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Landsvirkjun

Seismic Monitoring in Krafla

November 2015 to November 2016

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Abstract:

The seismic network installed in Krafla has been under continuous development since 2013. Data is streaming in real-time and data analysis is carried out on a daily basis. In this report, the operation of the network and the analysis of the seismic activity for the period from November 1st 2015 to October 31st 2016 is presented. A total of 5037 earthquake were recorded, of which 4531 could be relocated using the hypoDD software.

The results of the analysis of seismicity are comparable those presented in last year's report. Most earthquakes occurred at one to two km depth. The brittle-ductile boundary lies in about 2.3 km depth. To SW the depth is somewhat larger that might indicate lateral limit of a magma chamber. The magnitudes range from -0.53 to 3.36. The b-value is higher than one indicating a weak crust.

The Vp/Vs ratio inside the geothermal area is 1.71 and 1.78 outside of it.

For selected events, representing different areas within the geothermal field focal mechanism were calculated based on pick polarities suing the FPFIT software. They indicate a highly variable, extension dominated stress regime.

The seismic activity shows a semi-annual trend. Both in spring and autumn more earthquakes are recorded than in summer and winter. A cause has not been clearly identified but variations in injection rates or seasonal variations in precipitation are conceivable.

Keywords:

Seismicity, earthquakes, brittle-ductile boundary, Vp/Vs ratio, focal mechanism, seasonal variations, Krafla, Landsvirkjun, ÍSOR

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Table of contents

List of tables

List of figures

1 Introduction

In this report we present the results of the earthquake monitoring in Krafla geothermal area during the time period from November 1st 2015 to October 31st 2016. 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. Data is also achieved from the Icelandic regional seismic network, the SIL-network, which is operated by the Icelandic Meteorological Office (IMO). ÍSOR processes, analyses and interprets the data in the context of the geothermal field.

2 The seismic network

The local permanent seismic network in Krafla geothermal area, including the stations installed in Námafjall and in Þeistareykir, consists of 17 stations. During the time period discussed in this report only one change in position were made to the layout of the network. In October the station HDH was demounted and reinstalled north northeast of its former location as HDHA.

In addition to the network run by LV and ÍSOR, we are having access to 6 seismic stations in the area which are run by the Icelandic Meteorological Office (IMO) as a part of the national seismic network (The SIL network).

Description of the stations is shown in Table 1 and their location in Figure 1.

In this report the area and the seismic activity analysed is limited to the area plotted in Figure 1.

Table 1. *Seismic stations in Krafla, their locations and type of sensors and digitizers.*

Station name	Latitude	Longitude	Elevation [m]	Depth [m]	Sensor	Digitizer	Begin data End time *
GRT	65.702178	-16.730277	611.0	-	Lennartz LE-3Dlite	Reftek	29.09.2006
HHK	65.690815	-16.807241	467.0	46.0	Lennartz LE-3D5s	Reftek	27.09.2006
HVET5	65.711570	-16.769200	652.0	9.0	Lennartz LE-3Dlite	Reftek	21.10.2015
LHN	65.717229	-16.781867	545.0	60.0	OYO Geospace	Reftek	14.05.2008
SBS	65.687880	-16.758784	445.0	57.0	OYO Geospace	Reftek	30.09.2006
SPB	65.724682	-16.754413	569.0	26.0	Lennartz LE-3D5s	Reftek	27.09.2006
GFJ	65.747990	-16.849720	531.0	-	Lennartz LE-3D5s	Reftek	30.08.2013
HDH	65.745583	-16.735417	655.0	-	Lennartz LE-3Dlite	Guralp	02.09.2013 18.10.2016*
HDHA	65.751033	-16.72845	645.0	-	Lennartz LE-3Dlite	Guralp	19.10.2016
HVA	65.728217	-16.842483	541.0	-	Lennartz LE-3D5s	Reftek	30.08.2013
HYD	65.722317	-16.693730	634.0	-	Lennartz LE-3D5s	Guralp	04.09.2013
SHN	65.700410	-16.862990	527.0	-	Lennartz LE-3D5s	Guralp	28.08.2013
BEINI	65.622630	-16.861340	312.0	-	Lennartz LE-3Dlite	Reftek	16.05.2014
DALFJ	65.669410	-16.830260	472.0	-	Lennartz LE-3Dlite	Reftek	12.06.2014
HSPHO	65.623340	-16.807500	372.0	-	Lennartz LE-3Dlite	Reftek	06.06.2014
THORF	65.837300	-16.889590	447.0	-	Lennartz LE-3Dlite	Reftek	01.09.2014
THEIG	65.903270	-16.957630	400.0	-	Lennartz LE-3D5s	Reftek	16.10.2014
GAESK	65.844840	-17.000070	400.0	-	Lennartz LE-3D5s	Reftek	05.09.2014
DIM (IMO)	65.96151	-16.93192	266.0	-	Lennartz LE-3D5s	Guralp	19.11.2008
GHA (IMO)	65.84346	-16.66291	396.0	-	Lennartz LE-3D5s	Guralp	19.03.2008
KVO (IMO)	65.71392	-16.8813	572.0	-	Lennartz LE-3D5s	Guralp	23.06.2002
MEL (IMO)	65.57002	-16.65725	370.0	-	GUREESPB	G24h	01.10.2009
REN (IMO)	65.64699	-16.90591	338.0	-	Lennartz LE-3D5s	G24e	03.11.1996
SKI (IMO)	65.86982	-17.02696	316.0	-	Lennartz LE-3D5s	Guralp	19.11.2008

