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Seismic Monitoring in Krafla, Námafjall and Þeistareykir

November 2017 to November 2018

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Title: Seismic Monitoring in Krafla, Námafjall and Þeistareykir. November 2017 to November 2018.

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Abstract: From November 2016 to October 2017 more than 4900 earthquakes were located in the greater Krafla area including the Námafjall and Þeistareykir geothermal areas. In Krafla, earthquakes are up to 2.5 km deep while reaching down to 6 and 8 km in Þeistareykir and Námafjall, respectively. The magnitude distribution also differs significantly in the three areas from a wide range in Krafla to a higher ratio of bigger magnitudes in Þeistareykir and only small magnitudes in Námafjall. Velocity ratios calculated from Wadati diagrams show decreased values both in the Krafla and Námafjall geothermal areas. In Þeistareykir the ratio is higher and about the same as typical for the Icelandic crust. Injection rates in well K-26 and K-39 in Krafla had both stable phases as well as rapid changes throughout the year but no fluctuation in measured earthquake numbers can be related to changes in reinjection rates. Focal mechanisms of selected earthquakes show a mixture of normal and intermediate faulting mechanism revealing strong lateral variations in the overall extensional stress regime. The semi-annual fluctuation pattern of the number of earthquakes extends into 2018.

Keywords:

Seismicity, earthquakes, Vp/Vs ratio, b values, focal mechanism, seasonal variations
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1 Introduction

In this report, we present the results of the earthquake monitoring in Krafla geothermal area from November 1st 2017 until October 31st 2018 including the earthquake activity in Þeistareykir and Námafjall geothermal areas. The task involves the development and maintenance of the local seismic network, automatic data transfer to Landsvirkjun (LV, The National Power Company) and to Iceland GeoSurvey (ÍSOR) and the processing and analysis of the data. LV owns and runs the seismic stations and takes care of the maintenance of the stations as well as the data transfer in cooperation with ÍSOR. ÍSOR processes, analyses and interprets the data in the context of the geothermal field.

2 The seismic network

In the period described in this report the seismic network remains unchanged in comparison to the year before, consisting of 18 stations operated by ÍSOR on behalf of LV in the Krafla, Námafjall and Þeistareykir geothermal areas and 6 local stations of the national network operated by the IMO. For a detailed description of the seismic stations and a map of the network see Blanck et al. (2018).

3 Recorded earthquakes

With the Krafla seismic network, a total of 4903 earthquakes from November 1st 2017 until October 31st 2018 were located. During the same period the IMO recorded 403 events in the same area.

Daily activity varies and is both continuous and of swarm-like nature. Swarms appear as vertical lines in Figure 1. On 14 days no earthquakes were recorded and the maximum of 51 events was recorded on January 29th, 2018. The average is 11.8 events per day. In the winter months, smaller magnitude earthquakes appear to be missing (Figure 2) what is possibly a result of the decrease in sensitivity of the network due to weather conditions.

