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Using Seismicity to Map Fractures in Hengill, SW-Iceland

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ABSTRACT

The Hengill high-temperature geothermal field in SW-Iceland has been developed and exploited since 1990. A second power plant started production in 2006 about 10 km to the southeast of the first and together they produce 420 MW electricity and 430 MW of warm water. Hence, the Hengill geothermal area is of great importance for electricity and hot water production in Iceland and understanding the dynamics of the area is of great scientific and economical interest. Hengill is located on a tectonic triple junction in Southwest Iceland connecting the Reykjanes Volcanic Zone, the Western Volcanic Zone and the South Iceland Seismic Zone. Between 1993 and 1999, the area was subject to a significant volcano-tectonic event which caused 8 cm uplift over a period of 4 years which has been explained by a small magmatic intrusion. The uplift induced more than 90 thousand earthquakes in the Hengill region which highlights the intensity of the stresses that must have been present in the crust prior to the onset of the uplift. With time the seismicity propagated south from the uplift-source region and into the neighboring the South Iceland Seismic Zone, where two events of $M_L > 5$ were generated in 1998 less than 10 km from the uplift center. We use micro-earthquakes to study fault activation in the source area and development over time. Locations of the earthquakes are improved significantly by the use cross-correlation to refine wave arrival times and application of a double-difference algorithm. The relocated earthquake distribution shows that the faults are activated in agreement with the regional stress field rather than respecting the uplift geometry. This underlines the fact that the stress caused by the uplift is small in comparison to the regional stress and functions as a mere trigger for the seismicity.

1. INTRODUCTION

1.1 Geological Setting

In Iceland, the vast majority of earthquakes occur along the plate boundaries, that is the rifting zones and transform segments. Most of this activity is concentrated around the central volcanoes and geothermal areas along the rift and earthquakes are mostly of small magnitudes ($M_L < 2$). Intraplate earthquakes are rare but can be recorded occasionally, e.g. in the Westfjords (Jakobsdóttir, 2008). Between the North American and Eurasian continental plates and the Hreppar microplate, the Hengill volcano is located on a triple junction in Southwest Iceland connecting two extending and one conservative plate boundary (Einarsson, 2008) (Figure 1): (1) the Reykjanes Volcanic Zone which is the on-land continuation of the Mid-ocean spreading ridge between the North American and the Eurasian plate boundary, (2) the Western Volcanic Zone which is a spreading ridge from Hengill towards the NNE, and (3) the South Iceland Seismic Zone (SISZ), a transform zone connecting the Western and the Eastern Volcanic Zones. In this zone earthquakes of maximum magnitudes of M_S 7.2 can occur (Stefánsson and Halldórsson, 1988).

