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Triggered fault slip on June 17, 2000 on the Reykjanes Peninsula, SW-Iceland captured by radar interferometry

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[1] Dynamically triggered seismicity followed shortly after a M_s 6.6 earthquake in Iceland on June 17, 2000. Smaller earthquakes occurred on the Reykjanes Peninsula up to 100 km from the mainshock rupture. Using interferometric analysis of Synthetic Aperture Radar images (InSAR), we measure crustal deformation associated with three triggered deformation events. The largest of these occurred at Lake Kleifarvatn, 85 km west of the mainshock epicenter. Modeling of the InSAR data reveals strikeslip on a north-striking fault, with a geodetic moment of 6.2×10^{17} Nm, equivalent to magnitude M_w 5.8 earthquake. A seismological estimate of the moment is not yet available, because the seismic signature of this event is partly hidden by the mainshock waveform. The paucity of aftershocks on the triggered rupture plane suggests some aseismic slip there, compatible with a thin seismogenic crust, high heat-flow, hydrothermal alteration and the presence of fluids in the area. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 1243 Geodesy and Gravity: Space geodetic surveys; 7215 Seismology: Earthquake parameters; 8123 Tectonophysics: Dynamics, seismotectonics. **Citation:** Pagli, C., R. Pedersen, F. Sigmundsson, and K. L. Feigl, Triggered fault slip on June 17, 2000 on the Reykjanes Peninsula, SW-Iceland captured by radar interferometry, *Geophys. Res. Lett.*, *30*(6), 1273, doi:10.1029/2002GL015310, 2003.

1. Introduction

[2] The Mid-Atlantic ridge is exposed onland in Iceland, where it is segmented in a series of rift and transform zones (Figure 1). The ridge connects to the tip of the Reykjanes Peninsula in SW Iceland. A seismic zone running along its length at N76°E defines the central axis of the plate boundary [*Einarsson*, 1991]. The relative plate motion vector is 18.9 ± 0.5 mm/year in the direction N102° ± 1.1°E [*DeMets et al.*, 1994], approximately 30° oblique to the plate boundary. The Peninsula holds four active NE-trending volcanic systems (Figure 1) with volcanism alternating between periods of high activity and relative quiescence. The last known eruption occurred in 1240 AD [*Einarsson*, 1991]. The Peninsula also experiences high seismicity, characterized by normal faulting on NE striking planes or strike-slip on N or E trending planes [*Einarsson*, 1991]. Except for the Hengill area, the Peninsula was relatively quiet from 1974 to 1999, following a period of high activity between 1967 and 1973. The seismicity mostly occurs between 1 and 5 km depth. The oblique motion appears to cause bookshelf deformation, whereby parallel N-S trending, right-lateral strike-slip faults accommodate the overall left-lateral transform motion.

[3] GPS surveys [e.g., *Hreinsdóttir et al.*, 2001] as well as InSAR studies of the 1992–1995 interval [*Vadon and Sigmundsson*, 1997] show that left-lateral shear strain accumulates across the plate boundary within a 5.0–6.5 km thick brittle crust. Subsidence along the plate boundary is also observed, suggesting that plate movements are not fully balanced by inflow of magma from depth. Additional subsidence occurs in the Reykjanes volcanic system (Figure 1) due to exploitation of the geothermal field there.

[4] The Reykjanes Peninsula links to the east with the South Iceland Seismic Zone (SISZ) that experienced two M_s 6.6 earthquakes on June 17 and 21, 2000. These were the largest events in the area since 1912. Right-lateral strike-slip motion occurred on two parallel N-S striking faults [*Pedersen et al.*, 2001; *Árnadóttir et al.*, 2001]. Within a few seconds of the M_s 6.6 event on June 17, triggered seismic activity took place along the Reykjanes Peninsula. In this paper, we study the associated deformation using interferometric analysis of Synthetic Aperture Radar (SAR) images.

