Magnetotelluric Constraints on the Occurrence of Lower Crustal Earthquakes in the Intra-plate Setting of Central Indian Tectonic Zone

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Abstract: Lower crustal earthquake occurrence in the Central Indian Tectonic Zone (CITZ) of the Indian sub-continent was investigated using magnetotelluric (MT) data. MT models across the CITZ, including the new resistivity model across the 1938 Satpura lower crustal earthquake epicenter, show low resistive (<80 Ωm) mid-lower crust and infer small volume (<1 vol%) of aqueous fluids existing in most part of lower crust. This in conjunction with xenoliths and other geophysical data supports a predominant brittle/semi-brittle lower crustal rheology. However, the local deep crustal zones with higher fluid content of 2.2%–6.5% which have been mapped imply high pore pressure conditions. The observation above and the significant strain rate in the region provide favorable conditions (strong/ moderate rock strength, moderate temperature, high pore pressure and high strain rate) for brittle failure in the lower crust. It can be inferred that the fluid-rich pockets in the mid-lower crust might have catalyzed earthquake generation by acting as the source of local stress (fluid pressure), which together with the regional stress produced critical seismogenic stress conditions. Alternatively, fluids reduce the shear strength of the rocks to favor tectonic stress concentration that can be transferred to seismogenic faults to trigger earthquakes.

Key words: Resistivity, fluids, lower crustal earthquake, intra-plate, Central Indian Tectonic Zone

1 Introduction

The Central Indian Tectonic Zone (CITZ) is considered to be the suture zone between the southern and northern blocks of Indian peninsular shield region (Fig. 1). This E-W to ENE-WSW oriented prominent tectonic feature of the Indian subcontinent, which almost extends from the western continental margin to the eastern Indian margin, was formed due to the Paleoproterozoic collision and subduction involving the various cratonic nuclei constituting the south and north Indian blocks (Naqvi et al., 1974; Yedekar et al., 1990; Acharyya, 2003; Roy and Prasad, 2003; Sarbadhikari and Bhowmik, 2008). The geochronological data demonstrate the evolution of the CITZ through multiphase tectonothermal events (Bhowmik et al., 2011; Mohanty, 2012) and thereby suggest that the area has been tectonically active since its formation. Neotectonic activity in the area is evident from the presence of thermal springs and significant seismicity (Ravishankar, 1988; Rajendran and Rajendran, 1998, 1999; Minissale et al., 2000). The seismicity in the region is represented with several small to moderate crustal earthquakes (Rajendran and Rajendran, 1999; Rao and Rao, 2006). Though, most of these earthquakes were focused within the upper crust (<15 km), at least two of the moderate earthquakes (1938 Satpura [M = 6.3, focal depth = ~40 km (Mukherjee, 1942)] and 1997 Jabalpur [Mw=6.0, Mw=5.8, focal depth=35–38 km (Rao et al., 2002; Gahalaut et al., 2004)] were lower crustal earthquakes. This unusual phenomenon of lower crustal origin of intra-plate (intra-continental) crustal earthquakes is curious. Because, globally, crustal earthquakes reported from intra-continental regions usually occur in the brittle upper crust and are not anticipated from the lower crust, which is generally considered as asseismic due to its ductile nature avoiding stress concentration and thereby brittle failure (Meissner and Streblau, 1982; Chen and Molnar, 1983). Moreover, only three of the intra-plate events from the Indian shield, namely the 2001 Bhuj earthquake [Mw =7.7, focal depth=20–28 km (Mishra and Zhao, 2003; Mandal and Pandey, 2010)] of Kutch rift region and the two reported from the CITZ, showed earthquake generation in lower crustal depth range of 20–40 km. Thus, it would be interesting to examine the physical conditions under these seismic zones and the responsible

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Fig. 1. Geology and tectonic elements in the Central Indian Tectonic Zone (CITZ) shown along with the location of geophysical profiles discussed in this study. Black rectangles represent the magnetotelluric (MT) sites along the new MT profile, while the purple rectangles marks the MT sites along five profiles (labeled MT-1 to MT-5 from west to east) previously studied by Abdul Azeez et al. (2013). Deep seismic sounding profiles in the region are shown with broken grey line and named from west to east as S1 to S5. Heat flow measurement locations (red inverted triangles) and the values reported by Roy and Rao (2000) are also marked. Inset map shows the various cratonic units and the mobile belts constituting the peninsular Indian shield. The rectangular black block marks the study region.
mechanisms that favor a brittle fracture in the ‘ductile’ lower crust.