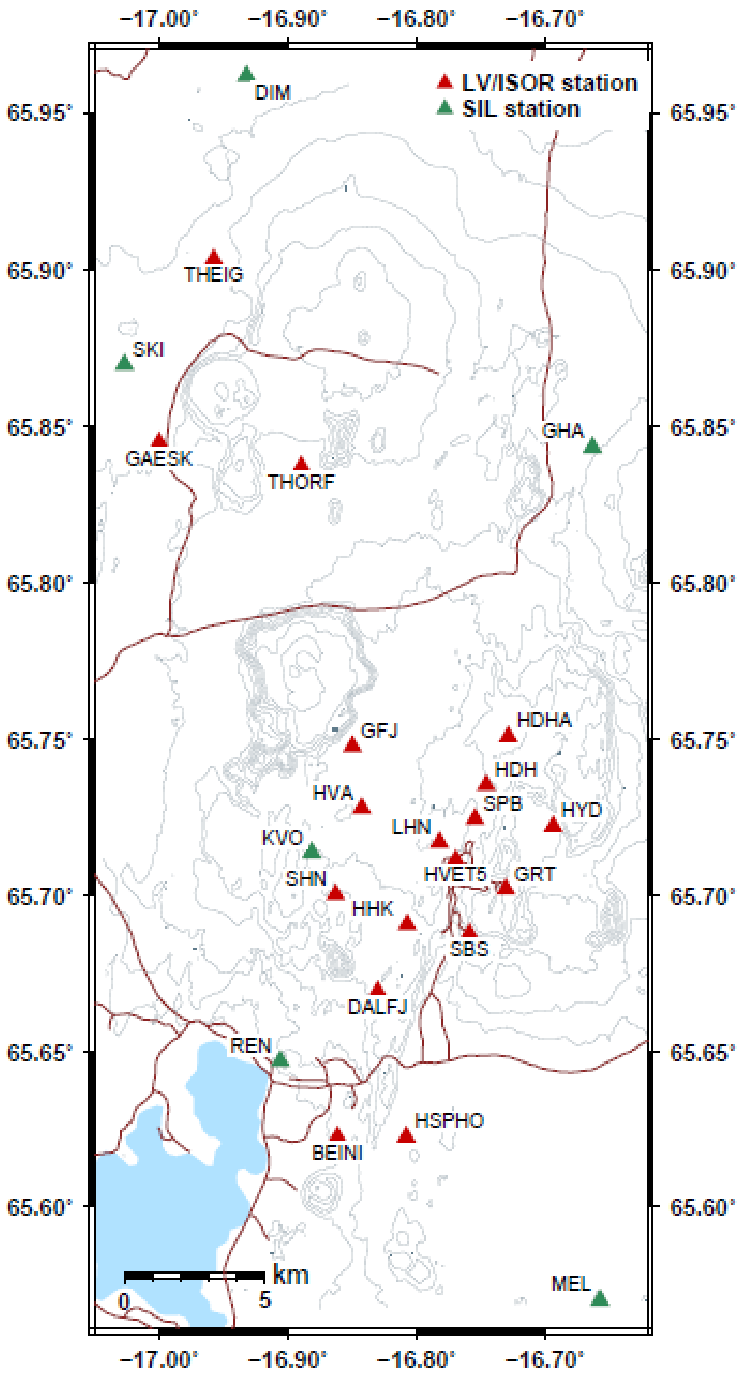

Figure 1. *Seismic network for monitoring Krafla, Þeistareykir and Námafjall geothermal areas. Red triangles stand for the locations of stations run by Landsvirkjun and ÍSOR. The green triangles show the locations of seismic stations run by the IMO which ÍSOR has access to. Both locations of stations HDH and HDHA are plotted.*

3 Recorded earthquakes

The Krafla seismic network located a total of 5037 earthquakes from November 1st 2015 until October 31st 2016. During the same period, the IMO recorded 438 events in the same area (Figure 1).

The daily amount of activity is subject to strong variations. On only two days no activity was recorded, the maximum number of events in one day was recorded on October 18th 2016 when 42 events could be located. The average is 13.8 events per day.

