LV-2016-008

Landsvirkjun

Seismic Monitoring in Krafla

November 2014 to November 2015

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Abstract:

The seismic network installed in Krafla in 2013 has continuously been development. 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 2014 to October 31st 2015 is presented. A total of 3624 earthquakes were recorded, thereof 2948 inside the seismic network. For comparison, 125 earthquakes were recorded in Krafla area in the same time by the SIL-network.

The results of the analysis of seismicity are comparable those presented in last year's report. The seismic activity in Krafla can be classified in 5 major clusters inside the caldera and a more diffuse activity outside of it. Most earthquakes occurred in one to two km depth. The brittle-ductile boundary lies in about 2.2 km depth inside the clusters and in about 3.2 km depth outside of them.

The Vp/Vs ratio inside Krafla caldera is 1.68 and 1.78 outside of it.

Seismicity in the near surroundings of two injection boreholes (KG-26 and IDDP-1) were compared to the injection rate. We see a major increase of seismic activity on days with higher injection rate.

Keywords:

Seismicity, earthquakes, brittle-ductile boundary, Vp/Vs ratio, induced seismicity, injections, Krafla, Landsvirkjun

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Project manager's signature	Reviewed by
Magnús Ólafsson	ÓGF

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1 Introduction

In this report we present the outcome of the earthquake monitoring in Krafla geothermal area during the time period from November 1st 2014 to October 31st 2015. 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.

From November 1st 2014 to October 31st 2015 only minor changes have been made to the network. Two stations were moved to new locations. Additionally, we now have access to 5 seismic stations in the area which are run by the Icelandic Meteorological Office (IMO). A total of 3624 earthquakes were recorded by the local network in Krafla, thereof 2948 which lie inside the network. The activity in this time period is comparable to last year when 3047 event were recorded. Also the spatial distribution of events is very similar to the year before but there is more shallow activity which is possibly induced seismicity as a result of injection. Vp/Vs ratios and relation between injection rates and seismic activity support this hypothesis.

2 Maintenance and data processing

From November 1st 2014 to October 31st 2015 a number of changes were made in both the locations of seismic stations and the data transfer systems. On September 12th the Hreindýrahóll station (HDH) was moved to a new location. The HVE stations had to be moved due to high temperatures in the borehole. The new location provided very noisy data, so on October 25th 2015 the HVE station was removed again and was recently installed in shothole THOR5 as station HVET5. For stations LHN, HHK, GRT, SBS new WiFi transmitters were installed and SBS which is now sending its data through a fibre optic cable. The seismometer installed at stations LHN had to be repaired as the connection to one of the components in the sensor was broken. Eventually the orientation of the WiFi antena located on Kröflufjall was optimized in respect to the locations of the seismic stations. Of all stations that are located in boreholes, the poles with the solar panels and the transmitting system were placed on sockets which are buried in the ground.

Real time data picking and event localization, first automatically and shortly after manually, is still carried out with the Seiscomp3 software as described in 2012 and earlier reports (e.g. Ágústsson et al., 2012). In April 2014 the Seiscomp software was updated with the latest version, "Jakarta". The problems concerning the reliability of magnitude estimations mentioned in last year's report (Blanck et al., 2014) is solved but the database has not been updated yet. Consequently, we do not address the magnitudes in this report.

3 The seismic network

The permanent seismic network in Krafla geothermal area contains 11 stations. Another three stations are operated the Námafjall and in Þeistareykir respectively what adds up to 17 stations used for localization of earthquakes in Krafla.

In addition, we now have access to 6 seismic stations which are run by Icelandic Meteorological Office (IMO) in the area.

Table 1. *Seismic stations in Krafla, their locations and information an installed sensors and digitizers.*

Station name	Latitude	Longitude	Elevation [m]	Depth [m]	Sensor	Digitizer	Begin data End data*
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
HVE	65.709720	-16.763140	509.0	22.0	Lennartz LE-3D5s	Reftek	22.05.2007 21.10.2015*
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	65.746633 65.745583*	-16.745067 -16.735417*	632.0	-	Lennartz LE-3Dlite	Guralp	02.09.2013
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

