

PRESSURE CHANGES IN ICELANDIC GEOTHERMAL RESERVOIRS ASSOCIATED WITH TWO LARGE EARTHQUAKES IN JUNE 2000

Grimur Björnsson, Ólafur G. Flovenz, Kristjan Saemundsson and Einar H. Einarsson

Orkustofnun
Grensasvegur 9
108 Reykjavik, Iceland
e-mail: grb@os.is, ogf@os.is, ks@os.is, eh@os.is,

ABSTRACT

Two large (6.6) earthquakes, which occurred on June 17 and 21 2000 in S-Iceland, caused some major changes in the pressure of several geothermal reservoirs. The pressure changes correlate near perfectly with the focal mechanism of the two quakes, i.e. reservoir pressure increased in areas of rock compression and decreased where dilation took place. Several secondary changes were also observed. The most pronounced are in wells, which happened to tap directly from the two 15-25 km long N-S striking fractures, formed by the quakes. Near instantaneous pressure drop of 1-10 bars were common in those wells. Few reservoirs maintain pressures higher than before the quakes and few appear permanently reduced in pressure. This is suggested to be a consequence of stress driven permeability changes. Some reservoir may have changed from being confined to unconfined as a result of stress changes. Pressure changes were observed up to 75 km away from the seismic epicenters. Many of those wells are now, 6 months after the quakes, still recovering. Also of interest are a few post-quake events of pressure rise/decline, presumed to be a consequence of stress relaxation in the crust. We believe that the currently evolving database of tectonically induced pressure changes in S-Iceland is significant for the general understanding of fractured geothermal reservoirs as well as for seismology.

INTRODUCTION

Seismic and geothermal activity are well known and closely related features in the Icelandic geological setting. This fact is in particular important for the domestic geothermal industry, which maps lineaments of active faulting to be used as a primary target in drilling. Unlike in many other countries, some Icelanders even consider seismic activity as a resource with very positive economical output in the long run.

The two June 2000 quakes caused intense and instantaneous pressure changes in many geothermal wells within the S-Iceland seismic zone. In fact so intense that it became immediately evident that a major hydrological event was taking place. The Geoscience Division of Orkustofnun therefore established, already on June 18, two groups of field observers. Their task was to record status of all wells possible in the seismic area and locate new surface fractures. At the same time, in-house scientist set up the necessary file and map environment to store and make preliminary analysis of the collected field data. This turned out to be work intensive assignment, due to the large volume of collected data and due to a second large quake, which struck on June 21. Furthermore, historical data strongly indicated that the seismic activity might continue with similar events farther to the west. High priority was therefore given to the installment of data logging stations, to continuously record well pressure in the western half of the seismic zone.

This paper gives a preliminary analysis of some of the hydrological data collected. The main geological and geothermal features of the S-Iceland seismic zone are described, with a special emphasis on the unusually high density of wells targeting visible seismic fractures in the area. Maps of pressure changes associated with the two quakes are presented and their close correlation with the focal mechanism of the quakes is discussed. Pressure changes in a few wells, where data loggers recorded these events continuously, are shown. Examples of pressure changes in wells in July to September 2000 are also presented.

GEOLOGICAL/GEOTHERMAL SETTING

Figure 1 shows a simplified geological map of Iceland, together with location of high and low temperature fields. The island is unique for its location astride the Mid-Atlantic spreading ridge and, furthermore, on the top of a mantle plume. These two dynamic systems greatly influence the country with

their rich supply of magma, tectonic faulting and spreading.

Spreading in Iceland is confined to the western and the eastern neovolcanic zones. They are characterized by more than 20 volcanic centers and their associated fissure swarms, mainly normal faults striking between N and NE. The high temperature reservoirs (>200°C) are all located inside these volcanic centers. The volcanic zones tend to shift ~100 km to the east every 2 million years. Most likely as a consequence of a stationary mantle plume and relative drifting of the Mid Atlantic ridge to the WNW. This explains the present location of the eastern neovolcanic zone. It also explains the existence of two transverse zones of high seismic activity the south and to the north (Figure 1).

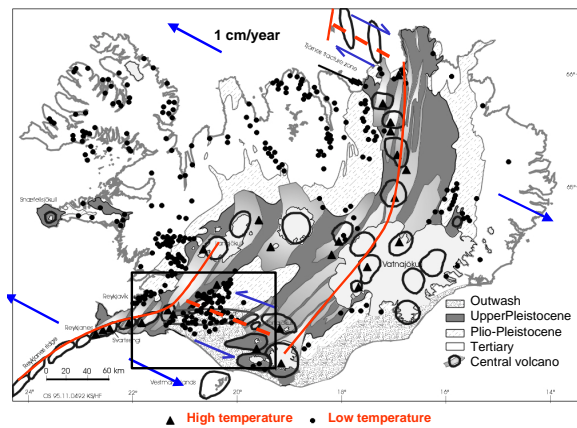


Figure 1. Simplified tectonic and geological map of Iceland. The S-Iceland seismic zone is within the rectangle. Arrows indicate directions of spreading. From ..

