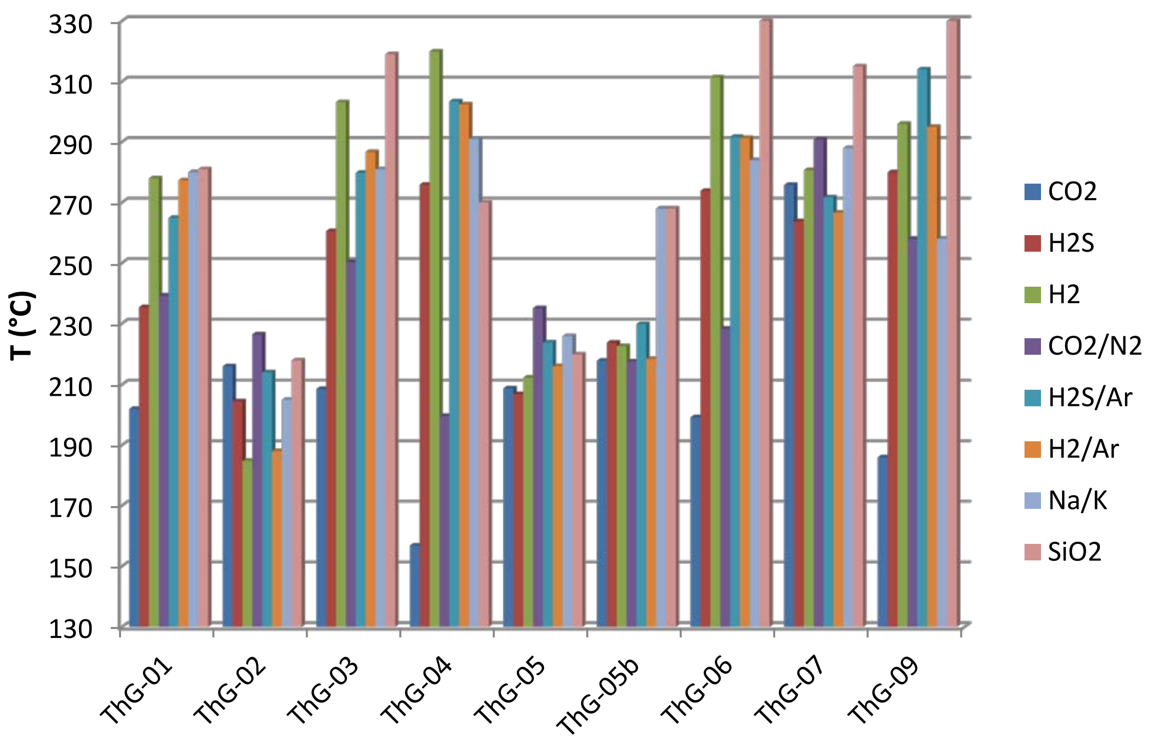

FIGURE 12: Geothermometry results for samples from productive wells in Theistareykir. Gas temperatures are from Arnórsson et al. (1998), Na/K-temperatures from Arnórsson et al. (1983) and quartz-temperatures from Fournier and Potter (1982).

Well ThG-5b, which was side-tracked from ThG-5 and drilled towards ThG-2 to a depth of about 2500 m seems to produce a similar vapour phase as wells ThG-2 and -5, but the liquid phase appears to be hotter (270°C). This would indicate that the well reaches below the ~200°C fractured zone postulated in the Tjarnarás sub-area. Contrarily, it appears that the vapour phase of well ThG-9 is hotter (290°C) than the liquid phase (260°C). However, the well had only discharged for one month when it was sampled, so these results should be taken with some reservation.

Another striking result of geothermometry is that the CO_2 and CO_2/N_2 geothermometers give systematically lower results for the hotter wells than the other geothermometers, and indeed the CO_2 concentrations in these wells are much lower than expected, both from thermodynamical calculations of mineral equilibria and from the observed CO_2 concentrations in fumarole steam. On the other hand, all gas geothermometers give similar results for the colder wells.

The stable hydrogen and oxygen isotope content of deep fluid discharges as calculated from the steam and water isotopic composition in accord with the steam/water ratio of the sample at the well head, calculated from the measured discharge enthalpy and the reservoir temperature are given in Figure 13. Also shown is the world meteoric water line (Craig, 1961).

