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Structure of the Seismically Active Kachchh Region

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ABSTRACT

A 3-D structural model for the Kachchh rift zone has been constructed based on the results from our earlier studies using S-to-P converted phase, and joint inversion of P-receiver functions and surface wave dispersion data, which reveals a a seismogenic crustal volume (~ 50x50x45 km^3) with large sediment thickness and marked crustal as well as asthenospheric thinning below the Kachchh rift zone (KRZ). A local earthquake velocity tomography using 24019 P- as well as 23825 S-wave arrival times of 3750 relocated events from 41 three- component seismographs has been performed. Vp and Vs tomograms detect a distinct very high velocity lower crustal anomaly (Vp: 6.8-7.8 km/s; Vs: 3.9-4.3 km/s; Vp/Vs:1.7-1.8) at deeper depths (≥ 20 km) below the central KRZ. Three high velocity anomalies at 5-30 km depths have also been mapped below the Wagad uplift, Kachchh rift and Banni regions. These high velocity anomalies are interpreted as mafic plutons, within the mapped crustal volume, which might have resulted from the 65 Ma Deccan plume episode. Relocations of most of M≥5 events (including 2001 Bhuj mainshock) fall either near the contacts between high and low velocity zones or in the high-velocity zones while some earthquakes (including the 1956 Anjar earthquake) also occurred in the low-velocity zones (8-18% drop in Vs, indicating the presence of fluids). We propose that mapping of such a scenario of crustal and lithospheric structure where resultant tectonic forces encourage seismicity is crucial for the assessment of the intraplate seismic hazard.

INTRODUCTION

The seismically active Mesozoic Kachchh rift zone is located in the state of Gujarat on the western part of India. Until today, this rift zone has experienced 7 earthquakes of M_w≥6 including two M_w7.7 earthquakes within a span of 182 years (Rastogi et al., 2014). The last M_w7.7 event occurred on 26 January 2001 in a region 4 km northwest of the Bhachau city, Kachchh, Gujarat (Gupta et al., 2001). The earthquake activity associated with the 2001 Bhuj mainshock has been occurring in a zone of 50 km x 50 km for the last two decades. The Bhuj earthquake sequence has already produced 1 M_w7.7, 17 M_w5.0-5.9, about 250 M_w4-4.9, and about 4000 M_w3-3.9 (Mandal, 2020). The available fault plane solutions of these intraplate earthquakes have mostly shown the movement on the south-dipping reverse faults (Mandal and Horton, 2007; Rastogi et al., 2014). The National Geophysical Research Institute, Hyderabad, India, had monitored this activity during 2001-2017, through a mobile seismic network of 5-18 three-component broadband seismograph stations, which led to an excellent dataset of digital waveforms of this earthquake sequence (Mandal, 2020). This dataset has enabled us to carry out several research investigations to delineate the seismic structure down to lithosphere-asthenosphere boundary below this rift zone.

