VEÐURSTOFA ÍSLANDS

Report

Ragnar Stefánsson
Gunnar B. Guðmundsson
Páll Halldórsson

The two large earthquakes in the South Iceland seismic zone on June 17 and 21, 2000

VÍ-G00010-JA04
Reykjavík
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1 Introduction

Two large earthquakes occurred on June 17 and 21, 2000, after 88 years of relative seismic quiescence in the central part of the South Iceland seismic zone (SISZ). SISZ is a 70 km EW transform zone in SW Iceland (Figure 1).

Earthquakes which have been estimated to reach magnitudes up to 7.1 (Ms) have frequently through the history caused enormous destruction in this area. The latest sequence of large earthquakes releasing a long-term build-up of strain in the area took place in 1896 and 1912, leaving the area seismically relatively inactive until June this year. The historical earthquakes in this zone of EW left-lateral shearing motion were in most cases released by right-lateral motion on NS faults that are arranged side by side along the EW transform zone. Displacements on NS faults do not repeat themselves in consecutive earthquake sequences. Faults due to the historical earthquakes are found in less than 5 km distance from each other [5, 6, 14].

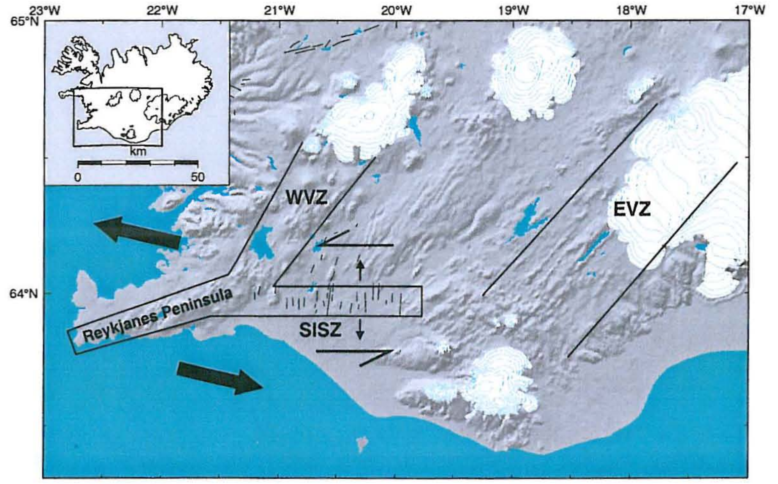

Figure 1. *The figure indicates the main rift zones of SW Iceland, the western volcanic zone (WVZ) and the eastern volcanic zone (EVZ). The South Iceland seismic zone (SISZ) in the sense of a 10 km wide zone and its prolongation in the Reykjanes peninsula are shown by rectangular boxes. The direction of the relative plate motion according to the NUVEL-1A plate model is shown by large arrows. The transversal plate motion and the extension across the SISZ are shown by lighter arrows.*

According to the NUVEL 1A plate model [2] the direction of the divergent motion across the plate boundary of the American and the European plates in Iceland is N103°E at a velocity of 1.86 cm/year. If all this motion is taken up by the SISZ, which lies almost due EW, the relative left-lateral motion across SISZ would be approximately 18 mm/year and an opening component across the zone could be around 4 mm/year.

Assuming a 15 km thick elastic/brittle crust, the strain build-up moment in shearing motion across the zone has been estimated to be 10^{20} Nm, during a period of 140 years, which from historical seismicity seems to be the time interval between successive total ripping throughout the zone. This is the same value as the moment estimated from historical earthquakes during the same 140 year periods. Earthquakes in the eastern part of the zone are larger than in the western part [8, 13]. Later it has been found that 10 km is a more adequate value for the depth of the seismogenic zone in this area which would lower the moment based on 2 cm shearing across the plates to $0.7 * 10^{20}$ Nm [14, 15].

2 The large earthquake on June 17

The June 17 earthquake had the following, preliminary, seismological parameters: According to the Icelandic Meteorological Office (IMO) the origin time was 15:40:40.94 GMT, the hypocenter 63.97°N and 20.37°W, and the depth 6.3 km. Preliminary modelling using volumetric strainmeters in the area gave the moment $6.1 * 10^{18}$ Nm, corresponding to moment magnitude of 6.4, noting however that the single fault model used did not comply with all the data, and thus indicating a more complicated model than a single strike-slip fault [K. Ágústsson, pers. communication, 2000]. The preliminary magnitudes by the National Earthquake Information Center (NEIC) in USA were Mb=5.7 and Ms=6.6 [10], and USGS Rapid Moment Tensor Solution gives a moment of $6.0 * 10^{18}$ Nm, assuming best fitting double-couple solution as a model, and moment magnitude of 6.5 [10]. (There are different relations used to relate moments and moment magnitudes. The moments are the basic things).