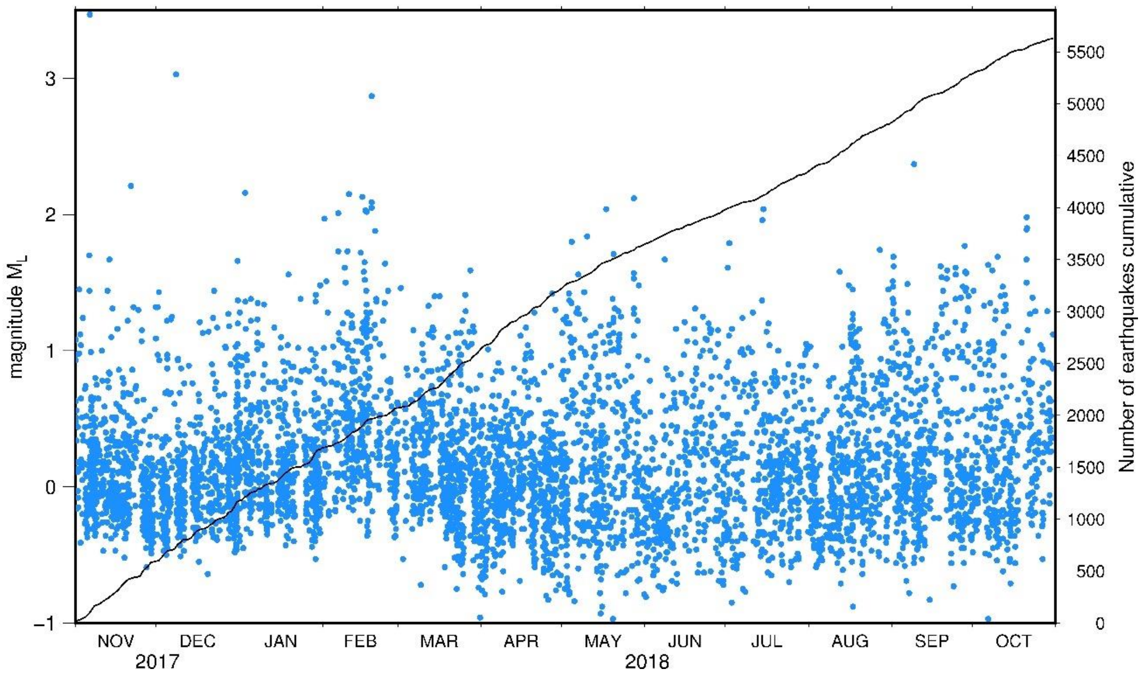

Figure 1. *Time-magnitude plot for the whole area as plotted in Figure 2. Each located earthquake is represented by a blue dot according to its origin time and magnitude. The activity is characterized by distinct swarms with short quiet periods. The cumulative number of earthquakes (black line) shows a smooth increase with time, indicating long term continuous seismic activity.*

4 Spatial distribution of events

In later analysis presented in this report we will refer to the sub-areas Þeistareykir, Krafla and Námafjall as defined by the black boxes in Figure 3. In total 4293 earthquakes were located in the box around the Krafla geothermal area, 197 in Námafjall and 319 in Þeistareykir.

Only 94 earthquakes have been located outside these defined sub-areas but within the frame on Figure 1. They will be included in the analysis presented later in this report in "all earthquakes".

In the Krafla geothermal area earthquakes are shallow, most of them above 3 km depth apart from a small area in the southwest corner of the Krafla geothermal area where earthquakes occur down to 4 km. The bigger earthquakes in Krafla are all located at the lower edge of the active layer or close to 2 km. There are two small clusters to the north and west of the Krafla area (outside the box), reaching 3 to 5 km depth. In Þeistareykir and Námafjall most earthquakes are recorded in 2 to 6 km and 2 to 8 km depth, respectively. Further, there is some activity in Gjástykki about 10 to 15 km north of Krafla.

While magnitudes in Krafla geothermal area vary widely, earthquakes recorded in Þeistareykir have a higher ratio of bigger magnitudes to smaller ones while seismicity in Námafjall is of lower magnitudes.

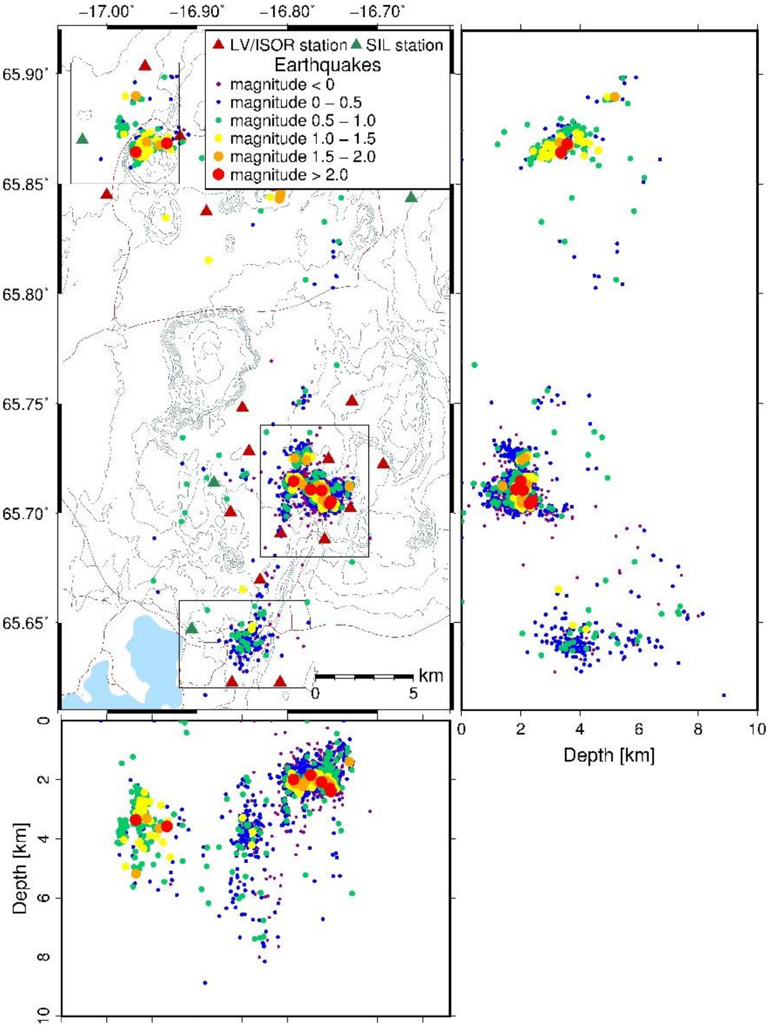

Figure 2. *Spatial distribution of earthquakes in surface projection and E-W and S-N sections.*

The depth distribution (Figure 3) shows that while in Krafla seismic activity is concentrated in a small depth range earthquake depths vary much more both in Þeistareykir and Námafjall. In Þeistareykir most earthquakes occur between 2.5 and 4.0 km depth. In Námafjall, most earthquakes are located between 3 and 5 km but in contrary to the other two areas does not fade as fast with depth but quite a few earthquakes are located between 5 and 6 km.

