Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Induced Seismic Activity during Drilling of Injection Wells at the Hellisheiði Power Plant, SW Iceland

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Keywords: induced seismicity, triggered seismicity, injection, plate boundary

ABSTRACT

Hellisheiði geothermal power plant is a 303 MWe and 133 MWth plant in SW Iceland owned by Reykjavík Energy. Production started in 2006 and increased gradually to full capacity in early 2011. The production field is to the south of Hengill central volcano, which is located at a plate-boundary triple junction in SW Iceland.

The Hengill-Hellisheiði area is seismically active, characterized by individual swarms that may last for five years or more and with a recurrence time of 20 to 40 years. The largest individual earthquakes have reached magnitudes of 5.5 Ml. Several structural lineaments can be observed, the most distinctive features being NE trending grabens, crater rows and hyaloclastite ridges.

The present main injection site for the geothermal fluid from the power plant at Húsmúli was taken into use in Sept. 2011 with full scale injection of 550 L/s. An intense seismic swarm followed with 4 earthquakes reaching magnitudes over 3 Ml (the largest was Ml = 3.8). The drilling of the injection boreholes at Húsmúli started in 2007 and seismic events associated with the drilling and testing of the boreholes were observed. Seismic activity was also observed during drilling and testing of production holes in 2003 to 2007.

Temporary seismic networks were installed around injection borehole HN-17 during its drilling. A seismic swarm associated with circulation loss of drilling fluids during the drilling was therefore well monitored by the temporary networks as well as the regional SIL network operated by the Meteorological Office. The earthquakes are mainly located north of the borehole with depth ranging from 0 - 3 km.

1. INTRODUCTION

Preparations for the Hellisheiði power plant started in 2001, but prior to that some exploration wells had been drilled (Jónasson, Þ., 2014). The first production holes, HE-holes, were drilled in 2001. Some of them are in Sleggjubeinsdalur, a small valley northeast of the power plant, but Húsmúli form the western side of that valley (Figure 1).

The re-injection site for the geothermal fluid was planned to the southwest of the power plant in Svínahraun and Gráuhnjúkar. In these areas 9 holes were drilled during the years 2001 to 2007 (HN-1 to HN-8 and HN-10 in Figure 1). The area turned out to have production capacity and it was decided to develop a new injection site at Húsmúli. Drilling started in Húsmúli in 2007 and the last hole was drilled in 2011. The holes in Húsmúli are HN-09, HN-11 to HN-17 or 8 holes.

When production started in 2006 a slightly increased seismic activity was observed with only small earthquakes associated with the injections in Gráuhnjúkar which reached maximum rate of about 350 L/s. At Húsmúli, seismic swarms were observed during drilling and testing of all re-injection holes. Furthermore, seismic activity at Húsmúli coincides with drilling of the productions holes in Sleggjubeinsdalur from 2003 to 2007, in particular drilling and testing of HE-8 (Björnsson, G., 2004).

In September 2011 a full scale re-injection started in Húsmúli with an injection rate of up to 550 L/s. An intense seismic swarm was triggered and the largest events were felt in neighboring communities. The activity decreased significantly during the following year. Gradually, the injectivity at Húsmúli has decreased and presently the former re-injection site at Gráuhnjúkar is also in use (Gunnararsson, G., 2013).

2. GEOLOGIC AND TECTONIC SETTING

Húsmúli is an interglacial lava shield located in the western part of the Hengill central volcano. The Hengill-Hellisheiði region is where the South Iceland Seismic Zone (SISZ), the Western Volcanic Zone (WVZ) of Iceland and the Reykjanes Peninsula (RP) oblique rift meet (Figure 1). Húsmúli is the oldest geological formation in the Hengill area with an age of about 115.000 years (Sæmundsson, K. et al. 2010). The formation can be traced in boreholes below the superimposed hyaolclastic units to the east of it where it is cut by normal faults with more than 180 m throw to the east. The bottom of the formation west of the faults is deduced to be just below the present surface surrounding Húsmúli based on drillings and gravity interpretations (Guðmundsson, M.T. and Högnadóttir, Þ., 2004)

The RP is an oblique rifting segment of the plate boundaries in Iceland and the tectonic character of Húsmúli has is similar to the tectonics of the peninsula. The most striking features on the RP are NE trending grabens and volcanic fissures producing crater rows and hyaloclastite ridges. Superimposed on these structures are N trending faults of varying age showing right-lateral, strike slip displacements. These are caused by earthquakes which can reach magnitudes of 6.3 Ml on the peninsula (Halldórsson, P., 2014).