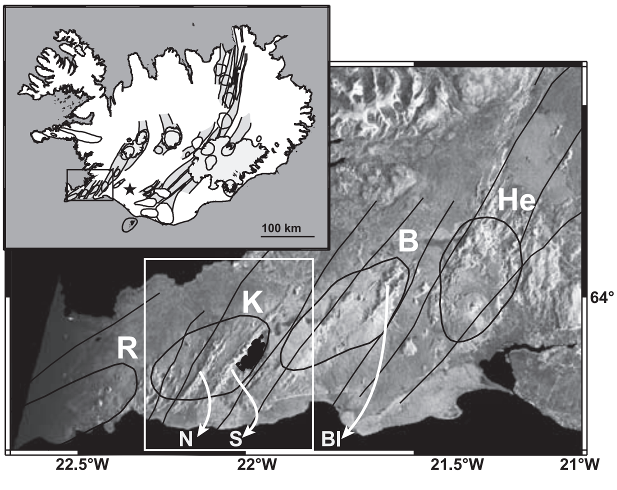

Figure 1. SAR amplitude image of the Reykjanes Peninsula. Overlaid are volcanic systems; central volcanoes (oval outlines) and fissure swarms: Reykjanes (R), Krísuvík (K), Brennisteinsfjöll (B) and Hengill (He). Núpshlídarháls (N) and Sveifluháls (S) are hyaloclastite ridges. Bl marks Mt. Bláfjöll. Lake Kleifarvatn is the black area just east of Sveifluháls. The rectangular box gives the location of the interferograms in Figure 2. Inset shows the plate boundary in Iceland with the study area as a box. Epicenter location of the M_s 6.6 event on June 17, 2000 is shown with a black star.

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Table 1. Interferometric Pairs by the ERS-2 Satellite in Track 367, Frame 2313

Figure	Orbits	From	To	Elapsed days	h_a (m)
2a	17756 23267	Sept.12, 1998	Oct. 2, 1999	385	104
2b	16754 27275	July 4, 1998	July 8, 2000	735	111
2c	27776 28277	Aug. 12, 2000	Sept. 16, 2000	35	118
2d	23267 28277	Oct. 2, 1999	Sept. 16, 2000	350	2654

The altitude of ambiguity, h_a, is the difference in topographic elevation that produces one (artefactual) fringe in a differential interferogram.

We focus on the largest triggered event, where seismological estimates of the moment are not yet available.

2. Radar Interferometry

[5] Differencing the phases of two SAR images, acquired at different times from about the same position in space, measures the ground deformation occurring during the time between acquisitions of the two images. The deformation is expressed as interferometric fringes on a map called an interferogram. Using images acquired by the ERS satellites, each fringe represents a change of 28 mm in the distance (range) along the line of sight from the radar antenna aboard the satellite to the target pixel on the ground. To calculate the interferograms, we use the standard two-pass method to remove topographic contributions with a digital elevation model in the PRISME/DIAPASON software developed at C.N.E.S., as described previously by *Feigl et al.* [2000]. This approach has already been used to measure crustal deformation in a number of areas in Iceland [e.g., *Vadon and Sigmundsson*, 1997; *Feigl et al.*, 2000; *Pedersen et al.*, 2001].

3. Deformation

[6] We analyzed a series of 13 interferograms covering the Reykjanes Peninsula, from ERS track 367, frame 2313, span-