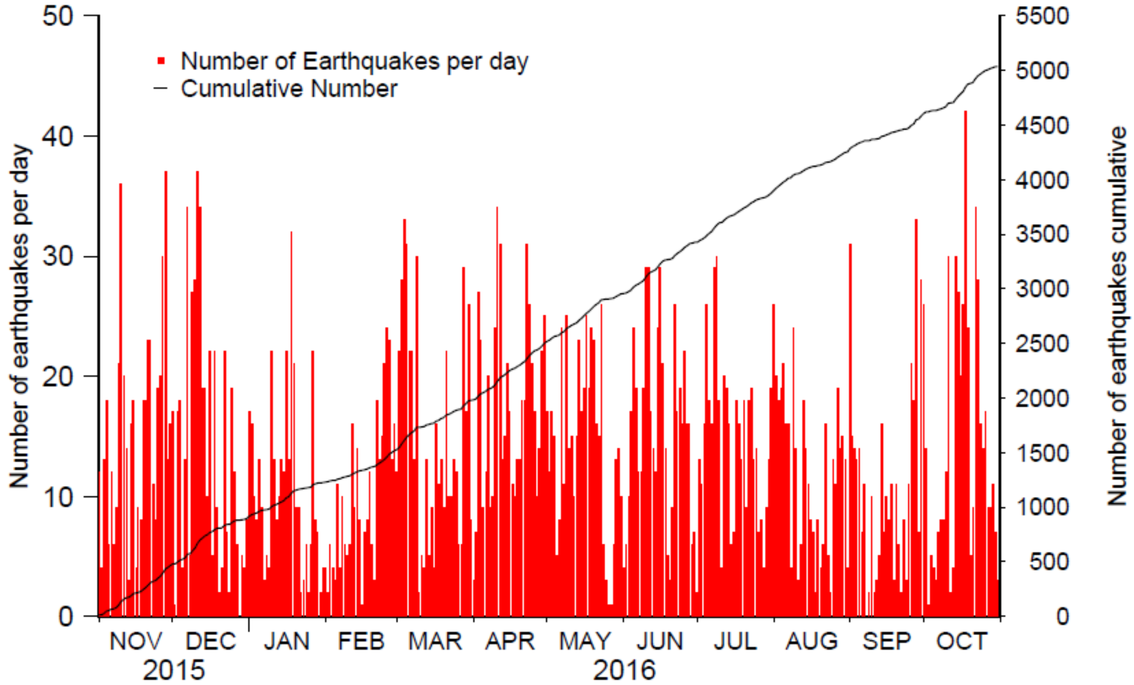

Figure 2. *Number of earthquakes recorded per day and the cumulative number of events. The red bars represent the number of earthquakes recorded per day. In total 5037 events were recorded in Krafla area, the average is 13.8 events per day. The number is subject to strong variations.*

4 Spatial distribution of event

Using the hypoDD program, of 5037 recorded earthquakes 4531 could be relocated. Only the relocated events are displayed in Figure 3 while for other analysis all recorded events are used.

The seismic activity is mainly limited to five clusters in which the vast majority of event has been located shallower then in about 2.3 km depth (Figures 3 and 4). To the southeast of the main production area this lower edge is slightly dipping reaching about 2.5 km depth. This distribution is very similar to what was discussed in last year's report (Blanck et al., 2016) where 5 limited clusters could be identified. Another, 6th, smaller and deeper cluster south of which already showed up in last year's data is becoming more and more visible (Ágústsson and Guðnason, 2016) due to the increased number of seismic stations installed in Námafjall area. It is located the west of the main production area and south of Leirhnjúkur. Events here are typically between 2.5 and 4 km deep. This deeper cluster indicates deepening of the brittle-ductile boundary and could mark the south western edge of the shallow heat source or magma chamber.

