The Theistareykir geothermal field, NE Iceland: fluid chemistry and production properties

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Abstract

Chemical analyses on samples from six high temperature geothermal wells in the Theistareykir geothermal field in NE Iceland are reported. The aquifer temperature is estimated to be in the range 270-290°C, although bedrock temperature exceeds 300°C. The wells have enthalpy ranging from liquid enthalpy at the aquifer temperature up to dry vapour enthalpy, in which case excess enthalpy is primarily due to phase segregation. The liquid is relatively dilute and under-saturated with respect to amorphous silica, down to about 10 bar-a.

Keywords: Theistareykir; Iceland; high-temperature; geothermal field; wells; geochemistry; geothermometry; excess enthalpy.

1. Introduction

The Theistareykir geothermal field lies in the Theistareykir fissure swarm in NE-Iceland (Figure 1a), which is the westernmost of the five NNE striking left-stepping en echelon volcanic systems that constitute the Northern Volcanic Zone. The high temperature geothermal activity is connected to recent magma intrusions. The most recent volcanic activity in the area occurred some 2500 years ago [1]. Ármannsson et al. [2] divided the Theistareykir geothermal area into five subareas (A, B, C, D, E)
(Figure 1b) on the basis of geology and geochemistry of fumaroles. Isotopic composition of fumaroles has confirmed this division [3,4]. Three of these areas (A, C, D) were considered promising for drilling.

In the years 2002 to 2011 nine deep wells were sunk into the Theistareykir field, with depths ranging from 1723 m to 2799 m. The bedrock temperature in five of the wells exceeded 300°C, with a maximum temperature of 380°C. The locations of the wells are shown in Figure 1b.

Flow tests were conducted some months after the drilling of each well, during which samples were collected for analysis. In addition, samples from wells 1, 3, 4 and 5 were collected in spring 2008 during discharge tests and samples from wells 1, 3, 4, 5b and 6 were collected during a discharge test in spring 2011. No samples have been collected from well 8 and the shallower and colder wells 2 and 5 have not been discharged since the original flow test. This contribution will primarily focus on the most recent complete samples from the six high-temperature wells, the chemical compositions of which are given in Table 1. Sveinbjörnsdóttir et al. [4] discuss the results of stable isotope analysis of the same samples.

2. Results

2.1. Geothermometry and aquifer conditions

The aquifer temperatures have been estimated using quartz [5], Na/K [6] and gas geothermometers [7]. The results and comparison with older samples suggest that the Na/K temperatures, which are quite stable for each well and lie in the range 270-290°C, are likely good estimates of the reservoir temperatures. These values agree well with the logged temperatures at the main feed zones. The quartz temperatures calculated for the medium and low enthalpy wells 1 and 5b lie very close to the Na/K temperatures but quartz temperatures for the high enthalpy wells 3, 6 and 7 are about 10-20°C higher than the Na/K temperatures (Figure 2a).
Table 1. Chemical composition (mg/kg) of samples from wells in Theistareykir. Sampling pressure (bar-g) and discharge enthalpy (kJ/kg) are also given.

| Well | Ps  | h  | pH  | CO₂ | H₂S | B  | SiO₂ | Na  | K   | Mg  | Ca  | F   | Cl  | SO₄ | CO₂ | H₂S | N₂  | CH₄ | H₂  |
|------|-----|----|-----|-----|-----|----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|      |     |    |     |     |     |    |      |     |     |     |     |     |     |     |     |     |     |     |     |
| 1    | 31.8| 1935| 8.46| 6.7 | 25.8| 1.53| 687  | 91.6| 19.0| 0.004| 0.14| 1.66| 93.9| 12.0| 970 | 300 | 47.8| 0.23| 16.3|
| 3    | 29.5| 2636| 8.57| 14.4| 59.2| 3.24| 852  | 114 | 23.9| 0.004| 0.76| 1.17| 92.5| 9.40| 1000| 530 | 34.9| 0.13| 26.5|
| 4    | 15.7| 2661| 8.41| 24.4| 26.5| 3.95| 663  | 71.7| 15.8| 0.019| 0.23| 1.42| 88.3| 3.22| 155 | 820 | 31.6| 0.14| 39.3|
| 5b   | 15.5| 1245| 8.22| 22.6| 45.8| 1.12| 659  | 106 | 19.8| 0.005| 0.23| 1.18| 56.4| 21.6| 2320| 290 | 237 | 0.72| 3.09|
| 6    | 31.5| 2676| 7.87| 12.2| 47.4| 4.53| 908  | 126 | 26.7| 0.003| 0.21| 1.07| 143 | 5.92| 720 | 780 | 50.8| 0.19| 31.2|
| 7    | 7.6 | 2377| 9.10| 108 | 56.0| 3.50| 1057 | 144 | 31.8| 0.005| 0.21| 1.06| 41.5| 8.36| 7290| 580 | 83.2| 3.74| 14.3|