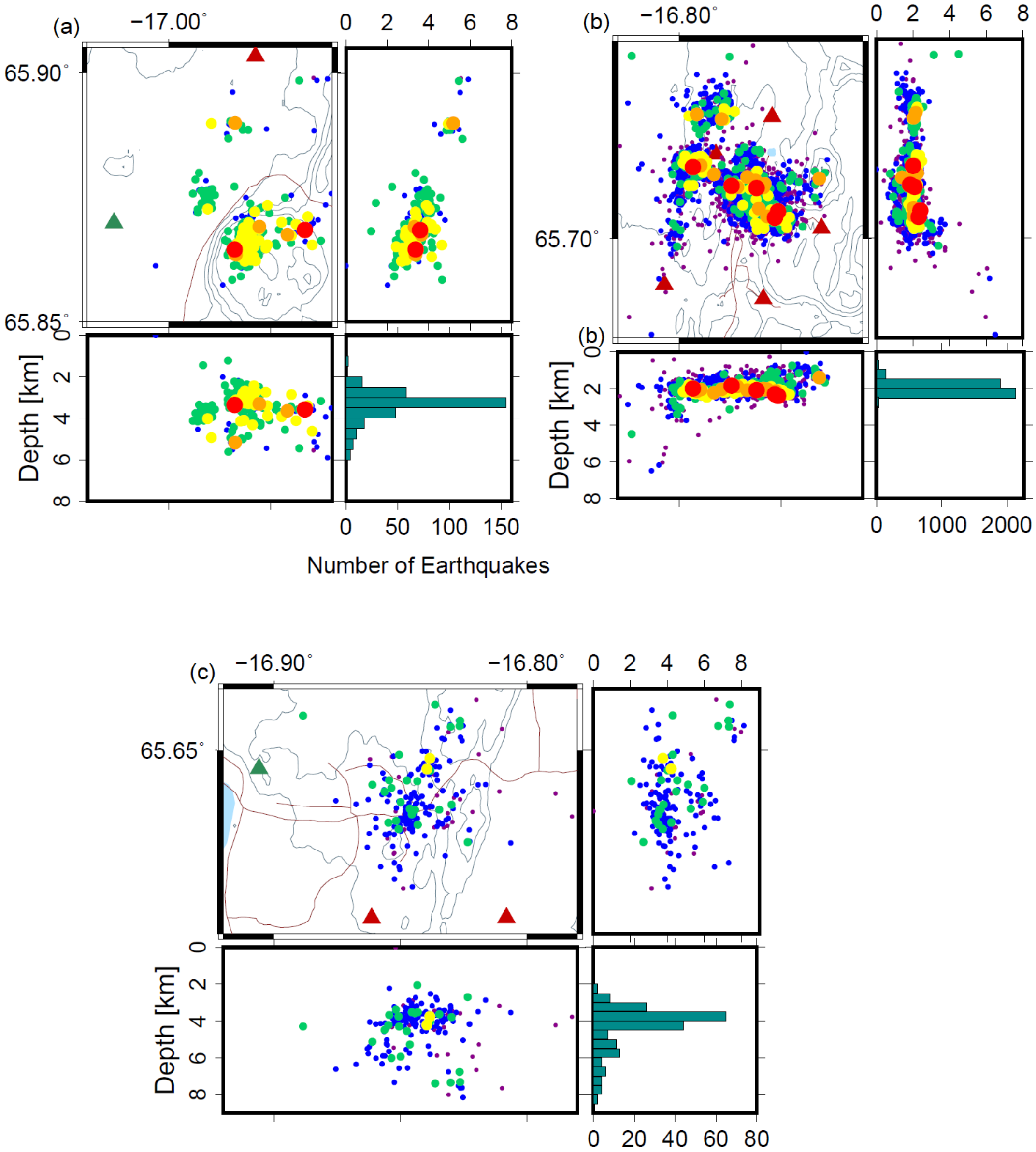

Figure 3. *Map view, NS and EW profiles and depth distribution of the events located in the Þeistareykir (a), Krafla (b) and Námafjall (c) geothermal areas.*

5 Vp/Vs ratio

Wadati diagrams (Wadati, 1933) were used to estimate Vp/Vs ratios in the Krafla, Þeistareykir and Námafjall geothermal areas. The travel time of the S-wave is plotted as a function of the P-wave travel time and the slope is determined using linear regression (Figure 5).

