International Workshop on Earthquakes in North Iceland
Húsavík, North Iceland, 31 May - 3 June 2016

Pre-earthquake activity in North-Iceland

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We describe seismic pre-earthquake activity before some significant earthquakes in North Iceland based on historical, old seismic and new micro-earthquake information (Figure 1) and hint at physical explanations. Four smaller recent earthquakes for which we had seismic system to record pre-earthquake activity are not marked in this figure but described later.

Our objective is not to find universal precursors to use for predictions. But to outline the problem and what kind of information may be available to detect and understand crustal processes that may lead to predictions of individual earthquakes.

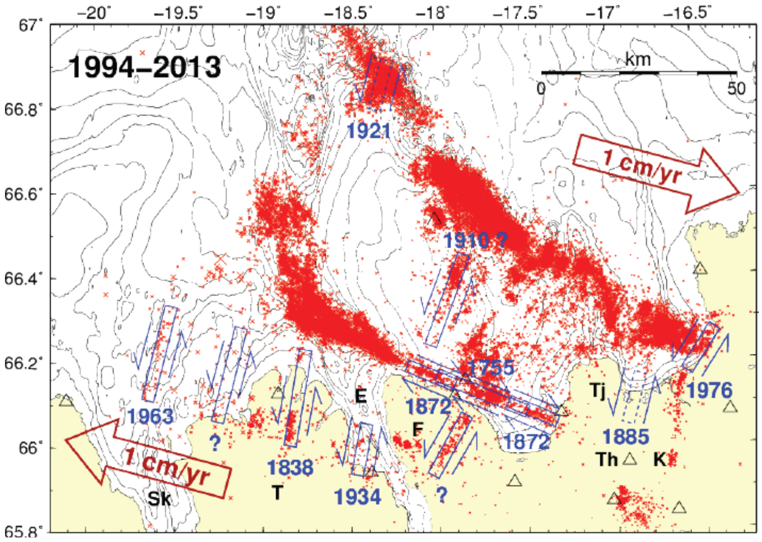

Figure 1. *Microearthquakes, shown by red dots during the marked period at the north coast of Iceland, outline the Tjörnes fracture zone. Boxes and arrows in blue color show results of efforts to find fault planes, and infer slip directions of historically and instrumentally evaluated magnitude 6–7 earthquakes in the area. Year numbers are used to identify the large earthquakes. Sk means Skagafjördur; E: Eyjafjördur; T: Tröllaskagi; F: Flateyjarskagi; Tj: Tjörnes; Th Theistareykir fissure swarm; K: Krafla fissure swarm. Plate velocity is shown by open arrows. (Stefansson et al (2008)*

Figure 1 gives an overview of earthquakes and seismic swarm activity at the north coast of Iceland. Earthquakes during the pre-seismograph period are located on basis of historical information. Fault planes are based on recent aftershock lines in the IMO catalogue and in some cases constrained by fault plane solutions *(Stefansson et al (2008)*. The location of the 1885 earthquake is estimated on basis on historical documents and of micro-earthquake measurements during 1972-1973 (Zwerev et al 1978).

The character of the pre-earthquake activity in North Iceland.

The central and eastern part of TFZ

1755: 5-6 earthquakes of probable magnitude of 5-5.5 were felt during an hour before the M7 earthquake in 1755 on the Húsavík-Flatey Fault (HFF), Figure 1. A likely position for the foreshocks is in the southernmost part of the Eyjafjarðaráll rift (Figure 2), near it´s bending to the

ESE striking HFF. This is based on where the foreshocks were reported, but also by comparison with the well recorded pre-process of the 2012 M5.6 earthquake (See later and Figure 2). We call this a rift-transform earthquake process.

