GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L19608, doi:10.1029/2004GL020768, 2004

Source parameters of the Bhuj earthquake, India of January 26, 2001 from height and gravity changes

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Received 17 June 2004; revised 28 August 2004; accepted 15 September 2004; published 9 October 2004.

[1] Height and gravity measurements observed along a profile across the epicentral area before and after the January 26, 2001, M_w 7.6 Bhuj earthquake show a maximum uplift of 1.57 ± 0.5 m and a corresponding gravity change of −393 ± 18 μGal. A best-fit, single-dislocation model inverted from the height-changes using non-linear optimization methods indicates that the high-slip rupture was well contained in the aftershock zone and likely did not break to depths shallower than ~10 km. Source parameters arrived in the present study agree well with those provided by seismic inversions and the distribution of aftershocks. Gravity data over the epicentral area are well modeled by the preferred model; however, a strong influence of shallow hydrological processes is inferred for three sites, two located on the Banni plains, whose mean gravity change ~280 μGal suggests a total mass redistribution of as much as 2.9 Mt. *INDEX TERMS:* 0920 Exploration Geophysics: Gravity methods; 1208 Geodesy and Gravity: Crustal movements—intraplate (8110); 1204 Geodesy and Gravity: Control surveys; 1242 Geodesy and Gravity: Seismic deformations (7205); 9320 Information Related to Geographic Region: Asia. **Citation:** Chandrasekhar, D. V., D. C. Mishra, B. Singh, V. Vijayakumar, and R. Bürgmann (2004), Source parameters of the Bhuj earthquake, India of January 26, 2001 from height and gravity changes, *Geophys. Res. Lett.*, *31*, L19608, doi:10.1029/2004GL020768.

1. Introduction

[2] The Bhuj earthquake of January 26, 2001 in Kachchh, India was one of the largest historic intraplate events (M_w = 7.6). An event of similar magnitude rocked Kachchh in 1819, resulting in a 90-km-long scarp like fold above a blind reverse fault [*Bilham*, 1999]. Small surface deformation such as lateral spreads, sand blows, mud volcanoes, craters, intense liquefaction and extensive dewatering in the low lying Rann of Kachchh was reported from field investigations [*Rajendran et al.*, 2001; *Wesnousky et al.*, 2001]; however, no surface rupture has been found in the epicentral region of the Bhuj earthquake.

[3] Fault plane solutions from teleseismic studies consistently suggest a reverse-slip mechanism for the Bhuj earthquake [*Antolik and Dreger*, 2003]. Whereas the lack of surface faulting and the depth distribution of aftershocks [*Negishi et al.*, 2002] suggest that the rupture was deeply buried, finite fault inversions of teleseismic broadband body waves by *Antolik and Dreger* [2003] suggest that in addition to the main high-slip asperity at depth substantial slip may have extended to near the surface. The coseismic N35°E displacement of 16 ± 8 mm obtained at Jamnagar ≈150 km south of the epicentral area is the only GPS-measured estimate of surface displacement; the analysis of motions of historic triangulation monuments of the Great Trigonometric Survey of India last surveyed in 1857 may provide additional constraints on horizontal motions [*Jade et al.*, 2002]. Here we present height and gravity changes to provide better insight into the source mechanics of the Bhuj earthquake.