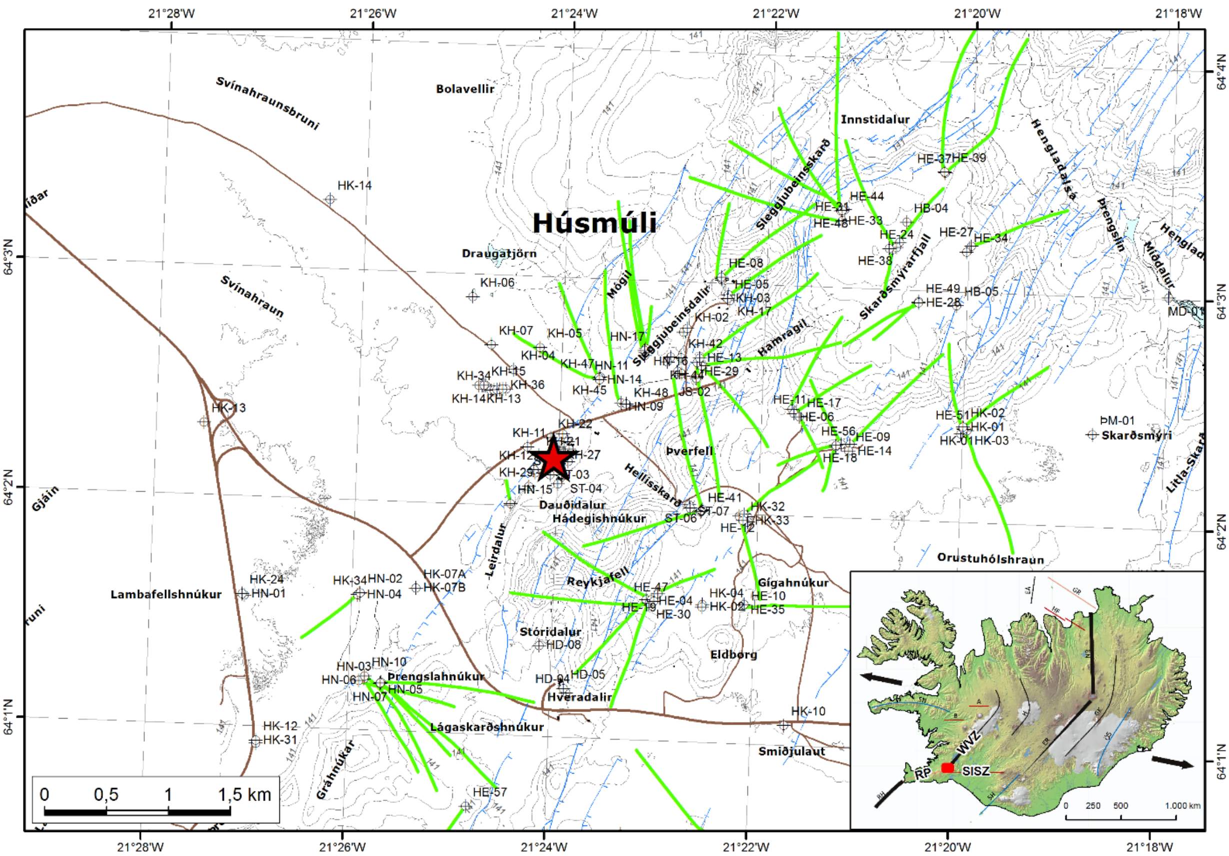

Figure 1: Borehole traces (green), major faults (blue) and names of localities in the Húsmúli area. The red star shows the location of the Hellisheiði power plant. The inset figure shows the plate boundaries and volcanic zones in Iceland and the direction of the plate movements (arrows). The location of Húsmúli is shown with a red dot.

On the RP the regional minimum stress is consistently close to horizontal around the NW direction (Kristjánsdóttir, S., 2013, Keiding, M. et al., 2009) The maximum stress is either close to horizontal around NE or vertical and then maximum and intermediate stresses are probably similar in size. The larger features of the tectonics in Húsmúli are in accordance with this. (Several other lineaments are observed which can be explained as Riedel shears (Khodayar, M., 2013). The stress field is probably also affected by the South Iceland Seismic zone and the Western Volcanic Zone giving rise to a more complicated pattern than within the zones themselves. Complicated seismic and tectonic patterns have also been observed farther to east within the Hengill-Hellisheiði area (Ágústsson, K., 1998, Hjaltadóttir, S. and Vogfjörð, K., 2009).

3. BACKGROUND SEISMIC ACTIVITY

Three short period seismometers were installed in Reykjavík in 1951 and 1952, and prior to that only one instrument was sporadically in operation from 1909. Four more stations were installed in 1958 to 1966 in Reykjavík and south, east and north Iceland. Installation of a new regional network started in 1973. It was operated by the Science Institute of the University of Iceland and the construction was based on experience gained by operation of temporary networks in cooperation with the Lamont-Doherty institute (Einarsson, P. and Björnsson, S., 1987). The network covered the Hengill-Hellisheiði area quite well. The present regional SIL network came into operation in 1991 and from 1993 Hengill-Hellisheiði area has been relatively well covered (Bödvarsson, R. et al., 1999).

Húsmúli is seismically active and seismic swarms occurred there during an episode of seismic activity in the Hengill-Hellisheiði area between 1993 and 1998 (Figure 2). The largest events during this period were of magnitude 3.4 Ml. These earthquakes, as well as recent ones, have been relocated using double difference algorithms (Vogfjörð. et al., 2012). The activity is mainly on N-S near vertical faults. These lines are the same as were active during the full scale re-injection 2011 and the focal mechanisms were then mainly strike slip, but several normal and reverse displacements were also interpreted (Bessason, B. et.al., 2012).

