Geodetic constraints on the Bhuj 2001 earthquake and surface deformation in the Kachchh Rift Basin

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[1] GPS measurement of historic survey points in the region of the Mw 7.6 Bhuj earthquake of 26 January 2001 reveal a rupture area 25 km × 15 km, with the top of the rupture located at least 9 km beneath the surface. The geodetic data also reveal north-south convergence of ∼18 mm/yr across the Rann of Kachchh since 1856. Convergence and the occurrence of south-dipping reverse earthquakes on the northern edge of the Kachchh mainland suggest that the region is one of incipient or ongoing tectonic uplift. The small rupture of the Bhuj earthquake indicates that other earthquakes are likely to occur in the region, although few clues exist to indicate the progression of future ruptures. **Citation:** Wallace, K., R. Bilham, F. Blume, V. K. Gaur, and V. Gahalaut (2006), Geodetic constraints on the Bhuj 2001 earthquake and surface deformation in the Kachchh Rift Basin, *Geophys. Res. Lett.*, *33*, L10301, doi:10.1029/2006GL025775.

1. Introduction

[2] The Mw 7.6 earthquake of 26 January 2001 resulted in nearly 20,000 deaths and over 150,000 injuries. Numerous villages in the epicentral region were reduced to rubble [*Bendick et al.*, 2001], and the felt area extended from Madras to Kathmandu [*Hough et al.*, 2002]. The earthquake occurred in the Kachchh Rift Basin of western India, a region of significant historic seismicity several hundred kilometers from the nearest plate boundary (Figure 1). The 2001 earthquake and other historic earthquakes in the region were reverse faulting events, consistent with NW-directed compression.

[3] The earthquake was unusual for its depth, intraplate location, and small source area. Teleseismic and geodetic estimates indicate a moderately south-dipping rupture no greater than 40 × 40 km, with the slip concentrated at depths of 10–35 km [*Negishi et al.*, 2002; *Antolik and Dreger*, 2003]. The primary rupture did not reach the surface [*Wesnousky et al.*, 2001].

[4] Past seismicity in the region includes the 1819 Rann of Kachchh earthquake [*Oldham*, 1926; *Bilham*, 1998], which had a felt area similar to the 2001 event [*Hough et al.*, 2002] and is believed to have created an uplifted tract of land 90 km long with a peak height of 4.3 m, known as the Allah Bund ('Dam of God') [*Burnes*, 1833]. Estimates of the magnitude of the 1819 earthquake range from Mw = 7.6 to Mw = 8.2 [*Hough et al.*, 2002; *Rajendran and Rajendran*, 2001; *Bilham*, 1998; *Ambraseys and Douglas*, 2004]. Another significant event was the Mw = 6.0 Anjar earthquake of 1956, which occurred on a NE-SW striking plane dipping ∼45°N, closely aligned with the stress field responsible for the 1819 event [*Chung and Gao*, 1995; *Bendick et al.*, 2001; *Rajendran and Rajendran*, 2001].

[5] The occurrence of two M > 7.5 earthquakes within 200 years has generated several theories about the tectonic setting of the Kachchh region. *Bilham et al.* [2003] suggest that the Bhuj earthquake and other intraplate Indian events may be related to the stress regime dictated by the flexure of the Indian plate. *Stein et al.* [2002] proposed that the region may be part of a "flake" of broken plate. It has also been suggested that the Bhuj earthquake was triggered by an increase in Coulomb stress due to the 1819 event [*To et al.*, 2004].

[6] Prior to 2001, geodetic data in the Bhuj region was sparse and of generally poor quality, impeding the determination of rupture by geodetic means. Using GPS measurements of historic Great Trigonometrical Survey of India (GTS) points, this study characterizes 140 years of surface deformation using linear strains and angular changes and estimates the co-seismic signal of the 2001 earthquake. The study also confirms a convergence signal across the Kachchh Rift Basin identified by *Jade et al.* [2003].

2. Data and Methods

[7] The points measured in 2001 were constructed in 1855–1865 by the Survey of India as part of the Kattywar and Cutch Coast Series of the South West Quadrilateral [*Cole*, 1890; *Strahan*, 1893]. The monuments consist of points inscribed in stone or bedrock and surrounded by stone or masonry pillars. Some monuments appeared to be unchanged from the GTS site descriptions; others have been reconstructed or altered. For these the offset between the original and current mark was measured and the uncertainties are included in the station position uncertainty.

