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RESERVOIR CONDITIONS AT 3-6 KM DEPTH IN THE HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND, ESTIMATED BY DEEP DRILLING, COLD WATER INJECTION AND SEISMIC MONITORING

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ABSTRACT

Reykjavik Energy recently drilled a 2808 m deep exploration well HE-8 in the Hellisheidi high-temperature field. The well is located at the western boundary of a NNE trending fissure swarm. Two main feedzones were encountered at 1350 og 2200 m depth. The bottomhole temperature appears not to exceed 300 °C, suggesting considerable fluid convection at this depth. When stimulating the well by cold water injection at the end of drilling and again after 3 months of warm-up, the well's injectivity increased from 1-2 up to 6-7 kg/s/bar. An intrinsic reservoir permeability of 3-6 milli-Darcys was estimated by modeling the transient pressure data collected. A total of 22 small quakes accompanied the cold water injection into well HE-8, mostly at 4-6 km depth. Fluid pressure changes inside the reservoir fracture network, during injection, are strongly suspected as a trigger for these quakes. It also implies that there is a pressure communication and good permeability between the feedzones at 1350 and 2000 m depth and the 4-6 km depth of the quake centers. Large normal faults, dipping to the east, are suspected as likely surfaces of quake generation. These downhole and seismic data suggest considerably deeper fluid convection cells than previously assumed and may result in an increased generating potential estimate for the Hellisheidi resource. The field therefore appears feasible as a target for drilling a very deep exploration well. The study shows that the regional stress field and the permeability field are related. Seismic monitoring during injection may become a valuable tool for locating permeable fault surfaces at great depths.

INTRODUCTION

Well HE-8 was drilled to 2804 m depth in the Hellisheidi high temperature field, Iceland, in July and August 2003. The well was drilled as a part of a resource assessment study being undertaken by Reykjavik Energy. This is also the deepest high-temperature well drilled to date in Iceland. The purpose of the assessment study is to evaluate the feasibility of commissioning a 40-60 MW electric and 200 MW thermal power plant during 2006-2008.

Due to insufficient injectivity of well HE-8 at end of drilling, a few days of well stimulation were added to the rig time. These resulted in the injectivity rising from ~2 up to 4-6 kg/s/bar (Jonsson et.al., 2003). Zones of major fluid losses were located by temperature logs near 1350 and 2200 m depth.

Abundant supply of cold water was available at the rig site, thanks to a local and productive ground water reservoir tapped by a nearby well. As an attempt to further stimulate well HE-8, the field operator decided to allow the well to heat up and then to shock it again thermally by a 1-2 week long, cold water injection. The heating period lasted for almost 3 months. In early November 2003 cold water was again injected into the well for 15 days and the well response to injection monitored. Lively seismic activity arose from the deep, cold water injection and 22 quakes were located in a 2x2 km area around well HE-8 during these two periods of injection activity.

In this paper the hydraulic and thermal response of well HE-8 to the cold water injection is described. Some principal reservoir properties are estimated by simple pressure transient modeling and compared to earlier estimates derived by a large scale, 3-D reservoir model. The seismic activity is correlated to the injection history. Finally, a conceptual model for the deeper part of the geothermal reservoir is put forward and its implications for the future resource management strategy.

Figure 1 shows the location of the Hengill mountain and several geothermal fields associated with this massive volcanic center. Figure 2 shows well locations within the Hellisheidi field.

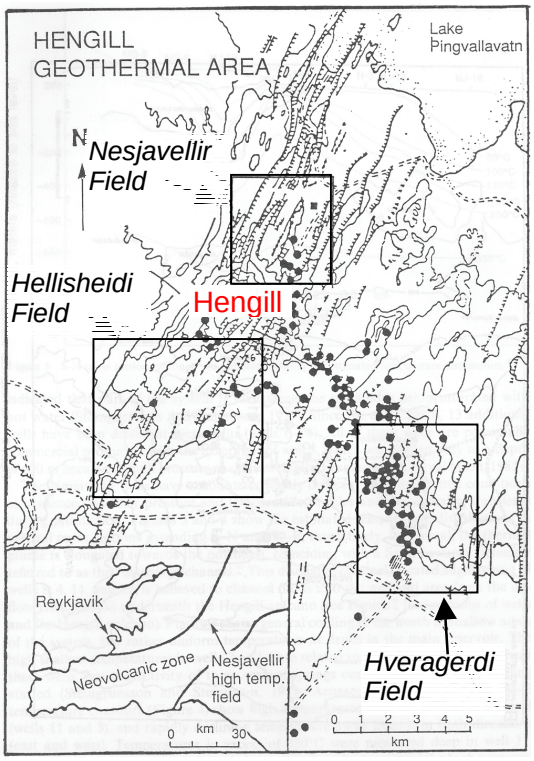

Figure 1. Geothermal fields near the Hengill volcanic center, SW-Iceland. Bullets show hot springs and fumaroles.

