Induced Earthquakes in the Hellisheiði Geothermal Field, Iceland

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ABSTRACT

The 300 MW Hellisheidi, Iceland geothermal power plant was commissioned in 2006 and as of July 2019, the 64th production well is being drilled. Additionally, there are 17 injection wells in the region. Drilling of a few of these wells has been accompanied by significant (M ~2-3) earthquakes [Vogfjord & Hjaltadottir, 2007; Agustsson et al., 2015], whereas no seismic events were observed during the drilling of others. Often the induced seismicity is coincident with either; 1) loss of circulation fluid, when drilling through large fractures, which absorb the drilling fluid or 2) well testing after completion of drilling, during which fluid is pushed into the hole with increasing pressure. Most of the wells are located in the highly fractured fissure swarm of the central volcano Hengill, which includes hyaloclastite ridges and lava fields and it is considered that the fluid flow is fracture dominated. In addition to the seismicity induced in connection to drilling, the level of seismicity in the region has been highly increased by reinjection of affluent water (including two Mw 4.0 earthquakes in 2011), as well as by the production itself. In the Hverahlid subregion, six wells have been drilled since 2006. During well testing of well HE-21, the first one drilled in the region, significant seismicity was observed [Vogfjord & Hjaltadottir, 2007], whereas no seismicity followed the drilling and well testing of HE-53 and HE-54. However, the seismicity increased significantly when production started in 2016 and has stayed elevated since. In this study we document the seismicity associated with the drilling of each well, and the ongoing volcano-tectonic activity in the region. Furthermore, we compare the seismicity during drilling with that during production/injection.

1. INTRODUCTION

The Hellisheiði Power plant is located south west of the Icelandic central volcano Hengill, which is situated on the triple junction where the Reykjanes Oblique Rift meets the South Iceland Seismic Zone and the Western Volcanic Belt (Fig 1a, Einarsson 2008).

The Hengill area is seismically active and experiences periods of intense seismic swarms. The latest period of intense seismicity lasted several years (in the 1990s) and was accompanied by uplift caused by a deep-seated source (Feigl et al., 2000), about 8 km to the east of the Hellisheiði Power plant. In recent years a center of steady deflation was observed, collocated or nearly collocated with the center of inflation in the 90s (Juncu et al., 2017).

The South Iceland seismic zone is a east-west oriented transform zone, on the order of 70 km long, characterized by bookshelf faulting (Einarsson et al., 1981). For this reason, although the transform strikes east-west, the zone is comprised of about 10-20 km long, north-south striking faults. Several large earthquakes occurred in the South Iceland Seismic Zone in the last decades. On June 17th, and June 21st, 2000, two magnitude M_w 6.5 and 6.4 earthquakes struck the zone, 50 and 30 km east of Hengill respectively. These earthquakes caused large ground motions and it was shown that several faults, up to 80 km to the west of the events, moved seismically during the intense shaking and aftershocks of these triggered earthquakes were recorded (Antonioli, 2006). Another earthquake doublet struck the region on May 29th, 2008, when a Mw 6.3 double event broke two subparallel faults, separated by about 4 km in space and 3 seconds in time, near the town of Hveragerði, about 10 km east of the Hellisheiði geothermal field (Hreinsdóttir et al, 2009). In the Hellisheiði region, both NNE-SSW oriented faults associated with the Reykjanes Rift, and N-S faults associated with the South Iceland Seismic Zone, can be observed (Steigerwald et al., 2018).

The 300 $MW_{electric}$, 133 $MW_{thermal}$, Hellisheiði, Iceland geothermal power plant was commissioned in 2006. A total of 63 wells have been drilled since 2001, to supply the power plant with steam and hot water. In 2007 an additional power plant was planned in the Hverahlíð region, about 4 km to the southeast of the Hellisheiði powerplant. However, due to the financial crisis in 2008, those plans were canceled after four wells (HE-21, HE-26, HE-36, HE-53, HE-54) had been drilled in the region. It was not until

2016 that the existing wells were connected to the Hellisheiði power plant, and production in the Hverahlíð region started in fall 2016. In 2017 and 2018 two additional wells (HE-59 and HE-60) were drilled.

