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Stimulation of geothermal wells in basaltic rock in Iceland

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Abstract

Stimulation operations are commonly part of the completion programs of geothermal wells drilled in the basaltic environment of Iceland. The purpose is to enhance the output of the wells either by improving near-well permeability that has been reduced by the drilling operation itself or to open up hydrological connections to permeable zones not intersected by the well in question. The methods used involve applying high-pressure water injection, sometimes through open-hole packers, or intermittent cold water injection with the purpose of thermal shocking. Stimulation operations are most commonly applied for a few hours to a few days while in a few instances stimulation operations have been conducted for some months. The stimulation operations often result in well productivity being improved by a factor of 2-3. Emphasis is placed on careful reservoir monitoring during stimulation operations. Seismic monitoring has only been applied in a few cases and examples are available where long-term water injection has caused a marked change in seismic activity as well situations where long-term high-pressure injection has caused no micro-seismic activity at all.

Keywords: geothermal, volcanic, stimulation, monitoring

1. Introduction

Iceland is a geologically young country (< 16 Myrs) lying on the Mid-Atlantic Ridge, which is the boundary between the North American and Eurasian tectonic plates. As a result of its location Iceland is tectonically and volcanically very active with abundant geothermal resources associated with this activity. A map of the country is presented in Fig. 1, which shows the volcanic zone passing through the country and the numerous geothermal areas.

The geothermal systems are classified as low-temperature or high-temperature systems. The low-temperature systems, which by definition have a reservoir temperature below 150°C, are all located outside the volcanic zone (see Fig. 1). About 250 such systems are known at present with the largest ones located in SW- and S-Iceland on the flanks of the volcanic zone, but smaller systems are found throughout the country. The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by the continuously ongoing tectonic activity, also play an essential role by providing the channels for the water circulating through the systems and mining the heat at depth (Axelsson and Gunnlaugsson, 2000). The low-temperature resources are suitable for direct uses, such as space heating.

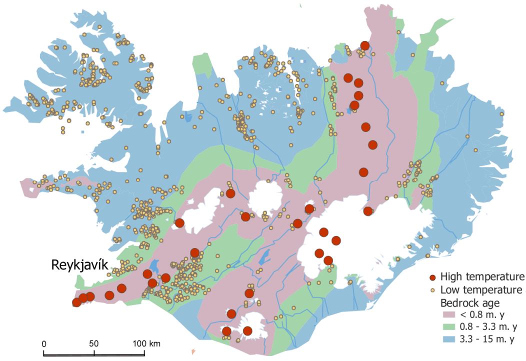

Figure 1. Locations of geothermal areas in Iceland. Also shown are the basic components of the geology of the island.

The high-temperature systems, which by definition have a reservoir temperature above 200°C, are located within the volcanic zone (Fig. 1). At least 26 high-temperature areas with steam fields are known at present in Iceland. These areas are directly linked to the active volcanic systems and the heat sources are believed to be mostly cooling magma

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bodies, i.e. intrusions of various shapes and sizes, as well as magma chambers. The high-temperature resources are suitable for electricity production, co-generation and industrial uses.

Geothermal resources account for just over half of the primary energy supply for the population of Iceland. The direct geothermal use in Iceland, mostly for space heating, totalled about 23,800 terajoules (TJ = 10^{12} J) in 2004, corresponding to 6,600 GWh/a. In addition, geothermal electricity production amounted to 1,484 GWh/a that same year (Ragnarsson, 2005). Geothermal electricity production is expected to have more than doubled in 2007.

This has required intensive exploration and drilling activity. It started during the middle of last century with intensive drilling commencing in the 1960's and 1970's. At the end of 2004 more than 570 geothermal production wells had been drilled in Iceland, with a total combined depth of about 550 km. In addition to this more than 900 exploration wells, deeper than 100 m, had been drilled in Iceland at this time.