Lower crustal seismicity is frequently reported from active plate boundary regions, such as active continental rifts and subduction zones (Doser and Yarwood, 1994; Seno and Saito, 1994; Shelly et al., 2006; Reyners et al., 2007; Keir et al., 2009; Soosalu et al., 2010). It is intriguing to observe such lower crustal seismicity as the necessary brittle failure associated with earthquakes is incompatible with the generally assumed ductile behavior of the normal (unaltered) lower crust due to increase in temperature with depth (Chen and Molnar, 1983). Hence, some process or mechanism must occur to keep the lower crust seismogenic. The suggested mechanisms for the lower crustal seismicity in these tectonic settings are chiefly attributed to fluid or magma movement/interaction at deep crustal levels (Reyners et al., 2007; Keir et al., 2009; Soosalu et al., 2010; Kotayama et al., 2012).

Intra-plate lower crustal earthquake occurrence is not a unique characteristic of the Indian shield as such events are reported from elsewhere (Chen, 1988; Fredrich et al., 1988; Wong and Chapman, 1990; Nyblade and Langston, 1995; Johnston, 1996; Lamontagne and Ranalli, 1996; Awad et al., 2005; Ma and Atkinson, 2006). Despite the confirmed reports of lower crustal seismicity from some continental intra-plate regions, lower crustal earthquakes are indeed considered to be very rare. Though the rheological condition and generation mechanism for the commonly observed shallow intra-plate seismicity are well conceived, no consensus has been made on the generation of intra-plate lower crustal earthquakes. Various reasons proposed for lower crustal seismicity in an intra-plate setting includes the sudden reactivation of pre-existing weak zones due to local stress variation (modification) related to regional plate tectonic forces, topography and crustal density inhomogeneities, fluid phases, etc. (Campbell, 1978; Sykes, 1978; Talwani and Rajendran, 1991; Zoback and Richardson, 1996; Kato et al., 2009). Since intra-plate seismicity is believed to occur mainly in the brittle layer, Simpson (1999) argued that some tectonic regimes may preserve brittle rheology down to the Moho, largely by dry mafic lower crust, that would facilitate earthquake nucleation in the lower crust. Such deep brittle-ductile transition zones were observed in continental rifted regions (Nyblade and Langston, 1995; Deverchere et al., 2001; Mandal and Pandey, 2011).

The deep crustal Jabalpur earthquake (21st May 1997, Mw = 5.8) in the CITZ occurred due to the reactivation of the Narmada South fault marking the southern boundary of the Narmada-Son paleo-rift structure (Acharyya et al., 1998; Kayal, 2000). Rajendran and Rajendran (1999) suggested a stress concentration model for the Jabalpur earthquake in which the localization and generation of deviatoric stresses due to rift pillows were envisaged. Similar earthquake generation mechanism, due to mafic intrusives in the lower crust, was also given by Rao et al. (2002) using waveform inversion studies. However, Gahalaut et al. (2004) argued for no correlation of rift pillow with the focal depth of earthquakes in the CITZ. They attributed the lower crustal seismicity to high pore pressure, low frictional coefficient and high strain rate, which could assist brittle failure in the lower crust. Recently, large intra-plate stresses associated with mafic intrusives were inferred from three dimensional computations of intra-plate stresses induced by topography and crustal heterogeneities in Jabalpur region (Mandal, 2010). According to Mandal (2010), these intra-plate stresses and the conditions of high pore pressure, as well as deep brittle-ductile transition, are the possible contributors for the deep crustal earthquakes.

Several studies have shown that the genesis of major earthquakes, more than a mere mechanical process, is closely connected to the physical and chemical conditions of the materials in the crust and mantle, such as fluids, magma and other heterogeneities. Geophysical methods, especially the magnetotelluric (MT) electromagnetic technique, can greatly contribute to the visualization of large scale structures at depth and helps to reveal the seismotectonic processes (e.g. Wong and Chapman, 1990; Hildenbrand et al., 2001; Lamontagne et al., 2003; Moore et al., 2007; Reyners et al., 2007; Chandrasekhar et al., 2012; Zhao et al., 2012; Zhang et al., 2015). In the present study, the seismogenic conditions within the CITZ lower crust are evaluated using electrical resistivity models obtained from MT data along profiles across the CITZ, which includes a new MT profile passing through the 1938 Satpura earthquake zone and another five MT profiles recently studied by Abdul Azeem et al. (2013), in conjunction with other available geophysical results.