Gupta et al. (2001) proposed a detailed velocity model down to the basement depth underlying the Kachchh rift zone for the first time based on results from the integrated Geophysical survey including seismic refraction, gravity, magnetic, and electrical. The velocity structure below the basement depth in Kachchh region has been constrained by results from the modelling of seismic refraction data from Jasdan-Sanchor CSS profile (Kaila et al., 1981; Mandal et al., 2004). This model was later modified by Mandal (2007) by performing the one-dimensional travel time inversion (using Velest code (Kissling, 1995)) of 2565 P arrivals and 2380 S arrivals from 658 aftershocks recorded at 8-18 three-component digital stations. On an average both the modified Vp and Vs structures (Fig. 1b) show an increase from surface to Moho depth (i.e. 40 km) except for a low velocity in the 34-40 km depth range. The first upper crustal layer (0-2 km) consisting of Tertiary and Jurassic sediments suggests an increase in Vp from 2.4 km/s to 2.92 km/s and a decrease in Vs from 1.0 km/s to 0.9 km/s in comparison to the above-discussed initial model. The second crustal layer (2-5 km) does not show any significant change in Vp or Vs in comparison to the initial model. In the 5-10 km depth range, compared to the initial model, Vp shows a decrease of 0.2 km/s (Vp: 5.9 km/s), whereas, Vs suggests a slight increase of 0.01 (Vs: 3.37 km/s). In the 10-16 km depth range, compared to the initial model, Vp shows a slight decrease of 0.02 km/s (Vp: 6.18 km/s), whereas, Vs suggests a slight increase of 0.04 (Vs: 3.60 km/s). Interestingly, in the 16-22 km depth range there is no change in Vs, but Vp shows a decrease of 0.33 km/s (Vp: 6.07 km/s). In the 22-29 km depth range, compared to the initial model, Vp shows a decrease of 0.07 km/s (Vp: 6.59 km/s), whereas, Vs shows a slight increase of 0.03 km/s (Vs: 3.73 km/s). There is an increase in both Vp and Vs in the 29-34 km depth range compared to the initial model. However, the low P- and S- wave velocities characterize the 34 – 40 km depth range, where Vp shows an increase of 0.1 km/s (Vp: 6.78) and Vs suggests a reduction of 0.36 km/s compared to the initial model. At the Moho depth (~40 km), Vp and Vs show no change compared to the initial model.

Three-dimensional Vp and Vs structures underlying the rift zone have been investigated by many investigators (Zhao et al., 2003; Kayal et al., 2003; Mandal and Pujol, 2006; Mandal, 2019). Here, a local earthquake velocity tomography is performed using Benz (1996)'s code and 24019 P- as well as 23825 S-wave arrival times of 3750 relocated events (through JHD (Pujol. 1988), with azimuthal gap < 180^o) from 41 three- component seismographs have been used, which divided a crustal volume of 200 km x 200 km x 50 km into 40 x 40 x 10 nodes with a uniform horizontal and vertical grid spacing of 5 km. The 1-D velocity model (Mandal, 2007; Fig. 1b) as discussed above is used as the initial velocity model for the tomography. Fig.1b shows the ray sampling of local earthquake tomographic study of the region. The RMS residuals for P and S waves are reduced from 0.855s to 0.210s, and 0.812s to 0.170s, respectively, within 14 iterations (Figs. 1d, e). We constructed depth cross-sections of Vp, Vs, and Vp/Vs tomograms along four N-S and four E-W profiles across the 2001 Bhuj mainshock to image the nature of crustal structure along and across the strike of the Kachchh seismic zone (Figs. 3a-x). Further, to check the robustness of our results, we performed checkerboard test at 15-20 and 25-30 km depth ranges by assigning alternately high (+5%) and low-velocity (-5%) perturbations for

