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The Response of the Reykjanes Geothermal System to 100 MWe Power Production: Fluid Chemistry and Surface Activity

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ABSTRACT

The 100 MWe Reykjanes Power Plant was commissioned in May 2006. During the first three years of operation the pressure below the boiling level in the production zone has dropped by ~35bar. The drawdown has resulted in a formation of a steam cap in the upper part of the production zone of the system. As a result the discharge enthalpy of deep production wells has increased from 1210 - 1400 kJ/kg (liquid enthalpy at 275 - 310 °C) before May 2006 to 1450 - 1950 kJ/kg in 2008. Two relatively shallow wells (1225 and 960 m) have been drilled to produce saturated steam from the steam cap (enthalpy ~2700 kJ/kg).

Unequivocal signs of systematic, long term changes in the chemical composition of the Reykjanes geothermal fluid have not been observed so far. The CO_2 concentration of steam from production wells has not increased significantly despite increasing enthalpy of production well discharge. Furthermore, the CO_2 concentration in steam from the two dry-steam wells is not significantly higher than in steam from wet wells. The gas concentrations in steam from the steam cap indicate that the liquid feeding steam cap has been significantly degassed with respect to CO_2 but not with H_2S.

The pressure drawdown since May 2006 has invigorated surface activity significantly. The thermal anomaly at the surface has increased in size, particularly toward the south east. Discharge from steam vents in 2007 was almost an order of magnitude higher than in 2004. The soil diffuse degassing of CO_2 has increased by 40% and the estimated total steam flow (through steam vents and soil) from the geothermal reservoir has increased by 50% since the power plant was commissioned. The increase in surface activity due to power production appears to be of a comparable magnitude to an increase in activity resulting from earthquakes in 1967.

1. INTRODUCTION

The Reykjanes geothermal system is located on the SW-tip of the Reykjanes Peninsula in SW-Iceland. The reservoir temperature below 1 km depth ranges from about 275 to 310 °C and the fluid is hydrothermally modified seawater with some addition of magmatic gases (Arnórsson, 1978). The areal extent of surface manifestations is of the order of 2 km^2 (Palmason et al., 1985) and extensive drilling seems to indicate that the productive part of the geothermal system is not significantly larger. The surface manifestations at Reykjanes include steam vents, mud pits and warm ground. The intensity of the surface activity is known to vary over time; it increases abruptly as a result of seismic activity and then decreases slowly over time until the next seismic events occur.

In May 2006 a 100 MWe Power Plant was commissioned at Reykjanes. Before that time one well was in production, supplying steam to a fish drying plant and a small turbine. When the Reykjanes Power Plant started operation the production from the system increased by a factor of 16, from about 50 to 800 kg/s (Hjartarson and Juliusson, 2007). This increase in production resulted in a dramatic pressure drop in the reservoir amounting to about 35 bar in the first three years. The pressure drop and associated drawdown has resulted in formation of a steam cap over the liquid dominated part of the reservoir. The formation of the steam cap has allowed production of dry steam from shallow wells. The pressure drawdown has also caused increased boiling in the system resulting in significant increase in the surface geothermal activity.

The objective of this communication is to describe the changes observed in surface activity in response to increased production and also to present some observations on the evolution of the gas content of steam formed in the system.

2. PRESSURE DRAWDOWN AND DISCHARGE ENTHALPY

The history of geothermal production from the Reykjanes system dates back to 1970 when the first proper production well, RN-8, was taken into production. During the period from 1970 to 2006 at least one well was in production with the exception of the period from 1975 to 1978. The production before 2006 generally averaged between 40 and 80 kg/s. Pressure and temperature measurements were carried out at irregular intervals during the first years of operation but in later years with more regularity and with more reliable tools. Early pressure measurements in well RN-8, and later RN-9 and RN-12, show that the production before May 2006 did not significantly affect the pressure below the boiling level in the reservoir. This is illustrated in Figure 1 that shows pressure in production wells and observation wells at 1500 m b.s.l. from beginning of 2004 into 2009. In the period before May 2006 the pressure measurements at this depth level are between 118 and 123 bar-g and no systematic change with time is observed.