The S-Iceland seismic zone is rich in low-temperature resources (<150°C). Regional temperature gradient is high, typically in the range of 80-120°C/km in the uppermost 1 km. Although the general direction of the transverse motion is between ESE and WNW, the seismic fracturing is mainly seen on surface as right-lateral slip on vertical surfaces striking NS. Conjugate ENE-WSW left lateral faults occur less frequently. Around 25 such active fracture systems, younger than 10,000 years, are presently known. These are commonly 10-15 km long although longer ones exist.

Many of the active fracture systems are characterized with geothermal activity on the surface. The best known is the Great Geysir, from which the international name geyser is derived. Geological mapping shows clearly that the S-Iceland geothermal reservoirs and the seismic fracture systems are one and the same feature. The hot springs thus commonly line up along the fracture systems, together with cold water springs. Due to density effects, temperature

reversals are common. Often hot water floats on top of the colder fluid. Mixing of the two water types is a rule and great care must therefore be put into casing jobs for new, hot water wells. Also there are indications that the end points of the active fracture systems are hotter than their center segments.

Figure 2 presents in a histogram the depth of 420 geothermal wells, deeper than 100 m, drilled to date in S-Iceland. Due to high permeability and therefore rapid convection of hot fluid in the seismic fractures, most of the geothermal wells are only 200-600 m in total depth. Local farm communities, thanks to low cost and high success rate, therefore drill many. Their output capacity ranges from 5 to 130 l/s of 50 to 150°C water. Approximately 70 low-temperature heating services rely on these wells and natural flow from hot springs. A total production rate figure is, however, not available. Guessing an average pumping capacity of 10 l/s for each of the heating services, results in 700 l/s total.

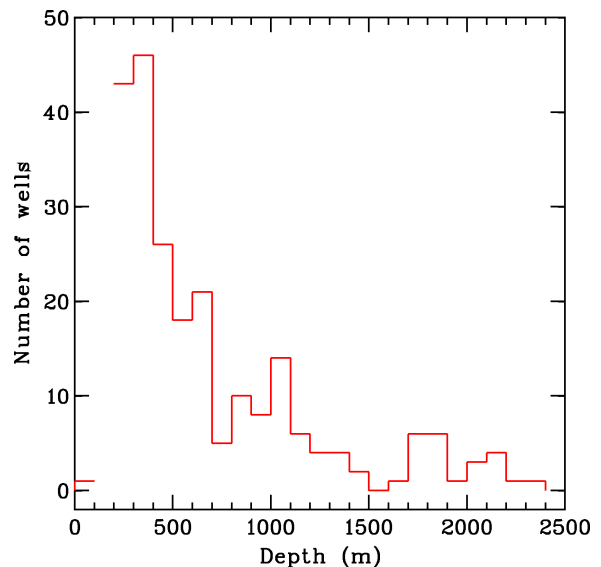


Figure 2. A histogram showing wells deeper than 100 m in S-Iceland.

Figure 3 shows the location of wells in S-Iceland presently recorded in a database of Orkustofnun. Also shown are seismic fractures mapped prior to the June 2000 quakes. The figure demonstrates clearly a unique feature of the S-Iceland lowlands; namely that possibly no other major seismic zone in the world is so densely and uniformly covered with water wells.

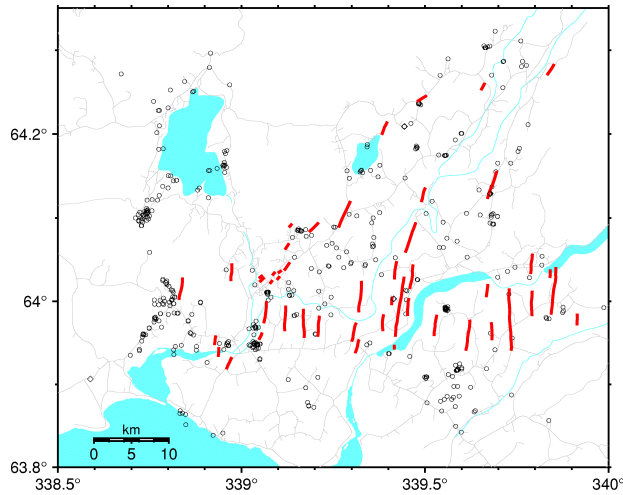


Figure 3. Location of water wells (circles) and active fracture systems (thick lines) in the S-Iceland seismic zone. Fracture data from Saemundsson and Einarsson (1987).

FOCAL MECHANISM AND PRESSURE CHANGES

Figure 4 presents a location map of the S-Iceland seismic zone together with a number of selected wells, to be discussed in this paper. Also shown are quake epicenters between June 17 to June 23, size 2 or greater. The two largest quakes are marked and also location of ruptured grounds. Both events are observed as right lateral, strike-slip origin. Ground ruptures group on two lines from south to north. Total length of these structures is 20 to 30 km.

