Postseismic deformation and stress changes following the 1819 Rann of Kachchh, India earthquake: Was the 2001 Bhuj earthquake a triggered event?

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[1] The 2001 M_w 7.6 Bhuj earthquake occurred in an intraplate region with rather unusual active seismicity, including an earlier major earthquake, the 1819 Rann of Kachchh earthquake (M7.7). We examine if static coseismic and transient postseismic deformation following the 1819 earthquake contributed to the enhanced seismicity in the region and the occurrence of the 2001 Bhuj earthquake, ∼100 km away and almost two centuries later. Based on the Indian shield setting, great rupture depth of the 2001 event and lack of significant early postseismic deformation measured following the 2001 event, we infer that little viscous relaxation occurs in the lower crust and choose an upper mantle effective viscosity of 10^{19} Pas. The predicted Coulomb failure stress (DCFS) on the rupture plane of the 2001 event increased by more than 0.1 bar at 20 km depth, which is a small but possibly significant amount. Stress change from the 1819 event may have also affected the occurrence of other historic earthquakes in this region. We also evaluate the postseismic deformation and ΔCFS in this region due to the 2001 event. Positive ΔCFS from the 2001 event occur to the NW and SE of the Bhuj earthquake rupture. *INDEX TERMS:* 1208 Geodesy and Gravity: Crustal movements—intraplate (8110); 8100 Tectonophysics; 8164 Tectonophysics: Stresses—crust and lithosphere. **Citation:** To, A., R. Bürgmann, and F. Pollitz (2004), Postseismic deformation and stress changes following the 1819 Rann of Kachchh, India earthquake: Was the 2001 Bhuj earthquake a triggered event?, *Geophys. Res. Lett.*, *31*, L13609, doi:10.1029/2004GL020220.

1. Introduction

[2] The M_w 7.6 26 January 2001 Bhuj earthquake was the most deadly earthquake to strike India in its recorded history; about 20,000 people were killed and 166,000 people were injured [e.g., *Bendick et al.*, 2001]. Although this region is >300 km from boundaries of the Indian plate, it has experienced several damaging earthquakes (Figure 1). Among those, the 1819 Allah Bund (or Great Rann of Kachchh) earthquake ranks as one of the largest among global intraplate earthquakes [*Johnston and Kanter*, 1990]. The 1819 earthquake produced an about 90-km-long, 6-km-wide and 3-to-6-m-high uplift known as the Allah Bund [*Oldham*, 1926; *Bilham*, 1998; *Rajendran and Rajendran*, 2001]. From the surface deformation the magnitude is estimated to be $M_w = 7.7 \pm 0.2$ [*Bilham*, 1998]. Considering the intra-plate setting and apparent low Holocene deformation rates in the region [*Wesnousky et al.*, 2001], the occurrence of two M > 7.5 and ∼10 M > 5 earthquakes in 200 years warrants evaluation of a causal link between the events leading to such accelerated moment release [*Bendick et al.*, 2001].

[3] Earthquakes and subsequent relaxation processes change the stress in the surrounding Earth's crust and can enhance or delay the occurrence of earthquakes on nearby faults. Here, we examine the possible connection between the occurrence of the 1819 Allah Bund earthquake and the 2001 Bhuj earthquake located about 100 km away. Numerous studies have shown a correlation between calculated positive coseismic stress changes (shear and normal stresses calculated using elastic dislocation models) and the location of aftershocks as well as triggering of moderate to large earthquakes [*Harris*, 1998]. Coulomb stress changes of >∼0.1 bar have been found to significantly impact seismicity patterns [*Reasenberg and Simpson*, 1992; *Harris*, 1998; *Stein*, 1999]. It has been suggested that postseismic relaxation in the lower crust and upper mantle also plays an important role in stress transfer and earthquakes triggering. For example a sequence of M > 8 earthquakes occurred in Mongolia from 1905 to 1967, where background loading is comparatively small. Each event occurred more than 10 years and 100 to 400 km apart. Coseismic stress changes are small at the remote distances and it is difficult to explain the 10 to 30 years time intervals between events. The earthquake sequence is well explained by taking into account the large and far reaching stress changes from postseismic viscous flow in the crust and upper mantle [*Chéry et al.*, 2001; *Pollitz et al.*, 2003].

