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Reinjection and Induced Seismicity in Geothermal Fields in Iceland

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ABSTRACT

Reinjection data from field operators and seismic catalogue data from the SIL network of the Iceland Meteorological Office (IMO) are used to describe and analyse re-injection into Icelandic geothermal fields and the corresponding seismicity. Unfortunately the resolution of the production and injection data is generally poor and local seismic networks were missing most of the time of exploitation and injection but is now being improved.

Fluid has been injected at 11 sites in 9 production fields; 4 low temperature fields and 5 high temperature fields. All the high temperature fields and one of the low temperature fields are located at plate boundaries where background seismicity is high and occur in swarms. Injection and exploitation at all these places seem to induce or modulate the seismicity. Most of these events are below local magnitude 2. No seismicity has been observed where fluid is injected at the 3 sites outside the plate boundaries.

Minor injection related seismicity has been observed at the Reykjanes field but high natural seismic swarms occur in the periphery of the production field with maximum observed local magnitude of 4.7. At the Svartsengi geothermal field the induced seismicity is low with largest observed event of 3.2. At the injection sites for the Hellisheidi power plant only minor seismicity has been observed at Gráuhnjúkar while at the Húsmúli injection site huge induced seismicity has been observed with numerous triggered events with magnitude in the range 3 -4. At Nesjavellir we observe moderate seismicity with a few events above local magnitude 2, the largest being 3.2. These events are within the production field but they are not necessarily related to injection rather than the production. At Krafla considerable seismicity started when injection was initiated but the events are generally below magnitude 2.0. At the low temperature field Laugaland í Holtum in the south Iceland Seismic zone lowering of the fluid pressure due to geothermal production and seasonal variation in the pressure seem to modulate the natural seismicity and might have delayed an impending 6.4 event on June 17th 2000 by several years but also affected its exact timing.

1. INTRODUCTION

Geothermal energy has been produced on commercial scale in Iceland for house heating since 1928 and for electricity since 1969. The country is rich in geothermal resources. It encompasses high temperature magmatic geothermal systems ($T_{reservoir}$ >200°C) as well as low temperature ($T_{reservoir}$ <120°C) and medium temperature systems ($T_{reservoir}$ 120 -150°C). There is a basic difference between the high temperature and low and medium temperature fields in Iceland with respect to the geology, physical properties and tectonic settings.

The known high temperature fields are all within the axial rift-zone that is the landward continuation of the Mid Atlantic Ridge (MAR) and related to active volcanic systems. They derive their energy form cooling magma bodies in the crust, either dykes or other intrusions or from a cooling magma chambers. The uppermost one kilometre in the rift-zone is made of highly porous and permeable formations mostly of young basaltic lavas and hyaloclastite. The tectonics of the high temperature fields varies from one field to another and can be rather complicated. It is primarily associated with crustal rifting and normal faulting but interaction with strike slip faults related to shifts in the rift axis are well known. The tectonics complicates further by presence of magma chambers and intrusion activity.

The low and medium temperature geothermal systems are almost all outside the axial rift-zone; the medium temperature fields being generally close to the volcanic rift-zone. Their reservoirs are fracture dominated in otherwise low permeability basaltic lavas or hyaloclastites. The heat is extracted from the relatively high background temperature gradient by convection in permeable fractures (Flóvenz & Sæmundsson, 1993). The tectonic origin of the permeable fracture are not always clear. In some cases they are clearly linked to the shear zones of the transform faults between rift segments like in the South Iceland Seismic Zone. There are also examples of low temperature fields where fissure swarms of the volcanic centres penetrates the older rock but without any surface volcanism. It has also been suggested that geothermal fractures are a consequences of the postglacial rebound of the crust (Bödvarsson, 1982). As expected for a region where the Mid Atlantic Ridge interferes with a hot spot, the overall seismicity in Iceland is high (Jakobsdóttir, 2008). Figure 1 shows a map of the seismicity of Iceland for the period 1994 to 2013 embedded on at simplified geological map. The data are from the the SIL network catalogue, the national seismic network operated by the Icelandic Meteorological Office (IMO). The figure shows clearly the main tectonic and geological patterns of the country; the volcanic centres in the axial rift zones, the axial part of the MAR, the transform faults and oblique rift zones in North and South Iceland that connects the rift segments in Iceland. The eastern part of Iceland outside axial rift-zone i.e. what belongs to the European plate, is almost void of both seismicity as well as surface geothermal activity. On the contrary, the part that belongs to the American plate outside the axial rift-zone is characterized by both intraplate earthquakes and hydrothermal systems supporting the hypothesis of tectonic origin of the low temperature systems.

2. REINJECTION

In the first decades of geothermal energy production in Iceland from low temperature fields the exploitation was more or less based on self-discharge from boreholes that limited considerably the pressure down-draw in the system. In the late 1950s pumping with down-hole pumps started that allowed the water level to be lowered to 200-300m below the wellhead. That escalated the production and use of geothermal energy for house heating and allowed exploitation of much less permeable fields than earlier. Some of these fields became overexploited and to maintain the production it was necessary to initiate re-injection of the fluid to reduce the long term pressure drop. The first re-injection experiment in a low temperature field in Iceland were made in 1993 (Axelsson et al 2000b) in Laugaland in Eyjafjörður and has since 1997 been a regular part of the field operation. Later, re-injection was successfully introduced in three other low temperature fields. Table 1 shows an overview of the re-injection sites in Iceland.

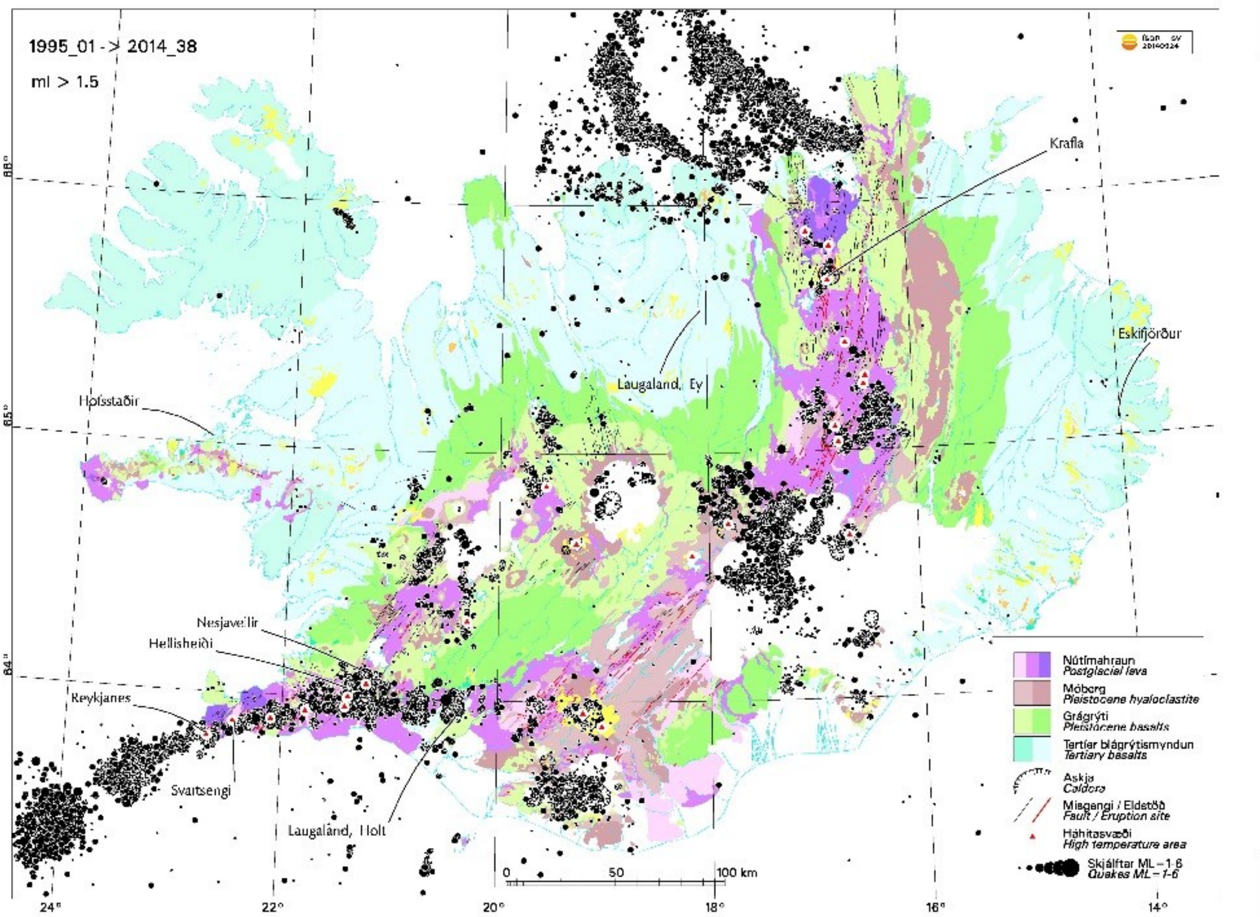

Figure 1: Earthquakes greater than 1.5 in local magnitude in Iceland 1994-2014. The epicenters show clearly the main tectonic boundaries; the oblique rifts just offshore North Iceland (Öxarfjördur-Grímsey) and on the Reykjanes peninsula, the MAR north and south of Iceland, the South Iceland Seismic Zone (SISZ) along 64°N, the Tjörnes transform zone. The reinjections sites are also shown.

