Size and orientation of the fault plane for the 2001 Gujarat, India earthquake (Mw7.7) from aftershock observations: A high stress drop event

H. Negishi
National Research Institute for Earth Science and Disaster Prevention, Japan

J. Mori
Disaster Prevention Research Institute, Kyoto University, Japan

T. Sato
Hirosaki University, Japan

R. Singh
Indian Institute of Technology, India

S. Kumar
Wadia Institute of Himalayan Geology, India

N. Hirata
Earthquake Research Institute, Tokyo University, Japan

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[1] We used a small array of portable seismographs to determine aftershock locations of the 2001 Gujarat earthquake. Our aftershock locations show a trend that dips toward the south at about 50° which is interpreted as the fault plane of the mainshock. The depth range of the aftershocks is from 10 to 35 km, which is somewhat deeper than other crustal earthquakes, and indicates that the faulting did not reach the surface. The area of the fault is about 40×40 km^2, which is small for a Mw7.7 earthquake and results in a high static stress drop of 13 to 25 MPa. There are no mapped faults or obvious topographic features along the surface projection of this fault. These findings show that very large damaging earthquakes can occur without producing surface faulting, which is an important issue for earthquake hazard assessments in continental regions. *INDEX TERMS:* 7212 Seismology: Earthquake ground motions and engineering; 7205 Seismology: Continental crust (1242); 7215 Seismology: Earthquake parameters; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics. **Citation:** Negishi, H., J. Mori, T. Sato, R. Singh, S. Kumar, and N. Hirata, Size and orientation of the fault plane for the 2001 Gujarat, India earthquake (Mw7.7) from aftershock observations: A high stress drop event, *Geophys. Res. Lett.*, *29*(20), 1949, doi:10.1029/2002GL015280, 2002.

1. Introduction

[2] When a very large shallow earthquake (Ms7.9, Mw7.7) occurred in the state of Gujarat, India on 26 January 2001, seismologists and geologists expected to see significant ground rupture along a large fault. The initial magnitude of this earthquake in India was larger than recent earthquakes in Taiwan and Turkey, where large surface displacements of 5 to 8 meters were observed [e.g., *Youd et al.*, 2000; *Ma et al.*, 1999]. Surprisingly, the Gujarat earthquake did not have obvious surface displacements for the main fault, although there were some small surface deformations attributed to shaking effects. The earthquake produced severe damage in the city of Bhuj and the surrounding area (over 20,000 deaths and over 400,000 buildings destroyed). For evaluating the intense shaking damage and understanding the regional tectonics, it is important to know the location and orientation of the causative fault.

[3] There are several mapped faults in the region [*Malik et al.*, 2001; *Rajendran and Rajendran*, 2001], and it was speculated that the earthquake may have occurred on one of these, such as the Kachchh Mainland fault. Teleseismic focal mechanisms from various groups (Harvard, USGS, ERI) showed consistent thrust mechanisms on an east-west trend, but it was not possible to distinguish if faulting occurred on the northward or southward dipping plane. Since there was no clear surface rupture, this study determines the location of the fault and estimates its size and orientation from aftershock locations. For this purpose, we deployed a temporary array of 7 seismographs in the region of the earthquake (Figure 1) from February 28 through March 6 to accurately locate aftershocks.

2. Instrument Deployment

[4] Planning the configuration of the array was difficult because of the lack of information on where the aftershocks were occurring and there were large differences between the mainshock epicenters determined by the Indian Meteorological Department (IMD) and USGS. Media coverage of

