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Landsvirkjun

Seismic Monitoring of Krafla

For the Period October 2013 to October 2014

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Title: Seismic Monitoring of Krafla. For the Period October 2013 to October 2014.

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Abstract:

In the summer of 2013 the seismic network of Krafla was extensively improved. Telemetry and regular analysis was in operation in October that year and in this report the operation of the network and the seismic activity for one year period from from October 2013 is described.

The operation of the network has generally been successful and datagaps are few. Noise generated by wind has been analysed and its effect on the sensitivity of the network. The magnitude of completeness is about 0.5 local magnitude but large number of smaller events are detected when the noise conditions are favorable. Just over 3000 events have been located within the Krafla caldera and many at greater distances, particularly in Bárðarbunga. To compare, 289 events were located by the regional SIL-network thus showing the importance of the sensitive local network.

The seismicity in Krafla is mainly confined to 5 distinct clusters in or close to the geothermal field. Outside these clusters but within the caldera rim of Krafla there is a diffused activity. Most of the earthquakes are located between one and two km depth. The depth of the brittle-ductile boundary is at about 2.2 km within the clusters but 3.6 km outside them. The Vp/Vs ratio is 1.68 within the clusters but 1.78 outside them and this value is observed at other locations in Iceland. The low Vp/Vs value in the geothermal field is an indication of a steam cap but it is also known that the value is low in silica rich rocks.

Correlation between seismicity and re-injections into wells KJ-26 and IDDP-1 exist.

Keywords:

seismicity, earthquakes, wind, brittle-ductile boundary, Vp/Vs ratio, induced seismicity, injections

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Approved by Landsvirkjun's project manager

Project manager's signature	Reviewed by
Magnús Ólafsson	ÓGF

Ágrip

Sumarið 2013 voru gerðar miklar endurbætur á jarðskjálftamælakerfinu í Kröflu og komst fjarskiptasamband og regluleg úrvinnsla á í október það ár. Í þessari skýrslu er gerð grein fyrir frammistöðu kerfisins og virkni í eitt ár frá október 2013.

Kerfið hefur í aðalatriðum staðið sig vel og gagnaheimtur með fjarskiptum gloppulitlar. Úrvinnsla hefur að sama skapi gengið vel. Athugað hefur verið hvaða áhrif vindstyrkur hefur á næmni kerfisins. Reikna má með að allir jarðskjálftar yfir 0,5 að stærð náist og umtalsverður fjöldi minni skjálfta þegar aðstæður eru góðar. Rúmlega 3000 skjálftar hafa verið staðsettir í Kröflu á tímabilinu en einnig margir utan kerfisins, einkum í Bárðarbungu. Til samanburðar er rétt að nefna að SIL-kerfið hefur staðsett 289 skjálfta á svæðinu á þessu tímabili þannig að ávinningur af þéttara og næmara neti er umtalsverður.

Jarðskjálftarnir eru að mestu í fimm allvel skilgreindum þyrpingum. Einnig er dreif skjálfta utan þessara þyrpinga en innan Kröfluöskjunnar. Flestir skjálftar eru á 1–2 km dýpi frá yfirborði og þykkt brotgjörnu skorpunnar í skjálftaþyrpingunum um 2,2 km. Utan þyrpinganna er brotgjarna skorpan talsvert þykkari, eða um 3,6 km.

Hlutafall p-bylgjuhraða og s-bylgjuhraða (Vp/Vs) er 1,68 í skjálftaþyrpingunum en utan þeirra 1,78 sem er svipað og annars staðar á Íslandi. Hið lága gildi í þyrpingunum er sennilega vegna gufupúða en einnig er þekkt að þetta hlutfall sé lágt í kísilríku bergi.

Tengsl eru á milli jarðskjálftavirkni og niðurdælinga í holur KJ-26 og IDDP-1.

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1 Introduction

This report approaches the status of the earthquake monitoring in Krafla geothermal area from October 25 2013 to October 31 2014. The task involves the installation and maintenance of a local seismic network, automatic data transfer to Landsvirkjun (LV, The National Power Company) and to Iceland GeoSurvey (ÍSOR) and processing and analyzing of the data. Landsvirkjun owns and runs the seismic stations and takes care of the data transfer in cooperation with ÍSOR. ÍSOR processes, analyzes and interprets the data in the context of the geothermal field.

2 Data acquisition and real time processing and maintenance

Data acquisition is online with wireless WiFi and GSM phones. The software that handles the data transfer are RTPD from RefTek and seedlink which is a part of the SeisComp3 software. The data acquisition has been successful for the most part. Late 2014 changes were made of the mobile phone network and transmission of data from several stations was down for some time. This is probably not lost data as the stations have internal backup that can be fetched at the stations.

The real-time picking and localization of events, first automatically and shortly after manually, is carried out with the SeisComp3 software as described in 2012 and earlier reports (e.g. Ágústsson et al., 2012b).

The estimation of earthquake magnitudes is so far not sufficient for an analysis. A configuration problem in the Seiscomp3 software causes that the different sensor types and data loggers are not taken into account when calculating the magnitude. The problem has been reported to the company GEMPA in Germany which provides the software. They are currently working on a solution.

3 The seismic Network

Since 2006 a seismic network consisting of 5–6 borehole seismometers has been operated in the Krafla geothermal field. The network was improved significantly in 2013 with five new conventional stations and four of the borehole sensors were replaced (Stefánsson, 2013). In 2014 three stations were installed around Námafjall and another three at Þeistareykir. Currently the network consists of 17 short period seismic stations (Figure 1 and Table 1).

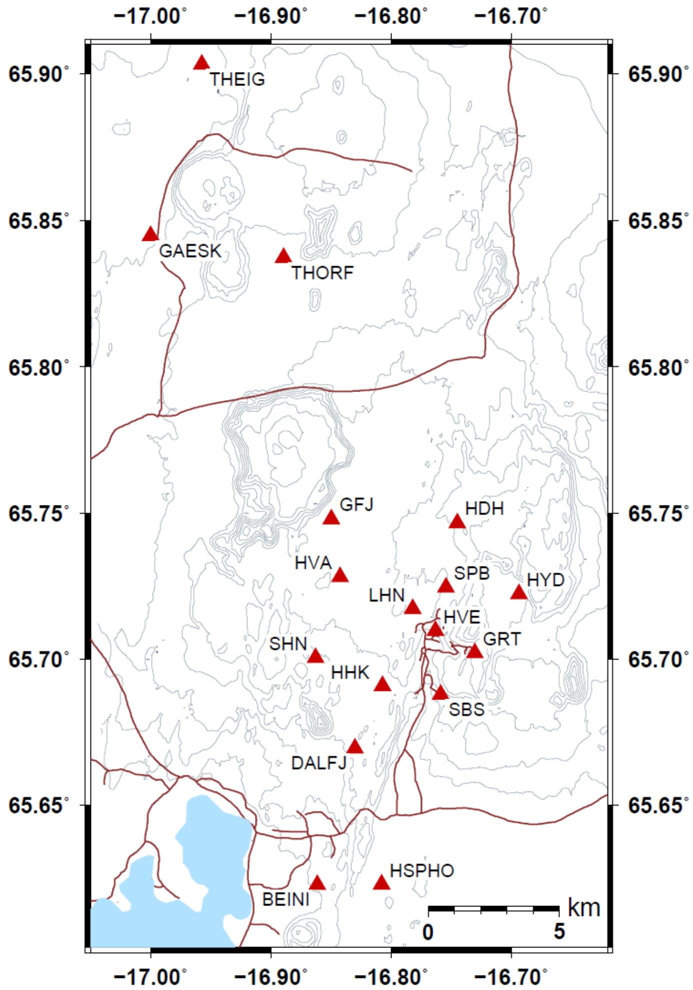

Figure 1. *Seismic network in Krafla, Námafjall and Þeistareykir. Eleven seismometers are operated in Krafla area, three in Námafjall and three in Þeistareykir.*

The stations that were added to the network in August and early September 2013 are conventional surface stations (GFJ, HDH, HVA, HYD and SHN). Before, the network consisted of six stations with borehole seismometers (GRT, HHK, HVE, LHN, SBS and SPB). The sensors at the borehole stations GRT, HHK, HVE and SPB were replaced. The stations covering the Námafjall area (BEINI, DALFJ and HSPHO) were installed in May and June 2014. Finally, the stations at Þeistareykir were installed in the autumn of 2014 (THORF, THEIG, GAESK). All the stations are on-line except THEIG and GAESK as internet connection to Þeistareykir was first established in January 2015. Therefore the data from the two stations has not been used for the analysis presented in this report. The same applies to the online data from the six stations of the SIL network that Landsvirkjun requested from the Iceland Meteorological Office.