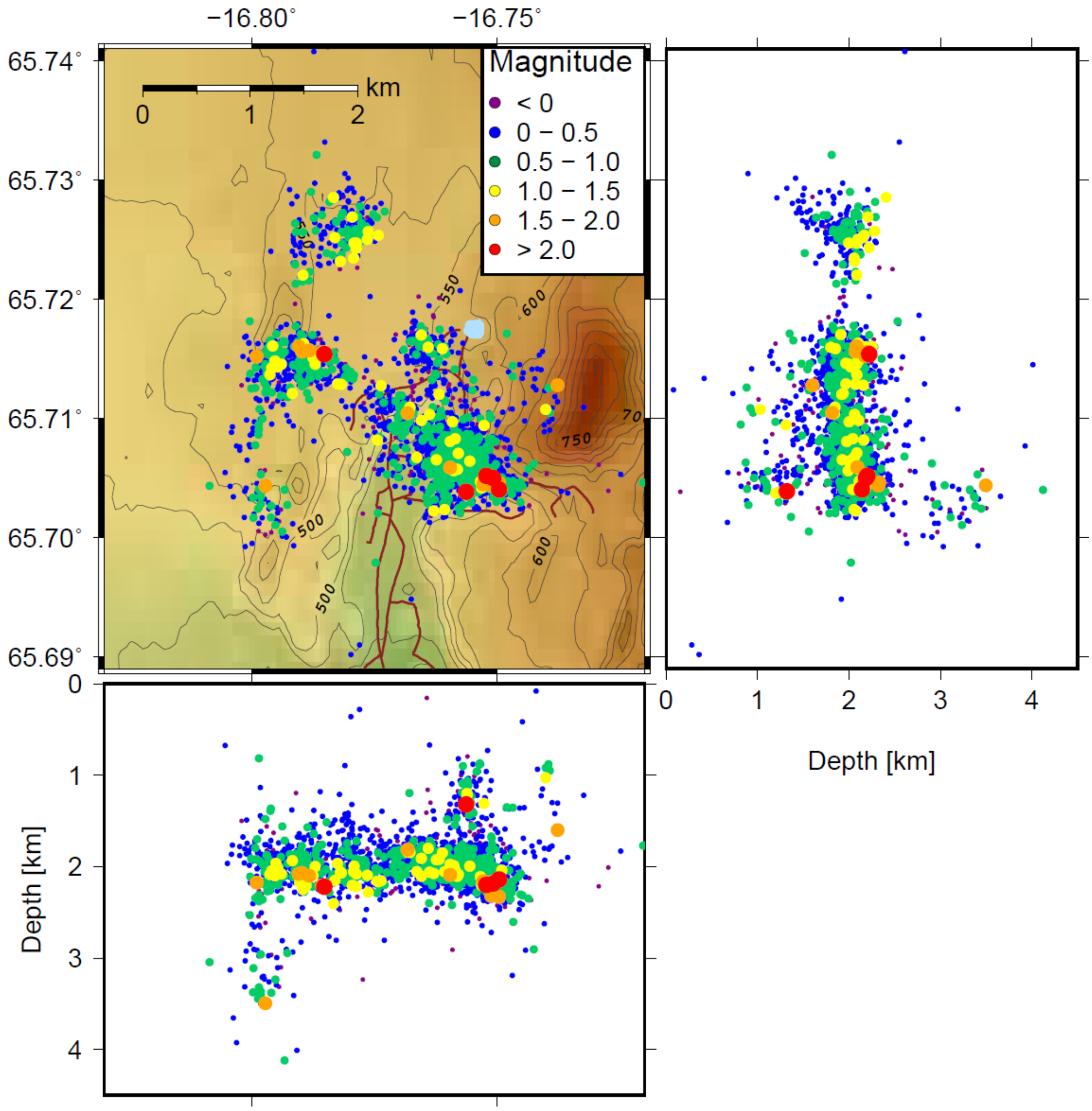

Figure 3. *Spatial distribution of earthquakes in surface projection and E-W and N-S sections.*

Taking a closer look at the magnitudes of the located epicentres of events, the magnitude distribution appears rather random and no patterns become clearly visible. There is possibly a clustering of bigger events in the southeast corner of the activity but with regard to the small number of big events this could also be coincidental. If we look at the depth distribution, however, the larger events (Ml > 1.0) are more or less clustered within a ~ 200 m thick horizontal layer centred at ~2 km depth.

Earthquake activity in Krafla is mostly recorded in 1.5 to 2.5 km depth with the deepest events being located at about 4 km depth in the SW part (Figure 4). The brittle ductile boundary, which is per definition the depth above which 95% of earthquakes have occurred, is in about 2.3 km depth. Therefore the thin horizontal layer of events in the magnitude range 1.0–3.0 seem to occur just above the brittle ductile boundary and might represent a zone of active heat mining from the underlying heat source.

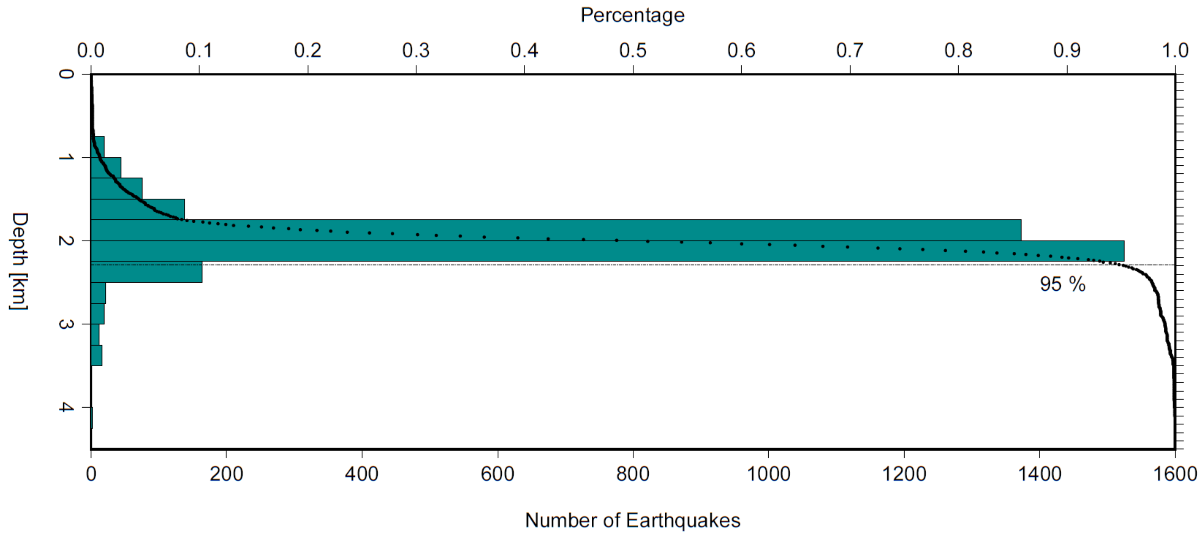

Figure 4. *Depth distribution of the events located in Krafla area. The main activity occurs in 1500 to 2500 m depth. 95% of the earthquakes are located shallower then 2300 m.*

