VEÐURSTOFA ÍSLANDS

Report
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About the state-of-the-art in providing earthquake warnings in Iceland

A report based on a presentation at the PREPARED Mid-Term Meeting in Reykjavík, January 30-31, 2004

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Contents

Introduction

This report is basically (with a few additions) identical with an introductionary report held at the PREPARED Mid-Term Meeting in Reykjavík, January 30-31, 2004. In spite of the name it is mainly based on seismological investigations. Its contents have been circulating around, however we thought at this moment it would be useful to have it printed, as a basis for the final spurt in the PREPARED-project.

The aim of our work in PREPARED is: Better earthquake hazard assessments, time dependent hazard assessments, and warnings. In our research proposal to the European Commission we have defined following scenarios for warning services that we hope to enhance during our project:

Scenarios

1) Years to month in advance: Concentration of various risk mitigating efforts, compiling background data, increased monitoring and data analysis, strengthening of infrastructure.

2) Weeks to days in advance: Activation of civil protection and rescue groups, increased sensor-based observations, raising in general the preparedness of people.

3) Hours to minutes in advance: Final civil preparations for an event that could occur instantly. If no event occurs within a specified period, then this scenario ends.

4) The earthquake occurs: Actions aiming to mitigate inpact on people and society, early information, now-casting, real-time damage assessment.

5) Post-quake information: Explaining the event, assessing and warning for further coupled hazards.

The objective of all partners in the PREPARED project is how shall we proceed to try to fulfill each step of the protocol above.

In this report some examples will be given of previous hazard situations in Iceland in light of the above protocol.

Additionally, some preliminary insights will be given on information provided by seismic data approaching the 2000 earthquakes, and hinted to the potential in the seismic data in developing tools for warnings.

Hazard assessment and long-term predictions

A time dependent hazard assessment or long-term prediction was stated 20 years ago for the area, suggesting that there was more than 80% probability that large earthquakes would break through the SISZ during the next 25 years. The earthquakes would probably start at the eastern part of the seismic zone with an event of magnitude 6.3 to 7.5, but during the next days or months a sequence of earthquakes would follow further west in the seismic zone (Einarsson 1985).

Later estimations of probable and possible magnitudes and hazard assessments indicated that the largest probable earthquake in this zone would not exceed magnitude 7.2 (Ms) (Halldórsson 1987; Stefánsson and Halldórsson 1988).

Based on these estimates, and a method for calculating time dependent hazard assessment based on large earthquake statistics and tectonical evolution, which has been applied for 20 years in Iceland (Páll Halldórsson, personal communication) there was, just before the year 2000 earthquakes, 98% probability of magnitude 6 earthquake within the next 25 years and a lower probability for a larger one.

In 1988 it was stated (Stefánsson and Halldórsson 1988) that there are strong indications that the next large earthquake of the size „approaching magnitude 7 in the SISZ will take place near longitude 20.3°-20.4°W" in the EW striking 10-20 km wide zone (Figure 1). Only the longitude is indicated because the impending earthquake was expected to be on NS fault plane in this EW zone at 63.9°-64.0°N. This prediction of place was based on a lack of strain release in historical earthquakes since the year 1700 in a narrow area (Halldórsson 1987; Stefánsson and Halldórsson 1988). The „next large earthquake", i.e. the earthquake of June 17, 2000 took place within the zone at 20.37°W, i.e. near the center of the 5 km area „predicted".

A similar but less indicative gap was also indicated for a narrow area around 20.7°W (Figure 1). Some years later it was pointed out that these two gaps coincided with a long-term concentration of microearthquake activity in the seismic zone (Stefánsson et al. 1993) and it was stated that these two sites were the most likely sites for the next earthquakes in SISZ, i.e. at 20.3º-20.4Wº and at 20.71Wº, i.e. within a few kilometers from the sites of the two year 2000 earthquakes (Stefánsson et al. 1993).

These „predictions" correspond to Stage 1) of the Scenarios above. They did not become a basis for special assessments of risks in the area. However, they influenced the build-up of scientific preparedness in the region, i.e. led to earthquake prediction research projects (the first was the SIL-project of 1988-1995) and to the build-up of a high-level monitoring system.

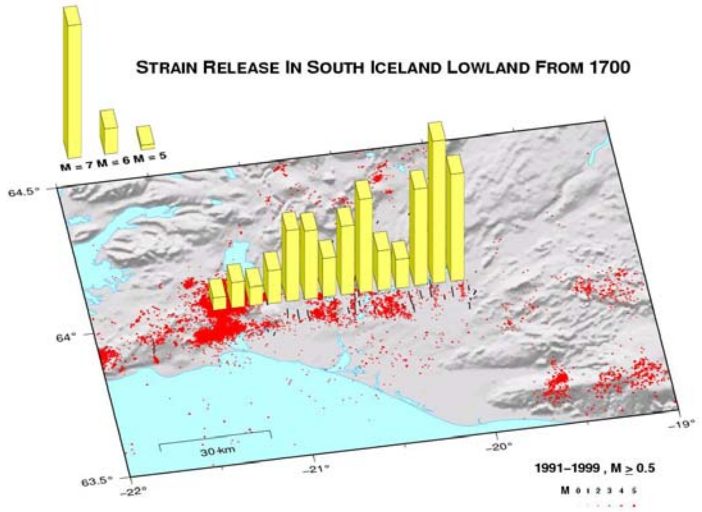


Figure 1. *The yellow pillars arranged along the SISZ in SW Iceland indicate release of strain energy in historical earthquakes from 1700 to 1999. Here Benioff strain is calculated from the magnitudes of each of the historical earthquakes. The half of the strain of each is put at the most probable location, while ¼ is put at each side to try to allow for probable location errors. Red dots show microearthquakes. Black lines indicate the position of known earthquake faults. Earthquakes tend to be larger in the eastern part than in the western part, which has been explained by thicker and stronger brittle/elastic crust there.*

These „predictions“ were put forward in scientific papers and as indications rather than as an official hazard assessment. Our hope is that a better understanding of the earthquake preparatory processes will make such assessments, as described here, more definite and physically better based and possibly lead to more decisisive actions regarding risk mitigating efforts.

Indications from microearthquakes about stress build-up before the year 2000 earthquakes

Were there any long-term or short-term indications from small earthquakes for stress build-up approaching the earthquakes? How was the seismicity time pattern at the two microearthquake clusters of the SISZ (Figure 2), where the next earthquakes were postulated?

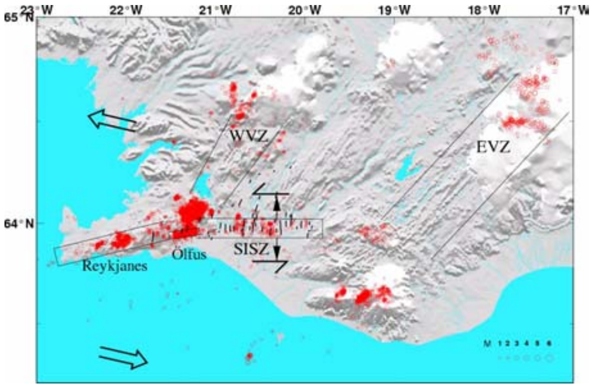


Figure 2. *The relation of the SISZ to the main features of the tectonics of SW Iceland. Arrows show the direction of the 1.85 cm/year plate motion in the region (NUVEL 1A, DeMets et al. 1994) and probable long-term motion across the SISZ. The western part of the seismic zone has a triple junction with the western volcanic zone and the Reykjanes peninsula. The eastern end of it links to the eastern volcanic zone. Red dots show microearthquakes in the area 1991-1999. The two minor clusters in the central zone during a pre-earthquake period (red dots) are the sites of the two year 2000 earthquakes. The largest cluster of the figure is in the triple junction/volcanic area which had high seismic activity during 1994-1998.*

In Figure 3 we consider the time evolution of seismicity in the two SISZ clusters of Figure 2, approaching the large earthquakes, by plotting the number of earthquakes larger than zero, which is near to the limit of completeness.