In May 2006 the 100 MWe Reykjanes Power Plant was commissioned and the production increased to about 800 kg/s. The effects of the increased production on pressure in the system are clearly illustrated in Figure 1. Pressure at 1500 m b.s.l. in the production wells dropped abruptly from ~120 bar-g to ~ 95 bar-g in the first year of operation, then more slowly by another 10 bar between May 2007 and May 2009. Note that the pressure did not drop as dramatically in well RN-16, which is an observation well located about 0.5 km NW of the production area.

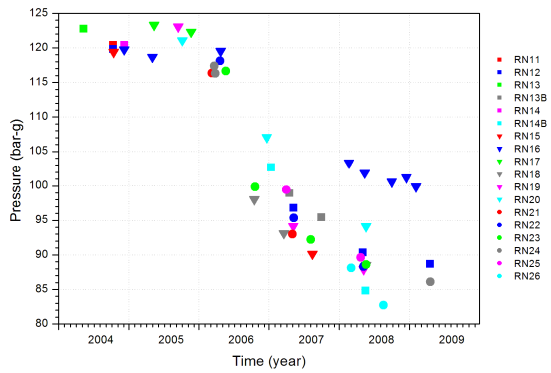

Figure 1: Pressure at 1500 m b.s.l. in wells at Reykjanes as a function of time. All wells shown are production wells except wells RN-16 and RN-20 (blue and cyan triangles)

The pressure change is, obviously, reflecting dropping boiling level in the system. As a consequence, feed zones at 800 to 1200 m depth that were liquid dominated before the commissioning of the Reykjanes Power Plant are now above the boiling level and supply mostly steam to the production wells while deeper feed zones supply liquid to the wells. This is illustrated on Figure 2 that shows the discharge enthalpy of production wells during well testing as a function time. Before May 2006 the discharge enthalpy of new wells ranged between 1150 and up to 1500 kJ/kg. The observed discharge enthalpy of the wells tested before May 2006 corresponds, in most cases, to the liquid enthalpy at the observed temperature at boiling level in the well. Well RN-18 is an exception as its discharge enthalpy was slightly higher. The discharge enthalpy of the deep wells tested in 2007 and 2008 is, on the other hand, significantly higher, ranging from 1450 to 1850 kJ/kg. The wide range of enthalpies observed for each well represents different discharge rates.

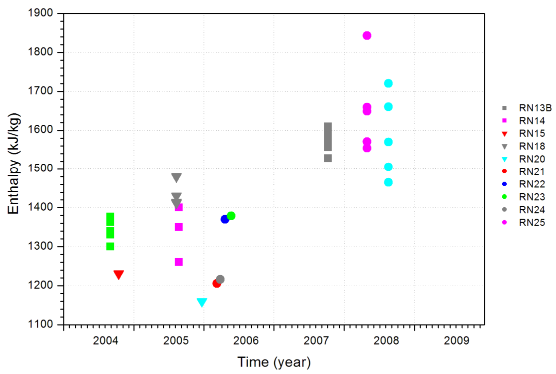

Figure 2: Discharge enthalpy of production wells as observed in production tests as a function of time

Two relatively shallow production wells were drilled in 2008 in order to produce steam from the new steam cap. The true vertical depth of these wells, RN-27 and RN-28, is 1225 and 960 m, respectively. The shut-in pressure of these wells just prior to their opening for flow was measured at 49.4 bar-g for RN-27 and 48.4 bar-g for RN-28. Discharge testing of these wells showed that these wells are very productive, yielding more than 30 kg/s of saturated steam at about 44 bar-g well head pressure.

3. GEOCHEMICAL PRODUCTION MONITORING

Historical data on the chemical composition of the Reykjanes geothermal fluids dates back to 1970 when RN-8 was tested. Samples were collected for gas and liquid phase analyses from that well at irregular intervals while it was in operation. In 1983 well RN-9 was taken into production along with RN-8 and since 1992 samples have been collected from that well twice a year. In recent years samples have been collected from every successful production well during testing and since 2006 samples have been collected from producing wells twice a year. Steam samples have also been collected from the steam pipelines at the inlet to the turbines for analyses of CO_2 and H_2S every three months since the Reykjanes Power Plant was commissioned.

