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THE THEISTAREYKIR GEOTHERMAL SYSTEM, NORTH EAST ICELAND: CASE HISTORY

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ABSTRACT

Surface exploration was carried out in the Theistareykir high-temperature geothermal area, NE-Iceland in 1972-1974 and 1981-1984, and the area monitored intermittently from 1991-2000. The results of surface exploration suggested that the temperature of the fluid was at least 280°C and that it was drawn from a single reservoir with good permeability. The recharge is from the southeast, and the origin of the fluid probably far to the south. The fluid may be 100 years old or more. The geothermal area has been divided into five sub-areas, three of which are expected to be productive. Wells have been drilled in all and the results of drilling do not contradict the results of the surface exploration. A conceptual model based on all the results has been established and a volumetric assessment of the geothermal suggests that the most likely value for production potential over 30 years is 348 MW_e.

1. INTRODUCTION

Theistareykir is a high-temperature geothermal area in NE-Iceland (Figure 1). For centuries it hosted the main sulphur mine in Iceland, providing the Danish king with raw material for gun powder. Early records tell of prospecting for sulphur, Bemmele nand Rutten (1955) mapped interglacial lavas and palagonite, and Kjartansson (1972) reported on exploration for clay. The first geothermal exploration was carried out in 1972-1974 (Grönvold and Karlsdóttir 1975), and a major geothermal assessment was made in 1981-1984 (Layugan 1981, Gíslason et al. 1984, Ármannsson et al. 1986, Darling and Ármannsson 1989). The area was monitored intermittently from 1991-2000 (Ármannsson et al. 2000), and Ármannsson (2001) reviewed research in the area up to the year 2000.

Gautason et al. (2000) suggested drill sites based on available knowledge. The first well was drilled in 2002, the second in 2003, the third in 2006, the fourth and fifth in 2007, 1 more drilled and another redrilled in 2008. The purpose of this paper is to reflect on the results of drilling with reference to information gained from surface exploration.

2. RESULTS OF SURFACE EXPLORATION

The main features in the geology of the area are an E-W trending heat source astride a N-S tectonic structure connected to an active central volcano. A N-S fissure swarm, 4-5 km wide stretches from Lake Mývatn in the south and to the sea in Öxarfjördur in the north. The area is covered in lavas all of