In the course of the IMAGE VSP experiment performed in Krafla in late May and early June 2014 three temporary stations (short period sensors) were installed (VIT, THP, HVG) and were in operations until September 2014. In addition 21 temporary stations were operated during the VSP IMAGE experiment and for a couple of months afterwards. This was a part of the DRG project (DRG - Deep Roots of Geothermal Systems supported by the GEORG - Geothermal Research Group) in Krafla.

Table 1. *The seismic network in Krafla. Stations marked with star have preliminary location.*

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 24.12.2014
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	-16.745067	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		-	Lennartz LE-3Dlite	Reftek	01.09.2014
THEIG*	65.903270	-16.957630		-	Lennartz LE-3D5s	Cube	16.10.2014
GAESK*	65.844840	-17.000070		-	Lennartz LE-3D5s	Cube	05.09.2014
VIT (temp.)	65.717461	-16.756442	565.0	-	Nanometrics Trillium Compact	Omnirecs Data-cube3	04.06.2014 20.08.2014
THP (temp.)	65.695305	-16.768722	456.0	-	Nanometrics Trillium Compact	Omnirecs Data-cube3	09.06.2014 15.07.2014
HVG (temp.)	65.710132	-16.764248	507.0	-	Nanometrics Trillium Compact	Omnirecs Data-cube3	04.06.2014 20.08.2014

4 Earthquakes recorded

In the period from October 25 2013 until October 31 2014 a total of 3047 seismic events within the Krafla area were located by the network. Additionally many earthquakes were recorded that do lie outside the network, particularly in Bárðarbunga, and are only poorly located. For the same time period the number of events located by the SIL network operated by the Icelandic Meteorological Office is 289 (Veðurstofa Íslands, n.d.).

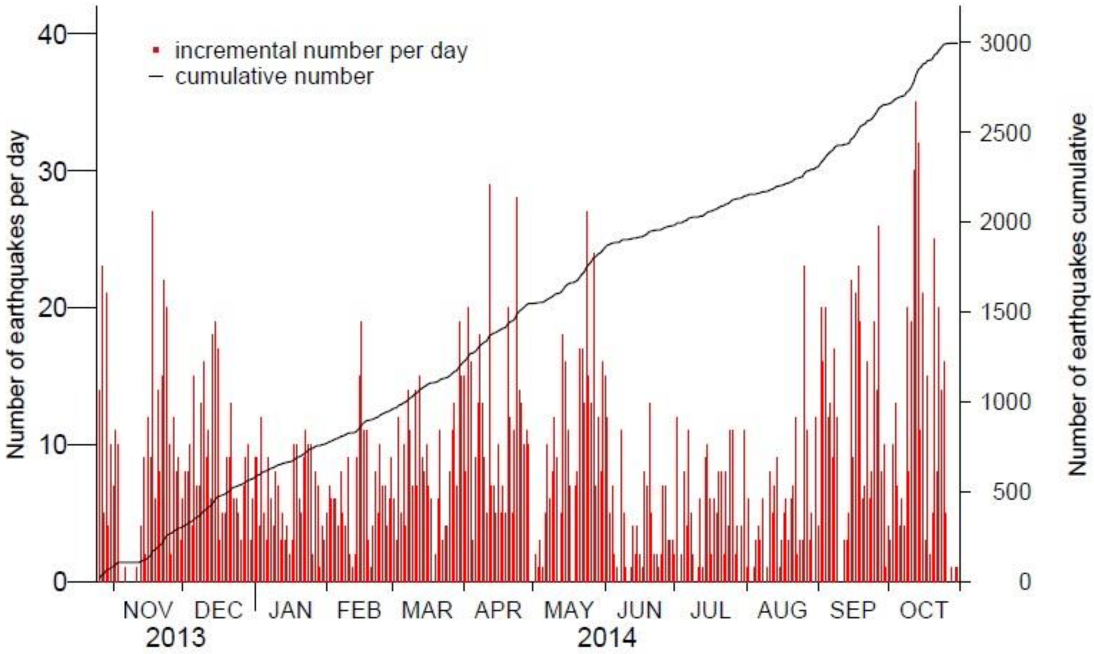

Figure 2. *Earthquakes per day in Krafla. From October 25 2013 until October 31 2014 there are 3047 well-located earthquakes in Krafla. The number of earthquakes is subject to strong fluctuations both on short and long time scale.*

The activity is subject to strong variations. The number of earthquakes varies from zero recorded earthquakes to 36 per day with an average of 8.2. The time period investigated is too short to identify seasonal variations. But it appears that activity is increased during the autumn months. Another period of enhanced activity reaches from late February to the beginning of June 2014.

Additional to the natural variations (air pressure, precipitation, variability of seismic activity) there is a number of factors that can cause fluctuations in the measured seismic activity. Both injection and production from wells can cause variations in seismic activity. In stormy weather background noise is high so smaller earthquakes are disguised and potentially missed. Furthermore, in bad weather the WiFi connection to the seismic stations occasionally breaks down and increases the possibility of not detecting smaller events.

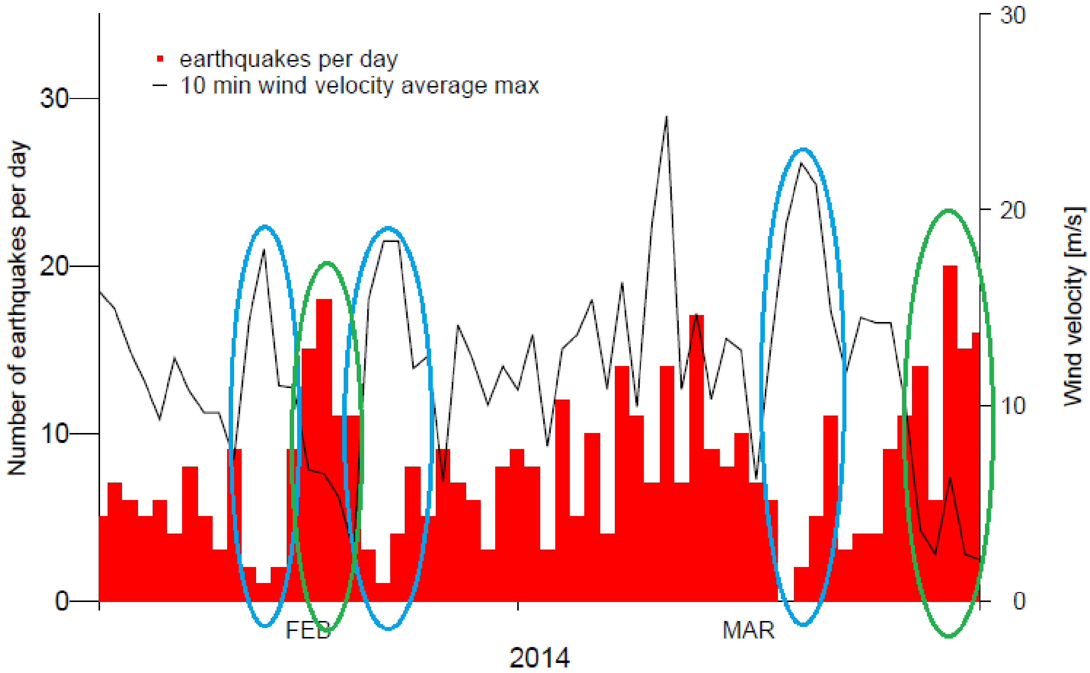

Figure 3. *Correlation between wind speed and number of recorded earthquakes per day. This section from February and March 2014 shows partly good matches between the measured 10 min. wind velocity average maximum per day and the recorded number of earthquakes. The two peaks in wind velocity around mid-February and in the beginning of the second half of March (blue ellipses) coincide with a low number of events as well as there are many earthquakes recorded during the low wind velocity in mid-February and late March (green ellipses).*