3.1 Non-Volatile Constituents

Figures 3 to 5 show the concentrations of Cl, K, and SO_4 in deep fluids from present production wells as a function of time. Deep fluid compositions are computed from analyses of liquid and steam samples that were collected at a known separator pressure. The reference temperatures for the deep fluid calculations for the wells were determined from down-hole temperature measurements and observed quartz temperatures. Excess steam in the discharge does not significantly affect the calculated concentrations of non-volatile constituents such as those shown in Figures 3 to 5 but erroneous reference temperatures will. If the reference temperature is overestimated the resulting concentrations for non-volatile components will be too low, and vice versa.

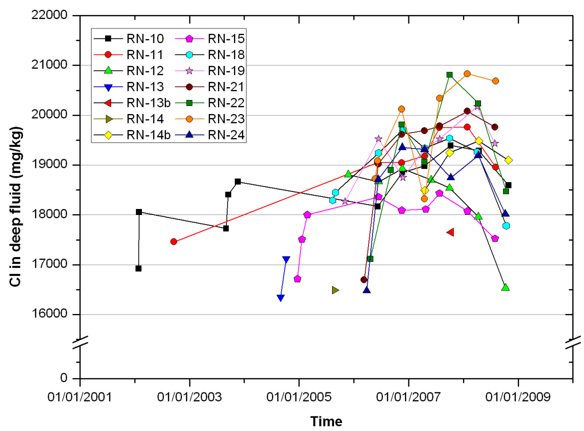

Figure 3: Concentration of Cl in deep fluid from Reykjanes production wells as a function of time

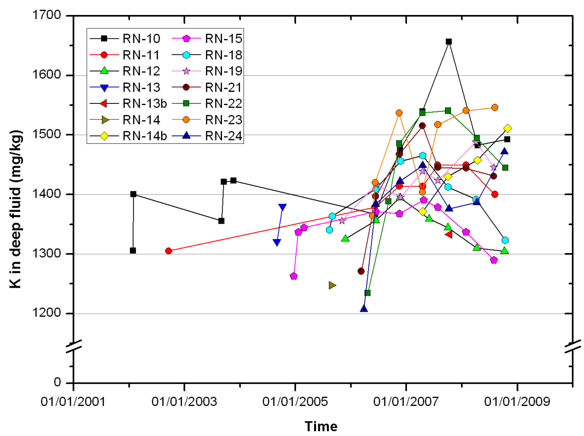

Figure 4: Concentration of K in deep fluid from Reykjanes production wells as a function of time

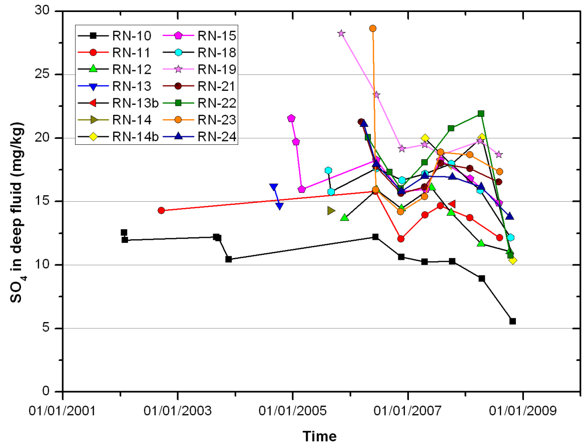

Figure 5: Concentration of SO_4 in deep fluid from Reykjanes production wells as a function of time

The concentration of many non-volatile constituents in deep fluid generally increased in the first few samples after May 2006 but now this trend has reversed in most cases. These patterns are still poorly defined; each well displays different pattern for a given constituent and the concentrations of different elements within a given well do not seem to fluctuate in sync with each other. The observed changes in the fluid chemistry may result, to some degree, from analytical uncertainty but other factors such as boiling, inflows of cold seawater or freshwater, changing temperature in feed zones, different water/rock ratios that the fluids have experienced may also play a role. At this point, however, it is not possible to conclude that long-term extensive system changes have been observed. The observed changes might just as well represent periodic fluctuations. Continued geochemical monitoring will eventually elucidate the nature of the observed changes.