According to IMO seismic database the aftershocks of the earthquake indicate a 16 km long fault, striking around N9°E and dipping 86° towards east, down to 10 km depth. The aftershocks deviate towards west at the southern end of an otherwise straight fault. According to the National Energy Authority surface fissures are found in a 24 km NS elongated area, coinciding in large with the aftershock area, and indicating a right-lateral motion [11]. The model for the earthquake mechanism obtained this way agrees very well with the USGS Rapid Moment Tensor Solution. Automatic fault plane solutions of the local SIL system in Iceland do not give well constrained solutions, however not contradicting the above solution.

Assuming the length of the fault plane to be 20 km and the width 9 km the moment above indicates that the earthquake involved approximately 0.9 m right-lateral slip on a NS plane.

Besides aftershock activity at a few kilometers distance from the fault, swarm activity took place at various sites towards west along the SISZ and the Reykjanes peninsula, only minutes after the main shock. An earthquake of magnitude 4.5 (ML and Mb) occurred 85 km to the west of the NS elongated fault, 5 minutes after the main shock, causing rockfall there. An earthquake swarm also started at 50 km distance to the north, migrating further north during the next days (Figure 2). According to continuous GPS monitoring, a GPS station to the south of the plate boundary on the Reykjanes peninsula moved two centimeters to east and one centimeter to south immediately, i.e. during the first 24 hours after the earthquake, compared to a GPS site in Reykjavík north of the plate boundary [Þóra Árnadóttir, pers. communication, 2000, and [9]]. The aftershocks and the continuous GPS measurements reflect fast redistributions of strains following the earthquake in an area up to 100 km away from it.

3 The second large earthquake occurring $3\frac{1}{2}$ day later

The June 21 earthquake had the following, preliminary, seismological parameters: According to IMO the origin time was 00:51:46.95, the hypocenter 63.98°N and 20.71°W, and the depth 5.1 km. The preliminary magnitudes by NEIC were Mb=6.1 and Ms=6.6 [10], and the USGS Rapid Moment Tensor Solution gives a moment of $5.2 * 10^{18}$ Nm, assuming best fitting double-couple solution as a model, and moment magnitude of 6.4 [10]. As in the first earthquake modelling by the strainmeter data indicated a more complicated source model for the earthquake than routinely used in such calculations.