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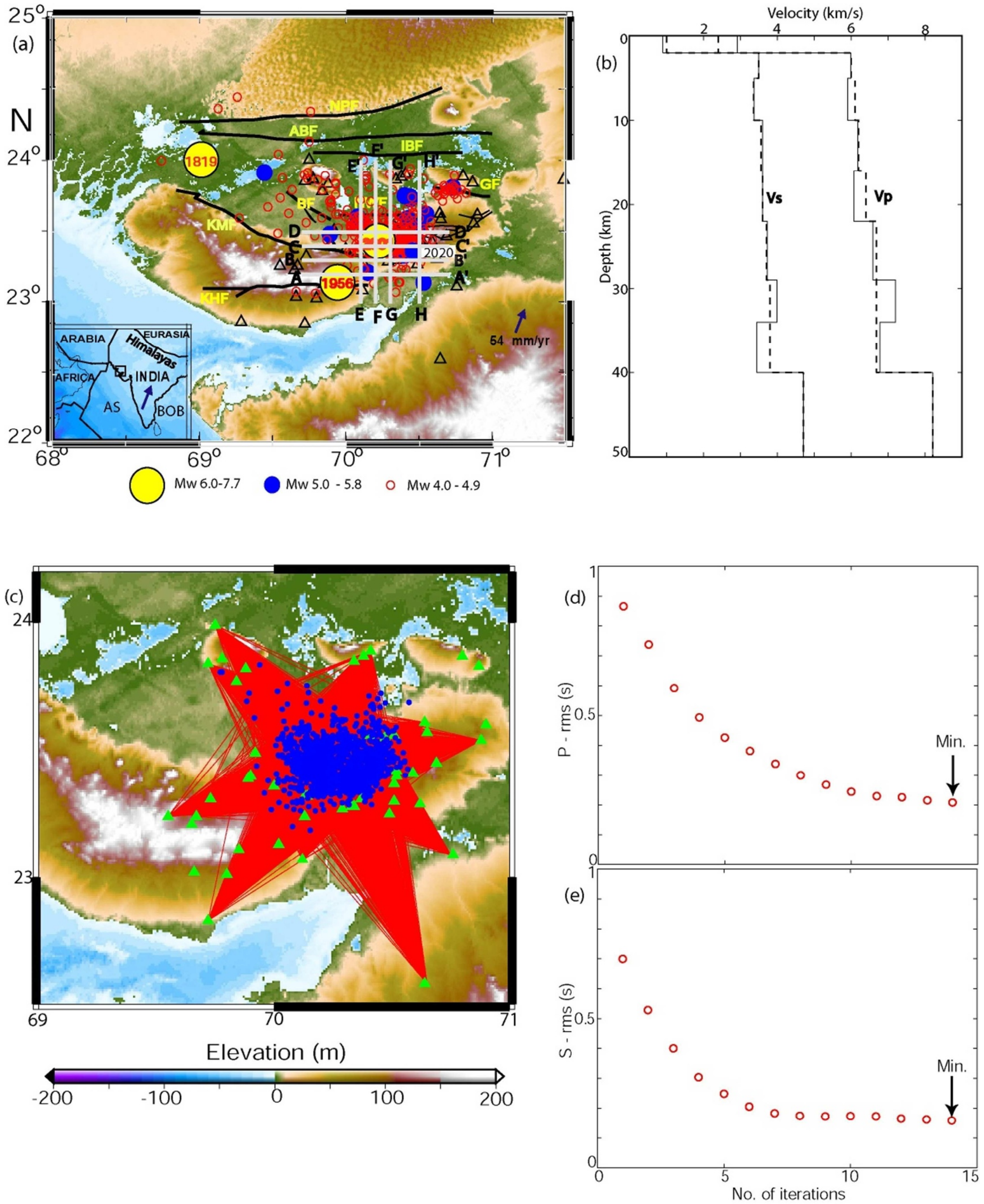

Fig.1. (a) Station location map of the Uttarakhand region. Open black triangles mark the location of broadband stations while small red circles mark the earthquake relocations obtained from simultaneous inversion. The solid black line represents faults. ABF: Allah bund fault; IBF: Island belt fault: NWF: north Wagad fault; GF: Gedi fault; KMF: Kachchh Mainland fault; KHF: Katrol hill fault. Large blue filled circles mark the epicentral locations of M5 events while large filled yellow circles represent $M_w \geq 6$ events viz. 1819 Kachchh, 2001 Bhuj, and 1956 Anjar earthquakes, **(b)** Initial P- and S- wave velocity models of Mandal (2007), **(c)** A plot showing ray sampling of the study area for local earthquake velocity tomography. Blue dots mark epicentres while green triangles represent broadband seismograph stations. A plot showing RMS residual vs. number of iterations for **(d)** P- and **(e)** S- wave tomography. An arrow marks the minimum RMS value obtained at 14 iterations of the P- and S- tomography.

individual grid nodes in 3-D (Figs. 4a-b). Our checkerboard test reveals a 90% retrieval of the Vp and Vs tomograms in the main seismogenic region at 15-20 and 25-30 km depths (Figs. 4c-f).