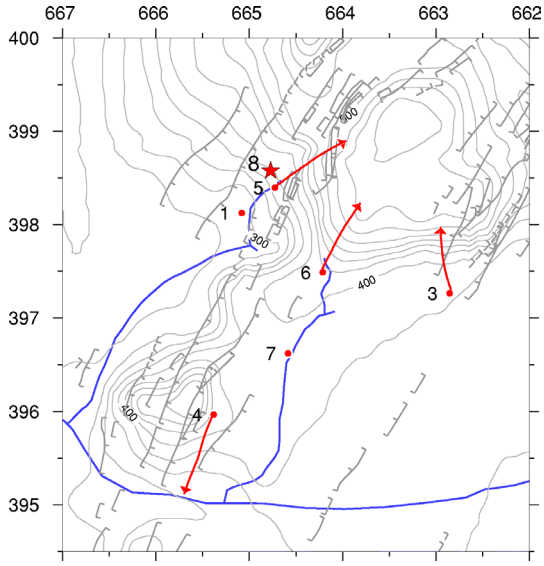

Figure 2. Well locations in the Hellisheidi geothermal field. Well HE-8 is shown by star. Elevation contours at every 25 m. Scale in km.

GEOLOGICAL SETTING

The Hengill volcanic center lies on the plate boundary, between the North America and the European crustal plates in SW-Iceland. These plates are diverging at a relative motion of 2 cm/year. The rifting of the two plates has opened a NNE trending system of normal faults with frequent magma intrusions. This rift zone is also highly permeable and numerous fumaroles and hot springs are found on surface (Bjornsson et al., 1986).

The Hengill volcanic system is currently active while its predecessor, the Hveragerdi system, is now extinct in terms of volcanic activity but still active seismically and hosts geothermal reservoirs. Three wellfields have been developed within the greater Hengill area: 1) Nesjavellir where a 90 MW electric and 200 MW thermal power plant is in operation, 2) Hellisheidi where a resource assessment is underway and 3) Hveragerdi where the geothermal resource is utilized by the local community (Figure 1).

The bedrock in the Hellisheidi area, where well HE-8 is located, is composed of basaltic lava layers, thick sequences of hyaloclastites and a few vertical intrusions. Two NNE striking volcanic fissures, which intersected the Hengill volcano ~2000 and ~5500 year ago, are believed to act as primary conduits for subsurface fluid flow in the region. Normal faulting is extensive and also dominantly striking to the NNE. Well HE-8 is drilled near the western boundary of the graben type fissure swarm of Hengill. Two major normal faults, dipping to the east, are seen on surface, one intersects the drillpad of well 8 while the other is located some 250 to the west of the well (Figure 2).

DRILLING HISTORY OF WELL HE-8

The drilling of well HE-8 started at the end of June 2003. The well is vertical and its design consists of a 144 m deep surface casing, 400 m deep and 13 3/8" anchor casing, and 933 m long 9 5/8" production casing. The open hole section was drilled with a 8 ½" bit. Planned total depth of 2500 m was reached on July 22nd. The next week was spent on well stimulation and geophysical logging. It was then decided to deepen the well and a final depth of 2808 m was reached on August 2nd. The well was completed with a 7 " slotted liner by August 8th. Altogether the drilling of well HE-8 only took 47 working days.

WELL STIMULATION DURING DRILLING

Only minor circulation losses had been encountered when well HE-8 reached 2400 m depth and the drill bit was pulled out for replacement. The well was flushed for a few hours, before pulling out the pipes. A rapid increase in circulation losses took place during this time period, ending in a total loss of 43 kg/s. The fine-grained drill cuttings, which were generated by the high revolution bottom hole assembly, were believed to clog temporarily natural feedzones in the well. This clogging eventually diminished during water circulation, after the drilling was stopped.