3.2 Gas Concentrations in Steam

The CO_2 and H_2S concentration in steam from the Reykjanes production wells has not changed significantly since the Power Plant started operation. This is conveniently illustrated by depicting the concentrations of these gases in steam at the turbine inlets in the Power Plant in Figures 6 and 7. The concentration of gases in steam at the inlet into the turbines represents the average steam composition from the production wells, after boiling to18 bar-g, weighted by the production rate of the wells.

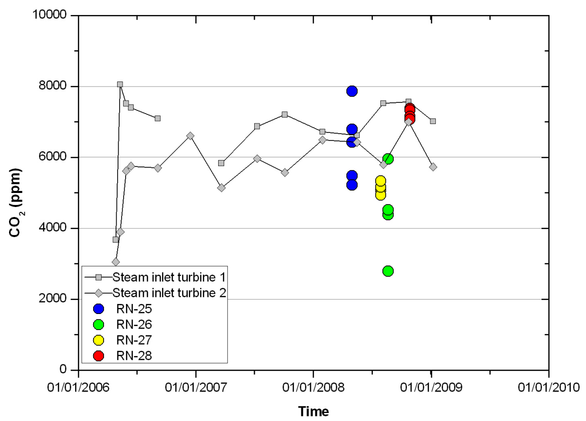

Figure 6: Concentration of CO_2 in steam from turbine inlets at Reykjanes as well as steam from recently tested production wells

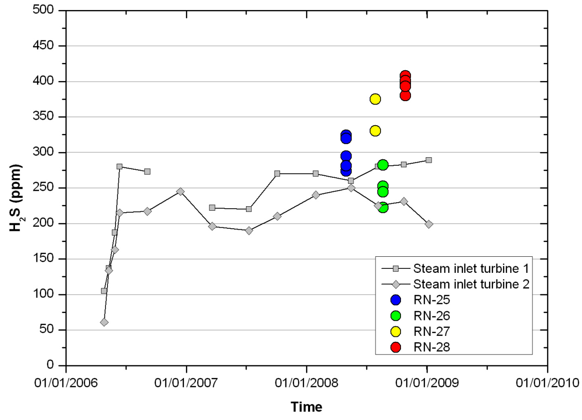

Figure 7: Concentration of H_2S in steam from turbine inlets at Reykjanes as well as steam from recently tested production wells

In addition to gas concentrations in steam from the turbine inlets, Figures 6 and 7 show CO_2 and H_2S concentrations in steam from production wells recently tested. Wells RN-25 and RN-26 are <2 km deep and produce a mixture of steam and water with enthalpy ranging from 1450 to 1850 kJ/kg depending on flow rate (cf. Fig. 2). The gas concentrations in steam from RN-25 and RN-26, depicted in Figures 6 and 7 are computed from gas concentrations observed at sampling pressure, steam fraction at sampling conditions, and assuming boiling to 18 bar-g. The shallow (<1200 m) wells, RN-27 and RN-28 are, on the other hand, steam wells and thus the observed gas concentration of these wells does not change as a result of pressure drop to 18 bar-g.

Figure 6 illustrates that the concentration of CO_2 in the steam from the new production wells is not significantly different from the average gas concentration in steam from the other wells. It is particularly interesting to observe that the CO_2 concentration in steam from the steam wells, RN-27 and RN-28 is very close to, or even lower than the CO_2 concentration of other production wells, whose discharge enthalpy is closer to that of liquid water than steam. Figure 7 shows that steam from wells RN-25 and RN-26 does not have significantly higher concentration of H_2S than other wells in the system. The H_2S concentration in steam from RN-27 and RN-28 is on the other hand up to two times greater than in other wells.