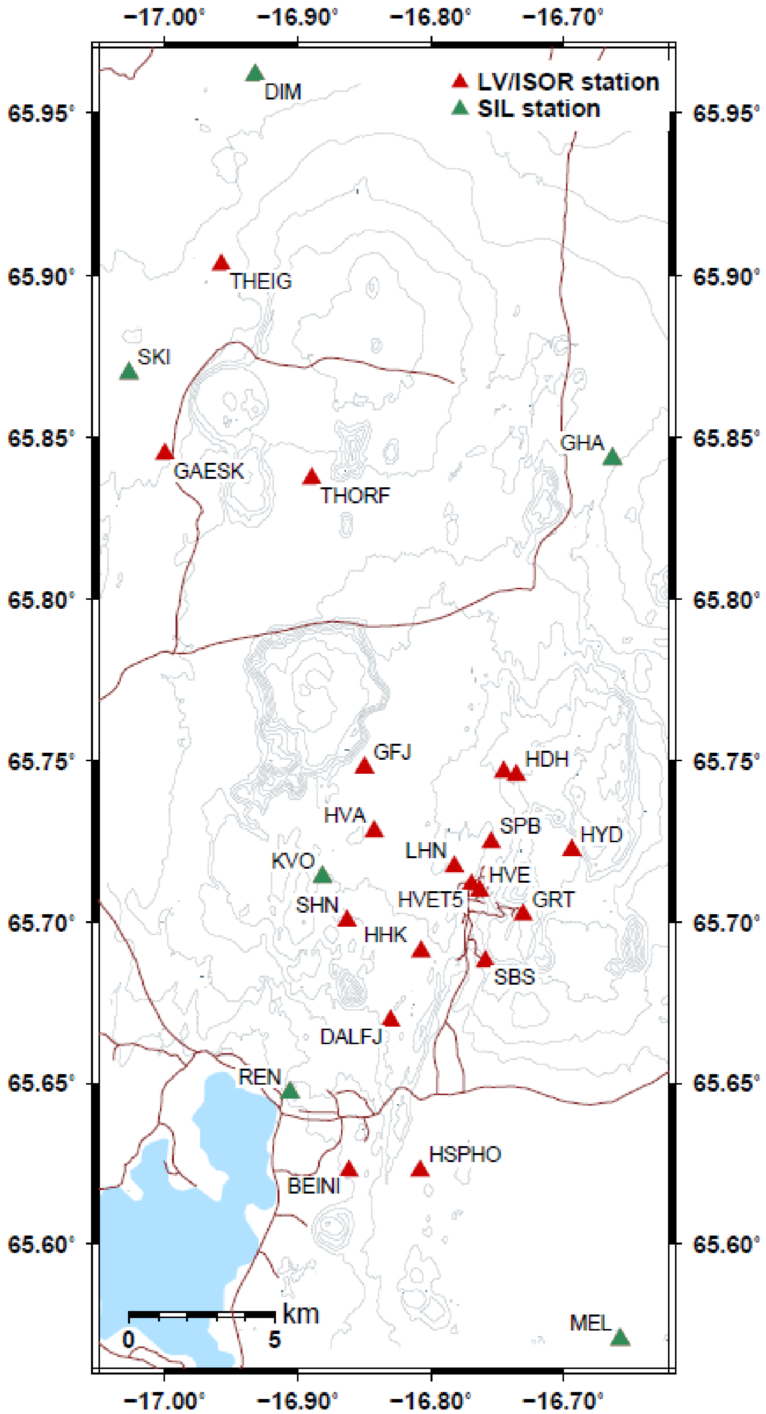

Figure 1. *Seismic network for monitoring Krafla, Þeistareykir and Námafjall geothermal areas. Red triangles symbolize the locations of stations run by Landsvirkjun and ÍSOR. The green triangles show the locations of seismic stations run by the IMO which ÍSOR has access to. For station HDH both the old and the new location are plotted.*

4 Recorded earthquakes

In the period from November 1st 2014 to October 31st 2015 a total of 3624 earthquakes were recorded by the permanent seismic network in Krafla and located with the Seiscomp3 software. Of those 2948 events lie inside the network and are used for the analysis presented later in this report. During the same period the IMO recorded 125 events in the area. The events that lie outside the network are only poorly located. They will only be used in the Vp/Vs ratio analysis where no location information is required.

The number of events recorded per day is subject to strong variations and varies from 0 to 38 (Figure 2), the average is 8.1 events per day. Semi-annual fluctuations or some seasonal variations as indicated by the data used in the 2014 report are not visible.

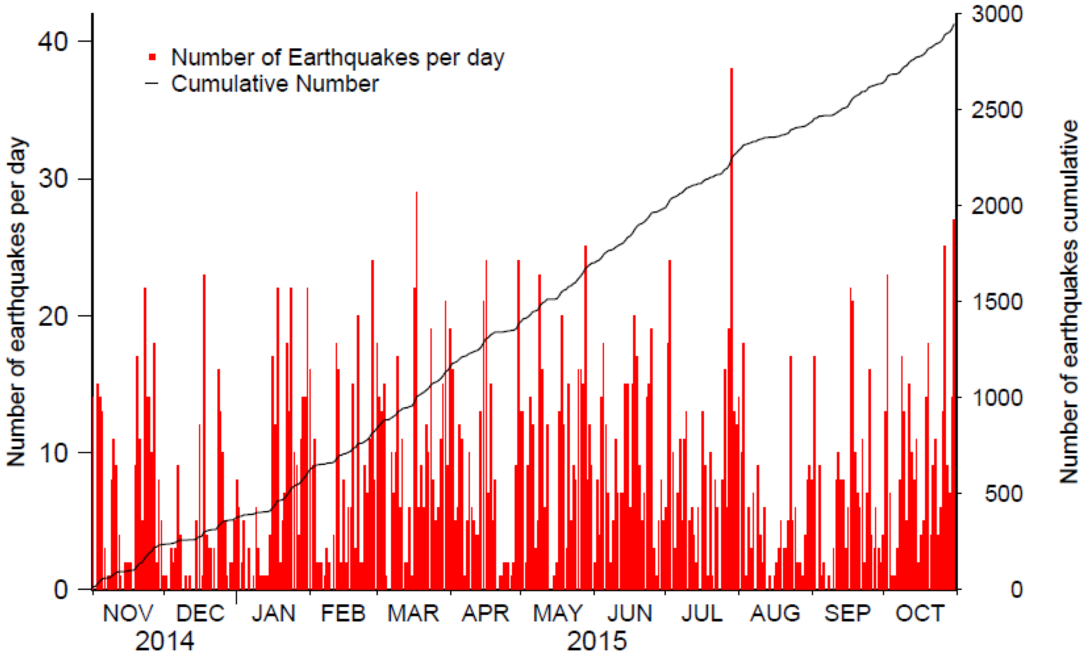

Figure 2. *Number of earthquakes recorded per day and the cumulative number of events. The red bars represent the number of earthquakes recorded per day. In total 2948 events were recorded in Krafla area, the average is 8.1 events per day. The number is subject to strong variations. These fluctuations can be caused by precipitation and natural variations in the seismicity. Other causes can be fluid injections or earthquakes were not recorded due to weather conditions (noise) or technical problems.*

5 Spatial distribution of events

Figure 3 shows the spatial distribution of the earthquakes recorded in Krafla geothermal area. The pattern the events form is very similar to the activity the year before (Blanck et al., 2014). The top view shows the same clusters as last year which can be associated with different working areas in Krafla. The side views show the same dipping of the lower edge of activity towards the southeast. The only change in activity we see is an increase of rather deep earthquakes (2–4 km) south of Leirhnúkur, in the southwest of the main production area. In the previous year we only saw few events here. This is probably due to a better sensitivity for this area since station DALFJ was installed (Figure 1).