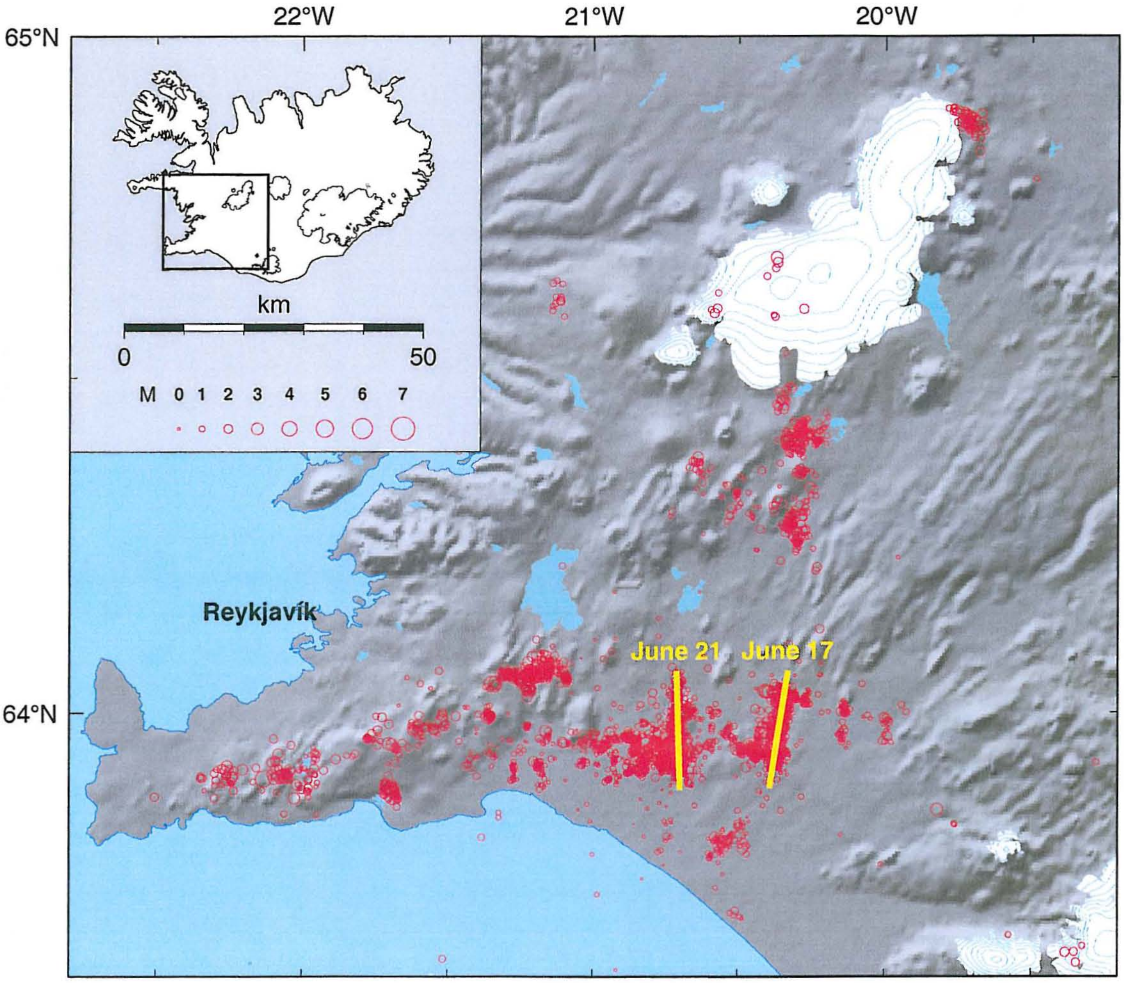

Figure 2. *The thick yellow lines show the fault planes of the two large earthquakes on June 17 and 21. The areas where aftershocks were activated are indicated with red circles.*

The aftershocks of the earthquake indicate a vertical 18 km long fault striking two degrees west of north reaching down to 8 km depth according to IMO. Surface fissures are found on a 23 km NS elongated area, coinciding in large with the aftershock area, and indicating right-lateral motion [11]. From fault area and moment, and by assuming 20 km fault length and 7 km fault width, a 1.1 m right-lateral slip on a NS fault is indicated similar to the first earthquake.

4 The effects of the earthquakes

The earthquakes were felt in Iceland within 200 km distance from the epicenter. They caused no serious injuries for people. The highest measured maximum acceleration was 84% of g in the June 21 earthquake according to the Earthquake Engineering Research Centre, University of Iceland [3]. Maximum acceleration in the June 17 earthquake at the village Hella was 47% of g [3]. No houses were collapsed but several houses are, however, so badly cracked that they have to be abandoned. Several incidents were reported of broken pipelines. Open surface fissures were observed with an opening of around a meter at various places along the faults. Hydrothermal activity increased in a large area around the faults. Most spectacular in this connection is that Geysir (the great geyser) started to gush water and steam frequently again after being more or less quiet for more than half a century. Changes of water level in boreholes were observed immediately after the earthquakes, agreeing very well with the observed mechanisms of the earthquakes [11].

5 Predictions for the earthquakes

A time dependent hazard assessment or long-term prediction was stated 15 years ago for the area, saying 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 end 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 to the west in the zone [4]. Later revisions of magnitudes and hazard assessments assume that the largest possible earthquake in this zone does not exceed magnitude 7.2 (Ms) [7, 13]. The time dependent hazard assessment based on this, just before the earthquakes, was that there was 98% probability of a magnitude 6 earthquake during the next 25 years and lower probability for a larger one.

On various grounds it was expected that the next SISZ earthquake would occur almost exactly where the June 17 earthquake occurred in reality. Most clearly this was stated in 1988 as follows: "... there are strong indications that the next large earthquake of size approaching 7 in this zone will take place near longitude 20.3°–20.4°W" [13]. This was based on lack of strain release in historical earthquakes since year 1700 in a narrow area [7, 13]. Such a gap was also indicated for a narrow area around 20.7°W although not as pronounced. Five years later it was pointed out that this coincided with a long-term concentration of microearthquake activity in the zone [14]. It was never stated clearly if the microearthquake activity was expressing aseismic strain release or if it was reflecting high stresses in preparation of a large earthquake, which however was assumed more likely. This question has now been answered by the nature. As there is a tendency in the seismic history for earthquake sequences to start east of the center of the zone and to trigger earthquakes further to the west it was also expected that the second earthquake would most probably occur very close to where the June 21 earthquake actually occurred. It was also expected on basis of historical intensitites and known earthquake faults that the fault plane of the earthquakes would be NS direction crossing the zone.

While it was thus assumed probable that the next large earthquake in the area would occur where the June 17 earthquake occurred, no clear precursory signals were recognized before it.

