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An insight into crack density, saturation rate, and porosity model of the 2001 Bhuj earthquake in the stable continental region of western India

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ABSTRACT

The 2001 Bhuj earthquake (Mw 7.6) source zone is examined in the light of crack density (ε), saturation rate (ξ) and porosity parameter (ψ) using new data set derived from a large aftershock sequence recorded by the Gujarat seismic network (GSNet) during November, 2006–December, 2009. Processes of rupture initiations of the mainshock and its aftershock sequence are better understood by synthesizing the dynamic snapshots of the source zone using the new dataset. Pattern of crustal heterogeneities associated with high-ε, high-ξ and high-ψ anomalies at depths varying from 20 km to 25 km is similar to those of earlier study by Mishra and Zhao (2003). The anomalous zone is found extended distinctly by 50–60 km in the lateral direction, indicating the reinforcement of cracks and fractured volume of rock matrix due to long aftershock sequence since 2001 Bhuj earthquake in the source area. It is inferred that the presence of a fluid-filled fractured rock matrix with super saturation may have affected the structural and seismogenic strengths of the source zone and is still contributing significantly to the geneses of earthquakes in and around the source zone. Anomalous pattern of high-ε with wider distribution of high-ξ indicates the existence of micro-cracks in the lower crust, while high-ψ suggests the cementation of cracks through permeation of residual magma/metamorphic fluids into the hypocenter zone. The results suggest that the existence of residual fluids in the fractured rock matrix in the mid to lower crust might have played a key role in triggering the 2001 mainshock and is still responsible for its continued long aftershock sequences.

1. Introduction

The Bhuj earthquake (Mw 7.6) of January 26, 2001, one of the deadliest Stable Continental Region (SCR) earthquake in the world, occurred in the Kachchh Rift Basin (KRB) of Gujarat state in western Indian peninsular shield (Gupta et al., 2001; Rastogi et al., 2001; Mishra et al., 2008). The epicenter of the earthquake (Fig. 1) was reported at 23.41°N and 70.23°E with a focal depth of 25 km (Kayal et al., 2002; Mishra and Zhao, 2003; Singh et al., 2011; Mishra, 2013). A maximum intensity of X+ on the modified Mercalli (MM) scale was assigned that describes the extent of damage in the area (Rastogi et al., 2001; Rastogi et al., 2011). The fault plane solution indicated a reverse faulting with a strike-slip component similar to that of 1956 Anjar earthquake that occurred to the south of Bhuj earthquake epicenter in the KRB (Chung and Gao, 1995) (Fig. 1). The 2001 mainshock rupture did not reach to the surface nor any obvious surface displacement on the known faults was reported although there were some small surface deformations due to the shaking effects (Wesnousky et al., 2001). Several reports on the mainshock and the immediate aftershock sequence were published with diverse interpretations by different researchers to address the generating processes of the mainshock and its aftershock sequence (Gupta et al., 2001; Rastogi et al., 2001; Wesnousky et al., 2001; Kayal et al., 2002; Negishi et al., 2002; Mishra and Zhao, 2003; Mishra, 2013). It is, worth to mention that earlier seismological studies for the 2001 Bhuj earthquake were based on results derived from smaller or limited data set.

The 2001 Bhuj earthquake was regarded as a unique event of stable continental region compared to other large crustal earthquakes, particularly in the short areal extent of the causative fault and its deeper hypocenter. The genesis of 2001 Bhuj earthquake were discussed in light of several theories and hypotheses so far proposed for explaining the genesis of intra-plate earthquakes and their continued aftershock activity (e.g. Sykes, 1978;

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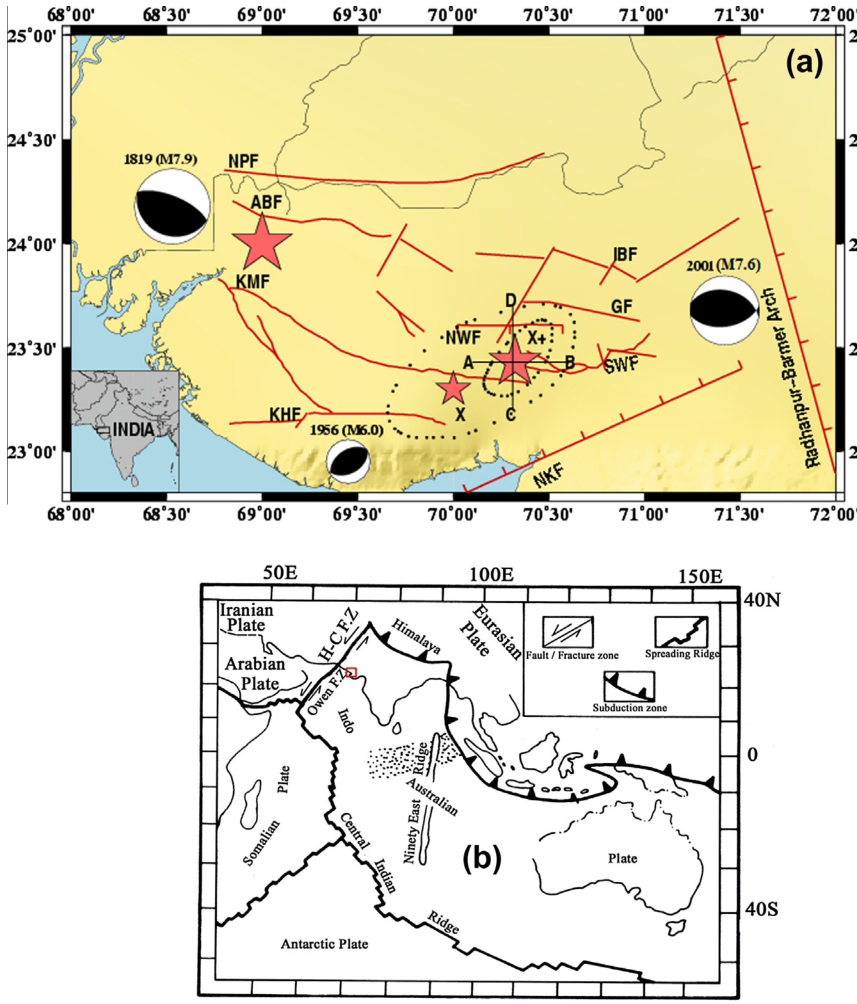