RESULTS AND DISCUSSION

Thickest Sedimentary Layer below the Central KRZ

Mandal (2007), Chopra et al. (2010) and Singh et al. (2014) have used the above velocity model to estimate sediment thicknesses at 52 stations within the Kachchh basin, using the travel time differences between the Sp converted phase from the vertical seismogram and S-phase from the transverse component. The sediment thickness estimates are found to range from 0.8 to 2.5 km, with a prominent E-W trending zone of large crustal thickness (> 1 km) below the central rift zone (Fig. 2a). The details of analysis of data to estimate the sediment thickness of the Kachchh basin using Sp converted phase could be found in Mandal (2007) and Singh et al. (2014). The modelled sediment thickness varies from 1.75 to 2.6 km underlying the central Kachchh rift, where most of the $M_w \geq 4.5$ earthquakes until today including the 2001 $M_w 7.7$ mainshock have occurred (Fig. 2a). While three independent mainshocks of $M_w \geq 4.5$ took place in the surrounding unrifted zones with sediment thickness of 1.2-1.4 km (Fig. 2a). Two

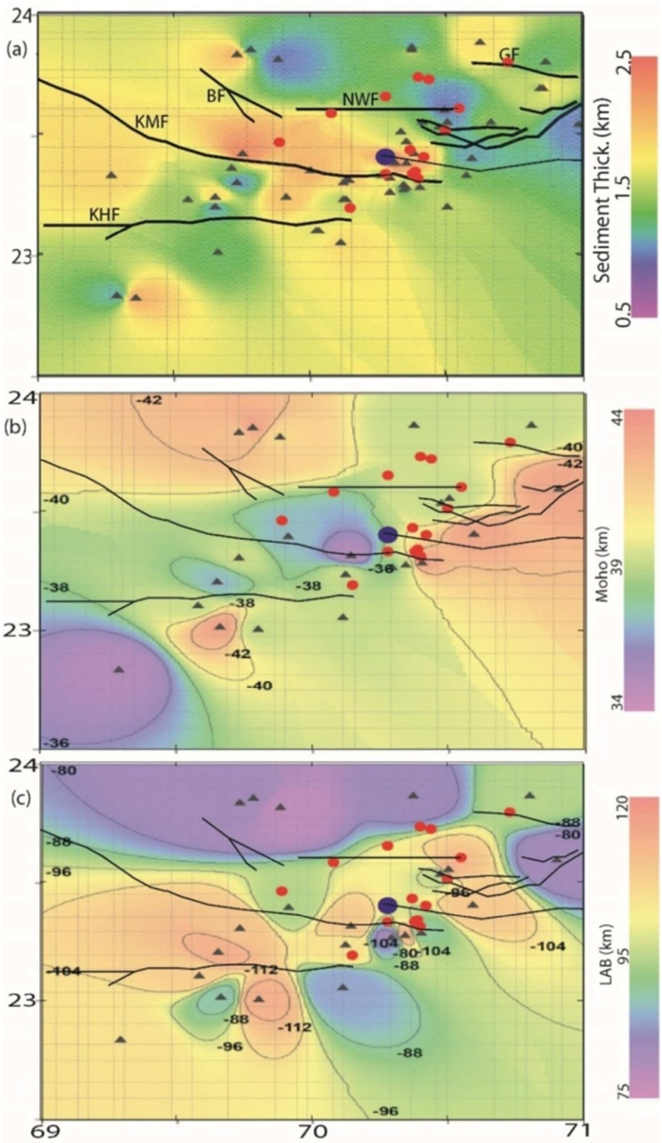

Fig.2. Contour plots of modelled **(a)** sediment thickness (in km) using S-to-p conversions at 53 three-component stations, **(b)** modelled Moho thickness (in km) using joint inversion of PRFs and surface wave dispersion data, and **(c)** lithosphere-asthenosphere boundary (LAB) thicknesses (in km) using joint inversion of PRFs and surface wave dispersion data. Medium filled red circles mark the M5 events while the 2001 Bhuj mainshock is shown by a large filled black circle. While broadband stations are shown by filled black triangles.

M_w≥4.5 events have also occurred along the Gedi fault, where sediment thicknesses are modelled to be 1.5-1.8 km. Spatial distribution of sediment thicknesses in Fig.3 also delineates a WNW-ESE rift structure, extending 100 km in length and 40 km in width.