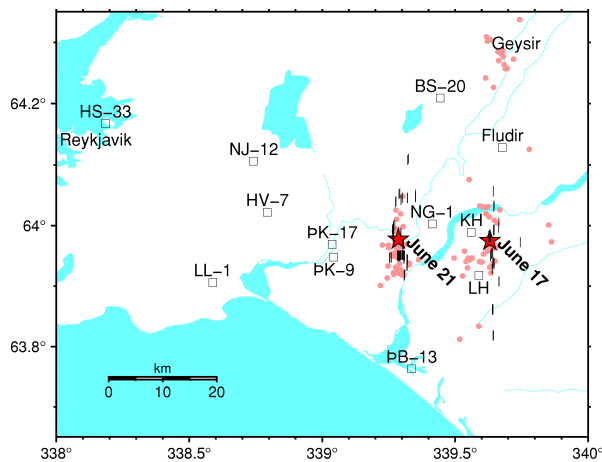


Figure 4. Location map of the June 17 and 21 quakes (stars), selected epicenters (gray dots), ground ruptures (lines) and wells of continuous pressure monitoring (boxes).

The first conclusion drawn from the waterlevel measurements is a map, showing near perfect correlation of pressure changes to the focal

mechanism of the June 17 quake (Figure 5). The four quadrants of rock compression and dilation show clearly up in the pressure pattern of wells. Note that the hydrological changes locate perfectly the quake epicenter.

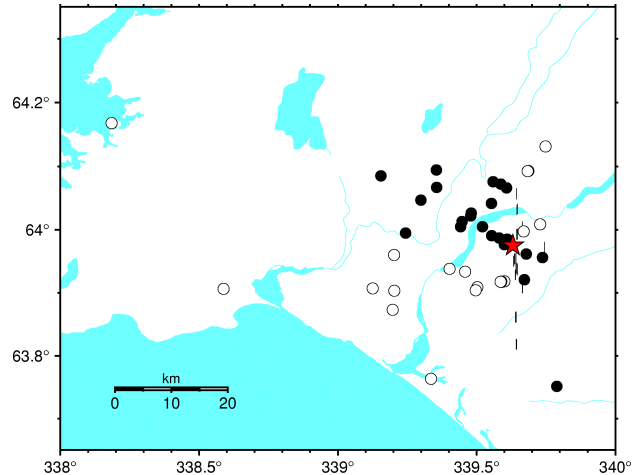


Figure 5. Wells of increased (bullets) and decreased pressure (open circles) after the June 17 quake. Quake epicenter is shown as a star and surface ruptures by lines.

The June 21 quake induced very similar response of well pressures to stress changes (Figure 6). Water level increased and many wells became artesian in the two quadrants of compression, relative to the quake epicenter. On the other hand, waterlevel of wells fell substantially in areas of dilation, in some cases drying out productive wells.

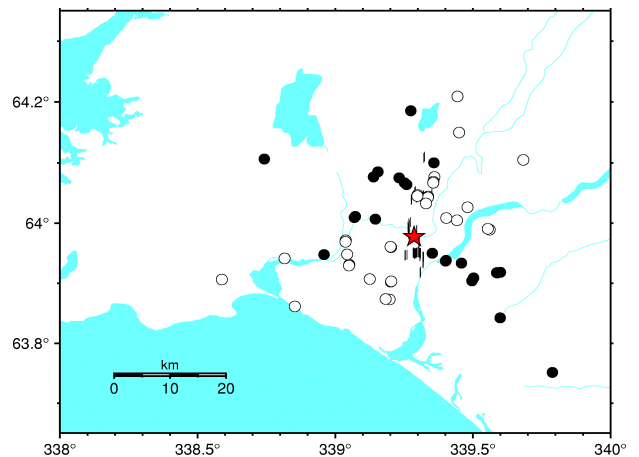


Figure 6. Wells of increased (bullets) and decreased pressure (open circles) after the June 21 quake. Quake epicenter is shown as a star and surface ruptures by lines.

Many well owners suffered damage from these two events. A few wells either quenched in artesian flow or waterlevel fell beneath existing submersible pumps. More damage, however, resulted from the sudden burst in artesian flow of wells connected to pump stations. Well cellars for example became over flooded and both electrical motors as well as electrical switches were damaged. Old asbestos pipes, supplying hot water, were twisted and broken. Fortunately, the strong technical basis and experience of the Icelandic geothermal industry allowed for rapid repair of the structural damages. Therefore, most heating services went back to normal operation within a few days.

PRESSURE CHANGES DURING THE QUAKES

This section describes pressure changes in wells marked on Figure 4. Most are monitored by regional heating services as a part of their reservoir management program. The respective well owners made both manual and automated records available to this study.