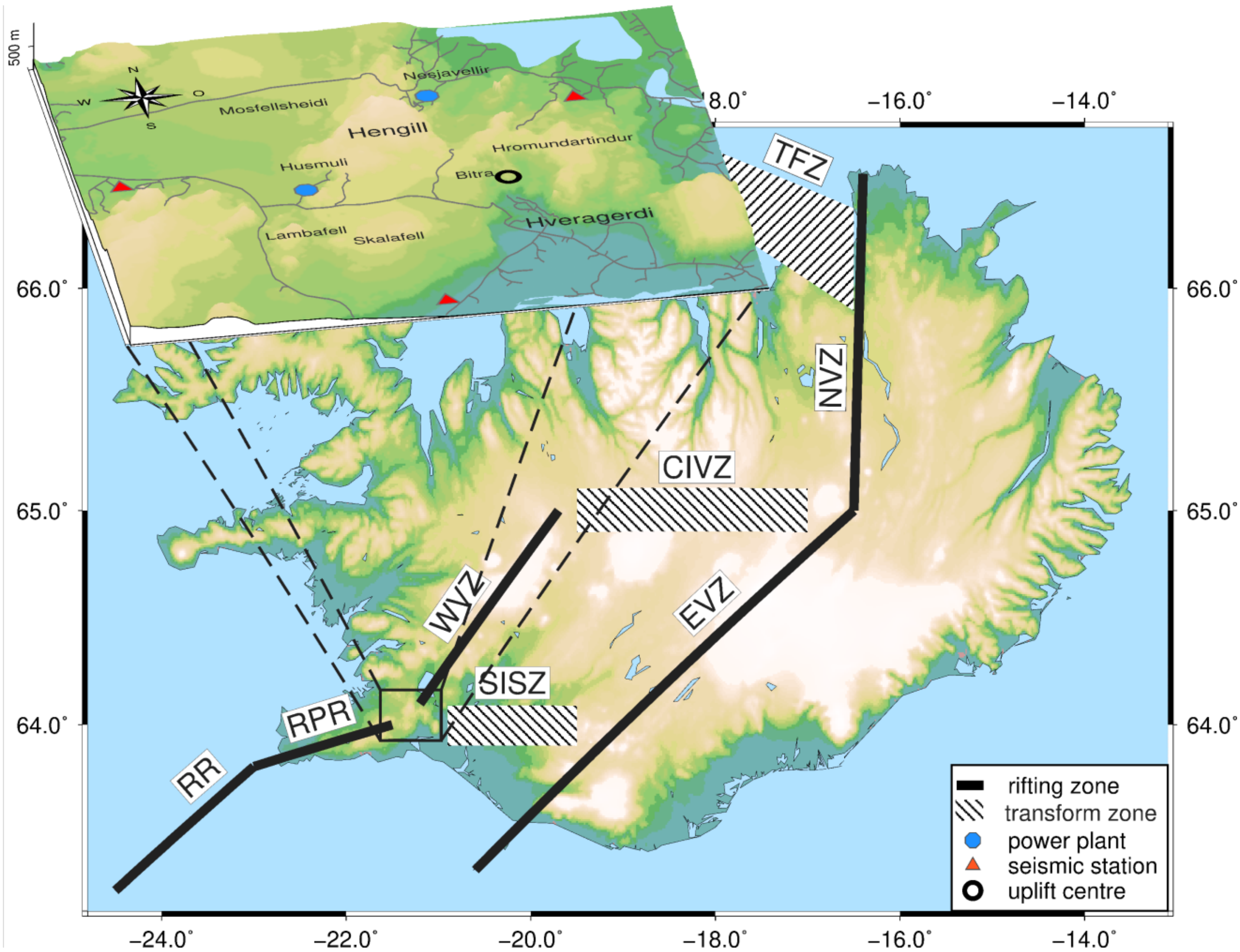

Figure 1: Location of the Hengill geothermal area in southwest Iceland. The triple junction is located at the intersection of the Reykjanes Peninula Rift (RPR), the Western Volcanic Zone (WVZ) and the South Iceland Seismic Zone (SISZ).

The Hengill volcano is one of about 30 active volcanic systems in Iceland with its last eruption occurring about 2000 years ago. The highest peak of the complex reaches 803 m a.s.l. and consists almost entirely of basaltic rocks. Numerous fumeroles and hot springs are visual indicators of a heat source in the shallow crust. The Hengill volcanic area has been studied extensively over the years including geological, geochemical, geodetic and geophysical studies. In the stress regime of the triple junction both tectonic extension and shear stresses occur, causing normal and strike-slip faulting events due to the plate motion. The region is seismically monitored by the Icelandic regional network since 1974. Additionally, major seismological studies have been carried out among others by Foulger (1988a and 1988b) and Miller et al. (1998) who studied earthquake distribution and focal mechanisms and moment tensors, respectively. The local seismic activity can be roughly classified into two groups: (1) infrequent episodes associated with the rifting process and (2) continuous activity of smaller magnitudes in the geothermal system. Up to 75% of earthquakes inside the high-temperature geothermal area have significantly non double-couple components and showed characteristics that were interpreted as tensile crack formation. An aseismic low velocity body and potential location for partial melt was described by Toomey and Foulger (1989) and Foulger (1995). These findings were later confirmed by Jousset et al. (2011) who carried out a 3D tomography and identified a low V_P/V_S ratio body in the same area as the low velocity body mentioned above. Together with resistivity measurements this body was interpreted as the heat source.

In this tectonically complex regime different processes interact and influence each other. Tectonical stresses induced by the plate motions are overlapped by magmatic and geothermal processes. All these processes induce stress that cause seismicity varying in size and other characteristics. In the 1990ies an uplift episode possibly caused by a small magmatic intrusion triggered more than 90.000 earthquakes. This allows us to map these faults at depth and to better understand the correlation between the different processes that act in this high complex area.

1.2 Geothermal Energy in Iceland

Geothermal energy production in Iceland provides 24% of the electricity needs of the country (Orkustofnun, 2015). This puts Iceland in second position worldwide where it is only beaten by Kenya. But as the electricity needs of the Icelandic industry are growing and most other unexploited geothermal areas in Iceland are protected for environmental reasons, efforts are made to further develop and expand existing geothermal power plants.

The Hengill geothermal field in SW-Iceland has been developed and exploited since 1990 by a power plant located NE of the volcano. A second power plant started production in 2006 about 10 km to the southeast of the first and together they produce 420 MW of electricity and 430 MW of warm water. Hence, the Hengill geothermal area is of great importance for electricity and hot water production in Iceland and understanding the dynamics of the area is of great scientific and economical interest.

