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Surface effects of triggered fault slip on Reykjanes Peninsula, SW Iceland

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Abstract

Three large earthquakes (M_w>4.5) were triggered within 5 min, 85 km west of a M_w 6.5 earthquake in the South Iceland Seismic Zone (SISZ). We report on surface effects of these triggered earthquakes, which include fresh rupture, widespread rockfall, disrupted rockslides and block slides. Field data confirm that the earthquakes occurred along N-striking right-lateral strike-slip faults. Field data also support the conclusion from modeling of InSAR data that deformation from the second triggered event was more significant than for the other two. A major hydrological effect was the draining of water through an open fissure on a lake bed, lowering the lake level by greater than 4 m. Field relationships suggest that a component of aseismic slip could have been facilitated by water draining into the fault zone.

Keywords: Faults; Field data; Iceland; Triggered earthquakes; Aseismic slip

1. Introduction

On June 17, 2000 at 15:40:41 GMT, the South Iceland Seismic Zone (SISZ) was shaken by a 6.5 M_w event (Fig. 1, inset A). Within seconds, swarms of smaller earthquakes were triggered westward from the main shock epicenter over 100 km of the plate boundary. Three of the largest rocked the central part of Reykjanes Peninsula (Fig. 1). These three events were spaced approximately 10 km apart and occurred within 5 min of one another. During the following year, fieldwork was conducted in a 420 km^2 area encompassing the epicenters of those earthquakes to examine the surface effects of each in order to better constrain fault characteristics.

2. Geologic setting

The Reykjanes Peninsula is an oblique on-shore segment of the Mid-Atlantic ridge plate boundary (Fig. 1, inset A). Due to this geometry, it exhibits

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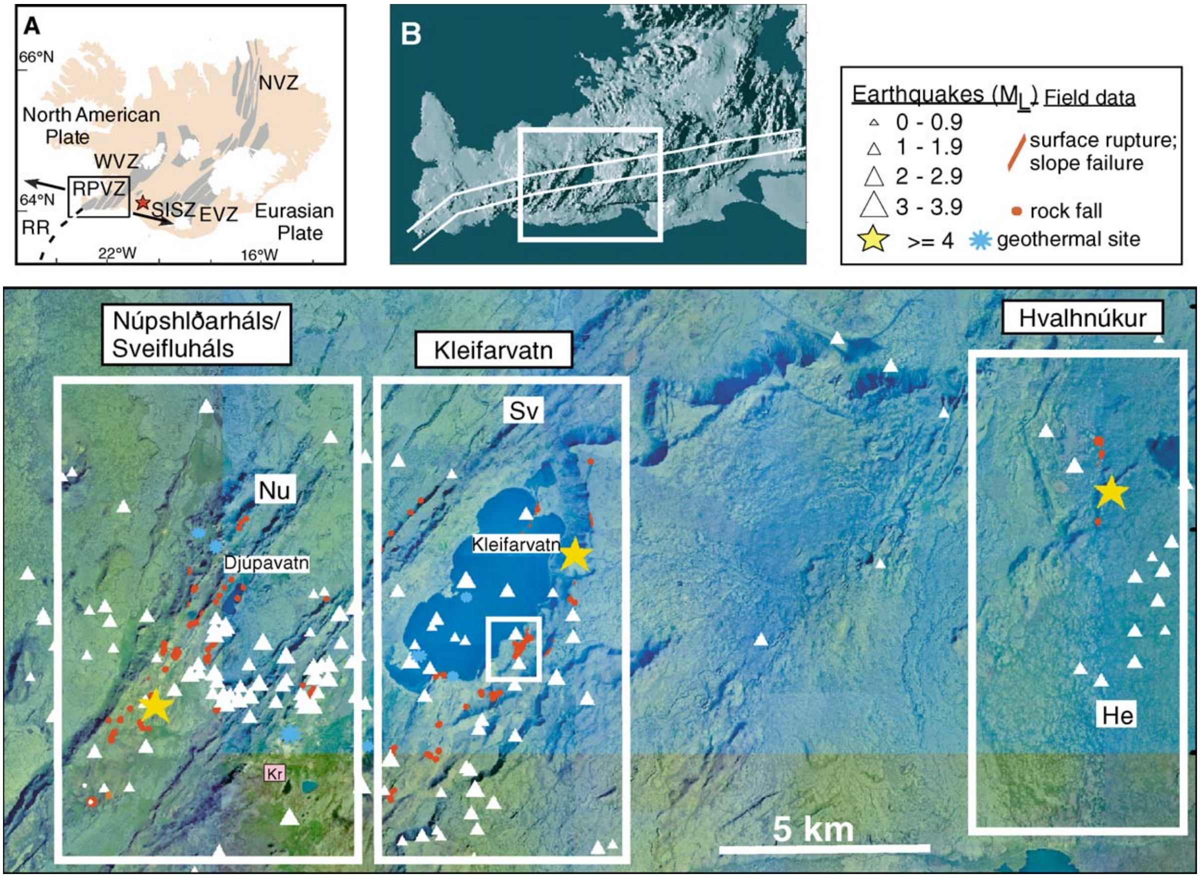