2. Pre and Post Earthquake Measurements of Gravity and Elevation

[4] During 1997–99 a high-resolution gravity survey was carried out in the Kachchh Basin in connection with hydrocarbon exploration for the Indian oil industry. Gravity observations were taken in the form of two-fold three-way loops closed within 90 minutes to keep the bias from linear drift of the gravimeter. Gravimeter readings were corrected for the earth's tide [*Wenzel*, 1998]. Gravity was measured using LaCoste-Romberg gravimeters having least count of 1 μGal with real measurement precision of around 10 μGal. Because of severe damage to permanent structures, we could locate only 20 stations along two profiles of the 1997–99 survey (Figure 1), in November of 2001. Profile I (Mundra–Bachau-Manfara-Chitrod) extends across the epicentral area of the Bhuj earthquake and Profile II (Mundra-Bhuj-Banni) is located west of it. Station 1 was taken as reference point for the data reduction to determine relative changes between the two surveys (see auxiliary material[1]). Geodetic leveling was an integral part of the entire survey and a closed network of secondary benchmarks was established by using a Leica NA 724 auto level with 40x telescope and tied to the Great Trigonometric Survey benchmarks of the Survey of India by adopting standard three-wire leveling procedures. Misclosure tolerance relative to a reference station is estimated to accumulate as ~4 mm/km$^{1/2}$. The observations in 2001 were carried out using identical second-order spirit leveling procedures and equipment (along Profile I, only), as well as with dual-frequency GPS (occupied for ~2 hours per station) along both the profiles. GPS data were processed using the Turbo® software [*Allen Osborne Associates, Inc.*, 1998]. To compare GPS heights measured relative to the reference ellipsoid with orthometric heights from leveling, elevations of the geoid above the ellipsoid must be estimated and applied. Thus, the GPS-derived height measurements with respect to the WGS-84 reference ellipsoid were corrected using the global geoid model EGM96 and the local, higher-resolution geoid determination computed from the

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0094-8276/04/2004GL020768$05.00

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020768.

