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ORIGINAL ARTICLE

Geophysical signatures of fluids in a reactivated Precambrian collisional suture in central India

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Abstract The Central India Tectonic Zone (CITZ) marks the trace of a major suture zone along which the south Indian and the north Indian continental blocks were assembled through subduction-accretion-collision tectonics in the Mesoproterozoic. The CITZ also witnessed the major, plume-related, late Cretaceous Deccan volcanic activity, covering substantial parts of the region with continental flood basalts and associated magmatic provinces. A number of major fault zones dissect the region, some of which are seismically active. Here we present results from gravity modeling along five regional profiles in the CITZ, and combine these results with magnetotelluric (MT) modeling results to explain the crustal architecture. The models show a resistive (more than 2000 $\Omega\cdot$m) and a normal density (2.70 g/cm^3) upper crust suggesting dominant tonalite–trondhjemite–granodiorite (TTG) composition. There is a marked correlation between both high-density (2.95 g/cm^3) and low-density (2.65 g/cm^3) regions with high conductive zones (<80 $\Omega\cdot$m) in the deep crust. We infer the presence of an interconnected grain boundary network of fluids or fluid-hosted structures, where the conductors are associated with gravity lows. Based on the conductive nature, we propose that the lower crustal rocks are fluid reservoirs, where the fluids occur as trapped phase within minerals, fluid-filled porosity, or as fluid-rich structural conduits. We envisage that substantial volume of fluids were transferred from mantle into the lower crust through the younger plume-related Deccan volcanism, as well as the reactivation, fracturing and expulsion of fluids transported to depth

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during the Mesoproterozoic subduction tectonics. Migration of the fluids into brittle fault zones such as the Narmada North Fault and the Narmada South Fault resulted in generating high pore pressures and weakening of the faults, as reflected in the seismicity. This inference is also supported by the presence of broad gravity lows near these faults, as well as the low velocity in the lower crust beneath regions of recent major earthquakes within the CITZ.

1. Introduction

Recent studies on the Precambrian terrains suggest that multiple tectonothermal events recorded from many of these regions relate to distinct plate tectonic cycles (e.g. Polat et al., 2009; Windley and Garde, 2009; Santosh et al., 2009a, b). Substantial amounts of melts and fluids are associated with both divergent and convergent plate boundary processes (see Santosh and Omori, 2008 for a recent review). The formation and exhumation of high grade metamorphic orogens within the Precambrian collisional sutures are considered to mark the final phase of a prolonged subduction-accretion history with the consumption of the intervening oceans, and culminating in Himalayan-style collision (e.g., Collins et al., 2007; Cawood et al., 2009; Santosh et al., 2009a, b; Santosh, 2010a, in press). During continent–continent collision in some of the Precambrian collisional sutures, deep underthrusting of organic graphite-bearing metasedimentary rocks has been attributed as one of the causes for the observed high electrical conductivity (e.g., Bologna et al., 2011). Subduction processes also carry substantial volumes of water into the deeper portions of the Earth (e.g., Maruyama et al., 2009), which is subsequently returned through plumes and magmas. One of the mechanisms by which fluid reservoirs develop in the deep crust is through their storage within abundant inclusions trapped in minerals as established from fluid inclusion studies in the deep crustal rocks formed in collisional orogens (e.g. Touret, 2001; Ohyama et al., 2008; Tsunogae et al., 2008, 2009; Tsunogae and Santosh, in press). Whereas aqueous fluids occur as an interconnected grain boundary network, CO_2-dominated fluids, sometimes mixed with water and brine, generally propagate along structural pathways (Santosh and Omori, 2008 and references therein). High conductivity in the lower crust as imaged in magnetotelluric studies from some regions have been correlated to fluid-filled porosity in the deep crust, which is replenished by various processes including underplated basaltic magmas (Wannamaker et al., 1997).