2 Brief Geology and Earthquake History

The CITZ was formed due to the collision and subsequent suturing between the southern peninsular block (made up of Dharwar, Singhbhum and Bastar cratons) and the northern foreland block (composed of Aravalli and Bundelkhand cratons) of India (Fig. 1). The collision tectonics initiated during the Neoarchean-Paleoproterozoic period (Naqvi et al., 1974; Yedekar et al., 1990; Acharya, 2003; Roy and Prasad, 2003; Sarbadhikari and Bhowmik, 2008). The region has experienced more deformation, metamorphism and
remobilization during the subsequent geological history (Biswas, 1987; Sarkar et al., 1998; Bhowmik et al., 2011 and references therein; Mohanty, 2012 and references therein), and the Late Cretaceous to Early Tertiary Deccan volcanism (~65 Ma) represents the last of such major tectonic event (Pande, 2002). The Deccan basalts cover a large part of the Western and Central India and, conceal the western and central parts of the CITZ (Fig. 1). The pre-existing weak zones (faults) that characterize the CITZ were believed to have acted as the major eruption channels for Deccan flood basalts (Bhattacherji et al., 1996; Sheth and Chandrasekharan, 1997). The wide variety of rock types, ranging in age from Neoarchean to Recent, exhibit the intense tectonic activity experienced by the area (Jain et al., 1995). Seismically active faults, exhibiting E-W to ENE-WSW surface trends, are mapped in the region (Fig. 1). The significant among these faults are Narmada North Fault [NNF], Narmada South Fault [NSF], Barwani-Sukta Fault [BSF], Gavligarh Fault [GF] and Purna Fault [PF] (Fig. 1). These faults are inferred to be vertical/near vertical features and some of them show deep extension into the Moho (Kaila et al., 1981, 1985, 1989). Nagananjayulu and Santhosh (2010), however, put constraints on to the depth extension of these faults and interpreted them as listric faults. The Narmada fault system marks the southern boundary of the CITZ; while the Tapti-Purna lineament is considered to be the southern limit (Acharyya and Roy, 2000). The lineament zone bounded by Narmada fault systems [Narmada South Fault (NSF) and Narmada North Fault (NNF)] is also described as Narmada-Son Lineament (NSL) zone. This is widely considered as a paleo-rift zone and has reactivated several times in the geologic past (Choubey, 1971).

The active tectonics of the CITZ is evident from the recent seismicity reported from the region (Rajendra and Rajendra, 1999; Rao et al., 2002; Mall et al., 2005, Mandal et al., 2013). Several earthquakes, ranging in magnitude from low (M=3) to moderate (M=6.5), have occurred in the CITZ and bordering areas (Fig. 2) during the last 70 years (Rajendra and Rajendra, 1999 and references therein; Mandal et al., 2013). Most of these seismic events were, in general, originated within the upper 15 km of the crust (Rajendra and Rajendra, 1999; Rao, 2000; Rao et al., 2002; Gahalaut et al., 2004; Rao and Rao, 2006). Nonetheless a few (at least two) among the major events have shown deep focal depths of 35-40 km (Rao et al., 2002). These events are namely the 1938 Satpura (M=6.3) and the 1997 Jabalpur (M<sub>s</sub>=6.0, M<sub>p</sub>=5.8) earthquakes (Fig. 2). Though not precise, due to insufficient data, the focal depth reported for 1938 Satpura earthquake is ~40 km (Mukherjee, 1942). The estimated focal depth of the Jabalpur earthquake, epicenter located ~400 km east of the 1938 Satpura earthquake, is 36 ± 4 km (Wallace, 1997; Singh et al., 1999; Rao et al., 2002; Gahalaut et al., 2004). The aftershocks of the Jabalpur earthquake also have confirmed deep hypocenter depths of

![Fig. 2. Epicenters of major earthquakes (Ms 5 or above) reported from the CITZ and neighbor areas are shown over the tectonic features in the region.](image-url)

Earthquake data for the period 1800-2012 from ISC and USGS are used. The MT and seismic profiles discussed in this paper are also marked. Inset shows the rose diagram of the geoelectric strike directions estimated using McNiece and Jones algorithm (MJ) and phase tensor analysis (PT).
time variations of the two orthogonal horizontal electric and magnetic field, as well as the vertical magnetic field, induced in the subsurface were measured. The MT instruments (GMS-05 and ADU-06) developed by M/s Metronix, Germany were used for data acquisition. The electric fields were measured using the non-polarizing Cd-CdCl2 electrodes and magnetic fields were measured using induction coils. The recorded electric and magnetic field time series data were processed using robust algorithms included in the Mapros software (Friedrichs, 2003) to obtain the MT impedances and the vertical transfer functions (tipper impedances) as a function of frequency. The overall data quality of MT impedances was good for most of the sites. Especially, the data in the 10–0.002 Hz (0.1–500 s) range showed better data quality owing to smooth varying data points with minimum error levels in its determination. Hence, the MT data analysis and modeling is restricted to the above range. However, the tipper impedances showed poor quality at many sites due to higher noise level in the vertical magnetic field data.