[4] Here, we explore quantitatively, in the framework of the Coulomb failure criterion, the idea that both coseismic and postseismic stress changes from the 1819 earthquake increased the likelihood of failure at the site of the 2001 event. We also calculate predicted regional surface displacements and stress changes resulting from the 2001 earthquake and subsequent relaxation.

2. Model Calculations

[5] We compute coseismic [*Pollitz*, 1996] and postseismic [*Pollitz*, 1997] deformation and stress changes using spheroidal and toroidal motion modes of a spherically stratified elastic-viscoelastic medium. The model is parameterized by specifying the fault geometry and slip of the source event and the depth dependent elastic and viscous parameters. Coulomb stress changes are evaluated along the slip direction on the receiver fault, such as on planes parallel

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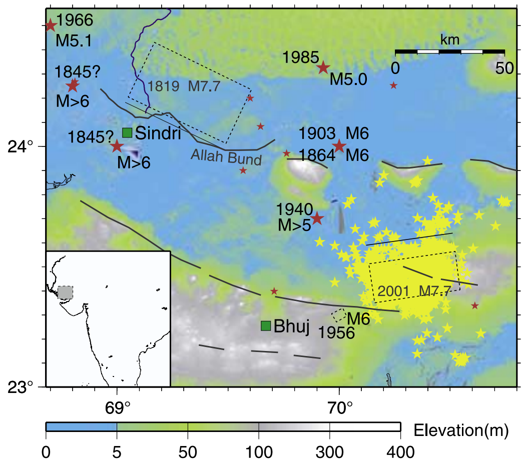

Figure 1. The location of major faults and post-1819 earthquakes (*Rajendran and Rajendran* [2001] for 1819–1966 events, and USGS-NEIC catalog.) Events of M > 5 are shown by large red star, M < 5 are shown by small red star. Dashed rectangles outline the fault geometry of the 1819, 1956, and 2001 events. The intersections of the faults with the surface are shown in thick gray lines. Yellow stars are aftershocks of the 2001 event [*Negishi et al.*, 2001].

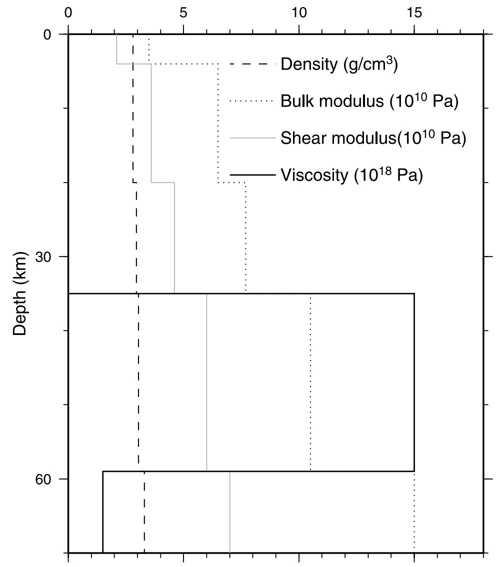

Figure 2. Viscoelastic stratification used for the calculation. Upper-mantle viscosities of 1.5×10^{17}, 1.5×10^{19} and 1.5×10^{21} Pas were considered.

to the rupture of the 2001 earthquake, and at a depth of 20 km, near which the 2001 earthquake nucleated.

2.1. 1819 Source Rupture Model

[6] The fault parameters chosen for the 1819 event are based on *Bilham* [1998] and *Bilham et al.* [2003]. *Bilham* [1998] suggested a shallow (from 10 km to near the surface) reverse-slip rupture on a 90-km-long 50–70° N-dipping fault plane to match the measured elevation changes from the event. *Bilham et al.* [2003] take the great depth and short lateral fault length of the 2001 rupture into consideration and incorporate new topographic and remote sensing observations of the morphology of the Allah Bund fault scarp to obtain updated fault parameters. The 1819 event is estimated to have a 50-km-long rupture dipping 45° to the north with 3–8 m slip. The slip is set to 5.5 m in this study, consistent with a $M_w = 7.7$ earthquake for a rupture extending to 30-km depth.