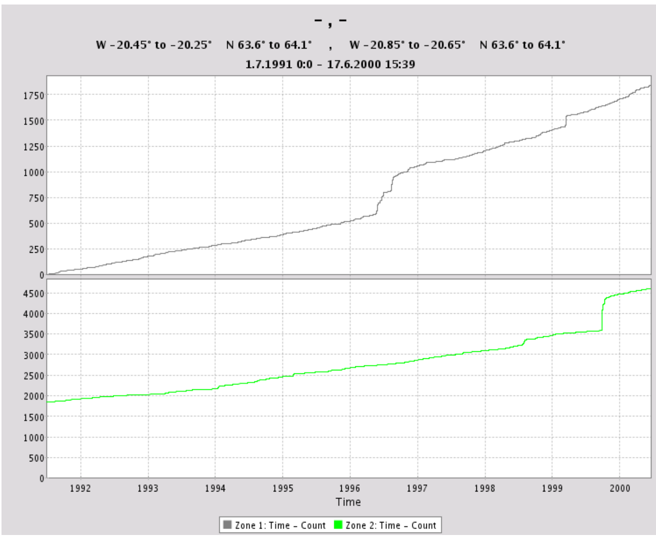


Figure 3. *The upper part shows cumulative number of earthquakes larger than 0 in the eastern cluster, cluster 1, i.e. where the first of the two earthquakes occurred. The lower part shows the evolution in the western cluster, cluster 2.*

Since the start of microearthquake monitoring in the region in 1991 there is a clear rate increase in cluster 1, i.e. where the first Ms=6.6 earthquake occurred (the upper part of Figure 3). The even rate increase of the number (exclude the swarms) indicates stress increase in the area. However, we do not know how to use this for estimating, even very roughly, the time of onset of the probably impending event.

It is interesting that the area around the second M=6.6 earthquake (cluster 2) does not show such rate increase in stress from microearthquakes (lower part of Figure 3). Certainly it has more release of larger earthquakes near the end of the period. This indicates that the second earthquake was not triggered by a gradual build-up of stress in its surroundings as was for the first one. It was in the stress shadow of the first earthquake asperity. It was probably triggered by the first earthquake.

Even if the general stress build-up, expressed by the seismicity rate, before the occurrence of the first M=6.6 earthquake, is not indicating closeness to fracture, there was a clustering of microearthquake activity close to the becoming (expected) fault during the weeks before it, which may be indicative of time to the break.

Short-term clustering of microearthquakes along the becoming fault shortly before the first large earthquake

Small earthquakes arranged along the impending earthquake fault shortly before the earthquake (Figure 4). The special clustering around the becoming hypocenter is of a special interest. This is at the probable asperity of the earthquake, which is starting to break. The seismic activity during this period is a part of a linear clustering of the activity along the fault, from being much more areally distributed. This clustering probably indicates that slow movement was gradually building up across the entire NS fault before the earthquake, straining gradually the withholding asperity in the middle which started to have microearthquakes shortly before the break.

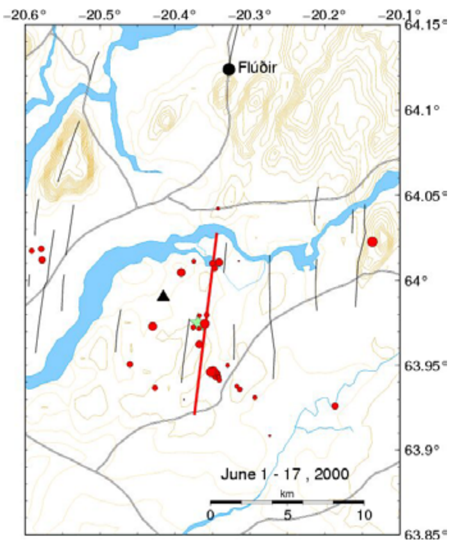


Figure 4. *The red line shows the fault plane of the first earthquake. Dots show small earthquakes, mostly near magnitude zero, 17 days before the first large earthquake, marked by the green star.*

Such a pattern of the nucleation of an earthquake is physically understandable. It is difficult to say in hindsight if this could have led to some kind of a short-term warning. Anyhow the pattern was not safely observed, the earthquakes were small (<1), until after manual evaluation partly after the M=6.6 earthquake occurred.

In hindsight we can say that we would possibly have been alarmed by this pattern if we would have:

- **Clearly taken into account the prediction of the place of the earthquake in our alarm system.**

- **An early information system which would highlight the ongoing clustering based on evaluated or automatic data. Before the earthquake the available alert system was only based on number and magnitudes of microseismicity in areas much larger than the focal preparation areas.**

- **Available algorithms which would, in the light of earlier experience and understanding, have highlighted clustering and other possible information on premonitory characteristics carried by microearthquakes in approacing such a crustal rupture.**

Having all this done and discovered, we might have been able to issue a low order warning to the Civil Defence and could have taken the initiative to enhanced monitoring in the area.

In a borehole at Flúðir, 10 km to the north of the fault (Figure 4), water level changes were signalled 24 hours before the earthquake and again one hour before it. This was not reported until after the earthquake and is unfortunately not well confirmed. A low order warning to the Civil Defence would possibly have led to more monitoring of the water level.

A warning was issued about the second large earthquake 26 hours before it occurred

Warning for a probably impending earthquake was issued 26 hours before the second earthquake occurred. A map was then sent to the Civil Defence, indicating the most likely fault and destruction area of an earthquake that might be as large as the first earthquake (Ms=6.6) or possibly smaller (Figure 5). The time of it was not predicted, but the Civil Defence was advised to prepare for that it might occur any time shortly.

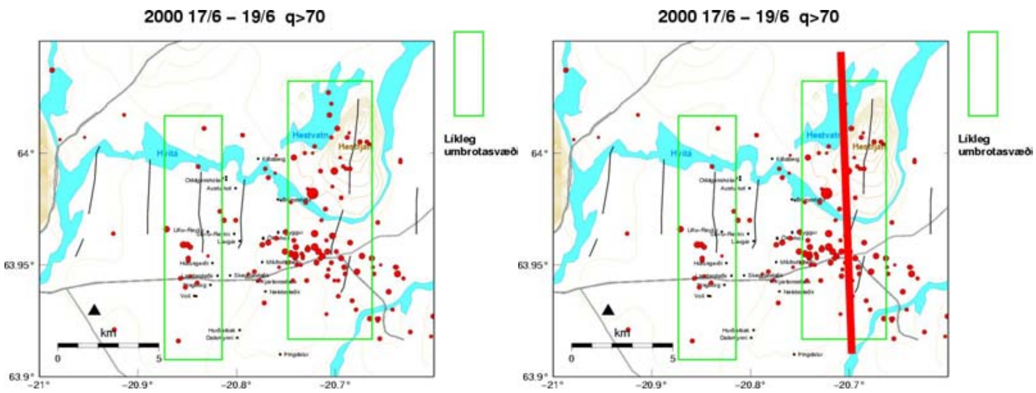


Figure 5. *To the left is the map that was sent to the Civil Defence 26 hours before the Ms=6.6 earthquake on June 21. The boxes indicated the area of probable most destruction. Dots indicate small earthquakes in the area after the first earthquake occurred 20 km further east. The larger box was assumed most likely to become the destruction area. To the right the earthquake fault of the June 21 earthquake has been included in the map, i.e. the red line, striking right through the box of the predicted most probable hazard area.*

Here we were in Stage 3 of our Scenarios. Of course we were not absolutely sure that this would happen, however the odds were so strong that we could not do anything else than issue this kind of warning. The basis for the warning is as follows: 1) Rapid increasing of seismicity in that area where it was forecasted that the second most likely earthquake would occur, and an expected tendency for seismicity to arrange along an impending fault rupture; 2) Evidence from history of westward migration of earthquakes; 3) Indications from history of an apparent 5 km/day migration velocity (not reported in a paper).