The wells discharging from Tjarnarás give the most ^{2}H enriched isotopic composition and about 2‰ oxygen shift. Bæjarfjall and the southern part of Theistareykjagrundir are slightly more depleted. The most depleted fluids are observed in wells near Ketilfjall. This is in accord with the results of Darling and Ármannsson (1989), and suggests that the origin of the fluid is far south of Theistareykir and that it is in part precipitation from a colder climate (Sveinbjörnsdóttir et al., 2013). This idea is sketched in Figure 14 (modified from Hjartarson et al., 2004).

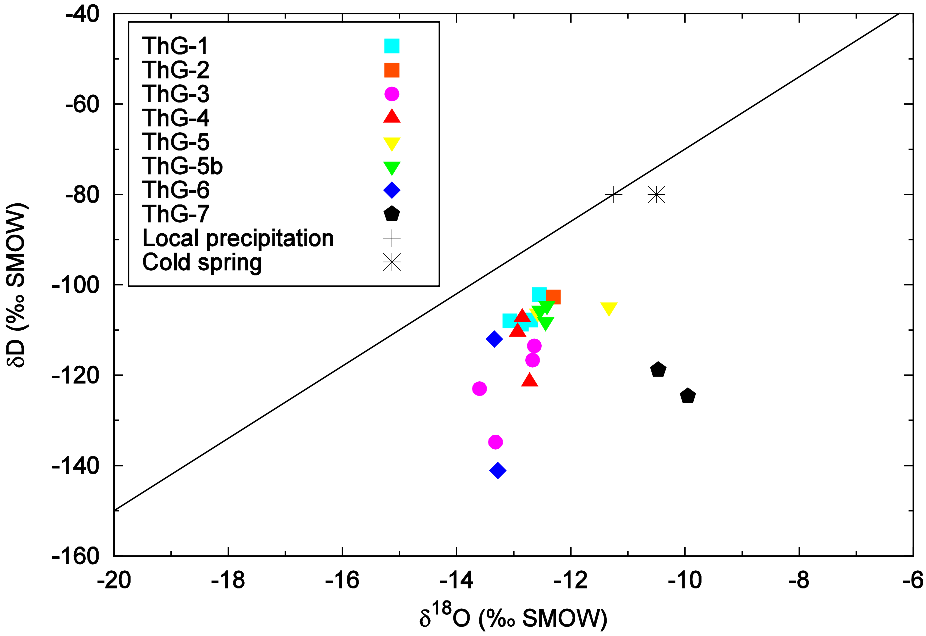

FIGURE 13: Stable isotope results for calculated deep liquid from Theistareykir wells. Also shown is the global meteoric water line and samples of local precipitation and spring water.

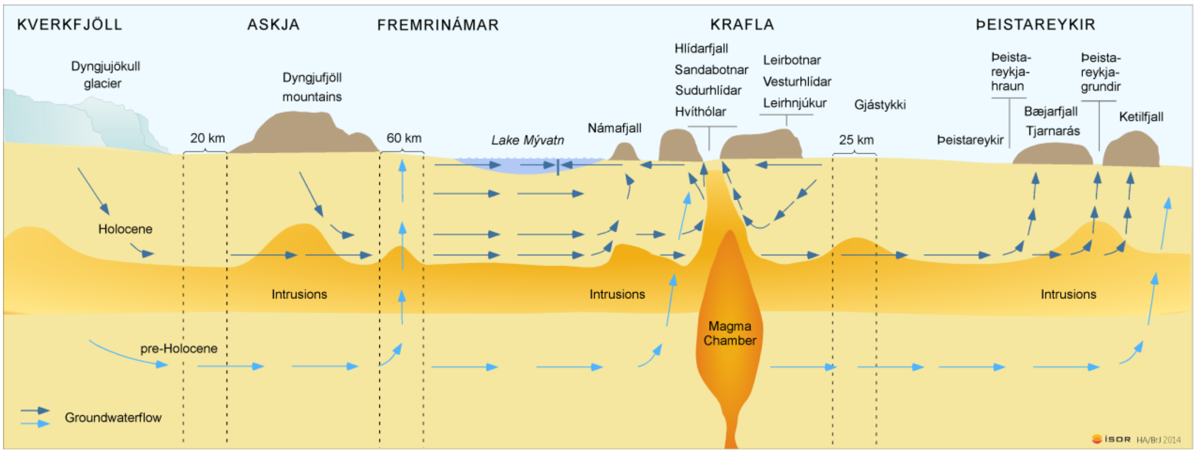

FIGURE 14: A conceptual hydrological model of the Northern Volcanic Zone. Modified from Hjartarson et al. (2004).