Fig. 1. The study area. White triangles: earthquakes that occurred in the 12-h period following the SISZ event; yellow stars: large triggered earthquakes. Red: location of mapped surface effects. Pink square: location of the Krísuvík SIL station. Blue stars: location of geothermal springs. Nu = Núpshliðarháls ridge. Sv = Sveifluháls ridge. He = Heiðin Há lava shield. Study areas enclosed in white boxes 1–3. Small white box in 2 shows area in Fig. 3. Color differences in the air photo are due to image processing and not an artefact of printing. Inset A: the plate boundary in Iceland (Einarsson and Saemundsson, 1992). RPVZ = Reykjanes Peninsula Volcanic Zone, SISZ = South Iceland Seismic Zone, WVZ = Western Volcanic Zone, EVZ = Eastern Volcanic Zone, NVZ = Northern Volcanic Zone. Arrows: direction of plate motion (DeMets et al., 1994). Red star: approximate location of the SISZ earthquake. Inset B: Reykjanes Peninsula, white box shows study area. White lines show the approximate location of the plate boundary zone.

characteristics of both divergent and transform-type plate boundaries. Northeast-striking normal faults and fissures accommodate extension and parallel the trend of eruptive fissures (Saemundsson, 1979; Clifton, 2000). Geophysical data have determined that the currently active plate boundary is a zone approximately 2 to 5 km wide with an average strike of 076° (Fig. 1B). Most of the seismicity on the peninsula occurs within this zone and has predominantly strike-slip focal mechanisms (Einarsson, 1991). GPS data gathered between 1986 and 2001 indicate that left lateral shear is being accommodated in this zone by ductile deformation below a locking depth of 6 km (Sturkell et al., 1994; Hreinsdóttir et al., 2001). Closer to the surface, left lateral shear is accommodated along N to NNE-striking right-lateral strike-slip faults in a style of deformation referred to as bookshelf faulting (Sigmundsson et al., 1995). The study area has high background seismicity and at least five earthquakes >M5 have occurred during the last century (Halldórsson and Stefánsson, 1987). Focal mechanisms are predominantly right-lateral strike slip (Einarsson, 1991). Earthquakes recorded during the last 12 years by the South Iceland Lowland (SIL) seismic network

(Stefánsson et al., 1993) indicate that the base of the seismogenic zone is between 8 and 11 km and most seismicity occurs at depths of 1 to 8 km. West to northwest trending structures localize geothermal activity in the neo-volcanic zone (Ívarsson, 1998). Geothermal sites in this study area lie along a WNW–ESE trend extending from the west side of Núpshlíðarháls to the southern end of Kleifarvatn. Optical leveling has been conducted periodically around the lake since 1985 (Tryggvason and Ólafsson, 1995), and survey results during the period 1985 to 1994 indicate that the lake either subsided towards the northwest or uplifted towards southeast at a rate of 0.1 cm/year.