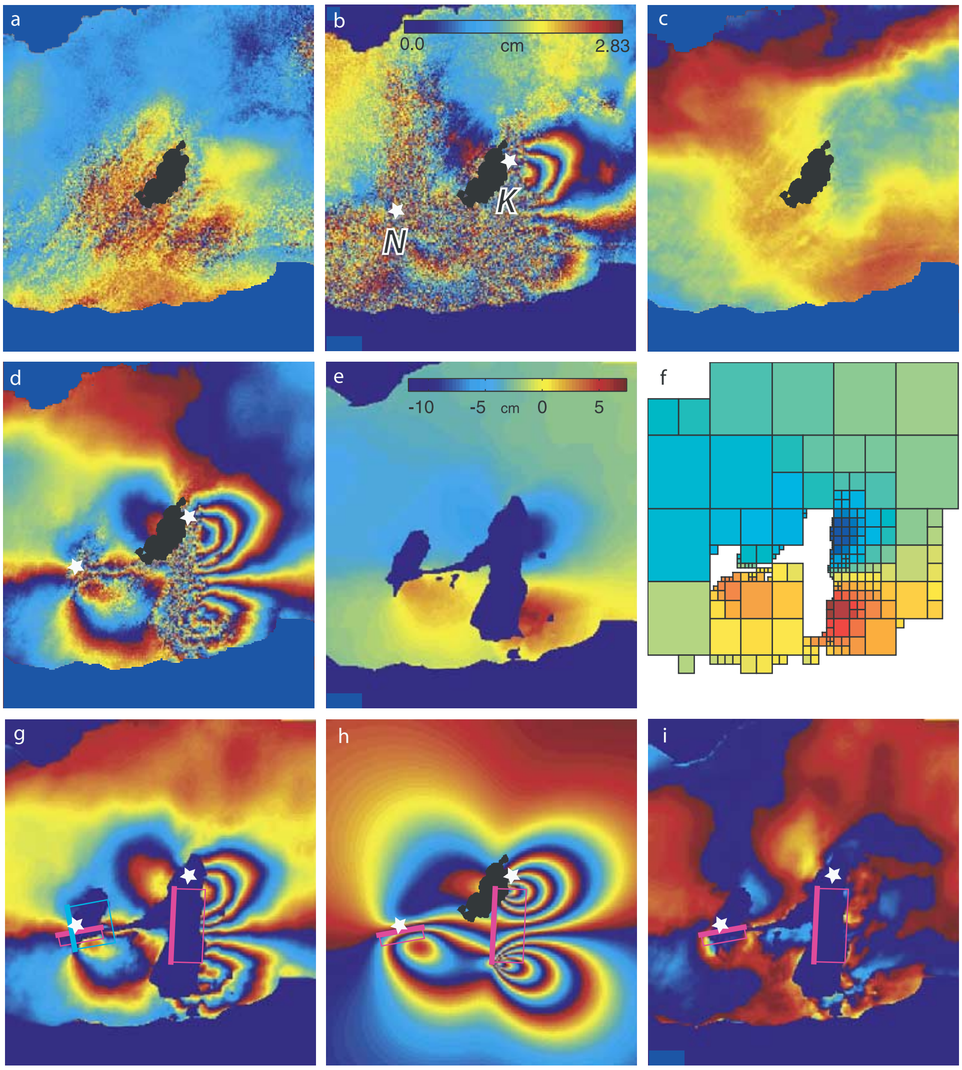

Figure 2. Interferograms spanning: (a) the preseismic interval, (b and d) the coseismic interval and (c) the postseismic interval (see Table 1). (e) Unwrapped interferogram in panel d, (f) quad-tree division, (g) rewrapped and tilted, (h) best-fit model and (i) residual. White stars show epicenters of the triggered earthquakes at Núpshlídarháls (N) and Kleifarvatn (K). The black area represents Lake Kleifarvatn. Red boxes mark the fault patches of Kleifarvatn and Núpshlídarháls 2 models. Blue box marks the fault patch of Núpshlídarháls 1 model. Color scale bar in panel b applies to the wrapped fringes in panels a, b, c, d, g, h and i. Color scale bar in panel e applies to the unwrapped range-changes in panels e and f.

Table 2. Best-Fit Faults Parameters

Location	Long. (°)	Lat. (°)	Depth (km)	Length (km)	Width (km)	Strike (°)	Dip (°)	Strike-slip (cm)	Throw (cm)
Kleifarvatn	−21.978	63.902	5.6	5.9	6.1	N2.5°E	66°E	56 right-lat.	11 dip-slip
Núpshlídarháls-1	−22.142	63.899	3.4	3.5	4.0	N10.3°W	35.5°E	24 right-lat.	3 thrust
Núpshlídarháls-2	−22.128	63.897	5.4	3.5	4.0	N79.5°E	76.6°S	20 left-lat.	19 thrust

Geographic coordinates give the center of the upper edge of the faults.

ning the 1993–2000 period. Four of these interferograms appear in this paper (Table 1 and Figure 2). We also examined two interferograms from frame 2313 of track 95. Since these interferograms span different times, we can separate the preseismic, coseismic and postseismic contributions for the events in June 2000. The best coseismic interferogram shows very good coherence across the whole Peninsula for the 11 months between October 2, 1999 and September 16, 2000 (Figure 2). The successful radar correlation is due to a combination of acquiring both images under similar conditions in the summer and high altitudes of ambiguity (Table 1).

