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Numerical modeling of seismicity and geodynamics of the Kachchh rift zone, Gujarat, India

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ABSTRACT

The numerical block-and-fault model of lithosphere dynamics and seismicity (BAFD) is used to understand crustal motion and features of the observed seismicity in the Kachchh rift zone, Gujarat, Western India. The block-model allows simulating seismicity and geodynamics simultaneously unlike other modeling approaches for studying seismicity or geodynamics. The model structure of Kachchh rift zone is composed of seven major crustal blocks separated by fault planes. Based on the orientation of boundary crustal block movements, we develop a set of numerical experiments to analyze the spatial distribution of earthquakes, frequency-to-magnitude relationships, earthquake focal mechanisms, velocity field, and fault slip rates in the model. The main results of our modeling suggest that an NNW–SSE trending compression is a principal driving force in the Kachchh rift zone that explains basic features of the regional seismicity, direction of block motions, and the presence of an extensional stress regime associated with the Cambay rift zone. Large synthetic events occur on the fault segments associated with the Allah-Bund fault, Katrol hill fault and north Wagad fault which have been causative faults for the 1819 Mw7.7 Allah-Bund, 1956 Mw6.0 Anjar and 2001 Mw7.7 Bhuj earthquakes. The frequency–magnitude distribution for both synthetic seismicity and observed seismicity shows a similar slope. The focal mechanisms of the synthetic events are found to be consistent with those of earthquakes in the region. A special attention has been paid to study long-term and post-seismic deformations. Our results are in a qualitative agreement with the GPS post-seismic observations in the Kachchh rift zone. We infer that the observed seismicity and crustal block motions are a consequence of the dynamics of the entire regional fault and block system rather than that of a single causative fault only.

1. Introduction

In this paper, we study the Kachchh rift zone (KRZ), which is presently seismically most active intraplate region in the Indian subcontinent, in general, and in the Gujarat state, in particular. Two large continental earthquakes, the 1819 Allah-Bund, Mw7.7, and the 2001 Bhuj, Mw7.7 have occurred in the region within a span of 182 years, which killed 22,000 people (Chung and Gao, 1995; Gupta et al., 2001; Rajendran and Rajendran, 2001).

We focus on the BAFD modeling of the KRZ with an objective to explain:

- the patterns of earthquake occurrences along the existing faults in terms of the regional driving forces
- the long-term crustal block motion and post-seismic deformation.

The concept of numerical BAFD modeling was introduced by Gabrielov et al. (1990), and described in detail by Soloviev and Ismail-Zadeh (2003). The block model simulates both fast (synthetic seismicity) and slow (tectonic motions) movements of blocks, and therefore permits to study seismicity and its connection with the geodynamics of a given region. Thus, it provides a straightforward tool for a broad range of problems, like the study of the dependence of seismicity on the general properties of the fault networks and rheology, and the formulation and testing of different hypothesis about driving tectonic forces controlling the seismicity and geodynamics in a studied region.

The method allows us to use a realistic geometry of the blocks, based on any relevant information, in particularly maps of morphostructural zoning. In BAFD modeling, driving tectonic forces (velocities of the boundary blocks and underlying medium) are prescribed using geodetic data (GPS) and geodynamic models. While the rheology of fault zones can also be incorporated using the existing knowledge of lithospheric structure (in terms of crust–mantle structure and velocities of seismic wave propagation) and heat flow data.

The model provides an effective capability to include the set of documented constraints supplied by widely available earthquake catalogs. This is done by means of the comparison of the frequency-to-magnitude relation, of the focal mechanisms, of earthquake productivity,

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and the spatial distribution of observed seismicity and synthetic seismicity.

Based on the experience accumulated so far, we can infer that the synthetic earthquake catalog reproduces not only some of the basic features of observed seismicity like (a) the Gutenberg–Richter law (Panza et al., 1997), (b) the space and time clustering of earthquakes (Maksimov and Soloviev, 1999) and (c) the dependence of the occurrence of large earthquakes on the fragmentation of the faults network, and on the rotation of blocks (Keilis-Borok et al., 1997), but also several regional features of seismicity, like (1) the epicenter distribution, (2) the relative level of seismic activity in different areas of the region and (3) the fault plane solution (Peresan et al., 2007; Soloviev et al., 2000).

In earlier studies the BAFD model has been used successfully to simulate the seismicity and geodynamics associated with many seismically active regions of the world including the Vrancea earthquake-prone region of the southeastern Carpathians (Ismail-Zadeh et al., 1999; Panza et al., 1997; Soloviev et al., 1999, 2000), Western Alps (Vorobieva et al., 2000), Sunda Arc (Soloviev and Ismail-Zadeh, 2003), Italy (Peresan et al., 2007), and Tibet–Himalaya (Ismail-Zadeh et al., 2007). All these regions are related to the zones of orogenic deformations along the plate boundaries. In this paper, we apply the BAFD model to the Kachchh rift zone for understanding of the causative mechanisms of earthquakes occurring in the intraplate seismic region.

2. Seismicity and tectonics of the Kachchh rift region

The study area covers the Kachchh region of the Gujarat state. Gujarat is the northwestern state of India, which falls in seismic zone V on the seismic zoning map of India (BIS, 2002) and is a region potential for generating up to magnitude 8 earthquakes. The Kachchh rift zone is the seismically most active region in the Gujarat state, which has already experienced two Mw7.7 events in 1819 and 2001, respectively. In 1956, another event of moderate magnitude (Mw6.0), known as the Anjar earthquake, occurred south of the epicenter of the 2001 Bhuj earthquake (Chung and Gao, 1995). In addition, Rajendran and Rajendran (2001) have also reported 15 historic and recent earthquakes of M 5–6 that struck the region.