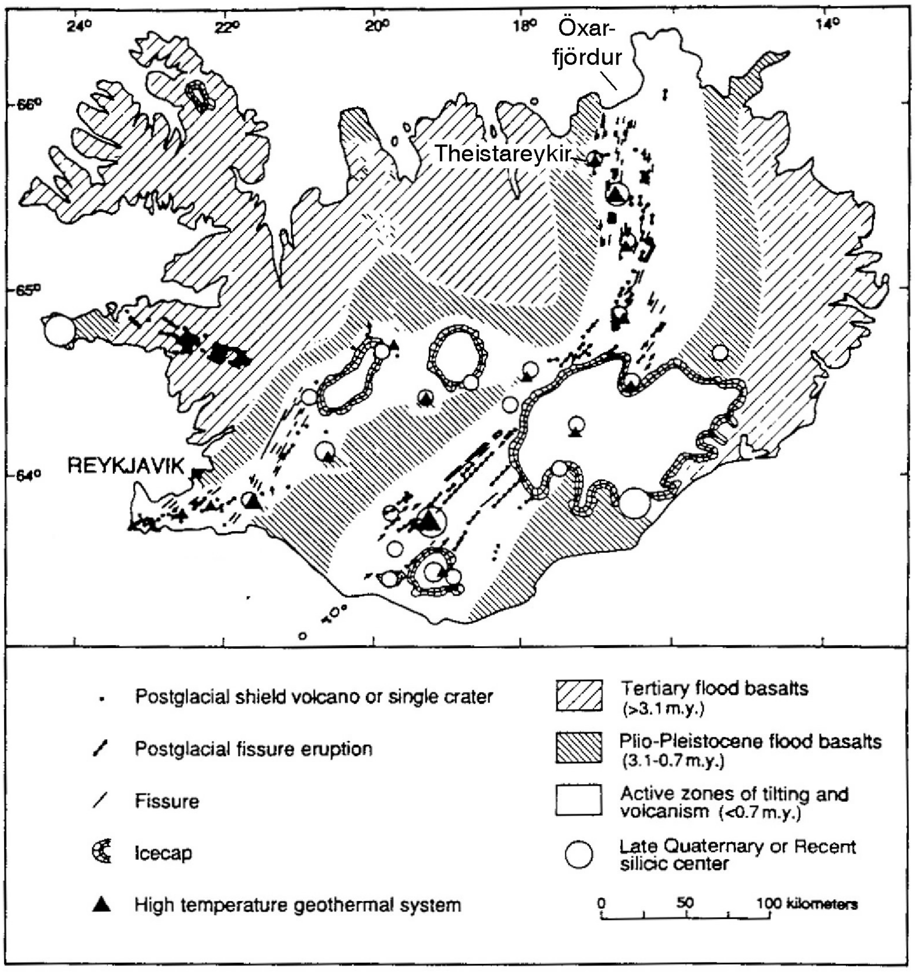

FIGURE 1: Iceland. Tectonic map (Saemundsson 1986). Location of Theistareykir

which except for one being erupted in the last stages of the Ice Age or shortly afterwards. The youngest lava is about 2700 year old.

Surface manifestations have been estimated to cover about 11 km^2 (Gíslason et al. 1985) as is shown on the geothermal map (Figure 2) (Saemundsson 2007) but recent TEM and MT soundings suggest that the extent of the actual geothermal area be up to 45 km^2. (Karlsdóttir et al. 2006, Yu et al. 2008 a,b) (Figure 3).

Ármannsson et al. (1986) divided the active surface area into five sub-areas (Figure 4), three of which (A, C and D) appeared promising for drilling. Gas geothermometers gave the temperature ranges shown in Table 1. Darling and Ármannsson (1989) concluded from isotope values for fumarole steam that, in area D (Tjarnarás), the steam had been condensed to a fraction of 0.15 to 0.25 of the original steam at temperatures in the range 130-200°C, and that gas geothermometer temperatures were probably too high. Their interpretation of isotope values for area C (Theistareykjagrundir) was that the steam was mostly secondary steam and that the geothermometer temperatures were probably too low.