2.2. Depth Dependent Viscoelastic Parameters

[7] The magnitude and pattern of postseismic deformation and stress changes depend strongly on the rheological layering of the crust and upper mantle, which in turn depends on composition, temperature and other environmental parameters. Seismic data show a Moho depth of 35–40 km [*Sarkar et al.*, 2002], which suggests that the 2001 earthquake and its 10–32-km-deep aftershocks ruptured to near the base of the crust. Thus the Indian shield is apparently significantly colder and less viscous than many plate boundary zones. Figure 2 shows the rheological model, which we adopt here. Density, bulk modulus, and shear modulus are consistent with seismic velocity and density layering used in other studies [*Antolik and Dreger*, 2003; *Negishi et al.*, 2002]. We chose the model viscosity of the upper mantle by calculating postseismic displacements for the 2001 Bhuj earthquake using a range of viscosity values, between 1.5×10^{17} and 1.5×10^{21} Pas, and by comparing the estimated deformation transients with early GPS measurements spanning a 6-month time period [*Jade et al.*, 2002; *Miyashita et al.*, 2001]. We adopted a model upper mantle viscosity of 1.5×10^{19} Pas.

2.3. Stress Change Calculations

[8] We calculate the coseismic and postseismic changes in Coulomb failure stress (ΔCFS) on the receiver fault. The geometry and slip direction (strike, dip and rake) of the receiver fault need to be specified for this calculation. Positive change in CFS indicates the increase in likelihood of failure on the receiver fault. It is given by $\Delta CFS = \sigma_s + \mu'\sigma_n$, where σ_s is the change in shear stress in the slip direction on the receiver fault, σ_n is the change in normal stress (tension positive), and μ' is the apparent coefficient of friction incorporating the influence of pore pressure. μ' value of 0.2 to 0.8 are widely used in other studies [e.g., *Harris*, 1998]. We present calculated ΔCFS given a range of friction coefficients, as well as changes of σ_s and σ_n (Table 1[1] and Figure 3). The receiver fault geometry of *Antolik and Dreger* [2003] for the Bhuj earthquake is adopted (strike = 82°, dip = 51°, rake = 77°).

3. Results

3.1. 1819 Earthquake Coseismic and Postseismic Stress Changes

[9] Figure 3 shows the CFS change from the 1819 event evaluated for faults with the geometry of the 2001 event at 20 km depth, close to the hypocentral depth of 22 km determined by *Antolik and Dreger* [2003]. The 1819 coseismic shear- and normal-stress changes at the hypocenter of the 2001 earthquake, are 0.06 bar and −0.09 bar, respectively, but stresses rise to 0.30 bar and −0.36 bar following 182 years of postseismic deformation. Within the range of μ'

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020220.