It is interesting to note that the oxygen isotope shift in fluid from well ThG-7, which was directionally drilled towards the east from a well pad just west of Mt. Ketilfjall, is much larger than that from other wells, about 6-7‰ (Figure 13). The well liquid is also quite different from that of the other wells, with bicarbonate as the dominant anion as opposed to chloride (see Table 4). This indicates that the well does indeed lie at the eastern boundary of the geothermal system.

4. CONCEPTUAL MODEL

On the basis of the data outlined in previous sections, a conceptual model (Figure 15) was presented by Gudmundsson et al. (2008). The model takes into account all data collected before that time, including results of surface exploration, resistivity data, well logs, drill cuttings and fluid samples from wells ThG-1 to -6. Data from wells ThG-7, -8 and -9 is not included in the model, nor is the work of Kristinsson et al. (2013a, 2013b).

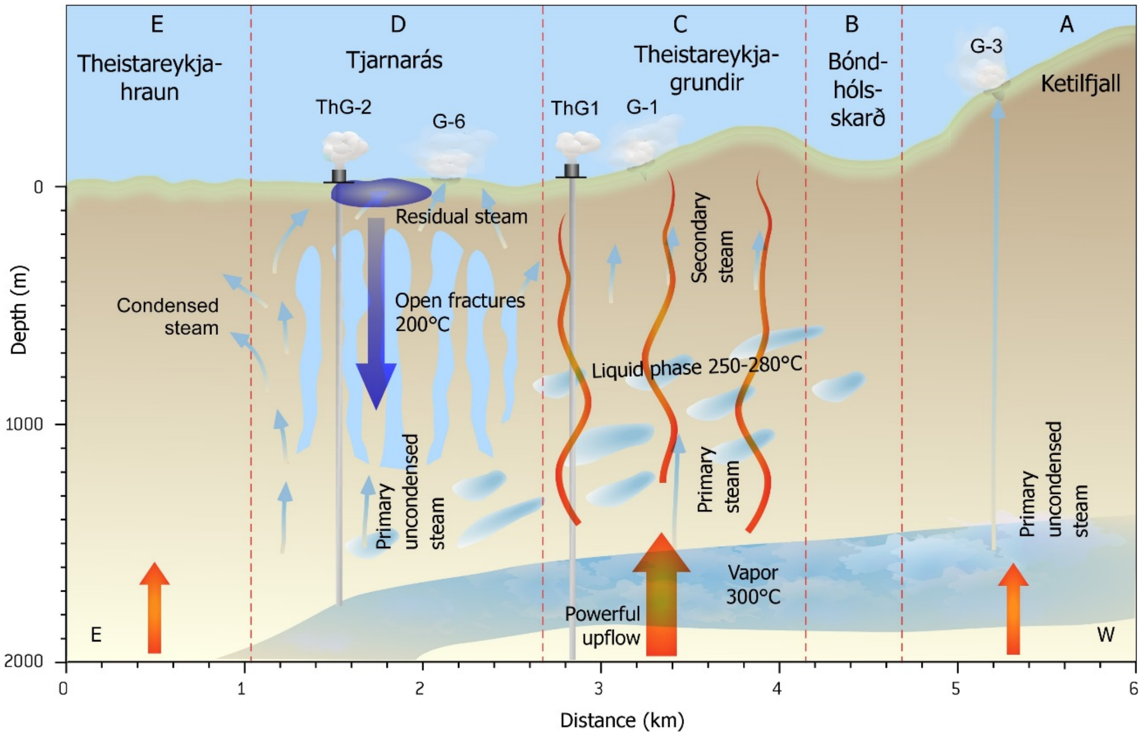

FIGURE 15: Conceptual model for the Theistareykir geothermal field (Gudmundsson et al., 2008). The possible upflow shown in sub-area E is not active.

The 2008 model assumes a powerful upflow below Theistareykjagrundir and the northern part of Mt. Bæjarfjall. This upflow is connected to the N-S trending fissure swarm and an E-W trending magmatic heat source. Other minor upflows may be connected to N-S fissures near Stórihver and Ketilfjall, but the system appears to have a boundary SW of Mt. Bæjarfjall. The fluid of the system has high enthalpy and a temperature of 280-290°C, with low concentrations of solids and dissolved gases. Open fractures beneath the Tjarnarás area reaching down to a depth of about 1200 m, cause cooling of the primary fluids to a temperature of about 200°C. At greater depth, hotter fluids are encountered. The origin of the fluid is far south of Theistareykir and is partly pre-Holocene precipitation.