The warning was released and it was very useful. Many people in the area told us that we should have issued it more openly, so people would have been better prepared. We did not advise the Civil Defence to do that. What we said openly was, that in general earthquakes should be expected further to the west after the first earthquake occurred.

Here we were in Stage 3 of our Scenarios and our warning served also partly the Stage 4.

A key element of PREPARED is to observe and model premonitory processes based on the experience of the year 2000 earthquakes

A basic approach is to create physically plausable models which can explain why and how stresses develop into fault ruptures. Not being able to measure absolute value of stresses in the fault areas in general, and not being able to tell at what stresses the crust faults will break, we have to concentrate on trying to observe premonitory processes which may trigger the earthquakes. Our experiences in PRENLAB and in many other research efforts, point to that a fluid mobility and rock fluid interaction is a key element.

Some significant features of the SISZ

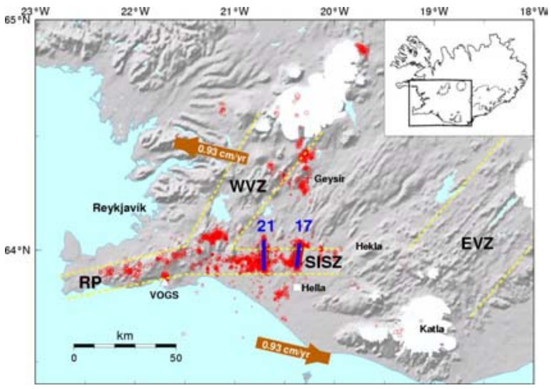


Figure 6. *SW Iceland. The South Iceland seismic zone (SISZ), the eastern and the western volcanic zones (EVZ, WVZ as well as the Reykjanes peninsula (RP) are indicated. Red dots show small earthquakes and the blue lines, marked 17 and 21 show the earthquake faults. The heavy arrows indicate the plate motion according to the NUVEL 1A plate model (De Mets et al. 1994).*

The angle of the transform zone SISZ to the NUVEL 1A plate model motion, indicates a 1.8 cm/year left-lateral motion along the EW zone, and significantly 0.4 cm/year NS, opening across the zone (Figure 2 and Figure 6). A plausible parallel is that fluids participate in the process of opening, and of weakening a 10 km wide zone. (See for example Stefansson and Halldórsson 1988). Pores originating in the ductile or semi-ductile material below the crust seek their way gradually or episodically up through the crust, bringing upward high lithostatic pressures. Pores with high fluid pressures most probably originating from below are gradually increased at the brittle ductile boundary and in the brittle crust until they are released during small or large scale pore fluid connections or ruptures and fluid flow along these ruptures or their pervasive material.

Tentative model of the SISZ earthquake preparatory processes, presented at the PRENLAB meeting in Strasbourg in March 1999

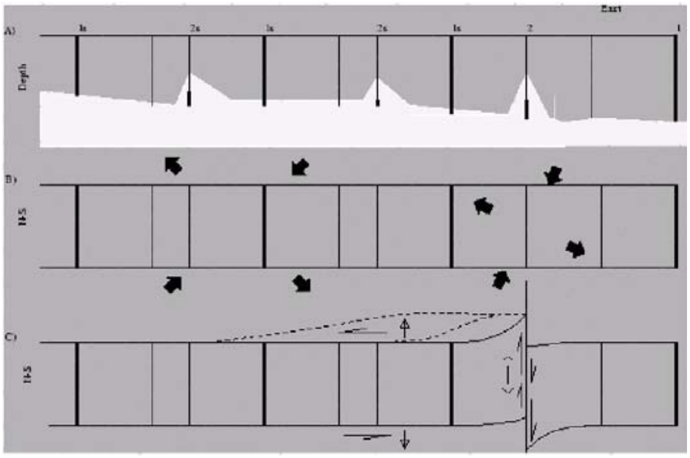


Figure 7. *The uppermost part of the figure shows a depth section from west to east along the SISZ. Thick vertical lines (marked by 1) indicate faults of recent earthquakes, i.e. earthquakes which have released strain in the area and significantly also pore pressures. The lighter horizontal lines (2) and the elevated white area indicate areas where pore pressures are building up from below and the predicted fault of a near future earthquake. The lower sections of the figure are horizontal sections, before and after earthquake stress release.*

The model (Figure 7 and Stefánsson 1999) predicts increased pore pressures migrating from below up into the elastic/brittle crust most probably during a long time, possibly up to hundreds of years at sites where there has not been a large crust-through or other pore pressure releasing event for that period. Where we have recently had earthquakes (marked by 1) the high pore pressures are not reaching as high up into the brittle crust.

Fluids carrying high pressures from below are episodically and gradually rising closer to the surface increasing pore pressures and corroding larger and larger part of the fault and expanding it until the earthquake is released. It helps the 100 year strain build-up to rupture the zone at that side.

Fluid movements and changes of fluid pressure at depth, linked with the approach of the year 2000 earthquakes

Microearthquakes at depth in the crust in the fault zone stem from the combined effect of tectonic strain build-up (shearing) and high pore pressures.

Dense clustering of microearthquakes characterizes the boundary between the elastic/brittle part of the crust and the ductile deeper part. The depth of the boundary is generally depending on the balance between increasing pressure by depth and increasing temperature. The depth of it in the SISZ at the site of the first year 2000 earthquake is approximately 8 km (Stefánsson et al. 1993). It is deeper to the east and shallower to the west. The depth of the microseismic boundary is influenced by strain rate, i.e. would be deeper at higher strain rates, during earthquakes and other fast deformation episodes. So for example the 8 km depth would correspond to the average slow strain rate across the SISZ. On the other hand heterogeneities in the crust, like old cracks and high density of fluid filled pores can significantly change the depth to the seismic boundary. Such assumptions comply well with the seismic observations as detailed later in this report.

Down in the ductile zone the crust yields complying with the confining strain. At the ductile brittle boundary fluids are released from the ductile layer and into the cracks created in the brittle layer which responds to the yielding by fracturing in presence of fluids that rise from below. This by time creates an intermediate layer between the ductile and the brittle zone of fluid filled cracks and relatively high fluid mobility. The fluids from this layer, which probably is to a large extent compressible water fluids, penetrates further up in the crust in response and complying with faulting that penetrates higher into the crust, mostly created in crust-through-cutting earthquakes.

In Figure 8 some main trends of the microseismic activity before and after the year 2000 earthquakes can be seen. The pre-eathquake and the past-earthquake activity of the first large earthquake is shown in the rectangular box. The past-earthquake activity of the second large earthquake is shown by almost NS elongated 15 km long lines, 20 km further west. An areal distribution of seismicity is seen at the same place in the pre-earthquake period.

Other features of the pre-earthquake activity are narrow NS lines of microearthquake activity mostly corresponding to recent large earthquake faults, i.e. during the last hundred years or so.

In the following we will describe what microearthquakes indicate about local stresses, stress migration and fault weakening in the 2000 earthquakes. We do not see the whole of the period of weakening or fault corrosion. We only see the last 9 years before the earthquakes, i.e. the SIL-period, when we observe earthquakes with magnitudes down to zero.