Peninsular India provides a typical example where plate tectonics operated in the Precambrian with a number of distinct Wilson Cycles and Supercontinental Cycles (Santosh et al., 2009b; Pradhan et al., 2010; Santosh, in press; Dharma Rao et al., 2011). The Archean cratons in this sub-continent formed part of the early supercratons in the Earth's history (Rogers and Santosh, 2003, 2004). The major Paleoproterozoic orogenic belts in Peninsular India extend from the northwestern through central to the eastern part of the Peninsula with some suspect terrains further south (Fig. 1). These belts, often referred to as mobile belts surrounding the Archean cratons, preserve a broadly similar tectonic history with regard to magmatism, metamorphism and sedimentation (reviewed in Naqvi, 2005; Santosh, in press; Valdiya, 2010). The major Paleoproterozoic terrains in Peninsular India are the Aravalli–Delhi, Singhbhum and Bhandara domains, as well as the Cuddapah–Eastern Ghats Belt at the eastern margin of the Dharwar Craton (Fig. 1b). Further south, in the crustal blocks constituting the mosaic of the Southern Granulite Terrain, a Late Neoproterozoic–Cambrian tectonic event dominates (Collins et al., 2007; Santosh et al., 2009b; Santosh, in press).

Among the various Precambrian continent–continent collisional zones in Peninsular India, the Central India Tectonic Zone (CITZ) that runs across the central part of the Peninsula divides the North Indian and the South Indian blocks along a Mesoproterozoic collision suture (Naganjaneyulu and Santosh, 2010). The CITZ witnessed several major tectonothermal events since its formation, including voluminous flood basalts and magmas associated with the late Cretaceous Deccan volcanism. The region is also characterized by major seismically active deep-seated faults. In this study, we provide a joint interpretation of the density and conductivity anomalies along the CITZ. In conjunction with gravity modeling, we attempt to better explain the conductivity anomalies in terms of the role of fluids within the collisional suture that witnessed multiple reactivation history. We also evaluate the implications of these models on the dynamics of earthquakes along active faults in this region.

2. The Central India Tectonic Zone

Amalgamating the northern and the southern crustal blocks in Peninsular India, the Central India Tectonic Zone (CITZ) is a major divide that runs for more than 800 km in length and 400 km in width (Fig. 1) (Radhakrishna and Naqvi, 1986; Acharyya, 2003 among others). The ENE–WSW striking CITZ incorporates a system of major shears/faults. The blocks to the north of CITZ have the Archean Bundelkhand craton as their nucleus, whereas the composite block to the south is composed of the Dharwar, Bastar (or Bhandara) and Singhbhum cratons. An overview of available geophysical and geological information on the CITZ and tectonic models are discussed in a recent synthesis (Naganjaneyulu and Santosh, 2010).

The CITZ zone also includes two major rifts – the Narmada and the Tapti – and the intervening Satpura belt which together define the Narmada–Son lineament (Jain et al., 1995). The crustal architecture of the CITZ, a seismically active zone (Fig. 2) (Fig. 1a, inset in Fig. 1b), has not been studied in detail. The major part of this region is covered by continental flood basalts and associated magmatic provinces of the Deccan Traps (Dessai et al., 2010).

The major faults in the region such as the Narmada North, the Narmada South, the Tapti, the Barwani Sukta, the Purna, and the Gavligarh, are oriented in E–W to ENE–WSW (Fig. 1a). The region between the Purna and the Gavligarh faults is termed as the Purna Graben; similarly, the region between the Gavligarh and Tapti faults is termed as the Tapti Valley. Various geophysical studies – magnetotellurics, seismic and gravity – undertaken in CITZ imaged these features. Magnetotelluric studies identified high-conductivity anomalies (Rao et al., 2004; Patro et al., 2005; Naganjaneyulu et al., 2010; Naganjaneyulu, 2010) in the deep

