Induced Seismicity During Reinjection of Wastewater in Hellisheidi Geothermal Field, SW Iceland

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ABSTRACT

In 2011 and 2012, a large number of earthquakes were induced during the reinjection of wastewater at the Hellisheidi geothermal power plant near the Hengill volcano in SW Iceland. The area is tectonically active, located close to the triple junction of an oblique spreading zone (Reykjanes Peninsula), a rift zone (the Western Volcanic Zone) and a transform zone (the South Iceland Seismic Zone). The injection started in September 2011 and the seismicity increased shortly after, with thousands of events recorded in the following months by the local network of the Icelandic Meteorological Office (IMO). The majority of events were small (M_l less than 3.0), but the two largest events reached M_l 3.8 and were widely felt in the area. An increase in seismicity was also observed during the drilling of the injection wells, associated with the loss of drilling fluid. From 2009 until 2013, Uppsala University (UU), Massachusetts Institute of Technology (MIT), Reykjavik University (RU), and Iceland GeoSurvey operated a dense temporary network of seismographs in the area. Data from this temporary network and the permanent IMO network was used to make a detailed analysis of the induced seismicity. The events that had been located by the IMO network were grouped into families based on waveform similarity. By using a typical event from each family as a template for cross correlation of the continuous dataset, we were able to quadruple the number of previously located events. Cross correlation differential travel time measurements were then used to relocate the expanded dataset of events with high accuracy. The time delay measurements were performed in the frequency domain ensuring subsample precision. We analyzed the spatial and temporal relationship between earthquakes and injection processes, and calculated focal mechanisms for the master events, giving an insight into the local stress field. The authors would like to acknowledge the IMO for access to waveform data.

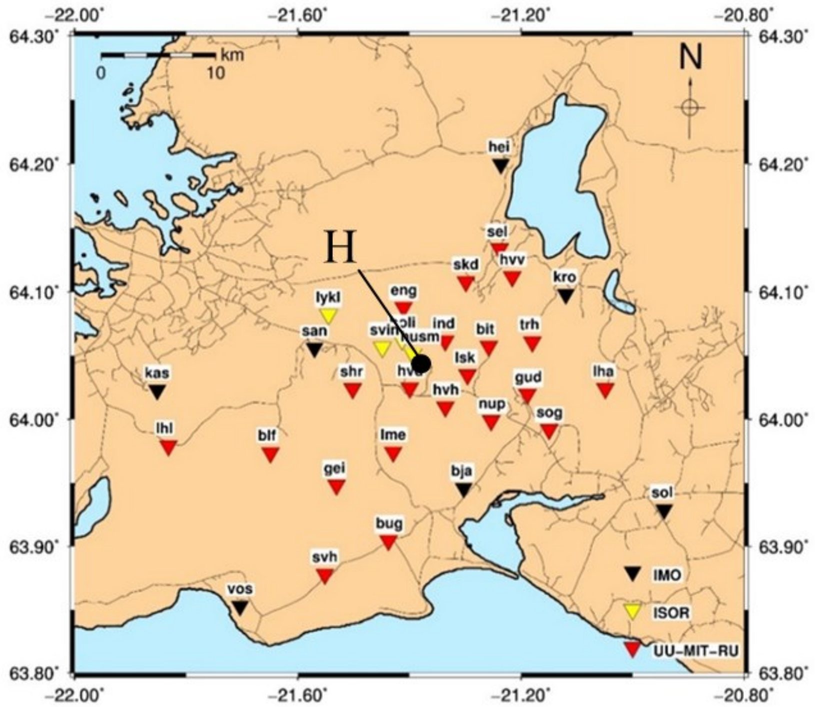

Figure 1: The research area is located in southwest Iceland and the approximate location of the Husmuli injection area is marked with an H. The figure shows the location of stations in a dense, temporary network run by Uppsala University, Massachusetts Institute of Technology, Reykjavik University, and the Icelandic Meteorological Office. It contained 32 stations and was operated from 2009 to 2013.