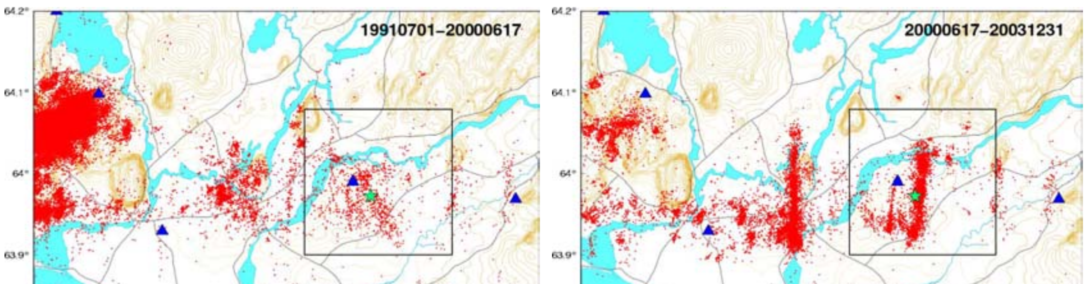
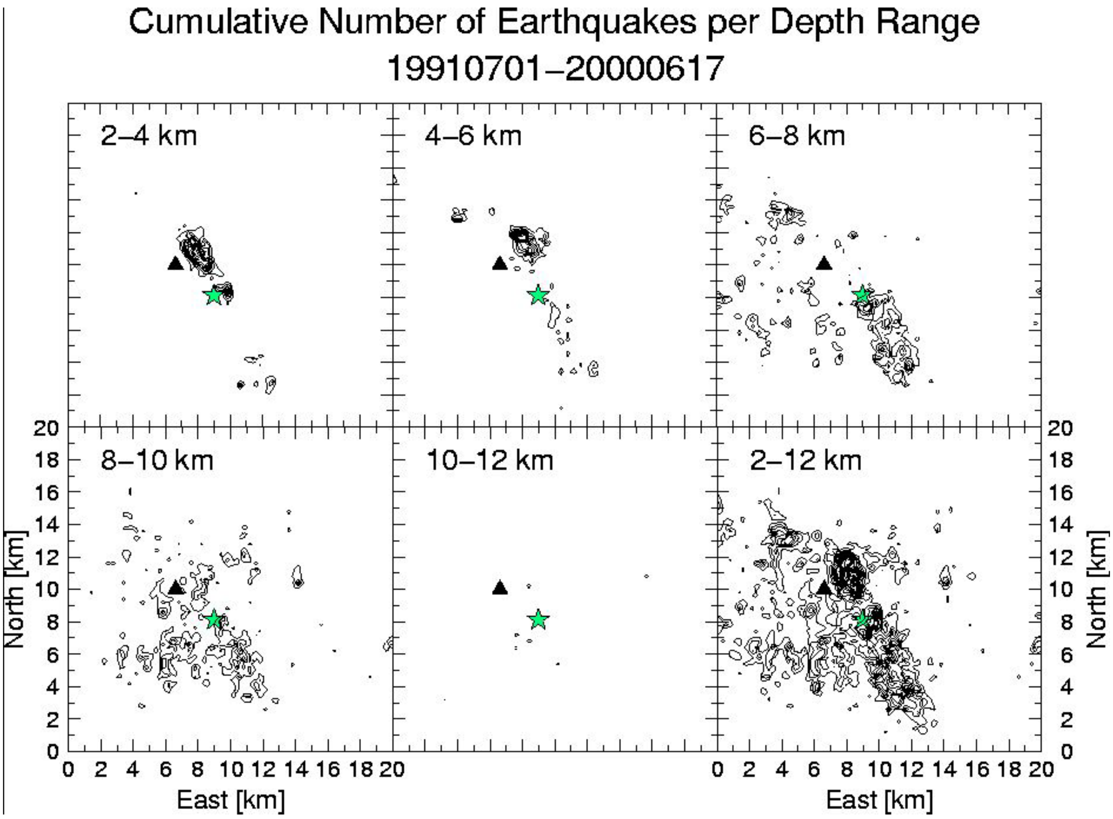


Figure 8. *Seismicity in the SISZ before (left) and after (right) the year 2000 earthquakes. The area of dense seismicity at the western end of the SISZ is at the junction between the SISZ and the western volcanic zone, displaying high seismic activity there during a volcano-tectonic episode 1994-2000. At the eastern end of the zone we are close to the junction of SISZ with the eastern volcanic zone.*

Some characteristics of the premonitory seismic patterns of the earthquakes

Above we have described in short seismicity changes before the earthquakes. In the following we will demonstrate some more features of premonitory changes, especially for the first earthquake, the June 17 event.

Changes in earthquake density prior to the June 17 earthquake



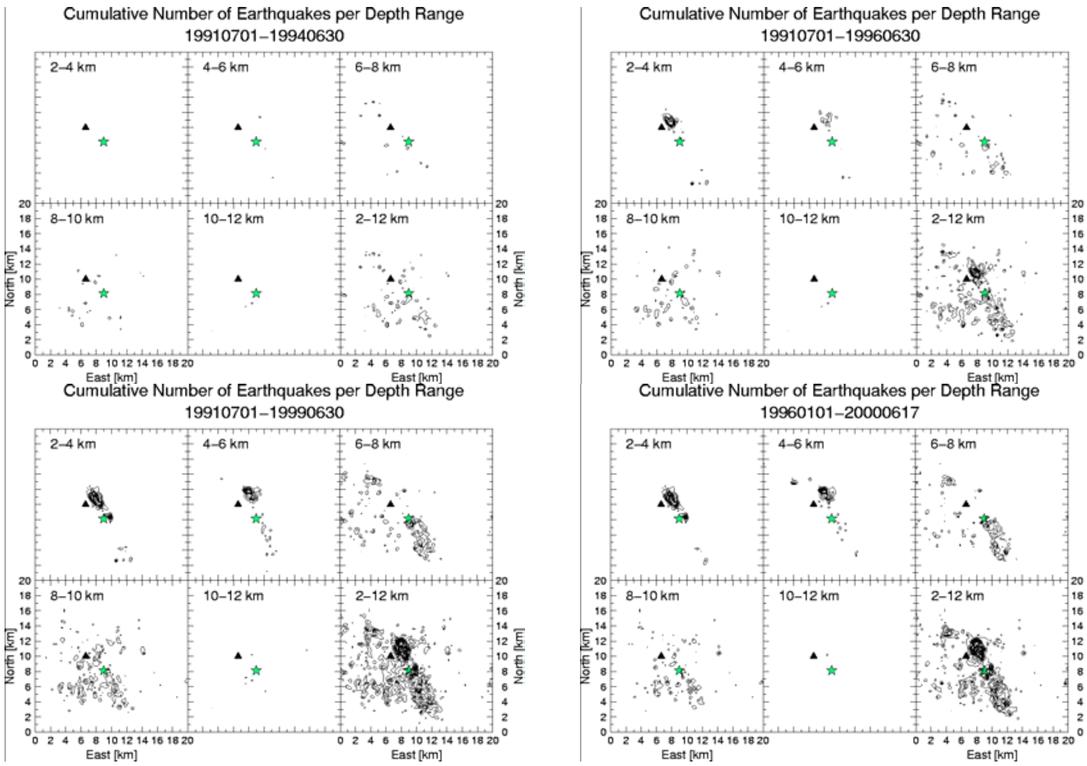


Figure 9. *Earthquake density at various depths in the epicentral area of the first earthquake (the star) during 10 years prior to it. The density in this figure and in the following density maps is found by counting quakes in grid windows of 0.25x0.25 km in the depth intervals and time periods indicated. Lines of density are drawn with interval of 1 earthquake number. The* ▲ *is the seismic station SAU. The upper part takes to the whole period, while the lower part indicates changes with time. The point zero here and in many of the following figures of the June 17 activity is several kilometers to the SW of the hypocenter, i.e. the green star at 63.90ºN and 20.55ºW.*

Following observations are made, from the patterns shown in Figure 8 and 9.