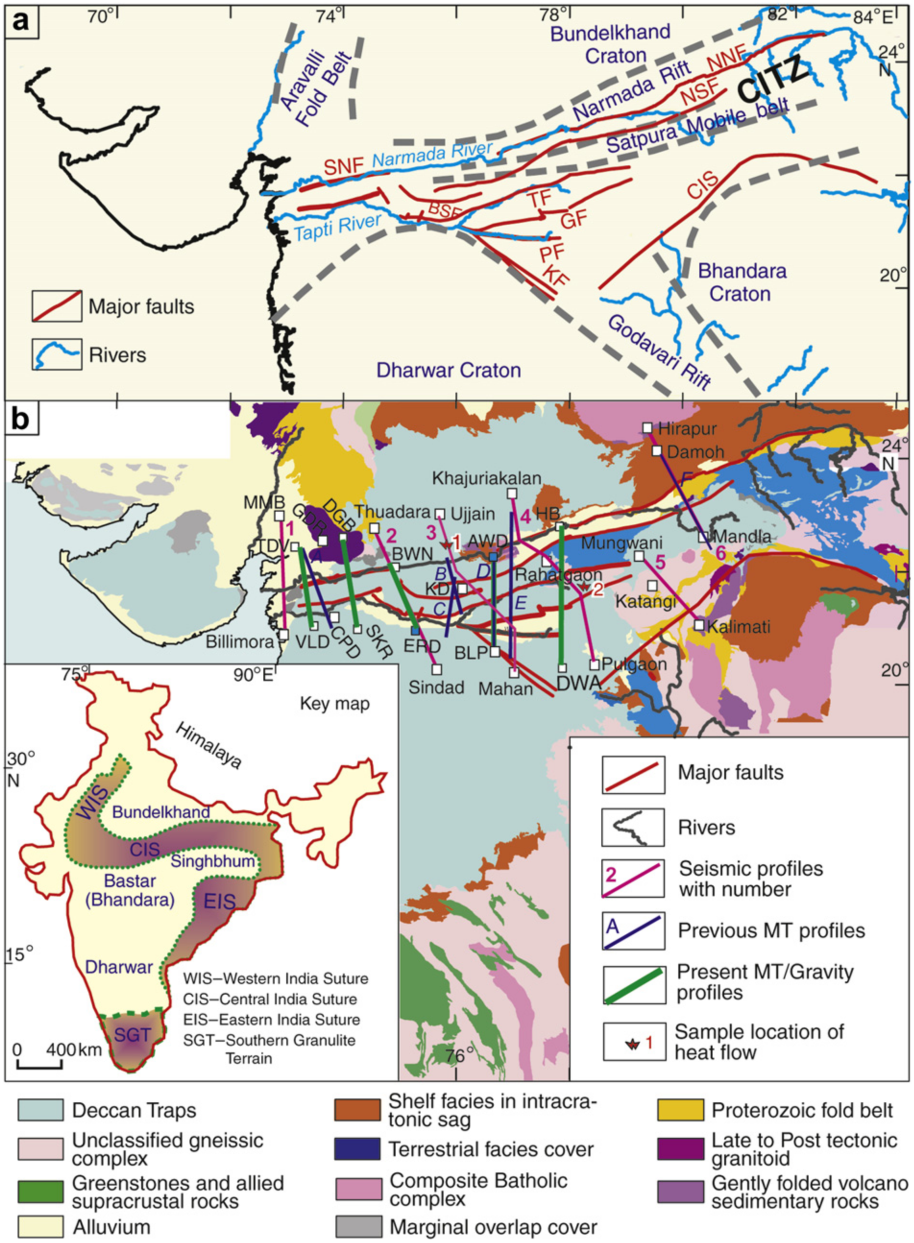

Figure 1 (a) Tectonic framework of Central India showing the major cratonic blocks of Dharwar, Bhandara (also known as Bastar) and Bundelkhand with inferred boundaries. The Central India suture zone welds the South and North Indian blocks and expressed as several shear systems and faults, some of which are currently active; (b) Geological map of the Central India Tectonic Zone (CITZ) showing the transects of DSS and MT; and heat flow measurements along with major faults in the region. MT data along Balapur–Andharwadi profile (D) are modeled by Dhanunjaya Naidu and Harinarayana (2009) and also by Azeez et al. (2010). Inset shows the disposition of the major cratonic blocks and tectonic elements within Peninsular India. BSF: Barwani Sukta Fault; GF: Gavligarh Fault; KF: Kaddam Fault; NNF: Narmada North Fault; NSF: Narmada South Fault; PF: Purna Fault; SNF: Son Narmada Fault; TF: Tapti Fault (modified after Kaila and Krishna, 1992, and Narula et al., 2000). VLD: Valod; TDV: Tundav; SKR: Sakri; DGB: Devgadh Baria; ERD: Erandol; BWN: Barwani; BLP: Balapur; AWD: Andharwadi; DWA: Darwha; HB: Hoshangabad; CPD: Chinchpada; KD: Khandwa; MMB: Mehmadabad.

crust. Gravity studies identified high-density bodies in the southern part and low-density bodies in the northern part of the CITZ (Verma and Banerjee, 1992). Previous seismic studies identified several Moho penetrating faults and also both high and low-velocity anomalies beneath various regions in the deep crust (Kaila et al., 1985, 1987, 1989, 1990).