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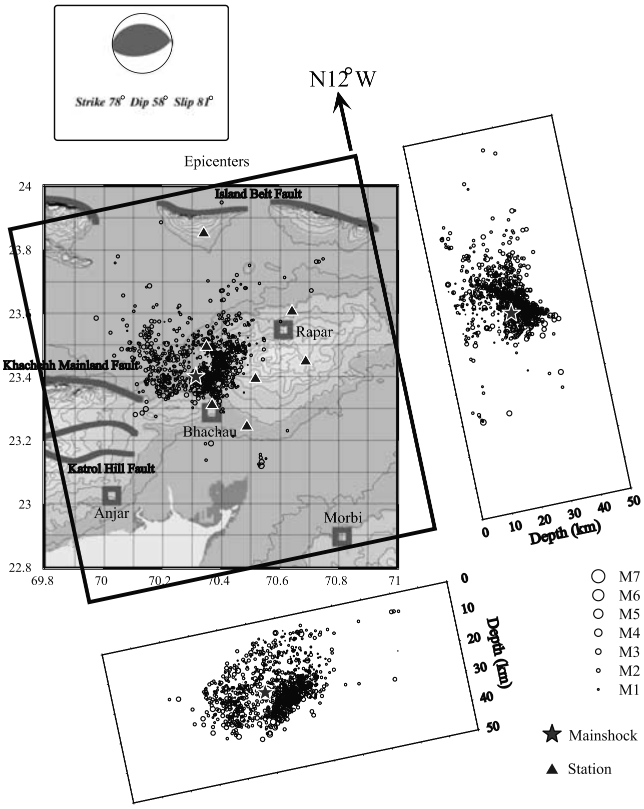

Figure 1. Locations of aftershocks determined in this study. Triangles show locations of temporary seismic stations. The cross section on the right is inferred to be perpendicular to the fault and the cross section on the bottom is parallel to the fault. Hypocenter location is from USGS.

the damage centered on Bhuj, suggesting that the city was located close to the fault, although this turned out not be the case and smaller villages east of Bhuj had more severe damage.

[5] We placed our stations mainly east of the epicenter in an array which extends about 70 km in the north-south direction and 40 km in the east-west direction (Figure 1). This decision was based largely on road accessibility to sites and some informal reports that many aftershocks were occurring in the eastern region. It was not difficult to find good sites for the seismometers with about half of the stations located on or close to rock outcrops. Also, cultural noise was generally low in the area.

[6] All the stations had three-component velocity sensors with natural frequencies of 1 or 2 Hz and 20 bit digital recorders with a sampling interval of 0.01 s. The array of 7 stations was in operation for about 7 days from February 28 through March 6. Details about the station locations and instrumentation are described in *Negishi et al.* [2001].

3. Aftershock Locations

[7] During the instrument deployment, we recorded a few thousand aftershocks and located 1428 of the larger events for this study. From the waveform data, P arrival times could usually be picked within about 0.02 seconds and S arrival times within about 0.1 seconds. Since there was almost always a station within a distance comparable to the hypocentral depth, there was good control on the depth determinations. Earthquake hypocenters were determined using the Joint Hypocenter Determination Program [*Engdahl et al.*, 1982] with the velocity model (Table 1) used by the National Geophysical Research Institute for locating earthquakes in the region (B.K. Rastogi, pers. Comm..) and station corrections determined in this study.

[8] Figure 1 shows the epicenters of 1428 aftershocks which were located using P and S arrivals from 5 to 7 stations. The RMS time residual ranged from about 0.02 to 0.07 seconds. The star shows the mainshock epicenter as determined by the USGS. The area of aftershocks, which may be interpreted as the area of the fault that ruptured during the mainshock, has dimensions of about 40 × 40 km^2, extending from about 23.3°N to 23.6°N in the north-south direction and 70.1°E to 70.5°E in the east-west direction. There is the possibility that the station distribution may bias our estimate of the size of the aftershock area. Since our stations are to the east, there may be more events toward the west that are not located by our network. Our network is able to locate small (M1.7 to M2.0) earthquakes 50 to 60 km away from the hypocenter, so we think that we are not missing any large features of the aftershock distribution. In addition, the area of aftershocks determined by our network is very similar to the results of the Univ. of Memphis [*Powell et al.*, 2001] study. They established a temporary seismic network that extended more evenly over a larger region that included Bhuj to the west.