The topography of the study area (Fig. 1, inset B) is dominated by undulating, volcanic ridges and rounded, flat-topped table mountains that result from Pleistocene subglacial fissure and central vent eruptions, respectively. Local relief is approximately 300 m. Post-glacial lava flows surround the ridges. The Heiðin Há lava shield forms a broad upland in the eastern part of the area. Lake Kleifarvatn is bounded partly by constructional volcanic features and partly by faults. Lake bathymetry consists of a series of en echelon shoals and deeps, with a maximum depth of 97 m. With a small catchment area and no outflow at the surface, the lake is sensitive to climate fluctuations. Regular, periodic lake level measurements began in 1930. Between 1930 and 1954, measurements were made between one and four times per year. From 1954 to 1963, measurements were taken twice a month, and continuous monitoring has been conducted by the Hydrological Service of the National Energy Authority since 1964.

3. Earthquake sequence

The first triggered earthquake, $M_w \sim 5$, occurred along the Hvalhnúkur fault 26 s after the SISZ event. The epicenter was near the northern end of the 6-km-long fault trace, at a depth of 8.9 ± 1.3 km (Fig. 1, box 3). The mechanism is not tightly constrained by the seismic data, but the best solutions cluster around a near-vertical, N-striking plane with right-lateral motion. The fault was the site of an $M = 5.4$ earthquake in 1968 (Icelandic Meteorological Office, 1968) and possibly an $M = 6.2$ event in 1929 (Ottósson 1980).

The second earthquake occurred 4 s later, 12 km to the west, along a previously unmapped fault near the eastern shore of Lake Kleifarvatn (Fig. 1, box 2). Its epicenter was shallow, 4 ± 2 km. Horizontal location accuracy is estimated within 2 km in latitude and 1 km in longitude. Many seismic stations were saturated by the two triggered events (Fig. 2). Magnitude, mechanism and a more precise location could not be determined for the event because its waveforms interfered with those of the first triggered event and the main shock. Timing suggests that these earthquakes were triggered dynamically by shear waves from the SISZ event traveling at a velocity of 2.5 km/s (Fig. 2).

An earthquake of $M_w = 4.8$ occurred 10 km to the west 4.21 min after the Kleifarvatn event (Fig. 1, box 1), in an area that had experienced destructive earthquakes in 1879 and 1905 (Gísladóttir, 1998). Its depth was 3.0 ± 0.7 km, and horizontal location accuracy is ± 500 m. The best-fitting mechanism is either right-lateral strike slip on a near-vertical plane striking just east of north, or left-lateral strike slip on a north-dipping, WNW-striking plane. A small thrust component may also be present. Because of its timing, this last earthquake was felt as a distinct event in the town of Hafnarfjörður 10 km to the north, and in Reykjavik, 25 km to the northeast.

4. Surface effects

4.1. Hvalhnúkur earthquake

The Hvalhnúkur fault strikes 010° and consists of 030°-trending, left-stepping, en-echelon open fractures separated by large pressure ridges composed of chaotic piles of meter-scale blocks of basalt (Erlendsson and Einarsson, 1996). Surface effects from the June 17th earthquake were minor and confined to within 1 km north and south of the epicenter (Fig. 1, box 3). Within grass-filled open fractures, gashes tens of centimeters in length exposed fresh soil and plant roots. The pressure ridges were loosened. Torn moss, rotated slabs of basalt and fallen blocks exposing unweathered surfaces all provide evidence that movement was recent, though exact timing is impossible to determine. While most of the observed effects could have resulted from shaking on a regional scale, their restricted distribution to within 1