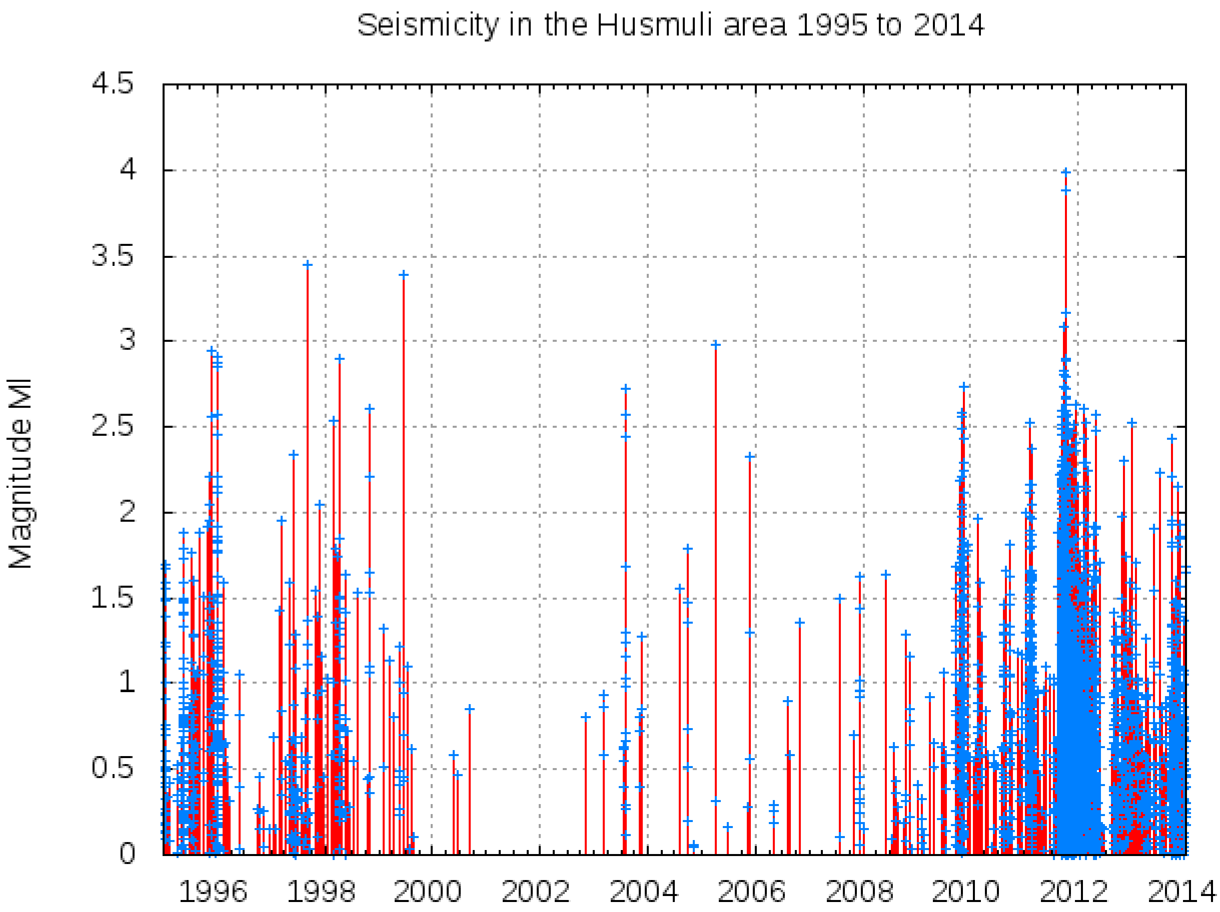

Figure 2: Overview of the seismic activity in the Húsmúli region from 1995 to 2014. The data is from the catalogue of the Icelandic Meteorological office.

Based on historical records and measurements prior to installation of the SIL network, episodes similar to the one that occurred between 1993 and 1998 seem to have occurred several times in the area with a recurrence interval of 20 to 40 years (Halldórsson, P., 2014, Halldórsson, P. et al., 2013). Whether the activity has been similar in Húsmúli during these episodes as in the 1993 to 1998 episode is not known.

From 2003 most of the swarms have occurred simultaneously with drilling and testing of boreholes.

4. DATA AND ANALYSIS

The data that have been analyzed in connection with the seismic activity during drilling of the injection wells are basically of four types from different partners:

1. Seismic data
2. Injection data including rate, pressure and temperature in the injection boreholes
3. Drill logs
4. Pressure and temperature in monitoring boreholes

4.1 Seismic monitoring

The SIL network, which is operated by the Icelandic Meteorological Office, has been in operation all the time the operations in the Hengill-Hellisheiði area have been ongoing.

Reykjavík University, Uppsala University and Massachusetts Institute of Technology operated a temporary seismic network, the HR-network, on the Reykjanes Peninsula 2009 to 20013. One purpose was to investigate the crustal structure of the peninsula and it is a part of a project in which Iceland GeoSurvey participates: Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization.