2. SEISMICITY IN THE HENGILL AREA

Between 1993 and 1999, the Hengill geothermal area was subjected to a significant volcano-tectonic event which caused 8 cm uplift over a period of 5 years. The uplift episode was first measured in geodetic data in 1986, gaining momentum from 1992 to 1994 (Sigmundsson et al., 1997). Based on several InSAR measurements, Sigmundsson et al. (1997) and later Feigl et al. (2000) modelled the uplift source and proposed a Mogi source in about 7 ± 2 km depth as a possible explanation of the uplift. A small magmatic intrusion was suggested to be the cause. The uplift was neither accompanied by harmonic tremor nor was the seismic activity migrating, indicating an inflating magma chamber rather than dike propagation (Sigmundsson et al., 1997).

The uplift was accompanied by more than 90 thousand earthquakes recorded by the SIL network (Jakobsdóttir, 2008) (Figure 2) which at that time consisted of 18 seismic stations covering the main seismically active zones in Iceland such as the Tjörnes fracture zone in the north of the country and the SISZ where the largest earthquakes in Iceland (M_L >6) occur. The Hengill area at the west end of the SISZ was monitored by 7 seismic stations. Another 4 stations were added to the regional network around the volcano in 1996 and 1997. The vast majority of the earthquakes were located between 2 and 8 km depth which is about the same depth range that is reported in various studies on the area (e.g. Foulger, 1988; Jousset et al., 2011).

In 1993 activity started to exceed the typical seismicity rate with an average of 86 earthquake recorded each month until October. In November 1993 until July 1994 activity decreased to < 20 earthquakes/month. In August 1994 a big earthquake swarm was recorded peaking from August 15 to August 25 with more than 5600 earthquakes focused north and northwest of the uplift center. From September 1994 to January 1995 earthquake rates went down to a minimum before taking off in February 1995. After that activity rates remained elevated with several hundred up to 7700 earthquakes per month until the end of 1998 with peaks in activity from April to August 1997 and September 1998, the single one month with highest number of earthquakes (> 18500).

With time the seismicity propagated south from the uplift-source region and into the neighboring SISZ where the episode reached its climax in 1998 when two earthquakes of magnitude M 5.5 and M 5.2 were recorded on June 4 and November 13. Two years later in the summer of 2000, two M 6.5 earthquakes occurred in the SISZ on June 17 and June 21 at about 35 and 20 km distance from the uplift center. This strengthens a hypothesis expressed by Sigmundsson et al. (1997) that in order for the uplift to cause the extensive amount earthquake activity observed, the crust must have been under high stress and already close to failure before the uplift episode started.

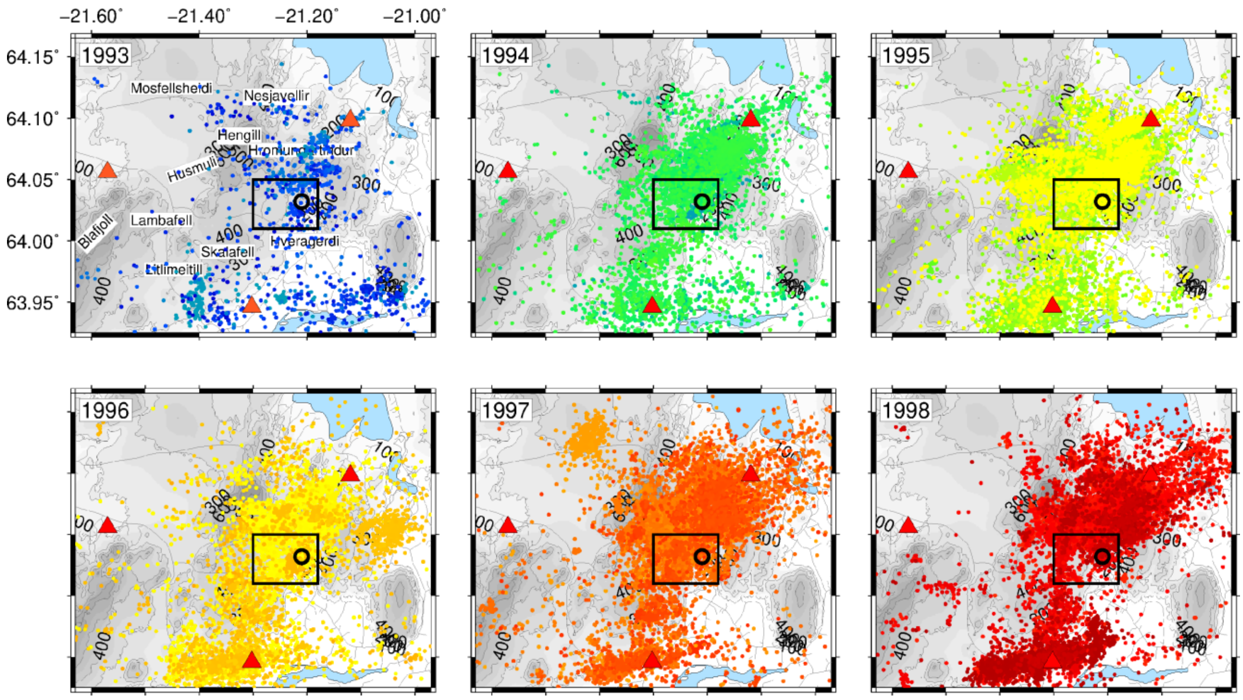

Figure 2: The seismic activity in the Hengill area in the years 1993 to 1998. Red triangles mark the locations of seismic stations, the locations of the modelled inflation center is marked by the black circle. In 1993, earthquake activity began to increase exceeding normal background activity. In 1994, seismic activity increased dramatically mainly north and northwest of the location later identified as the center of uplift. The black box marks the study area.