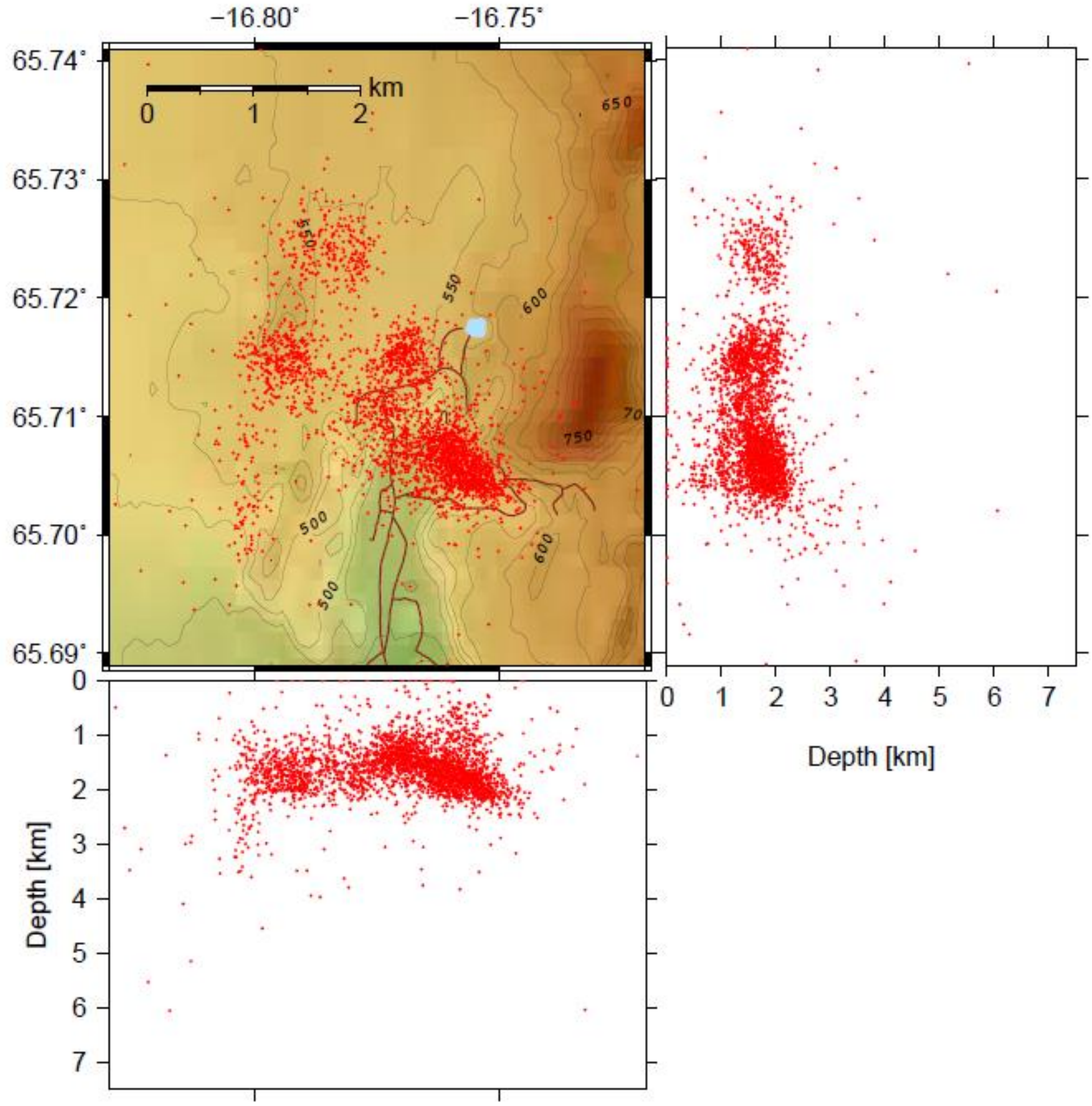

Figure 3. *Spatial distribution of earthquakes in surface projection and E-W and N-S sections.*

6 Depth distribution of events

The depth distribution of seismic events and especially the depth of the brittle-ductile boundary gives information on parameters of the bed rock such as temperature (e.g. Ágústsson and Flóvenz, 2005).

In Krafla the distribution of earthquakes with depth shows the main activity between 1 and 2.25 km depth with most earthquakes occurring between 1.5 and 2.0 km depth (Figure 4). 95% of the earthquakes are located shallower than 2.225 km. This means the calculated brittle-ductile boundary is slightly shallower than according to last year's data (2.250 km).

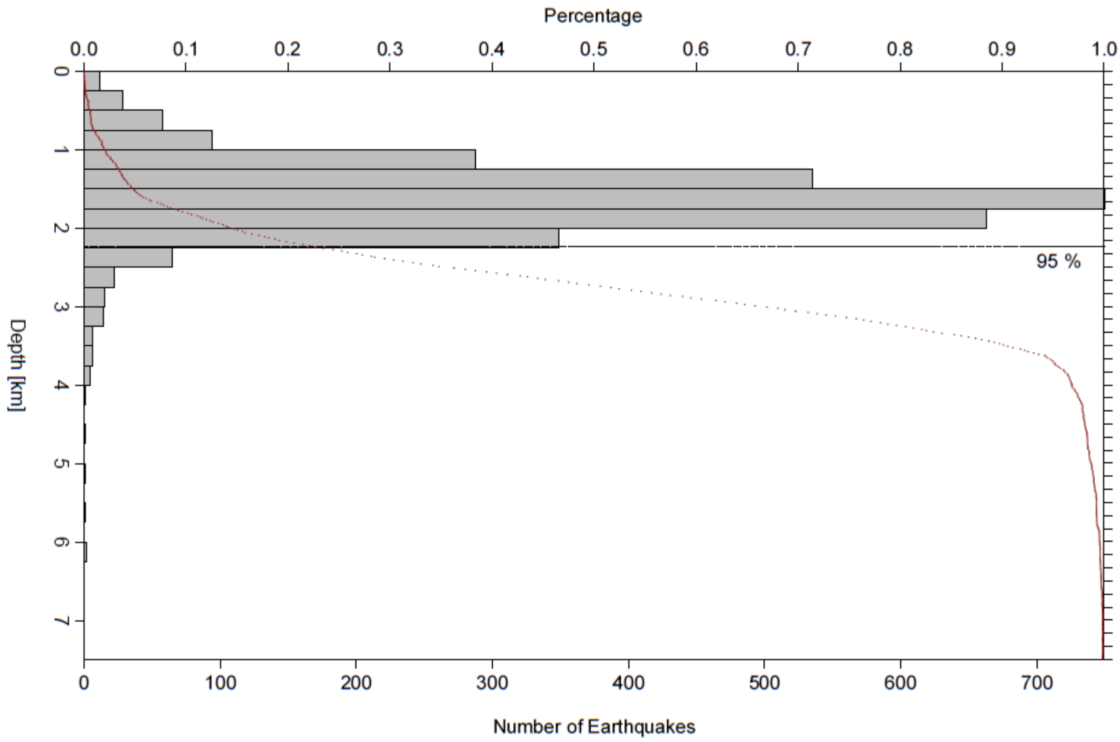

Figure 4. *Depth distribution of the events located in Krafla area. The main activity occurs in 1000 to 2250 m depth. 95 % of the earthquakes are located shallower then 2225 m.*