MT profile data are commonly interpreted using a twodimensional (2D) approach, which is applied here too to generate the subsurface resistivity model. The necessary validation of the 2D approach on the present data was investigated using the popular tensor decomposition algorithm of McNeice and Jones (2001), which is based on the method of Groom and Bailey (1989). This decomposition method separates the effect of near-surface and regional resistivity structures in the measured MT data and computes the regional geoelectric strike direction that is most consistent with the measured data. Figure 2 (inset) shows the rose diagram of the single-site single-frequency geoelectric strike values in the 0.1–500 s data range, computed for most of the sites using the strike analysis algorithm of McNeice and Jones (2001). Few sites, which showed scattered data points (hence more noise) in one of the impedance components, were not included in the strike computation. The computed strike values show highly consistent east-west (or north-south due to 90° ambiguity in strike determination) strike directions at different locations on the profile, and thus confirm a valid 2D subsurface assumption. Similar results were obtained using another different approach of Caldwell et al. (2004), known as the phase tensor analysis - a relatively new robust approach to determine strike from MT data (Fig. 2 inset). The estimated electric strikes from both the approaches are in good agreement with the regional surface tectonic trends of EW to ENE-WSW (Fig. 2). This was used to resolve the inherent 90° ambiguity in electric strike determination using tensor decomposition methods, and hence an approximate EW strike can be assumed. The profile electric strike required for the computation of the
2D MT responses was decided by multi-site, multi-frequency tensor-decomposition procedure, which yielded a best strike direction of N96°E for the present MT profile. Accordingly, the measured MT impedance tensor at the individual sites were rotated to the regional co-ordinate frame of N96°E, and the 2D MT responses parallel to the strike (transverse electric (TE) mode) and perpendicular to the strike (transverse magnetic (TM) mode) were derived. The MT sites were projected to a line perpendicular to the electric strike direction and the observed 2D responses (TE and TM data) were inverted using the nonlinear conjugate gradient (NLCG) algorithm of Rodi and Mackie (2001). Inversion strategies used by Abdul Azeez et al. (2013) in the systematic analysis of five MT profiles across the CITZ were followed here to enable a more realistic comparison of the resistivity models generated along the different profiles across the CITZ. Many inversion models were derived from different initial half-space models and for a range of inversion control parameters to identify the robust resistivity features in the subsurface resistivity models. All the different joint models showed consistent resistivity features. In similar line with the MT study by Abdul Azeez et al. (2013), along the five profiles covering the western to central part of CITZ, the final model for the interpretation of subsurface geology along the new MT profile was obtained after 200 iterations, using simultaneous inversion of the TE, TM and tipper (H_d) data from an initial half-space model of 100 Ωm. The inversion regularization parameter (τ) was set to 3 to emphasize better data fit. A horizontal smoothing factor (α) = 3 was used to the horizontal derivatives in the inversion to have increased smoothness in the horizontal direction. The interpreted resistivity model along the new MT profile is presented in Figure 3. The resistivity models obtained along the five MT profiles, previously studied by Abdul Azeez et al. (2013), are also presented in Figure 4 to provide a more comprehensive understanding of the resistivity structure along the strike of the CITZ. The root-mean-square (r.m.s.) error computed for the individual sites along the present MT profile (Fig. 3) and the overall r.m.s. error of 2.16 suggests an acceptable misfit between the observed and inversion model responses. The good agreement between the measured and inversion model responses can also be noticed from the measured and modeled apparent resistivity and phase pseudo sections (Fig. 5).

The resistivity models along the different MT profiles across the CITZ invariably show a general low resistivity (<80 Ωm) of the middle and lower crust (Fig. 3 and Fig. 4). But the low resistivity value is not uniform in the CITZ as localized features of extreme low values (1–10 Ohm.m) exists at upper and lower crustal levels, mostly underneath the known fault features. The low to moderate heat flow values (45–62 mW/m²) estimated (Roy and Rao, 2000), moderate temperatures (500–635°C) inferred at lower crustal depths (Rai and Thiagarajan, 2006; Mall and Sharma, 2009) and the active geodynamics of the region suggests the presence of aqueous fluids in the interconnected pores of the rock matrix is the most suitable explanation for the observed low resistivity in the mid-lower crust of the CITZ. A more detailed discussion on other possible low resistivity mechanisms in the CITZ has given in Abdul Azeez et al. (2013). The occurrence of aqueous fluids in the present crustal column of the CITZ can be attributed to the Late Cretaceous-Early Tertiary Deccan flood volcanism, the most recent major tectonic event in the region, which might have injected mantle fluids and magma into the crust. Also, the crystallization of the underplated magma and dehydration of heated rock would release fluids into surrounding crustal regions (e.g., Seno and Saio, 1994; Wammaker et al., 2008). In addition to the crustal fluids, the low resistivity in the CITZ may have contribution from hydrous minerals as they are observed in the xenoliths samples from the CITZ (Dessai et al., 2010).