Faults that were active from 1996 to 1998 have been mapped in detail by Vogfjörd et al. (2005), showing a variety of fault directions but with most faults being oriented in northerly direction or NNE or ENE striking in accordance with the local stress field. For some of these apparently ENE striking faults particularly in the southern region, it remains unclear whether they are not numerous smaller northerly faults arranged in a bookshelf manner as it is typically the case on the SISZ (reference) due to the limited resolution.

In this study, which is part of the research project titled “Interaction of geothermal, tectonic, and magmatic processes in the Hengill area, SW-Iceland”, supported by The Icelandic Centre of Research (Rannís), we focus on the activity in the direct vicinity of the uplift center (black box in Figure 2). The seismic activity as taken from the SIL catalog (Figure 3) appears to be rather diffuse and the alignments or location of faults are not obvious to the naked eye. In the study area the activity is not equally distributed around the center of uplift but in more than 1 km distance seismic activity is more dense to the north and west then to the east and south (Clifton et al., 2002). The activity becomes less distributed in depth and mostly confined to a depth range from ca. 4 to 8 km as the network is developed with time with the addition of seismic stations in 1996 (orange and red colored earthquakes in Figure 3). Azimuthal coverage is good but due to the network layout with no station in the center of activity, we expect that depth is the least constrained of the location coordinates.