[7] Our four coseismic interferograms (of which only two appear in Table 1 and Figure 2) show three distinct and consistent deformation signals, which we name geographically. They all lie to the west of the June 17 main shock that appears to have triggered them dynamically. From east to west (and in chronological order), they are Bláfjöll, Kleifarvatn and Núpshlídarháls (Figures 1 and 2). The first InSAR signature at Bláfjöll is the weakest of the three and is not interpreted here. The second InSAR signature, near Lake Kleifarvatn, is the largest. There the deformation pattern consists of more than two fringes arranged in three different lobes, with two lobes occurring on the east side of the fault that moved. The third signal, at Núpshlídarháls exhibits one lobe, which widens in an E-W oriented area. The signal consists of up to two fringes and interferes with the larger signal at Lake Kleifarvatn.

[8] The postseismic interferogram shows no significant local deformation after 12 August 2000 (Figure 2). The preseismic interferogram shows a small shortening in range around the Kleifarvatn area but we cannot exclude the possibility of an atmospheric artifact. To constrain the time of the main signal at Kleifarvatn, we note that it appears in the shortest co-seismic interferogram, spanning from October 2, 1999 to August 12, 2000, as well as in one spanning July 20, 1998–June 19, 2000. In contrast, another interferogram spanning the period June 19, 2000–July 24, 2000, shows no deformation in the same area. Therefore, the deformation must have ceased before June 19, 2000.

[9] Field investigations reveal several rock falls and surface ruptures as well as reactivation of two faults at Lake Kleifarvatn and Sveifluháls that probably occurred on June 17, 2000 [*Clifton et al.*, 2001]. The eastern shore of Lake Kleifarvatn is disrupted in typical strike-slip faulting structures, such as *en echelon* fissures and push-ups along a 200 m long fault segment. In addition, the water level in Lake Kleifarvatn began to fall on June 17, according to measurements by the National Energy Authority [*Clifton et al.*, 2001]. In the following 14 months, the water level fell 4 meters, or 9 mm/day on average, decreasing the total volume by 12% by January 2002. In the lake bed, there are visible fractures where water was seen draining out. We infer that these fractures opened on June 17, 2000.

[10] To understand the timing of the triggered seismicity, the Icelandic Meteorological Office has examined seismograms recorded from the SIL network [*K. Vogfjörd*, personal communication, 2002]. It recorded extensive triggered activity along the Reykjanes Peninsula within a few seconds of the M_s 6.6 main shock at 15:40:40 GMT, on June 17 in SISZ. The three largest events on the peninsula occurred in a sequence from east to west. The first event occurred in Bláfjöll at 15:41:07 GMT, then at Kleifarvatn at 15:41:11 GMT and finally at Núpshlídarháls at 15:45:27 GMT (A. E. Clifton et al., Surface effects of triggered fault slip on Reykjanes Peninsula, SW Iceland, submitted to *Tectonophysics*, 2002). We assume that these three events correspond to the three signatures we observe in the interferograms. Coulomb static stress changes caused by the earthquake on June 17, 2000 are small and unlikely to have triggered fault movements along the Reykjanes Peninsula [*Árnadóttir et al.*, 2003]. Dynamic triggering is suggested, as the times and positions of the first two events indicate a propagation speed of the order of several km/s. Seismic waves from the main shock are likely to have triggered the subsequent seismicity. Consequently, the triggered events interfere with the main shock signal. As a result, reliable seismological estimates for the mechanism and moment magnitude for Bláfjöll and Núpshlídarháls events are not yet available. The hypocentral location of the Kleifarvatn event is also poorly resolved.

4. Modeling

[11] To explain the observed fringe pattern, we assume two shear dislocations in the conventional elastic half space model [*Okada*, 1985] with a Poisson's ratio of 0.25 and a shear modulus (rigidity) of 30 GPa. We take the unit vector in the direction from ground to satellite to be constant (0.408, −0.112, 0.906) for the east, north and vertical components, respectively. To estimate the 18 free fault parameters as well as a bilinear planar correction, we use two approaches. First, we use a trial-and-error procedure, based on the RNGCHN program [*Feigl and Dupré*, 1999], minimizing the misfit between the modeled and the observed fringe patterns, as documented by *Pagli* [2002].