Some of the recent magnetotelluric models from the CITZ region also show anomalous conductivity features (Azeez et al., 2010). The causes for elevated conductivity in the deep crust are still a topic of debate. Several authors attributed such anomalous conductivity to the presence of fluids, mantle degassing, presence of thin mineral films (graphite, sulfide and/or magnetite) and silicate melts (Shankland and Ander, 1983; Hyndman and Shearer, 1989; Gough, 1986, 1992; Jones, 1992; Glover and Vine, 1992; Mareschal et al., 1992; Nesbitt, 1993; Duba et al., 1994; Frost and Bucher, 1994; Schilling et al., 1997, among others). The

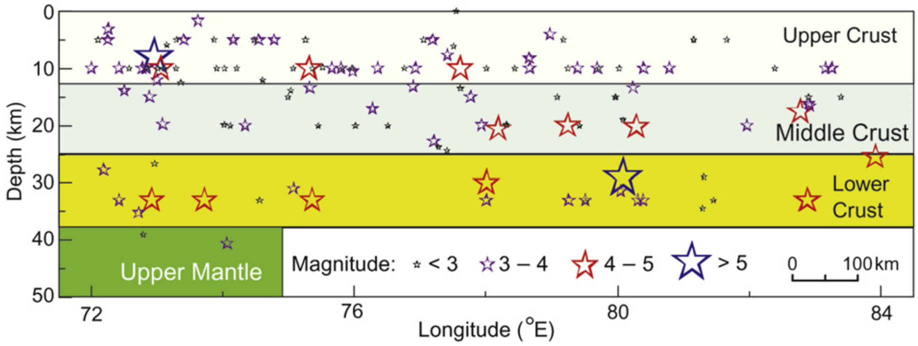

Figure 2 Stars indicate International Seismological Center reported depth distribution of earthquakes (January, 1965–March, 2011) in the CITZ. The crustal division is indicative only.

presence or absence of these factors should also be reflected in other physical parameters such as density and velocity. For example, the presence of melt and fluids reduce the density as well as the seismic velocity. Furthermore, each of these factors is controlled by the pressure-temperature conditions, tectonic environment, pore geometry, and resistivity, among other parameters (Nesbitt, 1993; Frost and Bucher, 1994).

3. Previous geophysical studies

We provide a brief overview of the results obtained from previous seismic, gravity, MT, heat flow, and seismological investigations from the CITZ. Seismic studies were carried out along six profiles estimated variation in crustal thickness from 32 to 45 km with several deep faults reaching Moho (Fig. 3a). The crustal velocities in this region are 6.8, 7.1–7.3, ∼8.0 km/s respectively for the upper crust, lower crust and for upper mantle (Kaila and Krishna, 1992). Seismic studies by Tewari and Kumar (2003) show low-velocity layers (6.3 km/s) sandwiched between high velocity layers (6.6 and 6.8 km/s). Moho depth is varying from 35 to 45 km (Fig. 3b) as estimated along the Mahan–Ujjain profile. Gravity modeling studies were carried out along the seismic profiles (e.g. Verma and Banerjee, 1992; Singh and Meissner, 1995; Tewari and Kumar, 2003). The general feature in the Bouguer gravity anomaly map is that the southern part is characterized by a high-density crust compared to its northern counter part in the CITZ. Bouguer gravity anomaly along two profiles is shown in Fig. 4a. The gravity models indicate both high-density mafic/ultramafic and low-density felsic intrusions in the deep crust with detectable thicknesses (for example, see Fig. 4b). These anomalous – both high-density and low-density – bodies are present not only beneath the Narmada and the Tapti Faults, but are widely distributed beneath the CITZ. In another gravity study a high-density (3.02 g/cm^3) layer with thickness ranging from 2 km to 20 km is imaged near the crust–mantle boundary, with a suggested link between the Deccan flood basalts and the mafic magmas underplated at the base of the crust (Singh and Meissner, 1995) (Fig. 4c). Models from Tewari and Kumar (2003) suggested upwarped high-density (2.9 g/cm^3) layer in the upper crust sandwiched between two low-density layers (2.7 g/cm^3) (Fig. 4d).