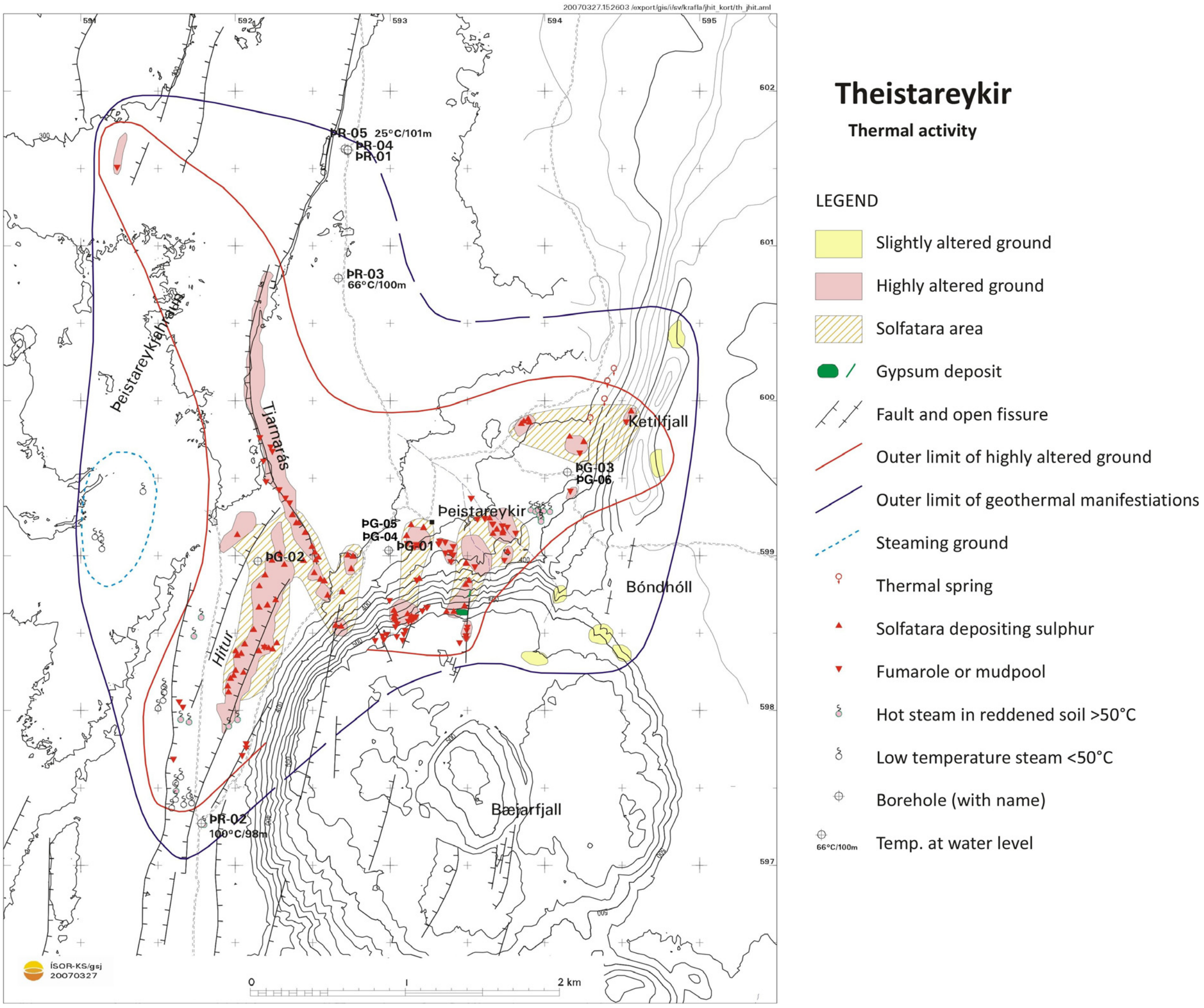

FIGURE 2: A geothermal map of the Theistareykir geothermal system

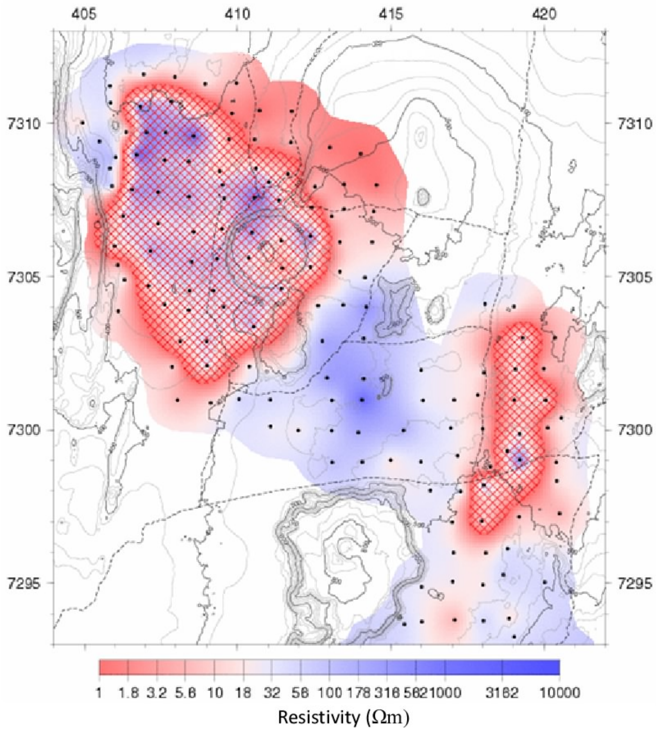

FIGURE 3: Resistivity at 500 m.b.sl. at Theistareykir.(top left) and Gjástykki (bottom right) (Karlsdóttir et al. 2006). High resistivity cores are surrounded by low resistivity