The geothermal brine extracted from the Hellisheiði area, is reinjected in the reinjection fields. As part of the original design of the power plant, the Gráuhnúkar area, about 2 km south of the power plant, was selected as the reinjection area. Several wells were drilled for that purpose and reinjection there started in 2007. However, during drilling it was discovered that the formation temperature area was much hotter than previously expected. For this reason, it has been considered to repurpose the area as a production area. An additional reinjection area was selected in Húsmúli, about 1 km to the north of the powerplant, with the drilling of several new injection wells in the time period between late 2007 and early 2011, and reinjection starting in September 2011. Other wells have also been used intermittently for reinjection, providing pressure support for the geothermal system.

Very little seismicity had been observed in the Gráuhnúkar reinjection area and induced seismicity was therefore not expected in the new reinjection field in Húsmúli. However, some induced seismicity had been observed during the drilling of well HE-21 in the Hverahlíð production area (Vogfjord and Hjaltadottir, 2007), and large swarms of earthquakes were observed during drilling of wells in the Húsmúli injection area (Ágústsson et al., 2015). When injection started in Húsmúli in September 2011 the rate of seismicity increased drastically, culminating in two large events, M 4.0 and 3.8 occurring on October 15th, 2011. The larger events were felt over a wide area, but many of the smaller events were felt in the nearby community of Hveragerði, causing discomfort for the inhabitants that had experienced destructive earthquakes in the vicinity of town just three years earlier. A working group was formed to manage the seismicity and a traffic light system for responding to events and changes in reinjection was established (Bessason et al., 2012). The reinjection in Húsmúli caused a local uplift of 2 cm during the first year (Juncu et al., 2017).

In this study we review the seismicity since 1995 and compare with both natural and anthropogenic processes ongoing in the region.