Well HE-8 became tight again while deeped from 2400 to 2500 m depth. Therefore, a weeklong period was spent on well stimulation, using an Icelandic practice that might be called the "*cooling string approach*". In this method only drillpipes are sent down to the well bottom. When in place, the well is cooled rapidly by pumping 50-60 kg/s of cold water through the pipes for 10-20 hours, depending on circulation loss. Then the well is allowed to warm up again by stopping the cold water injection for 12-24 hours. At that time, the well is cooled again by several hours of cold water injection down the pipes. Electric pressure and temperature tools are kept downhole during the injection and pressure fall-off tests are used to estimate the injectivity index. Mud logs are also analyzed for changes in the standpipe pressure and circulation losses. These cycles of cooling and heating are repeated until the injectivity index becomes stable between, as a minimum, two consecutive cycles.

Well HE-8 became practically tight again when deepened from 2500 to 2808 m. When flushing the well at end of drilling, circulation losses increased in similar manner as when the well depth was 2500 m. Standard well completion measurements were carried out at this time, lithological logging and step rate injection test. The well injectivity was estimated to range between 4 and 6 kg/s/bar at completion (Jonsson et. al, 2003).

WELL WARM-UP AND SECOND STIMULATION ATTEMPT

After 3 months of warm-up, a near constant 50 kg/s flow of 20 °C water was pumped again into well HE-8 between November 3rd and 18th 2003. The well accepted this fluid without pressure buildup on the wellhead. A pressure fall-off test at end of injection resulted in an injectivity factor of 6-7 kg/s/bar.

Figure 3 shows temperature logs in well HE-8, collected at end of drilling, during warm-up and after the November injection period. Also drawn is an estimated formation temperature profile. Few items are of special interest here. Firstly, that the bottomhole temperature (2808 m) appears not to exceed 300 °C. This is in agreement with the thermal alteration of the formation (Jonsson et al., 2003) but must be considered low, as the well is located only 4 km to the SW of the active Hengill central volcano. Fluid convection down to 3 km depth is the most direct explanation for this phenomena.

Also of interest in Figure 3 are abrupt slope changes in temperature profiles collected during injection, that correlate with location of the main feedzones of the well, at 1350 and 2200 m. Finally, a temperature log taken right after the November injection period, shows cooling as far as to 2700 m depth, indicating that the well has a minor loss zone this deep.

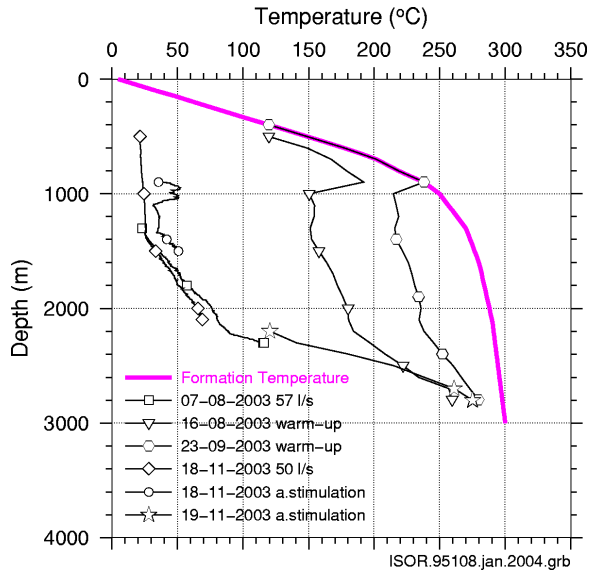

Figure 3. Temperature logs from well HE-8 prior to, during and after the November injection.

Figure 4 shows selected pressure profiles in well HE-8 prior to, during and after the November injection. Of interest here is a pressure pivot point at 1200 m depth, observed during warm-up. The pivot point location is generally assumed to coincide with the depth to the best feedzone of a well (Grant et al., 1982). In the case of well HE-8, that depth correlates with the main feedzone location at 1350 m depth.

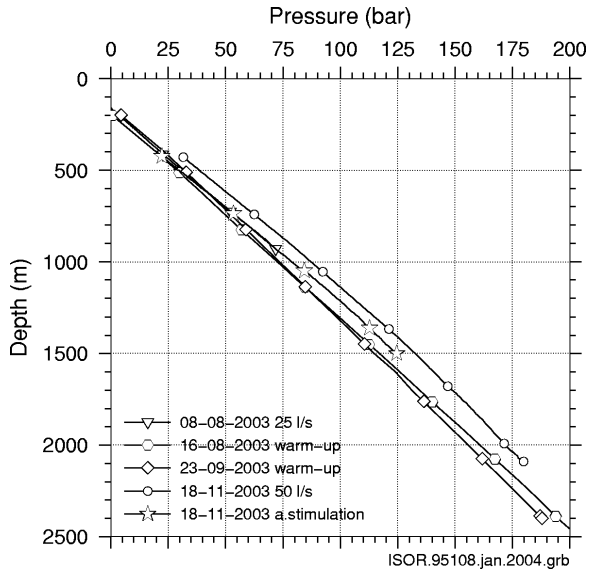

Figure 4. Pressure logs in well HE-8 prior to, during and after cold water injection.