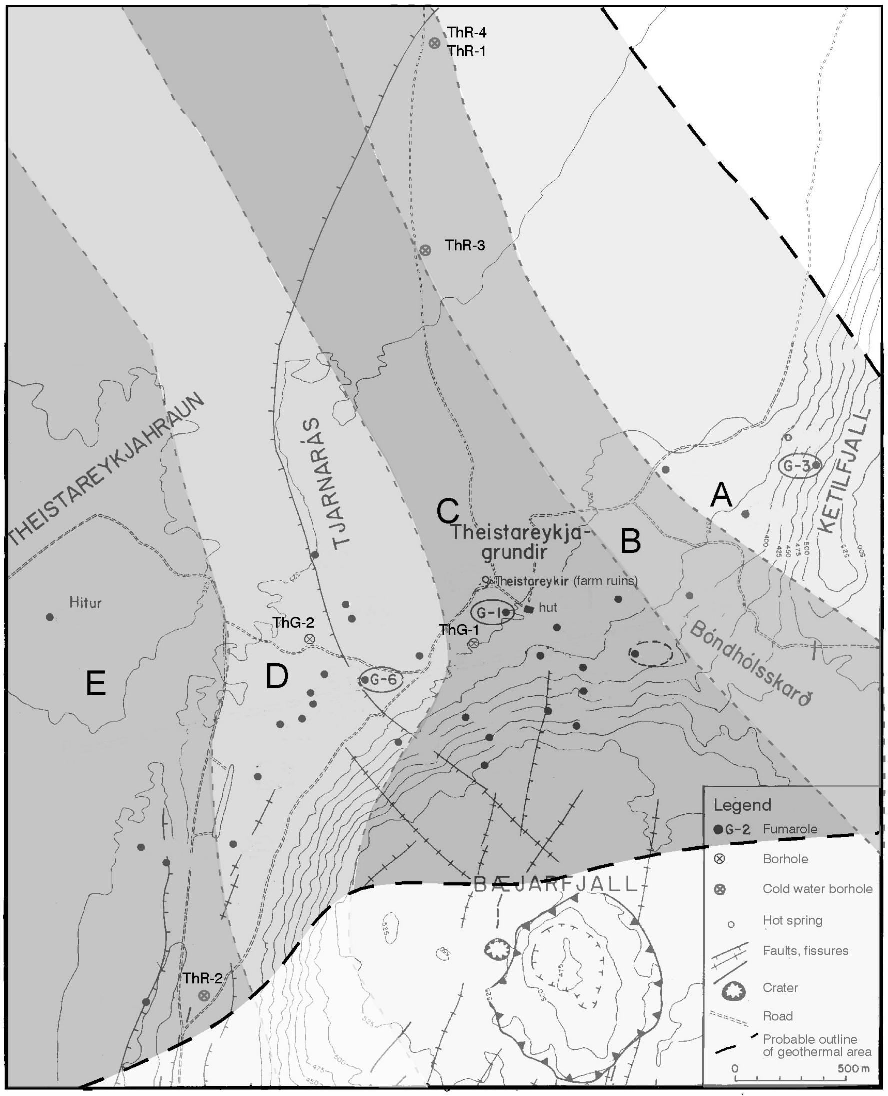

FIGURE 4: Theistareykir. Division into five subareas (Ármannsson et al. 1986). Geothermal and cold water boreholes in and north of the geothermal area are shown as well as three fumaroles sampled during monitoring 1991-2000

They concluded, however, that the steam rising from area A (Ketilfjall) was undisturbed and that the geothermometer temperatures were close to true values. Ármannsson et al. (1986) proposed a deep inflow to the area from the southeast with area C closest to the source. Thus area C was considered promising even though the gas geothermometer values seemed rather low. A relatively large, cool, shallow flow was predicted through Bóndhólsskard (Figure 4), preventing primary steam from rising to the surface in area B. Areas C and D are more accessible than area A, and therefore the suggestion was that the first drillholes be situated in these two subareas. The dissolved solids content of the steam was very low suggesting that the reservoir fluid was dilute. Low radon concentrations were interpreted to suggest good permeability especially in area D.

TABLE 1: Gas geothermometer temperatures in A, C and D (°C)

Subarea	**1980´s (°C)**	**Fumarole**	**1991 (°C)**
A	272-315	G-3	289
C	232-271	G-1	284
D	274-309	G-6	263

3. MONITORING AND HEAT LOSS

The area was visited again in 1991 at the beginning of a monitoring program in which some unexploited high-temperature areas were to be monitored to establish the extent of natural changes in geothermal areas as opposed to changes due to production (Ármannsson et al. 2000). Changes in surface manifestations were mapped and steam samples collected from 3 fumaroles, one from each of areas A, C and D. At that time considerable changes in surface manifestations were observed, mainly cooling in area D (Figure 5). There was information from local people that following earthquakes in 1958 the surface activity in the area had increased drastically but had been declining since. The gas geothermometer temperature for the fumarole from area D (G-6, Figures 4 and 5) had decreased drastically, but little change or a slight increase were recorded for gas geothermometer temperatures for fumarole steam from areas A (G-3, Figures 4 and 5) and C (G-1, Figures 4and 5; Table 1). It is possible that the secondary effects suggested by Darling and Ármannsson (1989), condensation and formation of secondary steam, were less pronounced this time. The area has been visited a few more times, but it has remained relatively unchanged after 1991.