Considerable energy production from Icelandic high temperature fields in Iceland stated in 1976 in the Svartsengi power plant followed by the Krafla plant in 1978, Nesjavellir in 1990, Reykjanes in 2006 and Hellisheiði in 2006. In all cases but the last one the effluent from the plants was initially disposed on the surface and reinjection was not initiated until many years later in order to counteract pressure drop and reduce environmental effects of surface disposal.

3. SEISMICITY AT RE-INJECTION SITES

Injection of fluid into the ground has created induced seismicity at various sites worldwide and has be well described in recent papers (e.g. Evans et al., 2012, Ellsworth 2011). In the case of Iceland, all the injection sites in the high temperature fields and one of the low temperature injection sites are located at the plate boundaries with high natural background seismicity. Therefore the possibility of induced seismicity was neither of concern for the producers nor the public since possible induced earthquakes would simply disappear in the high natural seismicity and not be specifically noticed by the public. This changed however when voluminous reinjection started at the Hellisheiði power plant in 2011. It caused intensive induced seismicity with local magnitude up to 3.9 and numerous earthquakes were felt in the nearby village of Hveragerði.

In the following text we describe the re-injection and the related seismicity at the individual injection sites in Iceland. The seismic data we use are primarily from the seismic catalogue of the SIL network of the Icelandic Meteorological Office (IMO) but also from recently installed local networks at Krafla and Reykjanes operated by Iceland GeoSurvey (ÍSOR) and a couple of temporary networks. The production data are from the relevant energy companies.

3.1 Laugaland in Eyjafjördur, N-Iceland

The Laugaland geothermal system is a typical low temperature system, embedded in 6-10 m.y. old flood basalt in Eyjafjörður in N-Iceland. The reservoir temperature is 90-100°C and reaches from roughly 500m depth to at least 2500m. Most of the feed zones in the production wells are however between 500 and 1500m depth and are known sometimes to follow some of the subvertical dykes that intersect the lava pile. Before production started in the year 1976 the geothermal reservoir was over-pressurized, the estimated well head pressure was around 2 MPa (Flóvenz et al., 2010). During the production the reservoir pressure fell rapidly to roughly 200 m depth below wellhead or a total pressure reduction of 4 MPa. To keep the water level above 240 m the production had to be reduced from 150 L/s in 1979 to 45 L/s in 1996. To maintain the level of production at sustainable rate it was decided to start re-injection in to a 2820m deep well (LJ-8) located 250-300 m away from the production wells. A small scale reinjection experiment using hot water was conducted in 1991 and based on the results a full scale injection experiment was initiated 1997 and lasted until 1999 (Axelsson et al. 2000a & b) The experiment was quite successful so after that the reinjection has been kept at similar level. During the injection experiment in 1997-1999 6-22°C hot return water from the district heating system in the town of Akureyri was injected the rate of 8-20 L/s and with wellhead pressure between 0.8 and 2.8 MPa (Fig.2). Due to seasonal production the water level varies between 100 and 200 m below wellhead and the pressure difference between the injection well and the reservoir is in the range of 1,8 to 4,8 MPa.

Table 1: Overview of the geothermal injection sites in Iceland until 2014.

Re-injection site	Period	Injection depth (m)	Annual average injection, (kg/s)	Seismicity	Largest earthquake
Laugaland í Eyjafirði	1997	390 - 1875	~15	None	**< -1.0**
Hofstaðir	2007	369	~10	None	**<1.5**
Eskifjörður	2008	<400	7-8	None	**<1.5**
Laugaland í Holtum	2000	<1000	(<5)	Large	**6.6**
Gráuhnjúkar	2006	>800	100-350	Minor	**2.0**
Húsmúli	2011	760-2250	200-550	Very large	**3.9**
Svartsengi, central	1984-99	1000-2000	~0-55,	Minor	**1.9**
Svartsengi, pheriphery	2001	600-1200	~50 – 220,	Small	**3.2**
Reykjanes, central	2009	>1000	45-79	Small,	**<2.0[1]**
Nesjavellir	2004	300-500	160	Considerable	**3.2**
Krafla	2002	1000-2000	80	Large	**2.2**

[1]Maximum observed magnitude is 4.7 just outside the production field.

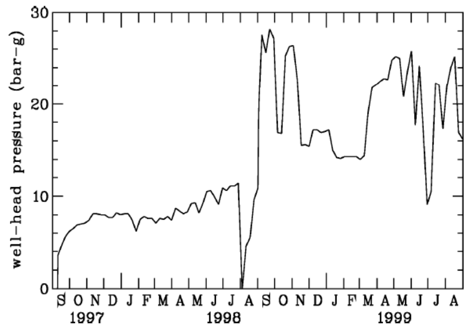

Figure 2: Well head pressure during the injection experiment at Laugaland in Eyjafjördur

Although there is no known seismicity in the vicinity of Laugaland it was decided to install a seismic network to monitor possible induced earthquakes since the area is densely populated. A network of 5 stations surrounding the injection site was installed and operated during the injection test (Axelsson et al. 2000a). The sensitivity limits of the network was estimated to be at m_l =-1. Despite the fact that there was produced up to 4.8 MPa pressure difference and fluctuations in the wellhead pressure and injected volume not a single earthquake was found in the geothermal field during the injection. The reason for the absence of earthquakes might be due to the fact that the reservoir pressure had already be lowered over large area due the 20 years of production and pore pressure increase in the reservoir was far from recover to the original state apart from the immediate vicinity of the injection wells.

3.2 Laugaland in Holtum in S-Iceland

The South Iceland Seismic Zone (SISZ) is around 80 km long east-west transform zone, connecting the eastern and western volcanic zones of Iceland (Fig.1). It is characterized by high seismicity occurring on series of parallel north south trending dextral faults (Einarsson et al, 1981). The zone is known for series of large earthquakes (LME) with magnitudes ranging from 5 to 7, increasing eastwards corresponding to eastward thickening of the brittle crust (Tryggvason et al, 2001), in line with thickening of the crust (Bjarnason et al, 1993) and lowering of the heat flow (Flóvenz and Sæmundsson, 1993). The time interval between the large magnitude earthquakes episodes is of the order of one century and each episode can last from a few weeks to several decades. A large episode occurred in 1896 and 1912 and again in 1998 to 2008 (e.g. Hjaltadóttir, 2009).The SISZ is also known for intensive low to medium temperature geothermal activity in typical convective fracture systems. The geothermal energy is extracted at numerous places in the area where the permeability is mainly controlled by the recent faults. Huge pressure variations were observed due to two LMEs in the year 2000 (Björnsson et al, 2001).

Laugaland í Holtum is located in the eastern part of the SISZ. (Figure 1). Production of hot water started in 1982 for heating purposes in the nearby villages, Hella and Hvolsvöllur. Local geological and geophysical studies including head-on resistivity profiling indicated that the upflow zone of geothermal fluid is related to intersection of two low resistivity fractures, one striking N15°E and the other striking N75°E. The latter has the same strike as the distribution of hot springs at the surface. It was suggested that the N15°E fracture is feeding the hot water into the N75°E fracture that seems to be more permeable at shallow depths (Georgsson and Guðlaugsson, 1984).