1. INTRODUCTION

The Hellisheidi power plant is located at the outskirts of the Hengill volcanic system. The Hengill system is both seismically and tectonically active and is at the meeting point of three plate boundaries: The Reykjanes Peninsula, the Western Volcanic Zone, and the South Iceland Seismic Zone. The Hellisheidi power plant began operation in 2006 and produces 303 MW_e and 133 MW_{th}. It is operated by Reykjavik Energy which is obligated to reinject wastewater from the powerplant below the groundwater table. The reinjection recharges the geothermal system and counteracts drawdown as well as being used for carbon sequestration (Snaebjornsdottir et al., 2018). Two injection sites are in use for the Hellisheidi power plant, Grauhnukar and Husmuli. Grauhnukar was the first injection site and has only shown moderate seismic activity since injection started. The temperature at the Grauhnukar site turned out to be high enough to qualify for production and a second injection site was chosen at Husmuli, just to the north of the power plant. Prominent faults on the surface were thought to be good candidates for receiving the reinjected wastewater. The injection wells in Husmuli were drilled in the years 2007 - 2011. During the drilling of some of these wells, an increase in seismic activity was detected which has been associated with circulation loss of drill fluids (Agustsson et al., 2015). The reinjection started in Husmuli in September 2011. Almost immediately seismic activity increased considerably, culminating in two 3.8 magnitude earthquakes which could be felt in neighboring communities. Seismicity has since decreased as stress is released in the area and changes in reinjection rate are executed gradually to minimize seismic activity. During the time period from September 2011, when the injection started, until the end of April 2012 the IMO located around 4,500 events at the Husmuli site. Our work has focused on this time period when the seismic activity was highest. During this time a temporary seismic network was in operation in the area, run by UU, RU, MIT, and Iceland GeoSurvey. The location of the network as well as seismic stations from the IMO can be seen in

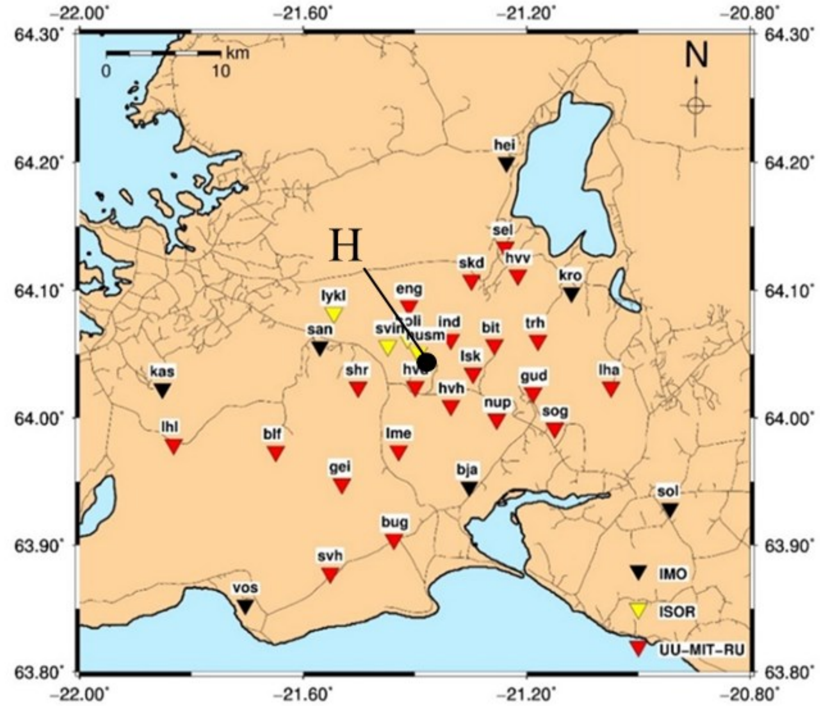

Figure 1. Seismicity is still detected in Husmuli but has decreased significantly.

