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Induced Seismicity during Reinjection of Wastewater in Hellisheidi Geothermal Field, Southwest Iceland

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ABSTRACT

In 2011 a new injection field was taken into operation for the Hellisheidi Power Plant in southwest Iceland. The power plant stands on the edge of the Hengill geothermal area and produces 303 MW_e and 133 MW_{th}. It started operation in 2006 and the company is required by law to inject wastewater back into the ground. Shortly after the injection started in 2011 the seismicity increased, with thousands of events being recorded by the Icelandic Meteorological Office. The majority of events were small ($M_l < 3.0$), but the two largest events reached M_l 3.8 and were widely felt in the area. An increase in seismicity had also been detected during the drilling of the injection wells, associated with the loss of drilling fluid. The area is located close to the triple junction of an oblique spreading zone (Reykjanes Peninsula), a rift zone (the Western Volcanic Zone) and a transform (the South Iceland Seismic Zone) and is naturally seismically active. The seismic events were recorded by a dense network of seismographs operated in the area by Uppsala University, MIT, Reykjavik University, the Icelandic Meteorological Office, and Iceland GeoSurvey from 2009 to 2013. By grouping the waveforms into families based on their similarity and using cross correlation we can both find more events than have previously been located and get precise time measurements allowing us to locate the earthquakes with more accuracy. By comparing seismic activity with the injection process we hope to get a better understanding of the forces at work.

1. INTRODUCTION

The Hellisheidi Power Plant started operation in 2006. It is located on the edge of the Hengill geothermal area (see Fig. 1) and produces 303 MW_e and 133 MW_{th} (ON). This makes it one of the largest geothermal power plants in the world. The plant´s purpose is to meet increasing demand for electricity and hot water for space heating in the industrial and domestic sectors (Mannvit). The power company, ON Power, operating the plant is required by law to inject all geothermal wastewater from the production back into the ground, below the groundwater table. This is also feasible to counteract the pressure drop in the system during production. The first injection field, Grauhnukar, was located to the south of the power plant. The injection wells there turned out to be hot and the area was considered to have production capacity. In light of this a new injection field was proposed to the north of the plant. The new injection wells were directionally drilled towards NW in Husmuli in the period of 2007 to 2011 and taken into operation in September 2011. Shortly after the injection started the seismicity increased, with thousands of events recorded by the Icelandic Meteorological Office (Bessason et al., 2012). The majority of events were small ($M_l < 3.0$), but the two largest events reached M_l 3.8 and were felt in neighboring communities.

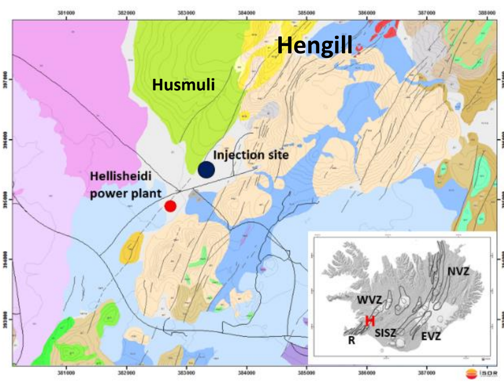

Figure 1: The Hengill geothermal area in southwest Iceland (red letter H in inset picture) is located at the triple junction of Reykjanes Peninsula (R), the Western Volcanic Zone (WVZ), and the South Iceland Seismic Zone (SISZ). The Hellisheidi Power Plant (shown with red dot on the map) is located on the edge of the system. The Husmuli injection site is shown as a blue dot to the northeast of the power plant.

An increase in seismicity was also detected during the drilling of the injection wells, associated with circulation losses of drilling fluid (Agustsson et al., 2015). Induced seismicity has been linked to production in other fields in Iceland, both high and low temperature fields. Most of these events are small, below M_l 2.0 (Flovenz et al., 2015). Most geothermal fields in Iceland are located within the volcanic zones. The Hengill geothermal area, where the Hellisheidi geothermal field is located, is no exception. It is located close to the triple junction of an oblique spreading zone (the Reykjanes Peninsula), a rift zone (the Western Volcanic Zone) and a transform (the South Iceland Seismic Zone) and natural seismic activity is high in the area. An intense swarm occured in the Hengill area in 1994 – 1998, including several swarms in Husmuli where the new injection field is located. This activity in Hengill has been linked to a possible magmatic intrusion (Sigmundsson et al, 1997). The area is characterized by NNE-SSW trending normal faults and N-S striking strike-slip faults. It is mostly hyaloclastites formed under a glacier but volcanic activity in the area is as recent as 2,000, 5,800, and 10,000 years ago.