Production showed soon that the permeability of the system was very low. As a consequence there was a large pressure down-draw, the lowest values were observed in 1998 corresponding to roughly 2.5 MPa. Seasonal hot water demand causes large seasonal variation in the production and corresponding inverse variations in the reservoir pressure as can be seen on Figure 3. The seasonal variations in water level between summer and winter were of the order of 70-95 m prior to the year 2000 corresponding to 0,7-0,9 MPa pressure change within the production wells. After the year 2000 the oscillations were slightly less corresponding to 0.6 MPa. As the production was limited by the down-draw and did hardly meet the hot water demands a new geothermal field, Kaldárholt, was developed some 10 km north-northwest of Laugaland where permeability is much higher but reservoir temperature lower. The production came on line in January 2000 and at the same time the production at Laugaland was rapidly reduced over a couple of months from 25 L/s to 12 L/s. In addition injection of a few litres per second of 65°C water from Kaldárholt into the Laugaland field was initiated in order to speed up the pressure recovery. The consequence was a rapid increase in pressure in the geothermal system and in June it exceeded the maximum pressure level from the previous year. On June 17th 2000, the National Day of Iceland, a magnitude 6.4 earthquake stroke the area with epicentre approximately 6 km away from the geothermal wells. This was a strike slip event on a north-south striking fault plane (Björnsson et al, 2000, Stefánsson et al, 2000), more precisely on a fault pattern with overall direction N7°E but is composed of many smaller sections with differing strikes (Hjaltadóttir, 2009). The earthquake ruptured about 15km long NNE trending fault system towards the surface (Clifton and Einarsson, 2005) and the distance from the injection well to the fracture is about 2 km. Analysis of the aftershock activity shows that it was mainly confined to the margins and centre of the 12.5km long, 10 km deep, north-south striking, near vertical fault that is composed of three patches, each striking a few degrees east of the overall fault strike (Hjaltadóttir, 2009). Naturally, the questions rises if this earthquake was influenced by the production of geothermal fluid. If so, this is far the largest earthquake induced or triggered in the world by geothermal production.

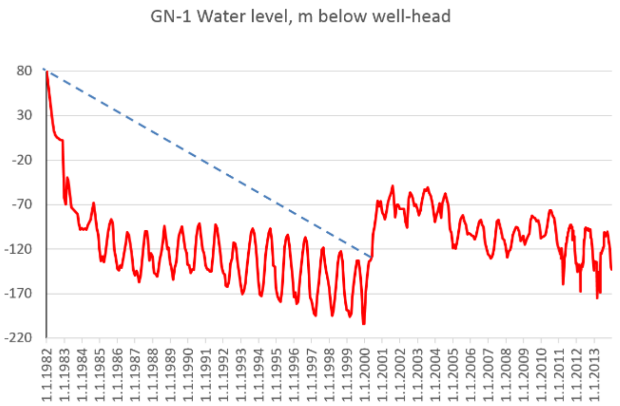

Figure 3: Water level (pressure) in the well GN-1 in the center of the geothermal field at Laugaland in Holtum. Data from Reykjavik Energy. The dashed line shows the minimum water table (fluid pressure) needed to reach critical stress. It is based on the fact that critical stress was reached on June 17th 2000 but not at the start of the production in 1982. The slope of this line should reflect the maximum rate of stress build-up due the tectonic forces in the area.

The seismicity of the SISZ has been well monitored from 1991 after the installation of the SIL network (Jakobsdóttir, 2008). In order to investigate the possible relation between the geothermal energy production and the seismicity we have selected a 300 km^2 area around the geothermal field covering the fracture of the June 17th earthquake. The resulting seismicity is shown as a time plot of magnitudes for the period 1995 to 2013 in Figure 4. On these figure we notice a more or less continuous microseismic activity over the whole period in the local magnitude range -1 to 2. In addition we see the LME occurring in June 2000. We may also notice small scale periodic variation in the seismicity.

Figure 5 shows the spatial distribution of the epicentres within this area from 1995 to 2013. The following features should especially be noted:

- Prior to the LME of the June 17th 2000 the microseismic activity was scattered over the whole area north of Laugaland but with obvious concentration of earthquakes along a N25°W line indicating a fault zone with that direction. There is no sign of any NS or NNE lineaments during this period but short hidden en echelon segments cannot be ruled out.

- The epicentre pattern completely changes after the LME on June 17th 2000. After that the overwhelming part of the micro-seismicity occur on two parallel lines with direction around N7°E; one about 20 km long corresponding to the fault that was ruptured by the LME and another much shorter but just west of the geothermal field. This has been analysed in more details by Hjaltadóttir (2009).
- The post LME maps of the epicentres also show two less prominent lineaments close to the geothermal field. The first one is clear and with NNW direction from the southern end of the June 17th fault. The second lineament is parallel but faint and is just west of the geothermal area. The southern end of the latter is at the geothermal exploitation site. The shorter N7°E lineament connects the two NNW lineaments.
- All the four above lineaments end abruptly toward south at the same latitude as the geothermal field at Laugaland and with 2 km distance from the boreholes.
- The epicentre of LME of June 17th happens to be almost at the intersection of the two most prominent lineaments, the N25°W lineament that was active prior to June 17th 2000 and the fault ruptured by the June 17th earthquake.
- It should be noted here that the lineament direction N7°E is similar to the dominant direction of the faults formed by the LME within SISZ. It is also practically the same as suggested by Georgsson and Guðlaugsson (1984) to be the feeding fracture of the geothermal system and based on resistivity profiling. If we extrapolate northwards the N7°E line suggested by Georgsson and Guðlaugsson it comes very close to the epicentrum of the LME of June 17th 2000.

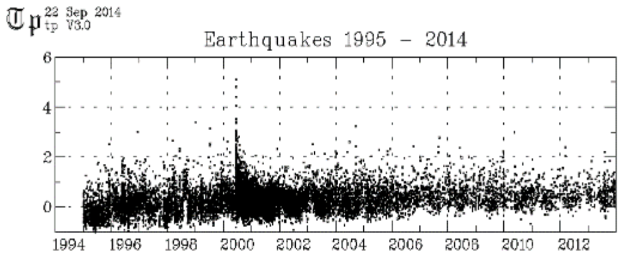

Figure 4: Earthquakes in the vicinity of the Laugaland in Holtum. Magnitude of the quakes is plotted against time. The data are from the catalogue of the Icelandic Meteorological Office (IMO).

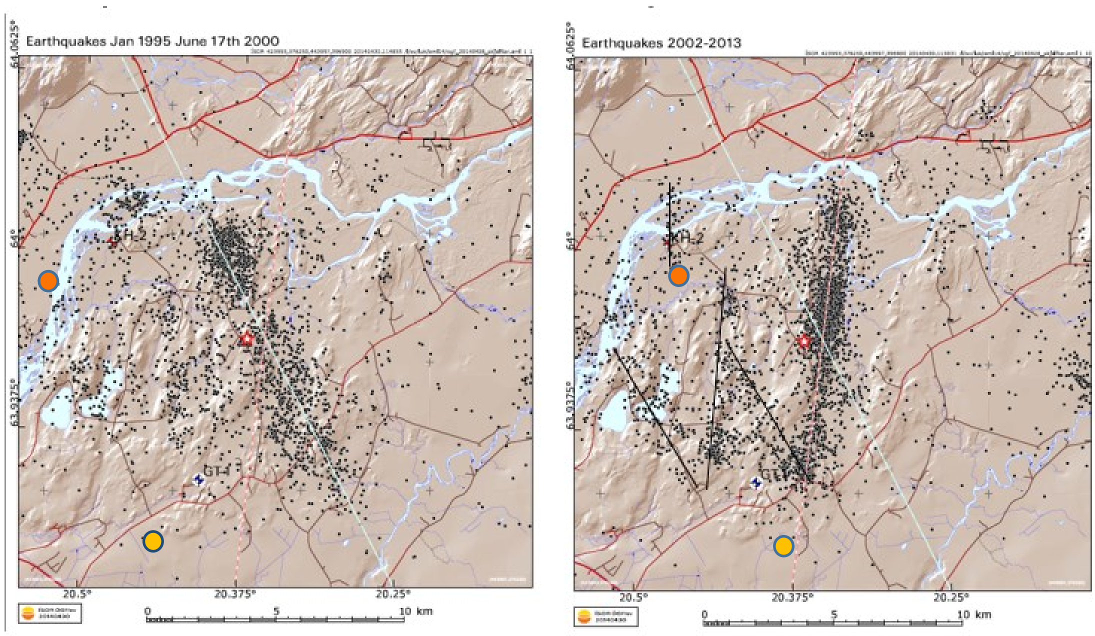

Figure 5: Locations of earthquakes around Laugaland. Note the concentration of quakes along a NNW line prior to the magnitude 6.4 event in 2000, shown by a star, and how the following quakes follows a NNE trending line. The injection well GT-1 at Laugaland is marked by the yellow dot and the production well KH-2 at Kaldárholt with orange.