Stimulation operations are commonly an integral part of the completion programs of geothermal wells drilled in Iceland, for high-temperature as well as low-temperature wells (Steingrímsson and Gudmundsson, 2005). The purpose is to enhance the output of the wells and the operations are usually conducted at the end of drilling. Emphasis is placed on careful well- and reservoir monitoring during stimulation operations in Iceland.

This paper reviews the stimulation operations conducted in geothermal wells drilled in the basaltic environment of Iceland, both the procedures used, the results and associated monitoring. A few representative examples are presented as well as results of a few cases of micro-seismic monitoring.

2. Stimulation operations

The purpose of geothermal production well stimulation is to enhance the output, or productivity, of the wells either by improving near-well permeability that has been reduced by the drilling operation itself (feed-zones clogged by drill cuttings or drilling-mud) or to open up hydrological paths to permeable zones not intersected by the well in question. In the case of injection wells the purpose is similarly to enhance the injectivity of such wells.

2.1 Methods and procedures

The following are the principal methods used for stimulation operations:

- (A) Air-lift aided drilling and air-lift cleaning.
- (B) Water circulation through drill string at well bottom.
- (C) Well-head water injection, often at high pressure.
- (D) Water injection above, or below, inflatable open-hole packers.
- (E) Water injection through double packers.
- (F) Intermittent cold water injection and well heating-up.
- (G) Acidizing by well-head acid injection or acid injection through packers or coil-tubes.

Of these methods (A), (B), (C), (D) and (F) are regularly used in Iceland. Air-lift aided drilling (A), which has proven to be successful in preventing the clogging-up of feed-zone during drilling, is not a stimulation operation per se, but helps in maximizing well output. A schematic illustration of the setup for this procedure is presented in Fig. 2(a). Air-lift cleaning (A) and water circulation (B), at the end of drilling, help to restore feed-zone permeability reduced during drilling. Both these methods are a regular part of drilling operations in low-temperature fields in Iceland and the latter method (B) is also used during high-temperature drilling (see also (F)).

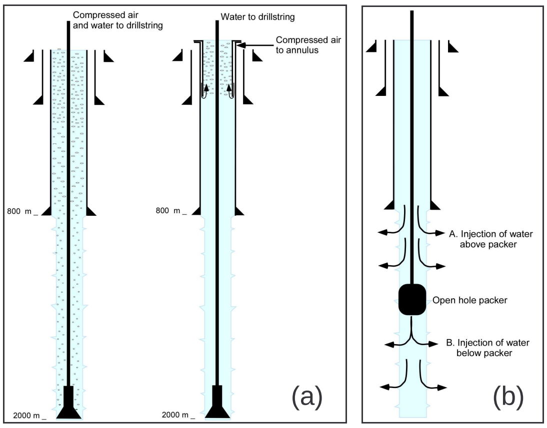

Figure 2. Schematic illustration of the setup for (a) air-lift aided drilling and (b) stimulation with an inflatable open-hole packer.

Methods (C) and (D) can be looked upon as proper stimulation methods. They both involve the injection of cold water, most often at high pressures, either through the well-head or above or below a packer placed at a specific depth. The pressures applied can be of the order of a few MPa, to some tens of MPa, with water flow-rates determined by the capacity of the equipment used and the water supply as well as the injectivity of the well involved. By using inflatable packers the stimulation can be focused on specific well intervals rather than the whole open section (see Fig. 2(b)). Method

(C) is frequently used in drilling operations in Iceland while method (D) has mostly been used during low-temperature drilling. The latter method should be as applicable for high-temperature situations. These methods are not as commonly applied as methods (A) and (B), however, being limited to wells with productivity below expectations. Some examples of low temperature stimulation operations are presented below.

Double packers (E) have hardly been used in stimulation operations in Iceland to-date, even though they have the potential of being more powerful as a stimulation tool then single packers. This is because they can be used to focus all the water injected into a specific, short interval, at higher pressures.