Well HS-33 is the westernmost well of those shown on Figure 4. It is located near shore, to the north of Iceland capital Reykjavik. The well is tapping a fractured system striking NS. Figure 7 shows its waterlevel history around the June 17 quake.

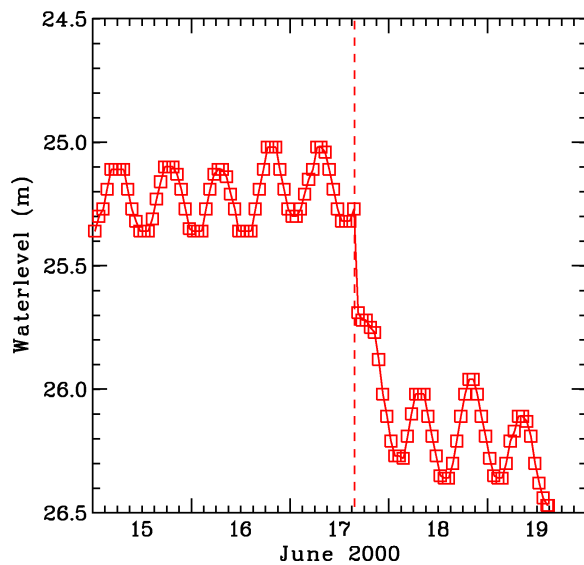


Figure 7. Waterlevel history of well HS-33 in Reykjavik, adjacent to the June 17 quake. Dashed line shows time of quake.

Despite the dominating tidal signal, a sharp and immediate waterlevel drop of 0.5 m is recorded. A closer look also shows that there is an additional tail of pressure decline for the next 2-4 hours after the quake. These two events combined result in a 1 m

waterlevel change, when measured peak to peak between the high tides adjacent to the quake.

The Reykjavik Energy Inc. is the owner of well HS-33 and also well NJ-12 in the Nesjavellir high-temperature field. The company installed a data logger in well NJ-12 on June 20, in order to monitor possible stress related pressure changes in this large and important reservoir. The June 21 quake is therefore properly recorded in this well. This time the crust stress is increased, raising the waterlevel accordingly. Like in well HS-33, an immediate pressure change of 0.5 meters concurs the quake, followed by a 3 hour long post-quake rise period of 0.3 meters. The reservoir pressure then gradually recovers to former pressure during the 9 days of available data.

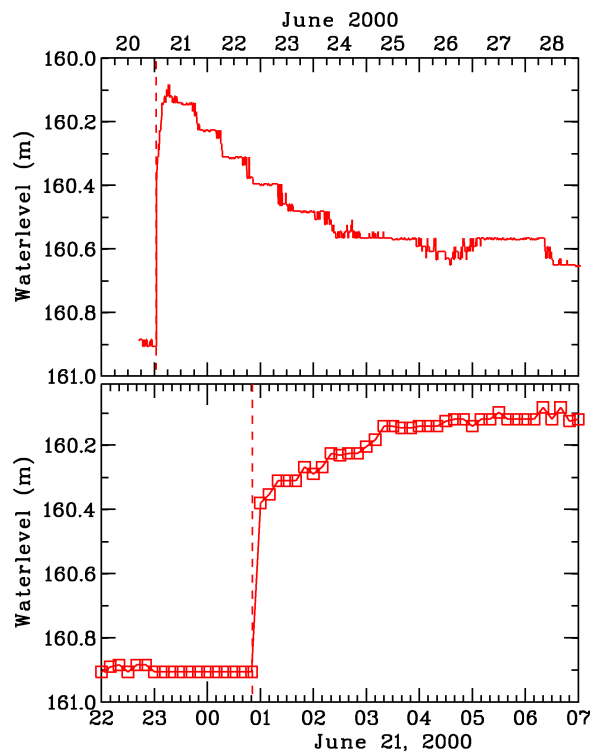


Figure 8. Changes in waterlevel of well NJ-12 associated with the June 21 quake. Upper graph time scale is 9 days whereas the lower is only 9 hours. Dashed lines show time of quake.

It should be noted that well NJ-12 is located 34 km from the June 21 quake while well HS-33 is 75 km from the June 17 event. A similar pressure change is, however, observed in both. Many reasons may explain why the Nesjavellir response is so mild. Most likely are different storativities of the two reservoirs. The Reykjavik reservoir is fully liquid water saturated while Nesjavellir has a substantial volume of boiling pore fluid. The steam “cushion” in Nesjavellir may therefore both balance the reservoir

pressure by condensation and, furthermore, slow down the pressure recovery after the quake.

Figure 9 shows pressure change of observation well PK-9 caused by the June 17 quake. Two types of pressure events are evident in the graph. An immediate pressure drop of 0.2 bars accompanies the quake. Then an unexplained pressure rise follows, despite relatively stable production from the reservoir. Reservoir modeling is needed here to determine if the post-quake pressure rise is due to production or an indicator for rapid stress concentration, finally triggering the June 21 quake.