The near constant gas composition in the Reykjanes steam during the formation of the steam cap is very interesting considering the experience from Wairakei, New Zealand and Svartsengi, Iceland. In these systems the gas concentration was as much as two orders of magnitude greater in the steam cap than had been observed in the steam from wells producing from the liquid dominated part of the reservoir (Clotworthy, 2000; Bjarnason, 1996). The conventional explanation for the high concentration of gas in the steam caps in Wairakei and Svartsengi is that the steam in the caps was formed by small amount of boiling from a very large volume of liquid. Applying this line of reasoning to the Reykjanes system one can conclude that the low CO_2 concentration in the steam cap is suggesting that the volume ratio between the steam cap and the liquid feeding it is much larger in Reykjanes than in Wairakei and Svartsengi. In other words, the formation of the steam cap in Reykjanes is a result of relatively large amount of boiling from a relatively small volume of liquid.

The CO_2 concentrations observed in the steam from the steam wells indicate that they are fed by a liquid with a significantly lower dissolved CO_2 than the liquid feeding the wet wells, i.e. the steam produced from the steam wells is formed by boiling of a degassed liquid. Computed deep liquid concentrations of CO_2 in the wet production wells at Reykjanes ranged between 900 and 2000 mg/kg before the enthalpy started increasing. Essentially all dissolved CO_2, exists as undissociated carbonic acid in the deep fluid in the system. The deep fluid concentrations of this gas in the liquid feeding RN-27 are significantly lower as will be shown below.

It is possible to constrain the concentration of gases in the deep fluid that feeds the steam cap by observed gas concentrations in the steam, measured pressure in the well, estimated enthalpy of the deep liquid before boiling, and gas solubility constants at the maximum temperature of steam in the well. The maximum downhole pressure observed in the steam phase in wells RN-27 and RN-28 during flow testing is around 52 bar-a and the temperature is around 266 °C. If we assume that the steam that is produced from the wells forms by boiling a liquid with initial temperature of 290 to 300 °C then the steam fraction after boiling to 266 °C (and 52 bar) will be 0.076 to 0.11. The mass balance for the gases during boiling can be expressed as

$$m_g^{dl} = m_g^s X + m_g^{bl}(1-X) , \quad (1)$$

where m_g refers to concentration of a gas g in moles/kg and X refers to steam fraction and the superscripts *dl*, *s*, and *bl*, refer to the deep or initial liquid, the steam, and the boiled liquid respectively. The gas concentration of the steam is known and the concentration of the gas in the boiled liquid can be assessed through the equilibrium constant relationship for the dissolution of gas, g, in water:

$$\log K_g + \log P_g = \log m_g^{dl} . \quad (2)$$

Here *Pg* refers to the partial pressure of a gas *g* in the steam, which we take to be equal to the fugacity of the gas. Similarly we assume that the concentration of the gas in the deep fluid is equal to its activity. The logK values for CO_2 and H_2S dissolution at 266 °C, computed by SUPCRT92 (Johnson et al., 1992), are equal to -1.897 and -1.520, respectively. Using observed CO_2 concentrations for steam in well RN-27 the resulting concentration of the dissolved gas in the initial liquid are between 450 and 600 mg/kg depending on the selected steam fraction. This amounts to half or one third of the concentration of these gases in the deep liquid feeding the wet wells before power production. Corresponding numbers for RN-28 are 625 and 870 mg/kg, which are slightly lower than the lowest pre-power plant CO_2 concentrations of the wet wells.

The resulting values for deep fluid H_2S concentration for wells RN-27 and RN-28 are between 30 and 45 mg/kg. These values are in the range of observed pre-power plant deep fluid concentrations of the wet wells (30 to 60 mg/kg). This presents an apparent discrepancy i.e. the liquid that feeds the steam cap appears to be degassed with respect to CO_2 but not with H_2S. The slightly higher solubility of H_2S than CO_2 may explain this to some degree. However, it is also possible that this may be a result of interactions between the fluid and secondary minerals in the system. Calcite is very scarce in the deeper part of the Reykjanes system (Wiese et al., 2008) but sulfides are common, both as natural secondary minerals (Franzson et al., 2002) and they are also known to form in response to production, in wells and presumably in any boiling aquifer (Hardardottir et al., 2009 in review). It is therefore possible that fluids that have degassed as a result of boiling may replenish their H_2S concentration by dissolving sulfides but not the CO_2 as carbonate phases are not present.