Figure 5 shows the distribution of seismic activity in different depth layers. Especially the layers 1000 to 1500 m, 1500 to 2000 m and partly 2000 to 2500 m emphasize how spatially limited the occurrence of earthquakes is. As in last year's report the depth of the brittle-ductile boundary is also calculated for each of the 5 clusters separately (see Figure 6).

The results are shown in Figure 7. In cluster a) the brittle-ductile boundary is with 2.16 km exactly as deep as last year (2.16 km). In cluster b) the boundary is with 2.12 km a bit shallower (2.2 km last year). The same applies to cluster c) and d) where the boundaries lie in 1.79 and 2.00 km depth resp. based on this year's data (1.91 and 2.15 km last year). In cluster e) last year's and this year's results are the same (2.18 km this year and 2.12 km last year).

For area f) which is a pooling of those events that lies within the network but outside the 5 clusters the calculated brittle-ductile boundary is with 3.16 km also a bit shallower than last year (3.58 km).

Even though we see a few more deep events in this year's data the majority of events are shallower than last year. The depth distribution in the different clusters shows that the deep events (> 5 km) are all located outside the 5 clusters in which the majority of the activity occurs.

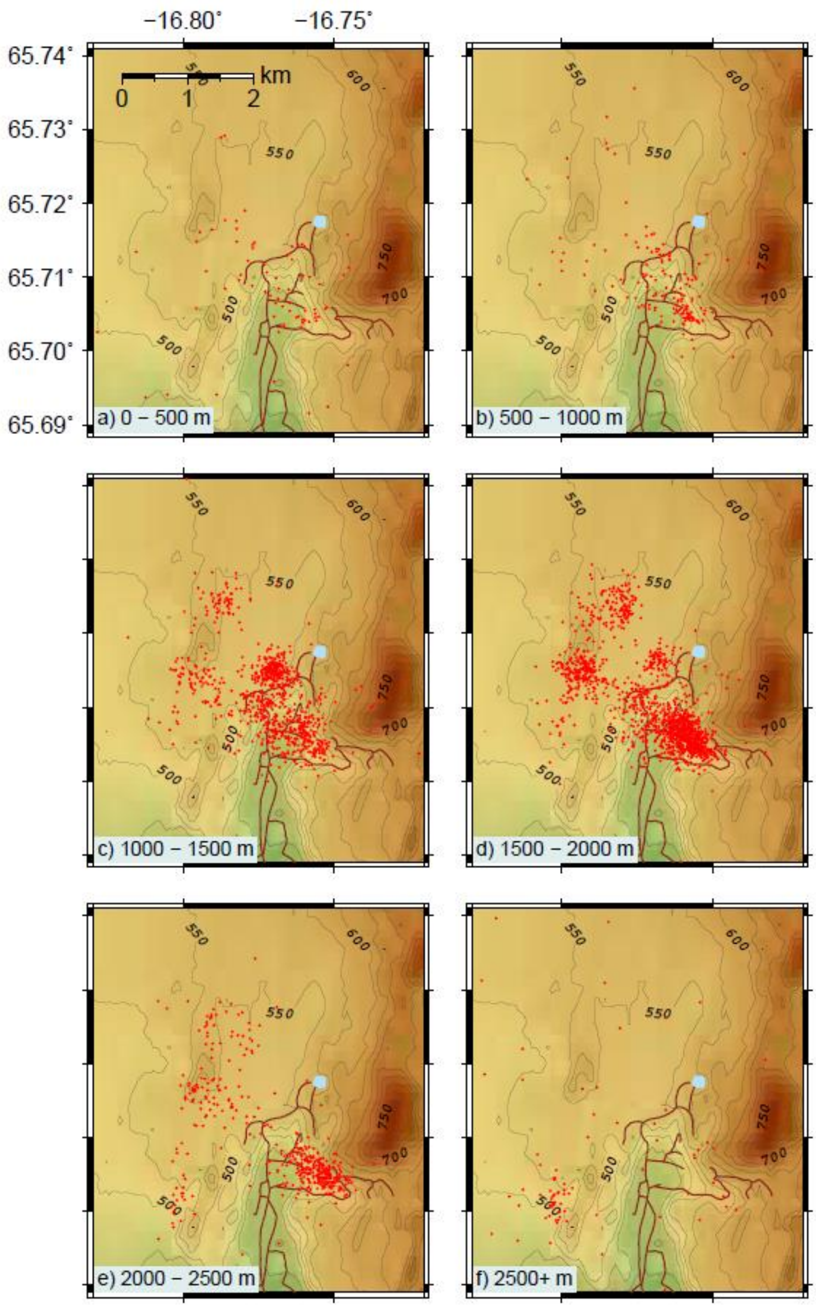

Figure 5. *Seismic activity distribution in different depth intervals. Each figure a) – e) represents a 500 m thick layer. Figure f) shows all events located deeper than 2500 m. The main activity occurs between 1000 and 2000 m depth where the activity is clearly divided into 5 different clusters.*