As described already in last year's annual report (Blanck et al., 2018), we select only earthquakes and recording from stations inside the areas (areas as defined by boxes in

Figure 2) to get information about the crust in the geothermal areas only since the Wadati method is averaging the Vp/Vs ratio over all ray paths.

In the Krafla geothermal area, the Vp/Vs ratio derived from the Wadati diagram is 1.70 ± 0.01 and 1.72 ± 0.02 in Námafjall which is identical to last years' result. In Þeistareykir the ratio derived from this years' data is with 1.76 ± 0.01 slightly higher than last years' result (1.74 ± 0.02) and therewith even closer to the Vp/Vs ratios typically found in Icelandic crust which is 1.75 to 1.78 (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al., 2001).

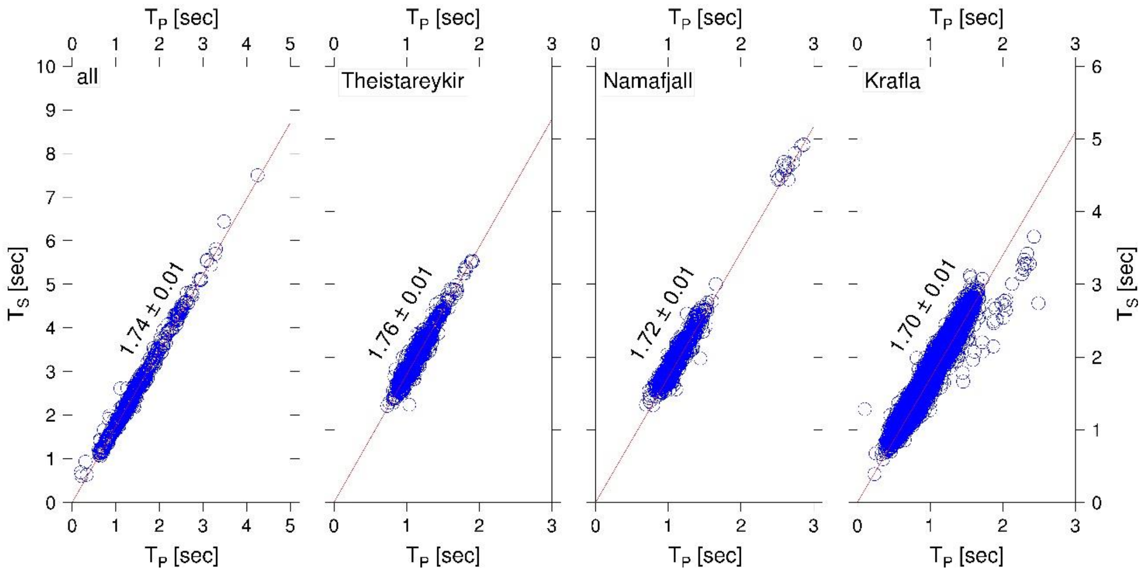

Figure 4. *Vp/Vs ratio calculated from all earthquakes as well as for the Krafla, Þeistareykir and Námafjall geothermal areas. The ratio is lowest in Krafla with 1.70 while the average derived from all earthquakes and stations is 1.74.*

6 Injection rate and earthquake activity

For the period covered in this report, injection rate information for well K-26 and K-39 is available with high time resolution (recordings every 5 min). To match the injection rate to the seismic activity (number of events per day) we calculate an average injection rate for each day. To compare the injection rate and the numbers of recorded earthquakes we chose a small area around the wells as indicated in Figure 5 (red and green boxes respectively).

K-26: For most of the time injections rates are between 60 and 80 l/s with some smaller and bigger interruptions when the injection rate drops down temporarily. From August 13 to October 16 injection is mostly down with small interruptions.

K-39: From November 2017 to the beginning of July 2018 the injection rate is rather stable between 50 and 60 l/s with short periods of lower injection rate on November 21st and from May 29th to June 12th. From July to the end of October 2018 the injection rate is again rather stable and varies between 27 to 31 l/s with some lower values in August.

In both cases the earthquake activity is fluctuating but no relation to the injection rate can be identified. Since we know that geothermal often respond very rapidly to changes in injection and even production (Cardiff et al., 2018), we would expect a clear increase or decrease in activity following changes in injection immediately. If there is activity that can be related to the changes in injection rate, it is smaller than the natural fluctuations. However, it becomes obvious on Figure 5 that less earthquakes occur around K-39 when the injection rate is lower but there is no a sharp transition.