5 Magnitude distribution

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. This relation is described with a straight line determined by constants a and b:

$$\log N = a - b * M$$

where N is the number of earthquakes of a given magnitude M and larger. While the intercept a is depending on the number of earthquake in the time and area chosen, the slope b is typically about 1 for normal crust. This relation has shown to be valid for global earthquakes catalogues as well as for smaller seismically active areas. Deviations from the slope being b = 1 are typically found for very small events which are not all recorded by both global and local networks, this is the so-called „roll-off".

In Krafla magnitudes from -0.53 to 3.36 have been measured (Figure 5). The b value is about 1 for events of magnitude 1.5 and bigger. For smaller events (magnitude 0 to 1.5) the b value appears to be slightly increased, a relatively high number of small earthquakes has been recorded. This points to a local weaker crust in which stress cannot build up to high levels but instead is released early by numerous small earthquakes. For events of magnitude smaller than 0 the earthquake catalogue is incomplete due to the limited sensitivity of the seismic network. A similar magnitude frequency distribution is observed in Námafjall where the seismogenic crust is considerably thicker than in Krafla (Ágústsson and Guðnason, 2016).

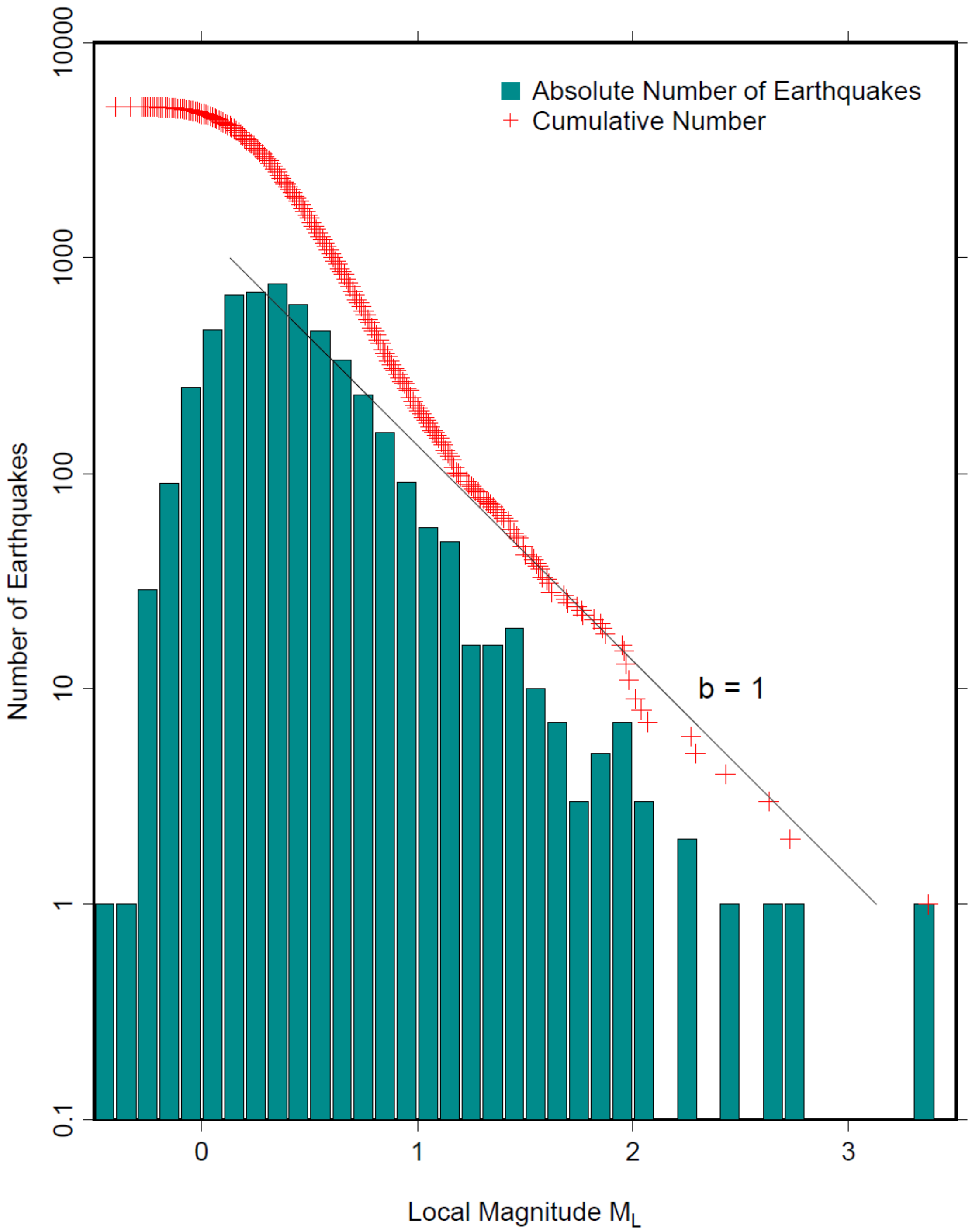

Figure 5. *Magnitude-frequency relation. Measured magnitudes vary from -0.53 to 3.36. Green bars represent the absolute number and the red stars the cumulative number of earthquakes. For earthquakes with magnitude > 1.5 the b value is about 1, for earthquake of magnitude 0 to 1.5 the b value is increased.*

6 Vp/Vs ratio