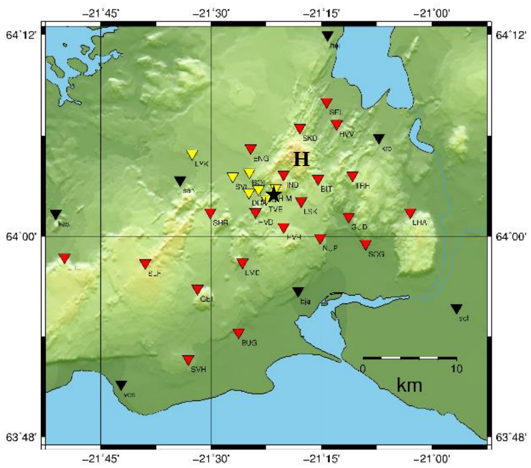

Figure 2: Map showing the station network in operation in the Hengill area from 2009-2013. Red triangles are stations from UU, MIT, and RU, black triangles are stations from the IMO network and the yellow triangles show stations from ISOR. The Hengill area is marked by the letter H and the black stars shows the approximate location of the seismic activity.

2.1 Induced seismic activity

The seismic events induced by the injection were recorded by a dense network of seismographs operated in the area by Uppsala University (UU), MIT, Reykjavik University (RU), the Icelandic Meteorological Office (IMO), and Iceland Geosurvey (ISOR) from 2009 to 2013 (see Fig. 2). The stations are located closer to the main induced activity than the IMO network stations, enabling us to locate more earthquakes and with more accuracy. By using relative relocation methods we can increase the accuracy even further.

The IMO has located around 12,000 events from the period between September 2011 (when the injection started) and June 2012. The injection is still going on but as expected the activity has steadily decreased. The events outline N-S striking faults in numerous swarms. The activity gradually migrated away from the injection wells, to the north and west (Bessason et al., 2012).

2. METHODS

Events during the injection have been located by the IMO. Using this data the earthquakes were sorted into families based on waveform similarity. Cross correlation was used to establish links between similar events, setting the cross correlation coefficient limit to 0.75 during the sorting process. Once the families have been determined the waveforms belonging to each family are stacked, giving us a mother template for each family (see Fig. 3). This has to be done for each station in the network individually. The waveforms are weighted with their signal-to-noise ratio according to Eq. 1:

$$f(t) = \frac{\sum \frac{u_i(t)}{A_i} C_i^2}{\sum C_i^2} \quad . \qquad [1]$$

f(t) is the stacked waveform of *i* events, $u_i(t)$ are the waveforms belonging to one family normalized by their maximum amplitude A_i, and C_i is the signal-to-noise ratio of the *i-th* waveform. Each template was then used to search through the continuous dataset to look for more events with similar waveform characteristics. In the search process the correlation coefficient limit was set to 0.8.

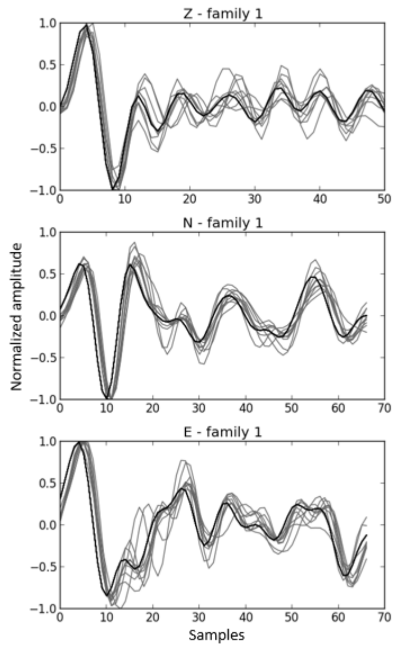

Figure 3: Example of a signal-to-noise ratio weighted stacks used as a template on station SAN. From top to bottom: The vertical component, the north component and the east component. The black line is the template waveform and the lighter grey lines are the waveforms belonging to this family. Each waveform is normalized with its maximum amplitude.

Cross correlation methods can also be used to get accurate time difference measurements between events for use in relative relocations. By performing the time lag measurements in the frequency domain the precision of the measurement can be less than the sample rate of the seismometer.