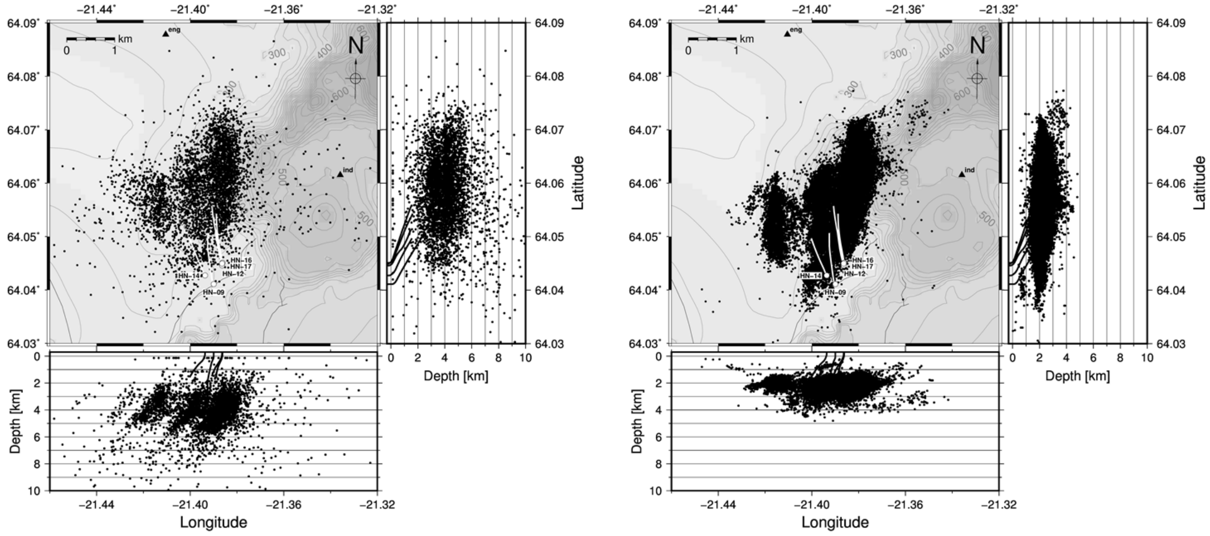

Figure 2: Comparison of earthquake locations from the IMO catalogue (left) and relative relocations of events located with a dense network operated by UU, MIT, RU, IMO and Iceland GeoSurvey (right). The relative relocations differ notably from the IMO locations, particularly in depth.

2. METHODS

Using the events located by IMO and waveforms provided by them we were able to group the events into families based on the similarities of their waveform. The similarity is measured with cross correlation techniques which also gives us sub sample accuracy of time difference measurements between a template event and its family members. The event in each family which had the highest signal-to-noise ratio was chosen as the template event. This template event was then used to search for more events in the data set. The sorting of a large number of events into families is challenging because likeness between different families is considerable, especially in a small area like Husmuli, and results can vary between stations (Schaff et al., 2004). Our main goals were to increase the number of locatable earthquakes and improve the hypocenter location, not to exhaustively find each event a place in a family. Accurate time difference measurements were achieved in the frequency domain and relative relocations found by a grid search in a 3D grid space.