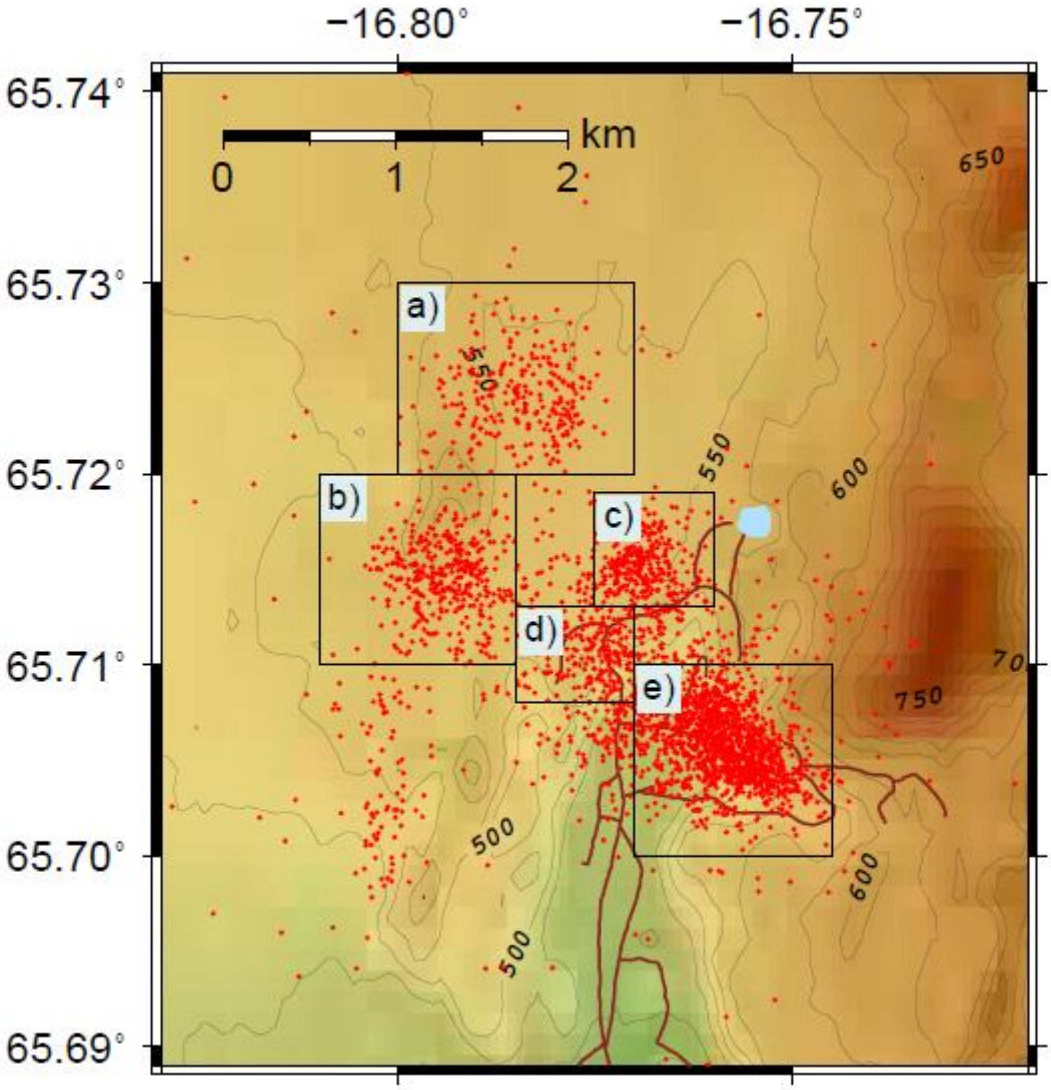

Figure 6. *Location of the five clusters a) to e) of earthquake activity.*

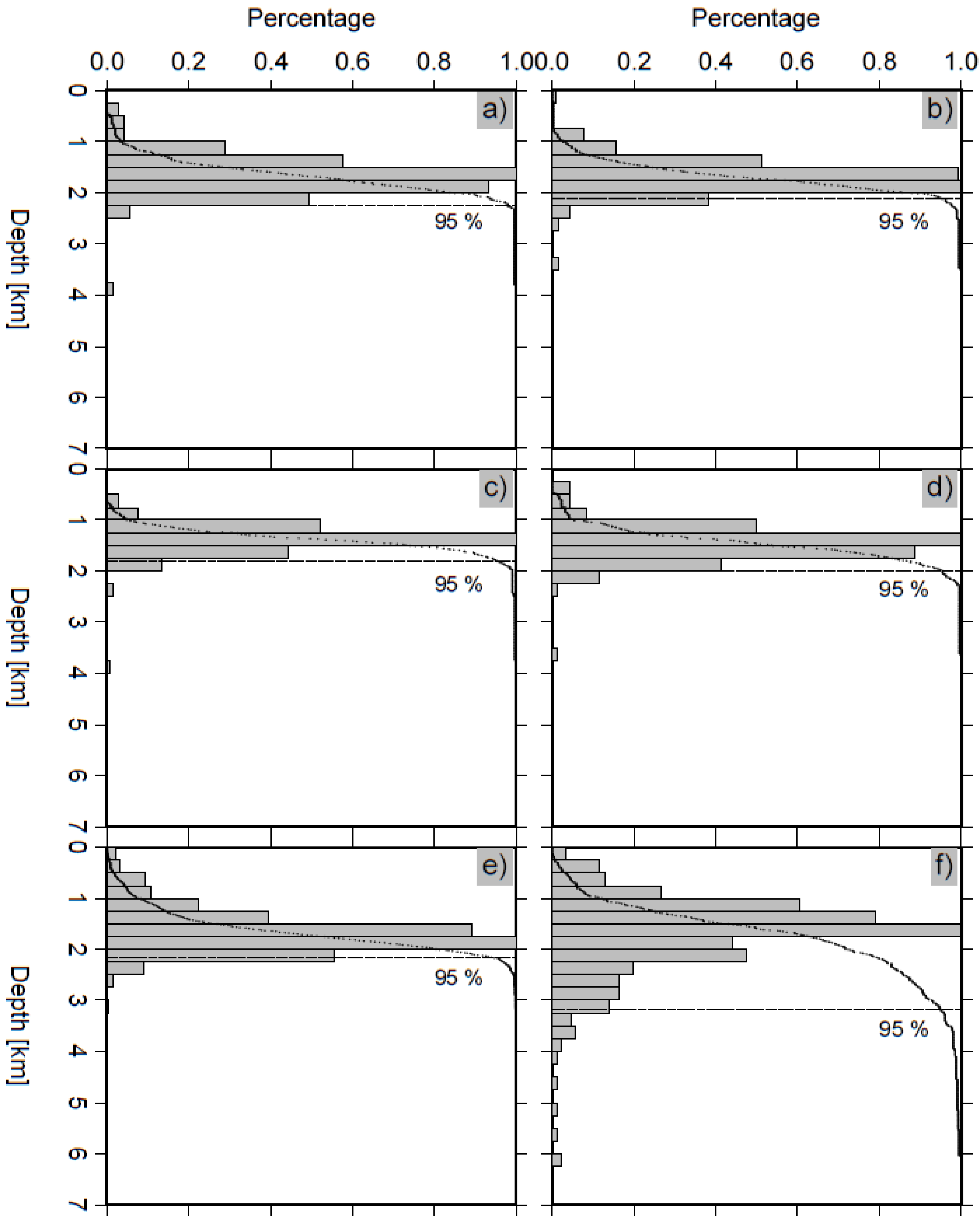

Figure 7. *Depth distribution in the clusters a) to e). In figure f) all events are summed up that lie outside the five clusters. The number of earthquakes is normalized with the maximum number of events in one layer in each cluster (grey columns). The dots show the cumulative number of events. 95 % percent of earthquakes were located above the depth marked with the dashed line. In cluster a) this depth is 2.255 km, in cluster b) it is 2.105 km, in cluster c) it is 1.805 km, in cluster d) it is 1.995 km and in cluster e) it is 2.175 km. For all the events outside the five clusters (f) the 95 %-line is in 3.185 km depth.*

7 Vp/Vs ratio

The Vp/Vs ratio provides information on rock properties and phase changes. For a perfect elastic medium this ratio is typically $\sqrt{3} = 1.73$. Studies on Icelandic crust suggest higher values between 1.75 and 1.79 (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al., 2001). The Wadati Method (Wadati, 1928) which is used for this calculations does not have the locations of events as input but only the travel times which allows to also include earthquakes recorded outside the network with poorly constraint location in this analysis.