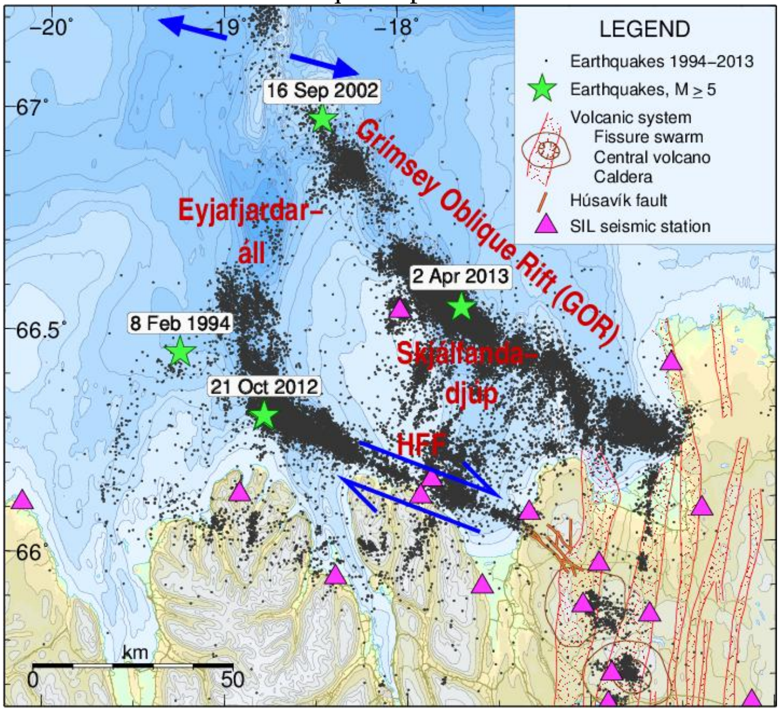

Figure 2 *Black dots are earthquake epicenters 1994-2013 off the Iceland north coast. Green stars are M5.5-5.9 earthquakes with day of occurrence. Húsavík town often mentioned in text is at the eastern end of HFF.*

1872. Two days before two M6.5 earthquakes on April 18, 1972 (Figure 1) intensive earthquake activity was reported near Húsavík and again 6 hours before the first large earthquake. There was one hour between the two large earthquakes the first one on HFF just west of Húsavík the second one farther west (Figure 1). Four years earlier, at the end of 1867, M5-6 earthquake stroke the area with probable epicenter on Tj (Figure 1) east of Húsavík, and an eruption was reported north of Tj shortly after. This suggests that these two M6.5 earthquakes are a part rift-transform process into the HFF, at this time starting from the N-S Theistareykir-fissureswarm (Th in Figure 1).
1885. There was no earthquake activity reported before this M6.3 earthquake in Kelduhverfi (Figure 1). The earthquake is well located in an inhabited area, so the lack of pre-seismic activity points to that possible foreshocks were smaller than M2 i.e. as we have seen in the SISZ before a "tectonic" strike slip earthquake there.
1910. The M7 earthquake north of Iceland 1910 (Figure 1) occurred at least 20 km from closest inhabited area so possible foreshocks would have to be M3-M4 to be reported felt by people at that time. So this earthquake was probably "tectonic" i.e. not a part of a rift-transform process.
1976. The M6.2 earthquake of 1976, the Kópasker earthquake, is a part of a rift-transform process in the Krafla fissure swarm. Rifting started December 20 at 10 17 am by intensive swarm at the Krafla caldera (K in Figure 1), coinciding with a minor eruption there. This marks the start of a rifting which moved fast from just south of Krafla to the junction to GOR in Öxarfjördur (Figure 2 and 3). The most seismic activity and the sequence of largest earthquakes (reaching M5) which followed this rifting intensively for 2-3 weeks were at the northern end of the Krafla fissureswarm near the bending to GOR. Total E-W widening at 66.1°N for these 2-3 weeks is of the order of two meters. (See Sigurðsson. O. 1980).