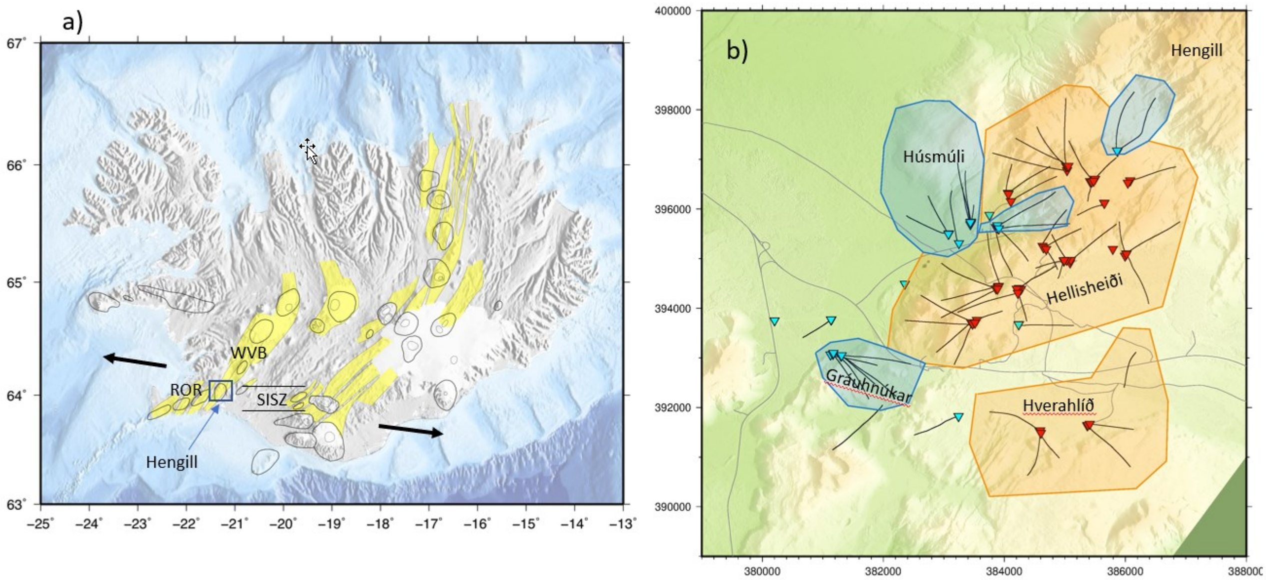

Figure 1: a) The Hengill Central Volcano is situated on the triple junction between the Reykjanes Oblique Rift (ROR), the South Iceland Seismic Zone (SISZ) and the Western Volcanic Belt (WVB). Marked are central volcanoes and calderas (black circles) surrounded by corresponding fissure swarms (yellow). Spreading direction is shown with black arrows b) Production (Red/Orange) and reinjection (blue) zones and wells of the Hellisheiði Power Plant

2. HENGILL SEISMICITY

We use the seismic catalog of the Iceland Meteorological Office, as obtained from their website (www.vedur.is). The catalog retrieved covers the years from 1995/01-2019/06. The number of stations in the seismic network has been increasing through the years, making interpretation of changes in seismicity more difficult, however, we expect a completeness threshold just above M 1.

In this section we observe the seismicity in the Hengill region as a function of time, dividing the catalog into time periods of different lengths, associated with the various events affecting the seismicity in the region (Fig. 2). In general, the seismicity is distributed in clusters rather than aligning on continuous faults.

The first time period (1995-2000/05) is dominated by the intense seismicity associated with the uplift episode east and southeast of Hengill in the 1990s. The second time period (2000/06-2000/07) shows the background and triggered seismicity during two months around the two Mw 6.4 earthquakes in the South Iceland Seismic Zone. Notably there is a cluster of seismicity just south of the Hverahlíð production area. In the following years (2000/08-2006), before the start of operation of the Hellisheiði power plant, there is distributed seismicity in the region, notably to the east and southeast of Hengill where the intense seismicity was observed in the first time period.

In the following time period (2006-2010), the production in Hellisheiði geothermal field and the injection in Gráuhnúkar are ongoing and drilling has started in Húsmúli. It is interesting that out of these three processes, the drilling in Húsmúli triggers the most events, even more than ongoing injection in Gráuhnúkar. In this time period we also see the aftershock activity of the Hveragerði event in 2008, aligning on a north-south oriented fault to the east of the region.

During the next 6 years (2011-2016), the seismicity is dominated by the injection in Húsmúli, although an important increase in seismicity occurs on the border between the Hellisheiði production area and the Gráuhnúkar injection area. Finally, in the last 2.5 years the seismicity in Húsmúli has decreased and divided into two clusters, while the seismicity on the border between Gráuhnúkar and the Hellisheiði production field continues. Additionally, in this time period the seismicity in the Hverahlíð production field has increased significantly, coincident with the start of production in this area.

