GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 21, PAGES 4031-4033, NOVEMBER 1, 2001

Crustal deformation measured by GPS in the South Iceland Seismic Zone due to two large earthquakes in June 2000

Thóra Árnadóttir[1], Sigrún Hreinsdóttir[2,6], Gunnar Gudmundsson[3], Páll Einarsson[2], Michael Heinert[4], Christof Völksen[5,7]

Abstract. Two large earthquakes struck the South Iceland Seismic Zone in June 2000, the first on June 17 (M_W=6.5) and the second on June 21 (M_W=6.4). These are the largest earthquakes in the area in the past 88 years. A network of GPS stations was remeasured following the earthquakes. The whole network was last measured in 1995, and partly in 1999. We correct for the interseismic motion from 1995 to 2000, to obtain the coseismic displacements. The largest coseismic motion we observe is about 0.55 m in the epicentral area of the June 17 event. We model the surface deformation for the two earthquakes using rectangular dislocations in an elastic half space. Best fit uniform slip models indicate that the events occurred on two parallel, N–S vertical faults, with right-lateral strike slip motion. This is the same style of faulting believed to have occurred in large historical earthquake sequences in South Iceland.

1. Introduction

The South Iceland Seismic Zone (SISZ) is a left-lateral E–W transform zone that connects the Western Volcanic Zone (WVZ) and the Reykjanes Peninsula (RP) oblique rift zone in the west and the Eastern Volcanic Zone (EVZ) in the east (Figure 1). Numerous large ($M_S \geq 6$) earthquakes have occurred in the SISZ since Iceland was settled in the ninth century A.D. The first one to be instrumentally recorded occurred in 1912 in the eastern part of the SISZ with surface wave magnitude M_S=7.0 [*Gutenberg and Richter*, 1954; *Bjarnason et al.*, 1993]. This event has been used to calibrate the size of known earlier historical earthquakes in the area, based on accounts of structural damage. The N–S orientation and structure of mapped surface faults [*Einarsson and Eiríksson*, 1982; *Einarsson et al.*, 1981] and the N–S elongated zone of destruction for many of the historical earthquakes suggest that the relative plate motion is accommodated by right-lateral strike slip faulting on many parallel N–S oriented faults.

[1]Nordic Volcanological Institute, Reykjavík, Iceland.
[2]Science Institute, University of Iceland, Reykjavík, Iceland.
[3]Icelandic Meteorological Office, Reykjavík, Iceland.
[4]Technische Universität Braunschweig, Braunschweig, Germany.
[5]National Land Survey of Iceland, Akranes, Iceland.
[6]Now at Geophysical Institute, University of Alaska, Fairbanks.
[7]Now at Bayerische Akademie der Wissenschaften, Bayerische Kommission für die Internationale Erdmessung, Muenchen, Germany.

Paper number 2001GL013332.
0094-8276/01/2001GL013332$05.00

There have been sequences of several large earthquakes in the SISZ over a period of days to years, starting with a large earthquake in the eastern part of the SISZ and continuing with gradually smaller events further to the west. The time interval between large earthquake sequences in the SISZ ranges between 45 and 112 years [*Einarsson et al.*, 1981]. Such series of earthquakes occurred for example in 1630–1633, 1732–1734, 1784, 1896 and 2000.

The largest earthquake in the SISZ, since the 1912 event, occurred at 15:40:41 GMT on June 17, 2000. The hypocenter was located at 63.975°N, 20.370°W and 6.3 km depth, with a moment magnitude of M_W=6.5. A second large event followed at 00:51:47 GMT on June 21, 2000. The hypocentral location of this event was at 63.977°N, 20.713°W and 5.1 km depth, and the magnitude was M_W=6.4. The epicentral locations of the two earthquakes are shown with stars in Figure 1. The aftershocks in their epicentral areas, extended for about 16–18 km N–S, and from the surface down to about 10 km depth. Seismicity increased over a large area in SW Iceland following the June 17 main shock. Surface faulting was observed for both events. This indicates rupture on N–S trending faults, partly pre-existing.

The earthquake sequence in June 2000, was recorded by several local networks, *i.e.*, the SIL digital seismic network [*Stefánsson et al.*, 2000], a volumetric strain meter network (K. Ágústsson, pers. communication), a continuous GPS network, and a strong motion network. Crustal deformation signals were also recorded by InSAR [*Pedersen et al.*, 2001] and network GPS measurements (this study). In addition, the earthquakes caused significant changes in geothermal systems in the area (G. Björnsson, pers. communication), and were accompanied by premonitory and coseismic radon anomalies.