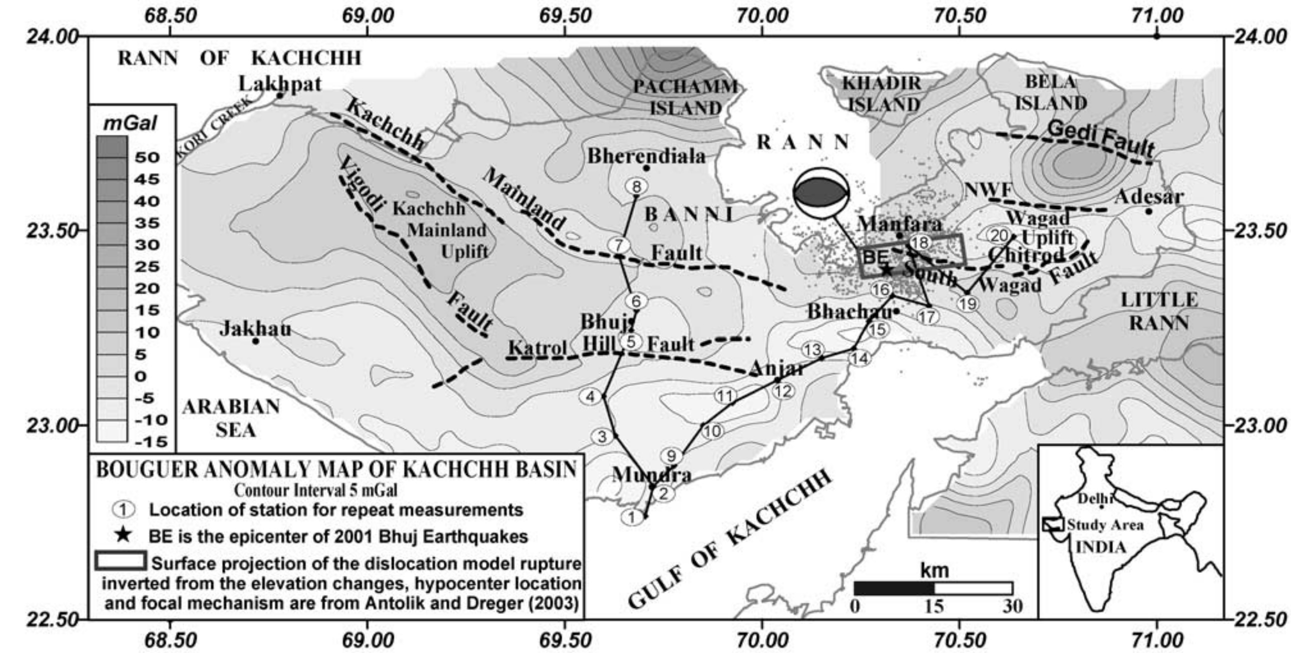

Figure 1. Bouguer anomaly map of Kachchh [after *Chandrasekhar and Misra*, 2002] showing major tectonic elements (mapped faults) [after *Biswas and Deshpande*, 1970] and the location of stations occupied along Profile I as 1, 2, 9–20 and Profile II as 1–8 for repeat observation. Grey dots indicate aftershock distribution from *Negishi et al.* [2002]. A hidden fault NWF inferred by *Chandrasekhar and Mishra* [2002].

closely spaced (1–2 km) free-air gravity data of *National Geophysical Research Institute* [1978] and *Chandrasekhar and Mishra* [2002]. One standard-deviation uncertainties in the GPS-measured, geoid corrected relative heights are about 0.06 to 0.15 m (Table 1[1]).

3. Results

[5] Figure 2a shows the change in elevation (leveling-leveling) from 1997 to 2001 along Profile I. The data indicate a gradual rise from Mundra to Bachau. Close to the epicenter at Manfara, the uplift increases steeply (to 1.57 ± 0.5 m) and then decreases to the east on the Wagad highland. Figure 2a also shows the similar trending coseismic uplift pattern measured using differential GPS, which shows a maximum change at Manfara of 1.67 ± 0.3 m. The observed gravity changes indicate a corresponding peak minimum located at Manfara (−393 ± 18 μGal). As expected, the elevation changes are strongly anti-correlated with the gravity changes. If we assume that the gravity changes are solely due to elevation change of a wide region (Bouguer gravity) we would expect gravity to change −0.19 μGal for 1 mm of uplift (Figure 2a). However, we calculate the full solution of gravity changes due to dislocation slip [*Okubo*, 1992] when comparing our source model to the gravity changes. The measurements along Profile II show small changes in elevation, whereas the gravity field shows an increase of up to 311 ± 8 μGal for sites located on the Banni plains (Figure 2b).

4. Coseismic Dislocation Model

[6] Dislocation models are widely used to infer the geometry and slip of sub-surface earthquake ruptures. *Okada* [1985] and *Okubo* [1992] derived analytical expressions for the displacements and gravity changes, respectively, due to faulting on a finite plane in an elastic, isotropic and homogeneous half-space. We use inverse methods to find a model that minimizes the weighted residual sum of squares, *WRSS*. We model relative elevation changes between each benchmark pair scaled by the variances and account for covariances between neighboring level sections. To determine a best-fit model, we use a constrained, nonlinear optimization algorithm [*Bürgmann et al.*, 1997], which allows us to estimate the geometry (parameterized by length, depth, width, dip, strike, and location) and the slip of a single model fault plane. As the data are not able to resolve each of these parameters, we apply additional constraints based on focal mechanism information [*Antolik and Dreger*, 2003] on the strike (82°) and dip (51°) of the rupture. Figure 2 shows the predicted height and gravity changes for all sites derived from this model.

[7] The small number, low precision and sparse spatial distribution of the height-change measurements limit our ability to uniquely determine the rupture parameters of the earthquake or develop more complex (e.g., multi-plane or slip distributed) models of the rupture. Nonetheless, the model we obtain in the inversion is well contained in the aftershock zone and consistent with rupture parameters derived from seismic data. The best-fit uniform-slip dislocation is 23 km long, 12 km wide, and dips S-ward at the constrained 51° dip angle from 12 to 22 km depth. Dip slip of 10.8 ± 0.5 m and small right-lateral strike slip of 0.7 ± 1.1 m on this dislocation provide a moment of 1.4 10^{20} Nm, which assuming a rigidity of 45 GPa [*Antolik and Dreger*, 2003], corresponds to a M_w = 7.4 event. This is less than the moment inferred from the moment tensor (3.6 10^{20} Nm) and the finite slip inversion (1.8 10^{20} Nm) of *Antolik and Dreger*