If we look closely at the time distribution in Figure 4 we may see that numbers of small earthquakes seem to be higher in the summertime compared to the wintertime and might reflect the annual variations in the water-table within the geothermal field. If correct, this means that the fluid pressure variations in the fractured geothermal field induce earthquakes on regular basis. To investigate this further we have counted all the earthquakes during this period and summarized per month per year. The reason for summarizing this is the different resolution of the data. While the seismic data are with resolution of milliseconds the water level data are only based on one or two readings per month. The result is presented in Table 2 and in Figure 6 that show clearly background seismicity of 300-400 events per year prior to the 6.4 magnitude event on June 17th 2000, then the high aftershock activity decaying slowly over a couple of years to a new background value of around 100 events annually.

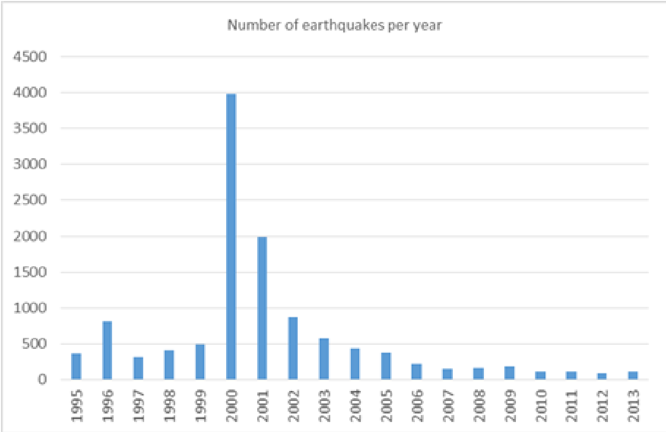

Figure 6: Time distribution of the earthquakes around Laugaland for the period 1995 to 2013.

Table 2: Number of earthquakes per calendar month per year during the period 1995 to 2013.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
1995	29	18	20	35	43	33	49	23	24	28	55	11	368
1996	30	23	39	21	159	135	44	207	42	30	55	36	821
1997	19	45	8	11	32	17	27	17	23	48	35	36	318
1998	32	33	37	44	27	23	30	31	46	55	24	29	411
1999	21	17	168	28	30	24	37	47	27	39	28	30	496
2000	24	37	57	31	23	773	1081	293	644	417	361	238	3979
2001	144	179	206	166	149	161	239	193	212	169	68	109	1995
2002	18	63	76	64	116	99	94	92	86	54	62	56	880
2003	38	7	31	56	58	56	58	67	48	76	36	44	575
2004	38	39	22	45	47	42	46	41	45	38	18	17	438
2005	20	26	32	42	26	21	38	37	40	50	26	16	374
2006	20	11	24	21	18	29	12	18	15	15	24	15	222
2007	16	13	15	12	22	9	15	12	20	7	13	2	156
2008	17	9	12	18	9	18	24	16	16	6	6	15	166
2009	11	16	14	12	14	7	28	22	27	7	8	19	185
2010	11	7	6	6	7	7	10	16	14	13	12	7	116
2011	12	9	11	3	11	15	19	6	12	5	8	2	113
2012	10	3	19	6	9	11	9	8	5	2	2	7	91
2013	3	13	2	7	5	8	16	19	18	6	7	15	119

To investigate further the possible relation between the water level and seismicity we have calculated the total sum of quakes per calendar month from 2002 to 2013 and compare with the average value of the water level in the geothermal field. The result is shown in Figure 7. The number of earthquakes show a clear annual variation with about 70% more quakes in the mid-summer high than in the winter low. To check if this could be some kind of regional phenomenon or seasonal variation in the sensitivity of the seismic network we have done the same with the Hestfjall fault zone that ruptured three days after the Laugaland zone in June 2000 (Hjaltadóttir, 2009). The fluid pressure in the Hestfjall fault is not likely to be seriously affected by geothermal production. The result is also presented in Figure 7 and show no similar seasonal variation in seismicity over the same period. Hence, it can be concluded that the annual variations in the seismicity at Laugaland are likely to be associated with fluid pressure variations in the geothermal reservoir. The average water table in the reservoir over the same period is also plotted on the left part of Figure 7. The water table data are only available as one value per month and the values plotted here for each month are the values at the end of the month or even the very beginning of the following one. The figure show on the average very regular seasonal variation of the seismicity and the water level in the reservoir; high water level and increased fluid pressure in the fault system in the summertime and low in wintertime and similar picture for the seismicity. These two parameters are however not totally in phase. We see that as soon as the fluid pressure starts to decrease in the fall there is corresponding lowering of the seismicity but as the minimum fluid pressure is approached in December to February the number of quakes start to increase before considerable average increase in water level occurs. Here it should be noted that large short term variation in water consumption during wintertime causes short time variation in fluid pressure that might be reflected in the total number of earthquakes as the seismicity might as well be related to fluid pressure changes as the absolute value of the fluid pressure.

Figure 8 shows the focal depth distribution with time during the period from 1995 to 2013. It shows clearly, that apart from a period around the large magnitude event in 2000 and few distinctive swarms before 2000 the most of the quakes are concentrated in the depth range 5 to 10 km in the middle crust, i.e. within the seismic layer 3, (Pálmason 1971, Flóvenz, 1980, Bjarnason et al

1993). This is especially noteworthy since it implies that only 0.5 – 0.6 MPa change in the fluid pressure within the geothermal field induces or modulates earthquakes at 5-10 km depth. We may also notice that the geothermal fracture that is exploited at Laugaland and shows the seasonal pressure variations are at minimum 2 km distance from the main fault so the actual fluid pressure variations in the main fault system should be lower. This relationship between rather low pressure oscillations and the seismicity might appear strange but not unique as even heavy rainfall in highly permeable carsic regions in Switzerland has been connected to temporarily increased seismicity (Husen et al. 2007).

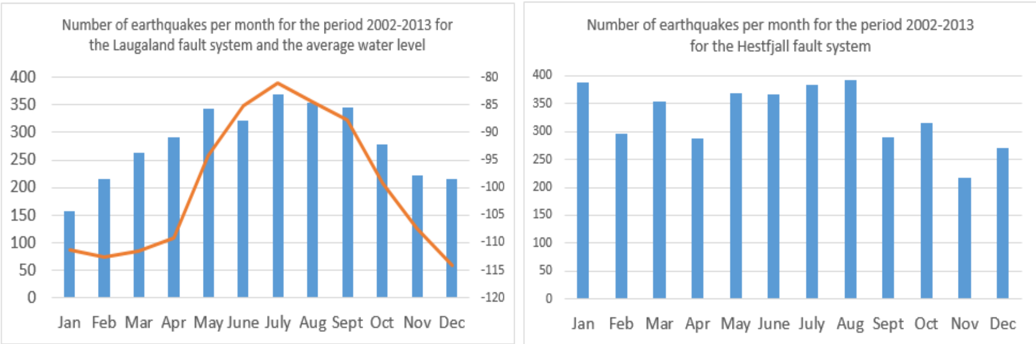

Figure 7: The graphs shows the total sum of earthquakes per calendar months from 2002 to 2013 for Laugaland and Hestfjall. Average water level at Laugaland in the respective months over the same period is also shown.

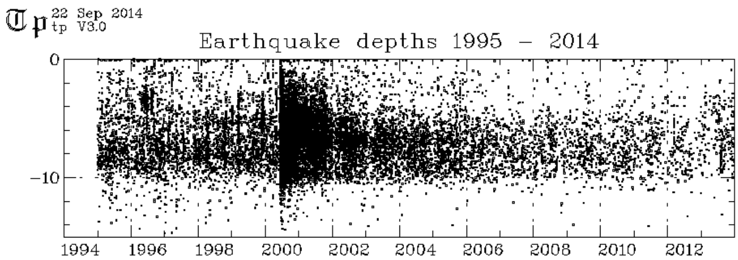

Figure 8: Depth distribution of earthquakes at Laugaland with time.

