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Inversions for earthquake focal mechanisms and regional stress in the Kachchh Rift Basin, western India: Tectonic implications

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ABSTRACT

More than a decade after the 2001 M_W 7.7 Bhuj earthquake in western India, aftershocks up to M_W 5.0 are still continuing around the rupture zone in the Kachchh Rift Basin. Over the years, some surrounding faults in the region have been activated, and a transverse fault generated an M_W 5.1 earthquake in 2012. Most of the earthquakes occur in the lower crust at depths between 15 and 35 km. We have determined focal mechanism solutions of 47 earthquakes (M_W 3.2–5.1) that were recorded by a 60-station broadband network during 2007–2014 within an area of 50 km radius of the 2001 main shock. South dipping nodal planes in most of the solutions correlate well with the active faults. The earthquakes near the epicenter of the 2001 main shock primarily show reverse-faulting mechanisms. The surrounding earthquakes in the area, however, show predominantly strike-slip mechanisms. The P axes of the earthquakes mostly oriented in north–south, and the T axes in east–west. However, the orientations of the P and T axes exhibit more complexity near the source area of the main shock. Stress field inversion of the solutions yields a dominant north–south compression, which is consistent with the ambient tectonic stress field owing to the northward movement of the Indian Plate with respect to the Eurasian Plate. The geodetic measurements are in reasonable agreement with our results.

1. Introduction

The Kachchh Rift Basin (KRB), in the westernmost part of the continental region of India, is seismically the most active region in India after the Himalaya where earthquakes of magnitudes in excess of 7.0 have occurred relatively frequently during the Holocene. The KRB and the adjoining region have been affected in the past by large damaging earthquakes. In 1668, an intensity X (M7) earthquake wrecked the town of Samaji (25.0°N, 68.0°E) in Pakistan, 200 km west of Kachchh on the Indus Delta (Burnes, 1835; Chandra, 1977). In 1819, another intensity X (M7.8) earthquake occurred ~100 km northwest of Bhuj (Fig. 1), resulting in an 80-km long and 6-m high scarp along the Allah Bund Fault (Johnston and Kanter, 1990). In 1845, an earthquake of MMI VIII hit Lakhpath in the western part of KRB (Oldham, 1883). In 1956, the M_W 6.0 (intensity VIII) Anjar earthquake caused 115 deaths (Tandon, 1959; Chandra, 1977; Chung and Gao, 1995). Nine damaging earthquakes of M5–6 have occurred during the past 155 years. One of the most disastrous Indian earthquakes of the new millennium occurred on the Republic Day of India on 26 January 2001 near Bhuj in the KRB with an intensity of X+ (M7.7) (Bendick et al., 2001; Antolik and Dreger, 2003; Rastogi, 2004; Singh et al., 2004). The fault plane solution of the mainshock of the 2001 Bhuj earthquake indicated a reverse faulting with a strike-slip component (e.g. Global Centroid Moment Tensor [GCMT] catalog; Antolik and Dreger, 2003), similar to that of the 1956 Anjar earthquake (Chung and Gao, 1995).

The 2001 Bhuj earthquake was a rare great intraplate earthquake, as the western boundary of the Indian Plate is about 400 km to the west, and the northern plate boundary is more than 1000 km away from the Himalayas. Ground deformation and acceleration due to the Bhuj earthquake caused large-scale destruction including 14,000 deaths, collapses or severe damages to over a million houses, and an economic loss of about US$10 billion (Directorate of Information Government of Gujarat, http://www.gujaratinformation.net). The fault responsible for the earthquake had not been known to be active previously and no surface rupture was mapped (Bodin and Horton, 2004) following the earthquake. The aftershocks of the Bhuj earthquake are still continuing (Singh et al., 2015) to this day. Every year, the region has on average one hundred or so small earthquakes (M_W 3–5). Such continental intraplate earthquakes seem to occur in existing zones of weakness