The discharge enthalpy of the wells ranges from liquid enthalpy to almost dry vapour enthalpy. Two phenomena are most likely to cause excess enthalpy in the discharge of a high-temperature well. One is that the discharge fluid extracts considerable heat from the reservoir rock as it undergoes depressurisation boiling on its way to the surface, and the other is that phase segregation takes place in the aquifer causing the liquid phase to be partially retained in the aquifer while the vapour phase flows to the surface. Glover et al. [8] presented a way to distinguish between these two scenarios, namely that in the first case, only heat is added to the discharge fluid and therefore the concentration of a conservative component should be independent of the discharge enthalpy, whereas phase segregation would cause the concentration of such a component in the total discharge to be linearly dependent on the enthalpy. Using this method and the silica concentration, it is evident that the excess enthalpy of the wells is due to phase segregation (Figure 2b).

2.2. Deep liquid composition

The composition of the deep liquid was calculated at a reference temperature chosen from the results of geothermometry and logging, assuming phase segregation at a temperature 30°C lower than the reservoir temperature and no initial aquifer vapour phase [9]. The results (Table 2) show differences between wells although some general characteristics are shared; near neutral pH, fairly low TDS etc.
Table 2. Calculated composition (mg/kg) of the deep liquid at the indicated aquifer temperatures.

| Well | Tref (°C) | pH  | B   | SiO₂ | Na   | K   | Mg  | Ca  | F    | Cl   | SO₄ | TDS | CO₂ | H₂S | N₂  | CH₄ | H₂  |
|------|-----------|-----|-----|------|------|-----|-----|-----|------|------|-----|-----|-----|-----|-----|-----|-----|
| 1    | 280       | 7.32| 1.35| 608  | 81.1 | 16.8| 0.004| 0.13| 1.47 | 83.1 | 10.6 | 897 | 99.8| 48.2| 4.31| 0.02| 1.47|
| 2    | 290       | 7.49| 2.86| 753  | 101  | 21.1| 0.004| 0.67| 1.03 | 81.8 | 8.28 | 1115| 103 | 94.7| 3.07| 0.01| 2.34|
| 3    | 290       | 7.24| 3.01| 506  | 58.0 | 13.0| 0.015| 0.17| 1.08 | 67.3 | 2.46 | 745 | 17.0| 124 | 2.94| 0.01| 3.66|
| 5b   | 270       | 6.97| 0.93| 550  | 88.4 | 16.5| 0.004| 0.19| 0.984| 47.0 | 18.0 | 862 | 404 | 86.5| 39.2| 0.12| 0.51|
| 6    | 280       | 7.17| 4.06| 813  | 113  | 23.9| 0.003| 0.19| 0.959| 128  | 5.30 | 1238| 71.7| 111 | 4.48| 0.02| 2.84|
| 7    | 290       | 7.46| 2.43| 735  | 100  | 22.1| 0.004| 0.15| 0.737| 28.9 | 5.82 | 1018| 877 | 127 | 8.21| 0.37| 1.42|

The deep liquid of wells 1 and 4 (area C) and wells 3 and 6 (area A, 6 is drilled into area C) is Na-Cl water with very low concentrations of CO₂ and N₂ whereas the deep liquid of well 7 (NE-part of area A) is Na-HCO₃ water with lower Cl concentrations and somewhat higher N₂ than the other high enthalpy wells. The liquid enthalpy well 5b (drilled into area D) lies somewhere in between with Na-Cl-HCO₃ water but much higher N₂ and lower H₂ than the other wells. The aquifer concentrations of H₂S and H₂ indicate that they are buffered by pyrite and pyrrhotite but attempts to fit the CO₂ concentrations to mineral buffers have not been conclusive. The deep liquid is close to saturation with respect to calcite and during boiling, it remains under-saturated with respect to amorphous silica to about 10 bar-a.

3. Concluding remarks

The observed CO₂ concentrations from wells in the central part of the Theistareykir field correspond to geothermometer temperatures of about 200°C, much lower than the estimated aquifer temperature. This unexplained phenomenon has been seen in some other hot wells in NE-Iceland, e.g. in Krafla [10].

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