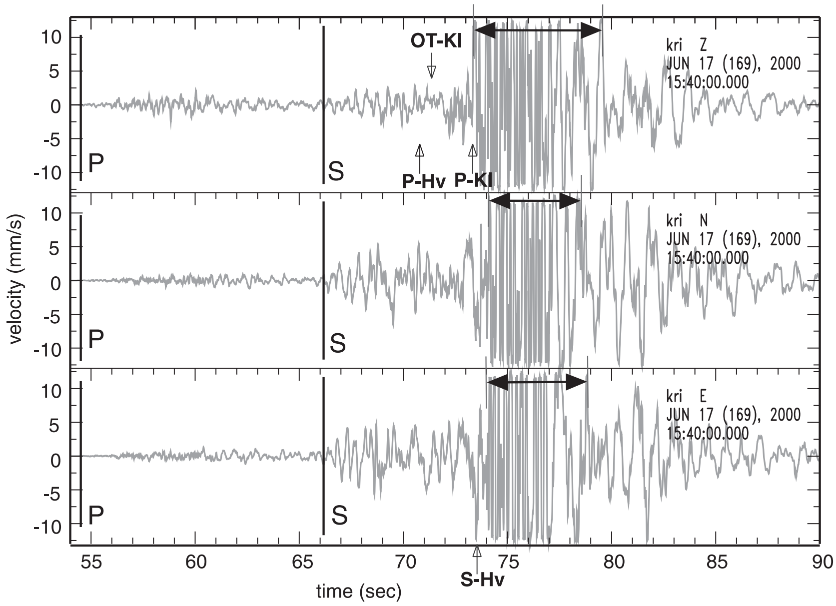

Fig. 2. Three component seismograms from the Krísuvík SIL station, showing P- and S-wave arrivals from the SISZ earthquake. Expected arrivals of the P- and S-waves from the Hvalhnúkur event are indicated (P-Hv and S-Hv). Origin time and P-wave arrival from the Kleifarvatn event are also shown (OT-Kl and P-Kl). Horizontal arrows show the times the different components were saturated. The vertical component clips after the arrival of the P-Kl; the horizontal components clip after the arrival of S-Hv.

km of the epicenter suggests that they were caused by fault movements directly below the fault trace. These field data support the determination from the seismic records that the fault area that experienced slip had a radius of ~ 1 km.

4.2. Kleifarvatn earthquake

Much more severe surface effects occurred along the strike of a fault zone trending 020°, bounding the eastern shore of Lake Kleifarvatn and continuing to the southwest (Fig. 1, box 2). An aa lava at the lakeshore was cut by a 200-m segment of left-stepping, northeast trending en echelon opening mode fractures (Fig. 3). The exact amount of opening is difficult to determine because jagged pieces of lava and torn clumps of soil and moss have fallen into the fractures, but appears to be on the order of tens of centimeters (Fig. 3A,B). Small pressure ridges of shattered lava formed between the fractures. This type of deformation is consistent with strike-slip faulting. Similar but much larger structures have been mapped in the SISZ (e.g. Bjarnason et al., 1993; Bergerat et al., 2003) as the result of earthquakes around $M = 7$.

An adjacent low (60-m relief) hill experienced fracturing on its southwest facing slope. Thin slabs of hyaloclastite were uplifted, and some opening resulted from gravity sliding. At the crest of the slope, a disrupted rockslide (sensu Keefer, 1984) was initiated along a line extending 87 m to the northeast (green lines in Fig. 3). Smaller slides occurred on the west-facing slope. On the flat hilltop, a chaotic network of fractures cut through both lava and soil (yellow points on the map in Fig. 3). Large boulders were rotated (Fig. 3C), lifted from the soil and some were shattered by collisions (Fig. 3D). The intensity of the disruption decreased to the north. The intensity and occurrence of the rockfall also decreased to the southwest and was found mainly on ridge tops and in zones of high joint density along the fault trace. Disturbed segments up to 325 m long were observed to the northeast, on the crest of the steep scarp that bounds Kleifarvatn for much of its length. Rockfall, disrupted rockslides and small-scale block slides were