During drilling and testing of HN-17 Iceland GeoSurvey operated 5 stations, the ÍSOR-network, located in the neighborhood of the borehole.

Location of the seismic stations is shown on Figure 3. They consisted of Guralp and RefTek recorders and Guralp CMG3ESP and Lennartz 5 s and 1 s sensors. The sampling rate of the Iceland GeoSurvey array was 250 samples/s and 100 samples/s for the others. These stations have not all been in operation simultaneously, but larger events are often observed on more than 20 stations.

The models that have been used for location are described in Vogfjörð. K. S., et al. (2012). The results presented here are based on single event locations and the location uncertainty is in most cases less than 500 m, both laterally and in depth.

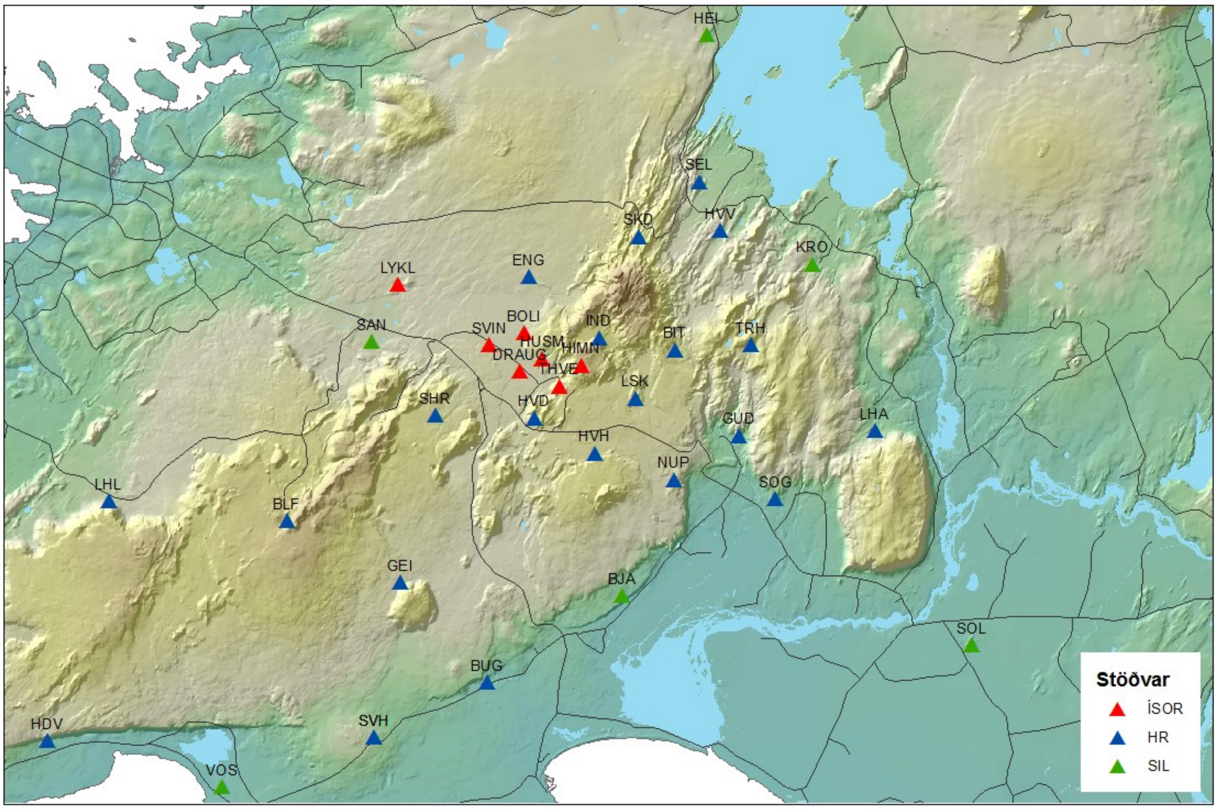

Figure 3: The location of seismic station used for analyzing the earthquakes during drilling of HN-17. The temporary networks were from Iceland GeoSurvey (ÍSOR), Uppsala University, Reykjavík University and Massachusetts Institute of Technology (HR). The permanent regional network is operated by the Icelandic Meteorological Office (SIL).

4.2 Injection data

Reykjavík Energy monitors the injection rates, well-head pressure and temperature of the injected fluid. These parameters have been logged with 10 min intervals from September 2011. Flow tests of the boreholes after drilling are finished and other injections have been made by Iceland GeoSurvey and Reykjavík Energy. During drilling of HN-17, geothermal fluid was injected in other boreholes in the area

4.3 Drill logs

During drilling, circulation losses, among other parameters, are monitored by the drilling company.

4.4 Pressure and temperature in monitoring boreholes

The injection borehole, HN-17, is close to HN-12 and HN-16 (Figure 4). To prevent drill cuttings from entering the aquifers and to enhance circulation recovery during drilling of phase 3 of HN-17, water was injected into HN-12 and HN-16. Pressure and temperature were monitored by Iceland GeoSurvey during this period and the following test period in surrounding boreholes. The holes that were monitored were HN-13, HN-14, as well as the injection hole HN-16.