Fig. 1. (a) A map showing the geotectonic setting of the Kachchh Rift Basin. The 2001 Bhuj mainshock epicenter and past historical damaging earthquakes are shown by red stars. Their respective fault plane solutions are also shown in equal area projection with white (tension) and black (compression) shades. Faults causing past seismicity in Kachchh region are marked in the figure as: Kachchh Mainland Fault, KMF; Katrol Hill Fault, KHF; Allah Bund Fault, ABF; Old ABF; Island Belt Fault, IBF; Gedi Fault, GF; Banni Fault, BF; North Wagad Fault, NWF; South Wagad Fault, SWF; Nagar Parkar Fault, NPF; North Kathiawar Fault, NKF. Elliptical areas show the distribution of the intensity values *X* and X^+ during the 2001 Bhuj earthquake. The two solid black lines, AB and CD, indicate locations of the cross sections. The rectangular box at lower left corner of map shows the location of the study region in the map of India. (b) Map showing a broader view of regional tectonics of India. The red rectangle represents the 2001 Bhuj earthquake region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Talwani,1988; Johnston and Kanter, 1990; Gupta 1993; Gupta et al., 1996). Based on 3-D velocity estimates by several previous researchers (Kayal et al., 2002; Mishra and Zhao, 2003; Mandal et al., 2004; Singh et al., 2011, 2012a,b; Mishra, 2013) for the 2001 Bhuj earthquake showed that involvement of fluids in the fault zone might have triggered the 2001 Bhuj mainshock, which is in good agreement with other earthquake source zones, elsewhere in the world (Lees, 1990; Johnson and McEvilly, 1995; Miller, 1996; Zhao and Negishi, 1998; Zhao and Mizuno 1999; Lees and Wu, 2000; Zhao et al., 2002; Zhao et al., 2004; Lin and Shearer, 2009). They interpreted that triggering of moderate to large earthquakes due to fluids is associated with elevated fluid pressures, rather than lithologic conditions. Recently, estimates of crack parameters from 3-D velocity (*Vp*, *Vs*) and Poisson's ratio (σ) tomograms using the theoretical concept of O'connell and Budiansky (1974) and Budiansky and O'connell (1976), documented the evidence to date for the presence of fluid at the 2001 Bhuj mainshock hypocenter (Mishra and Zhao, 2003; Mishra et al., 2008; Mishra, 2013), which are well corroborated with inferred results from the geophysical measurements using magnetotelluric technique of probing the deeper sub-surface of the 2001 Bhuj source area (Arora et al., 2002; Sastry et al., 2008). However, their estimates of crack parameters (ε, ξ, ψ) from the assimilated *Vp*, *Vs*, and σ structures were derived from the limited and small data set recorded by the sparse seismograph network consisted of 12-seismograph stations set up temporarily during the year 2001 (January 30, 2001–April 15, 2001).

The presence of fluids in the cracked volume of rock matrix has profound control on the velocity variation because of its direct control on the elastic modulus of the rock materials due to greater compressibility of porous/cracked volume of rocks than those of solid rock materials of the same composition (Walsh, 1965; Mishra, 2013). Study for sub-surface layers revealed that when cracks of rock gets filled with fluids, the type and state of fluids may make a large difference in the response of the seismic waves (Berryman, 2007). Seismic wave propagation through the sub-surface rock is strongly affected by the presence of fractures and cracks at both shallow and deeper layers because of enhanced anisotropy of the cracked volume of rocks (Walsh, 1965; Nur and Simmons, 1969; Walsh, 1981; Berryman, 2007). Direct estimates and observation of cracks and pores are difficult, partly because of their small size (Brace et al., 1972).

The precise estimates of cracks and pores of rock mass at shallower depths may be made in the laboratory by preparing a thin