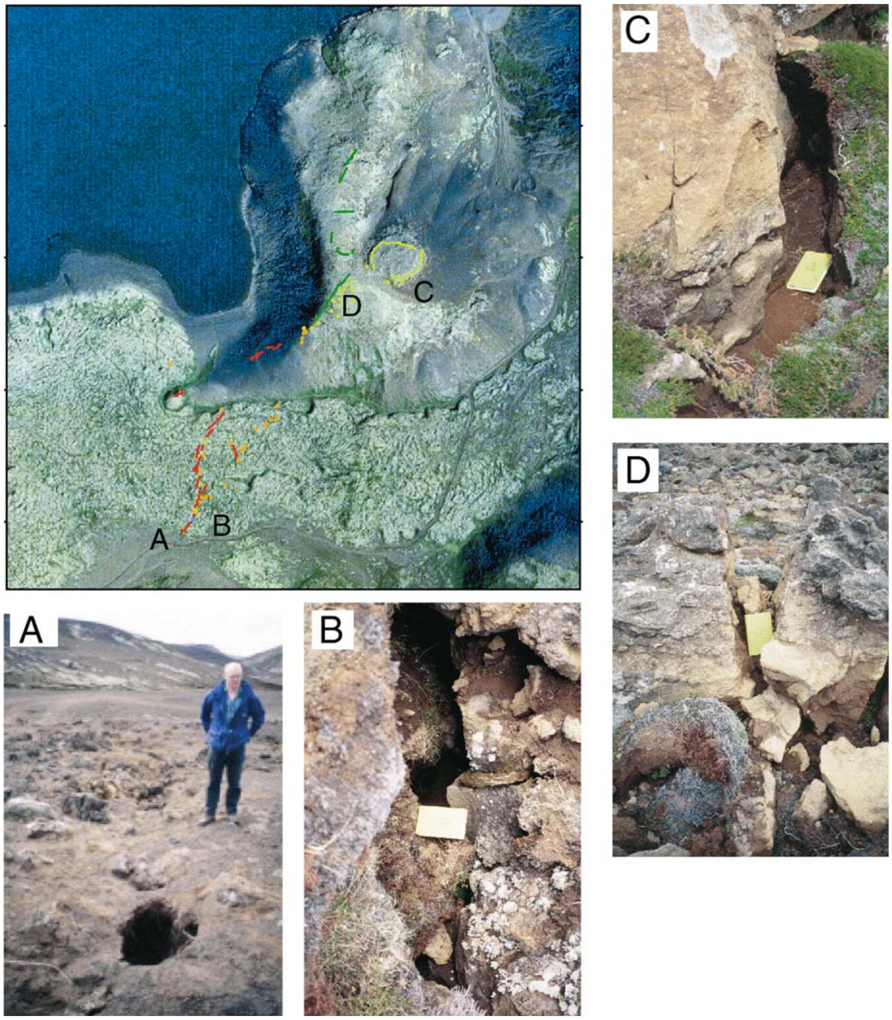

Fig. 3. 1999 Air photo showing area which experienced the greatest effects from the Kleifarvatn earthquake (small white box in Fig. 1). Red: surface rupture; orange: pressure ridges; green: origin of rock slides; yellow: chaotic disruption of surface. (A) and (B) fresh rupture; (C) soil torn from outcrop; (D) boulder shattered by shaking. (Air photo by Loftmyndir ehf., Reykjavik.)

most likely generated by shaking, as neither offset nor open fractures were observed. A series of fractures did, however, open up at the north end of Kleifarvatn, causing the most noticeable and unexpected effect of this series of earthquakes, the draining of the lake itself (Fig. 4). Two large fractures, 58 and 47 m in length visible above water level, striking 023° and 028°, respectively, with maximum surface width of 30 cm opened under the water surface along a northeast trending bathymetric high (Fig. 4B,C). Once the water level dropped sufficiently, water could be seen and heard flowing down the fractures. The rate of outflow below the surface of Kleifarvatn has been around 1.0 m^3/s on average since continuous recording of the water level started in 1964. Between June and August 2000 the outflow was 2.3 m^3/s and approximately 1.5 m^3/s during the subsequent 16 months. The water level dropped over 4 m since June 2000 but has been fairly stable since December 2001 (Fig. 4A). The lake has lost approximately 12% of its volume, and the gauge that measures the water