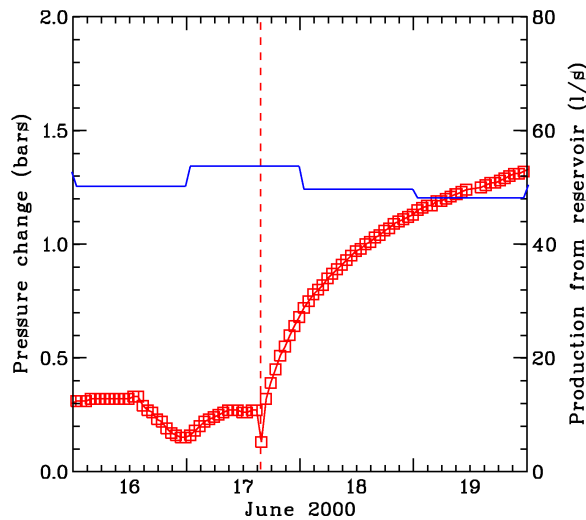


Figure 9. Pressure (squares) and reservoir production history (line) of observation well PK-9, next to the June 17 quake. Dashed line shows time of the quake.

Pressure data is also available for well PK-9 during the June 21 quake. A sharp pressure drop of 0.6 bars is observed immediately but no definite sign of a post-quake change similar to that trailing the June 17 event. Of interest are also pressure spikes near noon on June the 20th and after midnight on June 23rd.

Drastic pressure pulse shocked the Kaldarholt geothermal reservoir on June 17, where well KH-34 is located (marked KH on Figure 4). This was so drastic that wellheads were torn of observation wells and the remaining reservoir pressure became sufficient to spin a submersible pump and thus generate electricity into the national grid. A data logger was attached to this observation well on June 19th, in order to measure the pressure behavior of the reservoir. Figure 11 shows the response of the well to the June 21 quake. A very sharp pressure drop of 0.35 bars accompanies the quake, immediately followed by 10 minutes recovery of 0.1 bar. Note that the wellhead pressure prior to the quakes was less than 0.5 bars.

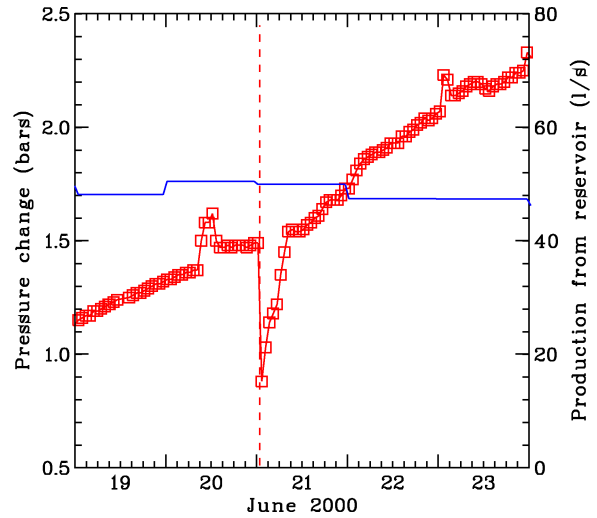


Figure 10. Pressure (squares) and reservoir production history (line) of observation well PK-9, adjacent to the June 21 quake. Dashed line presents the time of quake.

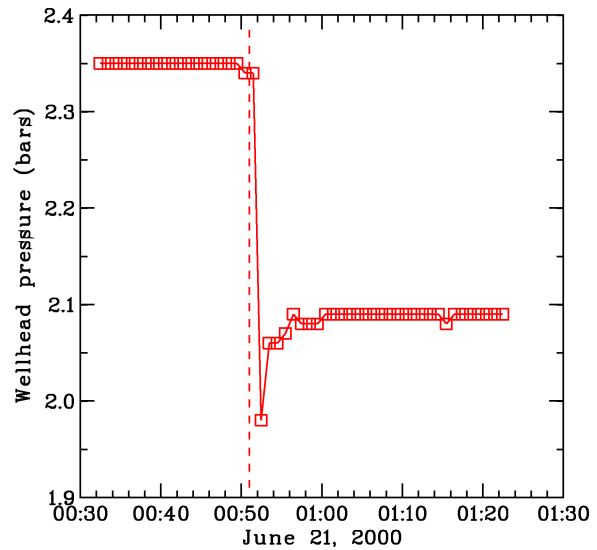


Figure 11. Pressure of observation well KH-34, around the June 21 quake. Dashed line shows time of the quake.

The Kaldarholt reservoir declined gradually in pressure after June 17 as a consequence of the enormous hot water discharge resulting from the June 17 compression. We estimated the total flowrate on June 18 in the neighborhood of 50 to 100 l/s of 40 to 60 °C water. This excludes invisible discharge to the groundwater lens. No other reservoir in S-Iceland came near this in tectonically induced artesian flow. Figure 12 presents the pressure recovery until mid July. It can be argued that all the recovery belongs to the June 17 event, as the first and the last portion of the pressure data can be fitted by a simple second order polynomial. The June 21 quake is therefore only a temporary perturbation lasting for 3 to 4 days.