3. LOCATIONS AND FOCAL MECHANISMS

In our work we were able to approximately quadruple the number of located events. By re-picking the template events with added stations from the temporary seismic stations, we were able to significantly improve the location of the template events, especially in depth. The main reason for the improvement is the proximity of the stations and increased coverage of the network. Figure 2 shows the comparison between the two datasets. The events located by the IMO reach down to 10 km depth but with a denser network no earthquakes are located beneath 5 km and most of them are at 1.5-4.0 km depth. The relocated events all have a relative uncertainty less than 100 m. In general, the activity delineates a N-S trend, with an inclination to NE-SW. If we look into individual families, which often contain events from a single swarm, they outline a clear fault. These faults have three main orientations, N-S, ~N20°E, and ~N60°E, which are comparable to previous reported fault orientations in Husmuli (Bessason et al., 2012). Examples of the three different types of faults can be seen in Figure 3. Overall, the seismic activity migrated to the north and to the west as time progressed. The northward migration is also evident in individual swarms, but in many cases the pattern is more complicated. When orientations of faults were investigated in relation to fault mechanisms we observed that certain types of mechanisms tend to fall on certain types of faults. Most of the fault mechanisms are strike-slip, with right lateral strike-slip events falling on N-S striking faults and left lateral strike-slip events falling on faults with ~N60°E orientation. Both of these types of fault mechanisms can be caused by the same stress field. Normal faulting events are fewer, about 17% of the total number of events, and tend to belong to families with fault orientation between N45°E and N70°E. The rest of the focal mechanisms are oblique (mix of strike-slip and normal faulting), and a few of the events have another type of faulting mechanism which could possibly be non-double couple events. Figure 4 shows an overview of the focal mechanisms. No clear connection can be found between location or depth and focal mechanisms.

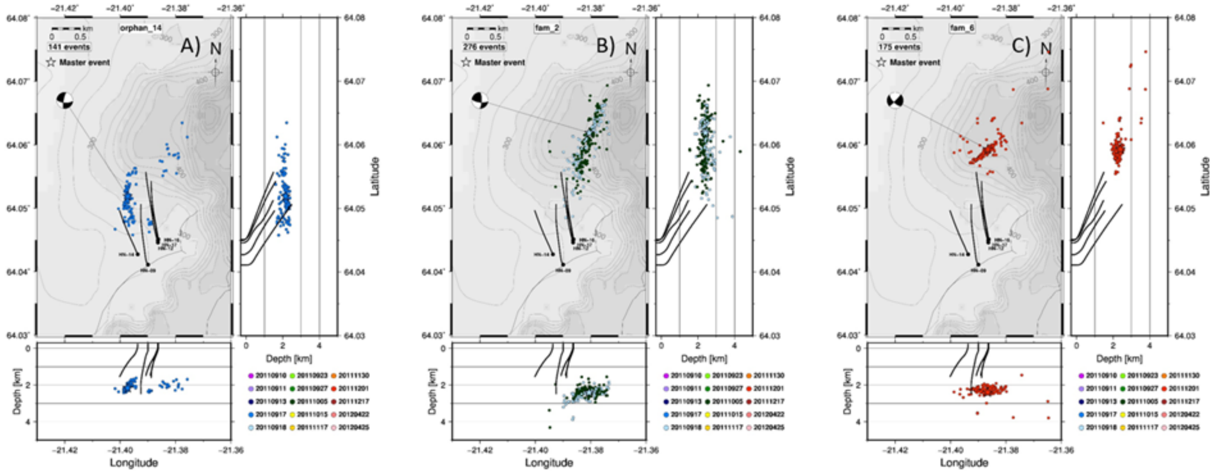

Figure 3: Examples of earthquakes in three different families. The events clearly delineate three different fault orientations. A) shows a fault with N-S orientation, B) shows a fault with ~N10°E orientation, and C) shows a fault with a ~N60°E orientation. Most families delineate faults with one of these three orientations.