2. GPS data and analysis

The SISZ was surveyed with GPS in 1986, 1989, 1992, 1995, 1999 and 2000. In this study we use data collected in 1995, 1999 and 2000. The GPS survey in August–September, 1995, was a collaboration between the Technical University of Braunschweig (TUB), the Nordic Volcanological Institute (NORDVULK) and the Science Institute, University of Iceland (SIUI) occupying a total of 61 stations. The 1995 data were previously analyzed by TUB [*Alex et al.*, 1999]. The September, 1999, GPS survey was a collaboration between TUB and the National Land Survey of Iceland (NLSI). A total of 32 stations, 14 of which had been observed in 1995, were occupied. The June 19 –30, 2000 survey was a collaboration between NORDVULK, SIUI and NLSI, 46 stations were occupied, 34 of which had been observed in 1995, and 14 in 1999. All the surveys were performed using dual-frequency GPS receivers, collecting data

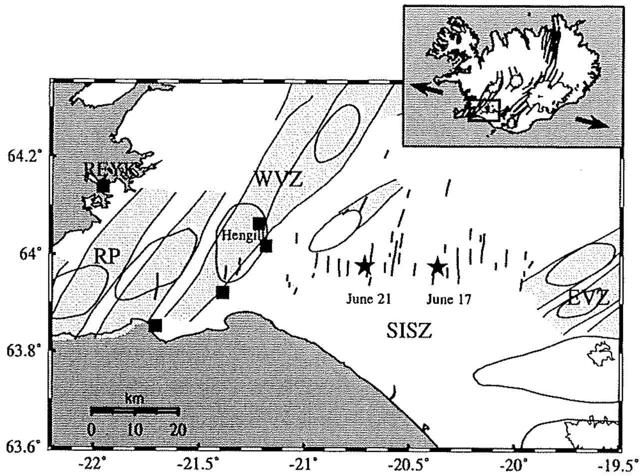

Figure 1. Map of the study area showing the tectonic setting of the SISZ area. Mapped N–S faults are shown with black lines [*Einarsson and Sæmundsson* 1987]. The light shaded areas are individual spreading segments with associated central volcanoes. The epicenter locations of the two large earthquakes in June 2000 are shown with stars. Black squares are continuous GPS stations. The locations of Reykjanes Peninsula (RP), Western Volcanic Zone (WVZ), Eastern Volcanic Zone (EVZ), Hengill volcano and Reykjavík (REYK) are marked. The insert shows a map of Iceland, with bold lines outlining the spreading segments in the neovolcanic zones. The study area is indicated with a box. The black arrows show the direction of the NUVEL-1A plate motion with half spreading rate of 9.7 mm/yr.

every 15 s, occupying stations for about 24 hours for one or more sessions. We analyze the GPS data using the Bernese V4.2 software package [*Hugentobler et al.*, 2001], and precise orbital information from CODE. Data from the IGS station in Reykjavík (REYK) and 4 continuous GPS stations in SW Iceland [*Árnadóttir et al.*, 2000] were included in the analysis of the 1999 and 2000 data.

3. Surface deformation and dislocation modeling

We calculate the surface deformation in the SISZ by taking differences of station coordinates for the epochs discussed in the previous section. The 1995 and 2000 surveys occupied the densest networks, but span not only the two earthquakes but also almost 5 years of interseismic motion. We have attempted to correct for the interseismic motion by calculating the 1995–1999 station displacements and estimating station displacements for all the stations observed in 2000. The coseismic motion is obtained by subtracting the interseismic motion from the 1995–2000 signal. The interseismic deformation observed in 1995–1999 is much smaller than the coseismic signal in the epicentral areas of the two large earthquakes. We observe large displacements at stations in the western end of the SISZ due to local deformation at Hengill volcano during 1995–1998 [*Hreinsdóttir et al.*, 2001]. We have corrected for this motion by subtracting vectors determined from a survey done in December 1998 from the 1995–2000 signal.

The non-linear inversion algorithm described by *Árnadóttir and Segall* [1994] was used to estimate the best fit fault parameters and amount of slip for the June 17 and 21 earthquakes, assuming two rectangular uniform slip dislocations in an elastic half-space. The epicenters of the two earthquakes are only about 17 km apart, and they occurred within 3 1/2 days of each other. The geodetic network is not dense enough to allow us to clearly separate the two events in space and time. The model for the June 21 event is not as well constrained by the data as for the first event, since no station is close to the epicentral area. We have not included data from the closest station (indicated by a green vector in Figure 2) because we suspect that the motion there is influenced by local deformation. This station is at the top of a mountain and evidence of strong ground shaking and ground cracking was observed nearby. There is a strong trade-off between the amount of slip and the fault width, especially for the June 21 event. We therefore fixed the dip of both faults to vertical, and the depth of the June 21 fault based on aftershock locations. The models are otherwise not constrained by the main shock hypocenters nor locations of surface faulting. Table 1 gives the best-fit fault parameters and Figure 2 shows the observed and calculated horizontal displacements. The surface projections of the dislocation models are shown with green lines. The models fit about 96% of the signal, with a $\chi_\nu{}^2 = 4.1$ (a $\chi_\nu{}^2 = 1$ indicates perfect fit). The geodetic moment given in Table 1 is calculated from the relation $M_0 = \mu A u$, with $\mu = 3 \times 10^{10}$ N/m^2, A the area and u the total slip. The geodetic moments for our models agree well with the seismic moment for the June 17 and 21 earthquakes of 6.0×10^{18} Nm and 5.2×10^{18} Nm respectively (NEIC).

