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Variations of seismic velocities in the Kachchh rift zone, Gujarat, India, during 2001–2013

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ABSTRACT

We herein study variations of seismic velocities in the main rupture zone (MRZ) of the Mw 7.7 2001 Bhuj earthquake for the time periods [2001–05, 2006–08, 2009–10 and 2011–13], by constructing dVp(%), dVs(%) and d(Vp/Vs)(%) tomograms using high-quality arrival times of 28,902 P- and 28,696 S-waves from 4644 precise JHD (joint hypocentral determination) relocations of local events. Differential tomograms for 2001–05 reveal a marked decrease in seismic velocities (low dVp, low dVs and high d(Vp/Vs)) in the MRZ (at 5–35 km depths) during 2001–10, which is attributed to an increase in crack/fracture density (higher pore fluid pressure) resulted from the intense fracturing that occurred during the mainshock and post-seismic periods. While we observe a slight recovery or increase in seismic velocities 2011–13, this could be related to the healing process (lower pore fluid pressure due to sealing of cracks) of the causative fault zone of the 2001 Bhuj mainshock. The temporal reduction in seismic velocities is observed to be higher at deeper levels (more fluid enrichment under near-lithostatic pressure) than that at shallower levels. Fluid source for low velocity zone (LVZ) at 0–10 km depths (with high d(Vp/Vs)) could be attributed to the presence of meteoric water or soft alluvium sediments with higher water content, while fluid source for LVZ at 10–35 km depths could be due to the presence of brine fluids (released from the metamorphic dewatering) and volatile CO_2 (emanating from the crystallization of carbonatite melts in the asthenosphere), in fractures and pores. We also imaged two prominent LVZs associated with the Katrol Hill fault zone and Island Belt fault zone, extending from shallow upper-crust to sub-crustal depth, which might be facilitating the deeper circulation of metamorphic fluids/volatile CO_2, thereby, the generation of lower crustal earthquakes occurring in the Kachchh rift zone.

1. Introduction

It is well-established that temporal variation of crustal seismic velocities in tectonic regions can be explained in terms of stress induced changes in crack porosity (Anderson and Whitcomb, 1975). Thus, seismic velocities show time-dependent behaviors, for example decrease in Vp/Vs prior to the occurrence of earthquakes that supports the Nur dilatancy hypothesis (Kondratenko and Nersesov, 1962; Nur, 1992; Aggarwal et al., 1973). Measurements of P delays from teleseismic events would further support the idea that there is a possibility of temporal variation of crustal P wave velocities in tectonic regions (Kanamori and Chung, 1974). Opening of new dry cracks (Nur, 1992) and widening of preexisting wet cracks (Whitcomb et al., 1973) are proposed to be probable mechanisms for explaining Vp and Vp/Vs anomaly,while, the increase or decrease in velocity prior to the earthquake has been attributed to the closing of cracks (Brady, 1974) or diffusion of water into the newly opened or widened cracks (Nur, 1992). In recent years, the local earthquake tomography has been applied with increasing success to study the changes in seismic velocities within fault zones responsible for large/strong earthquakes (Eberhart-Philhps and Michael, 1993; Zhao et al., 1976; Thurber et al., 1997; Wang and Zhao, 2006; Mandal and Pujol, 2006). In this paper, we use local earthquake tomography to study the variations of seismic velocities (during 2001–13) within the fault zone before and after the devastating 2001 Mw 7.7 Bhuj earthquake, Gujarat, India.

The Mesozoic Kachchh rift zone is located in the Gujarat state, northwestern India. The area has already experienced two Mw 7.7 events within a span of 182 years (Mandal et al., 2004a). Earthquakes (up to Mw 7.8) have occurred on E–W trending faults in about 250 km × 150 km size Kachchh rift basin of 184 Ma age (Courtillot et al., 1986; Rajendran et al., 2008). Return period of large earthquakes of Mw 7.7 is estimated as 200 yr in the whole basin and 800 yr along individual faults (Rajendran et al., 2008). On 26 January 2001, the deadliest intraplate earthquake of Mw ~ 7.7 took place in the Kachchh rift zone, which killed 20,000 people (Fig. 1). The 2001 Bhuj earthquake sequence occurred along a south dipping (~45°) hidden reverse fault, extending from 2 to 40 km depth. This suggests a rupture of the size of entire crust (Mandal and Pandey, 2010). Note that local deformations