Finally, our observation raises the question if the June 17th earthquake was triggered by the geothermal fluid production. It is well known that the continuous movement of the east west plate boundaries in S-Iceland builds up regional stress that from time to time is released in a series of large magnitude events on north south trending faults. Reports of historical earthquakes in SISZ indicate that the typical redundancy time of the earthquake series is of the order of one century. The previous episode covering most of the SISZ was in 1896 with one additional LME in 1912 in the easternmost part of it. In 1784 a similar LME period occurred. It follows that around the year 2000 the stress build up had lasted long enough so the next LME series was due. Hence, it was inevitable that a new series of LME was impending, it would most likely have struck within a few years regardless of any fluid production from the geothermal fields in the SISZ. But we have however indications that the pressure oscillation in the geothermal field induce or modulate the seismicity in the fault zone and the onset of the LME was exactly where the N25°W trending responding fault intersected the N7°E trending fault activated during the LME. It is also noteworthy that the LME happened in June when the fluid pressure had just exceeded the maximum pressure of the past year and after more rapid rise in the fluid pressure in the first months of the year 2000 than during previous production years. Figure 3 shows the measured and calculated water table since the start of the production until the end of 2013. We have also inferred a line showing the possible fluid pressure (water table) that might have been necessary to initiate the rupture. This line is constructed under the assumption that the fluid pressure was exactly high enough on June 17th 2000 to trigger the earthquake but at the beginning of the production in 1982 the fluid pressure was not enough to initiate the LME. The slope of this line is some sort of measure of the minimum stress accumulation rate in the area and also defines the maximum time that the pressure down-draw in the geothermal field might have delayed the onset of the pending earthquake. Hence it can be concluded that the geothermal production at Laugaland caused reduction in fluid pressure of the fault system that might have delayed the imminent earthquake by up to 18 years and affected its exact onset timing.

To sum up, we conclude from our observations the following about the Laugaland geothermal field:

1. The fluid oscillations in the geothermal field caused by the geothermal fluid production seems to induce or modulate earthquakes that mostly were concentrated along a N25°W fault zone prior to the magnitude 6.4 earthquake on June 17th 2000. The magnitude of these earthquakes are almost entirely below local magnitude 2.0.

2. The June 17th LME occurred on a N7°E overall trending fault where it cuts the N25°W seismic lineament. Prior to the LME there was a small gap in the micro-seismicity on the N25°W lineament almost where the LME epicentre was.

3. After the LME the seismicity has been mainly concentrated on the 20 km long N7°E fault, a short parallel fault as well as two faint NNW lineaments, probably parallel to the N25°W one.
4. The microseismicity on the N25°W lineament mostly ceased after the June 17th earthquake.
5. The main microseismic activity is at 5-10 km depth so the fluid oscillation in the geothermal field at 1-2 km depth seems to affect the seismicity much deeper.
6. The pressure down draw in the geothermal field might have delayed the impending LME up to 18 years. This delay would, however, only have had minor influence on the size of the earthquake.
7. The rapidly increased fluid recovery pressure caused by less production and small reinjection in the first half of the year 2000 might have triggered the impending earthquake of June 17th 2000. The quake is, however, primarily caused by about one century of stress accumulation in the South Iceland Seismic Zone.

3.3 Hofstaðir in W-Iceland

Hofstaðir are located in the Miocene basaltic crust of the Snæfellsnes peninsula (Axelsson et al., 2005). It is not far away from NW striking Holocene minor intraplate volcanism. The Hofstaðir field is a hidden field i.e. there are no signs of hydrothermal activity at the surface but it was discovered by heat flow measurements. Utilization of the field started in 1999 with average yearly production of the order of 19 L/s. The reservoir has fairly good internal permeability but long time production shows that the system acts like a closed system with continuously increasing down-draw (Axelsson et al., 2005). To counteract the down draw re-injection of about 10 L/s into the geothermal fracture system was initiated in 2007 (Gaoxuan et al., 2010). Since then no earthquakes have been reported in the database of the IMO so the re-injection seems to be aseismic. It should be noted here that area is outside the SIL network with the next seismic station at 70-80 km distance. Hence the earthquakes much less than magnitude 2.0 would hardly be detected at Hofstaðir.

3.4 Eskifjörður in E-Iceland

Eskifjörður is located in the Micocene basaltic crust of the Eastern fiords of Iceland, uninterrupted of more recent volcanic activity. There is only minor geothermal activity known east of the volcanic zone i.e. on the European plate in Iceland. The first indications of a hidden geothermal field in Eskifjörður was given by resistivity measurements in 1978 (Hersir and Flóvenz, 1978), supported by temperature gradient wells in the late nineties (Stapi, 1999) but first confirmed by 1327 m deep production well in 2002. The average production from the field is close to 20L/s (Halldórsdóttir and Gautason, 2013). As the productivity of the system was too low re-injection of 7-8 L/s was started in 2008 at depth less than 400 m. No local seismic stations have been operated close to Eskifjörður and the area is poorly covered by the national seismic network. The nearest station is 50 km away. No seismicity has been observed related to the geothermal system but the network would hardly pick up an earthquake much less than magnitude 2.0.

3 5 Svartsengi high temperature field

The Svartsengi high temperature field is located on the Reykjanes peninsula in an oblique rift zone connecting the axial part of the Reykjanes Ridge and the Western volcanic zone of Iceland. The reservoir temperature is close to 240°C and the field has been exploited for house heating purposes since 1976 and for cogeneration of heat and power since 1978. The effluent from the power plant was initially disposed on the surface where it was supposed to mix with the groundwater current through the highly permeable surface lava. Precipitation did however soon form an impermeable layer in the lava leading to the formation of a lagoon, later known as the Blue Lagoon.

The production rose year by year and reached annual average production of 300 kg/s in 1986, followed by pressure decrease in the reservoir of the order of 1.5 MPa at 700 m depth (Vatnasksil 1996). Subsidence and gravity low also formed over the production field (Eysteinsson, 2000). To counter-act the pressure reduction some re-injection was initiated in 1984. The injection was continued at variable rate until 1990 with average annual rate of 10 – 55 kg/s. Three injection wells were used, all located within or close to the central production field. No earthquake activity is known to have followed the injection but the seismic network had very poor coverage during this period. Well SV-12 was used from 1984 to 1988 and SV-05 from 1988 to 1990 when the injection was stopped. In 1993 the injection was started in well SV-06 and a temporary seismic network was installed (Brandsdóttir et al., 2002). No induced seismicity was detected and the absence of seismicity was related to the fact that the pressure down draw in the field was already 20 bars that might have raised the fracture limit. With exception of 1998 and 1999 the injection was practically paused from 1995 to 2001 when a new injection site was established at the periphery of the production field. Since then the injection has be increasing most of the time and reached average injection of 244 kg/s in 2013 (Vatnaskil, 2014). Figure 9 shows the development of the seismicity. It is obvious that the injection at the new site in the periphery of the production field induces some seismicity.

Guðnason (2014) reports the result of a temporary seismic network that was in operation at the outer part of the Reykjanes peninsula from December 2008 to May 2009. It recorded an earthquake swarm close to the Svartsengi injection wells. Of the 82 earthquakes located around Svartsengi by the temporary network only 15 were located by the SIL network alone or 18%. This shows clearly that a local seismic network is needed to provide sufficient information about induced seismicity. Of these 82 earthquakes 29 occurred in a swarm during about 5 hours on March 6th 2009, all with local magnitude less than 2.0. The relative location of the events is shown in Figure 10. It shows that most of the events are clustered less than 1 km north of the injection wells at 4-5 km depth and traces of the swarm are located along a line further northwards. It is noteworthy that the depth of the earthquakes decreases with distance from the injection wells. Guðnason (2014) obtained focal planes solutions for 26 of the Svartsengi quakes based on the polarity of the first arrival of the P waves. About half of the fault plane solutions show a significant strike-slip component. The rest of the fault plane solutions show almost an equal number of normal and reverse displacements and no clear pattern of fault plane solutions is evident. Unfortunately, the injection data for this period only exist as average injection per calendar month so it is not possible to conclude it the swarm on March 6th 2009 was related to changes in the injection rate. On the contrary to earlier considerations it can be concluded from the above discussion that there is considerable induced seismicity related to the injection site of Svartsengi.

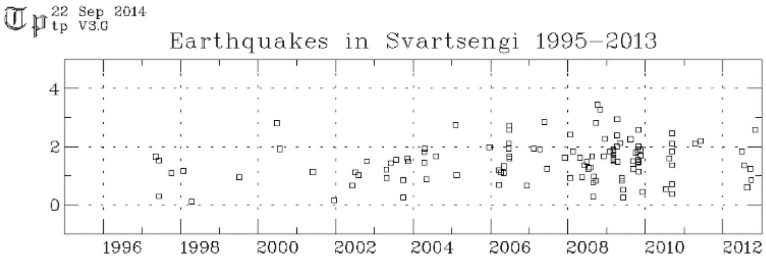

Figure 9: Seismicity in Svartsengi 1995 to 2013. Injection was started at a new site in 2001, increasing with time and inducing seismicity. Data from the SIL network of IMO.