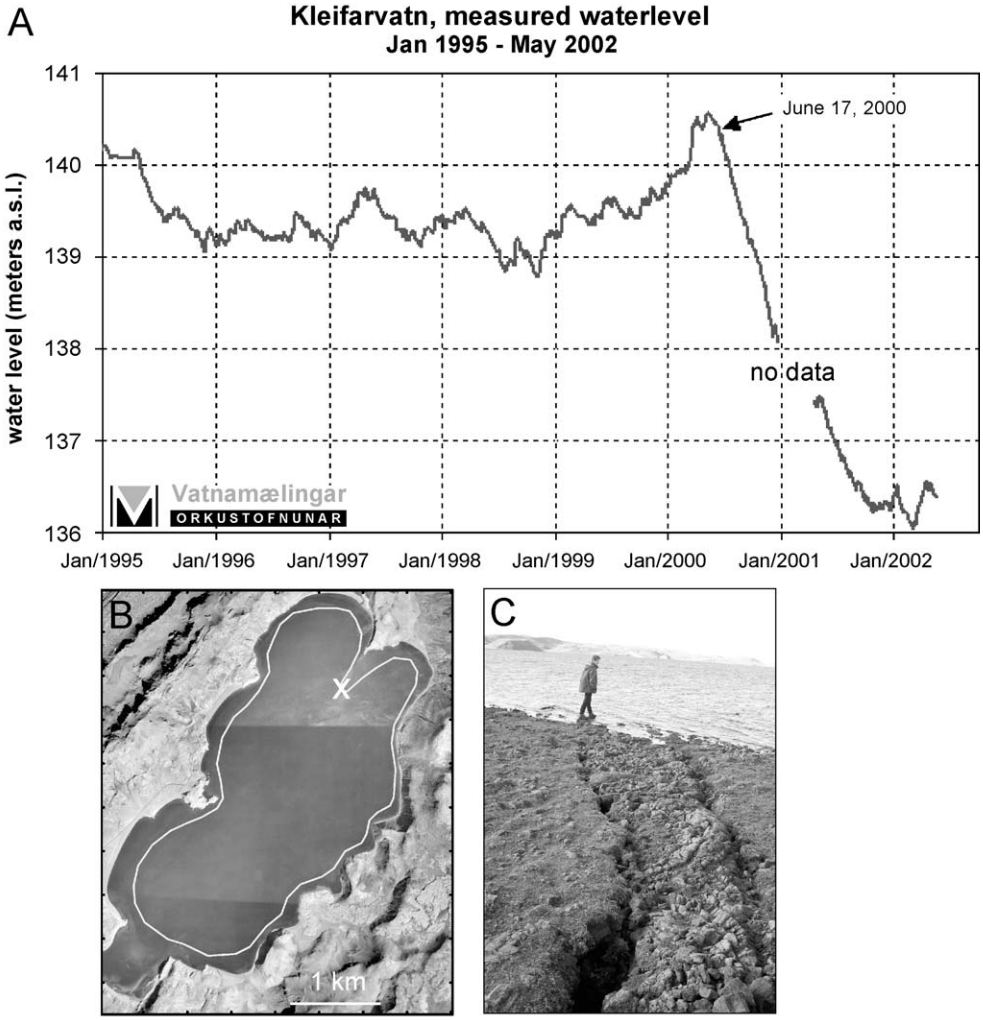

Fig. 4. (A) Water level measurements made by the National Energy Authority Hydrological Service (meters above sea level) at Kleifarvatn between January 1995 and May 2002. Gap with no data represents period when the lake level dropped below the measuring instrument. (B) 1999 Air photo of Kleifarvatn. White line shows approximate present shoreline. X marks the location of fissures, which opened up as a result of the Kleifarvatn earthquake. (C) Open fissures at the lakeshore, photographed in August 2001.

level had to be moved twice. Visual inspection of the fractures during July 2002 indicates that they are filling with sediment and outflow is reduced, but still continuing.

4.3. Núpshlíðarháls earthquake

Widespread rockfall and minor surface rupture occurred along the Núpshlíðarháls ridge just west of Djúpavatn. Minor, subvertical fault surfaces were found close to the base of the west-facing slope, and open fissures were found at all elevations. The fissures, with opening on the order of centimeters, generally follow topography, indicating that they are related to rotational or translational block sliding of slope material. The fault surfaces at the base may be related to minor thrusting at the toe of a block slide.

Rockfall and block sliding was observed on several steep slopes between Djúpavatn and the earthquake epicenter 3 km to the south. The intensity of deformation decreased toward south and was concentrated along north-trending structures, which crosscut the central segment of the northeast trending volcanic ridge. This same segment of the ridge crosses the high temperature geothermal area, and is at the center of maximum volcanic production.