To quantify the correlation of weather conditions and number of measured earthquakes the wind speed measured at the MYV weather station at Mývatn and the number of earthquakes were plotted (Figure 3). In the beginning a number of different wind observations were used, e.g. 10 min. velocity average maximum and minimum, gust winds maximum and minimum. Those parameters vary in amplitude but they follow all the same trend. So for reasons of clarity only one of the wind parameters was plotted and as an example the months February and March were chosen. The figure shows that partly good matches can be identified, e.g. in mid-February and the second half of March where high wind velocities coincide with small numbers of recorded earthquakes and vice versa. On the other hand, no correlation can be seen at the beginning and end of February as well as in the first half of March.

For better visualization of a possible connection, wind speed and the number of earthquakes recorded was plotted for each day where both data was available (Figure 4). The plot clearly shows a decrease of events with increasing wind speed. But the distribution does not indicate linear behavior. So no correction for the wind to derive a "real" number of events is possible. However, it is obvious that the number of recorded earthquakes is strongly reduced when the wind speed exceeds 18–20 m/s.

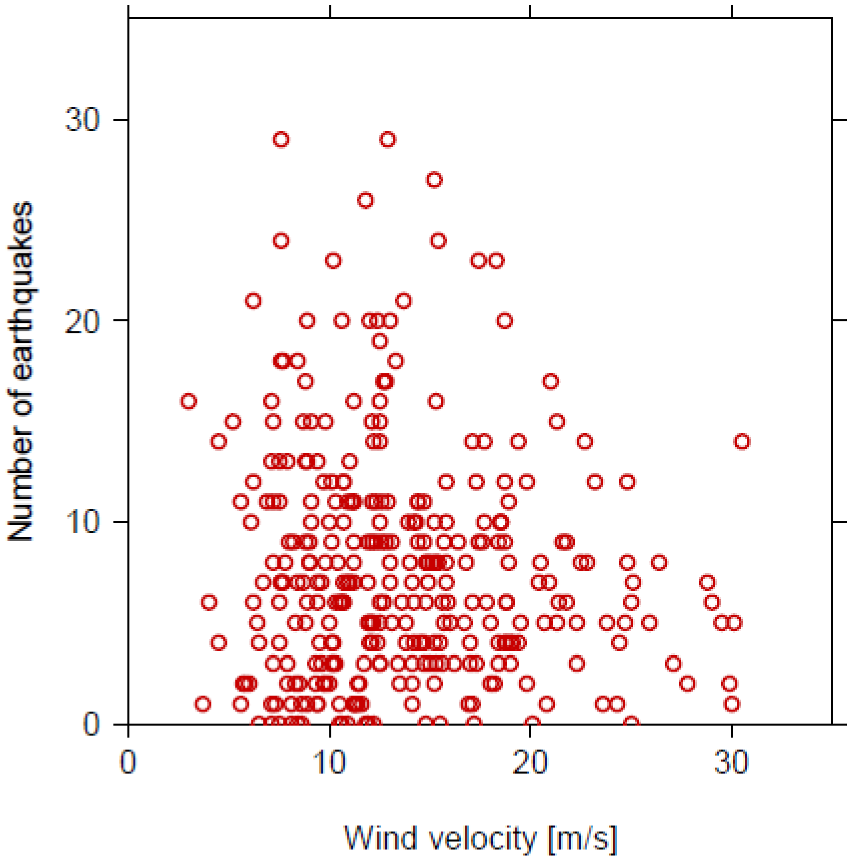

Figure 4. *Recorded earthquakes per day as a function of maximum 10 min. average wind velocity. For each day with known wind velocity one data point was drawn presenting the number of earthquakes recorded that day and the wind velocity. The distribution indicates a decrease of recorded events with increased wind velocity.*

5 Spatial distribution

Figure 5 shows the spatial distribution of seismic events in Krafla. Both the surface projection and the N-S and E-W sections show the activity in locally confined areas. The main activity occurs in five clusters. The largest cluster is associated with the main production area south of Víti. The second cluster west of Víti lies in area around the IDDP-1 well. Two clusters are close to Leirhnjúkur, one NNE and another SSW of it. The smallest cluster is just north of Rauðhóll.

To identify fractures or fault zones in the subsurface the earthquakes need to be relocated with more precision as possible fractures would expose in alignment of earthquakes along them. However, there is indication in this dataset of a northward dipping fault at the IDDP-1 well in the same location as was identified in 2009 (Ágústsson et al., 2012a).

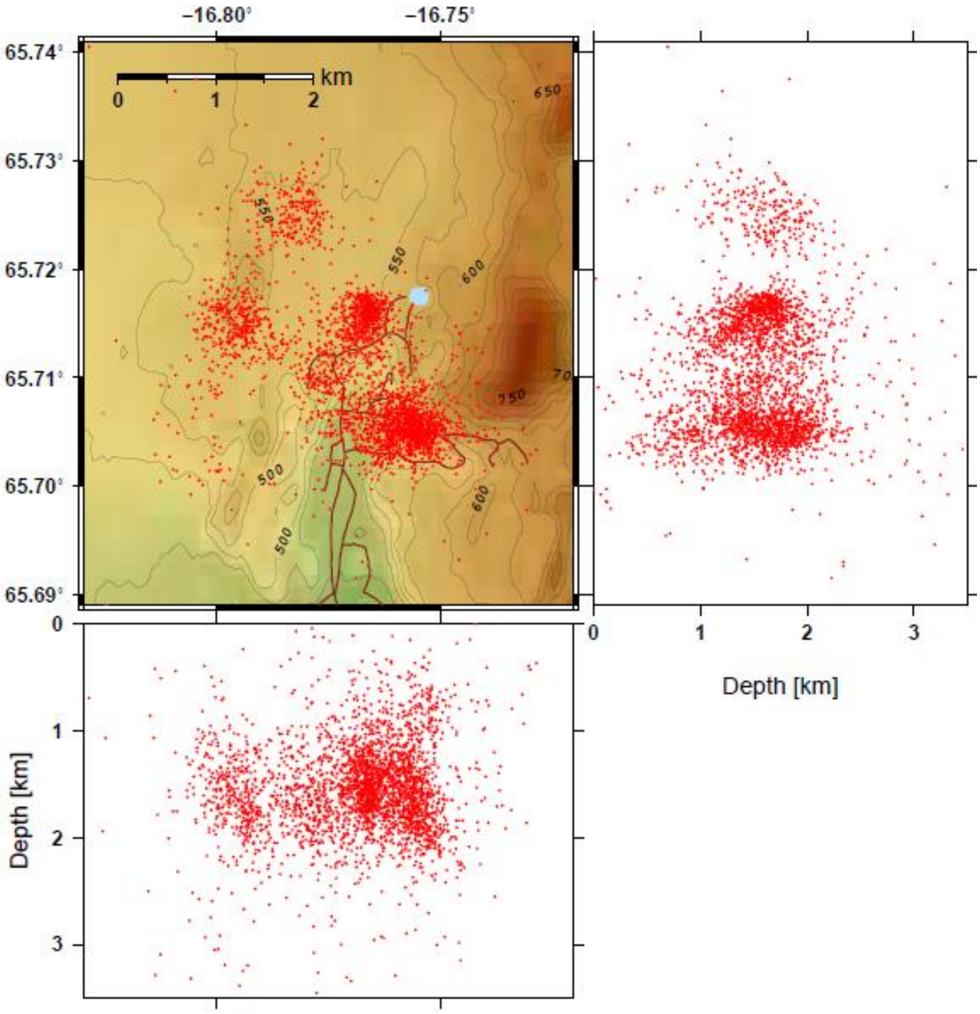

Figure 5. *Earthquakes locations in surface projection and E-W and N-S sections.*