MODELING PRESSURE FALL-OFF

Figure 5 shows the measured pressure recovery of well HE-8 at 1350 m depth, collected after the November injection period. Also shown is a pressure

curve computed by a well model that simulates infinite, confined and isotropic reservoir layer (Theis). Initially the pressure drop is fast and then slows down, as is to be expected. The initial pressure drop of 7-8 bars, after injecting 50 kg/s, results in an injectivity index of 6-7 kg/s/bar. This estimate is to be compared with 4-6 kg/s/bar at the end of drilling and suggests that the stimulation success is moderate.

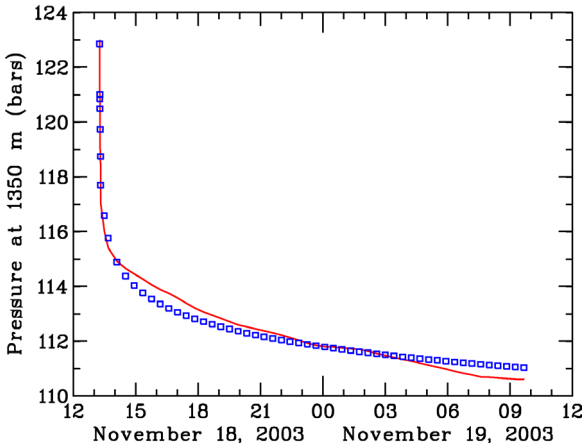

Figure 5. Measured (line) and simulated (boxes) pressure fall-off of well HE-8 after cold water injection in November 2003.

Table 1 presents reservoir model parameters, which were derived by matching the field data on Figure 5. Assuming that the injected fluid is displacing reservoir fluid at 280 °C and dynamic viscosity of ~$1x10^{-4}$ kg/m/s (cold spot approach, see Bodvarsson et al., 1984), results in permeability thickness near 3.3 Dm (Darcy-meters). The negative skin value obtained suggests fracture permeability near the well.

MODELING PRESSURE INTERFERENCE

Substantial pressure interference was observed between wells HE-8 and KhG-1 during the November injection test. These wells are sited 500 m apart (Figure 2). The pressure response in well KhG-1 is shown in Figure 6 together with a computed curve that is based on the same reservoir model as in Figure 5. The model properties are given in Table 1. A similar value is obtained for the transmissivity while the storativity differs by a factor of two.

Applying the same hot reservoir approach for the pressure interference model as for the pressure fall-off model results in a permeability-thickness estimate of 2.6 Dm instead of 3.3 Dm previously. Furthermore, one can assume that the thickness of the reservoir, connecting the two wells, is similar as the well separation or 500 to 1000 m. This yields an intrinsic reservoir permeability estimate of 3 to 6 mD (milli-Darcy). For comparision, a new 3-D, distributed parameter reservoir model of the Hengill area has permeability in the order of 4-7 mD in the vicinity of well HE-8 (Bjornsson et.al., 2003).

Table 1. Properties of a simple, horizontal, confined and isotropic reservoir model that simulates pressure data collected during and after injection to well HE-8.

Model property	Well HE-8 fall-off	Well KhG-1 interference
Initial pressure (bars)	122.8	3.3
Transmissivity (m^3/Pa/s)	$3.3x10^{-8}$	2.6x10-8
Storativity (m/Pa)	$0.5x10^{-8}$	1.2x10-8
Skin	-4	
Wellbore storage, CD	20	
Misfit (RMS, %)	0.27	1.39