4. SURFACE ACTIVITY MONITORING

The abrupt pressure drawdown in the Reykjanes geothermal reservoir resulting from the start-up of the 100 MWe power plant in 2006 caused a dramatic invigoration of surface geothermal activity. Steam flow from the steam vents increased drastically and the hot ground around the steam vents expanded, killing vegetation. These rather spectacular consequences of the power production caught a lot of public and media attention. Fortunately, extensive baseline studies in 2004 and 2005 and soil temperature map from 1968 (Jónasson, 1968) provided an excellent opportunity to quantify the environmental changes resulting from the current power production and compare them with changes that occur by natural causes.

Geothermal surface manifestations at Reykjanes include warm and boiling ground, steam vents and mud pits. A survey of surface activity was carried out in Reykjanes in 2004 (Fridriksson et al. 2006). The areal extent of the warm ground was determined by areal thermal-IR imaging. Subsequently, the soil temperature and diffuse CO_2 soil degassing was measured on a 25 by 25 m grid over the area where activity was noted. In 2004 the steam flow rate from all the most significant steam vents was measured as well as the heat loss from the mud pits.

In 2005 the soil temperature and diffuse CO_2 flux measurements were repeated on a larger grid. When it became evident in July 2006 that the surface activity in Reykjanes had increased significantly the measurements were repeated yet again and since then the soil temperature and CO_2 flux measurements have been repeated every summer. In 2007 attempts were made to quantify the steam flow from the area as well. Results of the different measurements are summarized in Table 1.

Table 1. CO_2 flux and heat flow through soil and visible steam flow from the Reykjanes geothermal field 2004 to 2009.

Year	CO_2 flux[1] (ton/day)	Heat flow[1,2] (MW)	Steam flow[3] (kg/s)
2004	13.8	16.2	0.8
2005	13.2		
2006	18.5		
2007	18.7	37.4	6-7
2008	11.5	20.2	
2009			

[1] reported values refer to the area covered in 2004.
[2] determined from soil temperature by the Dawson method.
[3] measured and estimated steam flow from steam vents.

4.1 Soil Temperature

Figures 8 and 9 below show the soil temperature at 15 cm depth in the active geothermal surface area in 2004 and 2007, respectively. Color scale refers to °C. Visual comparison of the two figures shows that the size of the area affected by surface activity did increase significantly between 2004 and 2007. The warm ground has expanded to the north, east and south but the abrupt western edge of the warm ground area has not shifted. No measurements were conducted in the center of the geothermal field in 2007 (black dots show points of measurement) as it was not safe to access the violently active field. As a result of missing data from the center of the field the interpolated temperatures appear lower than they probably were.

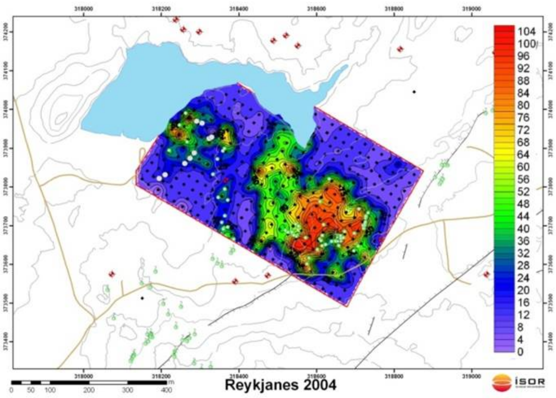

Figure 8: Soil temperature at 15 cm depth in the Reykjanes geothermal field in 2004. Black dots show measurement point, large open symbols refer to mud pits and smaller open symbols represent steam vents