Marked Crustal and Lithospheric Thinning below the Central KRZ

The crustal and lithospheric thicknesses have been modelled at 22 broadband stations in Kachchh, through the joint inversion of PRFs and surface wave group velocity dispersion (5-70 s) data (Mandal and Pandey, 2011; Mandal, 2019). The details of the joint inversion of PRFs and surface wave group velocity dispersion data could be found in Mandal (2019) and, Mandal and Pandey (2011). Modelled crustal (lithospheric) thicknesses vary from 37(76) km below the central rift zone to 43(113) km underlying the surrounding unrifted zones (Figs. 2b, c). However, the minimum crustal thickness of 35 km is also modelled at MND (near the coastal region) while minimum lithospheric thickness of 76 km is modelled at CHP in the central KRZ (Figs. 2b, c). The crustal thicknesses reveal a significant crustal thinning of 4-6 km below the central rift zone, where three M_w≥4.5 earthquakes including the 2001 M_w7.7 mainshock have occurred (Figs. 2b, c). We also notice that remaining eight earthquakes of M_w≥4.5 took place in the surrounding unrifted zones, with a relatively thicker crust. Modelled larger crustal thicknesses (40-43 km) characterize the surrounding un-rifted zones (Fig. 2b). The modelled LAB thicknesses depict a marked asthenospheric upwarping of 6-8 km below the just southeast corner of the central rift zone (Fig. 2c). The modelled marked crustal and asthenospheric thinning provides the evidence for key role played by the vertical tectonic forces in the crustal accretion of the KRZ. Note that line of sight (LOS) mean surface deformation velocities estimated using the SENTINEL-1A suggest a 4.5-6 mm/yr uplift below the central rift zone, during 2016-2020, which also supports the vertical tectonics model for the region (Kandregula et al., 2021; Lakhote et al., 2021).

Three-dimensional Lithospheric Structural Model below the KRZ

We construct a 3-D structural model of the rift zone based on above discussed estimates of sediment, crustal and lithospheric thicknesses (Figs. 2a-c). From this model, it is quite distinctly visible that a crustal volume of 50 x 50 x 45 km^3 below the central KRZ is significantly influenced by the crustal and asthenospheric thinning, which might be related to the Deccan plume episode of 65 Ma. This lithospheric volume is also observed to be characterized by the thickest sediments (~2.5 km) of the Kachchh basin (Figs. 2a-c). A half-graben structure (i.e. Samkhiyali graben (Rastogi et al., 2014)) with a marked gravity high of +40 mgal is also found to occur within this lithospheric volume below the central KRZ (Khan et al., 2016). Based on the movements of different existing faults, Biswas (2005) proposed a nucleation zone for the future earthquakes between SWF and Wagad uplift, which also lies within the above-discussed lithospheric volume. Further, we notice that most of the deeper (>15 km depth) earthquakes of M_w≥4.5 in the Kachchh rift zone have occurred within the mapped crustal volume (Figs. 2a-c). The mapped lithospheric volume seems to be representing a slightly southward dipping crystallized magma conduit that passes through the zones of marked concentrations of sediment, Moho and LAB contours below the KRZ (Figs. 2a-c). The chemical composition of rocks within this lithospheric column might have been modified significantly, due to the magma interaction during the plume episode. This process might have been increased the densities and velocities of rocks within this lithospheric column by intruding high density and high velocity mafic / ultramafic rocks from the deeper sources. Therefore, this lithospheric column could be acting as a stress accumulator in comparison to the surrounding less affected blocks.