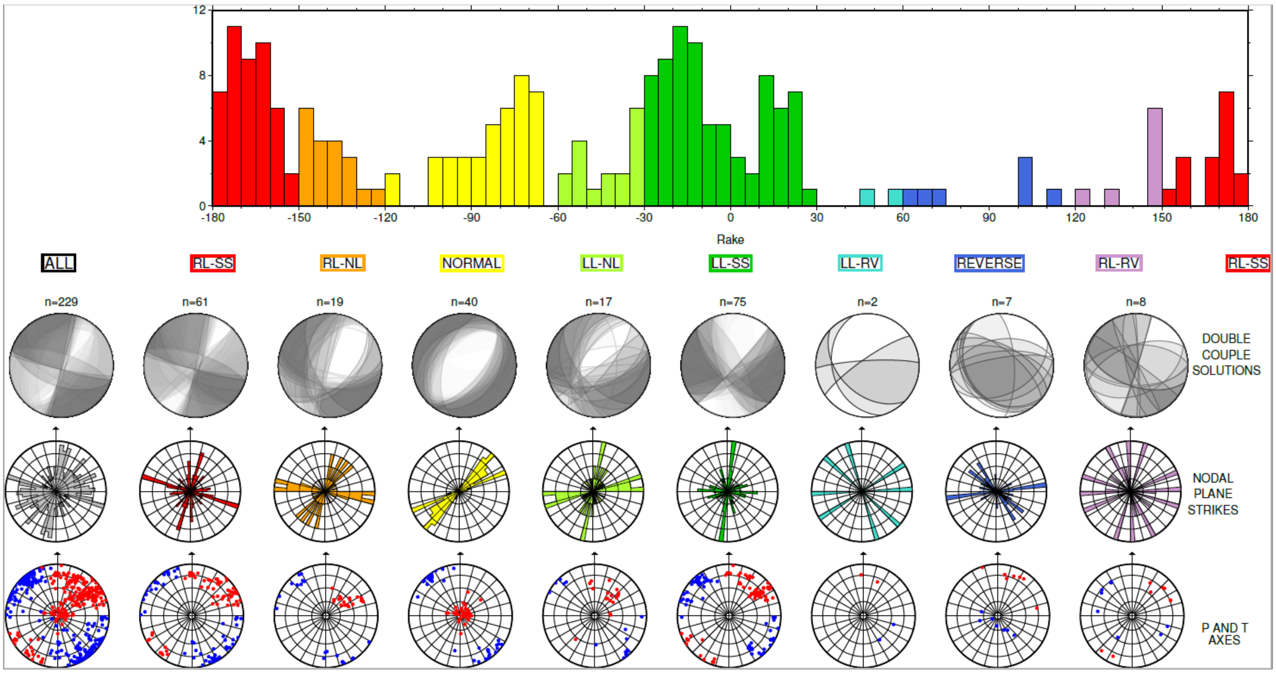

Figure 4: Focal mechanisms of master events. Most events are either strike-slip, normal faulting, or a mixture of the two.

4. SEISMICITY AND INJECTION

The original goal of the project was to investigate the relationship between seismicity and changes in the injection. A part of the dataset has been analyzed in order to conclude if the injection influences the seismicity. The relationship remains unclear, but there most likely is a connection between the two. Husmuli is located in a tectonically active area where stress continuously builds up. Seismic swarms which can most likely be associated with changes in injection release this built up stress. These seismic swarms take place in the same locations as naturally occurring swarms. This makes it difficult to discern between naturally and induced seismicity. In our case we find four cases of changes in rate of injection which directly correlate with an increase in seismicity. Additionally, we find two cases with a possible correlation, but nine cases where there is an increase in seismicity despite no changes in injection rate. Furthermore, there are examples of changes in injection rate followed by no changes in seismicity. Changes in temperature do not coincide either with increased seismicity, although it is known that the reception of the wells increases inversely with temperature (Gunnarsson et al., 2015). Figure 5Figure 8 show examples of each of these cases.