For this year's analysis the total of 2857 events where used to estimate the Vp/Vs ratio in Krafla area. For the velocity ratio of the surrounding crust 669 events could be used that where recorded by the network but lie outside and are only poorly located.

The Vp/Vs ratio calculated form the events inside the Krafla seismic network is 1.680. The other events suggest a ratio of 1.779 in the crust surrounding Krafla area. Within the error margin this is identical with last year's results (see above).

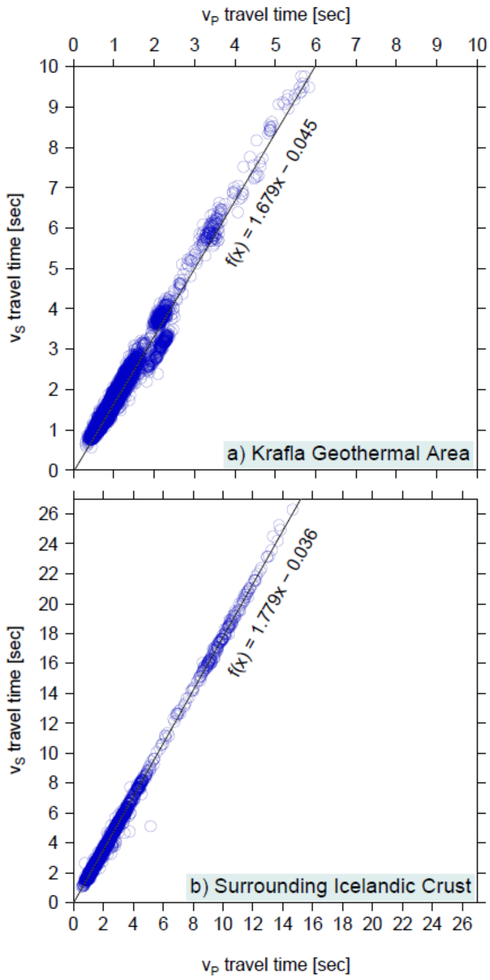

Figure 8. *Vp/Vs ratio in Krafla geothermal area and the surrounding crust. In Krafla the Vp/Vs ratio has been calculated to 1.679, outside the area it appears to be 1.779 what is consistent with other studies on the Icelandic crust (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al. 2001) where values are typically around 1.75 to 1.79.*

8 Comparison of injection rate and earthquake activity

Like in last year's report a comparison of the injection rate in 3 injection holes (KG-26, KJ-39 and the IDDP borehole) and the seismic activity in the nearby crust was carried out. The injection data was incomplete what made the analysis partly difficult.