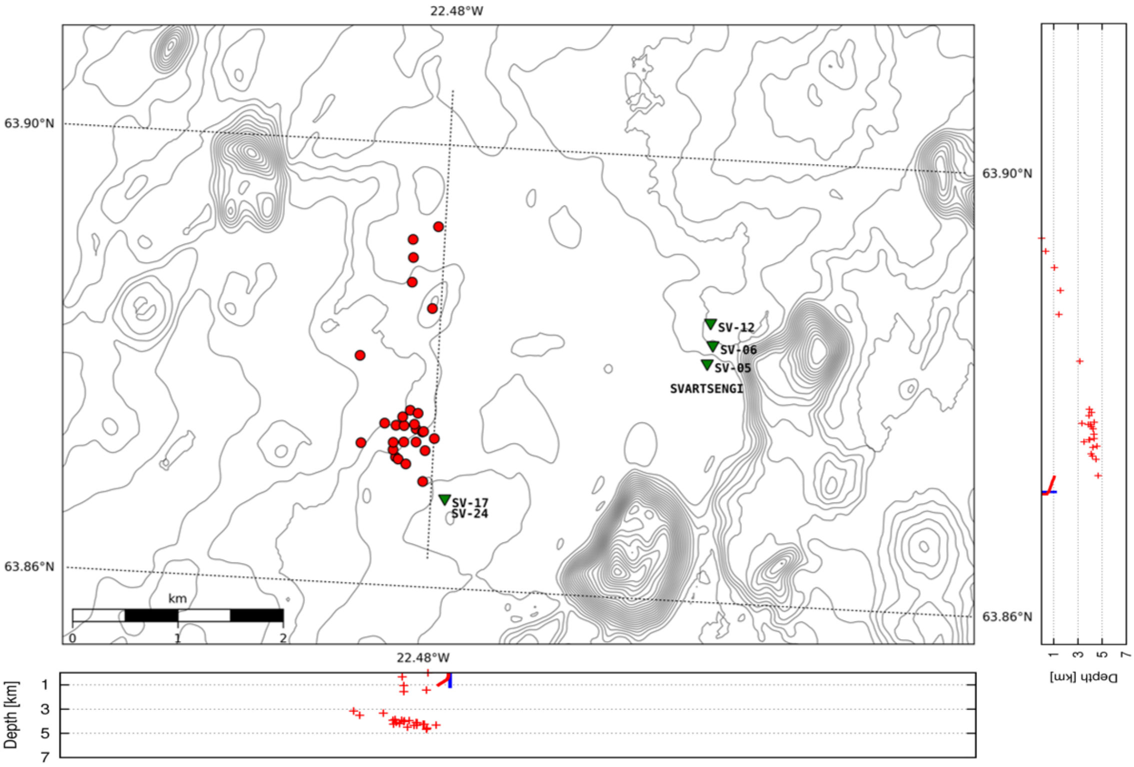

Figure 10: Relative relocations of the earthquake swarm from the 6th of March, 2009. The blue and red lines on the E-W and N-S depth sections show the projections of the track of the injection wells, SV-17 and SV-24.

3.6 Krafla high temperature field

Krafla power plant was designed as a 60 MW_e power plant. It came online in 1978 with 30 MW_e installed but the latter 30 MW_e was first in full operation 1999. In the beginning the effluent from the power plant was disposed at the surface into a small brook after initial cooling in an artificial pond. Permanent reinjection was initiated in 2002. The seismicity in Krafla has mainly been monitored by the SIL network (Figure 11). It improved a lot in recent years resulting in lower detection limit with time. In 2006 Landsvirkjun, the owner of the plant, had six permanent seismic stations, installed in shallow boreholes and a real time data acquisition system was installed by ISOR at the seismic stations in 2009. It was further expanded in 2013 by three additional surface stations. Since then around 5-10 events per day are typically located within the Krafla caldera. Most of the seismicity takes place within the geothermal field itself and 95% of all earthquakes are located above 2.7 km depth and only very few are below 3 km (Ágústsson et al., 2012). It has been shown that the depth distribution pattern in Iceland is clearly related to the background heat flow and can be interpreted as the brittle ductile boundary within the crust (Ágústsson and Flóvenz, 2005). This indicates that the brittle-ductile boundary in Krafla might be reached as shallow as at 2.7 km depth compared to typical depths of 10 to 15 km elsewhere in Iceland.

During the drilling of the IDDP-1 well in Krafla during 2009 a total circulation loss occurred over considerable period of time close to the top of a molten intrusion (Zierenberg et al., 2012). The circulation loss did induce numerous micro-earthquakes that were recorded by the local network (Ágústsson et al., 2012). The location of these events shows an interesting evolution. Soon after the injection of about 40-60 L/s started, induced seismicity appeared. At first the earthquakes started close to the permeable zone in the well at 2040 m depth and moved laterally away from it, most likely along the boundary layer between the magma and the overlying rock. Then suddenly the quakes started to move upwards along an inclined surface and later on activity was observed on the whole surface. This can be interpreted as an activation of a fault on which the injected fluid moves after it has been heated by the magma.

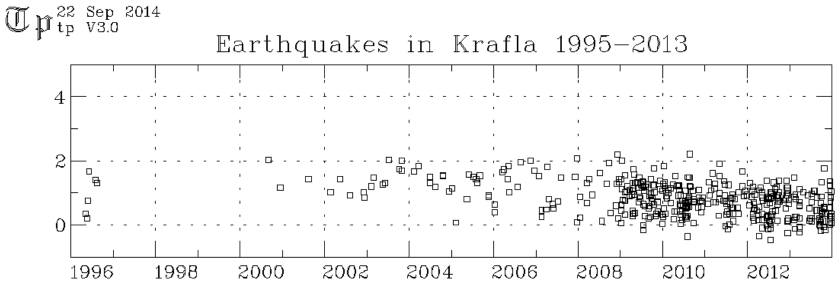

Figure 11: Earthquake activity in the Krafla geothermal field in 1995 to 2013 shown as magnitude-time plot. The data are from the SIL network of IMO. Note the onset of more or less continuous seismicity after injection was started in 2002. The increase in number of small quakes with time after that is partly due to improved seismic network. Most of these earthquakes are likely to be induced by the production or the re-injection. Note that the largest induced earthquakes are around local magnitude 2.2.

3.7 Hengill high temperature field

The Hengill volcanic complex is located at a triple point where the SISZ, Reykjanes oblique rift and the western axial volcanic riftzone of Iceland meet. The Hengill area is characterized by extensional tectonics of the NNE rift axis but in the southern part it is superimposed on NS strike slip faults belonging to the SISZ. NW structures and lineaments are also seen (Bessason et al., 2012). High temperature geothermal fields are associated with the largest part of the volcanic complex covering area of roughly 100 km^2. At present there are two large geothermal power plant in the area, Nesjavellir and Hellisheiði power plants.

Hengill is one of the most seismically active areas in the country, characterized by several year periods of unrest with intensive seismicity and several decades of low seismic activity in between. The last three unrest periods culminated in large magnitude events in 1935, 1955 and 1994 with local magnitudes of 6.0, 5.5 and 5.1 respectively (Bessason et al., 2012) These earthquakes most likely occur on NS striking strike slip faults. Occasionally a rift episode occurs with typical graben subsidence and normal faulting along the axial rift. The last rift episode was in 1789. Volcanic eruptions occur on extensive NNE fissures, the last one occurred about 2000 years B.P. In addition there are periods of volcanic unrest where magma intrudes the root of the geothermal system without escaping to the surface. An evidence of such activity was found in 1994-1995 (Sigmundsson et al., 1997).