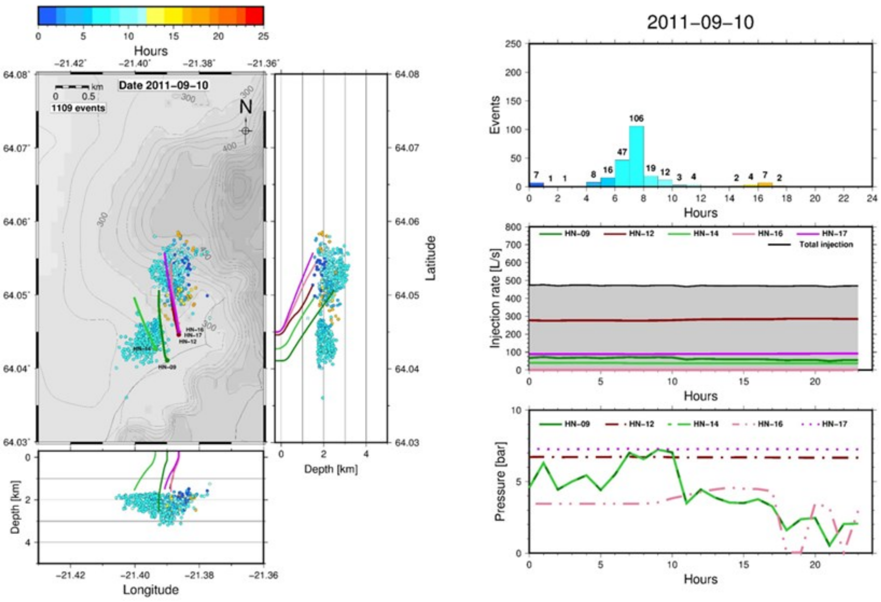

Figure 5: Example of seismic activity when no change in injection rate is noticeable. The image on the left shows seismic activity on September 10, 2011. The color represents the hour of the event origin time. The image on the right shows; on top: a histogram of the number of events on this day, middle: injection rate for individual wells and total injection rate, bottom: pressure in individual wells. Changes in pressure are measured when there is no change in injection rate which is unreasonable and the pressure changes are therefore disregarded.

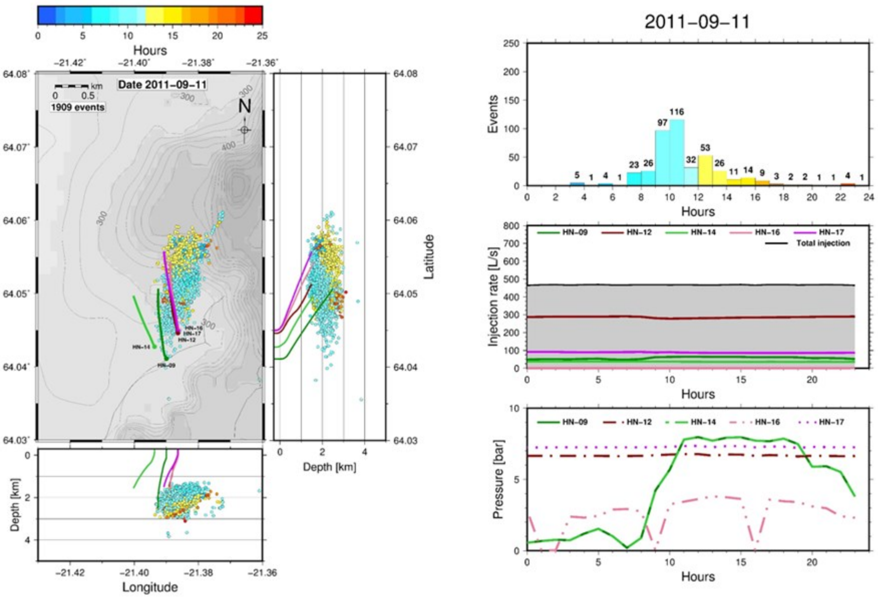

Figure 6: Example of possible change in injection rate followed by an increase in seismicity (wells HN-12 and HN-9). See explanation for the figures in Figure 5.