The rifting loaded the focal area of the Kópasker earthquake 13. January and the stress released in this strike slip earthquake was largely built up by the preceding rifting (See also Stefánsson et al 1979). However 6 days of relatively low activity preceded it in the epicentral area itself or until a magnitude 5 earthquake occurred just south of the focal area 9 hours before it.

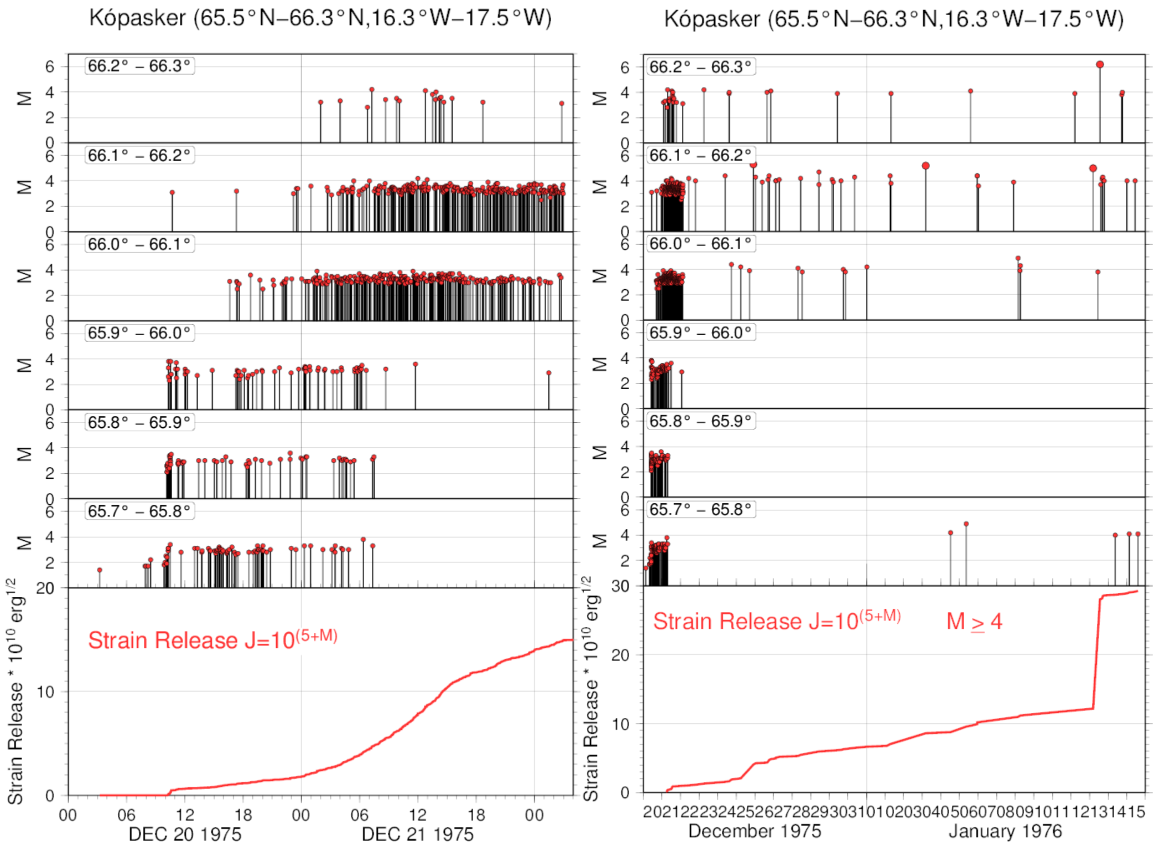

Figure 3. *The parft to the left shows monitored earthquake magnitudes (completeness M3) with time during two first two days of the Krafla Rifting Episode. The bottom M-row covers the Krafla Caldera at the south, and then the activity is shown in 11 km parts of the rift towards the northernmost part at 66.2°N-66.3°N where the Kópasker earthquake eventually occurred 23 days later. The part to the right (to the January 15) contains M4 or larger earthquakes only except for the first two days. This is based on IMO evaluations which so far have not reached below M4 for this sequence.*