Depth cross-sections of Vp, Vs and Vp/Vs tomograms along four E-W (A, B, C, and D as shown in Fig.1a) and four N-S (E, F, G, and H as shown in Fig.1a) profiles are shown in Figs. 3a-x. The E-W depth sections (Figs. 3a-l) clearly delineate three high velocity anomalies M1, M2, and M3, which are associated with Banni (BN), Kachchh rift (KR) and Wagad uplift (WU), respectively. While the N-S depth sections (Figs. 3m-x) detect three south dipping faults (e.g. NWF, KHF, GF) and the north dipping KMF, which are marked as A, D, E and B, respectively. The 2001 mainshock is found to occur on the NWF near a contact between high- and low- velocity zones (Figs. 3g-i,p-r,s-u). The imaged three high-velocity anomalies (M1, M2 and M3) are interpreted as crustal mafic plutons. Interestingly, the inferred mafic pluton associated with Banni region (M1) is modelled to be characterized by high Vp (10-20% increase), high Vs (8-17% increase) and low Vp/Vs (~1.65-1.7), which can be interpreted as comprise of mafic and rigid rocks. Whilst the inferred mafic plutons associated

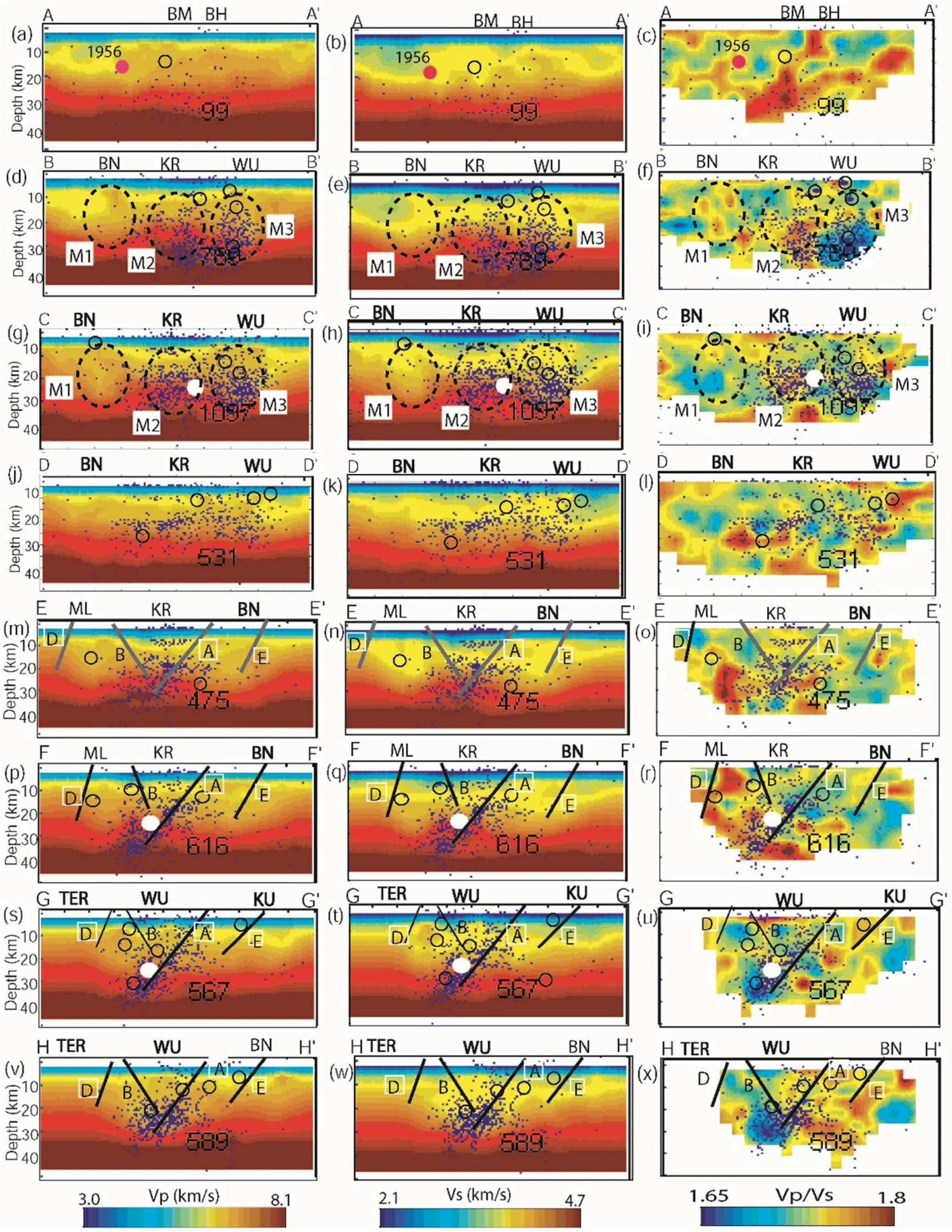

Fig.3. E-W depth cross-sections of Vp, Vs and Vp/Vs tomograms, which are obtained using input velocity model of Singh et al. (2019), along **(a-c)** Profile AA', **(d-f)** Profile BB', **(g-i)** Profile CC', **(j-l)** Profile DD'. N-S depth cross-sections of Vp, Vs and Vp/Vs along **(m-o)** Profile EE', **(p-r)** Profile FF', **(s-u)** Profile GG' and **(v-x)** Profile HH'. Black dots represent the hypocentral locations of earthquakes. The medium size open circles mark the locations of M5 earthquakes while the large white filled circle represents the 2001 Bhuj mainshock. A