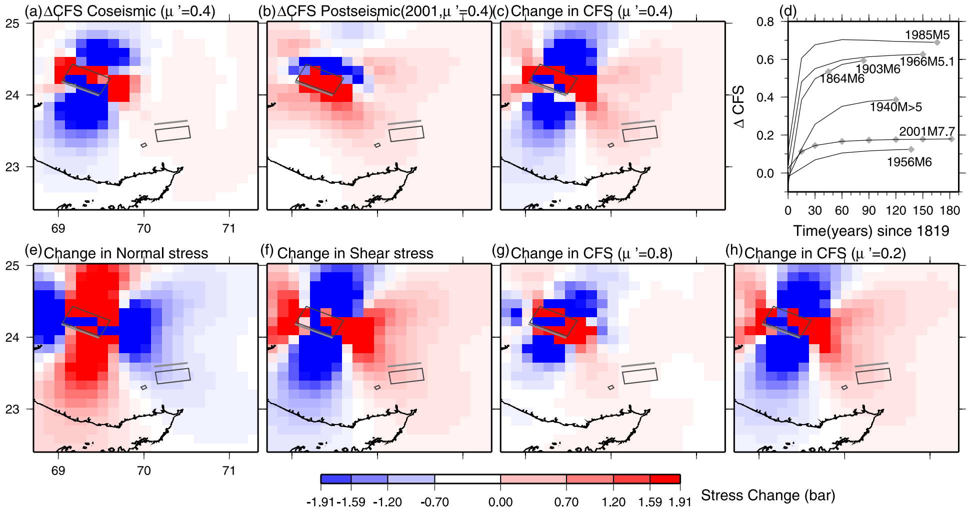

Figure 3. ΔCFS($\mu' = 0.4$) from (a) coseismic, (b) postseismic, and (c) coseismic and postseicmic deformation. (g) and (h) show ΔCFS from coseismic and postseismic deformation with μ' set at 0.2 and 0.8. The fault geometry of the 2001 rupture obtained from *Antolik and Dreger* [2001] is used and ΔCFS are evaluated at a depth of 20 km at the time of the 2001 earthquake. (e) and (f) show change of normal and shear stress from coseismic and postseimic deformation. (d) Change of CFS with time since 1819 at the hypocenter of the 2001 event and other M > 5 events in the region ($\mu' = 0.4$). Stress changes are calculated for E-W striking, 45°N or S-dipping reverse faults except for the 2001 [*Antolik and Dreger*, 2003] and 1956 event [*Chung and Gao*, 1995].

from 0.2 to 0.8, ΔCFS is positive at the location of the 2001 event. When μ' is set to 0.4, ΔCFS at the 2001 event location is 0.02 bar for the coseismic and 0.16 bar for the postseismic deformation (Figures 3a and 3b). The stress change at the 2001 hypocenter from the postseismic relaxation is 4–7 times greater than the immediate coseismic loading, which points to the importance of considering the contribution from viscoelastic relaxation of the lower crust and upper mantle in fault-interaction calculations. The ΔCFS distribution has a similar pattern at other depths and thus our stress-change estimates are not very sensitive to uncertainties in the hypocenter location. The total ΔCFS from coseismic and postseismic deformation are 0.17, 0.22 and 0.24 bar at the depth of 30 km, 10 km, and 0 km respectively with $\mu' = 0.4$. The change in CFS from the M_w 6.1 1956 Anjar earthquake (*Chung and Gao* [1995] at the location of 2001 is evaluated to be positive but very small (about +0.01 bar).

3.2. Postseismic Deformation of 2001 Bhuj Event

[10] To consider the potential impact of the Bhuj earthquake on future seismicity in the region and in anticipation of continued postseismic deformation measurements, we also evaluate the postseismic deformation and ΔCFS in this region due to the 2001 event. We constructed a coseismic fault model of the Bhuj earthquake based on the Harvard CMT solution, aftershock locations [*Negishi et al.*, 2001] and finite fault slip inversion results [*Antolik and Dreger*, 2003]. Strike, dip, rake and moment magnitude are set to 65°, 50°, 50°, and 3.6×10^{20} Nm, respectively. The slip distribution of *Antolik and Dreger* [2003] is taken into account, with larger amount of slip (8.2 m) confined to a small area in the center (25×15 km^2) and less slip (1.7 m) in the surrounding part. The model rupture is 40-km long and 10-to-32-km deep.

[11] To first order, major faults in the Rann of Kachchh region strike approximately in an E-W direction, dipping 40° to 50° to the south in the southern part and to the north in the northern part of the region. The faults in this region were formed under N-S tension, before the change to N-S compression occurred around 40 Ma, and therefore they have steeper dips compared to usual thrust faults [*Wesnousky et al.*, 2001].