Intermittent cold water injection, with periods of thermal recovery in-between the injection periods (F), is one of the most common methods used for high-temperature well stimulation in Iceland. This method is aimed at causing cracking through thermal shocking. Some examples of this are presented below.

The stimulation of wells through acidizing (G) is in its infancy in Iceland, however. Its efficiency is, of course, limited in the basaltic environment of Iceland. It is used to remove calcite scale deposits within wells. Acidizing could be a powerful stimulation tool by dissolving scaling material in fractures.

Stimulation operations in Iceland are most commonly applied for a few hours to a few days while the drill rig is still on location. In some instances stimulation operations have been conducted for longer periods, from several days up to a few weeks. This is done after the drill rig has been moved from a well, and has mostly been limited to intermittent cold water injection and heating (F).

2.2 Low-temperature examples

The stimulation of low-temperature geothermal wells through inflatable packers (D) started as early as 1970. This was in the Reykir (Mosfellssveit) geothermal area, which has been utilized for space-heating in near-by Reykjavík since 1944. During the 1970's the Reykir field was redeveloped through the drilling of 39 large diameter wells ranging in depth from 800 to 2040 m. All these wells were stimulated by injection above and below inflatable packers with considerable success (Tómasson and Thorsteinsson, 1978).

In the Reykir stimulation operations an inflateable packer was set in-between two of the main feed-zones of a given well and water in-turn injected above and below the packer. Injection rates varied between 15 and 100 l/s and pressure increases at the feed-zones ranged from a few bar up to as high as 150 bar at the lowest permeability feed-zones treated (Tómasson and Thorsteinsson, 1978). A Reykir stimulation operation normally lasted a few days.

The results of the Reykir stimulation operations were appraised by two methods (Tómasson and Thorsteinsson, 1978):

(i) By comparing the eventual productivity of a well to the productivity at the end of drilling (before stimulation operations commenced). Thus the productivity was estimated to have generally improved by a factor of 30-40.

(ii) By comparing the final productivity of a well to the cumulative circulation losses during drilling. Thus the productivity was estimated to have increased as much as three-fold.

The drastic improvement indicated by appraisal method (i) may be mostly attributed to the reopening of feed-zones clogged by drill-cuttings during the drilling operation. The improvement estimated by method (ii) may mostly be attributed to increased feed-zone permeability, partly due to the removal of zeolite- and calcite-vein deposits and partly to increased permeability of near-well fractures in hyaloclastic rocks.

The results of the redevelopment of the Reykir geothermal field, both drilling and stimulation operations, were that the production capacity of the field increased from about 300 l/s by free-flow at the beginning of the 1970's to more than 1500 l/s by pumping in 1977.

Well SN-12 in the Seltjarnarnes low-temperature field in SW-Iceland was drilled to a depth of 2714 m in the fall of 1994. The well appeared to be almost non-productive at the end of drilling. A comprehensive ten day stimulation program was, therefore, initiated (Tulinius *et al.*, 1996). The program involved, firstly, high-pressure well-head injection and, secondly, high-pressure injection below a packer placed at 1412 m depth. After about twelve hours of well-head stimulation the pressure dropped suddenly, indicating that the well had been stimulated (see Fig. 3). At the same time the water level response increased suddenly in two near-by monitoring wells. The saw-tooth appearance of the well-head pressure results from the fact that not enough water was available to maintain the desired injection flow-rate uninterrupted. During the second stimulation phase (packer at 1412 m) the well appeared to be stimulated even further.

Well SN-12 eventually produced about 35 l/s with a drawdown of roughly 60 m, and the stimulation had increased the yield of the well by a factor of nearly 60 (see Fig. 4). Thus well

SN-12, which appeared to be almost non-productive at the completion of drilling, had turned into a good production well. It is believed that during the stimulation some previously closed fractures, or interbed contacts, reopened connecting well SN-12 to the main fracture system of the geothermal reservoir.