6 Depth distribution

The distribution of earthquakes with depth from the surface shows that the main activity is in 1 to 2 km depth (Figure 6). 95% of the seismic events occur in a depth shallower than 2250 m. Below this depth the missing seismicity indicates ductile rock behavior. This boundary is usually referred to as the brittle-ductile boundary (BDB) and is temperature dependent. Ágústsson and Flóvenz (2005) associated the boundary with temperatures of about 750 ±100 °C. Extrapolation of laboratory measurements of non-glassy basalts predicts that the temperature at the brittle ductile boundary might occur at temperatures higher than 550 ±100°C (Violay et al., 2012). However, in case of continental crust and more silicic crustal material, the brittle ductile boundary can be expected even lower than 450°C (Chen and Molnar, 1983).

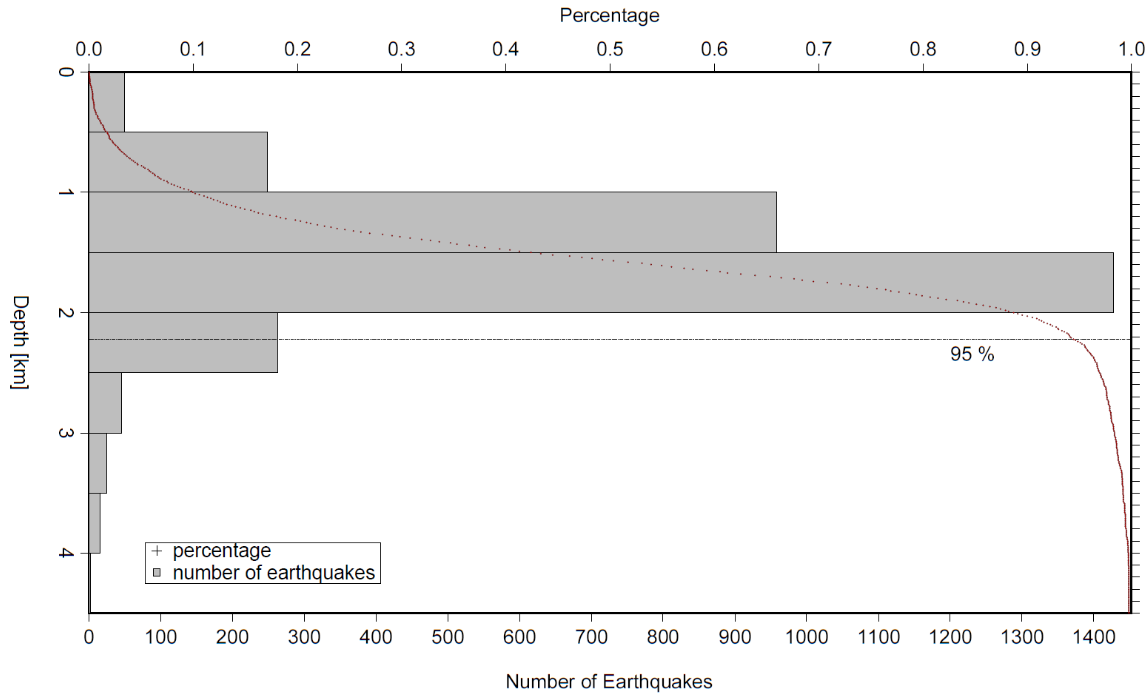

Figure 6. *Distribution of earthquakes with depth for the whole area in question. Most of the activity occurs in depths between 1000 and 2000 m. 95% of the events have focal depth shallower than 2250 m.*

For a better visibility of the activity distribution the events of each 500 m layer were plotted separately (Figure 7). The plots re-emphasize that the earthquakes occur in well-defined clusters. Especially in the depth interval from 1500 to 2000 m (Figure 7d) the distribution into five separated clusters can clearly be seen.

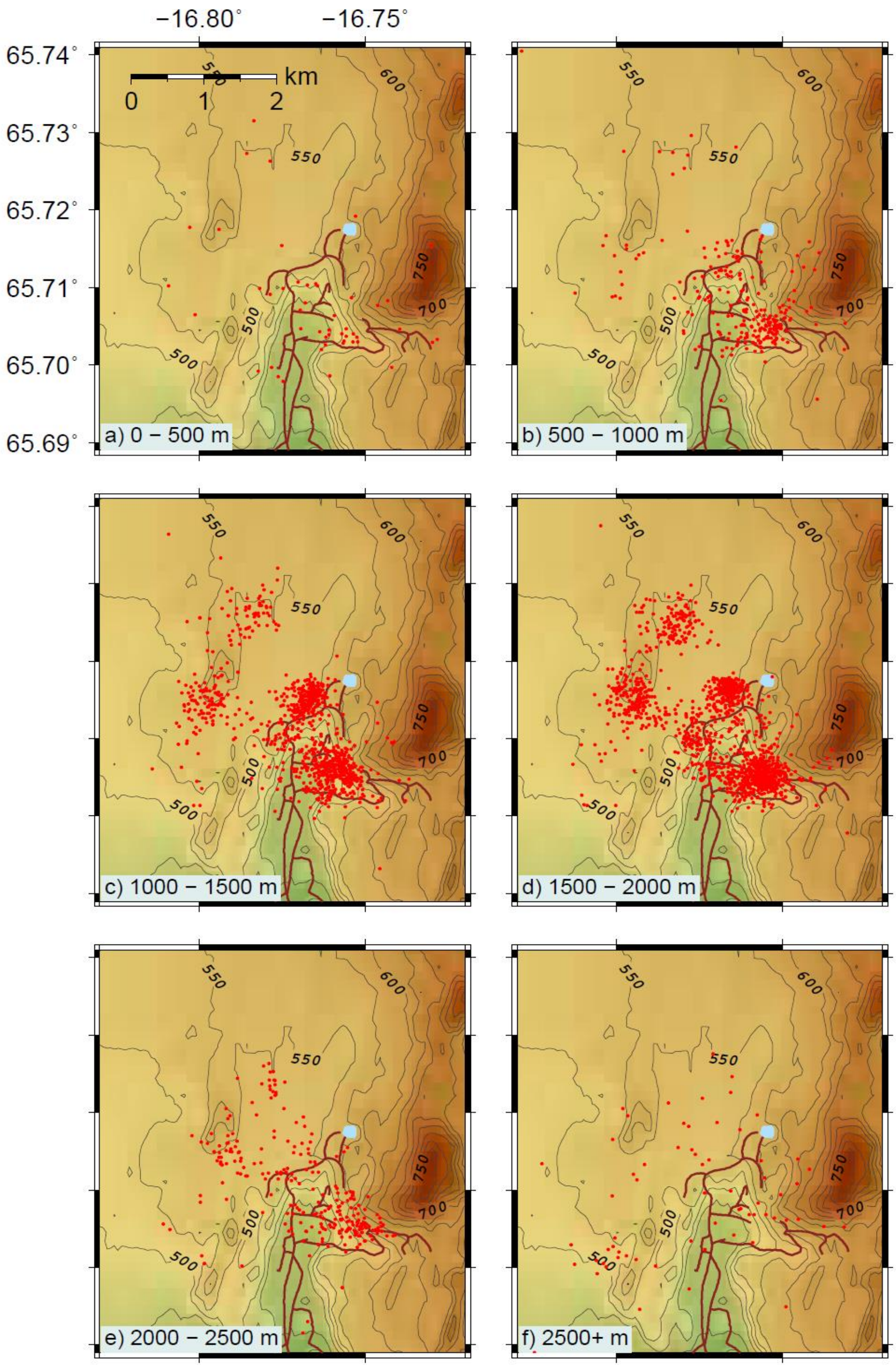

Figure 7. *Location of the activity in different depth intervals. Each illustration a) – e) represents a 500 m thick layer of the subsurface. In illustration f) all events deeper than 2500 m are shown. The main activity occurs between 1000 and 2000 m and clearly five separated clusters are visible.*

7 Depth distribution in the clusters

The distribution of earthquakes in the different depth intervals (Figure 7), especially from 1000 to 1500 m and from 1500 to 2000 m confirms that the activity mostly takes place in five spatially separated clusters. To investigate variations in the depth of the brittle-ductile boundary these clusters are spatially classified and the depth distribution is calculated for each of them. For the classification of the clusters see Figure 8.