[8] Nine intact monuments were occupied in the epicentral region and two outside the region, one north of the Rann of Kachchh in Pakistan and one on the Kathiawar Peninsula to the south (Figure 1 and Table 1). One site (DAJK, located at 70.81°E, 23.69°N) has been rebuilt 2 km from its original location and had to be discarded, leaving ten sites for the analysis. The data were recorded at 30 s intervals on Trimble 4000 and 5700 receivers with L1/L2 ground-plane and Zephyr Geodetic antennae, for durations of 6 hours to five days. The data were processed using Bernese 4.2 software. The coordinates were calculated in

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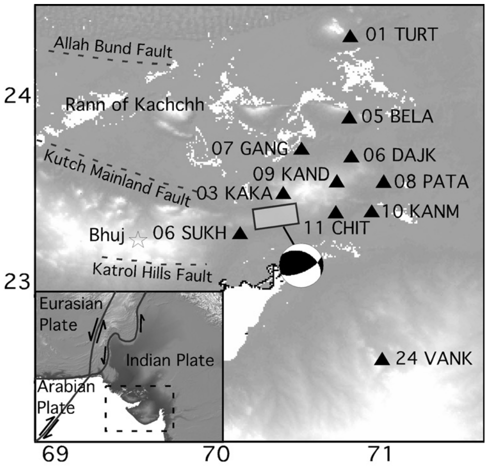

Figure 1. Geographic and tectonic setting of the Bhuj 2001 earthquake and major faults in the Kachchh rift region, including the location of the 1819 Allah Bund earthquake [*Wesnousky et al.*, 2001]. The triangles represent the eleven measured GTS/GPS campaign stations. The focal mechanism (shown offset from its actual location) is from the Harvard CMT catalogue; the shaded rectangle represents the best-fit fault rupture. Inset: Tectonic setting of Kachchh and the Kachchh rift basin with respect to the boundaries of the India, Eurasian, and Arabian plates.

the ITRF2000 reference frame, constrained by GPS stations at Bhuj and Anjar and eleven IGS stations (ALGO, GOLD, ZIMM, KIT3, IISC, IRKT, POL2, JOZE, LHAS, WUHN, and URUM).

[9] The GTS positions were measured with reference to the non-geocentric Everest spheroid, whose relation to the ITRF2000 reference frame is nonlinear and unspecified [*Bomford*, 1971]. Thus, displacements cannot be directly calculated from a coordinate transform. Another method of determining surface strain while avoiding the scale errors of different reference frames is to use angular changes, but this is possible only where three GTS triangle vertices are recovered [*Frank*, 1966]. Because the centrally-located site DAJK was unusable, only four sites in the campaign form complete triangles (KAND, CHIT, PATA, KANM) (Table 2).

[10] An earlier analysis extracted strain by assuming that points >200 km from the epicenter had not moved and displacements near the epicenter were entirely co-seismic [*Jade et al.*, 2003]. In the present analysis we determine strains from baseline length changes between the pre- and post-seismic surveys (Table 3). Direct measurement of a local baseline was not possible, but measurements of two early baselines in stable regions of southern India were found to be accurate to 3×10^{-6} [*Paul et al.*, 1995]. Strains are calculated from straight-line chords between all stations. For non-contiguous sites, the imprecisely defined origin of the Everest spheroid is estimated, and the GTS positions and heights are corrected for published sea level elevations and the local geoid [*Blume*, 1999].

[11] The parameters of the Bhuj earthquake are calculated by comparing the observed strains to those calculated using *Okada*'s [1985] equations for surface motion due to displacement on a buried rectangular dislocation in an elastic half-space. A series of gridsearches are performed for the parameters endpoint location, strike, dip, depth, length, down-dip width, rake and slip. The stations are weighted by their uncertainties, and the fit between the observed and calculated parameters is evaluated using the χ^2 statistic (Figure 2). A subset of the calculations is

Table 1. GPS Stations Coordinates and Uncertainties Used in the Analysis

	Coordinates			Uncertainties		
GPS Site	Lat.	Long.	Ht., m	Lat., m	Long., m	Ht., m
01 TURT	24.5724	70.7913	106.009	0.0054	0.0073	0.0107
03 KAKA	23.4964	70.3997	92.235	0.0056	0.0079	0.0130
05 BELA	23.9037	70.7567	182.258	0.0055	0.0075	0.0116
06 SUKH	23.2810	70.1642	56.847	0.0066	0.0087	0.0135
07 GANG	23.7353	70.4984	14.966	0.0082	0.0120	0.0267
08 PATA	23.5574	70.9445	35.863	0.0083	0.0106	0.0181
09 KAND	23.5605	70.6893	90.055	0.0091	0.0119	0.0243
10 KANM	23.3981	70.8775	41.552	0.0080	0.0099	0.0149
11 CHIT	23.3924	70.6840	98.355	0.0050	0.0073	0.0111
24 VANK	22.6030	70.9336	129.543	0.0098	0.0011	0.0161