In hindsight it is possible to point to several signals that may be related to stress increase in the preparatory stage of the earthquake. The volcano Hekla 30–35 km east of the epicenter has been anomalously active lately, and having its latest eruption at the end of February 2000. Seismologists wondered why there was not a flurry of small earthquakes to the west of Hekla following the eruption as usually after earlier eruptions. An explanation may be locking of the zone before a large earthquake. Anomalous strain signals were recorded in May and June on borehole strainmeters at stations 3 km and 20 km from the fault of the first earthquake [9]. Continuous GPS observations that have recently started around the volcanic complex of Katla and Eyjafjallajökull, 50–100 km to the east of the epicenter, showed anomalous signal 10 days before the earthquake [9]. These signals cannot, on a physical basis so far, be related to the earthquake.

There was a rate of increase of shear-wave splitting time before the earthquake appropriate for a local magnitude of 5.6 (Mb) but it is noted that duration of the rise was far to short and data too limited for such a conclusion [S. Crampin, pers. communication, 2000].

The only premonitory change that can directly be related to the earthquake is that several microearthquakes (ML 0–1) lined up deep along the fault of the impending earthquake weeks and days before its occurrence. Microearthquakes are, however, usual in the area, so it is too early to say if these earthquakes could have been of a predictive value.

The second earthquake, i.e. the earthquake on June 21, was expected as a probable continuation of the first earthquake, and was prepared for. This was most clearly declared by information to the state and the local civil defence services 26 hours before it occurred. It was stated in that communication that the most likely location of a probably impending earthquake would be on a NS fault within 1 km of the NS fault line that was realized in the earthquake. A second possible location was also indicated on a fault 5 km farther to the west. It was stated that the earthquake would be of comparable size to the first one or smaller. No time was given for the event, but the advice was that preparations should be made for an earthquake that might occur anytime within short. The warning was based on studying microearthquake activity on these faults. In hindsight the most significant immediate precursor of the earthquake may have been a period of total quiescence within two to three hours before followed by small quakes on the fault $1\frac{1}{2}$ hour before the earthquake.

6 The significance of these events and future perspectives in the SISZ

The moment released in these two earthquakes is $1.1 * 10^{19}$ Nm. The moment built up and released during 140 year earthquake cycles period has been estimated as $0.7\text{–}1 * 10^{20}$ Nm, the higher value based on estimated size of historical earthquakes. Assuming that the historical earthquake magnitudes have been overestimated and only 100 years have elapsed of the 140 year period, the moment build-up before the earthquakes would have been $4.6 * 10^{19}$ Nm. This still means that only a fourth of the stored moment would have been released in the two earthquakes. It is probable that what is left over of the moment is mostly stored in the easternmost part of the SISZ, where the largest earthquakes are to be expected as the elastic/brittle crust is thickest there.

Although all such results are uncertain because of the nature of the data which they are based on, it is probable that more is left over of moment in the SISZ than has been released in these earthquakes. The only one of the historical earthquakes that has an instrumentally based magnitude is the 1912 earthquake in the eastern part of the zone, with magnitude 7 (Ms). That earthquake [1] and the largest earthquake of 1896 (estimated magnitude 6.9 (Ms)) had considerably stronger surface fissure expressions than the recent earthquakes.

The build-up of strain since around 1900 up to year 2000 has not been enough for releasing an earthquake in the easternmost part of the zone, i.e. in the magnitude 7 range. It is probable that it will be released within a few decades to cope with what has been left over of moment after the recent earthquakes and what will be built up during next decades.

The above reasoning is based on a simple model of build-up of potential moment assuming steady plate motion across a homogeneous SISZ, however, with changing thickness of seismogenic crust, i.e. increasing from west to east. In this case the release of strain energy in earthquake episodes along the zone would preferably start in the east, but proceed in smaller, triggered earthquakes towards west. Although this has some support in history, both history and the recent events show deviations from such a model. It has been proposed that strain build-up for earthquakes is not only due to general plate motion, but has also a local build-up of stress, possibly caused by intrusion of fluids near the bottom of the seismogenic crust [12, 13]. Considering this suggests that it is still possible in a near future that an earthquake of comparable size to the recent earthquakes will occur to the west of these in the SISZ, either before a magnitude 7 earthquake in the eastern part or following such an earthquake as a triggered shock.

The multidisciplinary earthquake data that have been collected for the two recent earthquakes in the SISZ, seismic and intensity data, deformation data and hydrological data are of enormous significance for understanding and for modelling earthquake release processes in the SISZ. The study of historical seismicity as well as of earthquake faults will be revised in the light of the new data. The data collected are also of vast significance for approaching more complete and secure predictions for earthquakes in this zone.

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