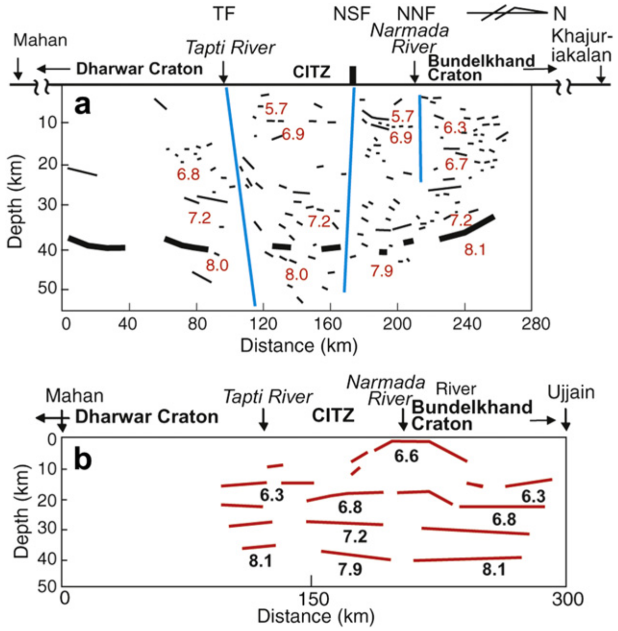

Figure 3 Seismic sections along various profiles shown in Fig. 1. (a) Reflection profile along Mahan–Narmada River part of Mahan–Ujjain profile joined with Narmada river–Khajuriakalan part of Pulgaon–Khajuriakalan profile (modified after Kaila et al., 1985; Kaila and Rao, 1986); (b) Mahan–Ujjain profile (modified after Tewari and Kumar, 2003). NNF: Narmada North Fault; NSF: Narmada South Fault; TF: Tapti Fault. Velocity values are given in km/s.

Several magnetotelluric studies carried out in the CITZ show high conductivity in the deep crust, possibly related to the presence of magmas and fluids at depth (Rao et al., 2004; Patro et al., 2005; Naganjaneyulu et al., 2010; Naganjaneyulu, 2010), particularly around the major faults in the region. Here we show the results from two profiles which suggest that the deep crustal conductivity could possibly be linked to underplated magmas and fluids. The upper crust in this region is reflected as a highly resistive (2000–10, 000 $\Omega \cdot m$) feature with a thickness varying from 10 to 25 km and can be attributed to felsic (tonalite–trondhjemite–granodiorite, TTG) crust. However, the imaged features are from the middle and lower crust and are distinctly characterized by both resistive and conductive bodies (Fig. 5). The low resistive features (5–20 $\Omega \cdot m$) in the deep crust between depths of 15 and 40 km are interpreted as a layered mafic intrusions related to underplated basalts due to Deccan volcanism. The region beneath the Son Narmada Fault shows anomalously high resistivity in the deep crust from 10 to 30 km and possibly represents subducted felsic (TTG) crust or sediments. The major faults – the Son Narmada, the Purna, the Gavligarh, the Tapti, and near the Narmada North Fault – within the CITZ also show the

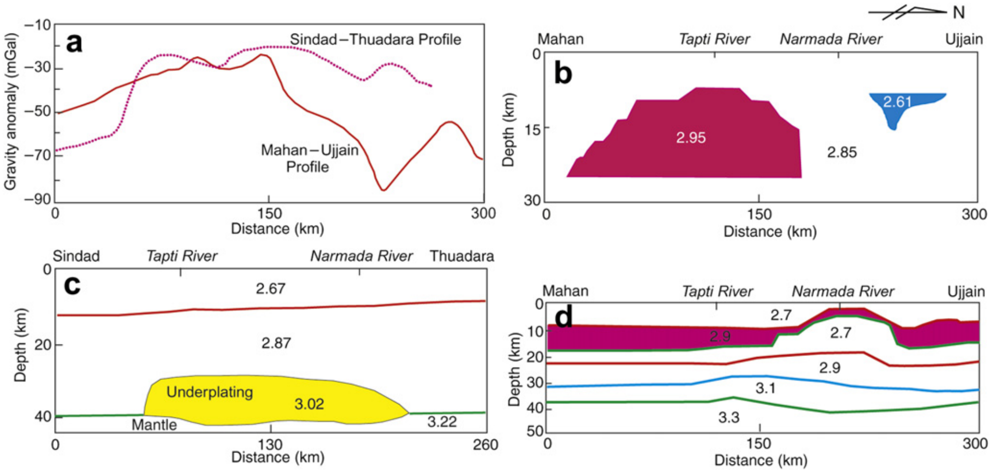

Figure 4 (a) Observed Bouguer gravity anomaly along Mahan–Ujjain profile and Sindad–Thuadara profiles. Gravity models showing (b) high-density and low-density intrusives along Mahan–Ujjain profile (modified after Verma and Banerjee, 1992); (c) underplating at the base of the crust along Sindad–Thuadara profile (modified after Singh and Meissner, 1995); (d) domal upwarp along Mahan–Ujjain profile (modified after Tewari and Kumar, 2003) with a higher density layer between two lower density layers. Density values are given in g/cm^3.