The major changes to the conceptual model since 2008 are that with the drilling of wells ThG-7 and -8, the size of the system is better constrained. It is now clear that the western part, Theistareykjahraun, is cold and that Mt. Ketilfjall appears to mark the eastern boundary of the system as well as the fissure swarm (Sæmundsson, 2007; Khodayar and Björnsson, 2013). Consequently, the extent of the geothermal system is likely to be confined to the area where active geothermal manifestations are found on surface. This criterion gives a surface area of about 11-15 km^2.

Karlsdóttir et al. (2012) performed a 3D inversion on the TEM/MT data and presented a three-dimensional resistivity model of Theistareykir. Their work confirms most of the ideas presented by Karlsdóttir et al. (2006) and identified three deep low resistivity bodies that may indicate the heat source and upflow zones. Their locations are below Mt. Ketilfjall (reaches 2 km b.sl.), under the SE part of Mt. Bæjarfjall (reaches 6 km b.sl.) and just north of Stórihver (reaches 8 km b.sl.). Two other low resistivity bodies were identified under the NW part of the survey area. They may indicate the heat source and appear to be connected to the Húsavík Fracture Zone.

Khodayar and Björnsson (2013) identified two young northerly graben structures within the fissure swarm, both of which are filled with post-glacial lavas. One of these structures, about 1.5 km wide, lies west of Bæjarfjall, and the surface activity in Randir appears to be connected to its eastern flank.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Landsvirkjun (Icelandic National Power Company) for allowing use of the data.

REFERENCES

Ármannsson, H., 2001: *Theistareykir. A review of research, exploration and its cost*. Orkustofnun, report OS-2001/035 (in Icelandic), 24 pp.

Ármannsson H., 2011: The Theistareykir geothermal system, northeast Iceland. Case history. *Presented at the Short Course on Exploration for Geothermal Resources, organised by UNU-GTP, GDC and KenGen, Lake Bogoria and Lake Naivasha, Kenya*, 10 pp.

Ármannsson, H., Gíslason, G., Torfason, H., 1986: Surface exploration of the Theistareykir high-temperature geothermal area, Iceland, with special reference to the application of geochemical methods. *Applied Geochemistry, 1,* 47-64.

Ármannsson, H., Kristmannsdóttir, H., Torfason, H., Ólafsson, M., 2000: Natural changes in unexploited high-temperature geothermal areas in Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu – Tohoku, Japan*, 521-526.

Arnórsson, S., Fridriksson, Th., Gunnarsson, I., 1998: Gas chemistry of the Krafla geothermal field. *Water-Rock Interaction, 9*, 612-616.

Arnórsson, S., Gunnlaugsson, E., Svavarsson, H., 1983: The chemistry of geothermal waters in Iceland – III. Chemical geochemistry in geothermal investigations. *Geochimica et Cosmochimica Acta, 47*, 567-577.

Arnórsson, S., Gunnlaugsson, E., 1985: New gas geothermometers for geothermal exploration – calibration and application. *Geochimica et Cosmochimica Acta, 49,* 1307-1325.

Arnórsson, S., Stefánsson, A., Bjarnason, J.Ö., 2007: Fluid-fluid interactions in geothermal systems. *Reviews in Mineralogy and Geochemistry, 65*, 259-312.

Bjarnason, J.Ö., 2010: *Manual for the chemical speciation program WATCH v. 2.4.* Iceland Water Chemistry Group, 9 pp. Website: http://www.geothermal.is/sites/geothermal.is/files/download/watch_readme.pdf

Craig, H., 1961: Isotopic variations in meteoric waters. *Science, 133,* 1702-1703.

Darling, W.G., Ármannsson, H., 1989: Stable isotope aspects of fluid flow in the Krafla, Námafjall and Theistareykir geothermal systems of northeast Iceland. *Chemical Geology, 76*, 197-213.

Fournier, R.O., Potter, R.W. II, 1982: A revised and expanded silica (quartz) geothermometer. *Geothermal Resources Council Bulletin, 11*, 3-9.

Gautason, B., Ármannsson, H., Árnason, K., Saemundsson, K., Flóvenz, Ó.G., Thórhallsson, S. (2000): *Thoughts on the next steps in the exploration of the Theistareykir geothermal area*. Orkustofnun, report BG-HÁ-KÁ-KS-ÓGF-SÞ-2000/04 (in Icelandic), 11 pp.