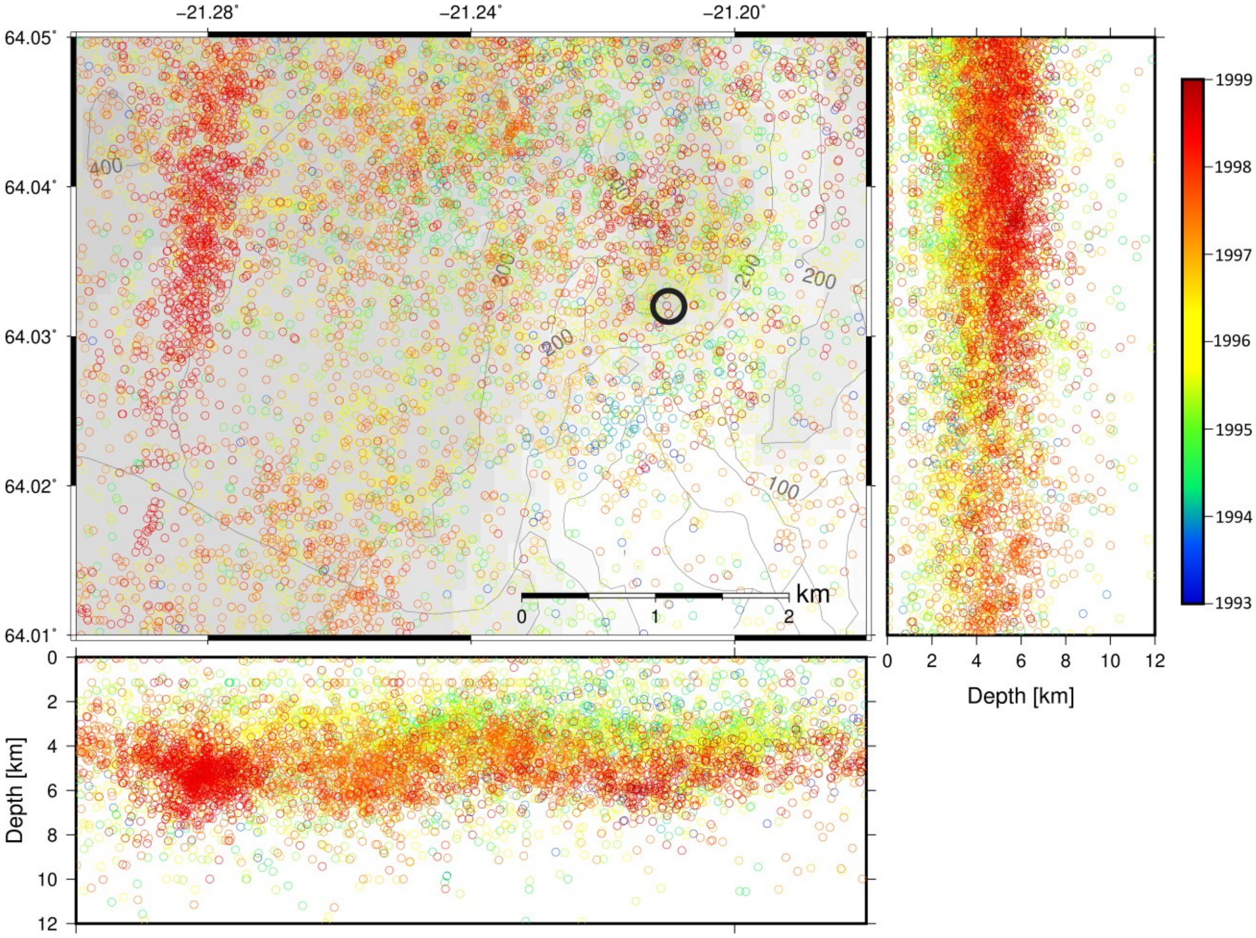

Figure 3: Seismic activity (catalogue locations) in the vicinity of the uplift center 1993 to 1998 in map view and in E-W and N-S profiles. The colors indicate time. While the activity is more scattered in the earlier years, it appears to become more spatially limited in 1997 and 1998 while moving away from the uplift center. Most of the activity is concentrated in the northwest while little or no activity is recorded southeast to the uplift center.

The seismicity is mostly continuous with varying intensity but we could identify about 2 swarm-like episodes per year in the vicinity of the uplift (Figure 4).

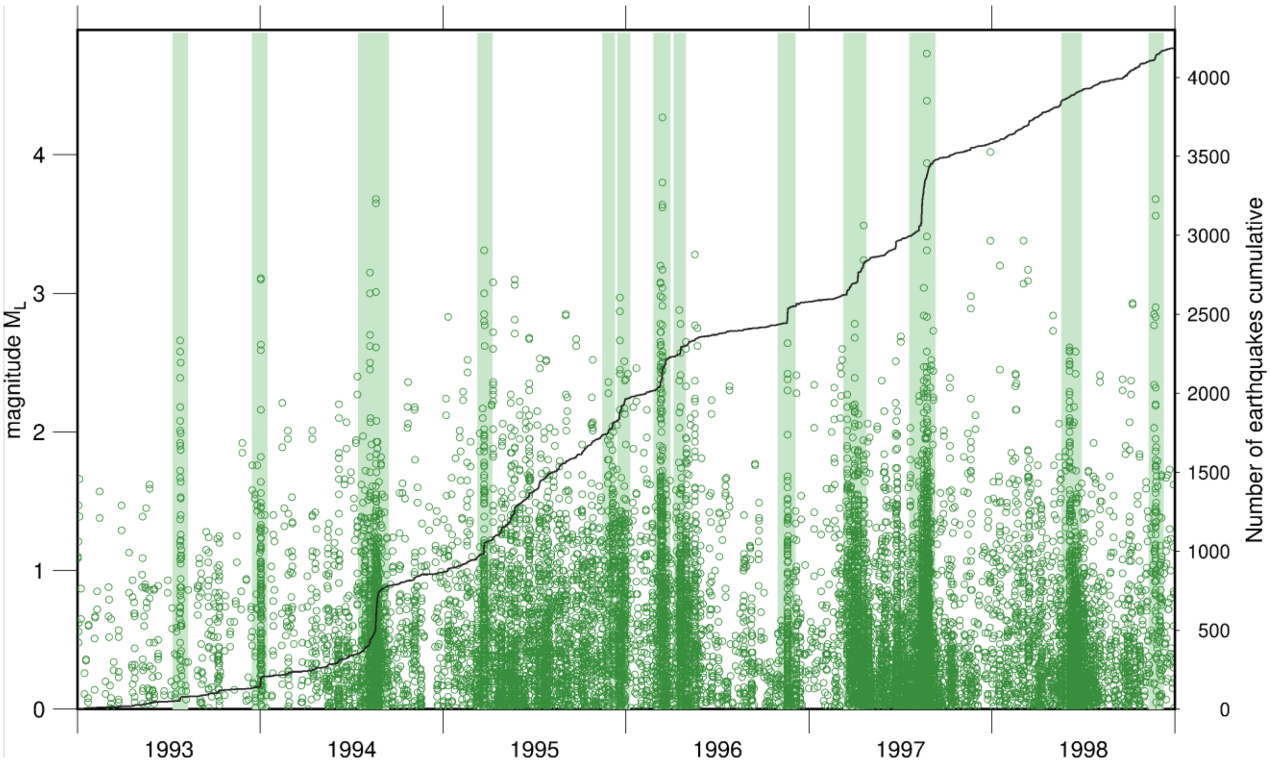

Figure 4: Time magnitude relation. Seismic activity is both continuous and of swarm-like nature. Periods of swarm-like activity appear as vertical lines in the plot and are marked in light-green.