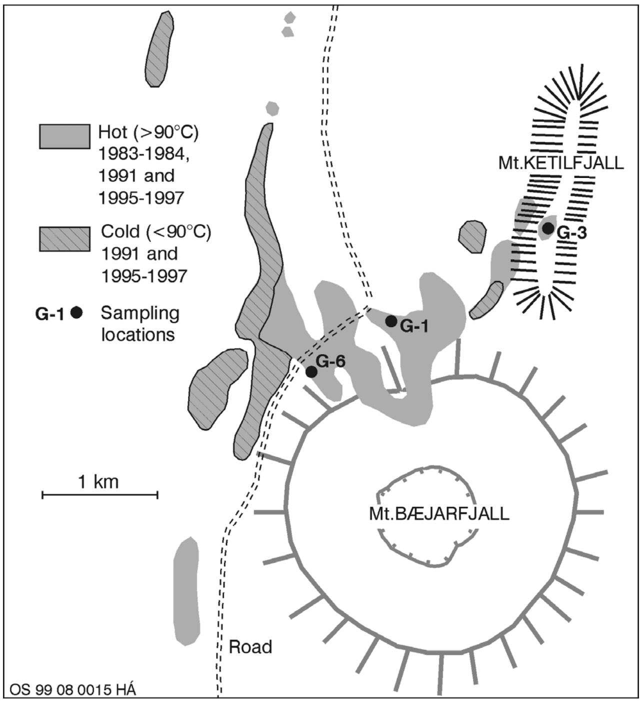

FIGURE 5: Theistareykir. Changes in surface manifestations from 1983-4 to 1991 (Ármannsson et al. 2000); fumarole sampling locations used during monitoring shown

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 Theistareykir area (Table 2). This estuary is believed to receive solely subsurface water from the Theistareykir area. The values are minimum values but they suggest a total output of 300 MW. Therefore a powerful geothermal system with a temperature of about 280°C recharged with dilute, probably relatively old, water from far south and with an isotope signature of $\delta D = -100‰$ and $\delta^{18}O = -12‰$ was predicted prior to drilling.

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	3.5×20×42≈300 MW
Areal extent of Theistareykir	15 km^2
Heat loss from area	300/15=20 MW/km^2= W/m2

4. RESULTS OF DRILLING

Prior to deep drilling, four shallow "cold water" wells, ThR-1-4 (Figure 3) 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.

Well ThG-1 was drilled in area C (Theistareykjagrundir; Figure 3) in autumn 2002 to a depth of 1953 m, with a casing to 614 m depth. The major inflows are at 620-640 m depth and 1620-1640 m depth. Other inflows are observed at 710, 860-880, 1050, 1230-1240, and 1350 m depths and possibly at 1780-1800 and 1900-1910 m depths. An overpressured aquifer was observed at 212 m depth (Gudmundsson et al. 2002). The well started discharging in late October 2002.

The results of chemical analysis suggest that in November 2002 the fluid was still contaminated by drilling fluid and thus the results from July 2003 (Table 3) are used for the purpose of interpretation. The measured enthalpy at the surface was 2180 kJ/kg and the total flow from the well 16-17 kg/s. The calculated steam fraction at depth at 280°C was 0.611.

The stable isotope composition for the total fluid was δD = -108‰ and $\delta^{18}O$ = -12.7‰, or a little lower than predicted. Thus the fluid probably originated as precipitation far to the south of the area, probably as far south as Vatnajökull, and it may also be 100 years old or more.

Geothermometer temperatures were calculated in six ways with the results reported in Table 4. As is apparent, the results come in pairs, and there is a significant difference between the pairs. It had been suggested that, in this part of the area, some secondary steam was formed in fumaroles. Using the calibrations of Arnórsson et al (1998) for the CO_2, H_2S and H_2 geothermometers, the same kind of pattern emerges from the results as for the fumaroles, i.e. CO_2 and H_2S temperatures around 240°C, but H_2 temperatures of about 300°C or higher. As H_2 and Ar are relatively insoluble at these conditions they may not be affected by the secondary steam formation whereas CO_2 and H_2S will dissolve in the water phase and be released again at a lower temperature.

One model that explains these geothermometer temperatures assumes that the main inflows are at 620-640 m and 1620-1640 m, that the upper inflow is essentially liquid phase at 280°C but the deeper one essentially vapour phase at 300°C or higher. The logged temperatures of well ThG-1 are 270-280°C at 6-700 m and 300-305°C at 1600-1700 m. The temperature of the liquid phase at 280°C is reflected in the results for the solute geothermometers, whereas the temperature of the steam phase is approximated by the H_2 and H_2/Ar temperatures. CO_2 and H_2S travel some way after being dissolved in the water phase and before the fluid flashes at a lower temperature.

Well ThG-2 was drilled October to December 2003. After some circulation losses suggesting aquifers in the top layers, the well was cased to a depth of about 260 m. Shortly after drilling started again, a total loss of circulation was encountered and persisted. Logging revealed a well diameter in excess of 30" over a 10 m interval. An attempt to seal off this interval by gradually pouring 120 m^3 of gravel and sand into the well and cementing with 140-150 m^3 of concrete failed to stop the circulation loss. Drilling was resumed, a total loss of circulation was encountered again at 327 m depth, but drilling was still continued with total loss to 617 m depth where it was cased again. The final depth was 1720 m, drilled again with a total loss of circulation (>50-55 l/s) from 657 m depth. It was finished with a slotted liner. Pumping tests suggested very high permeability.