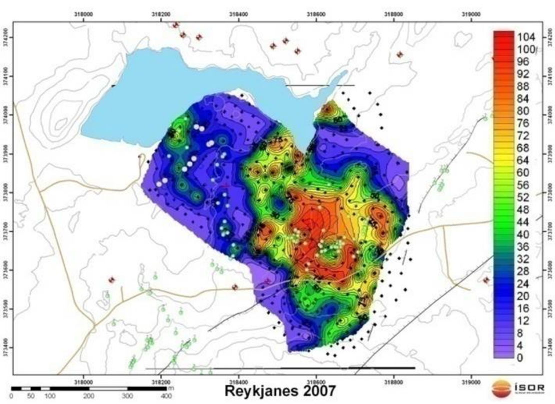

Figure 9: Soil temperature at 15 cm depth in the Reykjanes geothermal field in 2007. Black dots show measurement point, large open symbols refer to mud pits and smaller open symbols represent steam vents. Note that the soil temperature anomaly has expanded from 2004, particularly toward the south-east

Methods from Dawson (1964) were used to compute heat flux through the surface from observed temperature at 15 cm depth (T_{15}) or depth to the point where the temperature reached 97°C (d_{97}). Unfortunately, d97 data were not collected in 2005 and 2006 but Table 1 shows the total heat flow for 2004, 2007, and 2008. The heat flow as computed from the soil temperature data increased by a factor of 2.3 as a result of the power production between 2004 and 2007 but seems to be approaching pre-power plant values (if 2008 measurements will be verified by measurements in 2009).

As noted above, soil temperatures at 50 cm depth were measured in the summer of 1968. These measurements were carried out after the surface activity in the area had greatly increased as a result of earthquakes in September 1967 (Jónsson, 1968). The results are shown in Figure 10. Although the 1968 measurements are not directly comparable to the more recent soil temperature measurements they, nevertheless, provide very important opportunity to compare the magnitude of the activity increase due to the Reykjanes Power Plant to variations in the surface activity due to variations resulting from natural causes.

It appears that the size and shape of the thermal anomaly in the Gunnuhver area (see Fig. 10) in 1968 was similar to the thermal anomaly in 2007, at least on the north, east and south east sides. However, the main difference is the relatively large thermal anomaly on that stretches south toward the Skalafell crater on the 1968 map but no signs of this thermal anomaly have been seen in recent years. Comparison of these three maps indicates that even though the increased activity related to the commissioning of the Reykjanes Power Plant was very drastic it is not more dramatic than what can be expected from natural causes.

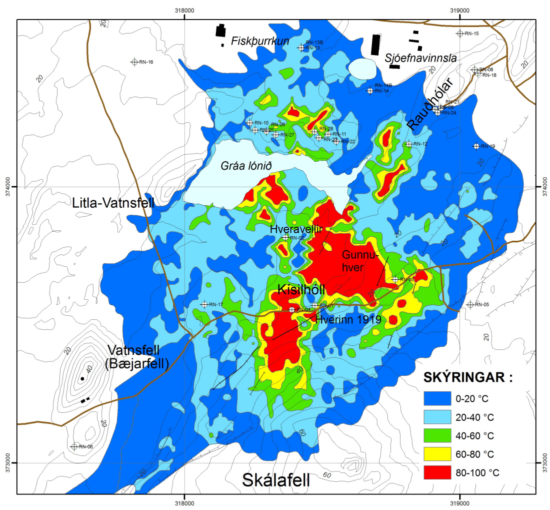

Figure 10: Soil temperature at 50 cm depth in the Reykjanes geothermal field in 1968

4.2 Steam Flow from Steam Vents

Because the steam emanating from steam vents is the most visible manifestation of geothermal activity in Reykjanes the significant increase of steam flow has been a focus of attention from the public and media. The results in Table 1 show that this is the parameter that increased most drastically in Reykjanes after the power plant was commissioned. The estimated steam discharge in 2007 was 2.5-6.0 kg/s compared to 0.8 kg/s in 2004. This amounts to an increase by a factor of 3.1 to 7.5.