Petrological investigations shows that free fluids may not be stable at lower crustal depths for a long geologic timescales (Bailey, 1990; Frost and Bucher, 1994). The free fluids can migrate upwards to upper crustal levels and/or be consumed in metamorphic reactions. Hence, the presence of interconnected fluids at depths requires a sustained fluid supply to keep it under continuous recharge. However, it is possible that some free aqueous fluids may remain in the deep crust (Sanders, 1991) as the life time of fluids in crust is about 100 Ma (Bailey, 1990; Vanyan and Gliko, 1999). The reflective nature of the mid-lower crust (Kaila et al., 1981, 1985, 1989) underneath this region also suggests the presence of fluids released from magma bodies. The volume of fluids required to produce low resistivity in an otherwise resistive deep crust (rock formation dominated by mafic granulites) can be estimated using Archie’s law (Archie, 1942). Assuming a cementation factor of m=1.5 and the resistivity range estimated for saline fluids (0.01–0.05 Ωm) at lower crustal pressure-temperature conditions (Nesbitt, 1993), only 0.6–1.8% interconnected pore fluid phase is required to explain the bulk resistivity of 20 Ωm observed beneath the CITZ. However, much higher volume % of fluids (2.2%–6.5%) is needed to produce the observed isolated more low resistive (1–5 Ωm), zones, which are chiefly present under the faults zones. The greater part of the lower crust of the CITZ is characterized with resistivity values ranging between 30–80 Ωm, which corresponds to small volume percentage (0.34%–1%) of
Fig. 3. Two-dimensional resistivity section (bottom) obtained for the new MT profile is shown without vertical exaggeration. The marked features in the resistivity section represent the enhanced conductive zones, which are discussed in the text. TR=Tapti River; TF=Tapti Fault; NR=Narmada River; NSF=Narmada South Fault; BSF=Barwani Sukta Fault. The root-mean-square (r.m.s.) misfit between the observed MT data and the computed responses of the inversion model for all the sites used in the inversion modelling are presented in the upper panel. The average misfit for the profile is also marked.

Fig. 4. Resistivity structure across the CITZ obtained along the five MT profiles studied recently by Abdul Azeez et al. (2013). Models are shown without any vertical exaggeration. Note that similar inversion algorithm and inversion strategies are used in obtaining all the resistivity sections discussed here. The marked features represent the enhanced conductive zones. TR=Tapti River; TF=Tapti Fault; NR=Narmada River; NF=Narmada Fault; NSF=Narmada South Fault; NNF=Narmada North Fault; PF=Purna Fault, GF=Gaviagarh Fault, BSF=Barwani Sukta Fault.
interconnected pore fluids.

3.2 Subsurface Rheology and Lower Crustal Seismicity

The deformation of the subsurface rock formations (rock rheology) under the stress conditions within the earth are of primary importance in understanding the occurrence and mechanism of earthquakes. The different rocks constituting the earth crust and mantle usually show either brittle (rock fails by rupture when the stress reach its yield stress) or ductile (rock deform by plastic or viscous flow when yield stress is attained) rheology, primarily controlled by the composition of the rock. In the continental crust, the brittle behavior prevails in the upper crust (felsic composition) and it gives way to the ductile behavior in the lower crust (predominantly mafic composition) due to the high temperature and pressure conditions exist at lower crustal depths. The transition from brittle to ductile, however, occurs over a depth range known as the brittle-ductile transition zone (Kirby, 1983; Ranalli, 1995). Both brittle and ductile processes can operate in this broad regime and hence represent a semi-brittle behavior (Carter and Kirby, 1978; Kirby, 1983). The maximum depth of the brittle-ductile transition zone represents the deepest part of the crustal seismic zone and the crustal region below this is often considered aseismic (Young et al., 1991).

The subsurface rock rheology is chiefly influenced by the mineralogy of the rock formation, fluid content and chemistry, temperature, pressure, and differential stress (and strain) conditions (Ranalli, 1995, 2000; Burgmann and Dresen, 2008). In general, brittle rheology is more likely for low temperature and pressure, and high strain rate conditions. Therefore, the near surface rocks show the lowest fracture strength and undergo brittle failure under sufficient stress. On the other hand, higher temperature and pressure, and lower strain rate favor ductile rheology. With the increase in pressure and temperature as depth increases, intracrystalline plasticity dominates the deformation regime so that rocks fail by ductile creep or flow (Paterson and Wong, 2005). A wide temperature range of 300–500°C is known for the brittle-ductile transition in rocks with felsic composition (e.g., Burgman and Dresen, 2008). The laboratory experiments by Tullis and Yund (1977) inferred brittle-ductile transition temperature range of 300–400°C and 450–550°C respectively for quartz and feldspar, which are the major constituent minerals of felsic rocks. Rocks with mafic mineralogy, however, shows higher brittle-ductile transition temperature range of 400–700°C for wet and dry conditions (Simpson, 2001). For example, the onset of ductile rheology in Orthopyroxene, the major component of mafic/ultramafic rocks, occurs in the temperature range