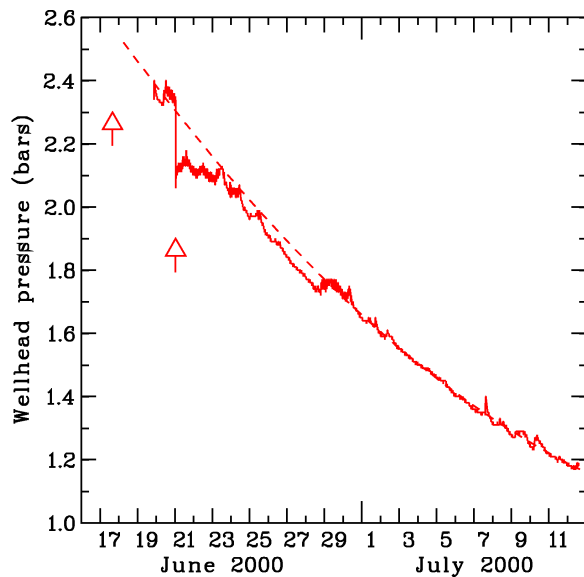


Figure 12. Pressure recovery of observation well KH-34, after the June 2000 quakes. Arrows show time of the quakes. Dashed line is a second order polynomial of the form: $P_0 = 2.6 - 0.082xN + 0.0011xN^2$ where P_0 is wellhead pressure and N is number of days after the June 17 quake.

One of the greatest pressure change, observed after the June 2000 quakes, affected the Laugaland field (marked LH on Figure 4). This highly permeable but low storage, fracture dominated system is located near the June 17 epicenter. Figure 13 shows the pressure and production history of this reservoir for all the year 2000. A minimum quake related pressure decline of 6 bars is clearly evident in the data, but may have reached as high value as 10 bars initially. The heating company who operates this field, suffered great structural damage. This drew attention from their reservoir during the first 24 hours after the quake. We can though confirm that the local, 240 m long submersible pump was non operational until June 18th afternoon, when the reservoir pressure had recovered sufficiently to sustain normal production.

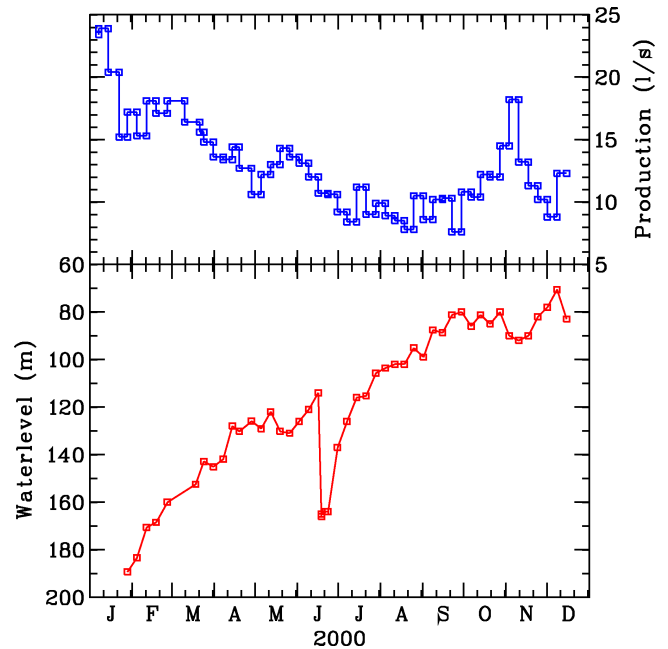


Figure 13. Pressure and production history of well LN-4 in the Laugaland field. Note that the long term pressure change results from annual cycling in production.

POST QUAKE CHANGES

This paper presents only a fraction of the field data now acquired in the S-Iceland seismic zone. In general we observe that the most disturbed wells have a pressure recovery period of a few weeks to a few months. Some are even still recovering. Well casing depths have proven to be important factor. For example we have monitored two wells with shallow and deep casings, like 10 m apart. The shallower well is picking up meteorological changes, like heavy rain, but not the deep one. Basically this means that free surface (groundwater) systems are unsuitable for pressure monitoring whereas the deeper, confined systems are much more likely to show pressure correlation with crustal stress changes.

In addition to this general pressure recovery trend, a few interesting pressure transients have been collected. Figure 14 presents the most interesting ones. The data is sampled in wells PK-17 and LL-1, located in the western sector of the seismic zone (Figure 4). Three sharp pulses of pressure rise are evident. Of special interest is a 6 hours time lag between the August 8 pressure pulses in the two wells. These wells are 20 km apart (Figure 4). Some type of viscous stress change and displacement may explain the time lag.

Of special interest is a permanent August 8/9 pressure decline in the Osabotnar high permeability and storage reservoir, which well 17 intersects.