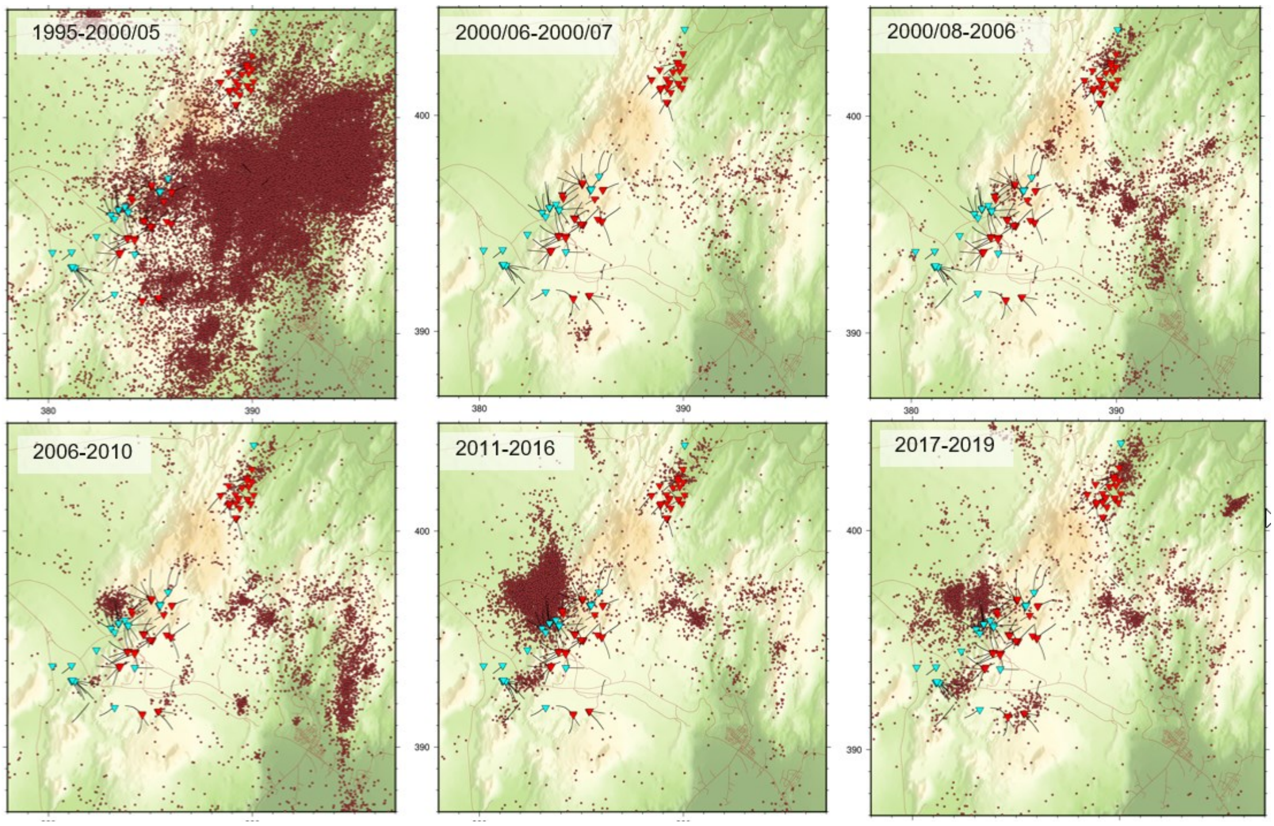

Figure 2: Seismicity in the Hengill region during different time periods. Events are marked with dark red dots, whereas injection and production wells are marked with blue and red inverted triangles and well trajectories with black lines. Roads are shown with brown lines.

3. SEISMICITY IN REINJECTION AND PRODUCTION AREAS

Next we compare the seismicity in the four different study areas to the ongoing volcano-tectonic activity in the region, as well as the drilling occurring in each zone.

The drilling of most of the wells in this region is divided in three stages. During the first two stages the well is sealed when loss of drill fluid occurs and therefore a large volume of drill fluid loss, possibly triggering earthquakes, is not expected during these stages. During the third stage there is often significant or full (> 50-65 l/s depending on well) drill fluid (water during this stage) loss during drilling. When this occurs, there is significant influx of cold (0-10°C) water into the formation, with the potential of triggering earthquakes. After drilling there is often a step test, designed to estimate the injectivity of the well. During this time there is also an influx of water into the formation.

During reinjection, warm or hot water (typically in the range of 60-80°C) is reinjected into the formation at rates of 0-150 L/s, depending on the well. In this section we plot the seismicity as a function of time, identifying the times at which there is drilling and what stage, and times during which step tests are performed.