Gautason, B., Gudmundsson, Á., Hjartarson, H., Blischke, A., Mortensen, A.K., Ingimarsdóttir, A., Gunnarsson, H.S., Sigurgeirsson, M.Á., Árnadóttir, S., Egilson, Th., 2010: Exploration drilling in the

Theistareykir high-temperature field, NE-Iceland: Stratigraphy, alteration and its relationship to temperature structure. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 5 pp.

Gíslason, G., Johnsen, G.V., Ármannsson, H., Torfason, H., Árnason, K., 1984: *Theistareykir. Surface exploration of the high-temperature geothermal area*. Orkustofnun, report OS-84089/JHD-16 (in Icelandic), 134 pp + 3 maps.

Grönvold, K., Karlsdóttir, R., 1975: *Theistareykir. An interim report on the surface exploration of the geothermal area*. Orkustofnun, report JHD-7501 (in Icelandic), 37 pp.

Gudmundsson, Á., Gautason, B., Axelsson, G., Lacasse, C., Thorgilsson, G., Ármannsson, H., Tulinius, H., Saemundsson, K., Karlsdóttir, R., Kjaran, S.P., Pálmarsson, S.Ó., Halldórsdóttir, S., 2008: *A conceptual model of the geothermal system at Theistareykir and a volumetric estimate of the geothermal potential*. Iceland GeoSurvey, Mannvit and Vatnaskil Consulting Engineers, report ÍSOR-2008/024 (in Icelandic), 57 pp.

Hafstad, Th.H., 1989: *Öxarfjördur: Groundwater investigations 1987-1988. A contribution to a special project on fish farming*. Orkustofnun, report OS-89039/VOD-08 B (in Icelandic), 25 pp.

Hafstad, Th.H., 2000: *Theistareykir: The drilling of a fresh water well*. Orkustofnun, report ThH-00/14 (in Icelandic), 6 pp.

Karlsdóttir, R., Eysteinsson, H., Magnússon, I.Th., Árnason, K., Kaldal, I., 2006: *TEM soundings at Theistareykir and Gjástykki 2004-2006*. Iceland GeoSurvey, report ÍSOR-2006/028 (in Icelandic), 88 pp.

Karlsdóttir, R., Vilhjálmsson, A.M., 2010: *MT and TEM measurements at Theistareykir in 2009*. Iceland GeoSurvey, report ÍSOR-2011/002 (in Icelandic), 62 pp.

Karlsdóttir, R., Vilhjálmsson, A.M., Árnason, K., Beyene, A.T., 2012: *Theistareykir geothermal area, Northern Iceland. 3D inversion of MT and TEM data.* Iceland GeoSurvey, report ÍSOR-2012/046, 173 pp + CD.

Khodayar, M., Björnsson, S., 2013: *Preliminary fracture analysis of Theistareykir geothermal field and surroundings, Northern rift zone and Tjörnes fracture zone.* Iceland GeoSurvey, report ÍSOR-2013/029, 57 pp + 2 maps.

Kristinsson, S.G., Fridriksson, Th., Ólafsson, M., Gunnarsdóttir, S.H, Níelsson, S., 2013a: *The Theistareykir, Krafla and Námafjall high-temperature geothermal areas. Monitoring of surface activity and groundwater*. Iceland GeoSurvey, report ÍSOR-2013/037 (in Icelandic), 152 pp.

Kristinsson, S.G., Óskarsson, F., Ólafsson, M., Óladóttir, A.A., Tryggvason, H.H., Fridriksson, Th., 2013b: *The Námafjall, Krafla and Theistareykir high-temperature geothermal areas. Monitoring of surface activity and groundwater in 2013*. Iceland GeoSurvey, report ÍSOR-2013/060 (in Icelandic), 160 pp.

Óskarsson, F., Ármannsson, H., Ólafsson, M., Sveinbjörnsdóttir, Á.E., Markússon, S.H., 2013: The Theistareykir geothermal field, NE-Iceland. Fluid chemistry and production properties. *Proceedings of the Fourteenth International Symposium on Water-Rock Interaction / Procedia Earth and Planetary Science, 7,* 644-647.

Sveinbjörnsdóttir, Á.E., Óskarsson, F., Ármannsson, H., Ólafsson, M., Markússon, S.H., Magnúsdóttir, S., 2013: The Theistareykir geothermal field, NE Iceland. Isotopic characteristics and origin of circulating fluids. *Proceedings of the Fourteenth International Symposium on Water-Rock Interaction / Procedia Earth and Planetary Science, 7,* 822-825.

Saemundsson, K., 2007: *The geology of Theistareykir.* Iceland GeoSurvey, short report ÍSOR-07270 (in Icelandic), 23 pp.