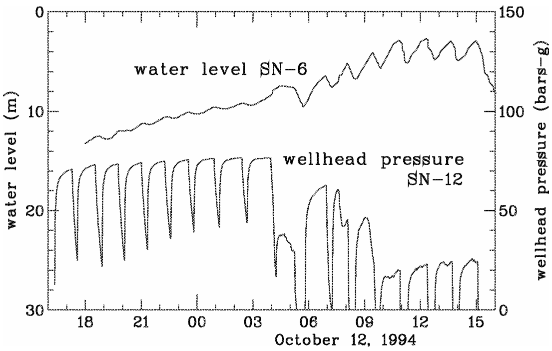

Figure 3. Water level in well SN-6 and well-head pressure of well SN-12, both in the Seltjarnarnes field SW-Iceland, during the well-head injection phase of the stimulation operations in well SN-12. From Tulinius et al. (1996)*.*

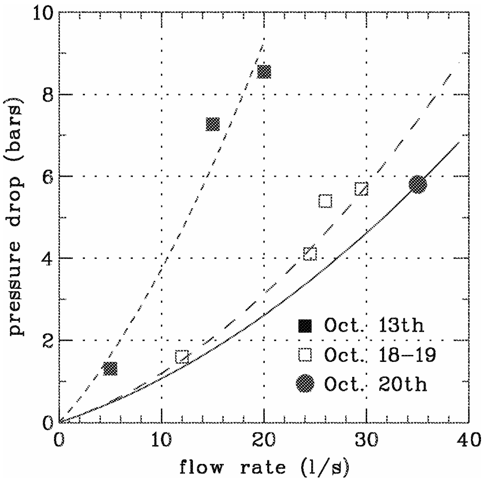

Figure 4. Results of production testing of well SN-12 in the Seltjarnarnes field during stimulation operations showing the gradual improvement in the potential of the well. Before the stimulations the well only yielded about 1.5 l/s with 150 m draw-down. From Tulinius et al. (1996)*.*

2.3 High-temperature examples

The Krafla geothermal power plant in NE-Iceland, which has been in operation since 1977, now produces electricity at a rate of 60 MW_e. Krafla is a high-temperature system inside the active Krafla volcanic complex in the NE-part of the volcanic zone of Iceland (see Fig. 1). Reservoir temperatures in the Krafla-system range from 210 to 340°C. About 30 production wells have been drilled in the area to date and a large part of these have been stimulated at the end of drilling. The stimulation operations have almost exclusively involved cold water injection/circulation, with intermittent periods of thermal recovery used in many cases (F). Inflatable packers and high pressures have not been employed in the Krafla stimulations (one exception). During such stimulation operations the drill string is kept in the well, or drill pipes without a drill-bit or drilling motor are placed at a desired depth (usually near bottom), and the injection/circulation alternated from being through the drill-string to being through the annulus between drill-string and borehole walls. After such cooling episodes injection is stopped to allow the well to heat up.

A good example from Krafla is well KJ-14, which was drilled to a depth of 2100 m in 1980 (Stefánsson *et al.*, 1982). At the end of drilling circulation losses were only about 4 – 8 l/s. During 3 days of stimulation, which included about 12 hours of heating up, circulation losses increased to about 40 l/s (see Fig. 5). Following the stimulation operation the transmissivity of the reservoir around the well was estimated as $khg/\upsilon = 3{\cdot}10^{-4}$ m^2/s, which indicated that well KJ-14 would be the most productive well drilled in Krafla up to that time. This was confirmed during production testing of the well when it yielded about 15 kg/s of steam.