[9] The cross sections in Figure 1 are oriented in N12°W and S78°W directions, which are inferred to be close to the directions perpendicular and parallel to the fault from the mainshock focal mechanism (Kikuchi and Yamanaka, pers. comm.) In the N12°W cross section, there is a trend in the aftershocks that dips toward the south at an angle of about 50°. This is interpreted to be the fault plane of the mainshock. There are also many events that are not on this trend, forming a complex pattern to the aftershock distribution. We think that these locations are correct and that many aftershocks occurred in regions away from the main fault plane. Projecting the aftershocks onto other directions within a range of about ±15°, does not change the distribution significantly and still shows the southward dipping trend.

[10] In the two cross sections, the depth range of aftershocks is from about 10 to 35 km, which we interpret to be the depth range of the faulting. The aftershocks do not reach the surface, which is consistent with the observations that there was no obvious surface faulting for the earthquake. This depth range is deeper than most large crustal earthquakes and is one feature that makes this event particularly important for understanding intraplate earthquakes.

Table 1. Velocity Model Used in This Study

Depth to top of Layer (km)	P Velocity (km/sec)	S Velocity (km/sec)
0.0	2.30	1.33
0.2	4.99	2.88
0.3	3.40	1.96
2.9	4.70	2.72
3.0	5.76	3.33
6.0	6.21	3.59
20.5	7.01	4.05
30.0	6.66	3.85
37.0	8.47	4.90

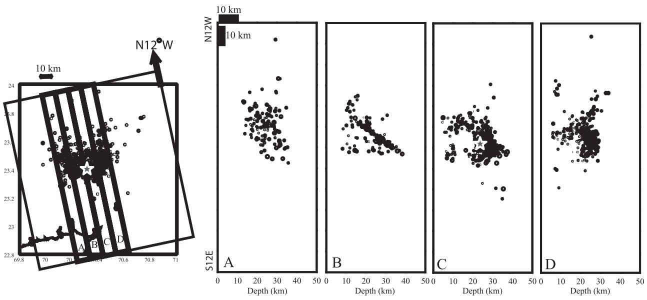

Figure 2. Detailed cross sections of the aftershock distribution.

[11] Figure 2 shows more detailed slices of the seismicity cross section. In the western portion of the aftershock zone, there is a clear southward dipping trend. However, in the eastern region the pattern of aftershocks is more complex. In section D, there is a suggestion of a conjugate fault with a dip in the opposite direction of the mainfault.

4. Relationship of Aftershocks to Mainshock Fault

[12] Our locations of aftershocks indicate a plane that dips toward the south at about 50° which is interpreted as the fault plane of the mainshock. The surface projection of this plane does not match any of the mapped faults in the area. The aftershocks are east and north of the Kachchh Mainland fault and south of the Allah Bund-Island Belt Faults (Figure 3). Our aftershock locations along with the mainshock focal mechanisms indicates a fault that strikes east or east-northeast. If this plane is extended to the surface, it would intersect the ground surface near the southern edge of the Rann of Kachchh, west of the city of Rapar. There are no obvious geological or topographic indications of a fault in this area.

[13] In the map view and cross section along the fault, there is an area of relatively few aftershocks in the region surrounding the mainshock hypocenter. This area near the hypocenter is also where the largest amount of slip occurred during the earthquake [*Mori et al.*, 2001]. This is similar to observations in other earthquakes which show aftershocks distributions that tend to cluster around the edges of large asperities [*Mendoza and Hartzell*, 1988].

[14] The overall dimensions of the aftershock distribution is small for an Mw 7.7 earthquake. For example, the similar magnitude 1999 Chichi Taiwan, (Mw7.7) had an aftershock area of about 40×100 km^2 [*Hirata et al.*, 2000] which is more than twice the size of the West India earthquake aftershock area. The small area implies that the static stress is high. If we assume that the region of the aftershocks is comparable to the area of the fault, the area has a radius (r) of about 20 to 25 km. Using the formula for a circular fault [*Eshelby*, 1957]

$$\Delta\sigma = 7/16 * \mathrm{Mo}/\mathrm{r}^3$$

the static stress drop is 12.6 to 24.6 MPa (126 to 246 bars) for a moment of 4.5×10^{20} Nm. This is a high value for a large earthquake. Intraplate earthquakes tend to have higher static stress drops than interplate earthquakes [*Kanamori and Anderson*, 1975], but this stress drop is high even among intraplate events (Figure 4). The high stress drop indicates that the near-field strong ground motions from this earthquake may have been particularly strong.