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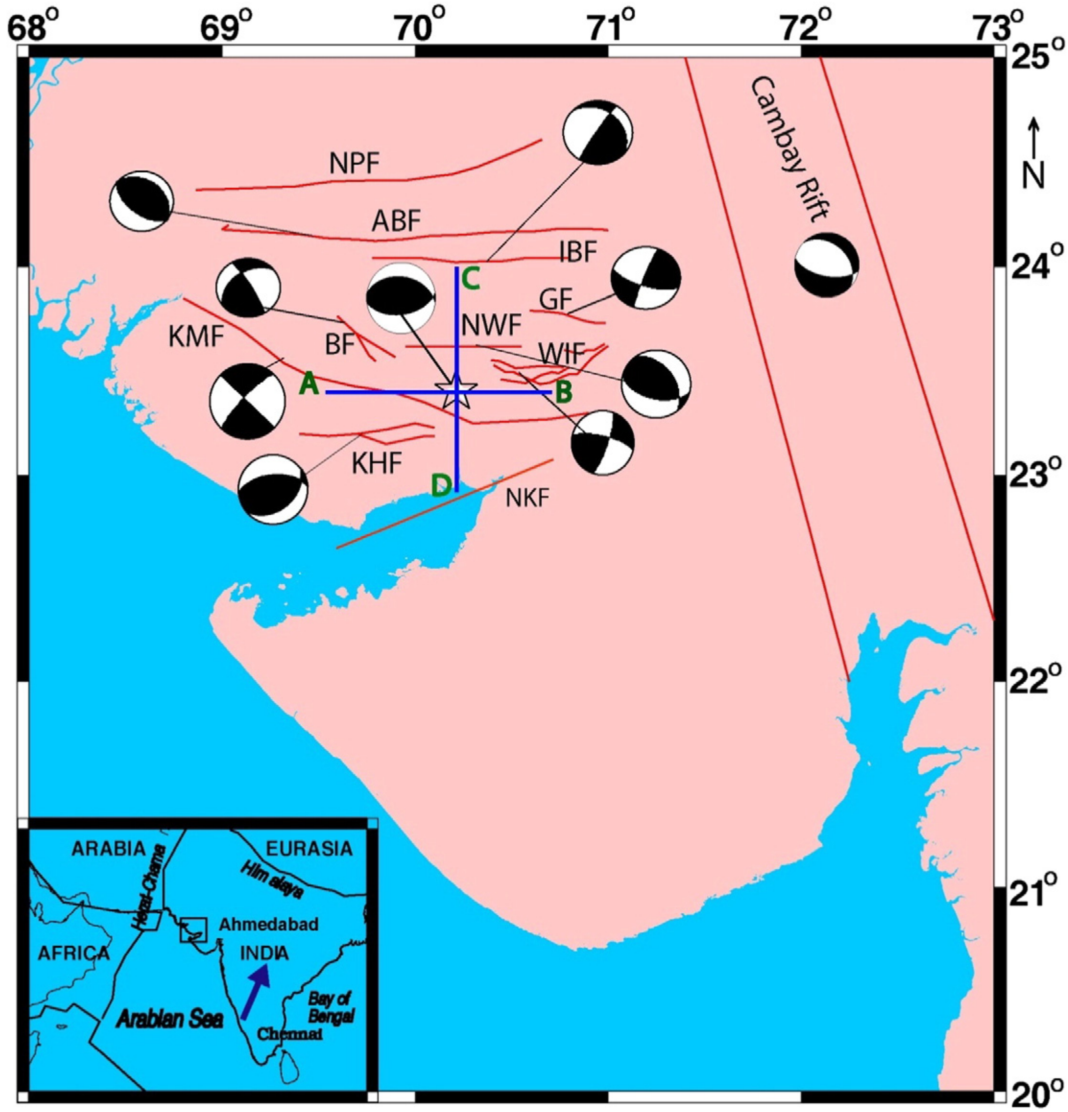

Fig. 1. A plot showing major faults and associated available fault plane solutions in the Kachchh seismic zone, Gujarat, India. Major faults (solid lines): ABF, Allah Bund Fault; IBF, Island Belt fault; NKF, North Kathiawar Fault; KMF, Kachchh mainland fault; KHF, Katrol Hill fault; NPF, Nagar Parkar fault; NWF, North Wagad Fault; GF, Gedi Fault; WIF, Wagad imbricate faults. The locations of AB (in EW direction) and CD (in NS direction) profiles across the 2001 Bhuj mainshock location (marked by a star) are shown by thick solid lines. The inset is showing the key map for the area with reference to Indian plate boundaries (dark lines). The study area is marked by a square symbol. The big arrow indicates the absolute plate motion (APM) direction or the prevailing compression direction as obtained from the NUVEL1A plate model (DeMets et al., 1990).

from GPS measurements during 2008–2013 show small movements of 2–3 mm/yr (Rastogi et al., 2013). Thus, the shear deformation for the adjustment process in the Bhuj earthquake zone is now negligible as deduced from the GPS data (Rastogi et al., 2013). Until today, the continued aftershock activity of the 2001 Bhuj earthquake includes 13 Mw ≥ 5, 250 Mw ≥ 4 and about 4000 Mw ≥ 3 events, resulting in a large dataset for the 2001 Bhuj earthquake sequence. Aftershocks in the 2001 Mw 7.7 rupture zone of 20 km radius have continued for more than 13 years at M ≤ 6 level. However, the activity spread over 100 km distance by 2006 in Kachchh (Rastogi et al., 2013). Thus, the continuous aftershock activity during 2001–13 has led to recording of numerous local events occurring all through the crust, which provide a unique opportunity to image the finer crustal structure of the Kachchh rift zone.

Through local earthquake tomography, gravity, magnetic and seismic refraction studies, large-scale crustal intrusives and underplated magma have been delineated at the lower crustal levels below the Kachchh rift zone (KRZ) (Kayal et al., 2002; Mishra et al., 2005; Mandal and Pujol, 2006; Sarkar et al., 2007; Mandal and Chadha, 2008; Mandal and Pandey, 2010). Earlier 3-D inversion modeling of travel time data has delineated a fluid-filled fractured zone with high crack density, high saturation rate and high porosity in the main rupture zone of the 2001 mainshock (Mishra and Zhao, 2003; Mandal et al., 2004a; Mandal and Chadha, 2008; Mishra, 2014). However, these studies were limited by poor resolution due to poor station coverage and an insufficient number of aftershocks, which calls for a fresh 3-D velocity imaging of the KRZ using large number of aftershocks and better azimuthal coverage that has been achieved through continuous recording of aftershocks during 2001–13 by a well-designed seismic network. This network is regularly distributed and provides a dense and homogeneous ray coverage to assure good resolutions.

Delineation of a crustal (~3–7 km) and lithospheric (~6–12 km) thinning depicts the presence of a complex crust–mantle structure underlying the KRZ, which might have resulted from the lithospheric extension and Deccan–Reunion mantle plume interaction at 65 Ma (Mandal and Pandey, 2010; Mandal, 2011; Mandal, 2012). Further, the presence of low shear velocity zone at the lithosphere asthenosphere