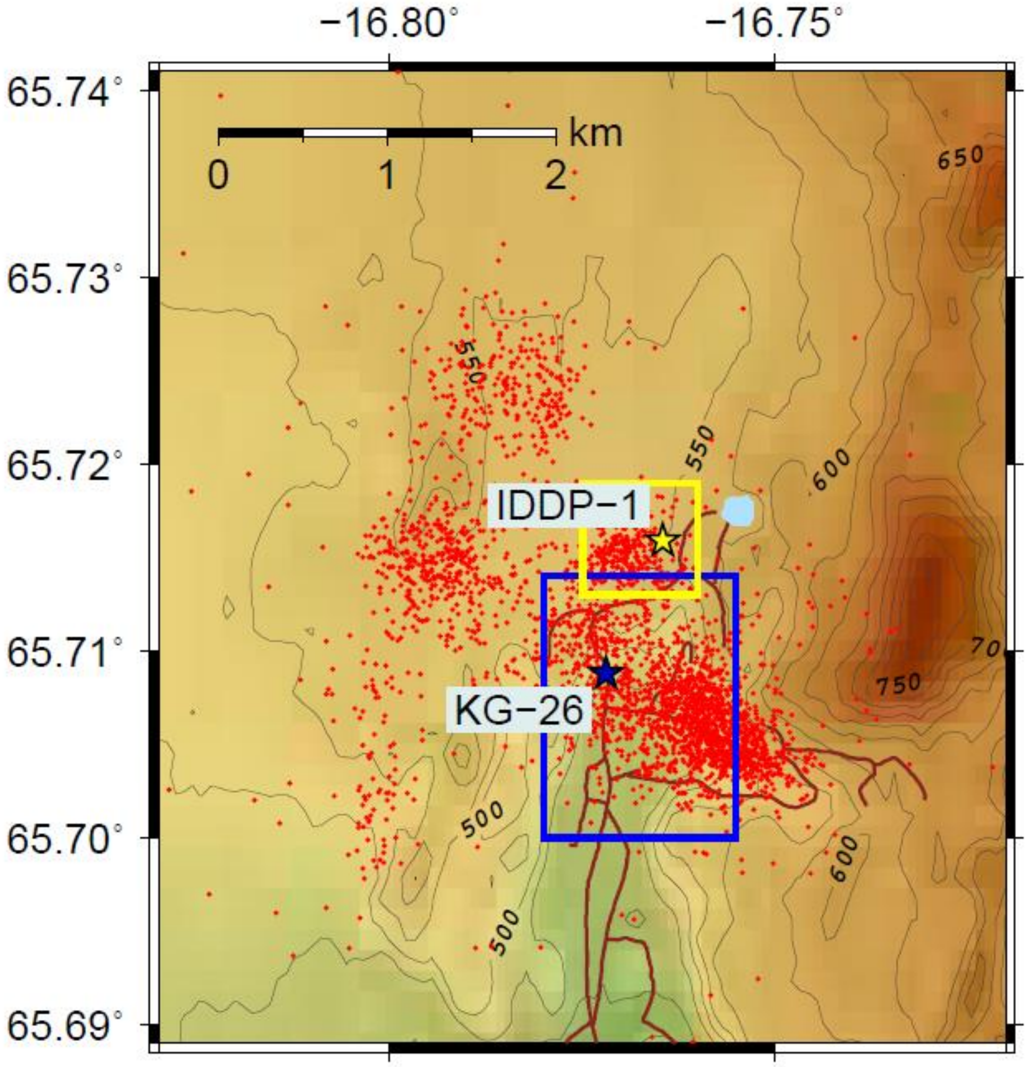

Figure 9. *Location of the IDDP-1 and KG-26 borehole and the area around them where changes in seismic activity was analysed.*

KG-26

In the KG-26 borehole was used for injection almost constantly throughout the investigated time period. The injection rate is typically 65 to 70 l/s. From December 7th to December 16th 2014 the injection was interrupted. From January 1st to January 21st the injection was irregular with lower injection rates and some days without any injection. The same applies to the period from August 10th to October 14th. For analysis the time periods with no injection or varying rates where combined and compared to those periods with higher, more stable injection rate (Figure 10).

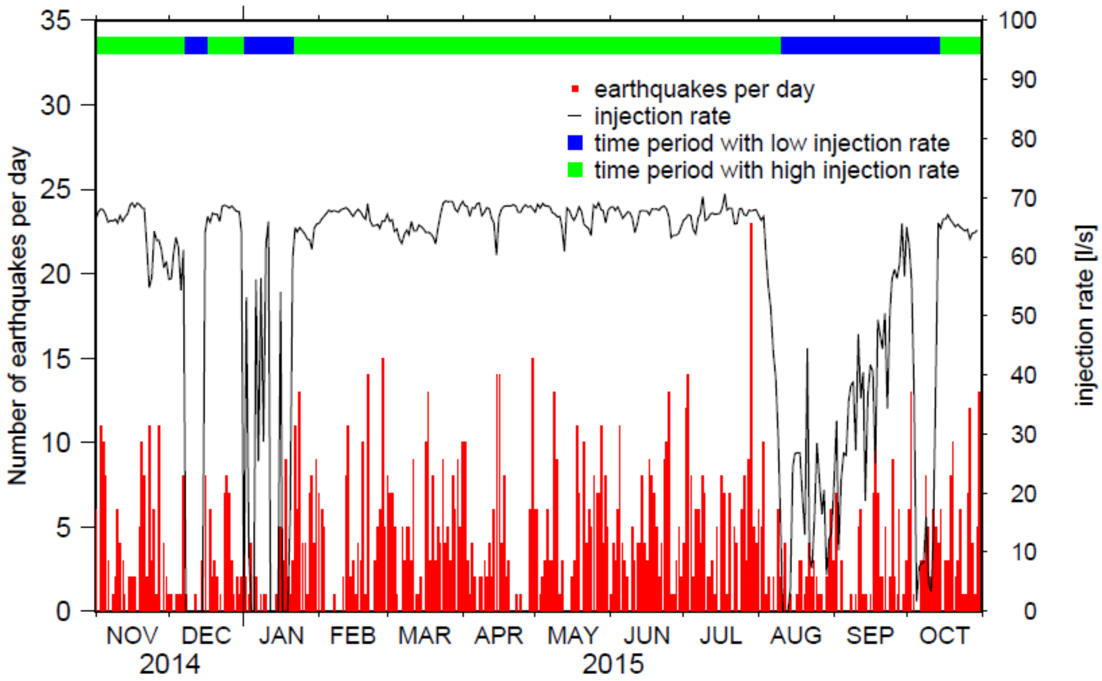

Figure 10. *KG-26 injection rate and earthquake injection. Time periods marks green are considered to be times with high injection rate. The blue marked times with low or irregular injection rate.*

Table 2. *Average number of events recorded by days and number of days with 5 or more and 10 or more earthquakes on days with low or high injection rate in borehole KG-26.*

	Average number of earthquakes per day	Number of days with 5 or more earthquakes	Number of days with 10 or more earthquakes
Low injection rate (97 days)	2.6	21 (21.65 %)	2 (2.06 %)
High injection rate (268 days)	4.5	115 (42.91 %)	22 (8.21 %)

The average number of earthquakes per day during days with a lower/fluctuating injection rate is 2.6. On days with a higher, more steady injection rate, the average is almost double with 4.5 events recorded per day. Also both the percentage of days with 5 or more resp. 10 or more events is significantly increased on days with high injection rate (compare table 2).

KJ-39

KJ-39 was used for injection in the end of 2014 and in January 2015 (Figure 10). Then the injection rate was about 50 l/s. For the rest of the time no data on injection rate is available. This makes an analysis not possible.