3.1 Gráuhnúkar reinjection area

The Gráuhnúkar reinjection area is relatively quiet seismically. During the volcanic unrest in the 90s, there were only very few earthquakes observed there, and there were no triggered events during the earthquakes in the South Iceland Seismic Zone in 2000 or 2008. There were also no earthquakes observed during drilling of the injection wells of the region. However, there has been increasing seismicity after reinjection started in 2007, with several events of magnitude M 2.5-3 recorded between 2014 and 2016. The number of larger events has been diminishing since 2017.

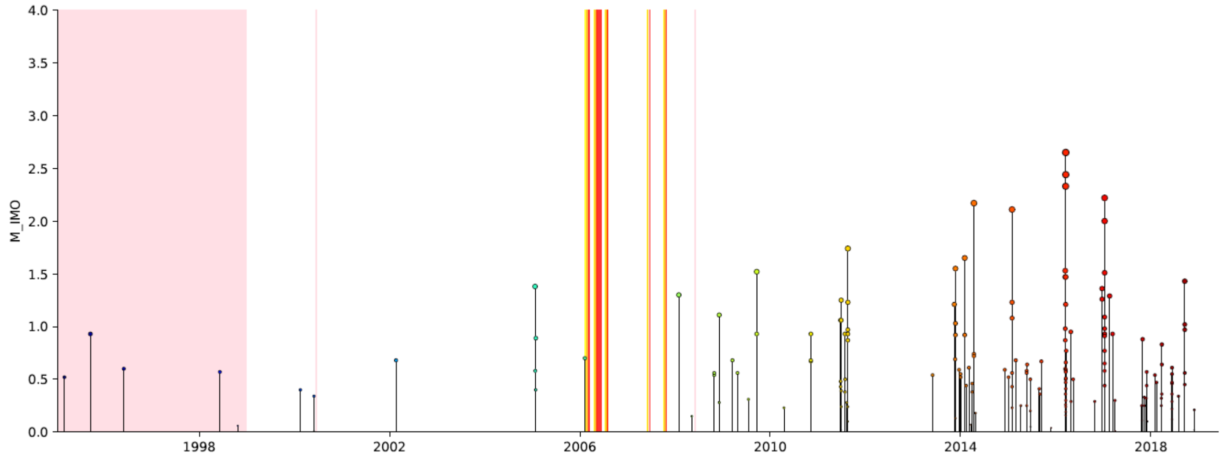

Figure 3: Seismicity in the Gráuhnúkar reinjection field as a function of time. The magnitude is shown on the vertical axis and year on the horizontal axis. Periods of tectonic activity are marked with pink, of drilling of stage 1 marked with yellow (drill typically at depths <100m), of stage 2 with orange (drill typically at depths 100-900m), and of stage 3 with red (drill typically below about 900m). The color of the dots changes as a function of time. Periods of step tests are marked with purple where available.

3.2 Húsmúli reinjection area

The Húsmúli reinjection region was relatively more active than the Gráuhnúkar one during the inflation period in the 90s, although neither of them was very active. From 1998 the area was very quiet until start of 2007 when a small seismic swarm hit the area. this occurred after start of production in the neighboring Hellisheiði field, and during the drilling of well HN-09. Seismic activity was also seen during drilling several of the other wells in the area (HN-11, HN-14 and HN-17). This seismicity has been studied in with a denser network and more detailed analysis (Ágústsson et al., 2015), revealing a correlation with increase in drill fluid loss and distribution of seismicity on NS or NNE-SSW structures.

When full scale reinjection started in September of 2011, the seismicity increased very significantly, with several earthquakes felt in the neighboring areas. The intensity decreased markedly after 2011 but has remained elevated. The seismicity has decreased further since the last large swarm in 2016.