[12] For more robust estimates, we apply a formal inversion procedure after unwrapping using a ''heat bath'' simulated annealing algorithm followed by a derivative based method. The technique is described by *Cervelli et al.* [2001]. For computational convenience the data size was reduced using quad-tree partitioning, a two-dimensional quantization algorithm [e.g., *Jónsson et al.*, 2002]. The resultant data (Figure 2f) represents the statistically significant part of the deformation signals. The annealing algorithm locates an approximate solution within a set of bounds. We leave most bounds fairly loose because we lack useful a priori information, but fix four parameters. For the Kleifarvatn fault we fix the east coordinate and require the fault to extend to the surface. For the Núpshlídarháls event we also fix the size of the fault plane. After annealing, a derivative based method finds the optimal solution.

[13] For the Kleifarvatn event, the algorithm finds a fault striking approximately N-S (Table 2). The optimum solution consists of a 5.9 km long fault, extending from the surface to 5.6 km depth, striking approximately N, dipping 66°E with 56 cm of right-lateral strike-slip and 11 cm of dip-slip. The corresponding moment M_o is 6.2×10^{17} Nm. This value corresponds to an earthquake moment magnitude M_w 5.8, using the formula $M_w = ((2/3) \times \log M_o) - 6.03$.

[14] For the Núpshlídarháls event, we find two plausible solutions that correspond to two perpendicular faults (Table 2). One solution consists of a 3.5 km long fault, extending from 1.1 km below the surface to 3.4 km depth, striking N10°W, dipping 35°E with 24 cm of right-lateral strike-slip and 3 cm of thrust-slip. An alternative solution consists of a 3.5 km long fault, extending from 1.5 km below the surface to 5.4 km depth, striking N79°E, dipping 77°S with 20 cm of left-lateral strike-slip and 19 cm of thrust-slip. Seismic moment for both solutions is about 1.0×10^{17} Nm, corresponding to magnitude M_w 5.3. Figure 2 shows the E-striking Núpshlídarháls solution. This model coupled with the Kleifarvatn one gives an RMS of 4.2 mm, but the N-striking solution gives an RMS of 4.4 mm. To better understand the observed deformation, our data could be combined with GPS results and repeated lake leveling at Kleifarvatn.

5. Discussion and Conclusions

[15] We have identified three deformation signals on the Reykjanes Peninsula in InSAR interferograms, corresponding to three earthquakes on June 17, 2000 recorded by the Icelandic Meteorological Office. Their timing suggests that they were triggered by an earlier M_s 6.6 event, over 60 km to the east. The ratio of distance to time between the events gives a speed of several km/s, suggesting that propagating seismic waves triggered the slip dynamically.

[16] Our model for the Kleifarvatn event, the largest observed signature, suggests fault slip corresponding to a M_w 5.8 earthquake. Despite its size, this event does not appear in the worldwide seismicity catalogs. Earlier, we had suggested that the event at Kleifarvatn was a slow earthquake [*Pagli et al.*, 2002], based on the absence of seismic detection of this event. Further inspection of seismic recordings of the M_s 6.6 main shock on June 17, 2000 has, however, revealed intermixed waveforms originating from an earthquake at Kleifarvatn at 15:41:11 GMT, but its moment has not yet been reliably estimated by seismological methods (K. Vogfjörd, personal communication, 2002). On the other hand, the U.S.G.S. catalog includes the later Núpshlídarháls event with m_b 4.9.

[17] The aftershock pattern at Núpshlídarháls consists of 58 aftershocks with an average local magnitude M_L 2.4 that takes about 6 weeks to decay, according to the SIL seismological database. At Kleifarvatn, however, the pattern also decayed rapidly, over a 6-week period, following the June 17 mainshock but the about 47 recorded aftershocks average only 0.9 in local magnitude M_L. Interestingly, fewer aftershock with smaller magnitude occurred at Kleifarvatn than at Núpshlídarháls. This observation contradicts the geodetic moments estimated from the InSAR data that find the Kleifarvatn moment release to be five times larger than for the Núpshlídarháls event.

[18] We suggest that the paucity of aftershocks on the Kleifarvatn fault plane indicates aseismic slip. Possible reasons for aseismic slip occurring at Kleifarvatn may be thin seismogenic crust and high heat flow. Presence of both the water of the lake and clay minerals, resulting from hydrothermal alteration, may also have favored slow rupture by reducing the friction on the fault plane. The hypothesis can be tested with further interpretation of seismic recordings.

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