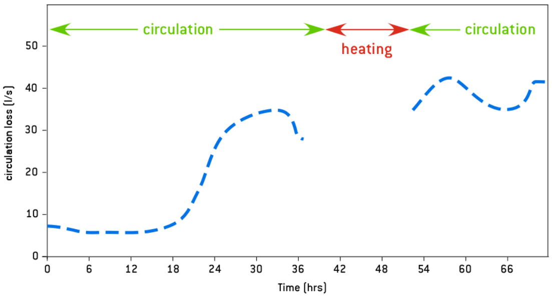

Figure 5. Circulation losses during stimulation of well KJ-14 in Krafla, NE-Iceland, at the end of August 1980. Based on Stefánsson et al. *(1982).*

The successful stimulation of well KJ-14, as well as other such high-temperature cases, has been partly attributed to the opening of pre-existing fractures by thermal stresses as well as creation of new fractures by thermal cracking. This is in addition to the reopening of feed-zones clogged by drill cuttings. It may be mentioned that Flores *et al.* (2005) present the results of a comparative, techno-economic study of different well stimulation techniques, partly based on information on stimulation operations in the Krafla field. They show that thermal fracturing is potentially the most attractive, but least understood, stimulation technique.

The Hengill volcanic system, which lies in the volcanic zone of SW-Iceland some 30 km east of Reykjavík, is another area were intense high-temperature drilling has been ongoing during the last decades. Three geothermal production fields are associated with the Hengill system; (1) the Nesjavellir field where geothermal production started in 1990 and a 120 MW_e electrical and 290 MW_t thermal power plant is now in operation, (2) the Hellisheidi field where a 90 MW_e electrical power plant will start operating in 2006 and (3) the Hveragerdi field that is utilized for different direct purposes by the local community.

Stimulation procedures comparable to those used at Krafla have been used for many of the wells drilled at Nesjavellir and Hellisheidi, i.e. cold water injection/circulation with intermittent thermal recovery periods for a few days at the end of drilling. Recently the stimulation procedures have been modified in order to increase their potential for success. This involves continuing the stimulation of wells after drill rigs have been removed, often for a few weeks. Thus much longer heating and cooling periods can be realized, resulting in greater thermal stresses with more stimulation potential. In this case the cold water is injected through the well-head.

This modified stimulation procedure has been applied to some wells in the Hengill region, in particular wells with lower than average injectivity at end of drilling. One example is well HE-8, which was drilled to a depth of a little over 2800 m in 2003 (Björnsson, 2004). This is one of the deepest wells drilled in Iceland to date. The injectivity of the well at end of drilling was of the order of 1 – 2 (kg/s)/bar. After standard stimulation procedures involving a few heating/cooling cycles, as described above, well HE-8 was allowed to heat up for about 3 months. Following this 50 kg/s af 20°C water were injected into the well for about two weeks, which concluded the stimulation of the well. Pressure transient testing at the end of the stimulation program indicated an injectivity of 6 – 7 (kg/s)/bar for the well, a quite drastic improvement from the injectivity estimated at the end of drilling.

Again the stimulation of well HE-8 is partly attributed to the reopening of feed-zones clogged by drill cuttings and partly to increased near-well permeability resulting from thermal stresses/cracking. The re-opening of clogged feed-zones is believed to be particularly significant when high-speed bottom hole drilling motor assemblies are used instead of conventional drilling methods, as the former method produces smaller drill cuttings. This may explain 50-75% of the stimulation in the case of well HE-8.

A more recent Hengill example involves well HE-21, which was drilled to a depth of 2100 m in the Hellisheidi field in early 2006. The drilling of this well concluded without a significant loss of circulation. At first the well was stimulated for two days through a few cycles of cold water circulation and heating, during which injection rates varied between 40 and 70 l/s, with injection pressures as high as 5 bar. After the drill rig had been removed, and the open section of the well had been allowed to heat to 250-320°C, stimulation operations were continued. This involved two periods of cold water injection lasting 24 and 40 hours, respectively.

Data from the stimulation program for well HE-21 have not been fully analyzed yet, but a gradual rise in injectivity was observed, from near zero to 30 l/s. It may also be mentioned that the well was imaged by an acoustic televiewer, which revealed many near vertical fractures of variable orientation. Continuous thermal cracking over long depth sections was also seen.