3.8 Nesjavellir power plant

The Nesjavellir power plant is a 120 MW_e and 280 MW_{th} power plant located in the axial graben of the plate boundary in the northern part of the Hengill area. It supplies the hot water to Reykjavík. The discharge history of the effluent from the plant is described by Zarandi and Ívarsson (2010). The production of 100 MW_{th} of hot water started in 1990 and the effluent from the plant was discharged into a brook and disappeared through the porous surface lava into the groundwater. After start of electricity production of 60MW_e in 1998 up to 400-500 L/s of effluent was discharged into a 25 m deep well close to the power plant and the excess fluid into the brook. The production was increased to 90 MW_e in 2001 and to 120MW_e and 280 MW_{th} in 2005. Reinjection into deeper wells that were drilled and tested in early 2001 started in 2004 and the water enters the formation in the 400-550m depth range. The injection was initially on a small scale but was increased to 160 L/s later while the excess water still goes into the 25 m deep well. Figure 12 shows seismicity maps of Nesjavellir and the surrounding area for the periods 1995-2000 and 2001-2013 respectively. The former period was characterized by period of high seismicity in the whole Hengill area (Jakobsdóttir, 2008) while the latter period is with normal background seismicity. The figures show clearly that the post 2000 earthquake activity is mostly confined to the production and reinjection area of the power plant with 18 quakes in the local magnitude range 2.0 to 3.0 and one quake over 3.0. It is not obvious that the shallow injection is responsible for the seismicity within the production field but it is however most likely somehow connected to the geothermal exploitation.

3.9 Hellisheiði power plant

Hellisheiði 303 MW_e power plant came stepwise into production from 2006 to 2011 with additional 133 MW_{th} for house heating in Reykjavík. The plant is located in the central western part of the Hengill volcanic system and most of the best production wells are close to a 2000 year old eruptive fissure.

The power plant produces about 500 L/s of effluent that need to be re-injected according to the power production permit (Gunnarsson, 2013). Originally, it was decided to inject the effluent into the normal faults at Gráuhnjúkar, 2.3 km south of the power plant. Drilling there did, however, reveal considerable higher temperatures than expected and the wells did not receive enough water at moderate well head pressure. Therefore it was decided to look for another area to re-inject the fluid. Injection started at Gráuhnjúkar, at the commissioning of the power plant in 2006 and has been continued since although it was dramatically reduced in the fall of 2011 when a new injection site, Húsmúli, came into use. The new injection wells at Húsmúli were drilled at the periphery of the geothermal field about 1 km northwest of the power plant where major NNE faults, forming the westernmost part of the graben was the target for injection.

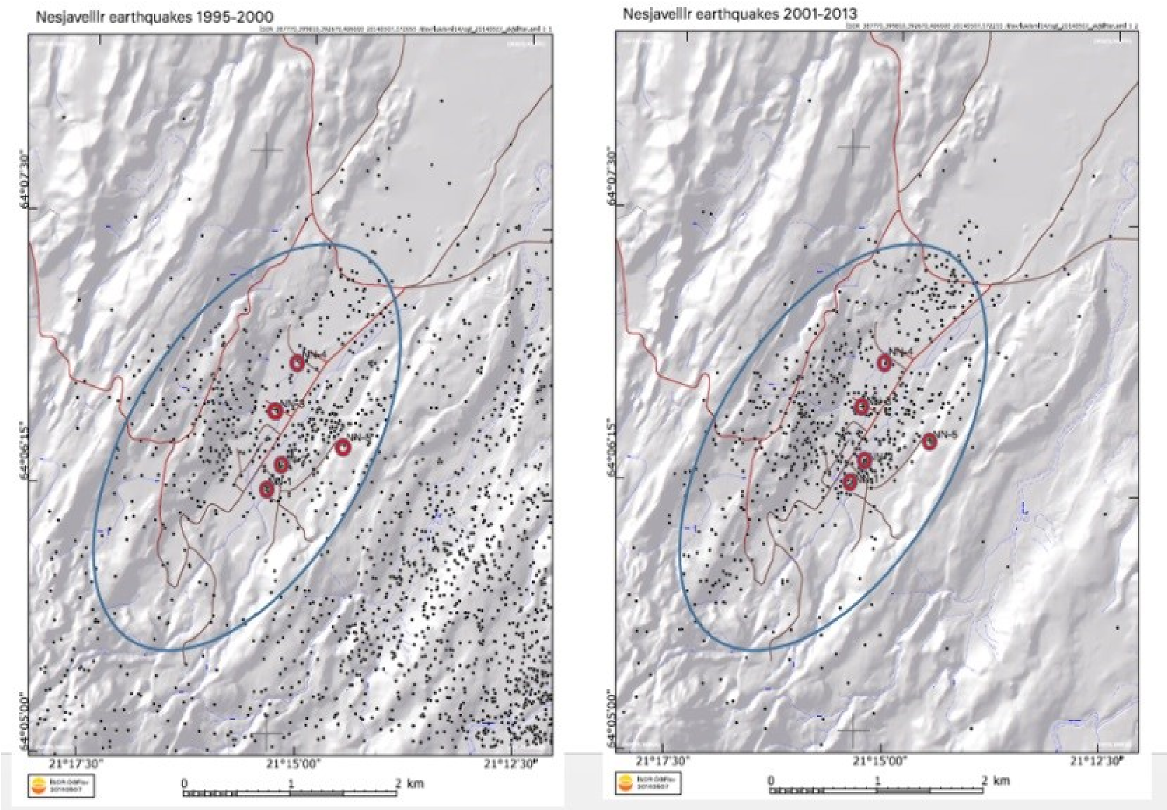

Figure 12: The seismicity at Nesjavellir during the seismic unrest in Hengill in 1995-2000 and for the post unrest period 2001-2013. The blue ellipse show the approximate location of the production field. The injection wells are marked with red circles. Data from the earthquake catalogue of IMO.

3.9.1 The Gráuhnjúkar injection site.

Injection was initiated in 2006 when the operation of the Hellisheiði power plant started. Unfortunately, the injection data was poorly monitored and it is first in 2009 that regular injection data for injection rate and temperature was collected. No local seismic monitoring was performed but the SIL network covers the area pretty well. No tracer tests were carried out to check if the fluid returned to the production field and no pressure monitoring wells were operated to evaluate the pressure response. Figure 13 shows the seismicity before and after the onset of re-injection at Gráuhnjúkar. Prior to the injection there was only low and scattered seismicity around Gráuhnjúkar despite the intensive earthquake swarm in the Hengill area during 1993 to 1998. After the reinjection started some earthquake activity appeared, mostly confined to the northernmost injection well. The largest magnitudes of the induced events were close to 2.0 but most of the quakes were below 1.5 in local magnitude.

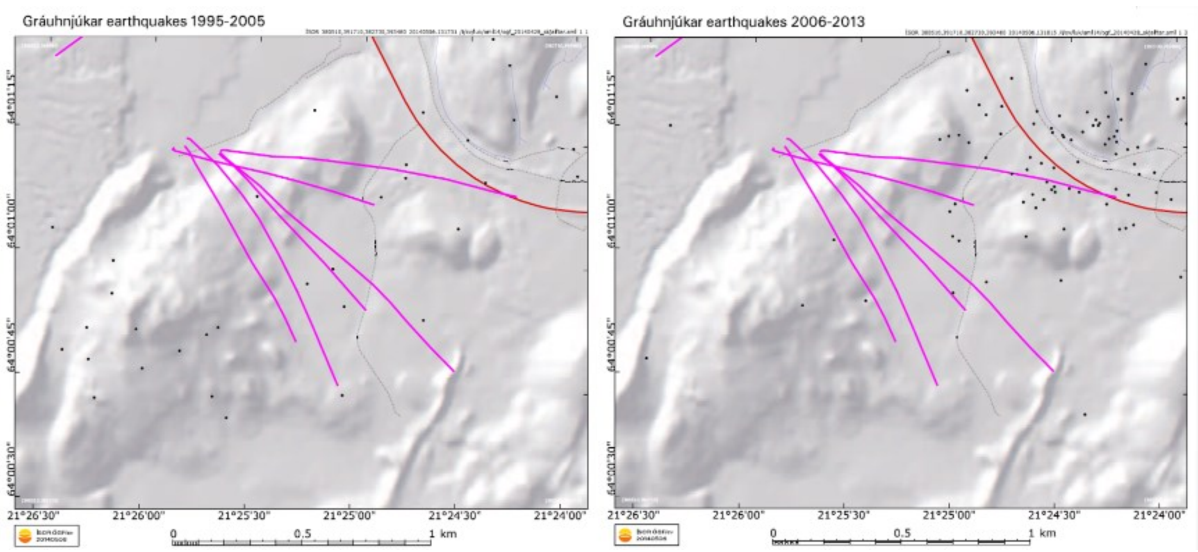

Figure 13: A map of the seismicity around the injection site at Gráuhnjúkar. The pink lines show the trajectories of the inclined wells that are drilled from almost the same platform and directed in the range E to SSE. Note the cluster of quakes that occurred close the northernmost injection well, an indication induced seismicity. The red line is a road.