According to our local sources, exploratory wells some 500 m to the west of ÞK-17, became artesian in that same week. Possibly the reservoir found there a discharge channel. The pressure of well ÞK-17 also changed to 24 hours cycling period after the August 8 event. The cycling correlates with daily, sun driven cycling of a major, glacier fed river in that same region. Altogether, these data suggest that the Osabotnar reservoir established a connection to the surface groundwater and river systems as a consequence of stress changes in early August. Or in other words, that the reservoir changed from a confined type to a free surface one.

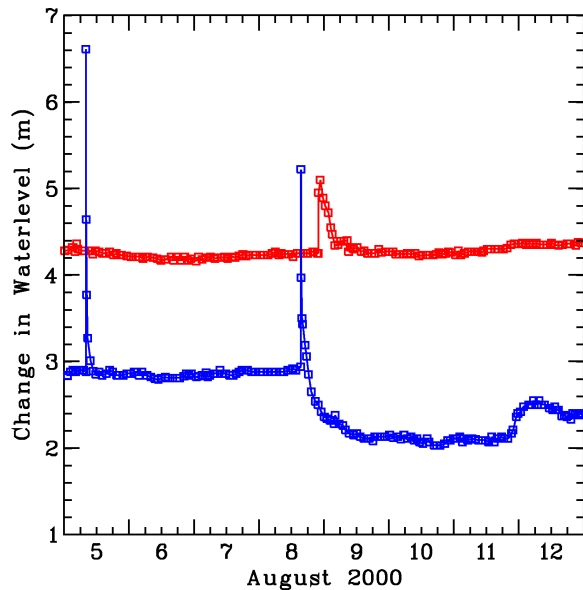


Figure 14. Pressure spikes observed in wells ÞK-17 and LL-1 in August 2000.

A POSSIBLE QUAKE PRECURSOR

A strong debate is going on among seismologists about the existence of earthquake precursors. Unfortunately this paper continues to add heat thereon. The reason is a “verbally recorded” June 16 pressure transient in the Fludir geothermal system, which is located at the northern tip of the June 17 seismic fracture (Figure 4). A data logger has been operated continuously in the field since 1995, measuring flowrate, temperature and wellhead pressure of a few artesian wells connected to a pumping station. The field is very productive and yields a maximum 80 l/s of 100°C water at 0.4 bars wellhead pressure.

Figure 15 shows the response of this reservoir to the June 17 quake. Note the drastic 0.3 bars pressure drop right after the quake. This transient is then trailed by a rapid pressure increase, which 14 hours later exceeds the pressure transducer maximum of 1 bar. At the same time many formerly extinct hot

springs in the area became active. This pressure change appears permanent and may have increased the generating capacity of the reservoir by 30-40%. Undoubtedly this means that the new, post quake stress field is favorable in terms of the large-scale reservoir permeability.

Unfortunately, the logger at Fludir has been programmed as a smart one, i.e., it makes 15 minute averages from a round buffer which stores the pressure every 5 seconds. The logger modem stalled on June 17 and was reset on the 18th. When a service man made drawings at the site, a strong, low-pressure spike was observed in the afternoon of June 16. Paper graphs were made and passed around but then unfortunately lost. This spike is not visible on Figure 15, after the averaging. In addition to this spike, a low pressure (<0.2 bars) warning message was sent by the logger to a pager, the only one of its kind in the 5 years continuous operation of the logger. But timing of this warning message was neither saved to a file for later confirmation.

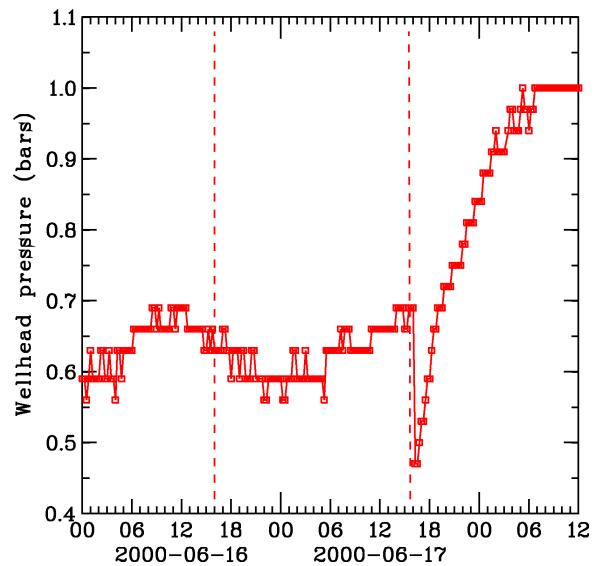


Figure 15. Pressure of the Fludir reservoir during the June 17 quake. Dashed lines show time of low-pressure warning message (left) and the quake (right).