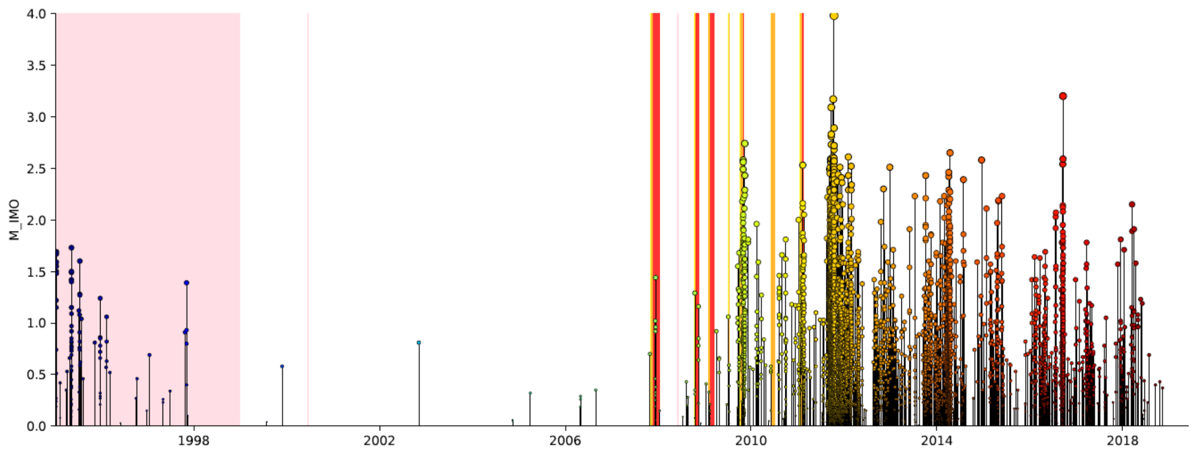

Figure 4. Seismicity in the Húsmúli reinjection field as a function of time. See Fig. 3 for description.

3.3 Hellisheiði reinjection area

There was important seismicity in the Hellisheiði reinjection area during the uplift episode in the 1990s, and the seismicity remained high even after year 1999. On June 17th, 2000, several events were detected in this zone, the largest of which had a magnitude of M 4.6, occurring a few hours after the mainshock in the South Iceland Seismic Zone.

Drilling in the region started in 2001 and continued with several wells drilled per year until year 2009. The drilling was especially intense between 2006 and 2009, with near continuous drilling. However, there is not a large number of swarms occurring during this time period, and except for a swarm occurring during drilling of well HE-08, there are no large swarms occurring during drilling in this zone. After the hiatus in drilling started in 2009, there has been continued elevated seismicity, with seismic swarms occurring intermittently.

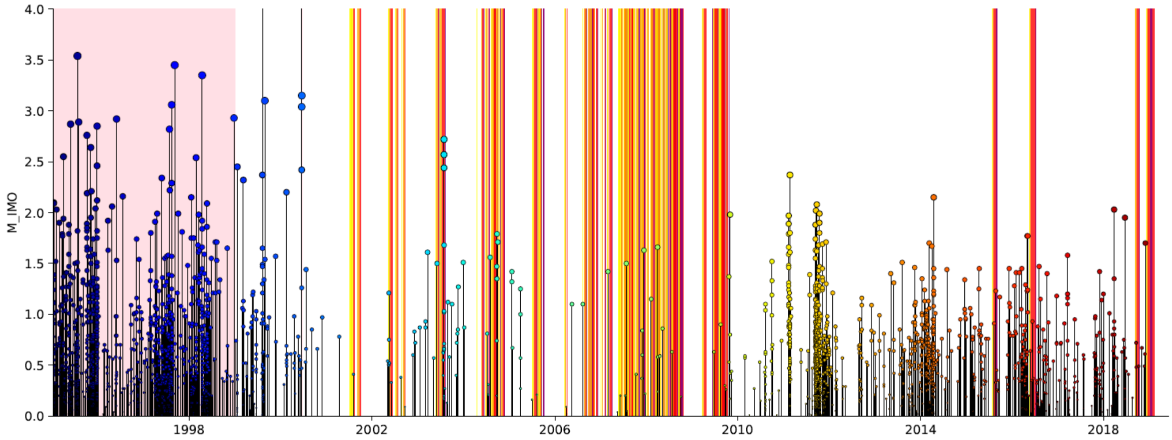

Figure 5: Seismicity in the Hellisheiði production field. See Fig. 3 for description.