Prior to 2011 the injection rate was of the order of 200 L/s but in June 2011 it was increased suddenly to 350 L/s. This increase was followed by an earthquake swarm that died out when the reinjection was reduced to less than 100 L/s in beginning of September 2011 when reinjection was started at Húsmúli. Since then the reinjection has been increasing again at Gráuhnjúkar due to reduced injectivity with time at Húsmúli and when the injection rate again approached 300 L/s the seismicity took off again

3.9.2 The Húsmúli injection site

The injection site of Húsmúli is located at the boarder of the Hengill area and is dominated by north easterly striking normal faults. The area was seismically active during the seismic unrest period in 1993 to 1994 (Vogfjörð et al., 2012). Seven injection wells were drilled at Húsmúli from 2008 to 2011. One of them was impermeable and one is only 1000m deep and used for monitoring. The remaining wells are quite permeable and are drilled to 2000 – 2900 m depth with casing depths of 600-700 m. The normal faults belonging to the central rift axis was the target for injection. During drilling of the last well in February 2011 intensive induced seismicity repeatedly occurred due to circulation loss and was monitored by a temporary local network installed and operated by ÍSOR (Ágústsson et al., 2014). Injection at Húsmúli started in September 2011 and in a few days the injection rate rose from zero to about 500 L/s. No local seismic network was installed but the area is fairly well covered by SIL network of IMO. Intensive seismicity followed the injection (Figure 14). From September 2011 to May 2012 about 4600 events were located by the SIL network with minimum observed magnitude of -0.4. About 150 events exceeded magnitude 2.0, 40 exceeded 2.5 and 8 were in the range 3-4, the largest events close to 4.0. Most of the events that were over magnitude 2.5 were felt in the village of Hveragerði, at distance of 10 km from the injection site and the largest earthquakes were also felt in Reykjavík at distance of 20-30 km (Bessason et al. 2012). Hveragerði was badly damage in May 2008 by an earthquake doublet of magnitude 5.8 and 5.9 (Decriem et al., 2010) and although the inhabitants are pretty used to small seismic events the repeated earthquakes from the injection site at Húsmúli did annoy and frighten the people and caused heavy protests even though damages were not reported. Reykjavík Energy, the owner and operator of the Hellisheiði plant was not prepared for the seismicity and had problems to react and explain what was happening and how to deal with the seismicity. It was not an option to abandon the injection as it would have needed shut down of the power plant. A few months later Reykjavik Energy created an expert group to analysed the situation and propose injection guidelines for Reykjavík Energy. The group consisted of expert from the University of Iceland, ÍSOR, IMO, Reykjavik Energy and the town of Hveragerdi under the leadership of Sveinbjörn Björnsson, professor emeritus in geophysics. The group presented a comprehensive report in the summer of 2012 (Bessason et al., 2012).

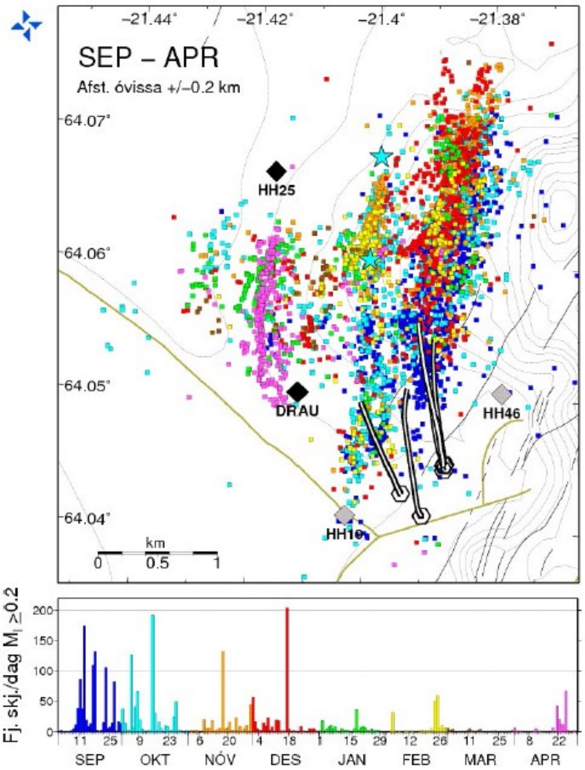

Figure 14: The epicentres induced from beginning of September 2011 till the end of April 2012 localized with accuracy of ±0.2 km. The colouring of the dots corresponds to the month when they occurred. The blue stars show the biggest events, which occurred in October 2011. The lower part of the figure show the number of events pr. day in this period (From Bessason et al. (2012).

3.10 Reykjanes high temperature field

The 100 MW_e Reykjanes power plant is located at the tip of the Reykjanes peninsula where the rift axis of the Mid-Atlantic Ridge comes on land. It came into operation in 2006 and re-injection started within the reservoir in 2009. The area is known for episodic high seismicity just west (Klein et al, 1977) and east (Guðnason and Ágústsson, 2014) of the geothermal field but with low seismicity inside it. A temporary network from December 2008 to May 2009 showed only small and scattered micro seismicity within the geothermal field that could not be coupled to the production or injection (Gudnason, 2014). Local network of 7 stations was installed at the end of 2012. Figure 15 show the location of the recorded earthquakes during 2013 and the first 5 months of 2014. In October 2013 an earthquake swarm occurred in the periphery just SE of the well field dominated by strike slip events on north-south focal planes and maximum magnitude of 4.7. There are relatively few quakes within the well field and these are of magnitude less than 2.0 and occur mainly as normal faults with a few strike slip and reverse events in between. Only a few earthquakes can be correlated with re-injection and these are shown as a cluster of red dots in Figure 15 in the north-western part of the well field.

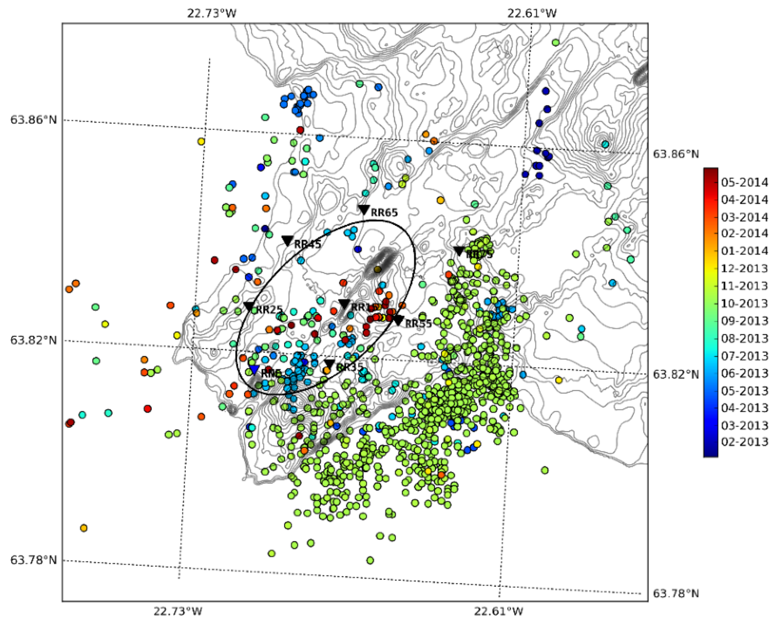

Figure 15: Location of earthquakes in the Reykjanes geothermal field from Jan 2013 to May 2014. The blue ellipse shows roughly the location of the well field. The green dots west of the well field belong to a swarm in October 2013. Relatively few quakes occur within the well field. The only injection related quakes are shown by the red dots in the NW part of the well field.

4. CONCLUSIONS

The above analysis of available data from fluid injection sites in Iceland shows clearly that induced seismicity is much more common than earlier thought. Of 11 reinjection sites exploitation related seismicity has occurred at 8 places, all being located at the seismically active plate boundaries, 7 at diverging boundaries and 1 at South Iceland transform zone. The three seismically silent injection sites are all located in intra-plate geothermal systems where production had already reduced the fluid pressure and injection rate is small. The magnitude of the production related earthquakes are normally lower than 2.0 but examples of triggered earthquakes up to 3.9 have been observed. Furthermore, long time down draw and 0.7-0.9 MPa seasonal variations in fluid pressure in a geothermal reservoir at the South Iceland Seismic Zone seem to modulate the seismicity and might have delayed an impending 6.4 earthquake by several years and affected its exact timing. Lack of regular high resolution monitoring of injection and production and absence of local seismic network hampers the conclusions that can be drawn about induced and production related seismicity but both are now being improved at the most important sites.

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