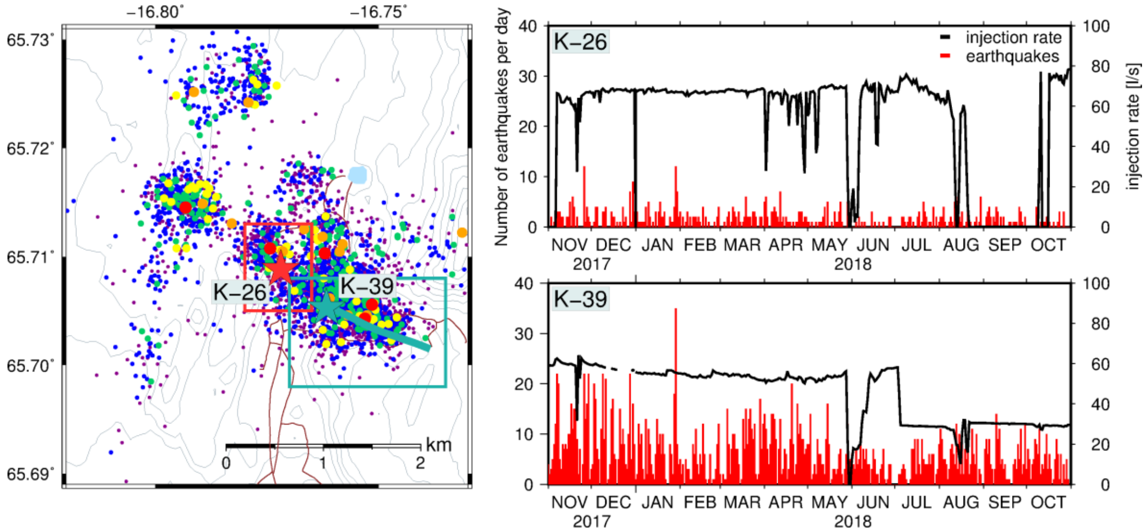

Figure 5. *Comparison of injection rate and earthquake number (right) for boreholes K-26 and K-39 as recorded inside the red and green box, respectively (left).*

7 Magnitude frequency relation

The frequency-magnitude relation, also called the Gutenberg-Richter relation (Gutenberg and Richter, 1956), describes the observation that small earthquakes are more common than those of bigger magnitude. For more detail, see Blanck et al. (2018).

Measured magnitudes vary from -1.72 to 2.37 in Krafla area. The catalogue is complete down to earthquakes of magnitudes around 0. In Þeistareykir the magnitudes range from -0.08 to 2.15 and in Námafjall from -0.30 to 1.18 (areas as defined by boxes in Figure 2). In Þeistareykir the catalogue is complete down to about magnitude 0.7 and in Námafall to magnitude 0.5 what is somewhat higher than in Krafla as the network density is smaller in these areas and consequently their sensitivity is smaller.

The slope of the cumulative number of events is the b value. For all events combined and for those in the Krafla geothermal area only, the b value is about 1.3 Figure 6). In Þeistareykir it is slightly higher with 1.5 and in Námafjall the b-value is 2.1. B values higher than 1 indicate a weak crust where stress cannot be sufficiently built up to cause bigger earthquakes.

While last year's report (Blanck et al., 2018) confirmed a composite magnitude distribution as suggested by Ágústsson and Guðnason (2016) caused by different magnitudes distributions for different depth intervals, this year's distribution is inconclusive and cannot reinforce this observation. Two bigger events of magnitude 1.14 and 1.18 seem to suggest that the distribution might be better described by two b-values, but these could also be outliers.