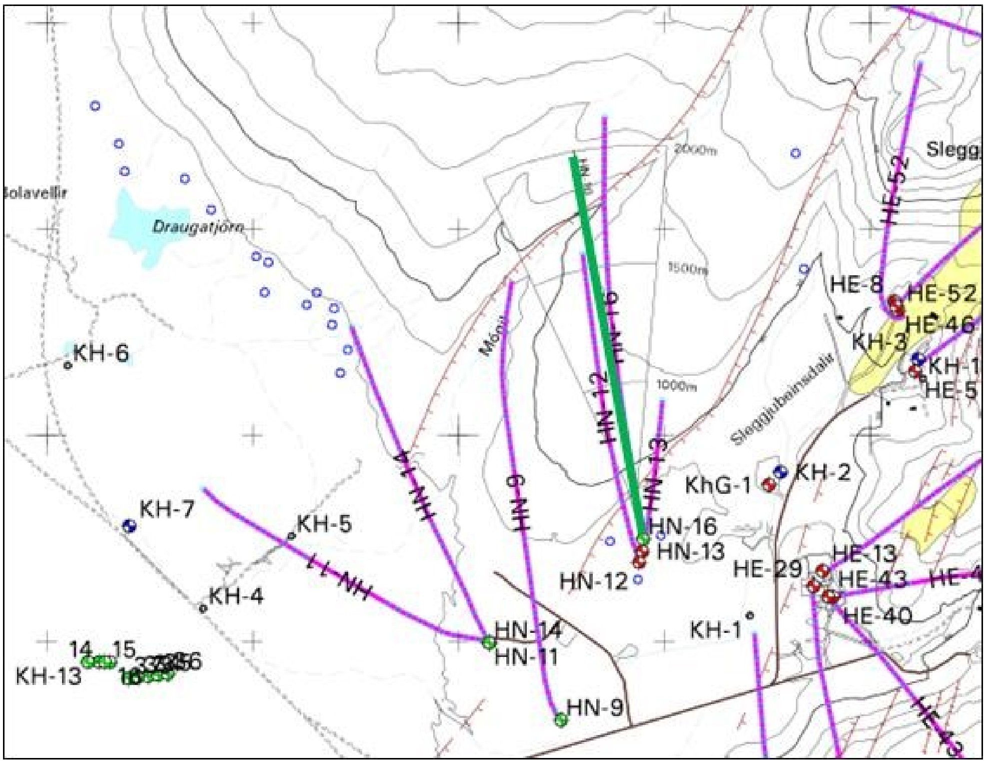

Figure 4: The locations and paths of boreholes that were monitored (HN-13, HN-14 and HN-16) during drilling of phase 3 of HN-17. The path of borehole HN-17 is shown with a green line. Simultaneous to the drilling injections were made in HN-12 and HN-16.

5. THE SEISMIC ACTIVITY DURING DRILLING OF HN-17

The drilling of HN-17 started the January 17, 2011 (Harðarson B.S., et al., 2011) and the drilling of the third phase, i.e. the production part, started on February 8th at a depth of 641 m. The drilling operations ended on February 26th and the final depth of 2200 m was reached on February 22th, 2011.

At about 11:05 on February 11th a total circulation loss of more than 60 L/s occurred at 1321 m depth. About 25 minutes later, an intense seismic swarm started (Figure 5), lasting about 24 hours (Harðarson. B. et al., 2011). Another swarm occurred on February 21st when the bottom feeders were cut. In between these large swarms, as well as on February 9th and 23rd there were periods of increased activity.