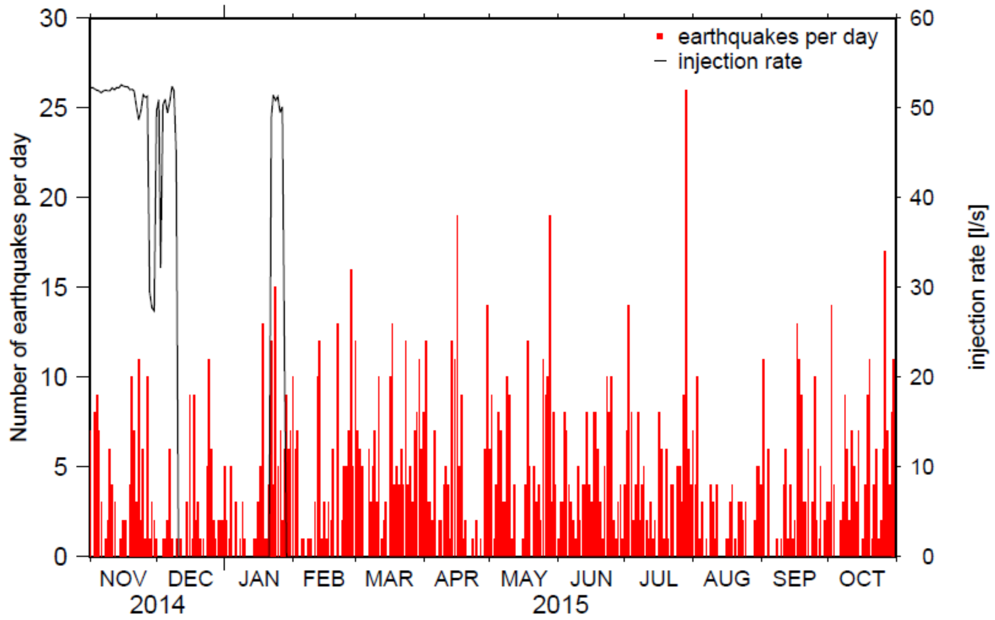

Figure 11. *KJ-39 injection rate and earthquake activity.*

IDDP-1

In the IDDP-1 borehole injection data is available from December 2014 until August 8th 2015. The data of the analysed period shows an injection rate of 24 l/s at the beginning of December which is lowered to about 14 l/s on December 10 and about constant to the end of the record. To analyse this almost constant injection data, the injection rates from the complete year 2014 where included (see Figure 11). For November 2014 and after August 8th 2015 there is no information on the injection rate and those time periods are not included in the following analysis.

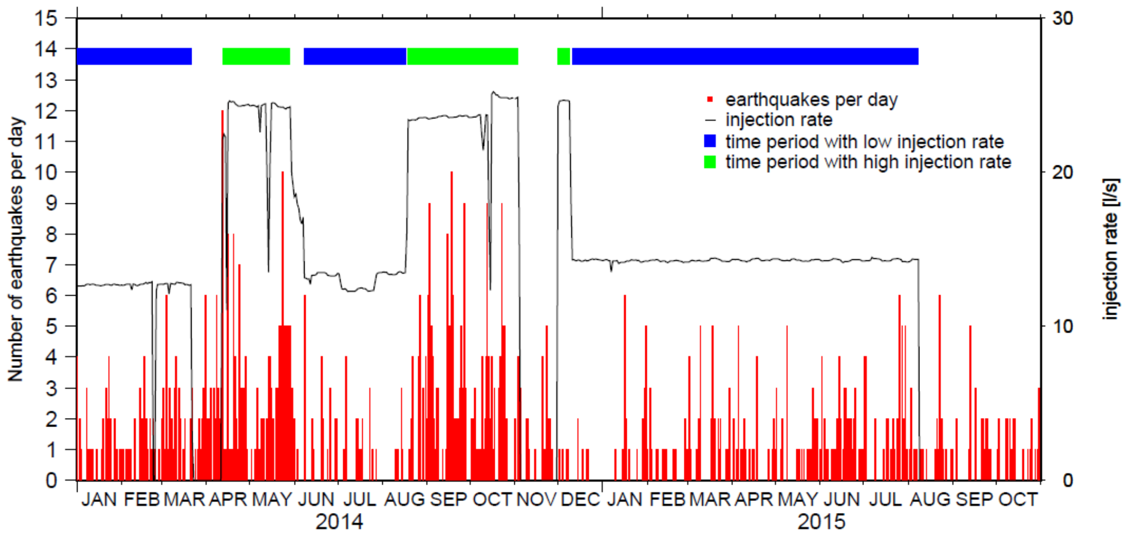

Figure 12. *IDDP-1 borehole injection rate and seismic activity. Blue bars mark time periods of low injection rate that are used for analysis and green bars marks those with high injection rate.*

On days with a lower injection rate the average number of earthquakes per day is 0.9 compared to 2.6 on days with higher injection rate. The difference in number of days with five or more resp. 10 or more events is significant (Table 3).

Table 3. *Average number of events recorded by days and number of days with 5 or more and 10 or more earthquakes on days with low or high injection rate in the IDDP-1 borehole.*

	Average number of earthquakes per day	Number of days with 5 or more earthquakes	Number of days with 10 or more earthquakes
Low injection rate (389 days)	0.9	4 (1.03 %)	0 (0 %)
High injection rate (134 days)	2.6	26 (19.40 %)	3 (2.24 %)

9 Summary

A total of 2948 earthquakes were located by the seismic network from November 1st 2014 until October 31st 2015. The spatial and depth distribution of those earthquake activity is similar to what we saw in last year's report. We see a few more deep events in the southwest what is probably due to better coverage since station DALFJ was set up. We also see that the majority of earthquakes is slightly shallower what results in a shallower, calculated brittle-ductile boundary. This is probably an artefact due to higher number of shallow induced earthquakes.

Vp/Vs ratios are identical to last year's results. The comparison of injection rate and seismic activity shows an increase of earthquake activity at days with higher injection rate compared to days with lower injection rate. For the KG-26 borehole the increase is as much as double, for the IDDP borehole the average is almost 3 times as high.

Overall we see an improvement in the regional coverage due to increase of number of seismic stations in strategically chosen sites.

10 References

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