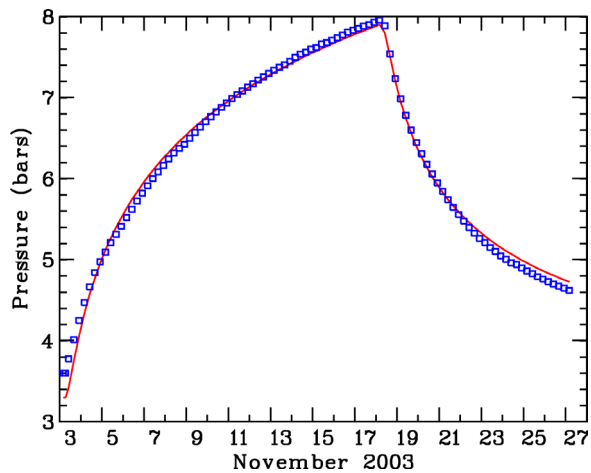

Figure 6. Measured (line) and simulated (boxes) pressure interference of well KhG-1, due to cold water injection to well HE-8.

SEISMIC ACTIVITY

The Icelandic Meteorological Office operates a national seismic network that is able to locate automatically most seismic activity in Iceland. Furthermore, they publish on the web weekly reports on the seismic activity nationwide. An inspection of these reports, during November 3 to 23, 2003, shows that the network located automatically 5 small quakes near well HE-8 (see the web site http://hraun.vedur.is/ja/viku/2003/vika_#/hen.gif where # are week numbers 45, 46 and 47).

The Meteorological Office allows direct access to their quake location database via an open web site. In order to understand whether the seismic activity near well HE-8 was purely coincidental, all quake locations between years 1993 and 2003 and in a 2x2 km area surrounding the well were retrieved from the database. In total 412 quakes had been detected within this area. Figure 7 shows how the quake activity evolved with time. The activity was intense between 1995 and 1999, coherent with very lively activity in the Hengill central volcano (Arnason and Magnusson, 2001). The years 2000, 2001 and 2002 are on the other hand very quiet, possibly due to stress relaxation that accompanied 2 large quakes that

shook the S-Iceland seismic zone in June 2000 (Arnadottir et al., 2003). Finally, there has been some activity in 2003, in particular in July and November.

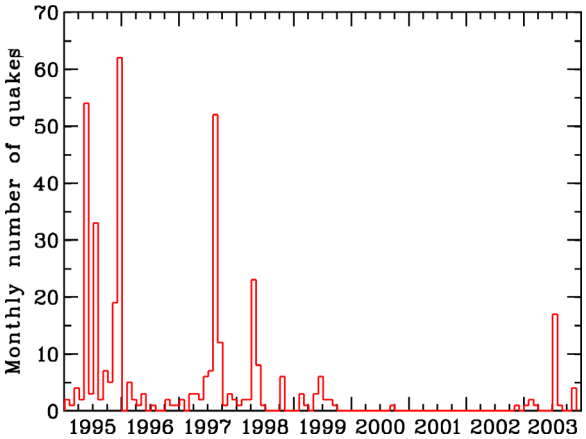

Figure 7. Monthly number of quakes in a 2x2 km area surrounding well HE-8 (Icelandic Meteorological Office, 2003).

Figure 9 shows the weekly number of quakes in the year 2003 only. A strong correlation with fluid losses in well HE-8 can now been seen. This applies in particular to late July and early August, when the 2400-2808 m section of HE-8 was drilled and stimulated. It is therefore concluded that injecting cold fluid into well 8 affects the local stress field next to the well. This perturbation has resulted in quake activity that correlates perfectly with the injection history. Also detected are 5 scattered quakes between October 2002 and March 2003 that may or may not correlate with discharge from directional well 5, located only 300 m to the SE of well 8 (Figure 2).

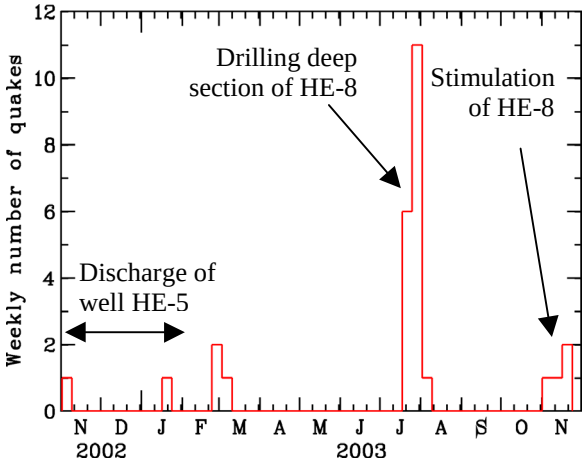

Figure 8. Weekly number of quakes in a 2x2 km area surrounding well HE-8.