Fig. 5. Observed MT data and the computed responses of the resistivity model (shown in Fig. 3) are shown as pseudo sections of TE (upper panel), TM (middle panel) and tipper (bottom panel) data.
of 600–700°C (Simpson, 2001). The brittle-ductile transition in felsic lithology vary with the geothermal gradient and usually range between 10 to 25 km (Dragoni and Pondrelli, 1991), but its presence has been inferred to depths of 40 km for mafic composition (Philippot, 1993). The aqueous fluids in the rock matrix can also influence the brittle-ductile transition zone by promoting brittle process through the effective stress phenomena and various chemical effects of water on deformation processes (e.g., Kirby, 1983). Presence of fluids would increase pore pressure, which reduce the effective normal stress and thus promote rock failure by reducing the fracture strength/frictional resistance (e.g., Seno and Saito, 1994; Reyners et al., 2007). Also, the aqueous fluids have weakening effects on the crustal rocks through the ‘water weakening’ processes such as adsorption, dissolution, diffusion and hydrothermal alteration (Kirby, 1983). The brittle-ductile transition depth is directly related to the strain rate, i.e., the transition depth increases with the increase of strain rate (Dragoni and Pondrelli, 1991). Due to the local variations in the above discussed subsurface physical conditions, the thickness and depth limits of the brittle-ductile transition zone can change considerably from one place to another (Chen and Molnar, 1983). Remotely measured geophysical properties of the subsurface rocks matrix provide indirect information on the physical conditions of the subsurface that control its rheology and help to explain the seismicity in the crustal column.

Significant lower crustal strength (anhydrous and/or cool crust) and stress accumulation or some other mechanism in the ductile deep crust (like fluid embrittlement / interaction), which could promote imbalances leading to earthquake generation, is required to keep the lower crust seismogenic. The seismic velocity (Kaila and Krishna, 1992; Tewari and Kumar, 2003; Rai et al., 2005; Sridhar et al., 2007; Jagadeesh and Rai, 2008; Murty et al., 2008; Dixit et al., 2010) and density (Singh and Meissner, 1995; Tewari and Kumar, 2003; Rao et al., 2011) structure of the CITZ invariably indicated mafic/ultramafic rock formations in the lower crust. The xenoliths data from the CITZ shows the presence of mafic granulate facies rocks (dominated by clinopyroxene, orthopyroxene and garnet mineralogy) that are interstratified by ultramafic rocks (Dessai et al., 2010). Such rock composition would have a brittle rheology except under abnormal conditions, such as very high temperature, pressure and porosity. Recent surface heat flow measurements made on the hard rock areas bordering the CITZ (Fig. 1) indicated low to moderate values, mean values ranging between 45-69 mW/m² (Roy and Rao 2000). Crustal geotherms computed from seismic velocity models, assuming a steady state conductive heat transfer, are also available for the CITZ (Rai et al., 2003; Rai and Thiagarajan, 2004, 2007; Sharma et al., 2005). These temperature depth profiles (Fig. 6) computed by various workers along some of the seismic profiles (Fig. 1) across the CITZ suggests a broad temperature range of 470–635°C at the Moho. Sharma et al. (2005), however, predicted little higher temperature range (600–700°C) at Moho depths from a simple one-dimensional geothermal modeling along the seismic profile S5 passing through Jabalpur area (Fig. 6). Rai et al. (2003) determined the two-dimensional thermal structure along the above profile and shown lower temperatures (510–535°C) at Moho depths (41–43 km). These estimated lower crustal/Moho temperatures does not exceed the maximum temperature limit reported to occur brittle-ductile transition in rocks (dry and wet conditions) with similar mineral compositions (Simpson, 2001) as found in the CITZ lower crust. On the basis of the above discussed lower crustal lithology and temperature conditions, it is reasonable to argue that the CITZ lower crust can have a semi-brittle rheology and ductility may not have induced in the lower crust. On the other hand, resistivity structure suggests highly fluidized zones (2.2–6.5 vol% porosity) at confined locations in the crust, which would aid weak ductile rheology. Nevertheless, the small volume (<1 vol%) of fluid in most part of the lower crust may not be sufficient to produce wide spread mechanical weakness in the rigid mafic lower crustal formation. These crustal characteristics perhaps suggest that the lower crust of CITZ might be preserving brittle/semi-brittle rheology in places (e.g. Simpson, 1999) that satisfy earthquake nucleation. Manglik and Singh (2002), from thermo-mechanical modeling studies, indicated an extended brittle-ductile transition zone to ~41 km depths under the CITZ. Similar kind of deepening of the brittle-ductile transition zone to the Moho, which could satisfactorily explain the lower crustal seismicity, has been reported for other continental rifted regions (Nyblade and Langston, 1995; Deverchere et al., 2001; Mandal and Pandey, 2011). Detailed studies of intra-plate seismic zones carried out by Lamontagne and Ranalli (1996) showed that in all likelihood the brittle-ductile transition is deeper than the maximum depth of earthquakes.