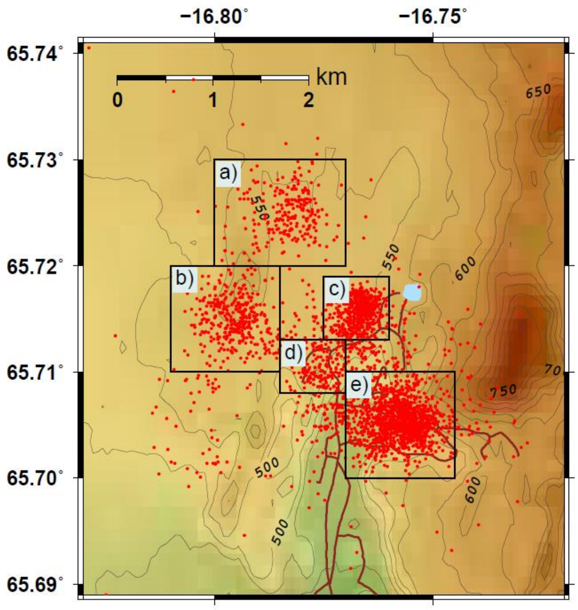

Figure 8. *Locations of clusters a) to e).*

In cluster a) 236 earthquakes were recorded, 364 in cluster b), 570 in cluster c), 177 in cluster d) and 1270 in cluster e). Events in Krafla area which do not lie in one of the clusters are summed up as a cluster f) which consists of 243 earthquakes.

The depth distribution of earthquakes in the clusters a), b), d) and e) show only small variations (Figure 9). The 95% of the activity occurs in depths shallower than 2.16 km, 2.2 km, 2.15 km and 2.12 km respectively with an average of 2.16 km.

Cluster c) surrounds the IDDP well where drilling in 2009 had to be stopped at 2.1 km depth when approximately 900°C rhyolitic magma was intersected (Friðleifsson et al., 2011). Using the same 95% approach here, the earthquake distribution with depth suggests that the brittle-ductile boundary lies about 250 m shallower depth there (at 1.91 km) than in the other clusters. This lifting of the 95% line might be due to a considerate number of shallow earthquakes induced by the injection taking place in the IDDP well. These shallow events may affect the natural seismic depth distribution and result in a seemingly decreased depth of the brittle-ductile boundary (Ágústsson et al., 2012a).

For comparison all events in the Krafla area which do not lie within one of those clusters were pooled and the depth calculated in which 95% of the events lie (Figure 9f). Here that depth is considerable larger, or 3.58 km.

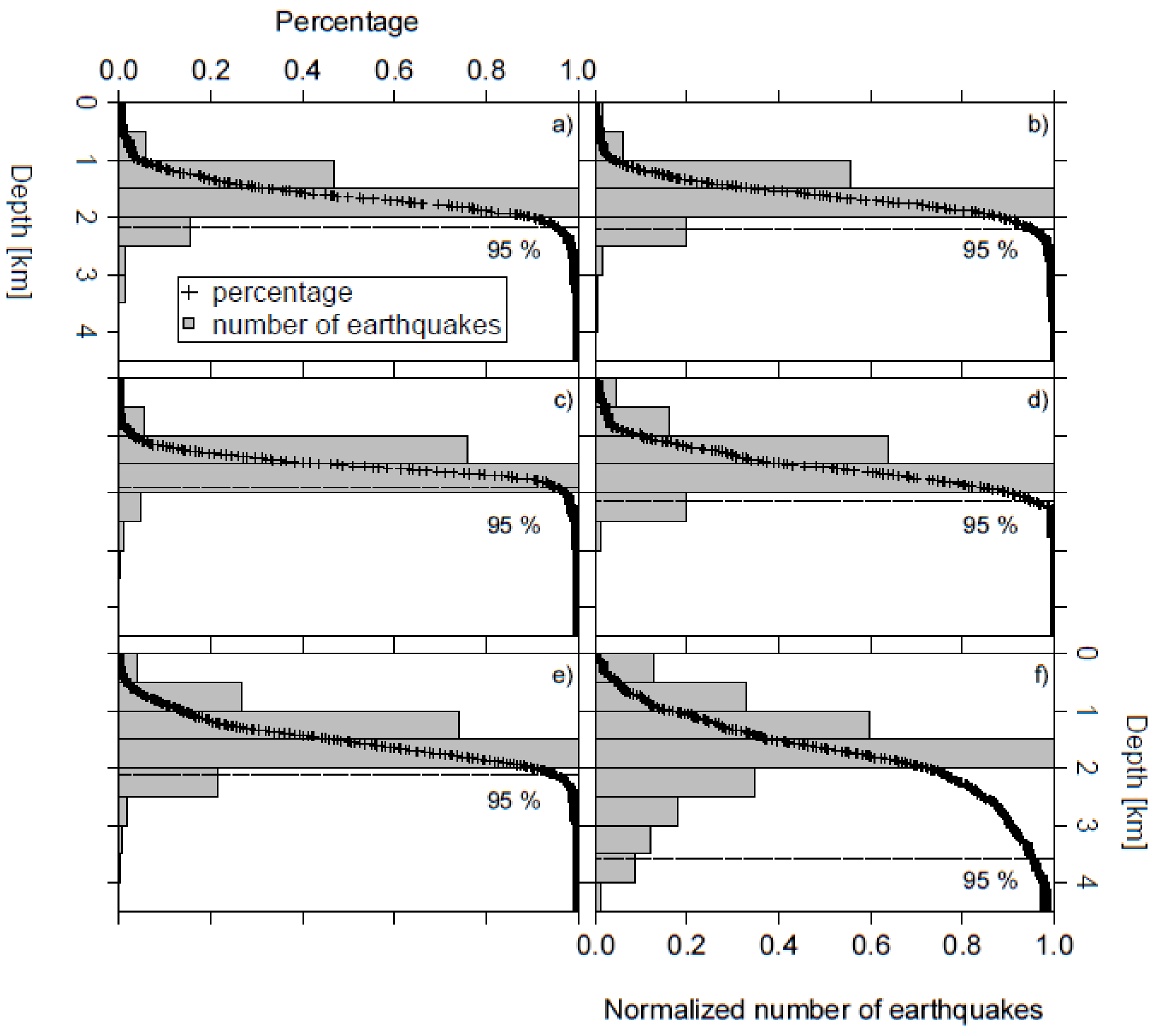

Figure 9. *Depth distribution of earthquakes in cluster a) to e). In f) all events are summed up that do not lie inside any of clusters a) to e) but within the Krafla area. The number of earthquakes is normalized with the maximal number of earthquakes in one layer in the cluster and is represented by a gray column. The crosses show the cumulative number of earthquakes in percent of the total number of events in the cluster. The dashed line represents the maximal focal depth of 95% of the events. In cluster a) 95% of the events occur in depths shallower than 2.16 km. In cluster b) the 95% line is in 2.2 km, in cluster c) in 1.91 km, in cluster d) in 2.15 km and in cluster e) in 2.12 km. While cluster a), b) d) and e) show similar values, the line lies about 250 m higher in cluster c). In the crust outside the clusters the 95% boundary is considerable deeper at 3.58 km depth.*

8 Vp/Vs ratio

Detailed information on velocity ratios is important to verify or improve the existing velocity model. The Standard Wadati method (Wadati, 1928) to derive the Vp/Vs ratio of the crust makes use of the arrival times both of the p- and s-waves. The location of the events is not needed. The result of this method describes the average of the velocity ratio in the crust the waves travel from source towards the seismic stations.