4. Discussion and conclusions

Repeated GPS surveys reveal large coseismic displacements in the epicentral areas of the earthquakes on June 17 and 21, 2000. Simple uniform slip dislocation models for the two events provide a good fit to the surface displacements, and indicate that the earthquakes ruptured vertical, parallel N–S oriented faults, with primarily right-lateral strike slip motion. N–S faulting is consistent with observations in other parts of the SISZ. Our fault models are slightly east of the main shock locations for both events. Detailed analysis of

Table 1. Best fit fault parameters for June 17 and 21, 2000 earthquakes from GPS measurements. The parameters are the fault length along strike, depth to center, width along dip, dip, strike east of north, location of the southern end of the fault, right-lateral strike slip (ss), dip slip (ds) and geodetic moment (M_0). A star indicates that the parameter is fixed before the inversion.

Model	Length (km)	Depth (km)	Width (km)	Dip (°)	Strike (°)	Lat. (°N)	Lon. (°W)	ss (m)	ds (m)	M_0 $\times 10^{18}$ (Nm)
June 17	9.5	5.0	9.8	90.0*	3.0	63.927	20.356	2.0	0.2	5.6
June 21	12.3	4.0*	8.0	90.0*	0.5	63.929	20.692	1.5	0.0	4.5

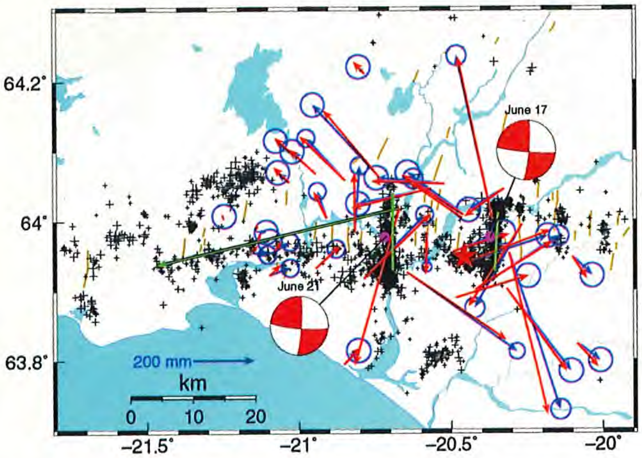

Figure 2. Observed (blue arrows) and calculated (red arrows) coseismic horizontal displacements for the best fit models for the June 17 and 21, 2000, earthquakes. Data shown with a green arrow are not included in the inversion (see text). The green lines show the surface projections of the two fault models. Aftershocks from June 17 to November 22, 2000, are shown with crosses, along with the largest aftershock on June 17 (red star), and the focal mechanisms for the two largest events (from NEIC).

the aftershocks may reveal changes in the fault geometries along strike, as suggested by the complicated pattern of surface faulting and the broadening of the aftershock zone at the southern end of the June 21 fault. The GPS data indicate high slip at shallow depth for the June 21 earthquake, although we are not able to resolve the details of the slip distribution from our data. The largest aftershock on June 17 (estimated $M_L = 5$ and indicated with star in Figure 2) occurred about 5 km SW of the June 17 mainshock. A cluster of aftershocks oriented N–S suggests that slip on a second fault may have occurred at the time, which could influence the deformation measured at the closest stations.

Our fault locations and geometries differ somewhat from the results of the InSAR analysis [*Pedersen et al.*, 2001]. Most importantly the faults in our models are shorter than in the corresponding InSAR models. The extent of aftershocks and surface faulting also suggest longer faults than our models indicate. Allowing the slip to taper to zero towards the ends of our models would lessen this discrepancy. The InSAR data also indicate about 105 mm of postseismic back-slip occurred on the central part of the June 17 fault sometime during the period from June 19 to July 24, 2000. The GPS data are not able to resolve this motion, but the signal may be, at least in part, included in our observations. The largest signals in the GPS data are horizontal displacements primarily in the N–S direction, which the InSAR data are least sensitive to. We plan to combine the GPS, InSAR and volumetric strain data in a future study to better constrain the fault geometries and slip distribution of the two events.