- Everyday seismicity is at around 8 km depth, however to some extent elevated up to 6 km. A volume of seismicity striking W29°N appears strongly above 8 km depth. We call the deeper part of this the dilavolume. The hypocenter of the June 17 earthquake is just above the middle of this volume. Activity migrates upwards from the dilavolume, episodically, at distinct parts of it, especially to NW, but also less intensively to SE, but not through the hypocenter, which thus appears as an asperity with minor seismic activity.

- Activity below 10 km is minor but it is of interest that it is concentrated just below the hypocenter.

Seismicity changes studied in 3-D volumes around the hypocenter along the dilavolume (Figure 10).

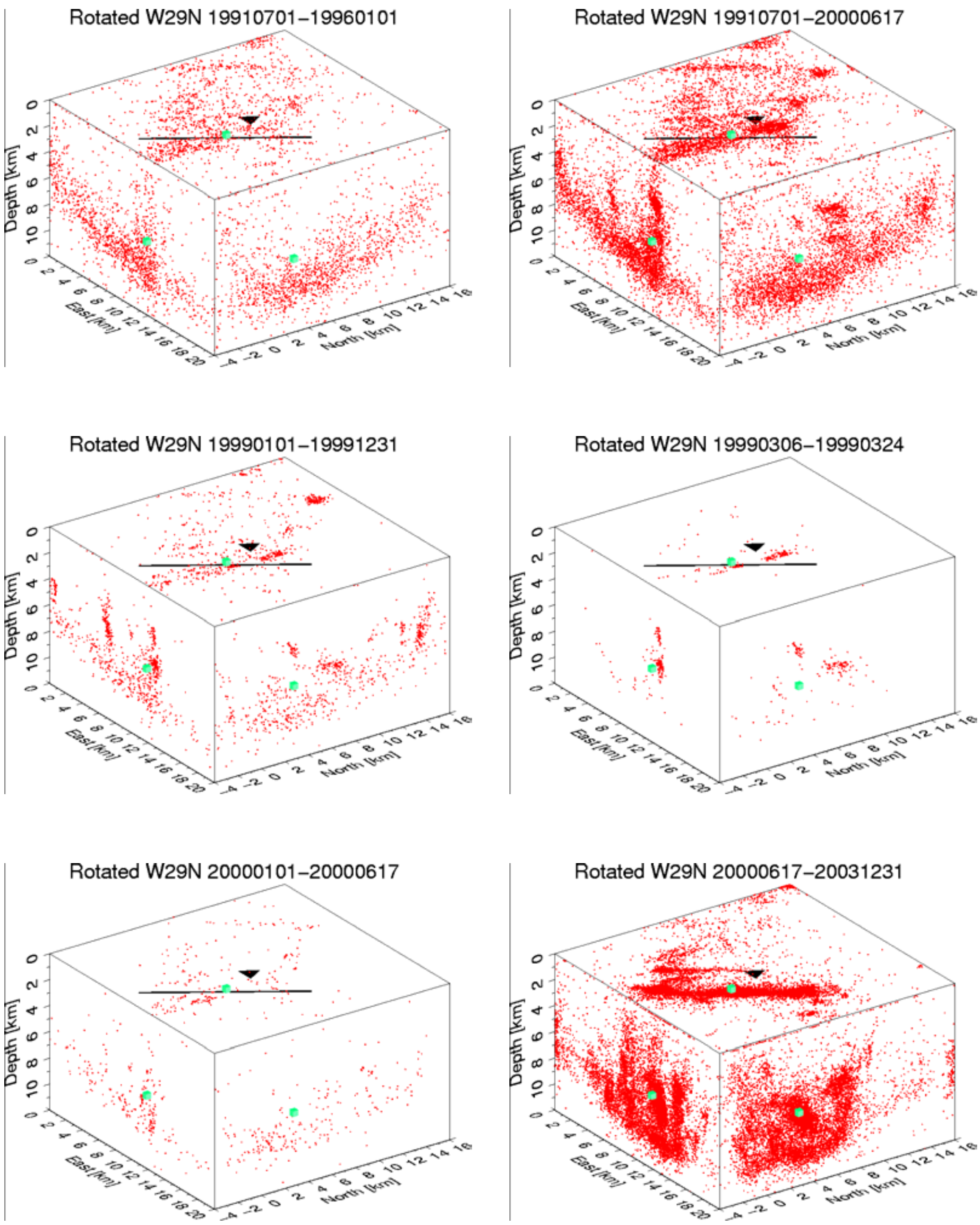


Figure 10. *In this figure as well as in the following boxes, microearthquake hypocenters are shown as dots projected onto three sides of the boxes. Here the studied 3-D boxes are oriented along the dilavolume, 29° west of north. The hypocenter (green dot) and the fault of the 17 June shock (line) is also marked as well as SAU, the close by seismic station. The two figures at the top show how the microseismic activity has elevated closer to the surface by time. The two figures in the second row show an epiodic shallowing of activity above the dilavolume. The figures in the bottom row show orientation of activity towards the fault plane, possibly in the left figure, but very clearly in the right figure, i.e. after the 17 June earthquake, where the dilavolume has disappeared. There is a westward movement of the aftershocks from the southern end of the fault.*

Seismicity evolution towards the June 17 earthquake in 3-D along the becoming fault (Figure 11).

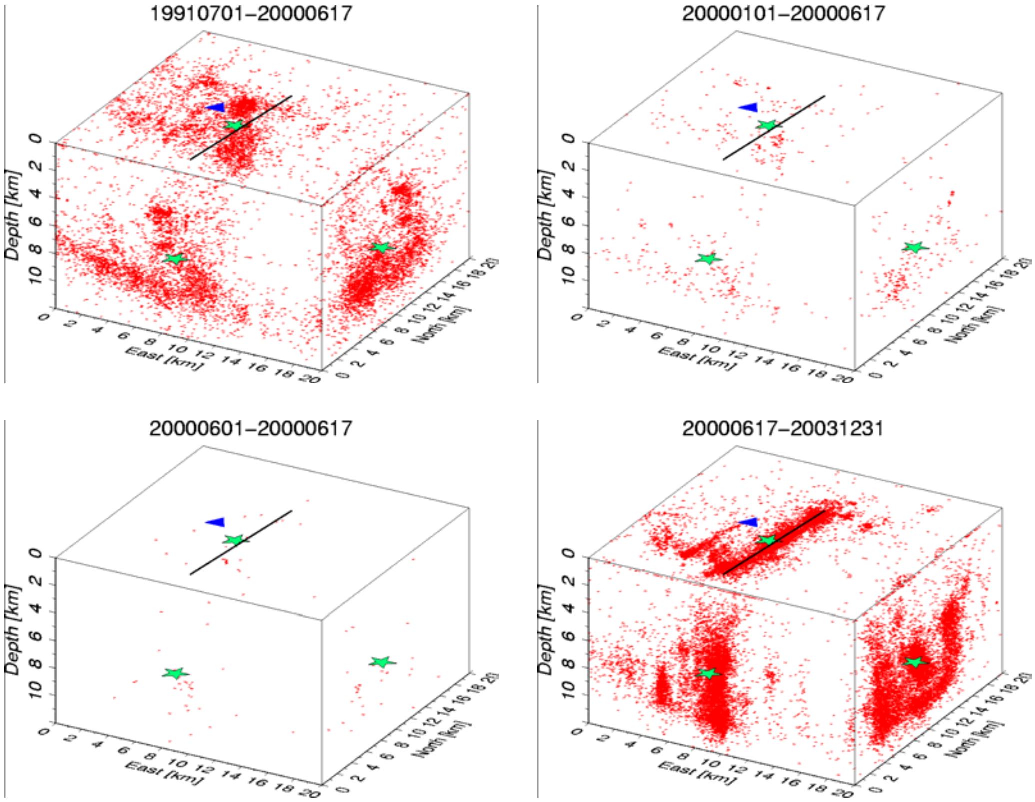


Figure 11. *Looking along the June 17 fault at seimicity changes from pre-earthquake towards post-earthquake situation. Clear orientation towards the fault direction is seen during the last 17 days before the earthquake. After the earthquake the seismicity is oriented along the fault and the W29°N dilavolume has disappeared.*

A close view of the microearthquake distribution in a 2 km thick slice around the June 17 fault (Figure 12).