Extremely strong flows are inferred from 260 m depth and considerably below this. There is a possibility that this constitutes a large cave or some such feature whose temperature has been estimated at a little over 200°C, and that this large flow might cause cooling of the rock over some distance from the cave, possibly sufficient to cause partial condensation of steam rising to the surface in the vicinity. It is suggested that this may be the mechanism responsible for the condensation of steam in area D suggested by Darling and Ármannsson (1989).

Using information from wells ThG-1 and ThG-2 a model of the flow in the system was constructed

(Figure 6) showing the large relatively cool flow in area D, the intermediate aquifers at 600-800 m depth and the deep hot aquifer at about 1600-1800 m depth.

Well ThG-3 was drilled in area A in 2006 to a depth of 2659 meters and the maximum temperature recorded was 380°C. Its flow oscillated with enthalpy varying from about 1600 to 2600 kJ/kg but has approached the higher value with time and eventually settled as a high enthalpy well giving 10-12 kg/s of high temperature steam. The total dissolved solids in the fluid are low and so is the gas concentration.

Wells ThG-4 and ThG-5 were both drilled directionally from the same well pad as ThG-1; ThG-4 to the SE beneath Mount Baejarfjall and well ThG-5 towards well ThG-2. Well ThG-4 is a high enthalpy well with a steam flow of 30 kg/s of high temperature steam but well ThG-5 is a low enthalpy well similar to well ThG-2 with a large liquid water flow. The concentration of dissolved solids and gas are low in these wells two and the results for the wells drilled after ThG-2 do not conflict with the model suggested in Figure 6.

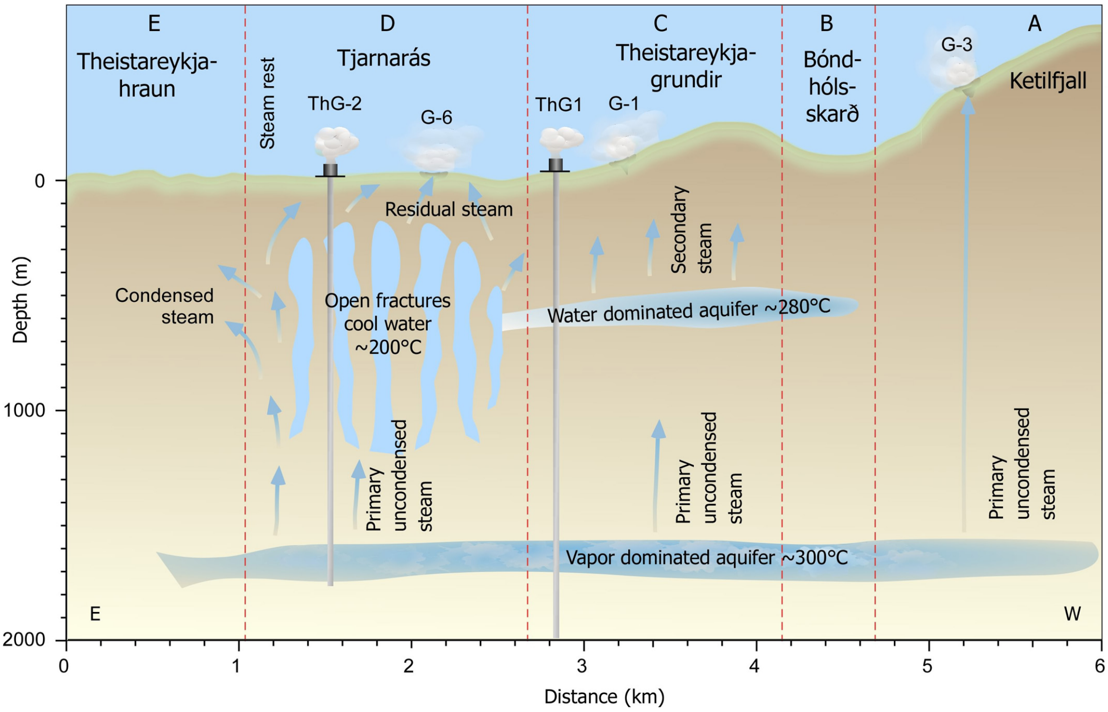

FIGURE 6: The most important aspects of fluid flow in the Theistareykir geothermal system based on surface exploration and results of drilling wells ThG-1 and ThG-2

Finally Well Th-G-5 was redrilled under a sharper angle in 2008 (ThG-5b) and well ThG-6 was drilled directionally from the well pad of well ThG-3 to the west. These wells have started discharging in early November. In late October the maximum temperature in ThG-5B was 300°C but ThG-06 312°C. In early December the enthalpy of ThG-5b flow was 1485 kJ/kg and the amount of high temperature steam 20.8 kg/s, but the enthalpy of the ThG-6 flow was 2663 kJ/kg and high temperature steam 13.2 kg/s.