Since the rheologic states of the crust and mantle are highly sensitive to temperature variations, evaluation of the subsurface temperature conditions should be made using adequate and accurate temperature data. In the case of CITZ, the available temperature data have certain limitations: (a) heat flow measurement over the region is sparse and non-uniform, thus may not be adequate to represent the true heat flow conditions in the region; (b) it
is difficult to assign quantitative confidence limits to the computed geotherms from seismic P-wave velocities, as the empirical relation used to compute heat production, which is further used for the estimation of the subsurface temperature field, is questionable (Fountain, 1986). In general, computed crustal geotherms can be mostly inaccurate as seen in the case of KTB and Kola boreholes (e.g., Burkhart et al., 1989). Despite these limitations, the available surface heat flow values are useful and can be considered as a qualitative reflection of the internal temperature conditions of the crust and mantle. The continental geotherms presented for different surface heat flows (Chapman, 1986; Pollack et al., 1993) indicate temperatures less than 700°C at 35–40 km depths for the surface heat flow range (45–68 mW/m²) observed over the CITZ. The Curie depth determined from magnetic data is one important proxy to give an idea about the thermal structure of the crust. The depth to the bottom of the magnetic sources (Curie depth) computed recently from aeromagnetic data showed values between 33 and 41 km for the area in and around Jabalpur earthquake epicenter (Bansal et al., 2013). Though the Curie temperature (the temperature above which rock lose their ferromagnetic magnetization) vary with the magnetic mineral (Haggerty, 1978), the Curie temperature of magnetite (the most abundant magnetic mineral in the crust), 580°C, is generally considered applicable to the lower continental crust (Shive et al., 1992). Thus, the Curie depth of 33–41 km suggests a temperature of ~580°C at these depths that corresponds to the lower crust/Moho depths in the CITZ. In summary, the low to moderate surface heat flow values and deep (33–41 km) magnetic Curie depths probably suggest that sufficient high thermal conditions may not exist at the base of the crust to cause ductile flow in the mafic/ultramafic (rich in pyroxene) rocks and thus a brittle/semi-brittle rheology is most likely in the CITZ lower crust. Seno and Saito (1994) pointed out that earthquake nucleation is unlikely in the lower crust of high (~100 mW/m²; e.g. Ranalli, 1997) and low (~40 mW/m²; e.g. Ranalli, 1997) surface heat flow regions as the regions will have very low and very high strength of the lower crust, respectively. They further suggested that intermediate heat flow (~60 mW/m²; e.g. Ranalli, 1997) is one of the necessary favorable factors for the generation of lower crustal earthquakes (Seno and Saito, 1994).

The presence of regional underplated mafic structure or localized mafic intrusions (rift pillows) was invoked previously to explain the generation of earthquakes in the CITZ deep crust (Rajendran and Rajendran, 1998; Rao et al., 2002). These models envisage the localization of
stresses and generation of deviatoric stresses due the underplated excess mass. The geophysical structure suggests that the presence of underplated mafic magma is a common feature and present almost all along the strike and width of the CITZ. But, the seismicity occurrence, especially the lower crustal events, does not show such wide-spread distribution in the area. Instead, the lower crustal events are limited to few locations (Fig. 2). This probably suggests no correlation between the mafic underplated structures and lower crustal seismicity (Gahalaut et al., 2004; Mall et al., 2005).

Intermediate heat flow is only one among the necessary conditions for lower crustal earthquakes to occur, because such heat flow conditions are common in many different tectonic areas of the world (Pollack and Chapman, 1977). In addition to intermediate temperature constraint, high pore pressure and high strain rate are the necessary conditions for earthquakes to occur in the lower crust (Seno and Saito, 1994; Ranalli, 1997). The presence of fluids in the CITZ, as inferred from the resistivity models, would adequately explain the causative agent for high pore pressure and low coefficient of friction (value ranges from 0.6–1 for most rock types, e.g. Burgmann and Dresen (2008)) required for earthquake nucleation at lower crustal depth (e.g. Lamontagne and Ranalli, 1996; Terakawa et al., 2016; Wannamaker et al., 2004). The pore fluid pressure provide necessary conditions to overcome the pressure from the rock column above the faults, which protect them from slipping, and reduce the stress needed for rock failure (Hubbert and Rubey, 1959). Gahalaut et al. (2004) constrained the source parameters of the Jabalpur (1997) aftershock events using static stress modeling and they proposed high pore pressure conditions that reduced the frictional coefficient for rock failure at lower crustal depths. Also, from stress modeling studies, Mandal (2010) has shown that the brittle failure associated with the Jabalpur earthquake may have occurred due to high fluid pressures at the hypocenter region. Rao and Rao (2006) also proposed the influence of fluids, produced by serpentinite dehydration in the lower crust, as the causative factor of the 1997 of Jabalpur earthquake. Irrespective of the regional and tectonic settings, fluids are proved to be a strong triggering agent for the earthquakes, both at shallow and deeper levels (Seno and Saito, 1994; Ogawa and Honkura, 2004; Wannamaker et al., 2004; Gurer and Bayrak, 2007; Reynolds et al., 2007; Terakawa et al., 2010). Hence, it would be appropriate to conclude that the fluids in the mid-lower crust play the key role for stress accumulation in the CITZ crust. A uniform north-south oriented regional stress pattern, assumed to be associated with the northward movement of Indian plate, is seen over the central Indian region (Mohanty, 2011). An additional local stress is needed to explain the seismicity. The fluids can be the source for the necessary local stress generation, which in tandem with the regional stresses create the necessary critical stress conditions for brittle fracturing of the lower crustal rocks.