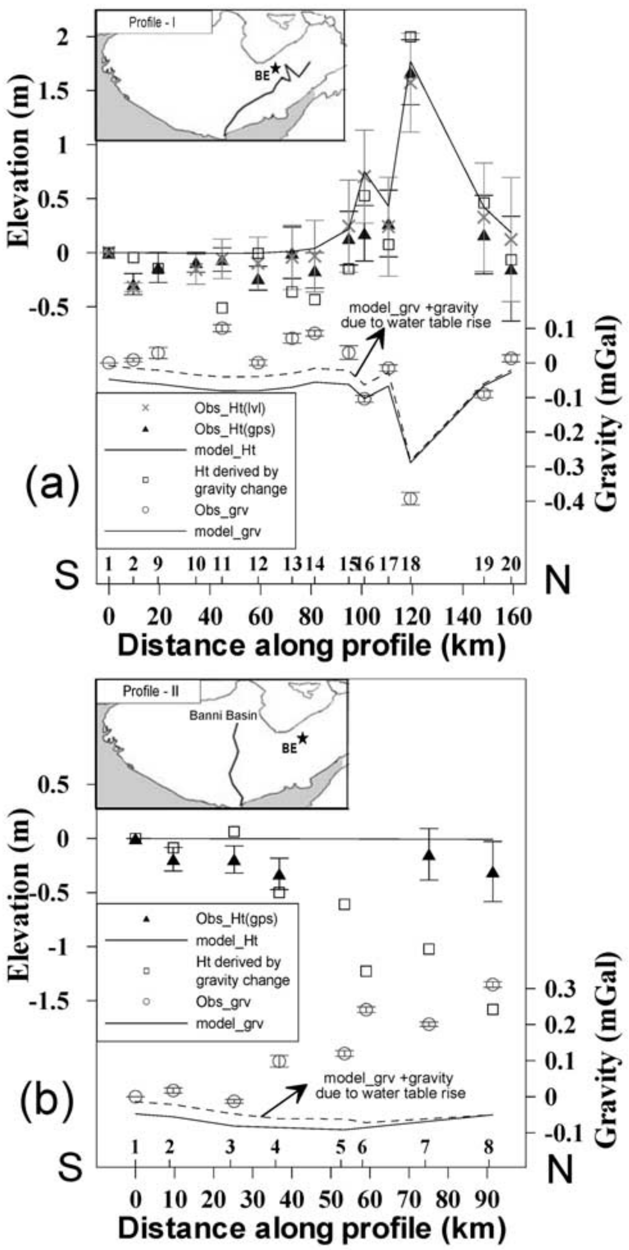

Figure 2. Measured gravity and elevation changes due to the Bhuj earthquake. (a) Gravity and height changes measured along Profile I between 1997–1999 and November of 2001. Error bars represent 1σ error relative to station 1. (b) Gravity and height changes along Profile II.

[2003]. The center of the top edge of the model rupture is located at 23.47°N, 70. 38°E. The *WRSS*/*degrees-of-freedom* misfit of this model is 4.3, suggesting that the data are adequately well fit within their uncertainties.