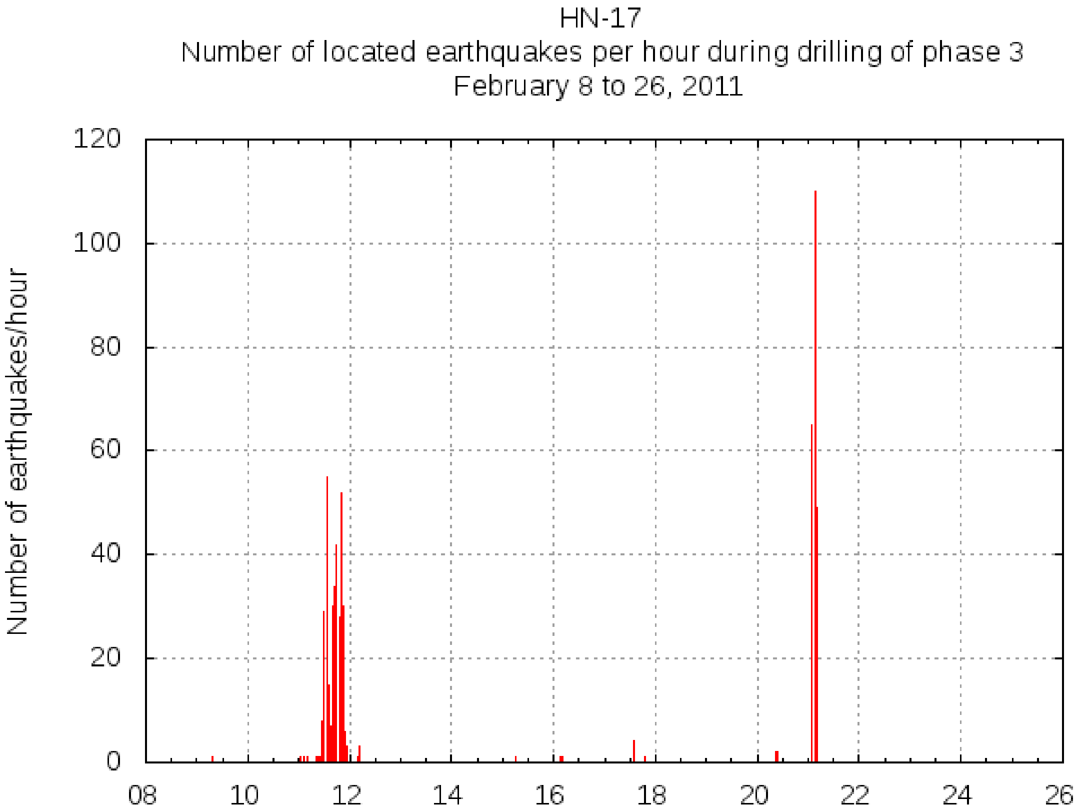

Figure 4: The figure shows number of earthquakes/hour during drilling of phase 3 of HN-17, the production part. The activity February 11 occurs when a feeder at 1321 m is cut and there is total circulation loss. The activity February 21 occurs when bottom feeders are cut.

Small circulation losses were observed at 855 m and 1028 m depth. After February 11th, circulation was only sporadically successful, so location of feeders cannot be based on the circulation losses. Temperature measurements with injections (Harðarson, et al., 2011) clearly show feeders at 900, 1320 and 2100 m depths and indications of a feeder at approximately 1700 m depth. Seismic activity occurred when the drill was at those depths.

The locations of events on February 11th and 21st, as well as the depth and distance of the earthquakes from the feeders at 1321 m depth and the bottom feeders are shown in Figure 6. On the 11th, the activated area seems to be on two separate fissures with NNW trend. The activity started on the eastern fault, but jumped to the western fault after 4 hours. The activity on February 21st filled the gap between the active areas of February 11th to some extent. Initially, the earthquakes occurred at 2.0 to 2.5 km depths from the surface. They gradually reached about 2.7 km depth in both swarms. Simultaneously, on February 11th the distance from estimated feeders to the nearest earthquakes increases from 0.3 to 1 km in 12 hours (~0.06 km/hour). This distance relation is more complicated on February 21st, but the minimum rate is about 1 km in 8 hours (~0.13 km/hour). It is difficult to estimate the velocity of the pressure front but it is on the order of 300 to 500 m/hour on the 21st.