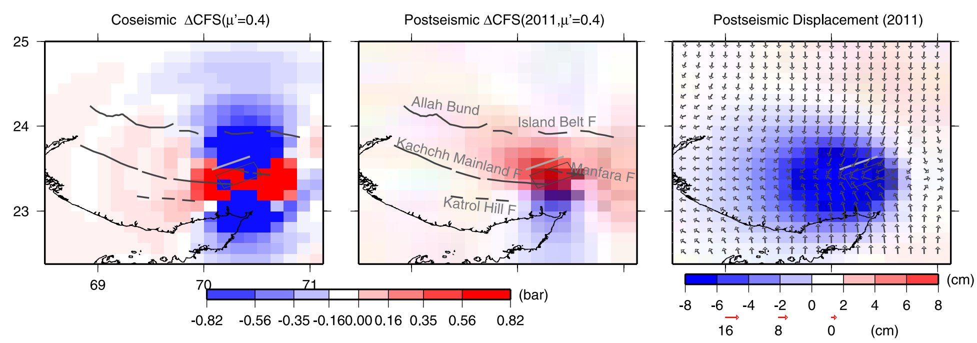

Figure 4. CFS ($\mu' = 0.4$) and postseismic surface displacements from 2001 earthquake evaluated for 10 years after the event. Stress changes are calculated for E-W striking, 45°N or S-dipping reverse faults.

[12] Figure 4 shows coseismic and postseismic (calculated for 2011) ΔCFS from the 2001 event, as well as the surface displacement field predicted from this model. Positive ΔCFS from the 2001 event occur to the NW and SE of the Bhuj earthquake rupture. If we consider the fault locations in the Rann of Kachh region, postseimic relaxation from the 2001 event enhances the stress on the Kachchh Mainland fault and faults in the Wagad highlands. The ΔCFS is slightly negative on the Katrol Hill fault.

4. Discussion

4.1. Model Sensitivity Analysis

[13] We examined the sensitivity of ΔCFS to the geometry of the 1819 fault rupture, the rheology stratification of the model and the geometry of the receiver fault. The result is provided in Table 1. In all of the models considered, we find more then 0.1 bar Coulomb stress increase on the 2001 event rupture. As stress changes as low as 0.1 bar can enhance the occurrence of an earthquakes [*Harris*, 1998], we conclude that the postseimic relaxation following the 1819 earthquake enhanced the loading on the 2001 rupture by a small, but possibly significant amount.

4.2. Stress Changes at Location of Other 1819–2001 Earthquakes

[14] We examined whether the stress change from the 1819 event affected the occurrence of other historic earthquakes in this region (shown in Figure 1). Although the locations of the pre-instrumental events are not well known [*Rajendran and Rajendran*, 2001], all $M > 5$ events occurred in the region where CFS increased by coseismic and postseimic loading from the 1819 event, if the receiver fault geometry is assumed to be an E-W striking, 45°N or S dipping fault plane. The calculated ΔCFS from coseismic and postseismic deformation for each event are +0.5 bar (1864), +0.6 bar (1903), +0.4 bar (1940), +0.6 bar (1966), +0.7 bar (1985) and +0.2 bar (1956). *Bilham et al.* [2003] proposed the possibility that the rupture of the 1819 event only ruptured along 50 km of the 90-km-long Allah Bund and that the subsequent 1845 event may have ruptured an adjacent segment to the west in a region where our calculations show coseismic and 25 years of postseimic deformation increased the Colomb failure stress by up to 1–4 bar along the Allah Bund strike.

5. Conclusions

[15] The coseismic and postseismic stress changes from the $M_w \approx 7.7$ 1819 Allah Bund earthquake encouraged failure on the 2001 Bhuj rupture fault plane. Computed ΔCFS changes range from 0.09–0.25 bar, depending on the choice of source and receiver fault geometry and the model rheology parameterization. Postseismic stress changes at the location of the 2001 earthquake exceed coseismic values by about a factor of 4 to 7. Other historic earthquakes in the region that occurred since 1819 also dominantly occurred in regions of enhanced ΔCFS from the 1819 earthquake. Coseismic and postseismic stress changes from the M_w = 7.6 2001 Bhuj earthquake will lead to comparable regional stress perturbations in the Rann of Kachchh region and might thus result in continued enhanced earthquake activity in an extended earthquake sequence in an otherwise low-strain rate, intra-plate setting.

[16] **Acknowledgments.** We thank Ruth Harris and an anonymous reviewer for helpful comments. Berkeley Seismological Laboratory Contribution #04-07.

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