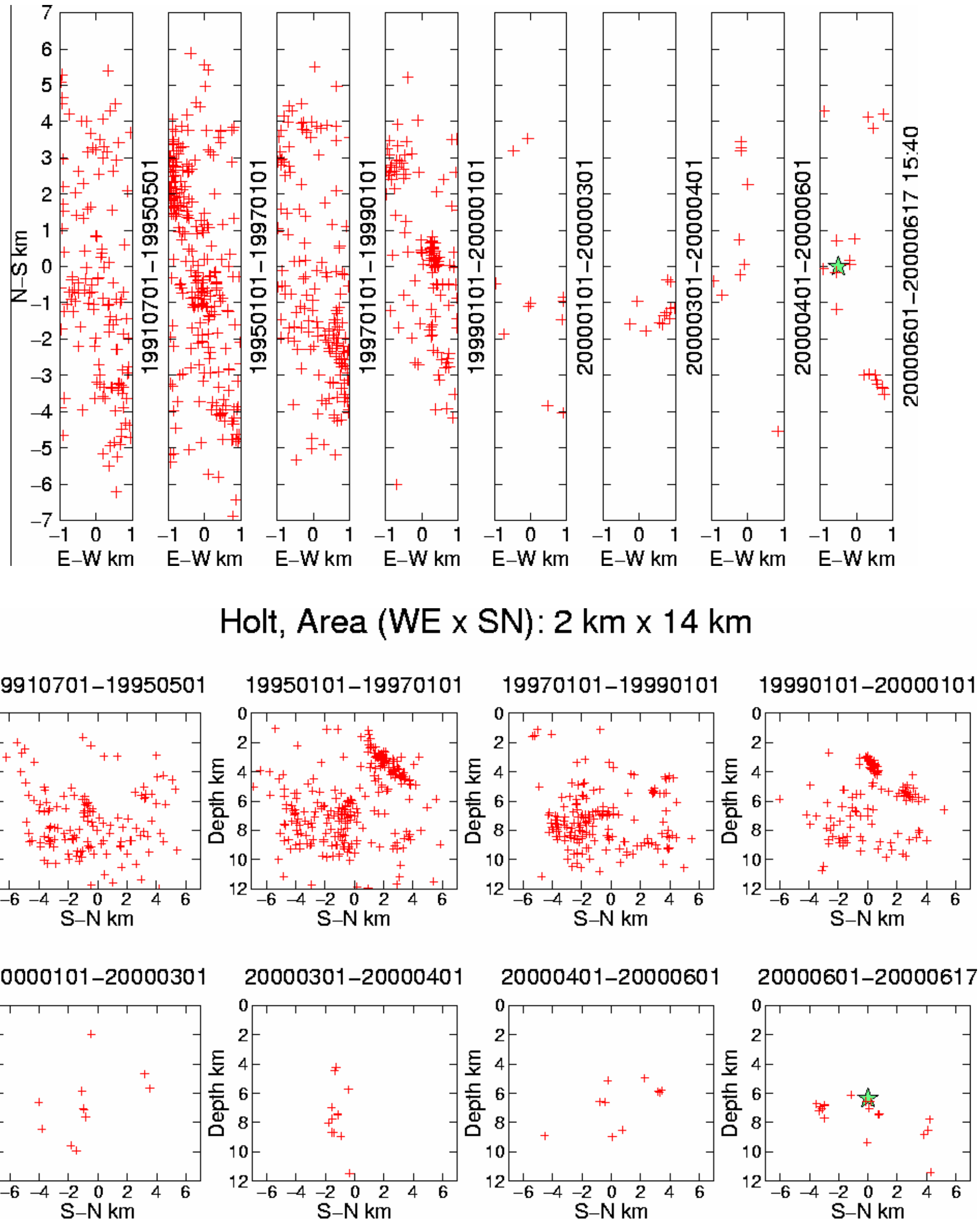


Figure 12. *A close view at the microearthquake distribution, within a kilometer, from the June 17 fault. In the upper image we look from above in the lower we look at the NS fault surface from the east to see evolution with time. To see the evolution from a spread activity to linear activity it is better to study Figures 9-11. In this figure we see better the process just before the earthquake, when some clustering towards the fault has taken place. The upper, farthest west image, shows the north and the south end of the fault, which has started to move. The earthquakes near the asperity started just before the earthquakes and started in the western part of the asperity, 1-2 km west of the fault, i.e at the June 17 hypocenter. In the lower image, the cross-section shows that there was a quiesence in the upper part of the fault some months before the earthquake, however the lower part delivered earthquakes smaller than 1. The lower part kept moving, probably shear movement, while the upper part was stiff, increasing in shear stress until it ruptured.*

Changes in directivity of sources and directions of horizontal compressions of individual microearthquakes (Figure 13).

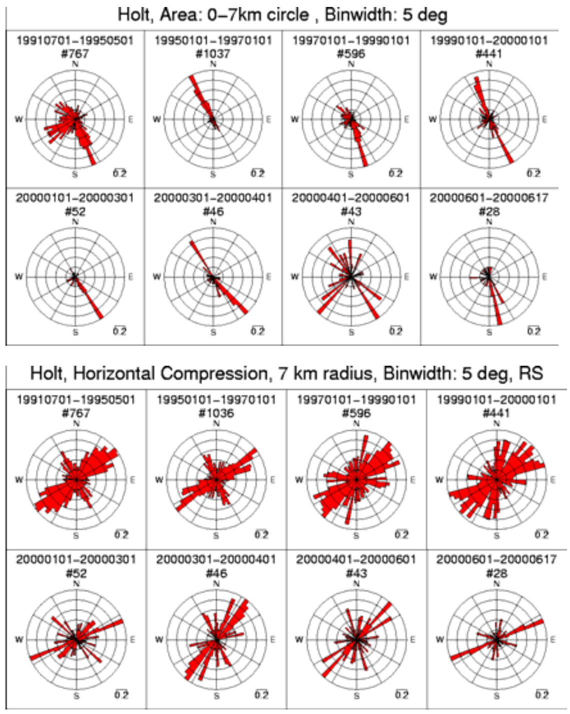


Figure 13. *The upper image is a rose diagram expressing the frequency of directions of microearthquakes seen from the hypocenter of the becoming June 17 earthquake. The direction of the earthquakes in the last period is just barely closer to the fault direction than in the earlier periods. The same tendency is observed in the lower image for the horizontal compressions (hc) of individual microearthquakes. Horizontal compressions striking 65-70° east from north are most frequent. According to definition one of the fault planes of each earthquake is 45° from the hc. So this indicates that the most frequent directions of microearthquake faults is 20-25° east of north. This could possibly express en echelon cracks 20° oblique to NS strike- slip on the deeper part of the fault.*

An example of microseismicity migrating upwards in the crust (Figure 14).