QUAKE LOCATIONS

It is of interest to have a closer look at the quake data available between July and November 2003 and try to correlate them with the local geological setting and the deep reservoir situation. In table 2 more detailed information on the 22 quakes located next to well HE-8 are shown. The table format and the database inquiry used to retrieve the data are practically the same as on the website of the Meteorological Office. Precaution should be used here as the locations are automatic and may change when seismologists have a closer look. The following analysis should therefore be regarded as preliminary.

Figure 9 shows the epicenters listed in Table 2 along with locations of wells in the Hellisheidi area. The epicenters either line up next to well HE-8 or to the east of the wellhead. This may imply that the fracture surface, which responds to the injected fluid, is dipping to the east.

Figure 10 shows depth and magnitude of the quakes listed in Table 2. Most are located at 4-6 km depth but a few penetrate down to 10 km depth. It also appears that the deeper the quakes, the stronger. This may suggest that the injection stimulated quakes are small and initially located at 4-6 km depth. However, as injection continues the quakes penetrate deeper and grow in size.

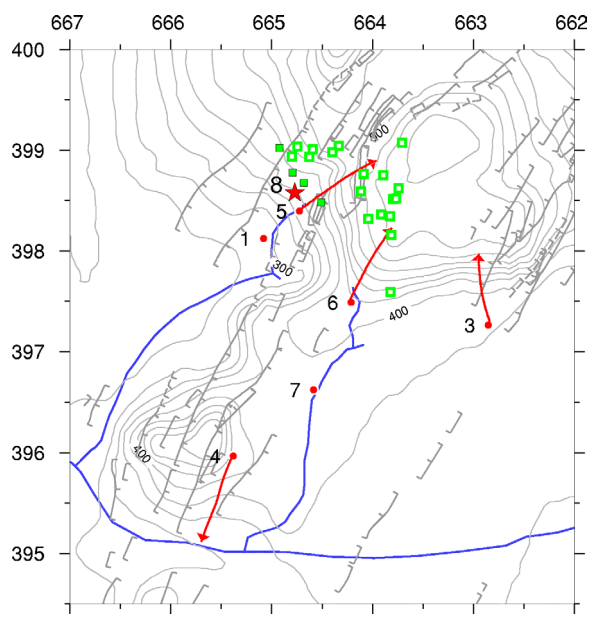

Figure 9. Well locations and quake epicenters near well HE-8. Wells are shown by black squares, quakes in July and August 2003 by open (□) and in November by filled (■) squares.

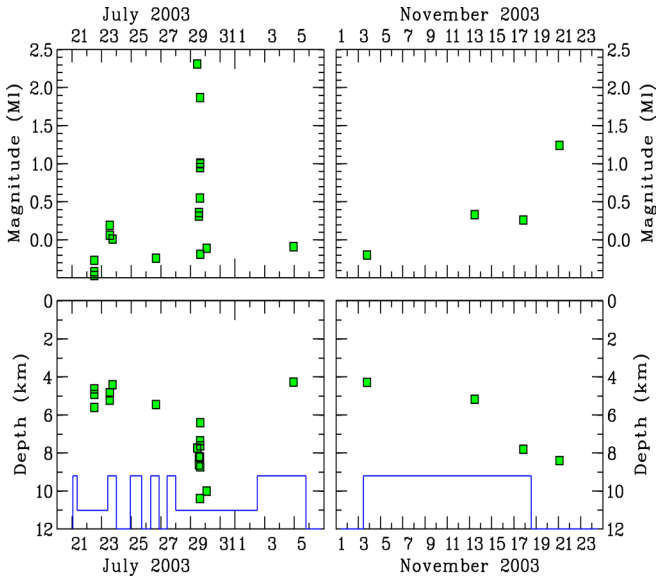

Figure 11. Magnitude and depth of quakes listed in Table 2, together with injection rates to well HE-8 (blue line). The injection rates refer to full (>50 kg/s), partial or no fluid losses into the well.

The quake data suggests that two normal faults have responded to the pressure changes associated with water injection to well HE-8. These faults are seen at surface to the west of and right through the wellpad of HE-8 (Figure 9). They dip gently to the east, in under the Hellisheidi wellfield. The cumulative vertical displacement of the eastward dipping normal faults in the region is huge, or of the order of 400 m in total, whereof 180 m belong to the next fault to the west of well HE-8 (Sæmundsson, 1992).