2.1 Relative Earthquake Relocation Method

Earthquakes were relocated using the Slunga software (Slunga et al., 1995). This software is not openly available but has been used by the Iceland Meteorological Office (IMO) for earthquake analysis for 25 years. Like all relocation algorithms it is based on the assumption that earthquakes of similar size that occur on the same or neighboring faults have similar waveforms, that is they have similar mechanisms and dominant frequency, so the time difference between the arrivals of the waveforms can be estimated with high accuracy using cross-correlation.

The seismicity is arranged into groups by the software and then the activity is relocated using all pairs of events in each group. Input parameters are the minimum and maximum number of earthquakes in a group as well as the size of the group (radius in km) and the distance between groups (distance between midpoints of groups in km). Years of usage and experience at the IMO suggest that 9 to 45 earthquakes per group yield best results. However, most of the groups contain 45 events. The size and distance of groups highly depends on the characteristics of the seismicity which are the size of the faults or fissure swarms where earthquakes are expected to be similar.

For each pair of events in a group a cross-correlation (CC) of the waveforms is carried out. Only pairs with a CC coefficient of 0.8 and higher are used for further analysis. This ensures that earthquakes that are spatially close but not similar are not relocated and do not appear in the output. Then a least squares problem is solved taking into account the absolute p and s arrival times together with the relative p, s and s-p arrival times for each group. Here, the CC coefficient is used to weight the arrival times of each pair of events. If an event if is more than one group, the final locations is an average of the different locations. Because of the inclusion of absolute travel times both absolute and relative locations are improved.

2.2 Relative Relocation Results

For our data set we tested several parameters, that is, varying the size and distance between groups. In a first step, we preselected those parameter sets where the earthquakes were best interconnected. As criteria we used the number of earthquakes that could be relocated and the number of groups that each event was a part of. The visual inspection of results from relocations with the different parameter sets revealed that the relative locations were hardly affected by the different group sizes. We saw however, that the absolute locations could vary up to 500 m horizontally, mostly in EW direction. Without additional information such as geological surface mapping of faults, assuming the activated faults are reaching all the way up to the surface, we are in no position to distinguish between the different parameter combinations and select a “best” result. And even in the case that a fault at depth coincided with a fault mapped on the surface, it would be very challenging to ascribe the seismic activity to a single fault since faults in Hengill often come in parallel swarms with distances on the order on the absolute uncertainties between the individual faults. The locations with the median of the parameters are shown in Figure 5.

The relocated earthquakes give a much clearer picture than the catalogue data. We see alignments and clustering of activity, most of which are either NNE or ENE trending. The depth is more refined and has probably improved the most considering the network geometry.