The June 16 pressure spike, if true, can be considered as a strong and easily detectable precursor to the June 17 quake. We find hard to reject it as a human or device error. The reason is another pressure spike, which was collected by our own data logger in well ÞB-13 in Þykkvabær on September the 16th, 2000 (location on Figure 4). This spike is shown on Figure 16. The well remains idle after showing very non-linear permeability during production test in 1999 at high drawdown (>350 m). After pumping 10 to 15 l/s of 80°C water for a few days, the flow suddenly quenched to practically zero, indicating a closure of

the permeable zone. The well is cased to 470 m depth and its only feedzone is associated with a fracture at 1170 m depth. This fracture is striking NS and dipping to the west according to a televiewer log. The fracture can be interpreted as the southern tip of the June 21 fracture system (Figure 4).

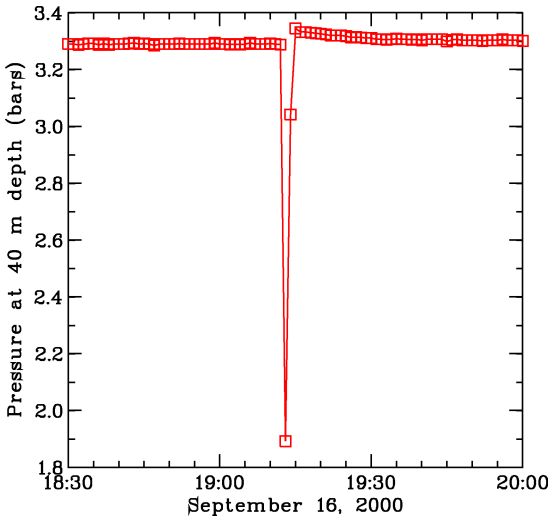


Figure 16. Low-pressure spike observed in well PB-13 in Thykkvibaer.

Three important conclusions can be drawn from Figure 16, assuming that the pressure spike is relevant as a quake precursor. Firstly that its time constant is on the order of 5 minutes. Secondly that fluid is rapidly drained from this low storage but highly permeable, fracture hosted geothermal system. The drainage is best explained by a sudden change of the fracture porosity, but why is beyond the scope of this paper. Thirdly that no large quake followed this particular event.

Figure 17 shows finally the pressure data of well PB-13 at a finer pressure scale. The low-pressure spike is here clearly overshoot and then trailed by a recovery period, lasting some 25 minutes. The shape of the recovery tail strongly suggests that this pressure signal is true and correctly observed by the on site data logger.

CONCLUSIONS

Some main conclusions drawn from quake related hydrological data in S-Icelandic geothermal reservoirs are:

- The S-Iceland seismic zone is unique for its numerous and widely distributed geothermal reservoir and wells. Many wells intersect active fractures generated by former seismic events.
- Quake induced pressure changes correlate near perfectly with quake focal mechanism.

- Pressure changes are recorded up to 75 km from the quake epicenters. The pressure change is typically in the range of 0.1 to 1 bar, but may have exceeded 10 bars in few cases.
- These pressure changes appear to be made up of two components. Firstly an immediate change, which then is trailed by 2-4 hours of additional pressure change.
- Crustal stress changes also have influenced the large-scale permeability of a few geothermal systems. For the time being it appears that these reservoirs have improved in long-term performance. Some reservoirs may have transformed from confined to unconfined status.
- A quake precursor may have been recorded by a data logger in the Fludir system on June 16. If true, it is suggested that such precursors have the shape of a very sharp pressure decline lasting only few minutes.

The authors are convinced that the hydrological data presented here is valuable for the general understanding of fractured geothermal reservoirs. As the reservoirs clearly respond to quakes and stress related features one might even conclude that hydrology is relevant and an important factor in seismological research.

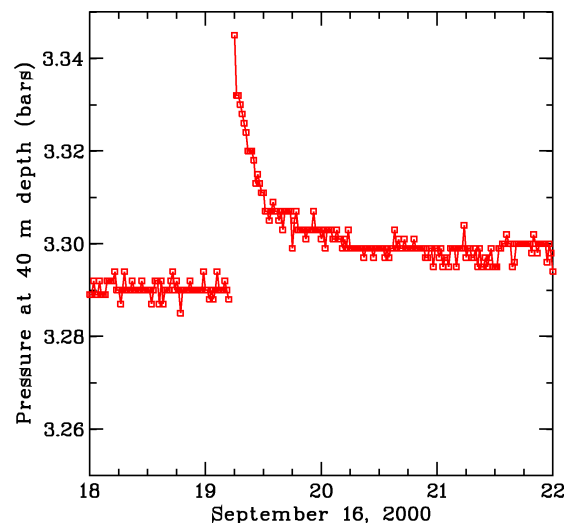


Figure 17. Recovery of a low-pressure spike observed in well PB-13.

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To be completed....

Smith, J. S., Bloggs, R. T. and Jones, E. R. (1974), "Magnetic Anomalies in Geothermal Systems," *Journal of Fluid Mechanics*, **254**, 73-79. Please include full title of journal articles or other references, journal, volume, date, pages.