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.

The results of temperature and pressure logging show wells ThG-2 and ThG-5 to be cooler than the others presumably reflecting cooling from the surface of the fissure system shown in Figure 2.

TABLE 3: Chemical composition of deep water and deep steam in fluid from well ThG-1, Theistareykir at 280°C

Constituent	**Water phase**	**Steam phase**
pH	7.96	
CO_2 mg/l	37.53	1463
H_2S mg/l	30.65	265
B mg/l	1.29	
SiO_2 mg/l	574.3	
Na mg/l	89.44	
K mg/l	18.36	
Mg mg/l	0.003	
Ca mg/l	0.38	
F mg/l	0.79	
Cl mg/l	80.81	
SO_4 mg/l	7.06	
Al mg/l	1.57	
Fe mg/l	0.0055	
Mo mg/l	0.0144	
Mn mg/l	0.0014	
Zn mg/l	0.0050	
As mg/l	0.0057	
H_2 mg/l		25.3
N_2 mg/l	0.10	33.8

TABLE 4: Chemical geothermometer results for fluid from well ThG-1, Theistareykir

Type	**Quartz**[1]	**Na/K**[2]	**CO_2**[3]	**H_2S**[3]	**H_2**[3]	**H_2/Ar**[4]
T(°C)	276	279	244	237	295	302

[1]Arnórsson et al. 1983, [2]Fournier 1977, [3]Arnórsson et al. 1998, [4]Giggenbach 1991.

5. CONCEPTUAL MODEL AND VOLUMETRIC ESTIMATE

The A conceptual model (Figure 7) has been presented on the lines of Figure 6 showing a strong upflow in area C, a weaker one in area A and a possible one in area E but a possible downflow in area D. The possible potential of the system has been estimated using the so-called Monte Carlo method and the most probable values are 348 MW_e (90% probability 191-622 MW_e) for 30 years, 209 MWe (90% probability 115-373 MWe) for 50 years and 104 MWe (90% probability 57-187 MW_e) for 100 years (Gudmundsson et al. 2008).

6. CONCLUSIONS

The results of surface exploration in the Theistareykir area suggested that it encompassed 3 distinct subareas (A, C and D, Figure 4) suitable for drilling, drawing fluid from a single base reservoir with a temperature of at least 280°C. The fluid originates far to the south of the area, and is probably more than 100 years old. Results for stable isotopes in fumarole steam suggested that in area D, there was condensation of fumarole steam during its passage from the reservoir to the surface, but that in area C the fumarole steam was in some cases secondary steam.