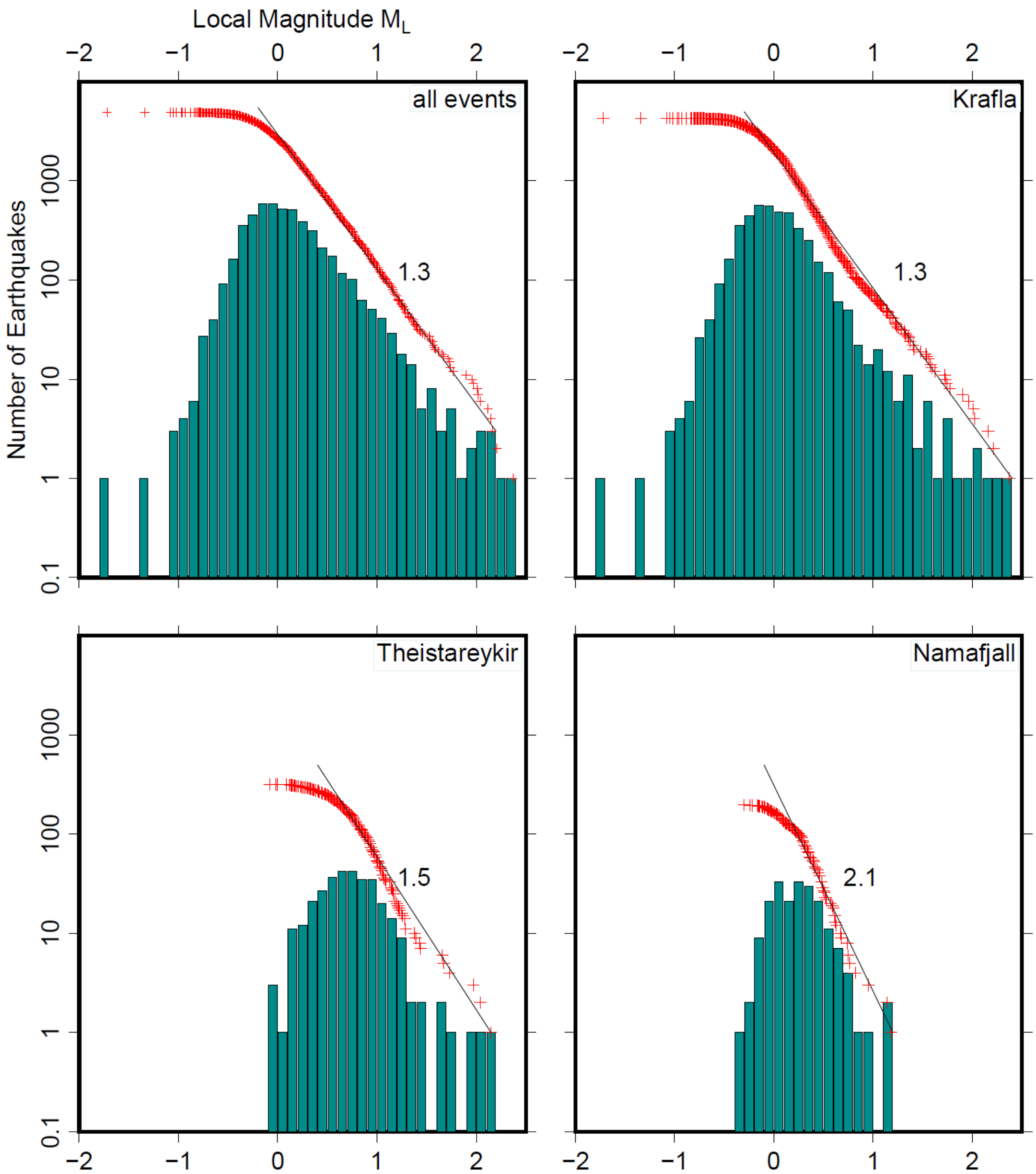

Figure 6. *Magnitude-frequency relation. Green bars represent the absolute number and the red stars the cumulative number of earthquakes. Black lines approximate the slope of the cumulative number, the b-values are given.*

8 Focal mechanisms

Focal mechanisms in geothermal areas show typically a great variety (e.g. Kristjánsdóttir, 2013; Guðnason et al., 2016). We used the HASH1.2 software (Hardebeck and Shearer, 2002) to calculate focal mechanisms for selected events. For more detail see Blanck et al. (2018).

We selected earthquakes based on the number of picks, magnitude (> M_L 1.5) and the geometry of the subnetwork recording the event, using only events with an azimuth gap between stations of less than 180°. Of the 23 earthquakes that fulfilled these criteria, HASH1.2 could calculate focal mechanisms for 16 of these, 15 in Krafla geothermal area and 1 in Þeistareykir. In 6 of these events the normal fault component is dominant, in 3 events the strike-slip component is dominant and 7, including the one in Þeistareykir, are intermediate (Figure 7).