The Vp/Vs ratio provides us with information on rock properties and phase changes of fluids present in the rock. Compared to 1.73 which is the Vp/Vs ratio in a perfect elastic medium, in Icelandic crust velocity ratios are typically slightly increased (between 1.75 and 1.79) as studies suggest (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al., 2001).

For this year's analysis the total of 5037 events where used to estimate the Vp/Vs ratio in Krafla area (including seismic stations and earthquakes in Þeistareykir and Námafjall) using a classical Wadati approach (Wadati, 1928). All the events located within the area represented in Figure 1 have been used for the calculation resulting in a value that averages along all ray paths (Figure 6b).

In Figure 6a only earthquakes in Krafla geothermal area and close stations were used in the Wadati diagram. Here the Vp/Vs ratio is with 1.71 slightly decreased.

Relatively low Vp/Vs ratio indicates lowering of P-wave velocity compared to S-wave velocity. In case of temperature approaching partial melt the shear strength of the rock is **reduced and the S-wave** velocity would drop drastically while the P-wave velocity is only weakly affected as it depends on the compressional strength. In the case of gas or steam in the pores in the compressional strength lowers compared to rock fluid filled pores while the shear strength is not affected. Therefore, a steam zone in a part of the reservoir is a likely explanation of the slightly reduced Vp/Vs ration within the Krafla geothermal area. Further analysis of the spatial distribution of Vp/Vs ratio might help to locate further the steam zone within the reservoir.

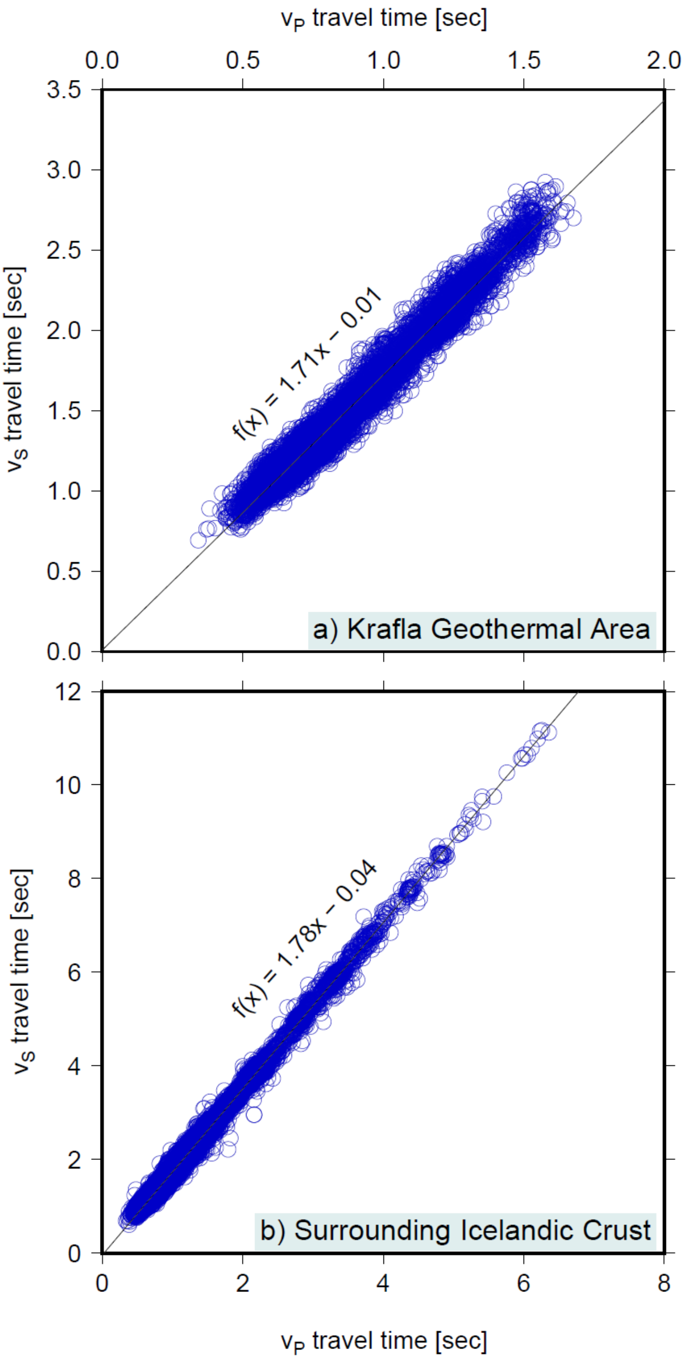

Figure 6. *Vp/Vs ratio in Krafla geothermal area. In Krafla and the surrounding crust the Vp/Vs ratio has been calculated to 1.78 what is consistent with other studies in Iceland (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al., 2001) where values are typically around 1.75 to 1.79. Inside the geothermal itself the ratio 1.71.*