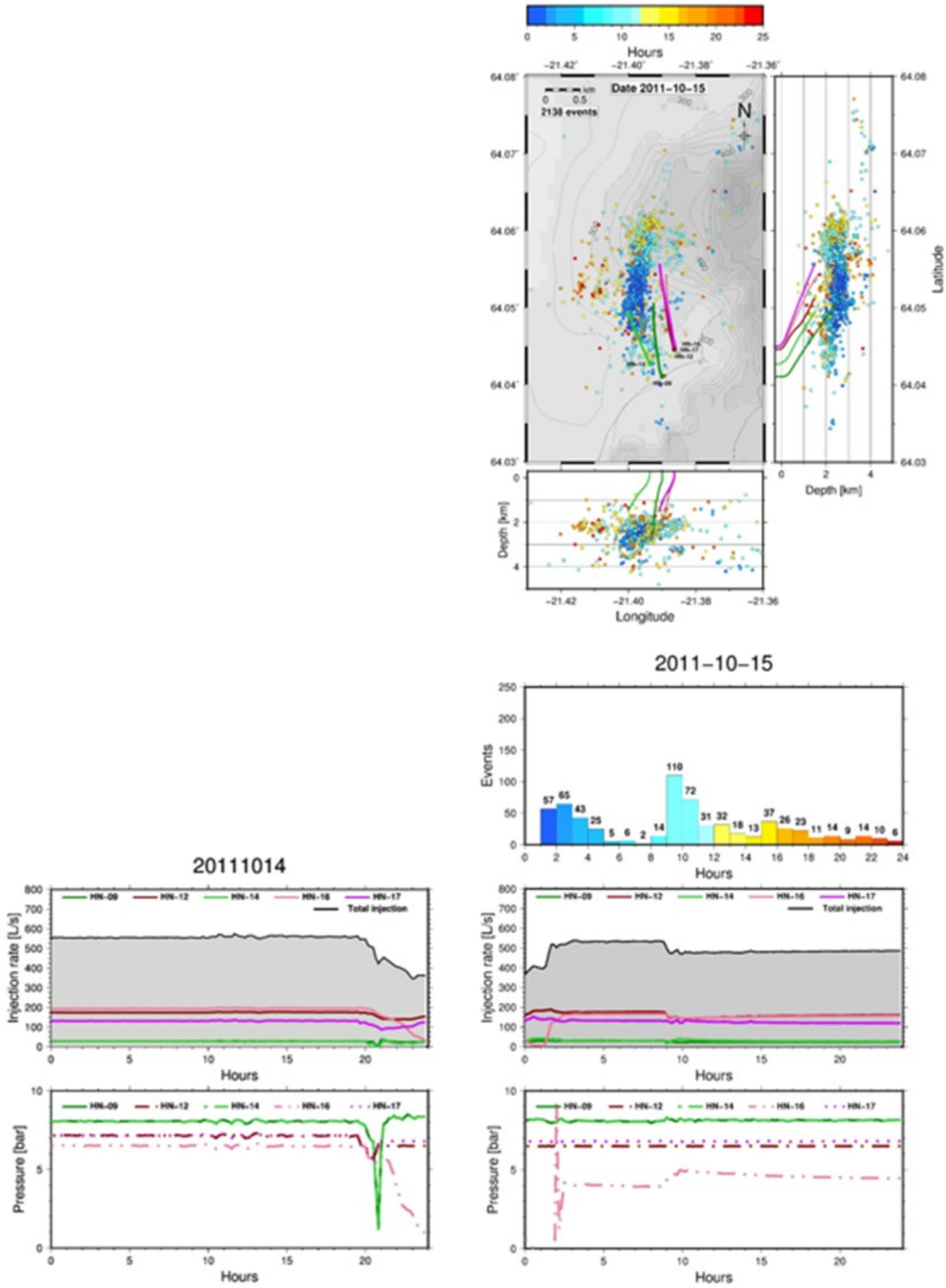

Figure 7: Example of a clear correlation between changes in injection rate and an increase in seismicity. The top image shows the locations of events on October 15, 2011. The bottom images show the number of events on October 15, the change in injection for all wells and the changes in pressure. On the left is shown the injection rate and pressure for the wells the day before.