CONCEPTUALIZING THE DEEP RESERVOIR

The subsurface data now available in and around well HE-8 has many implications when it comes to conceptualize and manage the geothermal resource in Hellisheidi. First of all it is a surprise that the bottomhole temperature of well HE-8 appears not to exceed 300 °C at 2808 m depth. The most direct explanation for this behavior is that fluid convection penetrates deep in this area, due to still significant permeability.

The quake activity associated with cold water injection into the well is another surprise. The near immediate quake activity at 4-6 km depth during injection is regarded here as a consequence of fluid pressure change in a fracture network. This pressure change causes a minor slip on fracture surfaces and, hence, a release of seismic energy. These displacements may have strained the fault system to the extent that a quake swarm took off on July 29 and penetrated deep into the crust (Figure 10).

Table 2. Quake location data near well HE-8 in July to November 2003 (Icelandic Meteorological Office, 2003).

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First date:          19900101  last date:          21001231
Minimum latitude:   64.04239  maximum latitude:   64.05935
Minimum longitude: -21.39607  maximum longitude: -21.35301
Minimum magnitude:  -1.00      maximum magnitude:   9.90
Maximum number of events to list=1000

412 events found

  date    time   latitude longitude depth    M0    Ml  N  Np Ns
20030722 121332 64.05527 -21.36606  4.62 -0.16 -0.42  6  5  6
20030722 121651 64.05499 -21.37450  4.91 -0.02 -0.47  5  4  5
20030722 122221 64.05288 -21.36081  5.60  0.40 -0.27  8  6  8
20030723 131938 64.05486 -21.37132  5.21  0.63  0.19  8  6  8
20030723 132005 64.05134 -21.36115  4.82  0.62  0.06  6  5  6
20030723 174129 64.05414 -21.37192  4.41  0.55  0.01  8  6  8
20030726 155654 64.05467 -21.36727  5.45 -0.08 -0.24  7  6  7
20030729 105016 64.05286 -21.35675  7.73  2.57  2.31 14 14  7
20030729 132208 64.05176 -21.35355  8.62  0.67  0.31  7  5  7
20030729 133932 64.04250 -21.35395  8.18  0.66  0.36  4  2  4
20030729 151827 64.04892 -21.35927 10.38  0.98  0.55  9  7  7
20030729 153356 64.05586 -21.35334  7.35  2.44  1.87 14 14 11
20030729 153600 64.04758 -21.35454  8.21  1.16  0.95 10  8  8
20030729 154040 64.05078 -21.35449  8.72  0.12 -0.19  4  4  3
20030729 154316 64.04928 -21.35494  7.61  1.24  1.00  8  8  6
20030729 154451 64.05083 -21.35391  6.40  1.30  1.01  7  7  7
20030730 020444 64.04939 -21.35683 10.00  0.29 -0.11  6  5  4
20030804 224132 64.05412 -21.37546  4.26  0.27 -0.09  6  5  6
20031103 185811 64.05183 -21.37277  4.27  0.40 -0.20  6  6  6
20031113 110341 64.05479 -21.37811  5.16  0.81  0.33  7  5  6
20031117 201342 64.05268 -21.37506  7.80  0.85  0.26  8  6  8

20031121 020805 64.05016 -21.36903  8.39  1.27  1.24 12 10 10
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The best feedzones of well HE-8 are located at 1350 and 2200 m depth while most of the injection stimulated quakes are located at 4-6 km depth. If the stress perturbation that led to the seismic activity is due to change in hydraulic pressure, it appears that the permeability in the area is preferentially vertical and may reach a depth of 4-6 km. This conclusion actually comes hand in hand with the relatively low bottomhole temperature of well HE-8 that can also be readily explained by deep fluid convection.

The Hengill volcanic center is well known for its intensive microseismicity. During years 1993-2000 more than 96,000 quakes were located at 2-8 km depth in the area (Arnason and Magnusson, 2001). Tomographic inversion of these quake data have led to the interesting conclusion that the crust in the Hengill area is characterized by anomalously low p wave velocity down to ~10 km depth. The study concluded that the velocity anomaly most likely has to do with high fluid content within the crust and, possibly, deep hydrothermal convection (Tryggvason et al., 2002). The data presented here support this general idea of very deep geothermal convection cells inside the Hengill system.

IMPLICATIONS FOR THE RESERVOIR ASSESMENT STUDY AND MANAGEMENT

A conceptual model of the Hellisheidi field, with fluid convection cells penetrating as deep as 4-6 km depth, has many positive implications for the Hellisheidi reservoir assessment and management. The present numerical reservoir model has, for example, a base layer reaching down to 2 km depth.