filled pink circle marks the location of the 1956 Anjar earthquake. Thick black line marks the NWF. The locations of these profiles are shown in Fig. 1a. Black dotted line in Fig. 3(v-x) marks a shallow south dipping inferred fault, which could be representing one of the imbricate faults associated with the Wagad uplift (Mandal, 2012). The dotted black circular areas (M1, M2, and M3) showed mapped high velocity zones, which are interpreted as mafic plutons. The solid thick black line "A" marks the south dipping NWF, "B" marks the north-dipping KMF, "C" represents the south dipping BF, "D" marks the south-dipping KHF, and "E" marks the south-dipping GF.

with the KR (M2) and WU (M3) are found to be associated with high Vp (10-20% increase), high Vs (8-17% increase) and high Vp/Vs (~1.7-1.8), which are interpreted as consisting of crystallized magma showing high Vp/Vs. The presence of a high velocity magmatic lower crustal layer (Vp: 6.8-7.8 km/s; Vs: 3.9-4.3 km/s; Vp/Vs:1.7-1.8) at 20-40 km below the region is clearly delineated from all the NS-EW depth cross-sections, which might have been resulted from the densification of the lower crust during the magmatism episodes associated with two phase rifting (viz. 180 Ma African and 90 Ma Madagaskar) and the 65 Ma Deccan mantle plume (Courtillot et al., 1986).

We notice that most of the $M_w \geq 5$ earthquakes including the 2001 Bhuj mainshock have occurred near the contacts between high- and low- velocity zones (Figs. 3a-x). The contacts between high-velocity (rigid strong rocks) and low-velocity (fluid filled weak zones) represent zones of high stress concentrations, thereby, resulting in the generation