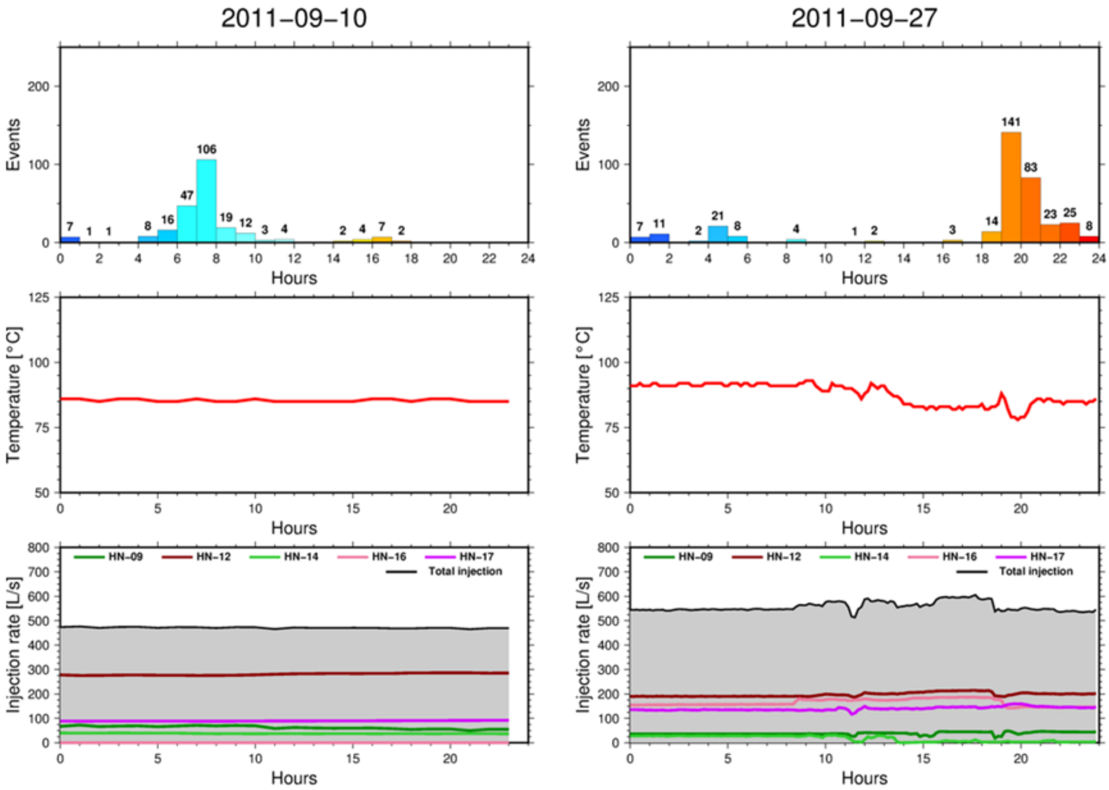

Figure 8: Two examples of seismicity in connection with changes in temperature of the injected fluid. Top: number of events per hour, middle: temperature of injected fluid, bottom: injection rate in each well as well as total injection rate. The image on the left shows no correlation between seismicity and temperature. The image on the right shows increased seismicity taking place at the same place as changes in temperature, but it is masked by changes in injection rate.

5. CONCLUSIONS

We were able to quadruple the number of located earthquakes in the first nine months of the injection at the Husmuli injection site at Hellisheidi power plant. The accuracy of the locations was improved significantly. The relationship between injection and seismicity is not clear, but the activity in Husmuli is characterized by short swarms taking place on faults with three main directions. In most cases the activity within each swarm moves from south to north and east to west with time. This suggests that the spread of pressure changes due to the injection is diffusive. Focal mechanisms are in accordance with the known stress field in the area but no obvious relation can be found between depth and type of focal mechanism.

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