So although the 1976 earthquake can be considered as a part of a rift-transform process in the long term, it is a "tectonic type strike slip earthquake" in the short term, i.e. in the focal area. There is 6 days of apparent quiescence, and may be 9 preceding hours of breaking it´s asperity, but of course we do not know this because the seismic detection limit was close to 3 at that time

2002. A M5.8 earthquake occurred far north, at 66.96°N, 18.45°W, on September 16 at 18:48. It was preceded by a swarm of earthquakes reaching magnitude 3 starting 2 months earlier, 15 of July, lasting for 5 days. The depth distribution for this pre-earthquake swarm appears to be relatively even from 5 km depth to 20, and the epicenters mainly around 5 km to the south of the main shock and partly of it 5 km to the north of it. Compared to background there is slightly increased seismic activity after the early pre-swarm, and from the beginning of September there is slow but steady increase in the number of earthquakes reaching magnitude 2.5 until a sudden onset of the 5.8 earthquake.

As said before the process ahead of the 2002 earthquake started two months before the earthquake, compared to one month by a comparable pre-process before the 2012 earthquake (It´s pattern is described in Figure 4).

2012. A M5.6 earthquake occurred at 66.31°N, 18.78°W on October 21 at 01.25. This location is at the bending of Eyjafjarðaráll rift into the HFF (Figure 2). A month earlier, in mid September a week long swarm activity started 7 km further north in the rift (Figure 4), with largest earthquake reaching magnitude 4.5. Relatively many earthquakes of this pre-swarm appear to have hypocenter below the brittle crust down to 20 km. A sequence of earthquakes reaching magnitudes 3 started one day before the 5.6 eq., and swarm activity of earthquakes reaching magnitudes 5.3 preceded it by 3 hours.

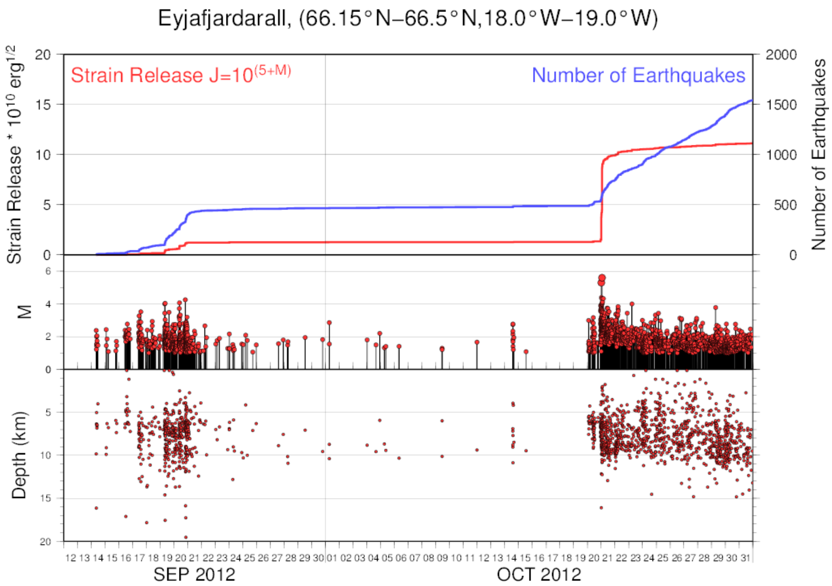

Figure 4. *Time plots show pre-earthquake activity, larger than M1 starting September 15 2012 in the Eyjafjardaráll rift (Figure 2) and main sequence including M5.6eq, starting October 20, 7 km farther south. Top shows cumulative strain release and number of earthquakes larger than 1, next row earthquakes and magnitudes. The third row shows the depths of hypocenters. All based on manual corrections by the IMO scientists of the SIL system automatic evaluations.*

The 2012 earthquake was a part of a swarm that lasted for 5 hours or so and preceded seismic activity migrating ESE along the western part of HFF. It is a part of a rift-transform process that started in mid September and lasted 5-6 months and faded out without triggering a large earthquake on the HFF.