7 Focal mechanism

A focal mechanism analysis of eight selected earthquakes was carried out using the FPFIT software. The FPFIT software is calculating the faulting mechanisms based on manual polarisation picks. A high number of picked polarisations can typically be achieved for events with higher magnitudes. Events were also chosen based on their location so that we get information from different clusters and subareas inside Krafla geothermal field.

Three of the biggest events ($M_L > 2.0$) are located in the southeast corner of the main production field (Figure 7). They show all normal faulting mechanisms with the faults being oriented about perpendicular to the rift zone. The event in the cluster north of Leirhnjúkur is also a pure normal fault but with a steep fault plane that is oriented in NE-SW direction. The events in the cluster south of Leirhnjúkur peak (the analysed event is actually east of the peak), in the Námafjall cluster and the cluster in-between Leirhnjúkur and the main production area have oblique faulting mechanisms and the event in the cluster around the IDDP-1 borehole is a strike-slip event.

The different focal mechanism indicate a stress regime dominated by extensional forces (7 out of 8 events occur partly on normal faults) but the directions of the fault planes are variable. No regional trend can be identified based on this small number of mechanisms.

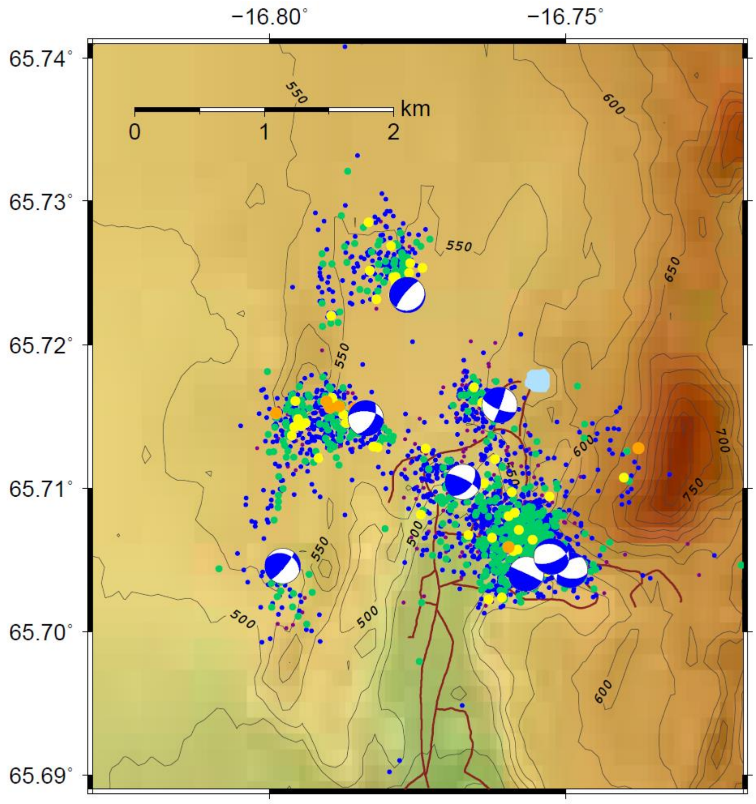

Figure 7. *Focal mechanisms of selected earthquakes in Krafla area. The eight analysed events show primary normal faulting with portions of strike-slip. Only one event (close to the IDDP1 borehole) is almost pure strike-slip.*

8 Seasonal variations

In the annual report on seismic activity in Krafla for the year 2014 the possibility of semi-annual variation was mentioned but could not be verified due to the limited time span covered. If seasonal variations exist with over 3 years of data collected by now, they should show more clearly now.

Figure 8 shows the daily number of events from October 25th 2013 until October 31st 2016. In this period, the average number of recorded earthquakes seems to have increased, possibly due to the development and enhanced sensitivity of the seismic network. In total 12,725 earthquakes have been used in for this analysis. A look with the naked eye suggests that the semi-annual trend like indicated by 2014's data could have continued. To verify this assumption the trend is isolated using the method of moving averages. The length of the window for calculating the average has to be chosen long enough to eliminate outliers and short enough to emphasize the trend, 45 days appeared suitable for this purpose.