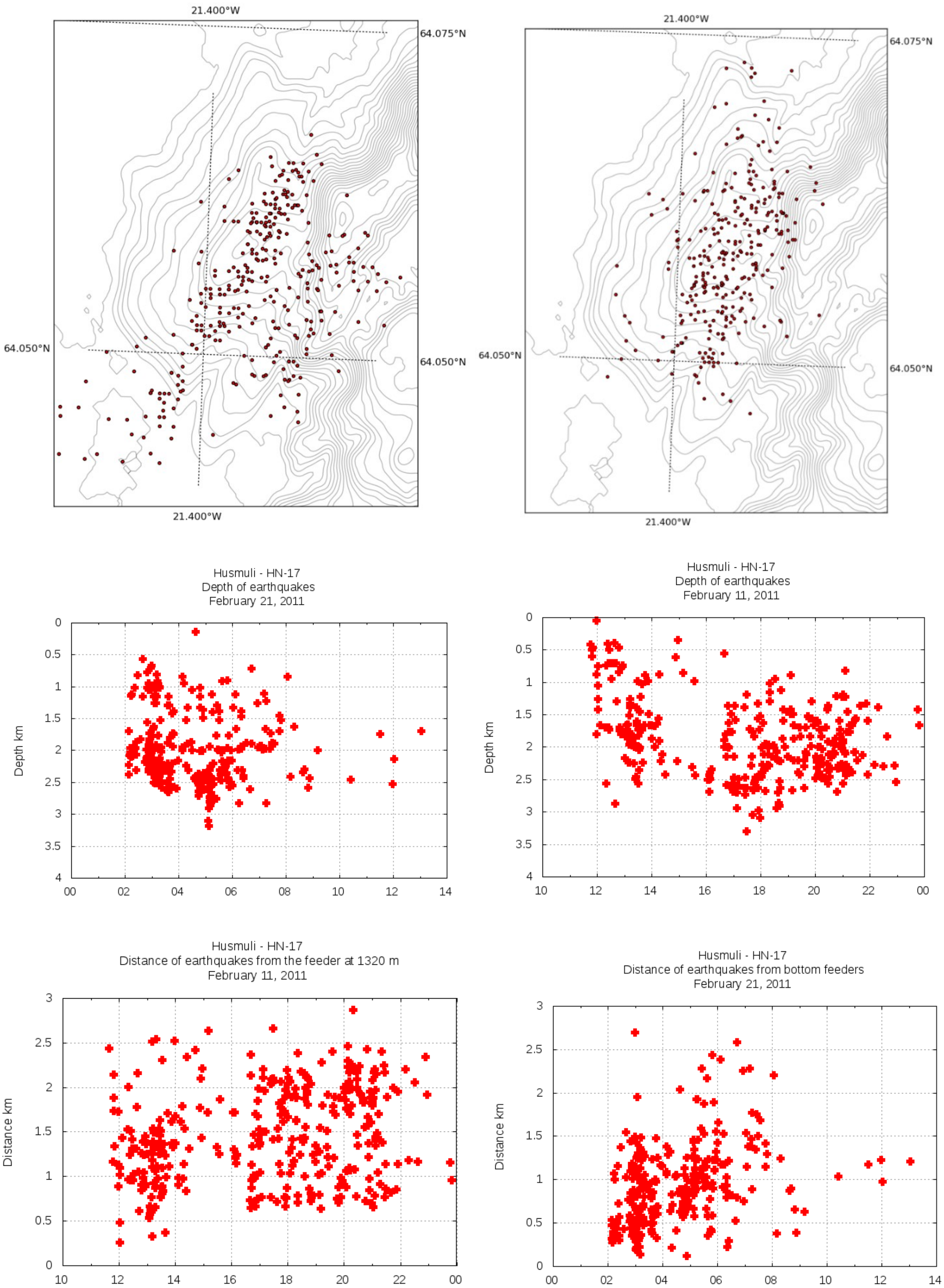

Figure 5: The top row shows the location of earthquakes February 11 (left) and February 21 (right). Below are shown the changes of depth and distance of earthquakes with time for the same two periods.

6. INJECTION, PRESSURE MEASUREMENTS AND SEISMICITY

During phase 3 drilling of HN-17, injections were made into HN-12 and HN-16, 75 L/s in each. This was an attempt to enhance circulation recovery and thereby decrease the probability that drill cuttings entered the permeable zones.

Initially, these injections did not seem to have much influence on the surrounding boreholes (Figure 7). On February 9th, some earthquakes occurred and a coseismic offset was observed in HN-14. Circulation loss of 1 or 2 L/s was observed as well as a pressure increase in HN-14. The pressure increase may be due to the circulation loss or that a connection between HN-12 and/or HN-16 on one side and HN-14 on the other was established. In the following, pressure in HN-14 increased, interrupted by coseismic pressure decrease episodes. A clear connection developed between HN-17 and HN-14 as can be seen during the tests after the drilling and injection into HN-12 and HN-16 finished. HN-13 did not experience pressure changes in phase with HN-14, but the coseismic offsets can be seen. The pressure changes in HN-16 were noisy during the injections into the hole, but on February 11th the pressure increased.