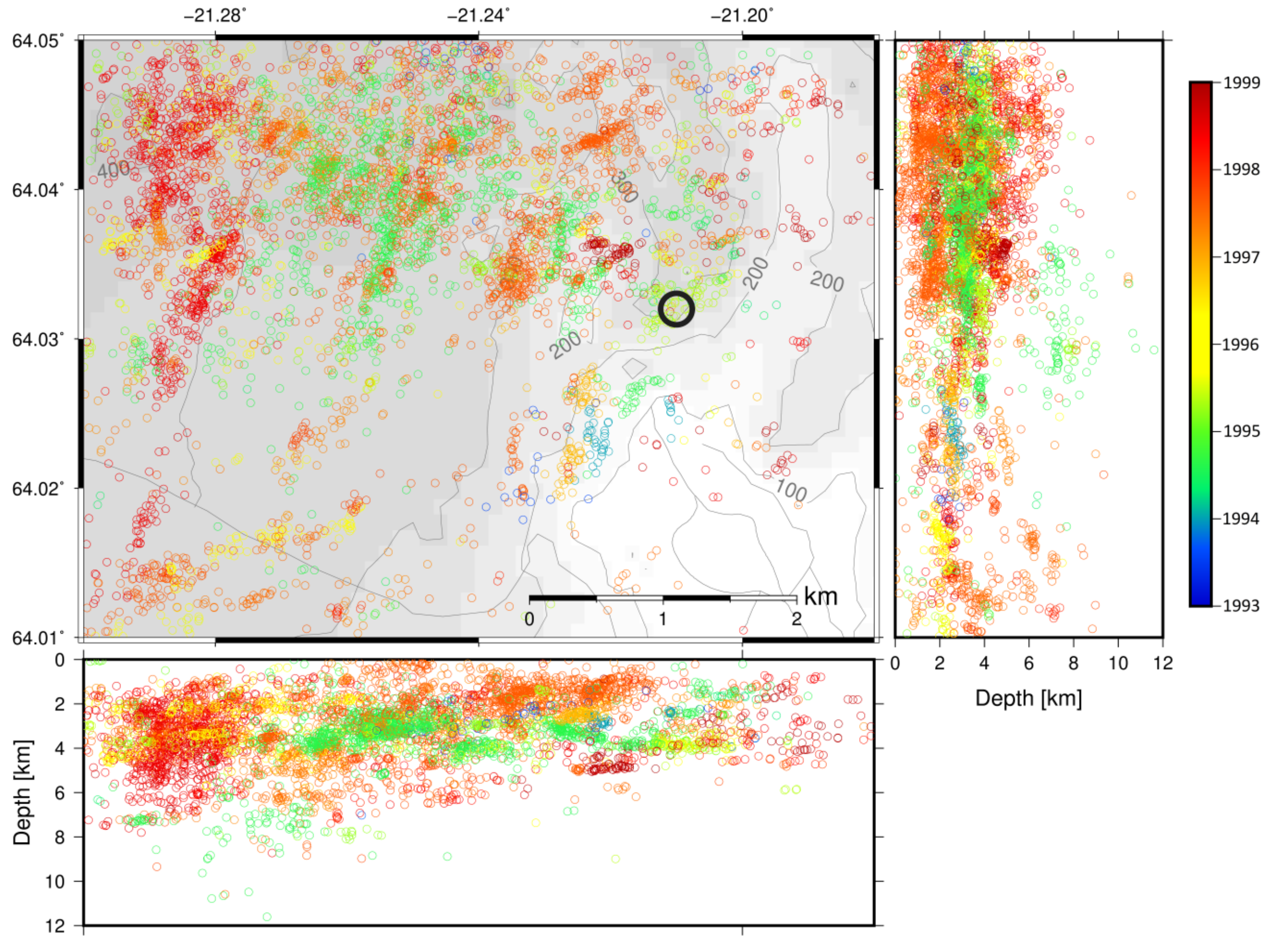

Figure 5: Map view and E-W and N-S profiles of the relocated earthquakes. The colors indicate time. The results have been filtered on the base of the formal error. Only earthquakes with horizontal relative errors of less than 100 m and depth relative errors of less than 300 m are plotted.

2.3 Absolute Location Accuracy

Using cross-correlation to achieve exact timing of p- and s-wave onset can be used not only to improve relative locations, but the absolute locations are also improved (Slunga et al., 1995). Accuracy of individually picked earthquakes in the SIL system is 500 to 700 m horizontally and up to 1000 m in depth based on picking accuracy and wavelength. If the distance between a pair of relocated earthquakes is small in comparison to the distance to the next station, a small change in the absolute locations of this pair of as little as 200 m will cause an arrival time difference of 0.5 ms, big enough to be identified with cross-correlation.

the absolute and relative uncertainties for each coordinate are given in the output. It remains unclear though, how exactly the uncertainties are calculated, so we use a different approach to roughly quantify the accuracy of the absolute locations. In the relocation process, different input parameters sets had been tested.

In a first step, the results are compared visually. The relative locations vary very little between parameter sets while the absolute location of the earthquake sequences show lateral movement of up to 500 m between sets. To refine this estimate further, we selected 7 “reasonable” sets of parameters and calculated the average and standard deviation of the coordinates and depths of ca. 1100 earthquakes. After excluding outliers, we used the average of the standard deviation of the different coordinates as a rough estimate of the accuracy. The standard deviation of the longitudes and latitudes suggest that the horizontal errors lie within ca. 300 m (Figure 6). Depth is much less refined due to the lack of a station right on top, so the vertical error is estimated to be about 1 km.