presence of conductors. The present day temperature–depth profile shows maximum temperature near the crust–mantle boundary (∼40 km) as around 600 °C (Fig. 6a, b) (Rai and Thiagarajan, 2006). Ambient temperature derived from mantle xenoliths for the same depths is about 1200 °C (Dessai et al., 2010) (Fig. 6c).

4. Recent magnetotelluric studies and constrained new gravity models

Recent magnetotelluric models (Azeez et al., 2010) along five profiles oriented approximately in N–S direction serve as cross sections of the CITZ and adds to the models proposed in earlier published results (Rao et al., 2004; Patro et al., 2005; Naganjaneyulu et al., 2010; Naganjaneyulu, 2010). For example, several conductive zones are located near known faults. The conductive zones in the mid crust show a resistivity <30 Ω·m. We show in Fig. 7 the simplified magnetotelluric crustal sections and note that the distribution of conductive zones is not only limited to the mid crust, but the conductive zones clearly extend into the upper mantle.

The main handicap in interpreting these results is that high quality seismic data are not available along these profiles. General velocity information available shows rather uniform features. Gravity and magnetotelluric studies inferred few additional features (see Verma and Banerjee, 1992; Naganjaneyulu et al., 2010 for more details). Hence, we used gravity anomalies and gravity modeling to explain the causative sources of modeled conductivity anomalies. The gravity values used in the study are derived from Bouguer

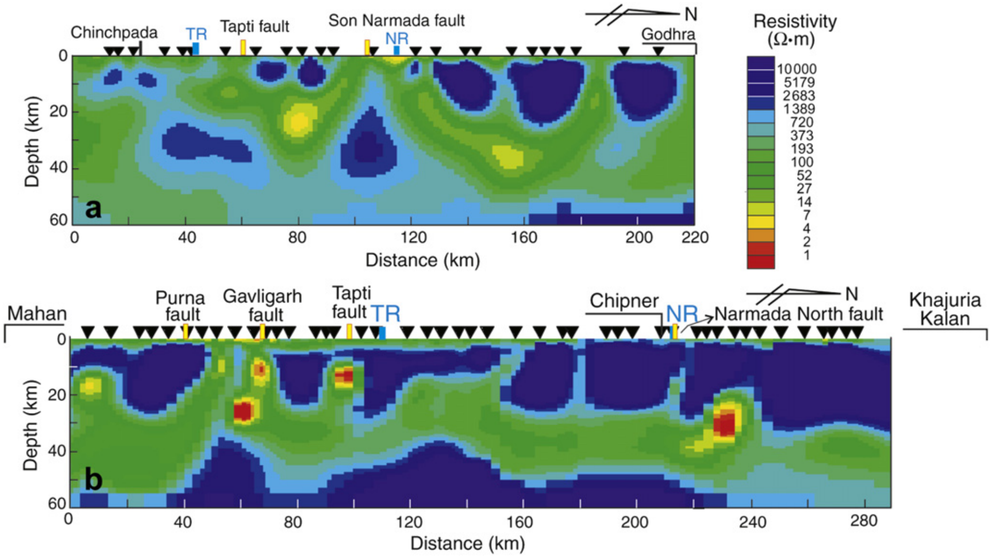

Figure 5 Two dimensional magnetotelluric models: (a) along Chinchpada–Godhra profile (modified after Naganjaneyulu, 2010); and (b) Mahan–Khajuria Kalan profile (modified after Naganjaneyulu et al., 2010). The models show a resistive upper crust (more than 2000 Ω·m) suggesting a dominant tonalite–trondhjemite–granodiorite (TTG) composition and correlation of high conductive zones (less than 30 Ω·m) in the deep crust with known faults in the region. NR: Narmada river; TR: Tapti river.