2013. A M5.5 earthquake occurred at 66.55°N, 17.66°W on April 2 at 00.59. It is in the Grímsey Oblique Rift (GOR) (Figure 2). A sequence of earthquakes probably related to the earthquake, ca 5 km north of it, started three months earlier, i.e. at the end of December 2012. On March 30, 43 hours before the 5.5 eq an intensive seismic sequence (M3) started in the focal area. The 5.5 earthquake is a distinct earthquake (not a swarm) with two magnitude 1.5 earthquakes within an hour before it.

It must be noted here that near the end of September 2012 a swarm lasting half a month started on the rift 5 km south of and 5 km north of the 2013 earthquake epicenter apparently below the brittle crust. Largest earthquakes of magnitude 3.5. This swarm 6 months before the 2013 earthquake is as concerns depth distribution and relative long lasting comparable to the swarms starting two months before the 2002 earthquake and one month before the 2012 earthquake (Figure 5)

The 9 earthquakes above, in the eastern and central part of the TFZ, are close to highly active rifting at present times (Figure 1). Still the pre-earthquake processes are of different types ranging from what is typical for earthquakes in a horizontal shear stress environment to earthquakes preceded by rifting, which in some cases also resemble tectonic earthquakes in the short term. In the recent well monitored earthquakes there is swarm activity months before which may be of relatively deep origin i.e. could indicate fluid upflow.

West TFZ, i.e. west of Eyjafjardaráll and south of it´s junction to HFF.

1838, 1934, 1963. As seen in Figure 1 the seismicity of this part of the TFZ suggests less lithostatic fluid pressure activity in releasing stresses than in the eastern part. The earthquake fault configuration resembles the SISZ (Stefansson et al 2011). The earthquakes of 1838 (M7), 1934(M6.2), 1963 (M7) did not have monitored foreshocks, meaning that the two first did not have foreshocks larger than M2 and the third one, far from inhabited area and old type seismic stations, not larger than M3. The pre-earthquake activity may be comparable with what is expected for a typical strike slip type earthquake, like the initial earthquake year 2000 in the SISZ, where the short

term pre-earthquake process was well expressed in earthquakes of magnitudes -0.5 – 1. Closeness of the northern end of the 1938 fault to the Eyjafjarðaráll rift suggests that a rifting there could have preceded it, although not reported felt by people.
1994. A magnitude 5.5 earthquake west of the Eyjafjardaráll rift. There was no pre-earthquake activity measured, meaning no earthquakes larger than 2 close to this epicenter during the first month of 1994, i.e. from the time the SIL system started in North Iceland. In fact no pre-earthquakes were measured down at magnitude 1, even if so small earthquakes were seen in the aftershocks.

Consequence for earthquake prediction research

Among significant findings of 20 years of earthquake prediction research in the South Iceland Seismic Zone (SISZ) are: No two earthquakes nor their preparatory processes are the same. Therefore the statistical approach to find universal precursors will be of limited use for prediction. However it has been found after earthquakes in Iceland as in many other places that pre-earthquake activity was really recorded where sensitivity of the monitoring was high enough. The initial earthquake of magnitude 6.6 in year 2000 in the SISZ had two to three weeks of M0 earthquakes which express a physically well explained process of nucleation towards the earthquake. Ten years of micro-earthquake monitoring down to magnitude zero revealed information about the hypocenters of the impending two large earthquakes of 2000. All this information expressed shearing process below the brittle crust which was gradually deforming it long before the large earthquakes stroke. Large earthquakes in the SISZ in 2000 and 2008 show although partly in a different way, that the earthquake process started below the brittle crust well before the earthquakes, and defines the fault that will eventually be ruptured. This marks the road to useful warnings /earthquake predictions in the SISZ: To monitor as well as possible the ongoing process and extrapolate to near time and short distances. Technology to extract detailed information from micro-earthquakes down to zero, even down to M-0.5, are the best existing method for doing this monitoring, but we should not exclude other methods that measure deformation and fracturing, that may constrain the information from micro-seismic based monitoring (Stefansson 2011, Stefansson et al 2011).