The pattern of steam vent emission also changed in addition to the increased steam flow. The majority of the flow became focused on a single very powerful vent about 50 m north of the location of the most intense steam vent activity in 2004. New steam vents also opened on the southern edge of the geothermal field as the thermal anomaly expanded toward the south (see Figs. 8 and 9), eventually crossing the road shown in Figures 8 to 10.

4.3 CO_2 Flux Through Soil

The total CO_2 flux from the geothermal field in different years is also shown in Table 1. The gas flux from the system decreased insignificantly between 2004 and 2005, but increased sharply by about 40% between 2005 and 2006; from 13.2 to 18.5 ton/day. A small increase was observed between 2006 and 2007. The CO_2 flux seems to have decreased dramatically between 2007 and 2008 but verification of the 2008 results is needed.

Fridriksson et al. (2006) argued that the flux of CO_2 that escapes from the geothermal system by different routes can be used to quantify the amount of steam that leaves the system. They used the observed concentration of CO_2 in steam from steam vents and drill-holes in the area to constrain the characteristic concentration of this gas in steam produced by the system. This allowed them to use the observed CO_2 flux to compute the steam flow from the reservoir. Their result was that in 2004 more than 97% of the total steam flow from the system was associated with the diffuse flow of CO_2 through the soil and less than 2% was released through steam vents.

As noted above, the concentration of CO_2 in steam produced in the system does not seem to have changed significantly despite the formation of a steam cap. As a result it is possible to use the observed increase in CO_2 flux through soil and the increased steam flow through steam vents to quantify the total increase in steam flow from the reservoir. For the sake of this simple calculation we assume that heat flow from mud pits has not increased between 2004 and 2007. Considering the observed increase in flow through steam vents and soil between 2004 and 2007 (factor 7.5 and 40% respectively) and the proportion of the flow through these pathways in 2004 (2% and 97%, respectively) we find that the commissioning of the Reykjanes Power Plant resulted in a 50% increase in the total steam flow from the system. Furthermore, in 2007 the proportion of steam emitted from steam vents had increased from about 2% to some 10% of the total steam flow.

CONCLUSIONS

The main observations of the present study are as follows:

- 100 MWe power generation from the Reykjanes geothermal system has resulted in dramatic pressure drop in the production zone amounting to about 35 bar in the first three years of operation. This has lead to the formation of a steam cap in the system and as a result the enthalpy of production wells has increased.

- During the first three years of operation of the Reykjanes Power Plant some changes have been observed in the concentration of the non-volatile dissolved constituents of the geothermal fluid. However, it is too early to conclude that systematic long-term patterns have emerged.

- Increased enthalpy of production wells and production testing of steam wells has, surprisingly, not resulted in increased gas concentration of the steam from these wells. This may indicate that the volume of fluid feeding the steam cap is small relative to the volume of the steam cap.

- The CO_2 concentration in steam from pure steam wells indicates that the fluid that feeds the steam cap is degassed with respect to this gas. This does not apply to H_2S.

- The pressure drop in the reservoir caused extensive boiling in the system and as a result the surface activity of the system increased significantly.

- The most dramatic effect on surface activity was an increase in steam flow from steam vents by a factor of 5 to 7.

- The area of warm and boiling ground expanded significantly to the east and south and somewhat to the north. Heat flux through soil increased by a factor of more than 2.3.

- Diffuse degassing through soil is the dominant pathway of CO_2 from the system. The flux of CO_2 through soil increased by about 40% between 2005 and 2006.

- Because the concentration of CO_2 in the steam of the steam cap is apparently very similar to steam produced naturally in the system before 2006 the total flux of CO_2 from the system is a good quantitative indicator of increased activity of the system. The total flux of CO_2 from the system increased by 50% between 2005 and 2006.

- Despite the significant expansion of the surface thermal anomaly after the Reykjanes Power Plant was commissioned in 2006 the anomaly is, nevertheless smaller than it was after the system was invigorated by earthquakes in 1967. The increase in surface activity since 2006 is thus within the range of natural variations of the system.

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