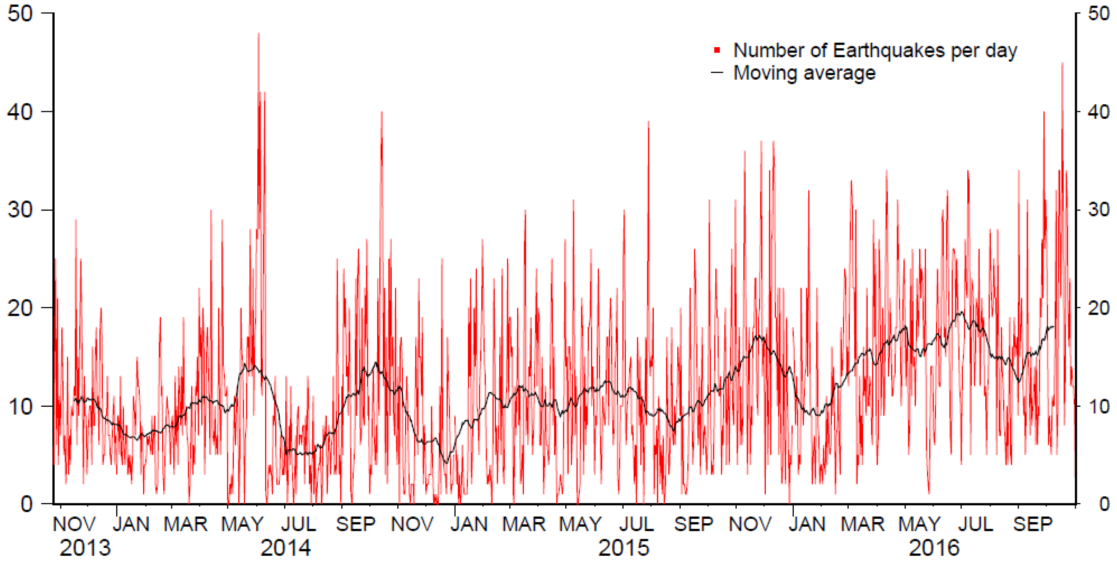

Figure 8. *Number of daily-recorded events from October 25th 2013 until October 31st 2016 (red curve). To isolate the trend a 45-days-average has been calculated which smoothened the curve and limits the impact of outliers (black curve). The trend shows periodical fluctuations with lower numbers of events in winter and summer and higher numbers in spring and autumn.*

The averaged/smoothened curve shows variations of earthquake numbers with the seasons. During the period of one year, the number of recorded events goes through two cycles of increase and decrease with the highest numbers recorded both in spring in April/May and in autumn in September/October/November. Low numbers of events are observed in the winter month in December/January/February and in the summer in July/August.

At first sight, it seems that the phases of higher number of events have different shapes in spring and autumn. In autumn, the slopes of the peak are steeper while in spring the peak appears wider and flatter with no clearly articulated tip.

Possible reasons for these seasonal changes are numerous and at this stage, we can only speculate. One reason to debate are changing noise levels caused by wind and weather or variations in injection rate in injection boreholes. Tests were conducted where only bigger events (magnitude > 0.5) where used for calculating the average. The recordings of these events should be less sensitive to weather generated changes in noise level. Therefore, if those were the main reason for the oscillations, the number of bigger events should be fairly stable. However, we see the seasonal changes also in these events what excludes noise as an only reason.

Another possible cause of this behaviour is seasonal variations in groundwater level where a slight elevation in the groundwater table increases the pore pressure and thereby reduces the strength of the rock. In the spring, the water level should rise due to snow melting, and again the autumn is usually rainier that the summer, explaining the peak in the fall. During the high winter, all precipitation is in the form of snow limiting the recharge of the groundwater system. This hypothesis has not been investigated by comparison with climate data but should be looked later when more annual cycles are collected.

9 Summary

From November 1st 2015 until October 31st 2016 only one seismic stations was relocated to improve its performance and no further changes were made. A total of 5037 earthquakes were located inside the seismic network in Krafla geothermal area. The spatial and depth distribution of those earthquake activity is similar to what we saw in last year's report. Earthquakes are mostly located in a few locally limited clusters typically shallower then 2.3 km with the exception of the cluster in the southwest, which is more prominent than it was in the past and where events are up to 4 km deep.

Earthquakes vary from -0.53 to 3.36 in magnitude. The magnitude-frequency relation shows an abundance of small events (magnitude 0 to 1.0) suggesting a weak crust where stress cannot build up to high levels but is released early in many small events. Vp/Vs ratios are consistent with earlier studies on the Icelandic crust. Slightly lower ratio inside the production field compared to the surrounding areas might indicate presence of steam in the porous rock at reservoir depth.

A comparison between injection rate and the number of earthquakes close to the injection wells could not be carried out because no injection rate data was made available to us. A tomography of the area could not be completed in time due to unsolved problems with the tomoDD software.

Focal mechanism analysis of selected earthquake indicated a primary extensive stress regime with strike-slip portions. The direction of fault planes is variable not showing a consistent regional trend.

The number of recorded events per day since October 2013 indicates semi-annual variations with high numbers of events in spring and autumn. We will follow up on this in next year's report to see if the cycle is repeating itself.

10 References

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