Table 2. Angular Changes, Observed Values and Uncertainties

Triangle	Angle, rad	Observed, rad	Change, mrad	Uncertainty, mrad
08, 10, 11,	0.5998	0.6052	5.42	0.0022
08, 11, 09	0.6149	0.6213	6.41	0.0017
09, 08, 10	0.7388	0.7364	−2.45	0.0045
09, 10, 11	0.8483	0.8395	−8.76	0.0034
10, 09, 08	1.1881	1.1787	−9.39	0.0028
10, 11, 09	0.7837	0.7817	−2.00	0.0047
11, 08, 10	0.5700	0.5760	5.96	0.0026
11, 09, 08	0.9396	0.9444	4.80	0.0050

Table 3. Baselines and Strains

Baseline	L, km	Azimuth	Strain, ppm
01, 05	74.57	182.71	−27.24
01, 07	99.06	197.77	−25.87
01, 08	114.02	172.12	−29.05
03, 06	35.84	225.15	19.77
03, 07	28.44	20.71	−33.88
03, 09	31.17	76.37	−33.38
03, 10	51.65	102.54	−21.49
03, 11	30.97	111.68	−23.81
03, 24	108.20	151.09	−8.00
03, 07	34.69	234.58	−3.67
05, 09	39.23	190.21	−4.63
06, 07	62.49	33.94	−9.80
06, 09	64.92	59.78	−3.74
06, 11	56.74	76.76	−0.51
06, 24	102.42	133.59	−3.72
07, 09	28.10	134.95	−1.24
07, 11	42.49	153.58	−5.71
08, 05	43.27	333.64	−6.28
08, 07	52.70	293.61	−6.79
08, 09	28.57	270.81	−14.40
08, 10	19.63	201.11	−14.76
08, 11	35.33	235.42	−10.28
09, 11	18.78	181.66	−9.83
10, 09	27.07	313.29	−15.56
10, 11	21.76	271.80	−10.22
10, 24	88.87	176.27	−5.65
11, 24	88.97	163.72	−8.03

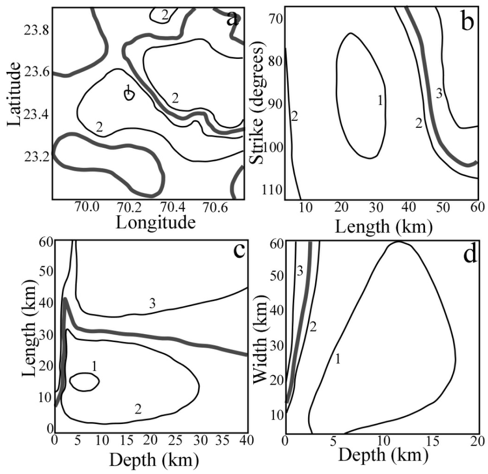

Figure 2. Results of the gridsearch method that compares observed strain values to those calculated from the *Okada* [1985] model to determine the best-fit parameters, shown in contours of the calculated χ^2 values. The bold lines represent the perimeter of the 1-σ range. The gridsearch is calculated for a number of parameter pairs: (a) Location of the endpoint in longitude and latitude. (b) Length and strike of the fault. (c) Depth to the top edge and length. (d) Depth to the top edge and down-dip width.

constrained by cosesimic changes from leveling data measured by *Chandrasekhar et al.* [2004] (Table 4). Initial calculations used no a priori assumptions about the location of the fault and revealed that the dip of the rupture is poorly constrained by the geodetic data. In subsequent calculations, the dip was fixed to 51°S, as determined from teleseismic data [*Antolik and Dreger*, 2003]. Other parameters determined by *Antolik and Dreger* [2003] are also used as initial values in the calculations: a western fault endpoint at 23.47°N, 70.28°E, a rupture size of 25 × 12 km, and a strike of 82°. The parameter ranges were varied as follows: fault endpoint ±100 km, strike ±45°, length 0–100 km, down-dip width 5–70 km, burial depth of the top edge 0–30 km, and dip-slip and strike-slip displacements ±20 m.

3. Results

[12] The gridsearch calculations were performed for both the angular changes and strain data. The results discussed below are from the strain gridsearch calculations. The results of the angular change gridsearches are consistent with the range of strain results but, because of the limited angular data available, do not further constrain any of the values.