3.4 Hverahlíð production area

The Hverahlíð production area was seismically active during the inflation period in the 90s, and there was an increase in seismicity after the event in the South Iceland Seismic Zone in the year 2000. After that, the period remained relatively quiet until 2016, except for a seismic swarm occurring during the drilling of well HE-21. This seismicity has been studied in some detail (Vogfjord & Hjaltadottir, 2007), and was found to occur on a NNE-SSW striking fault. Production in the field started in late 2016 and almost immediately the seismicity increased importantly, with an event of magnitude M 3.1 occurring in early 2018. The seismicity remains elevated as production continues.

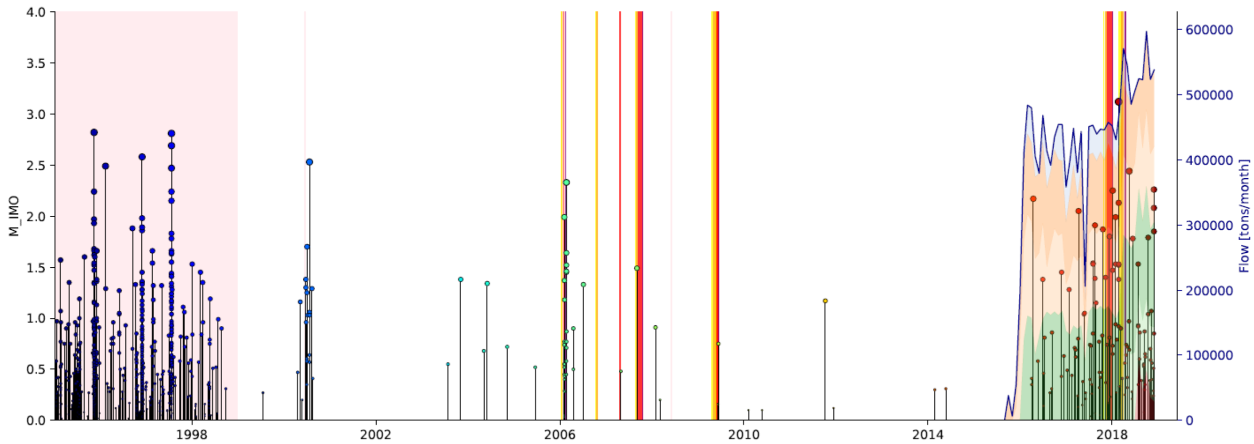

Figure 6: Seismicity in the Hverahlíð production field. See Fig. 3 for description of labels. Here the production of the field in tons/month is shown on the right axes. The total production is shown with the blue line and that of individual wells with separate colors.

4. CONCLUSIONS

We have compared the seismicity in two production areas and two reinjection areas utilized by the Hellisheiði geothermal power plant, Iceland. We find that earthquakes are triggered by volcanic activity, remote large earthquakes, loss of drill fluid during drilling and production. We find however, that the degree to which these activities depend heavily on area, f.ex. the injection in Gráuhnúkar caused very little seismicity initially, whereas seismicity increased substantially even just by loss of drill fluid in the Húsmúli reinjection field, reaching very high levels of seismicity during start of reinjection. We also find that the Hverahlíð production area started experiencing a large number of earthquakes at the start of production, whereas the same has not been observed in the Hellisheiði field, even if the number of wells is much larger.

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