3. RESULTS

A clear relationship can be found between rapid changes in the injection rate and increase in seismicity. Fig. 4 shows the changes in the injection rate (solid line) and the magnitude of earthquakes (circles) taking place over a four day period in October 2011, about one month after the start of injection. On the evening of October 14th electrical failure caused a rapid decrease in the injection rate. This had no effect on the earthquake activity. The injection rate was quickly build up to almost the previous level, resulting in a small swarm of events. Around six hours later the injection rate fell again for unknown reasons. This immediately induced another swarm of events, including the two biggest events of the entire months´ long activity ($M_l \sim 3.8$). The operators of the Hellisheidi power plant realized the connection between the rapid changes in the injection rate and seismicity and have since then had the policy of adjusting the rate of injection gradually.

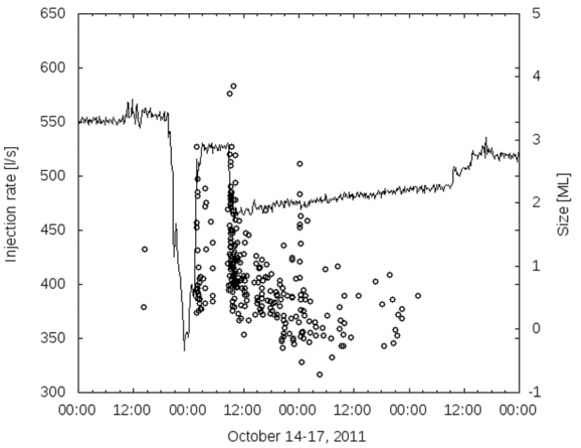

Figure 4: Injection rate and seismicity plotted together over a four day period from October 14-17, 2011. A clear temporal pattern can be seen in the seismic activity relating to rapid changes in the injection rate.

First results of using cross correlation methods to detect and locate events with a denser network indicate that we can find ten times as many earthquakes as the IMO had done with their sensitive network. Fig. 5 shows an example for one of the IMO stations, SAN. In the original family there were nine events, whereas the cross correlation found 105 events. The figure only shows the first forty events for clarity's sake.

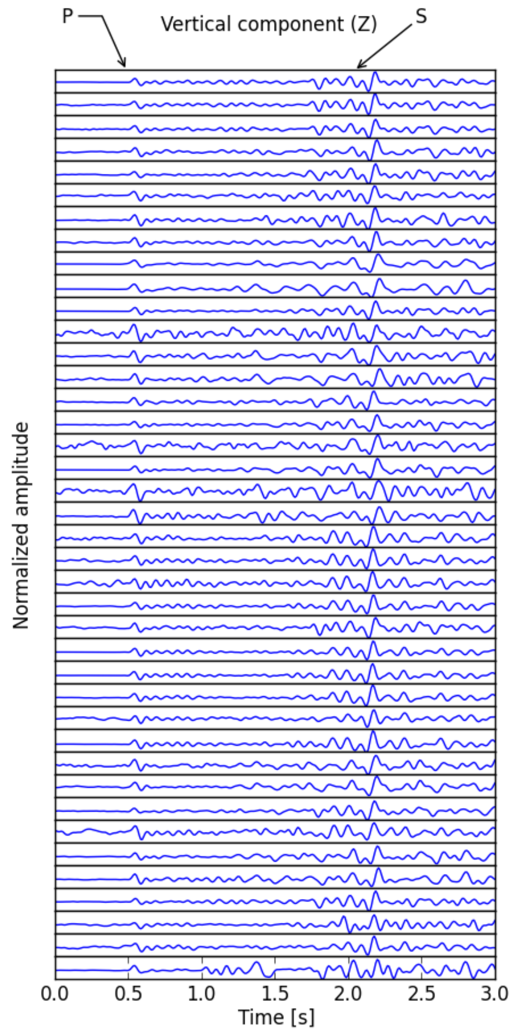

Figure 5: Example of events found by cross correlating a weighted stacked template for one family with the continuous data of one day. The original family had nine members, whereas 105 events were found by cross correlation. Here the first 40 events for one family on the vertical component of station SAN (IMO) are shown. The correlation was run on one day at the time.

Initial results for the relocation of the events imply that we can get the uncertainties of locations down to a few tens of meters. The complexity and size of the problem have slowed down our progress, but we are confident that interesting results are right around the corner.

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