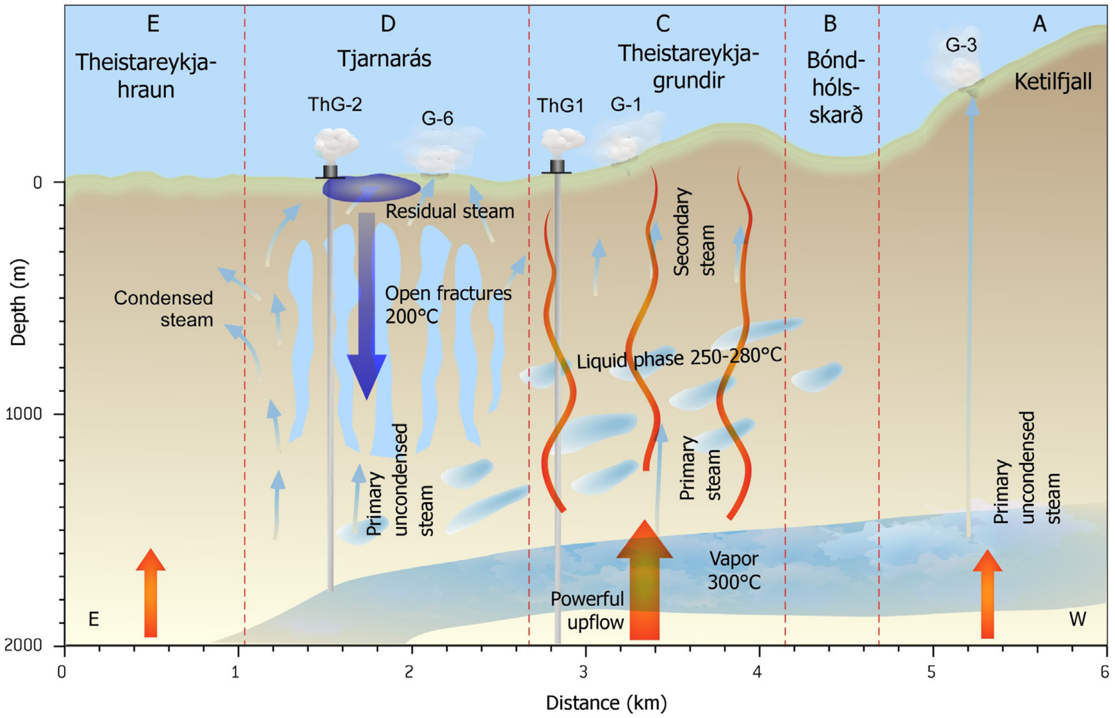

FIGURE 7: A conceptual model of the Theistareykir geothermal system (Gudmundsson et al. 2008)

During drilling of wells ThG-1 and 2 large inflows of relatively shallow cool water, which can explain condensation and secondary steam formation in area C and D, were encountered. Good permeability was predicted for area D from results of surface exploration. Thus the preliminary results of drilling do not contradict those of surface exploration.

The results for wells ThG-3 to ThG-6 confirm these results and show area C to be powerful probably above the main upflow although a smaller upflow is predicted for area A.

REFERENCES

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

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

Ármannsson, H., Kristmannsdóttir, H., Torfason, H. and Ólafsson, M., 2000: Natural changes in unexploited high-temperature geothermal areas in Iceland. *Proc. World Geothermal Congress 2000*, 521-526.

Arnórsson, S., Fridriksson, T. and Gunnarsson, I., 1998: Gas chemistry of the Krafla geothermal field, Iceland. In G.B. Arehartand J.R. Hulston (eds.) *Water-rock Interaction*, 613-616. Rotterdam: Balkema.

Arnórsson, S., Gunnlaugsson, E. and Svavarsson, H., 1983: The chemistry of geothermal waters in Iceland III. Chemical geothermometry in geothermal investigations. *Geochim. Cosmochim. Acta* 47: 567-577.

Bemmelen, R.W. and Rutten, M.G., 1955: *Table mountains of Northern Iceland*. Leiden. E.J. Brill.

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

Fournier, R.O., 1977: Chemical geothermometers and mixing models for geothermal systems. *Geothermics* 5: 41-50.

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

Giggenbach, W.F., 1991: Chemical techniques in geothermal exploration. In: D'Amore, F., (ed.), *Applications of geochemistry in geothermal reservoir development*. UNITAR/UNDP, Rome, 119-142.

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

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

Gudmundsson, Á., Gautason, B., Thordarson, S., Egilson, T. and Thorisson, S., 2002*: Exploration drilling at Theistareykir. Well Th.G-1. 3rd stage: Drilling of production part to 1953 m depth* (in Icelandic). Orkustofnun, report OS-2002/079, 59 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. and Halldórsdóttir, S., 2008: *A conceptual model of the geothermal system at Theistareykir and a volumetric estimate of the geothermal potential* (In Icelandic). Iceland GeoSurvey, VGK-Hönnun and Vatnaskil Engineering Office, report, 57 pp.

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

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

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

Kjartansson, H., 1972: *Clay formations in Dalasýsla and Thingeyjarsýsla distric*ts (in Icelandic). Orkustofnun, JKD report, 83 pp.

Layugan, D.B., 1981: *Geoelectrical soundings and its application in the Theistareykir high-temperature area.* UNU-GTP, Iceland, report 5, 101 pp.

Saemundsson, K., 1986: Subaerial volcanism in the western North Atlantic. In Vogt, PR. and Tucholke, B.E. (eds.) *The geology of North America, M: The Western North Atlantic Region.* Geological Society of America, Boulder, Colorado, 69-86.

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

Yu, G., He, L.F., He, Z.X., Strack, K.M. and Tulinus, H., 2008a: *Iceland Theistareykir 2-D MT survey. Data acquistion report*. KMS Technologies, KJT Enterprises Inc. and VGK-Hönnun.

Yu, G., He, L.F., He, Z.X., Strack, K.M. and Tulinus, H., 2008b: *Iceland Theistareykir 2-D MT survey. Data processing and intepretation*. KMS Technologies, KJT Enterprises Inc. and VGK-Hönnun.