The Vp/Vs ratio derived for the Krafla area with the Standard Wadati approach is 1.680 which is unusually low (1.73 is the expected value for an ideal elastic medium) (Figure 10). S-wave velocity depends mainly on the shear strength of the rock

$$\mathrm{Vs} = \sqrt{\frac{\mu}{\rho}}$$

where μ is the shear modulus and ϱ is the bulk density. This means that high shear strength (μ) results in high S-wave velocity but low shear strength, as when material is close to melting, means low S-wave velocity. Fluids have no shear strength and therefore S-waves do not propagate through fluid and molten material and create an S-wave shadow in seismic data.

The P-wave velocity depends additionally on the incompressibility

$$Vp = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}$$

where k denotes the incompressibility. This means that higher compressibility results in lower P-wave velocity. Gas and steam have very high compressibility compared to water. If the pores in a porous rock are filled with steam or gas or even supercritical fluid the rock will have increased compressibility (lower incompressibility) compared to rock with water filled pores and the P-wave velocity will lower without affecting the S-wave velocity. Low Vp/Vs ratio means a relative decrease in P-wave velocity compared to S-wave velocity and show material with high shear strength but and high compressibility. Therefore the low Vp/Vs ratio in Krafla is likely to be a consequence of a steam cap or boiling within the geothermal reservoir. By more detailed analysis of the Vp/Vs ratio it could be possible to estimate the extent and the volume of the steam zone.

Low velocity ratios are a common feature observed at shallow depths in geothermal areas (e.g. Walck, 1988; Julian et al., 1996; Muskin et al., 2013). They can be a consequence of high quartz content in granitic or andesitic rock (Christensen, 1996). Foulger et al. (1995) suggest mineral alteration or supercritical fluids. Tryggvason et al. (2001) also attribute a high Vp/Vs ratio below the Hengill geothermal system to supercritical fluids within the volcanic fissure system.

In Krafla we have rhyolite and probably a steam cap which both can explain this low Vp/Vs ratio. The volume of rhyolite in the uppermost 2 km of the Krafla reservoir might however not be enough to explain the low ratio so a steam cap is a much more likely explanation.

To compare the velocity ratio in the Krafla area the 265 earthquakes that lie outside the geothermal area were used for the calculation of the Vp/Vs ratio of the surrounding crust. These events are not well located but as mentioned above the Standard Wadati Method does not require location information. The Vp/Vs ratio outside of Krafla was calculated to be 1.782 (Figure 10) and corresponds to studies on the Icelandic crust which show values of about 1.75–1.79 (e.g. Brandsdóttir and Menke, 2008; Tryggvason et al., 2001). This shows that the low Vp/Vs is confined to the geothermal system which supports the steam cap explanation.

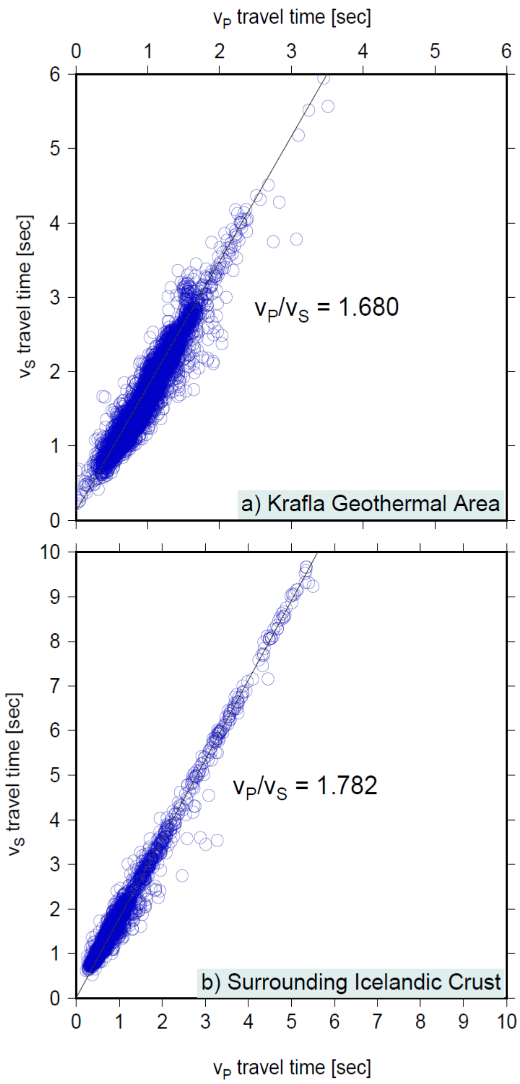

Figure 10. *Vp/Vs ratio in Krafla and surrounding crust.*

9 Comparison injection rate/number of earthquakes

For boreholes KJ-26, KJ-39 and the IDDP-1 well a comparison between the injection rate and the surrounding seismic activity was drawn. The location of the boreholes and the corresponding area are displayed in Figure 11. In the injection data provided by Landsvirkjun the injection rate is measured every 5 (KJ-26 and KJ-39) and every 10 (IDDP-1) minutes. For reasons of clarity and because the data on the number of earthquakes is given per day, the injection rates used in this analysis are average values per day.

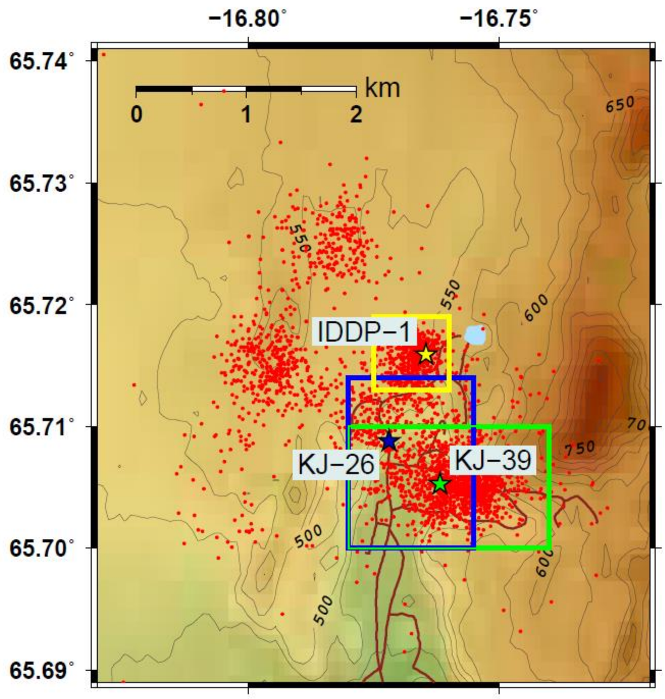

Figure 11. *Locations of boreholes KJ-26, KJ-39 and IDDP-1 and the areas used for comparison of number of earthquakes.*

9.1 KJ-26

In KJ-26 the injection rate was about 70 L/s and rather constant while injection was ongoing. The injection was not carried out continuously. From June 24 to September 16 injection was stopped. Furthermore, there is a decrease in injection rate in May 14 and 15 and an injection stop from June 7 until June 11. During the time periods with injection the number of earthquakes is higher than on days without. For detailed information see Table 2. The data does not indicate significant changes in seismic activity at the end of injection in June. The onset of injection in September is about the same time as in increase in seismic activity. Weather a causal connection exists or not is open to discussion.