On Sveifluháls ridge, separated from Núpshlíðarháls by a 1 km wide valley, large blocks fell from the most unstable and highest cliffs. However, because Sveifluháls is equidistant between Kleifarvatn and Núpshlíðarháls, and none saw the rocks falling, it is not clear which earthquake caused this. Evidence of possible fault reactivation was found on a low platform overlying the geothermal area on the eastern side of the ridge. A 200 m long series of linear pressure ridges trending 023° defines a previously unmapped fault segment. This small area experienced several shallow aftershocks with local magnitudes between 1 and 3 within minutes of the Kleifarvatn event. Fresh opening was observed at the base of the pressure ridges within grass-filled fissures and in soil between them. Large blocks within the pressure ridges had either fallen or rotated.

5. Discussion

Seismic and field evidence indicate that the Hvalhnúkur and Kleifarvatn earthquakes occurred on subparallel N- to NNE-striking strike-slip faults, and that they were dynamically triggered by shear waves traveling at 2.5 km/s from the SISZ main shock. The focal depth of the Hvalhnúkur event was 9 km, and modeling from InSAR indicates that the fault did not propagate to the surface (Pagli et al., 2003). This, along with the relatively low local relief on the Heiðin Há shield, can account for the small amount of visible surface disruption along and near the fault trace. Modeling of InSAR data for this event is still in progress, but preliminary results indicate that motion was primarily right-lateral strike slip on the order of 15 cm (Pagli et al., 2003).

The poor seismic resolution of the Kleifarvatn earthquake is not very helpful in determining fault parameters. A consequence of this is that the occurrence of the Kleifarvatn earthquake was not recognized until over 1 year later, when InSAR interferograms of Reykjanes Peninsula covering the period of the earthquakes revealed a deformation signal along the eastern shore of Lake Kleifarvatn significantly larger and clearer than the signals of the other two earthquakes. The best-fitting model of InSAR data (Pagli et al., in press) indicates that motion occurred on a 5.9 km-long, N-striking fault, dipping 60° to the east and extending from the surface to a depth of 5.6 km. Accordingly, the fault slipped 56 cm in a right-lateral sense and 11 cm down to the east, corresponding to a moment magnitude of $M_w = 5.8$. Field data are largely consistent with this model, although they cannot constrain the magnitude of the event. Compared with surface effects observed along strike-slip faults in the SISZ, the effects of the Kleifarvatn event are consistent with that expected for a large earthquake (M>5). However, we cannot rule out the possibility from field data alone that the primary surface rupture and compressional structures that formed were produced by a shallow event of lower magnitude that also propagated to the surface. Field data add possible constraints to the epicenter location. Both primary surface rupture and the largest disrupted rockslides occurred on the southeast shore of Kleifarvatn, at the area shown in Fig. 3. The left-stepping en echelon surface rupture at the lakeshore (red lines in Fig. 3) has the correct geometry to have resulted from right-lateral strike-slip fault movement. The rotation of boulders and disrupted slides originating on the low hyaloclastite slope nearby can also be best explained by strike-slip fault motion accompanied by severe shaking. The opening of N- to NNE-striking fissures with no vertical component of motion at the north end of the lake is also consistent with right-lateral motion on a N-striking fault. Most of the other surface effects described above can be explained by amplification of seismic waves along ridge crests and cliff edges. These effects are more pronounced to the south of the area shown in Fig. 3, and could indicate that fault slip propagated to the south. The amplitude of seismic waves produced by the rupture on a fault plane may be 10 times greater in the fault propagation direction (Keller and Pinter, 2002). However, in this case we cannot exclude the possibility that a decrease in intensity of rockfall and slumping towards north is an effect of topography and rock properties.