The region has been affected by two rifting phases at 184 Ma and 88 Ma, respectively, and the Cretaceous–Tertiary boundary Deccan volcanism at 65 Ma when it passed over the Reunion hotspot (Courtillot et al., 1986; White and McKenzie, 1995). Since 40 Ma, this region is under compression due to the Himalayan collision, which led to ongoing inversion tectonics in the region. The lateral motion during the drift stage of the plate induced horizontal stress and the near vertical normal faults, which were reactivated as reverse faults during the initiation of inversion cycle, became strike–slip faults involving divergent oblique–slip movements (Biswas, 2005).

The Kachchh basin is the earliest pericratonic rift basin formed on the western margin of the Indian plate during the Late Triassic breakup of the Gondwanaland (Biswas, 1987, 2005). The rift expanded from north to south by successive reactivation of primordial faults of Mid-Proterozoic Delhi fold belt (Biswas, 1987). The E–W trending rift basin is bound by Nagar Parkar uplift on the north and Kathiawar uplift (Saurashtra horst) on the south along sub-vertical Nagar Parkar and North Kathiawar faults (NPF & NKF). The rift is styled by three main uplifts, (from north to south) Island Belt, Kachchh Mainland and Wagad uplifts along three intra-rift faults, Island Belt fault (IBF), Kachchh Mainland fault (KMF), and South Wagad fault (SWF), with intervening grabens and half-grabens (Biswas, 1987). According to Biswas (1987), the Island Belt uplift is a narrow south tilted basement ridge which is broken and displaced by tear faults into four separate uplifts described as “islands”. The uplifts are upthrust basement blocks tilted along sub-vertical faults with initial normal separation. The structure is styled by tilted blocks and half-grabens within a south tilted asymmetric rift basin. The NKF is the bounding master fault along which the rift subsided most. From the existing geological knowledge, it is inferred that all the faults are sub-vertically dipping 90° to 75° toward the adjacent half-graben or graben (Biswas, 1987). In the eastern part a large uplift, Wagad Uplift, occurs between the Mainland and Island Belt uplifts, which are tilted opposite to the north with a narrow deformation zone along the faulted southern edge (Biswas, 2005). The backslope ends up against Bela horst of the Island Belt uplift while the Mainland and Wagad uplifts occur in *en echelon* pattern. Biswas and Khattri (2003) proposed that KMF and SWF are parts of a left stepping dextral strike–slip fault system. This is further supported by Biswas (2005) who suggested that SWF is the eastward continuation of KMF after side stepping with an overlap zone between Bhachau and Adhoi.

Another important tectonic feature in the Kachchh rift zone is a subsurface basement ridge — Median High that crosses the basin at right angle to its axis in the middle that divides the basin into a deeper western part and a shallower and more tetanized eastern part (Biswas and Khattri, 2003). We also notice that the rift is terminated in the east against a transverse subsurface basement ridge, Radhanpur Arch, which is the western shoulder of the adjacent N–S oriented Cambay rift. Biswas (2005) proposed that during the present compressive stage the Radhanpur arch acts as a stress barrier for eastward movements along the principal deformation zones, which is creating additional strain in this part of the basin between the arch and the Median High that makes this zone as the most favored site for rupture nucleation as evidenced by occurrences of closely spaced epicenters of two major earthquakes viz., 1956 Anjar (Mw6.0) and 2001 Bhuj (Mw7.7), in this zone and concentration of aftershock hypocenters around it. And, to the west the rift merges with offshore shelf. Further, Sen et al. (2009) noticed that igneous rocks extensively intruded the Mesozoic sediments during rifting followed post-rift hotspot related to Deccan volcanism. The presence of mafic/ultramafic magmatic bodies close to the crust–mantle boundary is also imaged through the modeling of seismological data (Mandal and Chadha, 2008; Mandal and Pandey, 2010).

Prior crustal velocity investigation using seismic refraction data in the Kachchh region suggests a large variation in the estimated Moho depths that varies from 37 to 45 km (Reddy et al., 2001), while the joint inversion of P-receiver functions and surface wave group velocity dispersion data reveals a thinning in crustal (36–42 km) and asthenospheric (62–77 km) thicknesses underlying the Kachchh rift zone relative to surrounding unrifted parts (Mandal, 2012).

The crustal structure in Kachchh seems to be composed of a number of heterogeneous blocks, which are separated by several E–W trending deep-seated crustal faults extending up to Moho depths. The focal mechanism solutions of earthquakes occurring in the Kachchh region show a dominant compressive regime with almost N–S trending P-axes (Antolik and Dreger, 2003; Chung and Gao, 1995; Mandal and Horton, 2007; Mandal et al., 2009).

3. Basic elements of the BAFD model

In the BAFD modeling, a seismic zone is assumed to be consisting of several crustal blocks separated by infinitely thin viscoelastic fault planes. So, the accumulation of strain and stress takes place on these fault planes. The movement of the structure is considered to be a consequence of the external motions that are prescribed at the segments of lateral confining boundary, and at the bottom of the structure. Next, it is assumed that the elastic stress at a point of the fault plane or block bottom is proportional to the difference between relative displacement and slippage (inelastic displacement). And, the rate of slippage is proportional to elastic stress through the following relation:

$$\boldsymbol{\sigma} = K(\Delta\mathbf{r} - \delta\mathbf{r}), \quad \frac{d\delta\mathbf{r}}{dt} = W\boldsymbol{\sigma}, \tag{1}$$