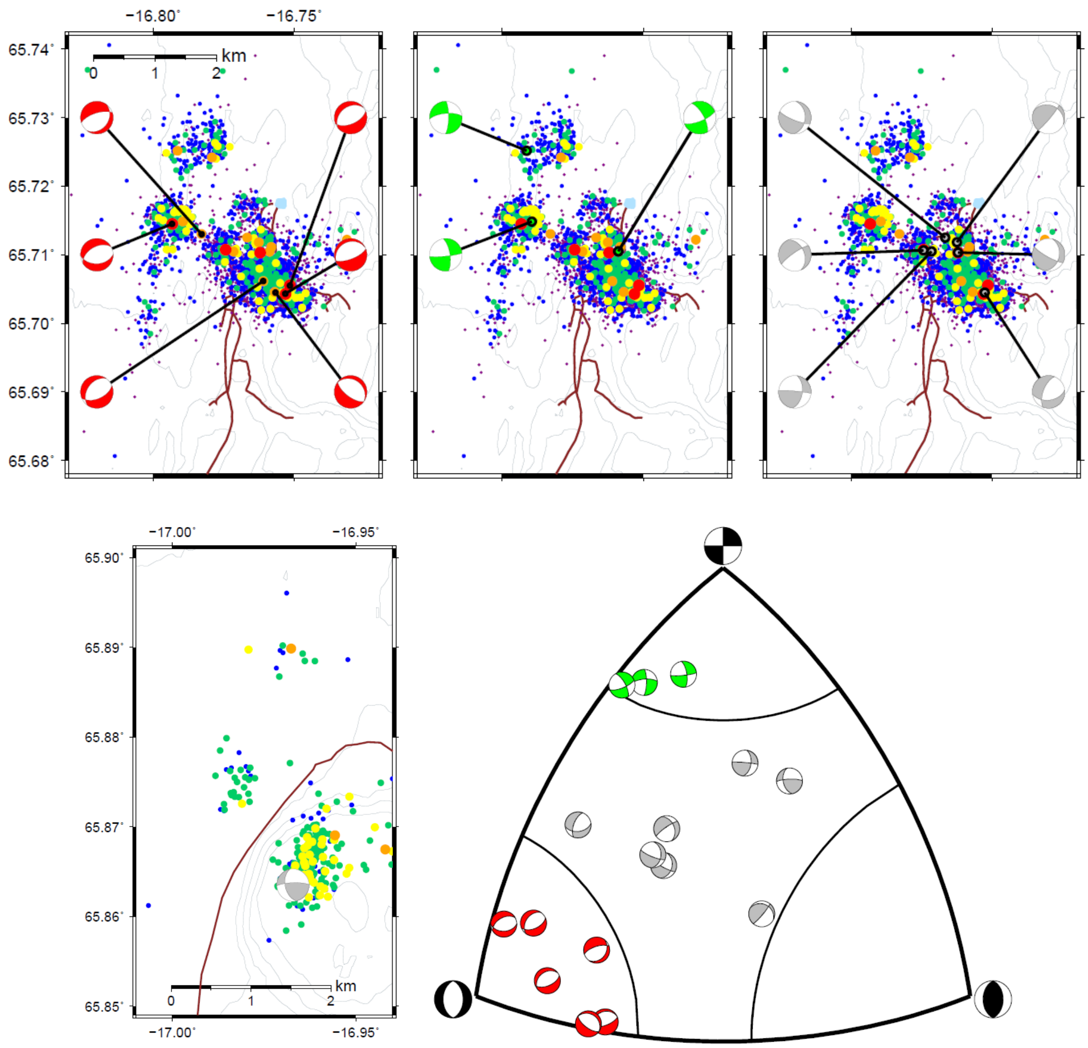

Figure 7. *Focal mechanisms for 16 selected events. These are lower hemisphere plots and the compressional quadrants are colored. The earthquake in Þeistareykir (bottom left) is located at 3.4 km depth while the earthquakes in Krafla (right) are 1.9 to 2.3 km deep. The triangle method from Frohlich (1992) was used to classify the mechanisms.*

Of the 6 normal faulting events, 5 are NE-SW oriented, the last one about perpendicular to the others. The strike-slip and intermediate events do not show a preferred rupture orientation. For a more detailed description of the focal mechanisms, see Table 1 below.

Table 1. *Details for selected events and their focal mechanism.*

	date	time	lat [°]	lon [°]	depth [km]	M_L	number of polarities	faulting mechanism	
1	21.11.2017	14:07:46.61	65.71066	-16.77433	1.84	2.21	10		intermediate
2	31.12.2017	08:11:47.91	65.86350	-16.96717	3.36	1.66	9		intermediate
3	03.01.2018	02:42:59.72	65.70550	-16.75150	2.40	2.16	11		strike-slip
4	19.01.2018	06:38:03.07	65.71050	-16.77150	1.88	1.56	11		intermediate
5	06.02.2018	19:39:14.20	65.71450	-16.79333	1.99	2.01	15		normal
6	06.02.2018	20:09:05.67	65.71484	-16.78950	2.05	1.73	15		intermediate
7	15.02.2018	05:18:30.74	65.70617	-16.76100	2.03	1.72	12		strike-slip
8	17.02.2018	09:37:47.42	65.70433	-16.75317	2.30	2.02	14		normal
9	28.03.2018	00:19:18.20	65.71300	-16.78283	2.22	1.59	22		normal
10	14.07.2018	19:39:10.90	65.72517	-16.79133	2.14	1.96	11		normal
11	12.08.2018	13:31:54.59	65.71183	-16.76250	2.07	1.58	11		strike-slip
12	27.08.2018	13:26:23.97	65.70450	-16.75667	2.03	1.74	16		normal
13	09.09.2018	07:23:02.96	65.71033	-16.76217	2.08	2.37	12		intermediate
14	19.09.2018	13:29:26.08	65.71050	-16.75883	2.01	1.54	13		normal
15	28.09.2018	04:44:30.26	65.71250	-16.76667	2.09	1.77	13		intermediate
16	21.10.2018	09:15:15.24	65.70450	-16.75267	2.14	1.90	12		intermediate

9 Semi-annual fluctuations

Here, we are updating the semi-annual variations in the number of recorded earthquakes as described in the previous annual reports (Blanck et al., 2017, 2018). Generally speaking, smaller numbers of earthquakes are recorded in the winter and summer months while the numbers are higher in spring and autumn months. The cause is object to conjecture. The data has been low pass filtered to eliminate outliers and short-term variations e.g. caused by weather and wind (Figure 12).