At least three of the recent drilling and completion/stimulation operations in the Hengill geothermal region have interestingly generated substantial microseismic activity, detected by the national seismic network operated by the Icelandic Meteorological Office (see http://www.vedur.is). These are the two wells discussed above, wells HE-8 and HE-21, in addition to well NJ-24, which was drilled in 2005 in the Nesjavellir field. The first two cases will be discussed further below.

2.4 Results

During stimulation operations success can often partly be attributed to the re-opening of feed-zones, or fractures, that have been blocked by drill cuttings during drilling. In low-temperature situations this occurs when reservoir pressure is lower than the pressure of the water column in the well being drilled, a situation that can be avoided by air-lift aided drilling (see (A) in section 2.1 above). Such an unbalanced pressure situation is also the case during most high-temperature drilling operations and feed-zone blocking appears to be particularly severe when drilling motor assemblies with high penetration rates are used, as has been mentioned.

Besides re-opening (cleaning) of feed-zones blocked by drill-cuttings, stimulation operations often result in additional improvement in well injectivity and productivity. This ranges from no improvement to an improvement that is commonly by a factor of 2-3. In exceptional cases even greater improvement is realized. Such “secondary” stimulations are attributed to the creation of new hydrological connections to permeable structures not intersected by the well in question, either through the removal of scale-deposits in fractures or through the opening of existing fractures, or even creation of new ones, through hydraulic or thermal stresses.

A higher “secondary” stimulation success ratio has been realized in the younger Quaternary formations of Iceland than in older Tertiary rocks. This is partly because fractures tend to be sealed in older formations in contrast with the younger ones. Yet it is also certain that crustal stress conditions play a key role here as in general in geothermal activity in Iceland and elsewhere. This has neither been studied systematically nor quantitatively in Iceland as of yet. More successful stimulation operations are to be expected where favourable stress conditions prevail, such as in the Quaternary regions of Iceland.

No clear picture has emerged on what geological conditions are most favourable for stimulations in high-temperature situations in Iceland. A clear correspondence between injectivity at the end of a stimulation operation and the productivity of a high-temperature well does not exist, in contrast to low-temperature wells where a simple one-to-one relationship exists. This can be clearly seen in Table 1 below, which shows relevant data for a number of production wells drilled in the Reykjanes high-temperature field in extreme SW-Iceland, where a 100 MW_e electrical power plant started operation in May 2006. The table seems to indicate that high injectivity wells have a productivity that is even higher than predicted by injectivity, while the wells with the lowest injectivity have even lower productivity indices.

Table 1. Information on geothermal production wells in the Reykjanes high-temperature field in SW-Iceland (II_1 = injectivity index at the end of drilling, II_2 = injectivity index at the end of stimulation operations and PI = productivity index based on production testing). Based on Hjartarson and Thórhallsson (2006).

Well	Depth (m)	Temp. (°C)	II_1	II_2	PI
RN-10	2050	310	-	6.6	2.3
RN-11	2250	295	-	>10	10
RN-12	2510	290	-	8-9	20-40
RN-13	2460	290	-	4-5	1-2
RN-14	2310	290	6	6-7	-
RN-15	2510	280	3.5	4	1
RN-16	2630	220	1.2	2	-
RN-18	1820	>285	5	5.4	1.5
RN-19	2250	250-260	5	5	-
RN-21	1710	275	6	13	6
RN-22	1680	305	10	10	15
RN-23	1920	305	-	38-48	50
RN-24	2110	>275	-	10-20	38

3. Monitoring

3.1 Well/reservoir monitoring

Emphasis is placed on careful well- and reservoir monitoring during stimulation operations in Iceland, both for the purpose of assessing the progress and results of the operations and to extract information on relevant reservoir properties as well. Tómasson and Thorsteinsson (1978), Tulinius *et el.* (1996) and Björnsson (2004) provide examples were such reservoir monitoring data is interpreted in the same manner as conventional pressure transient data. The following are the main parameters monitored during geothermal well stimulation operations in Iceland:

(1) Injection flow-rate, injection/well-head pressure or water level and injection temperature.