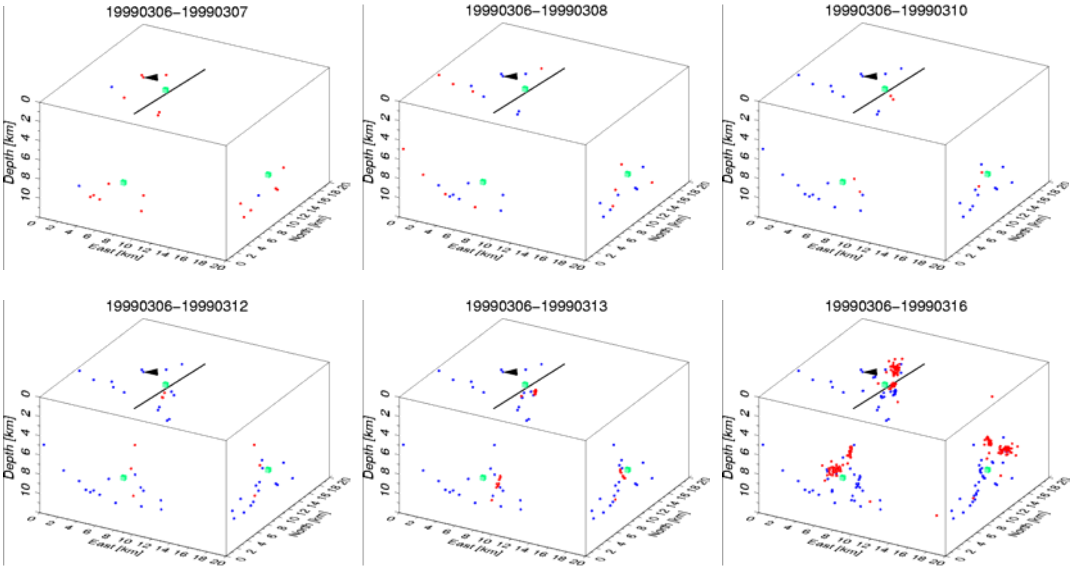


Figure 14. *During the period since 1991 we see only 3 swarms in this area which show bursts up into the shallower crust, besides the June 17 earthquake itself. In this figure we see an example of such a migration which takes 10 days, i.e. to migrate 5 km.*

Seismicity approaching the June 21 earthquake

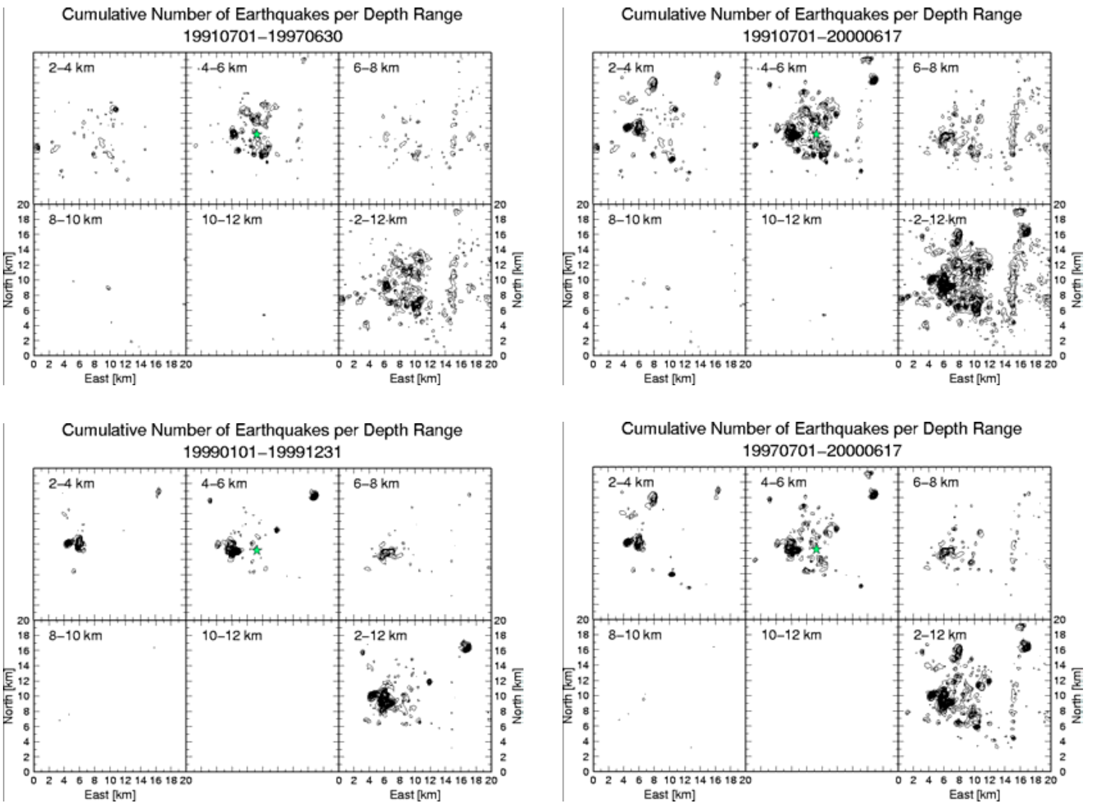


Figure 15. *Long-term change of the earthquake density in the epicentral area of the June 21 earthquake at various depths. The point zero in this and the following figures is several kilometers to the SW of the hypocenter, i.e. at 63.89º N and 20.90º W.*

The preparatory period of the June 21 earthquake goes from spread activity towards clustering with time, looking at the period as a whole (Figure 15). It clusters by time at shallower depth and it clusters geographycally a few kilometers to the west of the northern segment of the 21 June fault (Figure 17). This needs to be studied better quantitatively. The difference between the distributed activity before the large earthquakes and the linear activity after them is striking, comparing Figures 15, 16 and 17.

During the short period between the two large earthquakes the activity has gone east again compared to the 1999 activity and is linearely clusterd around the becoming June 21 fault (Figure 15 and Figure 16).

A general upper boundary of the activity is at 3 km, however seismic activity goes still shallower at 63.95ºN during 1999, and especially after a strong swarm that started late September 1999 at depth 7-7.5 km, rising up to 3 km at 63.98ºN and 20.78ºW.

As a part of the clustering towards the June 21 earthquake the fault of the historical earthquake on Skeið which is seen in microearthquake data for the first 7 years, especially between 6 and 8 km, disappears completely from the data after 1998 (Figure 15 upper and lower left), possibly related to pressure release by fluid transfer into the area that had swarm activity near the June 21 fault in 1998 and 1999.