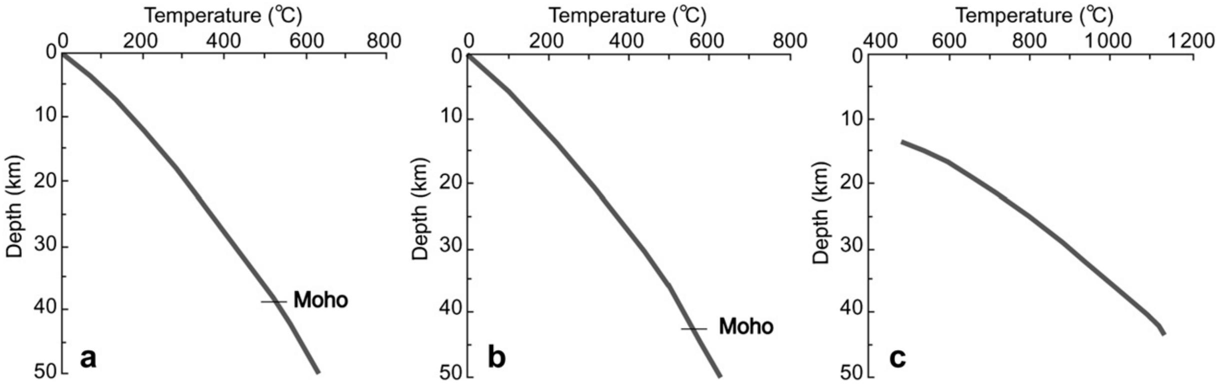

Figure 6 Modeled temperature–depth profile (a) near Ujjain; (b) near Rahatgaon in CITZ (modified after Rai and Thiagarajan, 2006); and (c) for CITZ (modified after Dessai et al., 2010).

gravity anomaly map of India (GSI-NGRI, 2006). The variations in the gravity values range from about −75 mGal to 10 mGal. Typically, regional gravity lows can be explained by thick crust or by low-density layers/intrusives in the crust. A thin crust or high-density layers/intrusives would produce regional gravity highs. In the present study, a three layered 40 km thick crust model is considered with densities 2.70, 2.80, 2.90 g/cm^3 respectively for each layer. The upper mantle density is 3.30 g/cm^3. To interpret the high conducting anomalies, we consider high-density (2.95 g/cm^3) and low-density (2.65 g/cm^3) bodies in the deep crust based on gravity highs or lows and the location of the conductivity zones. Values in the range from 2.60 to 2.70 g/cm^3 represent low-density features and a value of 2.90–3.00 g/cm^3 represent high-density features in this region (e.g. Verma and Banerjee, 1992). In the present study we ignored large conductive zones present at the edge of the models (e.g. C5 and C9) as well as the conductive zones in the upper mantle (e.g. C17 and C18). However, in doing so, we also considered both the trend – increasing or decreasing – and also magnitude of the gravity anomalies in the vicinity. Near the Narmada River conductive zones were observed at the crust–mantle boundary in previous magnetotelluric surveys (Gokarn et al., 2001; Naganjaneyulu, 2010; Naganjaneyulu et al., 2010). This signature is modeled with a low-density feature where conductive zones are present near crust–mantle boundary (C8) in the region beneath the Narmada River. Similarly, when two or more conductive zones are present at different depths one beneath the other, less priority is given to the conductive zone at greater depth as there is a possibility that conductors at depth may not well resolved. Also, we used the location of these conductive zones as guidance for introducing high-density and low-density features at depth only. It is known that the shape as well as the extent of these conductors normally depends on station spacing, data quality and periods used. Apart from these considerations some undulations in crustal layers are introduced to fit the gravity data. Overall there is a good agreement between the low and high-density features and conductive zones in the crust (Fig. 8). Even though we have not used velocity information in this