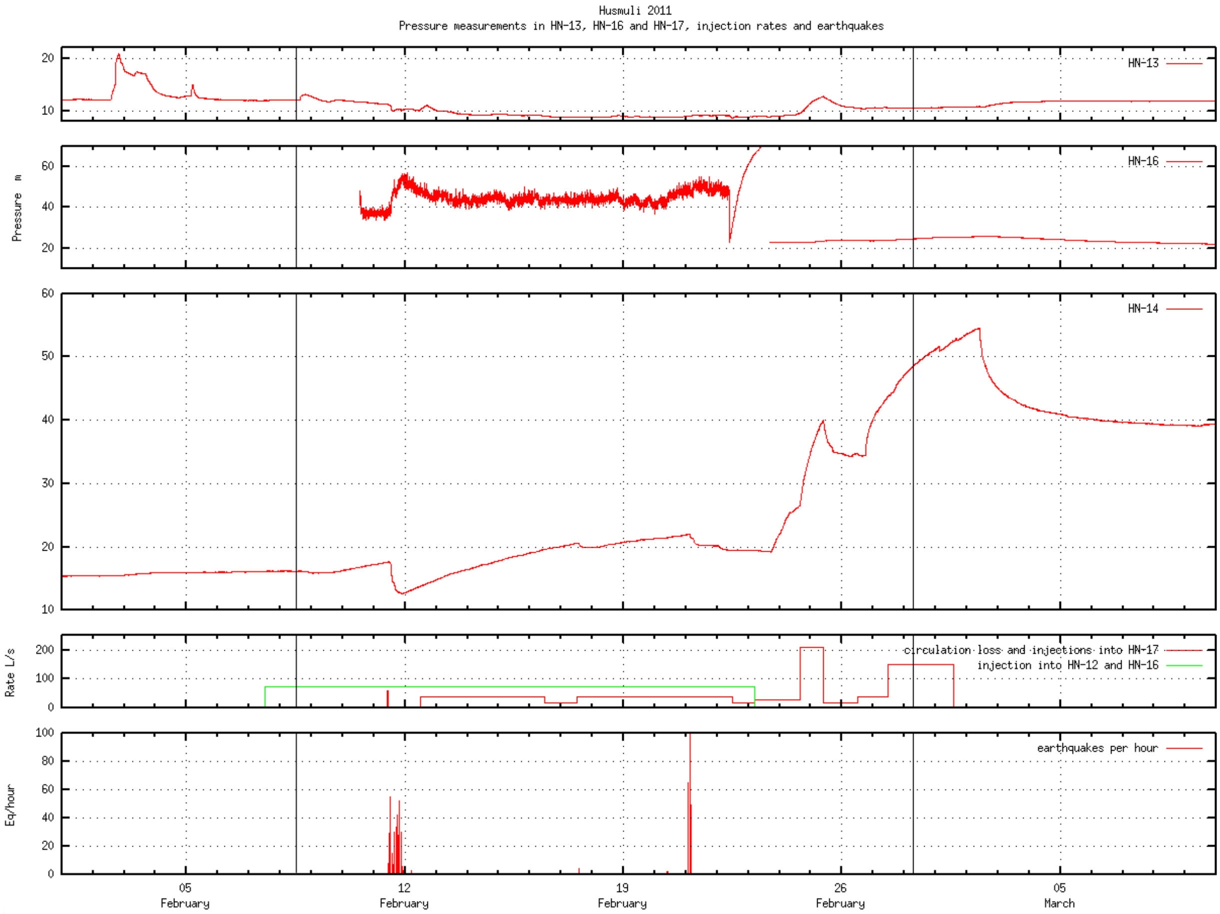

Figure 6: Pressure changes in boreholes in the vicinity of HN-17, injections and earthquakes during drilling of the production part (phase 3) of HN-17. The vertical lines show the start and end of drilling of Phase 3 of HN-17.

The injection rate in HN-17 varied from about 40 to 60 L/s after the total circulation loss at 1321 m depth. The wellhead pressure decreased on February 11th during the drilling at 10:59 and at 11:05 there was total circulation loss. Simultaneously, the moment and drilling speed increased. After that, equilibrium drilling was attempted with partial success and only occasionally drill cuttings came up. The injection rate varied between 40 and 70 l/s towards the end of the drilling.

7. DISCUSSION

The water level in the area is at approximately 200 m depth. The overpressure at the bottom of the holes during injections with no losses in circulation is between 2 and 3 MPa. With circulation losses this value is lower. The horizontal stress due to overburden can be estimated to be 10 to 20 MPa in the depth range of 1 to 2 km. The in situ tensional strength of basalt is 1.5 to 4 MPa, much smaller than the horizontal stress. In these conditions, fracking does not occur.

The orientation of the deviatoric stresses is most likely similar as on the Reykjanes peninsula, i.e. the minimum stress close to horizontal in NW direction and the maximum stress close to horizontal in NE direction or vertical. Probably, the maximum and intermediate stresses are similar in magnitude. Due to the small overpressure during the drilling and that the pattern of seismic release is consistent with the regional stresses one can conclude that these events are triggered.

According to the earthquake catalogs (historical and instrumental) earthquake unrest occurs with a 20 to 40 years interval in the Hellisheiði-Hengill area. However, the activity that starts again in 2003, only 5 years after the last seismic period, is associated with drilling.

When these conditions prevail, i.e. existing faults with different orientations and stress field where, most likely, there is little difference between maximum and intermediate stresses, faults that are activated by stress perturbations associated with injections can vary considerably in orientation although the regional stress is similar in the region. At the Krísuvík geothermal area, which is located on the Reykjanes Peninsula some 30 km west of Húsmúli, reverse, normal and strike-slip displacements are observed for events occurring on elongated swarms during short time interval (Kristjánsdóttir, S., 2013). These are zones that have usually been interpreted as single fractures but seem to be of more complicated nature. Uplift was observed at Krísuvík during summer of 2009 (Michalczewska, K. et al., 2012) which has not been explained. Possibly, pore pressure was increased and that as well as block rotations can have caused displacements on non-optimally oriented faults with respect to the regional stress field. Similar variability of mechanisms seem to occur at other geothermal areas in Iceland, e.g. Reykjanes (Guðnason. E. Á. and Ágústsson, K., 2012), Námaskarð and Þeistareykir (Hjaltadóttir, S. and Vogfjörð, K. S., 2011) in north Iceland.

8. CONCLUSION

Seismicity was triggered by less than 2 MPa overpressure during drilling of injection hole HN-17. The activity occurred on distinct NNE trending fault zones where individual faults have variable orientation as they are formed under the influence of temporally varying stress regimes caused by interactions between the South Iceland Seismic Zone, the Western Volcanic Zone and the Reykjanes Peninsula. The short time interval since the last natural seismic episode ended, the triggered activity and the low overpressure indicate that the stress is close to critical after the natural seismic episode. The pressure front seems to travel with 300 to 500 m/hour while the area that becomes relaxed increases by 50 to 150 m/hour.

9. ACKNOWLEDGEMENTS

We want to thank the Icelandic Meteorological Office for giving access to their seismic data. During operation of the network of Iceland GeoSurvey geophones were rented from the instrumental pool Loki, Iceland.

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