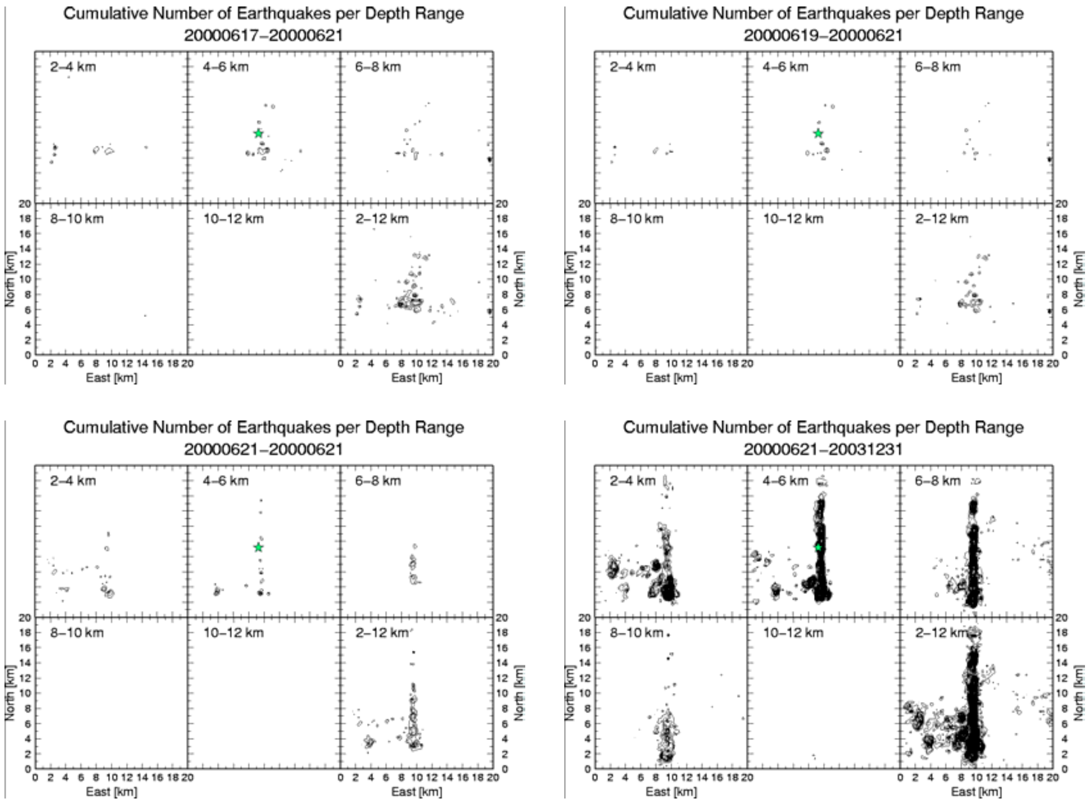


Figure 16. The earthquake distribution after the activation of the area by the June 21 earthquake. The upper two images show a NS line arrangement on the becoming fault, very clearly during the last days before the earthquake. The volume distribution (seen in Figure 15) has disappeared. This clustered and intensive activity is what was used for the prediction of the June 21 earthquake. The lower two images show the seismicity after the June 21 earthquake and some westward migration.

Cross-sections showing clusterings before and after the June 21 earthquake (Figure 17).

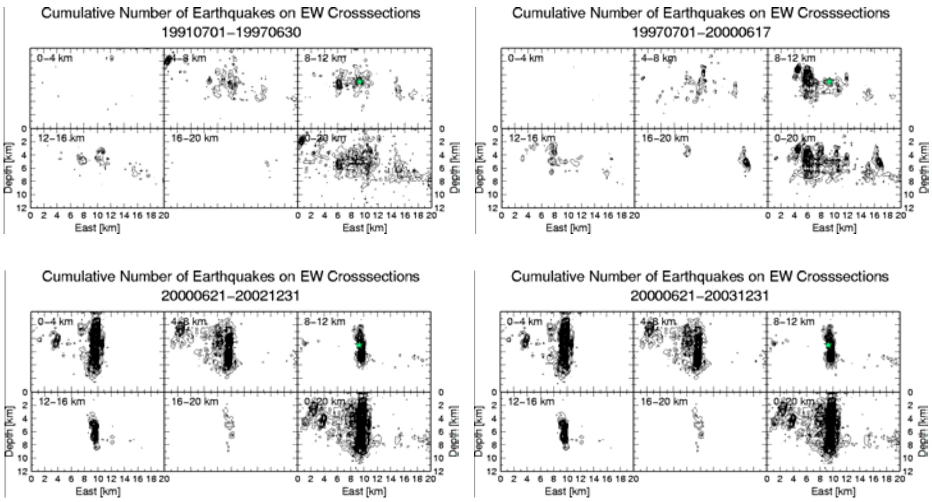


Figure 17. Cross-sections showing long-term EW clustering. The figure shows EW/depth distribution along 4 km wide and 20 km wide EW slices. The two upper images are taken before the activity started on June 17, the two lower show distribution of microseismicity after the June 21 earthquake.

Summary of premonitory seismic observations in the hypocenter area of the June 17 earthquake

In this area the everyday microseismic activity is located around 8 km depth in the crust, evenly distributed in time and space (Stefánsson et al. 1993). This everyday activity of small earthquakes is, however, elevated up to around 6 km into a volume which strikes 29° west of north. This volume crosses the middle of the impending earthquake fault below the hypocenter. We call this the dilavolume. A few episodes of larger microearthquakes occur higher up in the crust, above both end segments of the dilavolume. Only shortly before the main shock the microearthquakes start to arrange along the impending fault plane. It appears that there is a clustering process for a couple of years in the seismicity, from spread activity towards more concentrated activity or clusters. This has to be studied more quantitatively.

A well defined boundary is observed at 3 km depth above the NW segment of the dilavolume, high number of earthquakes just below the boundary and just a few above. This boundary has a diameter of around 1.5 km.

The dilavolume could be a deep signature of a 300.000 year old fault which has been rotated towards a direction approaching to be perpendicular to horizontal compression axis, arround 50° east of north. Therefore it is not favourable for being released in a large earthquake crossing the zone. However, it had to be released and it preferred a fault which had a more favourable direction to the stresses, i.e. in a right-lateral fault striking 30-40° NW of the horizontal compression, i.e. on a fault 10-20° east of north. However, it can only break upward through the crust in crust-through going earthquakes until it is rotated approximately 10-20° to the west of north. Then it seeks a rupture 10-20° to the east, i.e. 30-40º from the maximum horizontal compression.

Generally the larger earthquake swarms occur on vertical faults higher up in the crust and of course the large crust-through earthquakes. This idea has been opposed by the argument that it is unlikely that fluids would seek their way through the crust perpendicular to the highest stress, even if you have an old damage zone as gauges. This is of course a valid argument. However, local stress perturbations and local heteorogeneities can make this possible at some places. Here the asperity in the central part of the fault helps. The asperity does not yield complying with the general stress field as does its surroundings, which equals to that it exerts locally an „opposite“ stress field, which would favour upward fluid flow above the dilavolume.

Long-term plate movement, left laterally, shearing and opening a 10-20 km broad EW zone is responsible for stress build-up in the area, together with locally high pore pressures, created by fluids released from the ductile material below the brittle crust. It is local because each earthquake in the past released these fluid pressures locally and their build-up time could be hundreds of years for each place. Elevation of the pore pressures up into the brittle crust and the damage zone of the earthquake by time creates the conditions for local stress build-up and strike-slip motion across the damage zone.

The earthquake had a strong asperity in the center of the fault plane. This is mainly shown in the aftershock activity which puts its center to around 6 km depth and the diameter to 3 km (Vogfjörð 2004). Its existence explains also some patterns in the pre-earthquake activity.

There are indications in the microearthquakes that slow motion across the fault plane of the NS right-lateral fault started at depth at least 3 weeks before the earthquake. This motion increased the stress on the asperity until it nucleated in the western part of the 3 km asperity.

Summary of observations of premonitory seismicity in the hypo-center area of the June 21 earthquake

The activity has a time pattern from spread acticity towards a more linear activity approaching the earthquake similar to the June 17 earthquake. However, the spread activity is more evenly spread around the fault, not like a zone striking to it as in the June 17 earthquake. The reason might be that it does not have an asperity in the middle to modify locally the stress conditions in the same way as in the June 17 event.

It is suggested that the June 21 earthquake was in a stress shadow of the fault area of the first earthquake, which thus was its asperity.

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