Inversion of GPS data for Reykjanes Peninsula covering the period 1998 to 2000 confirms the conclusions based on InSAR data that slip along the Kleifarvatn fault was significantly larger than along either the Hvalhnúkur or the Núpshliðarháls faults (Árnadóttir, personal communication, 2003). No earthquake this large has thus far been found in the global seismic database on Reykjanes Peninsula on June 17, 2000. We suggest that much of the fault slip along the Kleifarvatn fault may have been aseismic and could have occurred over a period as long as 2 days. Independent interferograms constrain the timing of deformation between October 2, 1999 and June 19, 2000. We cannot rule out the occurrence of aseismic slip before the 17th of June. However, draining of water from the lake into the fault zone provides a possible mechanism which would allow aseismic slip to occur some time between the 17th and 19th of June. The water level in the lake began to decrease some time in early May, but this is consistent with normal yearly fluctuations. However, the largest single-day decrease was measured on 17th of June. If an earthquake of approximately $M = 5.0$ along the Kleifarvatn fault opened a series of fractures within a fault damage zone several hundred meters wide, water may have migrated rapidly along interconnected fractures toward the main slip plane. Studies of fault zones in Iceland have shown that the predominant fracture trends within a fault's damage zone are both parallel and perpendicular to the strike of the main slip plane and that this network of fractures has high connectivity (Gudmundsson et al., 2001). During faulting, the transmissivity of the fault core may increase by as much as $10^8 – 10^{11}$ times its interseismic value (Gudmundsson, 2001). Numerical modeling studies (Lee and Wolf, 1998) have shown that pore pressure fronts will tend to migrate obliquely toward a more permeable zone rather than downward in a less permeable medium. The same study showed that migration of a pore pressure front will be significantly faster, by as much as 100%, in a narrow fault zone than in a homogeneous rock body. The fractures at the north end of Lake Kleifarvatn are within 500 m of the fault in question. It is possible that water drained quickly into the fault core after the earthquake and increased the slip magnitude without generating additional seismic waves. However, without further data on the properties of the groundwater system, this is only speculation.

The Núpshlíðarháls earthquake occurred 4.21 min after the Kleifarvatn event, and could not have been dynamically triggered like the other two events. What accounts for the delay is uncertain. The Núpshlíðarháls fault was probably not as close to failure as the other two, and required some additional loading to bring it to failure. Coulomb stress calculations indicate that the Kleifarvatn earthquake increased the Coulomb failure stress in the region of the Núpshlíðarháls hypocenter and could have statically triggered slip on a N-striking, steeply dipping fault (Árnadóttir, personal communication, 2003). Another possibility is that perturbation of the geothermal system that lies between Kleifarvatn and Núpshlíðarháls provided the trigger. The best-fitting model of InSAR data (Pagli et al., 2003) indicates that this event originated either on a fault striking 350°, dipping 35° to the east, with 24 cm of right-lateral strike slip and 3 cm of thrust, or a fault striking 079°, and dipping 77° to the south, with almost equal amounts of left-lateral strike slip and thrust motion (20 and 19 cm, respectively). Neither alternative has the fault propagating to the surface. While neither InSAR nor seismic data can determine conclusively whether slip occurred on an N- or an E-striking fault, field evidence strongly points to failure along an N-striking fault. The surface is overwhelmingly dominated by N- to NE-striking fault traces, and mapped surface effects are distributed within a narrow north–south trending zone parallel to the major mapped surface faults on Núpshliðarháls ridge north of the epicenter. While no primary rupture was observed, the intensity and distribution of secondary effects is consistent with northward propagation of an N-striking fault. Possible reactivation of a strike-slip fault on Sveifluháls, overlying the geothermal system could be related to internal deformation of the hanging wall of an N-striking, shallowly E-dipping fault. However, it could more simply be attributed to perturbation of the geothermal system. In the present tectonic setting, any thrust component on a fault striking either north–south or east–west is unexpected. However, earthquake-generated pore-pressure changes in the groundwater system and/or the geothermal system might provide a component of thrust due to lateral loading of an east-dipping fault or small-scale uplift. Unfortunately, there is no local monitoring of either the geothermal or groundwater system in the area, so this speculation cannot be confirmed.

6. Conclusions

The events of June 17, 2000 show that major earthquakes in the SISZ can trigger large earthquakes on Reykjanes Peninsula, and that they can have significant effects, including both primary and secondary surface rupture, rockfall, block slides and even the draining of a lake. Surface effects are consistent with the occurrence of three earthquakes of $M\sim 5$ along three parallel, N-striking, right-lateral strike-slip faults, two of which straddle a large geothermal system. Field data are consistent with results of InSAR modeling which indicate that slip along the Kleifarvatn fault was greater than along the other two, and also suggest that the epicenter of the earthquake was along the southeastern shore of Lake Kleifarvatn. Field relationships allow for the possibility that water from Lake Kleifarvatn drained into fractures within the fault damage zone, migrated to the fault core and facilitated aseismic slip along the Kleifarvatn fault.

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