At the time being, the time series is still too short for periods of a year or longer to be identified reliably by spectral analysis, but a preliminary analysis of the filtered data indicates that apart from a half year fluctuation there is a second major period of about 500 days.

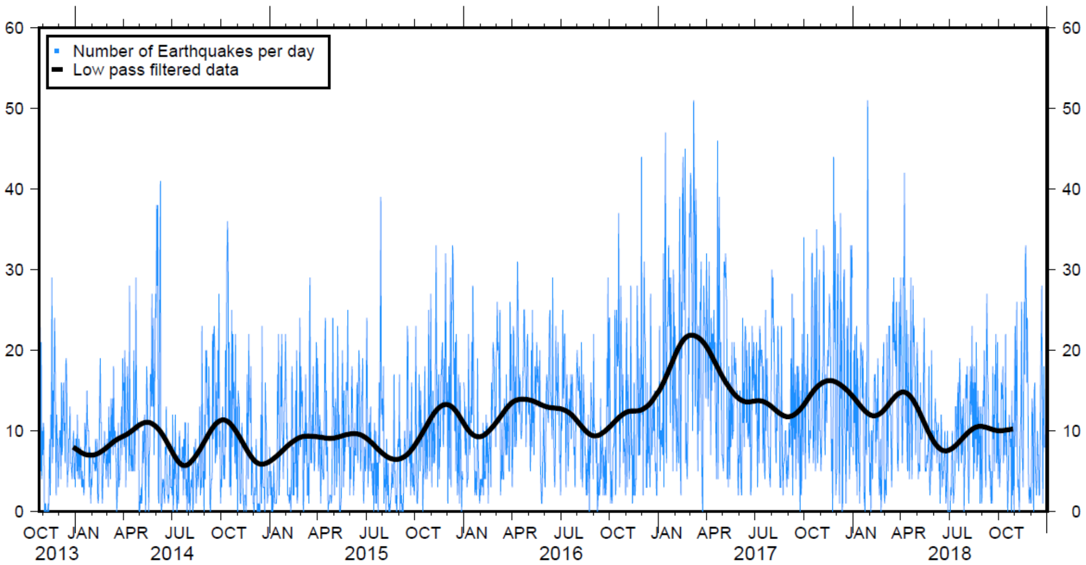

Figure 8. *Number of daily recorded events in Krafla geothermal area from October 25th 2013 until October 31st 2018 (blue curve) and low pass filtered (black curve). The semi-annual trend observed during the last three years continues.*

10 Summary

From November 2017 to October 2018 more than 4900 earthquakes were recorded in the greater Krafla area including the Námafjall and Þeistareykir geothermal areas. The vast majority of almost 4300 earthquakes was located in the Krafla geothermal area and only a few hundred in Þeistareykir and Námafjall. The activity in these two areas varies significantly from the activity in Krafla. Earthquakes have deeper origin and are located over a wider depth range. Magnitudes show the biggest variation in Þeistareykir where there are comparatively many earthquakes of higher magnitude and in Námafjall they are much smaller than in the other two areas.

The ratio of the seismic velocities (Vp/Vs) in the crust is lowest in Krafla with 1.70, slightly higher in Námafjall with 1.72 and in Þeistareykir it reaches 1.76 which is a standard value of the Icelandic crust. This indicates that no shallow magma chamber is present in Þeistareykir.

Injection rates for well K-26 and K-39 in Krafla are well documented and show both stable phases and variation in the injection rate but no correlation to the seismic activity could be identified in the vicinity of the wells. Surrounding K-39, there appears to be higher numbers of earthquakes while the injection rate is higher, but the change is smooth indicating that pressure changes associated with changes in injection rate can be a slow process.

Magnitudes of the seismic events differ significantly in the three geothermal areas. Furthermore, the magnitude frequency distribution is also quite different. In Krafla geothermal area the magnitude range is the widest while in Þeistareykir a significant high portion of events is comparably big (20 earthquakes with magnitudes higher then 1.2). This might partly be a consequence of the lower sensitivity of the local network. In Námafjall all earthquakes are smaller than magnitude M_L 1.2.

Focal mechanisms of selected earthquakes are mostly normal faulting dominated or show an intermediate mechanism. Strike-slip events were 3 and no thrust faulting could be identified. Nodal plane orientations show a great variety, signifying strong lateral variations in the overall expending stress regime.

The semi-annual fluctuation pattern of the number of earthquakes suggested first by Blanck et al. (2014) extends into 2018. Preliminary spectral analysis of the filtered data suggests a second major frequency of about 500 days to the 6-month periodicity.

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