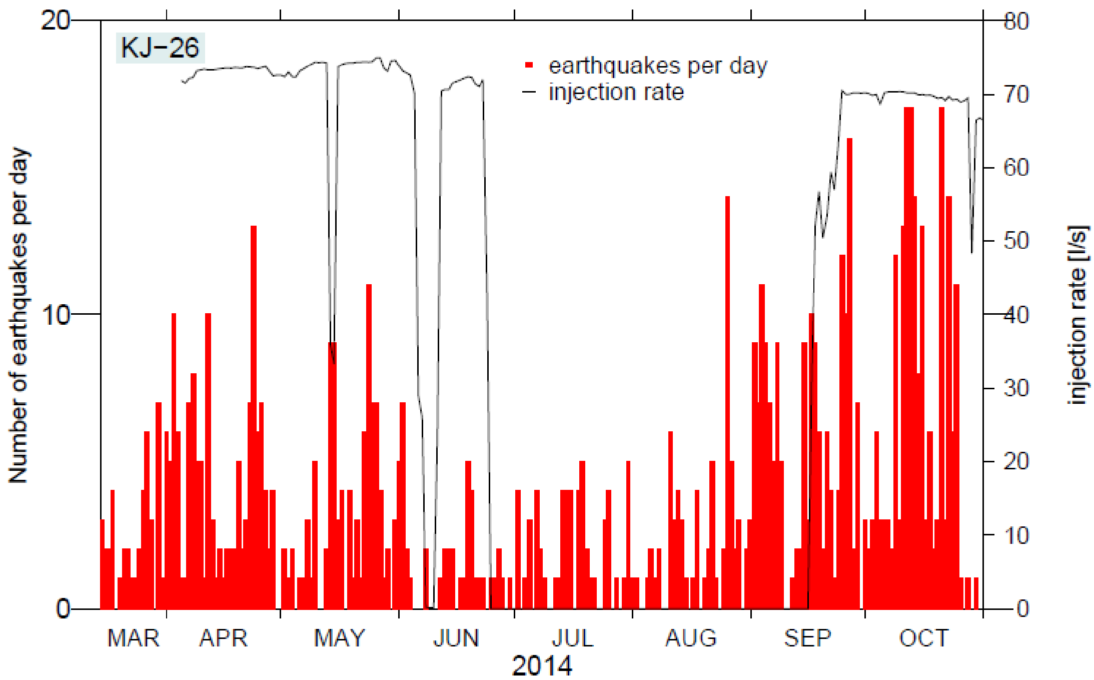

Figure 12. *Injection rate in borehole KJ-26. The black line stands for the injection rate in L/s, the red bars represent the number of recorded earthquakes in the crust close to the borehole.*

Table 2. *Seismicity around borehole KJ-26. During injection the number of events recorded per day is higher than on days without injection. Days with large numbers of events are more frequent.*

	Average number of earthquakes per day	Number of days with 5 or more earthquakes	Number of days with 10 or more earthquakes
Injection (126 days)	3.7	39 (31 %)	9 (7 %)
No injection (85 days)	2.1	13 (15 %)	1 (1 %)

9.2 KJ-39

In KJ-39 the injection rate is relatively constant (Figure 13). The injection rate fluctuates between about 45 and 55 L/s. Because there are no abrupt changes in the injection rate it is not possible to relate the fluctuations in the number of recorded events to it. In the investigated area used for comparison the average number of earthquakes per day is 3.4.

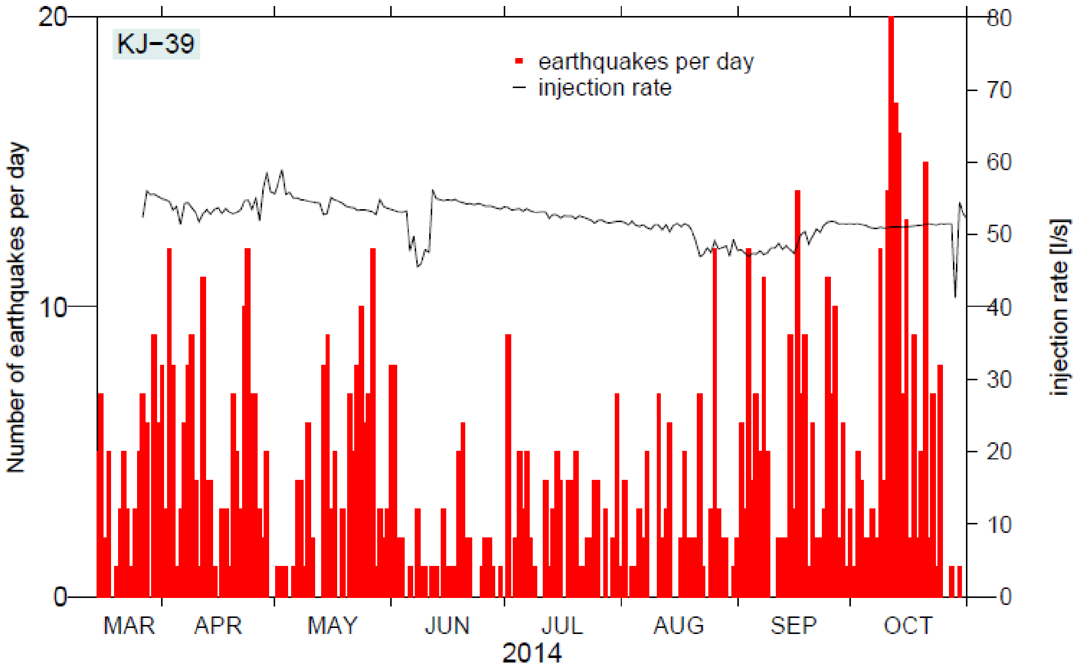

Figure 13. *Injection rate in borehole KJ-39. The black line stands for the injection rate in L/s, the red bars represent the number of recorded earthquakes in the crust close to the borehole. Note that the earthquakes used are also close to the injection well KJ-26.*

9.3 IDDP-1

For the IDDP-1 well information on the injection rate is available for the whole time period analyzed in this report. The injection rate in the IDDP-1 well was rather small compared to KJ-26 and KJ-39. There are two main injection rates with only small deviations which are about 13 and 24 L/s. There are gaps in the injection rate data (see Figure 14).