(2) Down-hole pressures with electronic or mechanical instruments. This was done as early as in the 1970’s in the Reykir field (see above).

(3) Temperature- and pressure profiles for wells being stimulated.

(4) Pressure interference in selected monitoring wells, as well as flow monitoring for near-by production wells. See example in Fig. 3 above.

(5) Monitoring of well injectivity/productivity through repeated step-rate tests.

Not all of these items are monitored in every stimulation program, what is monitored is dictated by the scale of a program and often limited by various technical aspects. Monitoring item (1) is, of course, rudimentary, while item (2), if monitored, provides the most valuable information. Item (3) is used to locate the feed-zones involved.

3.2 Seismic monitoring

Seismic monitoring is generally not applied in geothermal stimulation operations in Iceland. Yet, micro-seismic monitoring has been implemented in conjunction with three geothermal injection projects. They are the following:

(a) A low-temperature reinjection experiment was conducted in the Laugaland field in central N-Iceland from late 1997 through 1999 (Axelsson *et al.*, 2000). During the experiment 6 – 21 kg/s of 15-20°C water were injected into two low permeability wells at well-head pressures of up to 28 bar. Part of the experiment involved the installation of an automatic network of six ultrasensitive seismic monitoring stations around the field, which was expected to detect all seismic events, down to size M_L = -1, caused by the reinjection. No such events were detected, however, indicating that either the pressure increase at depth in the fractured Laugaland reservoir was not sufficient to cause earthquakes, or that the deviatoric stresses needed to trigger such events had already been released through two decades of hot water production and greatly varying reservoir pressure at Laugaland.

(b) The Svartsengi high-temperature geothermal field in SW-Iceland is utilized for co-generation of heat and electricity. Portable seismographs were operated around the field for 4 months in 1993 in order to monitor microearthquake activity throughout a reinjection test during which up to 30 kg/s of about 100°C water were injected by gravity into well SG-6 (Brandsdóttir *et al.*, 2002). No detectable earthquakes occurred within the Svartsengi field during the test and it was concluded that the pressure changes resulting from the injection were probably well below the level needed to induce seismicity. The more than 20 bar draw-down in the field has reduced pore-pressure and consequently increased rock strength, which in-turn may have raised the fracture limit of rocks in the Svartsengi system.

(c) During the summer of 2004 a 20-station seismic array was deployed around the Krafla field with the purpose of monitoring seismic activity before, during and after a 10-day break in reinjection into well K-26 (Lees *et al.*, 2004). Work on the data collected is in progress, it aims at using various seismic data processing techniques, on the high-quality data collected, to map the main subsurface fracture system of Krafla. Natural seismic activity at Krafla is not high at the present time and most of the events recorded did appear to be related to the reinjection, even though a clear relationship between changes in injection rates and seismicity did not emerge.

Even though seismic activity has not been specifically monitored during the stimulation operations discussed here seismic activity, associated with such operations, has been detected by the national seismic network as already mentioned.

During the drilling and stimulation of well HE-8 in the Hellisheidi field, which has been described above, 22 small earthquakes were detected, both at end of drilling in July and August 2003 as well as during the stimulation attempt in November the same year (Björnsson, 2004). A total of 18 quakes were detected during the July-August period and 4 in November, in a 2x2 km area surrounding the well (see figures 6 and 7) at a depth between approximately 4 and 6 km. As the quake activity correlates strongly with the injection activity, it is concluded that fluid pressure changes inside the local reservoir fracture network have triggered these quakes, i.e. it is suspected that the water pressure exceeded the minimum horizontal stress. The exact nature of the quakes is to be defined, however.