The findings reported here mark us the same road to go in the Nortrh. In some cases rifting in nearby zones load the becoming earthquake fault in similar manner as the deep faulting below it does in the SISZ. This appears in many cases in larger "foreshocks", but the final problem has to be solved on basis of information from the real source volume of the impending large earthquake itself, precisely where it will occur what fault, how big it will be, and when it will be, or will it really happen this time.

Real predictions or warnings before earthquakes should be useful to mitigate risk for people, and society in the long and the short term. To make this possible we need long term research of ongoing deep crustal pre-processes, in space and time, in the impending source volume, and methods to extrapolate this information in space and time to get as much information as possible about the earthquake before it eventually strikes. This can be carried out during long period watching at likely earthquake places which show measureable signals of preparation (Figure 5).

Warnings of non-occurrence are as significant as warnings for well defined hazard. They are necessary when the public can feel possible pre-earthquake activity. We should aim towards that continuous watching linked with scientific research can cope with such recordings, include them in the database and declare non-occurrence as well as occurrence.

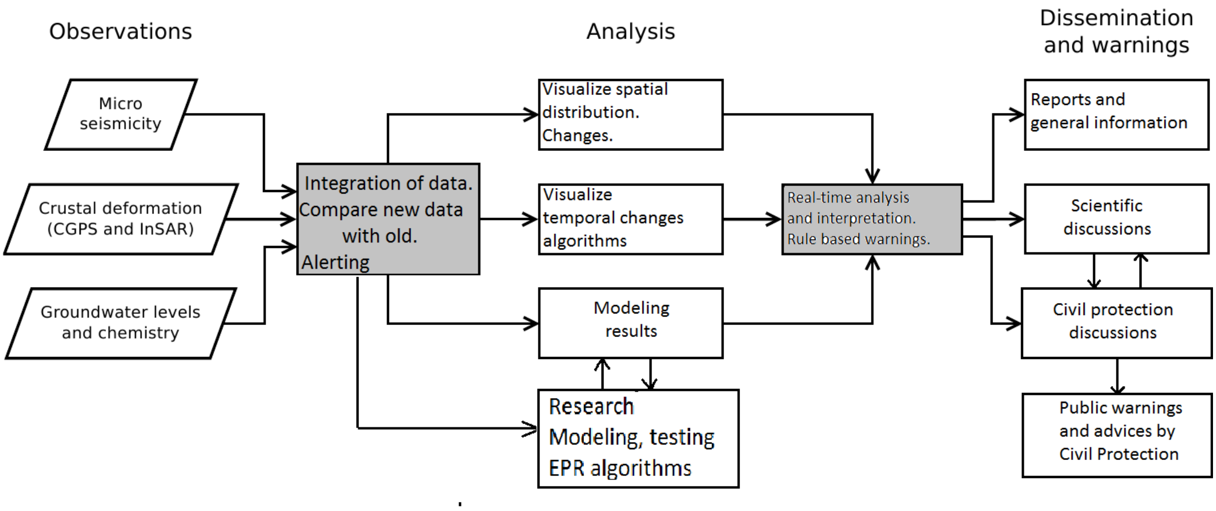

Figure 5. *This diagram is an attempt to demonstrate operations of a watching system, from observations and direct alerting, through manual and automatic analysis and research, towards rule based scientific warnings to the Civil Protection, and after consultation with scientists, to public warnings and advices issued by the Civil Protection Service.(Figure: M.J. Roberts personal communication)*

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