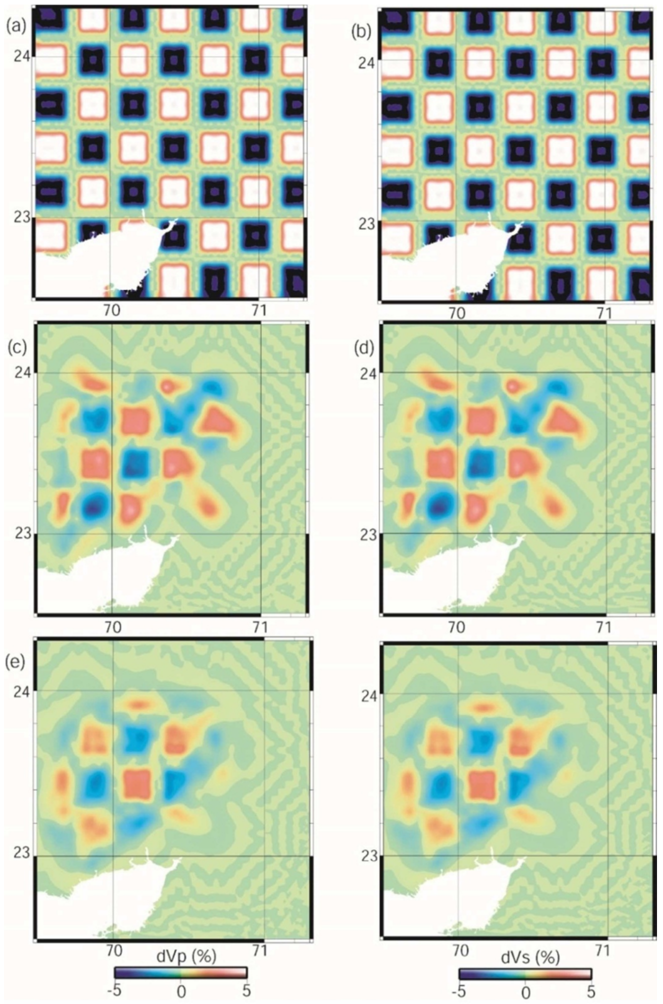

Fig.4. Results of Checkerboard test. **(a,b)** Input perturbation model, consisting of 1600 km^3 with velocities 5% compared to the starting model for P- and S- waves, **(c,d)** recovered perturbation models for P- and S- waves at 10-15 km depths, and **(e,f)** recovered perturbation models for P- and S- waves at 20-25 km depths.

of moderate to large earthquakes (Mandal and Pandey, 2011; Zhao and Negishi, 1998). We also notice occurrences of a few Me”5 events in high velocity zones (Figs. 3a-x), which probably comprise of rigid and brittle rocks that capable of accumulating large stresses to generate moderate earthquakes (Mandal and Pandey, 2011; Zhao and Negishi, 1998; Rastogi et al., 2014). While some Me”5 earthquakes including the 1956 Anjar earthquake are found to occur in the low velocity zones (Figs. 3a-c). A low velocity zone (Vp:5.8-6 km/s; Vs:3.3-3.5; Vp/Vs: 1.73-1.75) has also been detected at the hypocentral zone (~15 km) of the 1956 Anjar earthquake (Figs. 3a-c). Mid-lower crustal low velocity zones could be attributed to the presence of metamorphic fluids or volatile CO_2 (Mandal and Pandey, 2011; Zhao and Negishi, 1998; Rastogi et al., 2014), which might be playing the key role in triggering moderate intraplate earthquakes like the 1956 Anjar. Note that Copley et al. (2011) modelled a low frictional coefficient of 0.08 for the causative NWF of the 2001 Bhuj mainshock. They also proposed that the whole crust extending from surface down to 45 km depth below the KRZ is seismogenic. Given such a low frictional coefficient and crustal condition, the faults within this crustal volume underlying the KRZ could get triggered to generate earthquakes, by a small perturbation in stress regime due to any kind of local tectonic forces (like crustal fluid flows (Mandal, 2019), static stress migration from neighbouring faults (Mandal et al., 2007), volatile CO_2 emanating from the deep mantle (Mandal, 2019) etc.) or regional plate tectonic forces.

CONCLUSIONS

Our study detects a seismogenic crustal volume of 50 km x 50 km x 45 km below the Mesozoic Kachchh rift zone, which is characterized by a 2-km thick top basinal sedimentary layer, a 2-4 km thick crustal thinning and a 10-20 km thick asthenospheric up-warping. Further, our local earthquake tomography has mapped rigid high velocity crustal mafic plutons at 5-35 km depths underlying the Banni, central Kachchh rift and Wagad uplift zones. This kind of crustal and upper mantle structure apparently has brought the crustal faults within the rift zone near to critical stress level, thus, these faults, which are also characterized by small frictional coefficients, could get sudden movements to generate mid to lower crustal earthquakes due to small stress perturbation resulted from the crustal aqueous fluid flows or entrapped CO_2, static stress transfer from the neighbouring faults, or regional plate tectonic forces, thereby, resulting in continued earthquake activity at Kachchh, Gujarat, India, for the last two decades.

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