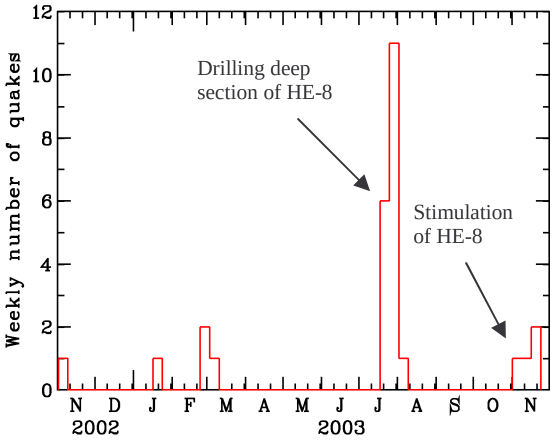

Figure 6. Weekly number of quakes in a 2x2 km area surrounding well HE-8 in the Hellisheidi field during drilling and stimulation. From Björnsson (2004).

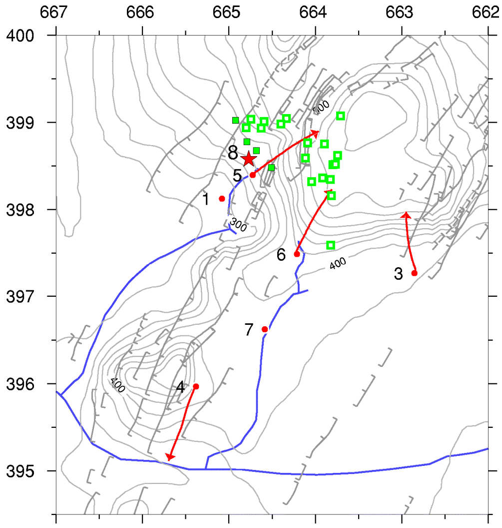

Figure 7. Well locations and quake epicenters near well HE-8 in the Hellisheidi field during drilling and stimulation. Wells are shown by red squares, quakes in July and August 2003 by open green boxes and in November by filled green boxes. From Björnsson (2004).

The correlation also implies that sufficient permeability, and direct pressure communication, exists between the two best feed-zones of well HE-8 at 1350 and 2000 m depth, on one hand, and the general 4-6 km depth of the quake centers, on the other hand. Large normal faults near well HE-8 that dip a few degrees to the east are suspected as likely surfaces of quake generation. The 4-6 km depth of penetration of fluid pressure changes suggests a considerably deeper geothermal reservoir than previously assumed.

An effort was recently made to better understand the coupled effect of current subsurface stress and the permeability distribution to cold water injection into well HE-21 in the Hellisheidi field, discussed above. As the well was flushed by cold water at completion several small quakes were located in the area. When cold water injection was repeated during a later stimulation phase (see above) no quakes were detected during 24 hours of injection. During a third injection test two mobile seismic stations were set up in the area for increased accuracy, onset of seismic activity was observed after more than 24 hours of injection. The activity continued for the remaining 40 hours of injection. Around 80 events were detected in the field data and interpretation is ongoing.

Quake epicenters during stimulation of well HE-21 are located at 3-6 km depth, substantially deeper than the water injection interval between 1 and 2 km depth, approximately. These data suggest that there is pressure communication between this injection interval and 3-6 km depth. If correct, the thermal resource may have considerable higher generation potential than currently assessed by models that reach a maximum of 2-3 km depth.

4. Concluding remarks

This paper has reviewed the stimulation techniques utilized in geothermal fields in Iceland. High-pressure injection through inflatable packers, is not as commonly applied in low-temperature wells as was the case 2-3 decades ago, partly because air-lift aided drilling has reduced the need for such stimulations. This method still has great potential in particular cases, however. Stimulation of high-temperature production wells through cyclic cooling and thermal shocking/fracturing has proven to be effective, especially when the stimulation period can be extended for several weeks after the drill rig has been removed. Seismic monitoring should be more commonly applied during long stimulation- and injection operations, since it may provide highly valuable resource information. The same applies to reservoir monitoring, such as interference monitoring.

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