[13] The best-fitting fault rupture is 25 × 15 km, striking 82°, with a burial depth of >5 km, ~12.6 m reverse slip and <5 m left-lateral slip. The range of acceptable solutions requires a length <40 km and a strike of 90 ± 10° (Figure 2). The western endpoint is located within 20 km of 23.5°N, 70.2°E and agrees well with other studies. The burial depth of 5–15 km, though not well-constrained by this study, is consistent with conclusions that slip was concentrated below depths of 10 km [*Antolik and Dreger*, 2003], with the top edge of the rupture at 10–12 km [*Negishi et al.*, 2002; *Chandrasekhar et al.*, 2004]. The slip and down-dip width of the fault are very poorly constrained by the geodetic data; the 1-σ range of the gridsearch results permit total uniform slip values from 8–13 m. *Antolik and Dreger* [2003] found a peak slip value of 12.4 m, suggesting that the high end of this range is a maximum rather than a uniform value. The leveling data of *Chandrasekhar et al.* [2004] (Table 4) as a vertical motion constraint on some of the points do not alter the results, indicating that the horizontal and vertical data are internally consistent.

[14] The data also reveal −25.9 to −29.1 μstrain between station TURT, north of the Rann of Kachchh in Pakistan, and stations of the epicentral region (GANG, BELA, and PATA) (Table 3). The convergent motion cannot be ascribed to the co-seismic signal of the earthquake, nor can it be explained by site reconstruction or instability. TURT is inscribed on granite, and the other three are original GTS monuments on competent surface rock. The data suggest that in the past 140 years there has been convergence across the Rann of Kachchh equivalent to a rate of ~18 mm/yr or total convergence of ~2.5 m. The angular changes of the triangles crossing the Rann is 0.2° for the largest angle and 0.05° for the smallest, compared to estimated angular errors of 0.49″ and 0.55″ in the original GTS measurement [*Cole*, 1890]. The current data cannot distinguish between steady convergence or coseismic deformation due to historical earthquakes. An earthquake during the 1856 survey caused enough deformation that remeasurement of some angles was required, but the changes were not published and it is unclear which triangles were affected.

4. Discussion and Conclusions

[15] With a poorly-constrained uniform slip estimate of 8–13 m, the best-fitting fault rupture area range of 375–1000 km^2 corresponds to a moment of $M_0 = 1.0 \times 10^{20}$–3.7×10^{20} Nm and a moment magnitude of Mw = 7.4–7.7. Using the relation for a circular fault of equivalent area [*Kanamori and Anderson*, 1975], the static stress drop for 13 m slip is 28–46 MPa, high even for an intraplate earthquake. For the more reasonable value of 8 m uniform slip, the static stress drop range is 18–29 MPa. The aftershock distribution [*Negishi et al.*, 2002; *Bodin and Horton*, 2004] and waveform inversions [*Antolik and Dreger*, 2003] suggest a fault area of 1000 km^2 or greater and a static stress drop of ~20 MPa. Thus, the larger fault area and lower slip found in this analysis agree best with other studies.

[16] The tectonic setting of the Bhuj earthquake is enigmatic. It occurred ~600 km south of the crest of the flexural bulge of the Indian plate, in a region in which the highest compressional stresses and associated ruptures controlled by flexure of the Indian plate are expected to occur at the surface, not in the lower crust [*Bilham et al.*, 2003]. The

Table 4. Vertical Deformation From Chandrasekhar

Leveling Location	Vertical, m	Station
23.4828, 70.5195	−0.148 m	CHIT
23.4613, 70.3701	1.670 m	KAKA
23.4828, 70.5195	−0.148 m	KAND
23.1734, 70.1515	0.000 m	SUKH

1819 and 2001 earthquakes and the observed convergence of ~18 mm/yr across the Rann of Kachchh, suggest that the Kachchh mainland may represent a region of uplift similar to the early evolution of the Shillong plateau, which has achieved an elevation of 1.6 km [*Bilham and England*, 2001]. The Bhuj earthquake may be one of several that cumulatively permit the northern edge of the Kachchh mainland to rise, but the >10 km depth of the earthquake means that surface geology provides only indirect information about the process.

[17] The size of the rupture shows that a relatively small part of the Kachchh structure slipped in 2001, and nearby regions are potential source regions for similar earthquakes. Although the magnitude of the 1819 Kachchh earthquake remains controversial, if the 1819 earthquake had a Mw $\leq$ 7.8 and similar stress drop and down-dip geometry, its rupture length would have been <80 km. The paucity of known historical earthquakes suggests that the region of the Kachchh Rift Basin between the 1819 and 2001 ruptures could fail in future earthquakes. The regions to the east and west are also potential locations for future earthquakes.

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