Acknowledgments. We thank everyone who participated in the various GPS network measurements in South Iceland, which we use data from. Comments from F. Sigmundsson and two anonymous reviewers improved the text. The figures were produced using the GMT public domain software. This work was supported in part by Icelandic Research Council grants 981050099 and 981050000, grant from the University of Iceland Research Fund (1995 and 1998 GPS surveys) and by a special grant from the Icelandic government to study the June 2000 earthquakes.

References

Alex, N., P. Einarsson, M. Heinert, W. Niemeier, B. Ritter, F. Sigmundsson, and S. Willgalis, GPS-Meskampagne 1995 zur Bestimmung von Deformationen der Erdkruste in Südwestisland, *Zeitschrift für Vermessungswesen, 12*, 377–388, 1999.

Árnadóttir, Th., and P. Segall, The 1989 Loma Prieta earthquake imaged from inversion of geodetic data, *J. Geophys. Res., 99*, 21,835–21,855, 1994.

Árnadóttir, Th., H. Geirsson, B.H. Bergsson, and C. Völksen, The Icelandic continuous GPS network – ISGPS, March 18, 1999–February 20, 2000, research report *VI-R00002-JA02*, Icelandic Meteorological Office, Reykjavík, June, 2000.

Bjarnason, I., P. Cowie, M.H. Anders, L. Seeber, and C. H. Scholz, The 1912 Iceland earthquake rupture: Growth and development of a nascent transform system, *Bull. Seismol. Soc. Am.*, 83, 416–435, 1993.

Einarsson, P., and J. Eiríksson, Earthquake fractures in the districts Land and Rangárvellir in the South Iceland Seismic Zone, *Jökull*, 32, 113–120, 1982.

Einarsson, P., and K. Sæmundsson, Earthquake epicenters 1982–1985 and volcanic systems in Iceland, In: Th.I. Sigfusson (editor), *Í hlutarins edli*, Map accompanying festschrift for Th. Sigurgeirsson, Menningarsjódur, Reykjavík, 1987.

Einarsson, P., S. Björnsson, G. Foulger, R. Stefánsson, and Th. Skaftadóttir, Seismicity pattern in the South Iceland Seismic Zone, in *Earthquake Prediction – An international review*, D. W. Simpson and P. G. Richards (editors), AGU, vol. 4, 141–151, 1981.

Gutenberg, B., and C. F. Richter, *Seismicity of the Earth and Associated Phenomena*, 2nd ed., Princeton University Press, Princeton, New Jersey, 1954.

Hreinsdóttir, S., P. Einarsson, and F. Sigmundsson, Crustal deformation at the oblique spreading Reykjanes Peninsula, SW Iceland: GPS measurements from 1993 to 1998, *J. Geophys. Res.,* (in press), 2001.

Pedersen, R., F. Sigmundsson, K. Feigl, and T. Árnadóttir, Coseismic interferograms of two M_s=6.6 earthquakes in the South Iceland Seismic Zone, June 2000, *Geophys. Res. Lett.,* (in press), 2001.

Hugentobler, U., S. Schaer, and P. Friedez, Bernese GPS software, Version 4.2, Astronomical Institute, University of Berne, Berne, Switzerland, 2001.

Stefánsson, R., G. Gudmundsson, P. Halldórsson, The two large earthquakes in the South Iceland Seismic Zone on June 17 and 21, 2000, URL: http://hraun.vedur.is/ja/-skyrslur/June17and21_2000/index.html, last modified July 26, 2000.

T. Árnadóttir, Nordic Volcanological Institute Grensásvegur 50, IS-108 Reykjavík, Iceland (thora@norvol.hi.is)

S. Hreinsdóttir, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, (sigrun@giseis.alaska.edu)

G. Gudmundsson, Department of Geophysics, Icelandic Meteorological Office, Bústadavegur 9, IS-150 Reykjavík, Iceland. (gg@vedur.is)

P. Einarsson, Science Institute, University of Iceland, Dunhagi 3, 107 Reykjavík, Iceland. (palli@raunvis.hi.is)

M. Heinert, Institut für Geodäsie und Photogrammetrie, Technische Universität Braunschweig, Gausstrase 22, D- 38106 Braunschweig, Germany. (m.heinert@tu-bs.de)

C. Völksen, Bayerische Akademie der Wissenschaften, Bayerische Kommission für die Internationale Erdmessung, Marstallplatz 8, D-80539 Muenchen, Germany. (voelksen@bek .badw-muenchen.de)

(Received April 23, 2001; accepted July 11, 2001.)