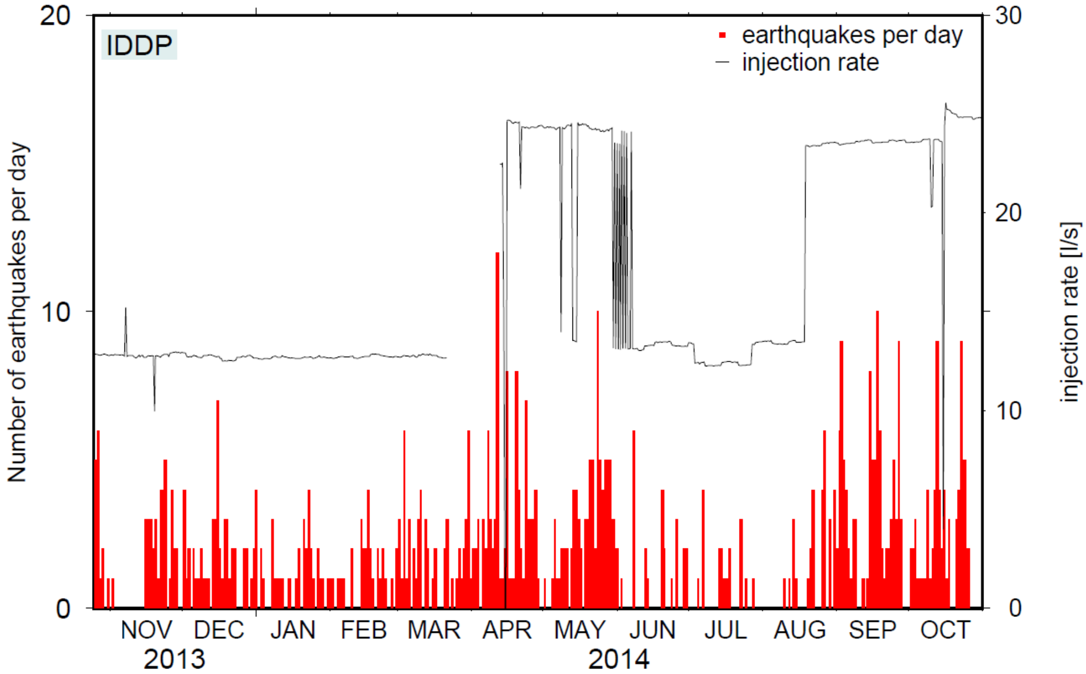

Figure 14. *Injection rate in IDDP-1 borehole. The black line stands for the injection rate in L/s, the red bars represent the number of recorded earthquakes in the crust close to the borehole.*

During the first 5 month until April 15, 2014, and later from the beginning of June until late August the injection rate is rather constant with a rate about 13 L/s. In April and May as well as from late August onward the injection rate is about 24 L/s with some short interruption when the injection rate is lowered to 13 L/s. At the end of May there is a time period of about a week where the injection rate fluctuates rapidly between 13 and 24 L/s. During the time periods with the higher injection rate the number of earthquakes is higher than on days with lower injection rate. For detailed information see Table 3.

Table 3. *Seismicity around the IDDP-1 well. On days with higher injection rate the number of events recorded per day is higher than on days with lower injection rate. Days with large numbers of events are more frequent.*

Injection rate [L/s]	Average number of earthquakes per day	Number of days with 5 or more earthquakes	Number of days with 10 or more earthquakes
24 (113 days)	2.7	25 (22 %)	2 (2 %)
13 (216 days)	1.1	6 (3 %)	0 (0 %)

10 Summary

This report covers the period from October 2013 to October 2014. During this period the operation of the seismic network has been successful. Data gaps are few. Several improvements, both on the stations and telemetry, have been discussed and plans on carrying them out in cooperation with LV have been made.

The sensitivity of the network and the quality of the locations have improved significantly with the new stations and new borehole sensors. A total of 3047 earthquakes were recorded during this year compared to 289 earthquakes recorded by the national network (SIL network). Full coverage of earthquakes with local magnitude above 0.5 can be expected. Many smaller events are however detected but how small quakes can be detected depends on noise conditions, especially wind speed.

Correlation of measured seismicity and measured wind speed show significant reduction in recorded quakes as the wind speed exceeds 18–20 m/s.

The magnitude estimate in the seismic software used (SeisComp3) is deficient at the moment but the software producer is taking measures to improve it. Therefore the magnitude determination is not reliable for detailed magnitude processing. The magnitudes are however roughly correct as they are calibrated with respect to the SIL network.

The depth distribution of the five clusters within the geothermal field in Krafla shows that the brittle-ductile boundary is about 1500 m shallower within the geothermally active area where the average depth is about 2160 m than in the surrounding crust where the brittle-ductile boundary is at about 3700 m depth. It is somewhat shallower around the IDDP-1 well and might be biased by the obviously induced earthquakes as was the result in 2009.

Almost all the earthquakes are within the seismic network and inside the caldera rim of the Krafla central volcano and location quality is similar. Therefore, this up doming of the brittle-ductile boundary below the geothermal field is real and noteworthy.

The number of recorded earthquakes in the crust surrounding the KJ-26 and the IDDP-1 well indicate a correlation between injection rate and the number of events. At KJ-26 the average number of events per day while injection is ongoing is higher than on days without injection. The IDDP-1 well shows similar behavior. On days with high injection rate the seismic activity is higher than on days with a smaller injection rate. In the well KJ-39 small variations in injection rate make interpretation difficult.

Calculations of the ratio between P-wave and S-wave velocities (Vp/Vs ratio) shows significant lower value within the geothermal reservoir than outside it. This indicates a considerable steam and/or gasses in the pore volume of the reservoir, possibly indicating a steam cap. Further analysis could possibly locate the steam zone.

The dataset offers new and more detailed analysis that can give valuable information on the structure and dynamics of the geothermal field in Krafla and as time passes for Námafjall and Þeistareykir as well.

11 References

Ágústsson, K. and Flóvenz, Ó. G. (2005). The thickness of the seismogenic crust in Iceland and its implications for geothermal systems in Iceland. Extended abstract, *WGC 2005, Turkey*.

Ágústsson, K., Flóvenz, Ó. G., Guðmundsson, Á. and Árnadóttir, S. (2012a). Induced seismicity in the Krafla high temperature field. *GRC Transactions, 36, 2012*, 975–980 (2012).

Ágústsson, K., Árnadóttir, S. and Flóvenz, Ó. G., (2012b). *Skjálftamælingar í Kröflu.* Iceland GeoSurvey, report, ÍSOR-2012/018, LV-2012/058.

Brandsdóttir, B. and Menke, W. (2008). The seismic structure of Iceland, *Jökull, 58,* 17–34.

Chen W-P., and Molnar P. (1983). Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, *J. Geophys Res*., *vol 88, B5*, 4183–4214.

Christensen, N. I. (1996). Poisson's ratio and crustal seismology. *Journal of Geophysical Research, 101 (B2)*, 3139–3156

Friðleifsson, G. Ó., Albertsson, A., Elders, W. A., Sigurdsson, Ó., Karlsdóttir, R. and Pálsson, B. (2011). The Iceland Deep Drilling Project (IDDP): Planning for the second well at Reykjanes. *GRC Transactions, vol. 35*, 347–354

Foulger, G. R., Miller, A. D., Julian, B. R. and Evans, J. R. (1995). Three-dimensional υp and υp/υs structure of the Hengill Triple Junction and Geothermal Area, Iceland, and the repeatability of tomographic inversion. *Geophysical Research Letters, vol. 22, issue 10*, 1309–1312

Julian, B. R., Ross, A., Foulger, G. R. and Evans, J. R. (1996). Three-dimensional seismic image of a geothermal reservoir: The Geysers, California. *Geophysical Research Letters, vol. 23, issue 6*, 685–688

Muskin, U., Bauer, K. and Haberland, C. (2013). Seismic Vp and Vp/Vs structure of the geothermal area around Tarutung (North Sumatra, Indonesia) derived from local earthquake tomography. *Journal of Volcanology and Geothermal Research, vol. 260*, 27–42.

Stefánsson, S. A. (2013). *Skjálftamælanet í Kröflu 2013. Endurbætur á borholuskjálftamælum og uppsetning yfirborðsskjálftamæla*. Iceland GeoSurvey, report, ÍSOR-2013/056, LV-2013–122.

Violay, M., B. Gibert, D. Mainprice, B. Evans, J.-M. Dautria, P. Azais, and P. Pezard (2012). An experimental study of the brittle-ductile transition of basalt at oceanic crust pressure and temperature conditions. *J. Geophys. Res., 117*, B03213, doi:10.1029/2011JB008884.

Wadati, K. (1928). Shallow and deep earthquakes. *Geophysical Magazine 1*, 162–202.

Walck, M. C. (1988). Three-dimensional Vp/Vs variations for the Coso Region, California. *J. Geophys. Res., 93(B3*), 2047–2052, doi: 10.1029/JB093iB03p02047.

Veðurstofa Íslands (n.d.). *Jarðskjálftar* (http://hraun.vedur.is/ja/viku/; Access: 16.02.2015).

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