This now appears to be an underestimate and, when properly accounted for, might result in an increased generating capacity of the resource from the present maximum of 120 MW electric and 400 MW thermal (Bjornsson et al., 2003; Bjornsson and Hjartarson, 2003). Harnessing the resource at 3-6 depths is, on the other hand, not straight forward. New development in the fields of drilling techniques, well and power plant design and reservoir modeling should be expected, in particular as the resource may enter supercritical conditions. The Icelandic deep drilling project (IDDP) is already addressing these challenges (Fridleifsson et al., 2003). The new data on well HE-8 may therefore put the Hellisheidi field on the table as a potential site for deep drilling in the future.

The 3-6 mD reservoir permeability estimate for the well doublet HE-5 and KHG-1, is of concern if massive drilling of deep (4-6 km) production wells comes into consideration in the Hellisheidi field. In particular whether this low permeability will restrict the average deep well output considerably. This is a question only to be addressed by undertaking the drilling of an exploratory well in the area. In the case of insufficient reservoir permeability, a very deep well will most likely pay off as an injection well. The new power plant currently under design is to be sited near well 8. Ideally, the injection field might be developed right underneath that same power plant.

CONCLUSIONS

The following conclusions can be drawn from the analysis of cold water injection into well HE-8 and the associated microseismicity:

1) The two main feedzones of well HE-8 are located at 1350 og 2200 m depth. A minor feedzone at 2700 m depth was also visible in downhole temperature data in November 2003.

2) Bottomhole temperature at 2808 m appears not to exceed 300 °C, regarded here as low when considering the short distance to the massive Hengill central volcano. Fluid convection cells reaching beond this depth might explain such a “low” temperature.

3) During warm-up, a pressure pivot point is seen at ~1200 m depth, in accordance with the best feedzone location at 1350 m.

4) Well HE-8 was stimulated by periodic cold water injection near the end of drilling in late July and early August 2003. The stimulation proved successful and increased the well injectivity from ~2 to 4-6 kg/s/bar.

5) After 3 months of warm-up, the well was stimulated again by ~50 kg/s injection rate of cold water. This resulted in an injectivity index of 6-7 kg/s/bar, indicating a moderate success of that second stimulation attempt.

6) A simple groundwater model (Theis) has been calibrated, based on pressure fall-off data in well HE-8 and pressure interference in well KhG-1 nearby. Both data yield a permeability-thickness product of the order of 3 Dm and a storativity of $0{,}5\text{-}1\times10^{-8}$ m/Pa. A skin factor of –4 was also evaluated for well HE-8, indicating a fracture dominated permeability next to the well.

7) Assuming a 500-1000 m thick reservoir zone results in an intrinsic permeability estimate of 3-6 mD near wells 1 and 8. This is in a good agreement with a recent numerical reservoir model, where the intrinsic permeability is 4-7 mD.

8) Considerably microseismic activity accompanied the cold water injection to well HE-8, both at end of drilling in July and August, as well as during the stimulation attempt in November 2003. A total of 18 quakes were detected during the July-August period and 4 in November, in a 2x2 km area surrounding the well.

9) As the quake activity correlates strongly with the injection activity, the author concludes that fluid pressure changes inside the local reservoir fracture network have triggered these quakes. It also implies that there exists a rapid pressure communication and, hence, permeability between the two best feedzones of well 8 at 1350 and 2000 m depth, on one hand, and the general 4-6 km depth to quake centers, on the other hand.

10) Large normal faults near well HE-8 that dip gently to the east are suspected as likely surfaces of quake generation.

11) The 4-6 km depth penetration of fluid pressure changes suggests a considerably thicker geothermal reservoir than previously assumed in a numerical reservoir model. A thicker reservoir consequently increases the accessible heat and mass in storage and, thereby, the maximum generating potential of the resource.

12) Drilling a 4-6 km deep exploration well in the Hellisheidi area therefore appears feasible as a long term goal in the field development. Depending on permeability, the well may either prove to be productive or, as a worst case, can be used for injection.

The seismic data that were collected during injection into well HE-8 show that the regional stress field and the regional permeability field are closely related in Hellisheidi. A careful analysis of the available quake data and possibly another injection phase, where a local seismic network is also operated, may prove to be a valuable tool for locating precisely the fault surfaces that are permeable in the area.

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