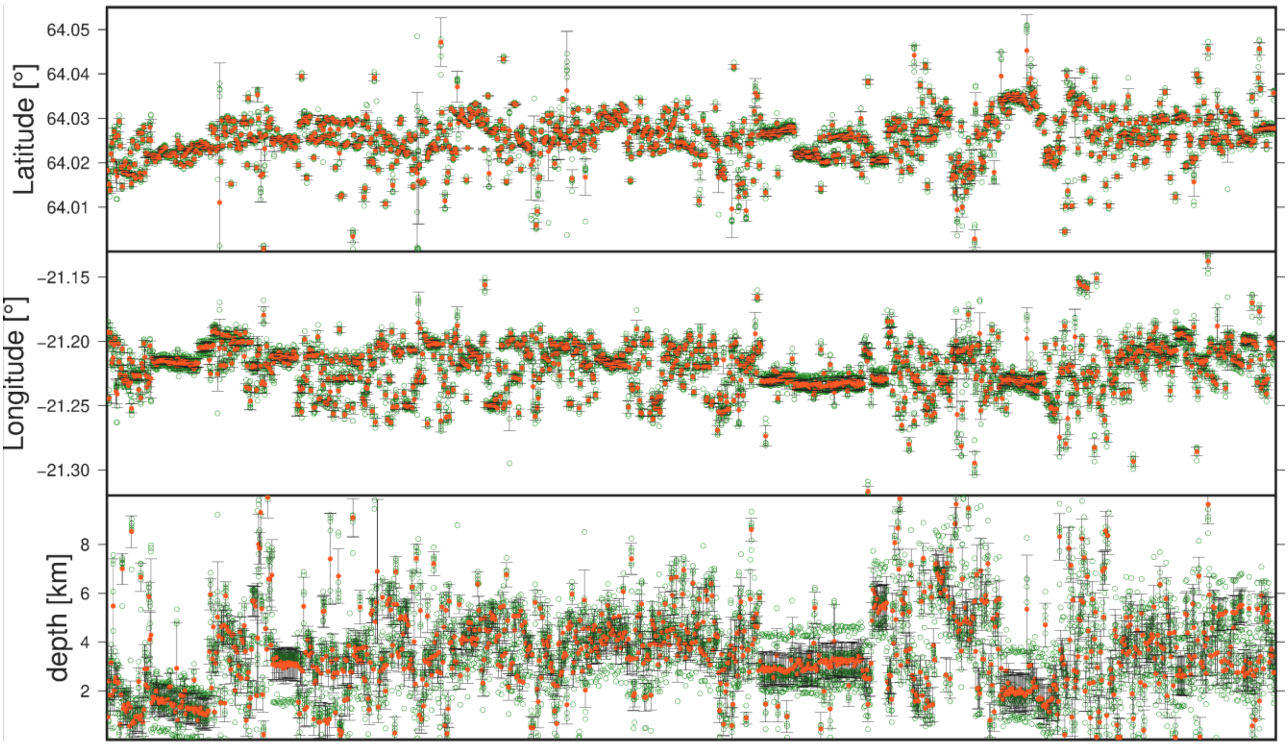

Figure 6: Latitude, longitude and depth of 1120 earthquakes obtained from 7 different runs of the Slunga software using different group size and distance parameters (green dots). Orange dots indicate the average of the 7 relocations and the error bars the standard deviation

3. DISCUSSION

An uplift episode in the last decade of the 20th century that was possibly caused by a magmatic intrusion triggered more than 90.000 earthquakes in the Hengill volcanic complex. The catalogue locations are diffuse not showing any structures, so we used a relocation algorithm that significantly improved the earthquake locations. Testing different parameters for the group sizes and distances between groups for the Slunga relocation program suggested that horizontal uncertainties are ca. 300 m and ca. 1 km vertical.

Fault orientations as revealed by the relocation are mostly NNE and ENE trending which is in agreement with regional stress field rather than reflecting the uplift source geometry. This indicates that the additional stress caused by the uplift is minor and acts as a mere trigger to the activity that otherwise might have occurred later anyway. Rather than new faults being created we probably see activation of suboptimal oriented faults with respect to the uplift, once more underlining how small the contribution of the uplift induced stress is in comparison to the regional stress. Pedersen et al. (2007) compared the stressing rate caused by the intrusion to the seismic moment release in Hengill from 1994 to 1999 as well as in two other intrusion events in Iceland that were accompanied by an increase in seismic activity. They found that there is no simple correlation between intrusion rate and seismicity and that each case must be considered individually taking the background stress field into account.

In the direct vicinity of the uplift center within a 2 to 3 km radius fault activation patterns vary a lot. In the northwest quadrant the biggest number of earthquakes was located. The area has been active repeatedly from 1994 to 1998. Earthquakes are clustered and both NNE and ENE alignments are clearly visible. In the northeast quadrant mostly ENE trending fault are activated. Only small clusters of earthquakes show extension in northerly direction and these alignments are only a few hundred meters in length. The southeast quadrant is the least active. Too few earthquakes were relocated here to see whether they align. In the southwest quadrant the picture is much clearer. Close to the uplift center NNE oriented, neighboring faults have been activated repeatedly but not continuously from 1993 to 1998. In the same quadrant but further to the west in about 3 to 5 km from the uplift center a long NEN trending fault and smaller neighboring faults have been activated in 1995 and 1996.

A study by Keiding et al. (2009) on the neighboring seismically active areas Krísúvík and Fagradalsfjall on the Reykjanes peninsula comparing stress derived from moment tensor inversion and strain calculated from GPS data that the stress is mostly driven by the plate motion and geothermal activity only acts as a secondary triggering mechanism. The same could be true for the uplift, only adding to the existing stress field but not changing it significantly.

4. CONCLUSIONS

Relative relocation significantly improves the resolution. Test show that the relative locations have very little uncertainties while the absolute locations of the earthquakes are to a certain degree depended on the parameter selection for the group sizes used by the algorithm.

Alignments, fault geometries and also areas with little or no activity are visible after the relocation. The faults that are activated mostly respect the regional stress field and the stress induced by the uplift functions as a trigger of the seismic activity.

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