5. Conclusions

[15] We located 1428 aftershocks of the 2001 Gujarat, India earthquake from February 28 through March 6. The distribution of aftershocks showed the following features.

1. The aftershocks showed a trend that dips toward the south at about 50°. This is interpreted as the fault plane of the mainshock.
2. The depth distribution of aftershocks is from about 10 to 35 km and does not extend to the surface.
3. The aftershocks cover an area of about 1260 to 1960 km^2. This is small for a Mw7.7 earthquake and implies a high static stress drop of 12.6 to 24.6 MPa.

[16] It was surprising that a large (Mw7.7) shallow earthquake that caused severe damage did not have surface

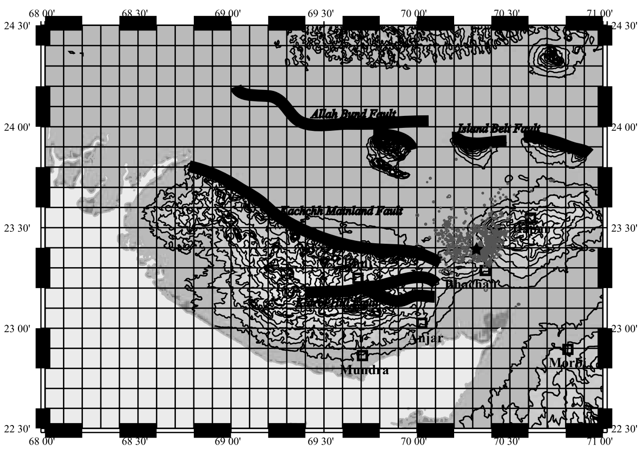

Figure 3. Aftershock locations of the 2001 Gujarat earthquake and mapped faults in the region.

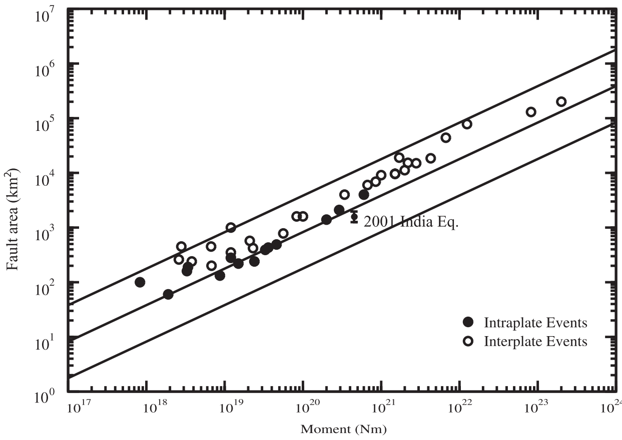

Figure 4. Relation between fault area and moment [data from *Kanamori and Anderson*, 1975] showing that the 2001 Gujarat event has a small source area and high static stress drop.

faulting. This is explained by our aftershock results which show that the fault plane of this event was slightly deeper than many large damaging earthquakes, extending from about 35 to 10 km depth. This result is important for evaluations of seismic hazards in continental areas. Large damaging earthquakes can occur on buried faults which show no displacement or topographic features at the surface. Earthquakes, such as the 2001 Gujarat event leave very little surface evidence of faulting that can be used to identify past earthquakes.

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H. Negishi, National Research Institute for Earth Science and Disaster Prevention, Japan.

J. Mori, Disaster Prevention Research Institute, Kyoto University, Japan.

T. Sato, Hirosaki University, Japan.

R. Singh, Indian Institute of Technology, India.

S. Kumar, Wadia Institute of Himalayan Geology, India.

N. Hirata, Earthquake Research Insitute, Tokyo University, Japan.