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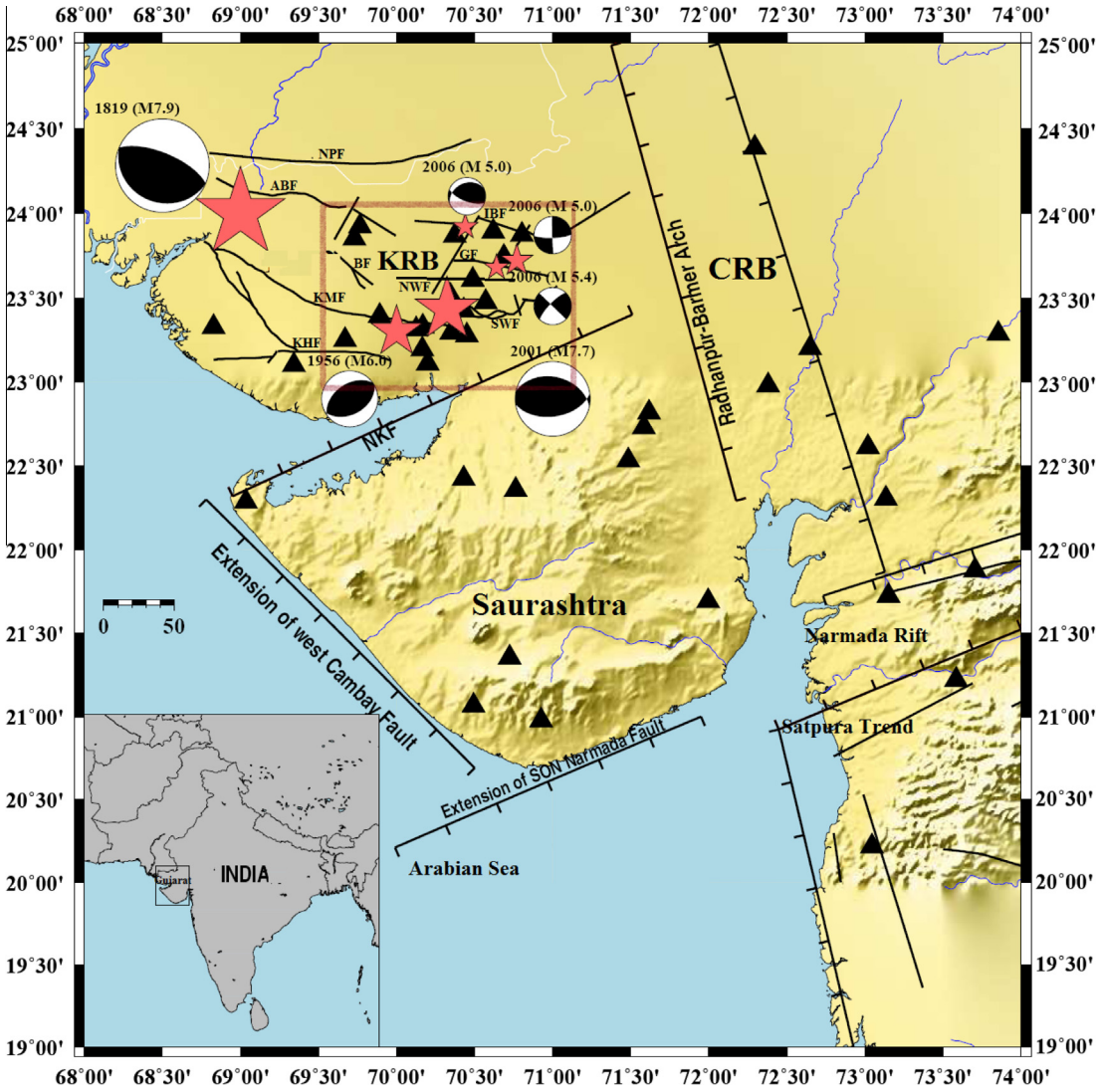

Fig. 1. Map showing the major tectonic features of the Gujarat State, India. Epicenters of damaging historical earthquakes and the 2001 Bhuj mainshock are indicated by red stars with sizes proportional to magnitudes. Beachballs depict the lower-hemisphere projection of the estimated focal mechanisms. Seismic stations are shown by black triangles. The box surrounding the KRB indicates the study region. Faults causing past seismicity in the Kachchh region are marked by black lines. They include: Allah Bund Fault (ABF); Island Belt Fault (IBF); Banni Fault (BF); Gedi Fault (GF); Kachchh Mainland Fault (KMF); South Wagad Fault (SWF); Katrol Hill Fault (KHF); and North Kathiwar Fault (NKF). The major rift basins are Kachchh Rift Basin (KRB) and Cambay Rift Basin (CRB). The black box in the lower-left inset map of India shows the location of the zoom-in region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by the reactivation of faults (Mckenzie, 1969; Sykes, 1978). More recently, a M_W 5.1 earthquake occurred on 19 June 2012 (23.654°N; 70.288°E), about 30 km north of the 2001 Bhuj mainshock along the NE-trending Khadir Transverse Fault (ISR Annual Report, 2013). The fault displaces the eastern part of Island Belt Fault and extends south to the western part of North Wagad Fault. The recorded maximum PGA at the nearest Chobari station (23.30°N; 72.63°E) on a soil site is 0.19g. However, the transverse faults are usually not expected to produce major earthquakes, and a few shocks also occurred in the same area in 2011.

Several studies have been devoted to understand the tectonic evolution and seismogenic environment of the region (e.g. Kayal et al., 2002; GSI, 2000, 2003; Mishra and Zhao, 2003; Mandal et al., 2004; Mandal and Johnston, 2006; Pandey et al., 2008; Singh et al., 2011, 2012; Rao et al., 2013a,b). They have discussed the geotectonic characteristics and their bearing on seismic structures, in particular the crustal heterogeneities, for understanding the seismic wave propagation and the damage pattern in the area. Geophysical investigations have also revealed strong crustal heterogeneities in the Bhuj source zone (Chandrasekhar and Mishra, 2002; Sastry et al., 2008; Naganjaneyulu et al., 2010). Geodetic observations demonstrated the spatial patterns of crustal motions in the KRB region (e.g. Reddy and Sunil, 2008; Chandrsekhar et al., 2009; Choudhury et al., 2013; Rastogi et al., 2014).

The focal mechanism of each earthquake provides information on the orientation of the stress field in the source region, and thus the orientation of the regional stress field can be obtained from the focal mechanisms of regionally distributed earthquakes (Patton and Zandt, 1991). The technique of inverting earthquake focal mechanisms for a uniform stress field has been proposed for decades (e.g. McKenzie, 1969; Angelier, 1979, 1984; Gephart and Forsyth, 1984; Michael, 1984). Hardebeck and Michael (2006) modified the linear stress inversion with bootstrapping (LSIB) method of Michael (1984, 1987) to allow for the spatial variation of stress field in the inversion. These approaches have been applied to estimate the spatial variation of stress field in various parts of the world (e.g. Michael, 1991; Zhao et al., 2013; Luo et al., 2015).

The study region is well equipped with a 60-station broadband seismic network, known as the Seismic Network of Gujarat (SeisNetG) that has recorded a large number of aftershocks since