Significant strain rate (contemporary average strain rate 1.6×10^{-8}/a), with respect to the Indian shield (6.01×10^{-9}/a) (Rao, 2000) and global strain rate computed for deforming tectonic boundaries (vary from 0.2×10^{-9} to 3.162×10^{-9}/a) (Kreemer et al., 2003), and local stress conditions required to trigger lower crustal earthquakes are inferred over the region (Banerjee et al., 2008; Mohanty, 2011; Rao, 2000). Studies of stable continental earthquakes have shown that rigid plates deform at strain rates of 10^{-10} to 10^{-7}/a (Zoback and Townend, 2001). Mohanty (2011) obtained an average value of ~ 54 mm/a for the velocity vector over the central Indian region and analysis of velocity data shows high shear strain rate of ~ 3×10^{-9}/a. The strain patterns determined from GPS measurements show close agreement with the above strain values determined from model velocity data (Mohanty, 2011). Banerjee et al. (2008) determined the surface velocities from GPS data in India and found a north-south shortening rate of ~0.3×10^{-9}/a, which may be accommodated by local deformation (convergence) of 2±1 mm/yr across central India.

Thus the MT models, using constraints from other geophysical and petrological results, help to evaluate the physical conditions present within the CITZ crust, which provide evidence of favorable conditions (namely strong/moderate lower crustal strength, moderate crustal temperatures, high pore pressure and high strain) for brittle failure to occur in the CITZ lower crust. Uncertainty still remains on the rheology of the lower crust (brittle/semi-brittle or ductile) due to the uncertainty in temperature conditions (as rock rheology highly depend on temperature) of the lower crust that arise from the inherent inaccuracies in the estimation of lower crustal temperatures from surface measurements. However, in the presence of fluids, the rheological status of the lower crust is not particularly important for earthquake generation as fluids are capable of catalyzing earthquake processes irrespective of the rheological condition (Becken et al., 2011; Gurer and Bayrak, 2007; Ogawa and Honkura, 2004). Because, even in the case of the general ductile behavior of the lower crust, high fluid pressures can facilitate brittle failure within an otherwise ductile regime (Thomas et al., 2009). The high porosity (more pore fluid volume) inferred at specific pockets in the lower crust would act as major earthquake triggering source by generating substantial local stress (and hence strain) condition, controlled by pore fluid pressure, in tandem...
with the regional tectonic stress related to the plate motion. Alternatively, the highly fluidized zones may have relatively low shear strength and act as weak zones suitable for tectonic stress concentration, which can be transferred to seismogenic faults in the area leading to earthquake. Thus, it can be argued that the seismicity in the CITZ lower crust is most likely being triggered by fluids.

4 Conclusions

The Central Indian Tectonic Zone (CITZ) of the Indian subcontinent is a major divide between the northern and southern cratonic blocks of peninsular India. This prominent tectonic feature, evolved during the Palaeoproterozoic time, now observes noticeable seismicity both at upper crustal and lower crustal depths. The subsurface geophysical characteristics of this vibrant tectonic zone were evaluated to understand the lower crustal seismicity using magnetotelluric (MT) studies. The seismic, gravity and petrological studies indicate mafic/ultramafic rock compositions, enriched with pyroxene minerals, in the CITZ lower crust. The geothermal constraints available from surface heat flow measurements and Curie depth estimations from aeromagnetic data do not suggest temperatures high enough to induce ductile rheology in a pyroxene rich mafic/ultramafic lower crustal formation. The crustal resistivity structure of the CITZ deduced from MT data suggests the presence of small volume (<1 vol%) of aqueous fluids in most part of the CITZ lower crust, and this in conjunction with the other geophysical and geologic constraints support a general brittle/semi-brittle rheology of the lower crust. However, highly fluidized zones (2.2–6.5vol%) at confined locations in the crust were evident from the resistivity images, which points to high pore pressure conditions in the deep crust. The above physical conditions of the CITZ crust, and the significant strain rate inferred over the region, indicate favorable conditions (namely strong/moderate lower crustal strength, moderate temperature conditions, high pore pressure and high strain) for brittle fractures to occur in the lower crust. The pore pressure generated by the considerable volume of pore fluids inferred at specific pockets in the lower crust would act as major earthquake triggering mechanism by generating substantial local stress (and hence strain) condition in tandem with the regional tectonic stress relates to the plate motion. It is also possible that the highly fluidized zones would act as weak zones suitable for tectonic stress concentration in the deep crust, which could be transferred onto seismogenic faults in the crust to generate earthquake.

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