[8] We tested our ability to rule out shallower upper rupture terminations. We find that while models terminating below 10 km are preferred, the inversion is able to find shallower ruptures that fit the data almost as well by adjusting some of the other free model parameters in response to the depth constraint. Single-dislocation models shallower than ~5 km systematically underfit the uplift of all but stations 17 and 18 and lead to increases in *WRSS* over the preferred model of 10% or more. If we add a second dislocation projecting up-dip of our preferred model plane up to 1 km below the surface, the inversion prefers thrust slip of 0.5 m and strike slip of 2 m on this second fault, with a minimal change in *WRSS*. The preferred 580-element distributed-slip dislocation model of *Antolik and Dreger* [2003], which includes a region of shallow moment release in addition to the main 25 km × 15 km rupture asperity near the hypocenter, is broadly consistent with the data, but results in a *WRSS* = 292, compared to the *WRSS* of 130 in our preferred model. The leveling data do not favor, but can't rule out slip at shallow depths.

5. Gravity Changes Due to Faulting and Subsurface Mass Redistribution

[9] We use the optimized model inverted from the elevation-change data to forward model the associated gravity changes using the solution of *Okubo* [1991, 1992]. We find that for the sites along Profile I the coseismic gravity changes are consistent with the model derived from the accompanying elevation changes. The difference between modeled and observed gravity up to 100 μGal for some sites along Profile I could be due to the influence of coseismic water table rise up to 8 m as reported by *Jain* [2003] and *Times News Network* [2004], contributing up to 40 μGal for an assumed porosity of ~10% for sediments in this area (Figure 2), further residual may come from the ocean-atmospheric loading.

[10] Differences in the observed and modeled field along Profile II of about 280 μGal can be attributed to coseismic shallow hydrological processes such as extensive dewatering [*Bernard et al.*, 2003] and intense liquefaction [*Rajendran et al.*, 2001], which are widely reported from the Banni plains, and might have caused significant subsurface mass redistribution. Coseismic mass redistribution can be estimated from the observed gravity change by using Gauss law: $\Delta m = \left(\frac{1}{2}\pi G\right)\oint \Delta g ds$, where G is the gravitational constant and Δg is the gravity change (m/s^2) in a surface area of *ds* [*Hammer*, 1945]. Applying this to the anomalous mean gravity change of 280 μGal over an area of 1000 km^2 affected by sand boils, craters, dewatering and liquefaction processes, we can gather that about 2900 t/km^2 of mass was redistributed in the Banni subsurface due to the Bhuj earthquake.

6. Discussion and Conclusion

[11] The Bhuj earthquake took place in a poorly instrumented region and lack of a surface rupture precludes a clear picture of the source kinematics. Our inversion results are consistent with the geometry and small rupture dimensions suggested in prior studies based on the distribution of aftershocks [*Negishi et al.*, 2002] and waveform inversions [*Antolik and Dreger*, 2003]. This indicates that the Bhuj earthquake was a high-stress drop event on a steep reverse fault in the lower crust. For comparison, the similarly large magnitude 1999 Chi-Chi earthquake (M_w = 7.6) ruptured an ~100-km-long and 30-km-wide segment of the Chelungpu fault in central Taiwan with offset of up to 10 m along its prominent surface trace [*Johnson et al.*, 2001].

[12] Although the projected intersection of the rupture plane with the earth's surface does not coincide with any

mapped fault of this area, it lies along the westward extension of a fault zone (NWF) that was inferred by *Chandrasekhar and Mishra* [2002] based on the gravity anomaly of the Kachchh basin. Even major earthquakes can and do occur on buried faults with no obvious geologic surface expression, which should be considered as a potential earthquake hazard in intraplate regions.

[13] The change in gravity along Profile I follows a linear inverse relationship with the elevation changes; i.e., 10 mm of height variation produces $\sim$2 μGal of gravity change. However, the change in gravity along the northern half of Profile II cannot be explained by the height changes alone. Instead, change appears to be due to mass redistribution by coseismic shallow hydrological processes in the Banni plains.

[14] **Acknowledgments.** D. V. Chandrasekhar, D. C. Mishra, B. Singh, and V. Vijayakumar are thankful to Director, NGRI for his support. We thank Dr. Jason Zhaos, Prof. Roger Bilham and two anonymous reviewers for their help and suggestions in improving the manuscript.

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