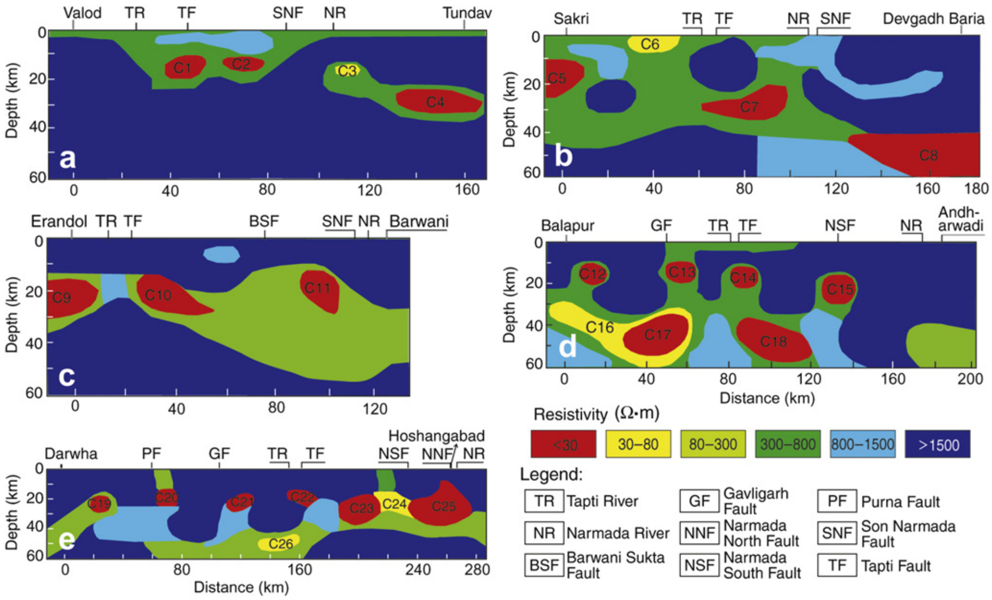

Figure 7 Simplified geoelectric structures obtained from 2–D MT models using NLCG scheme along five profiles (modified after Azeez et al., 2010). In all these five profiles a) Valod–Tundav, b) Sakri–Devgadh Baria, c) Erandol–Barwani, d) Balapur–Andharwadi and e) Darwha–Hoshangabad several conductors (less than 30 Ω·m) can be observed in the deep crust extending into upper Mantle.

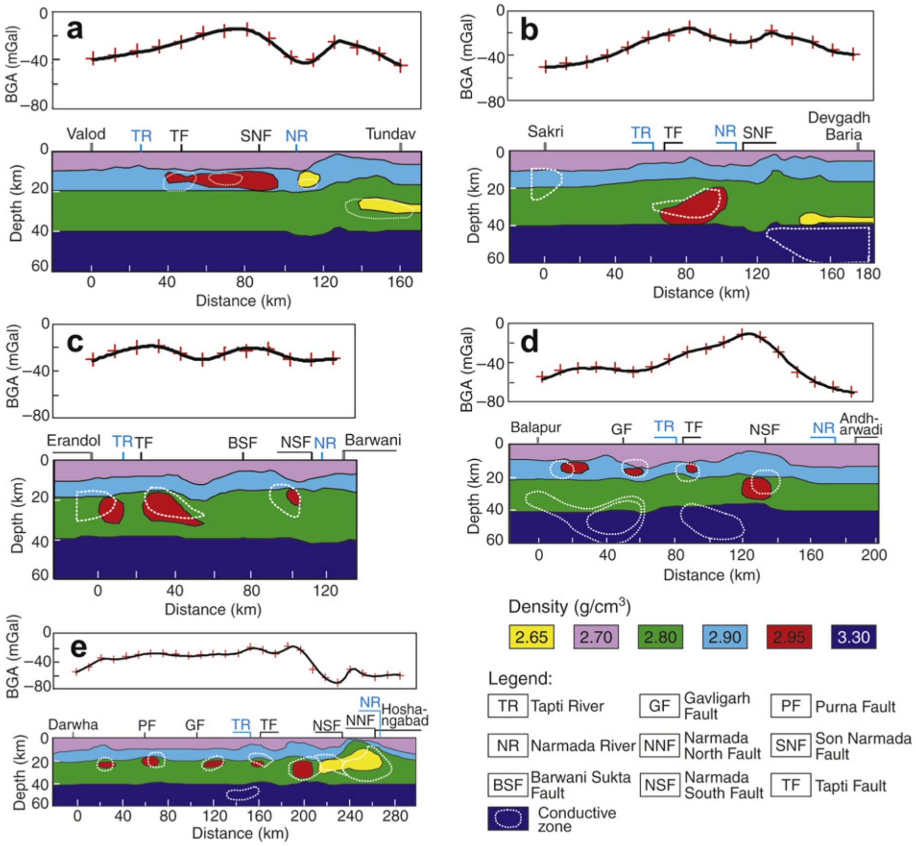

Figure 8 Constrained 2–D gravity models along a) Valod–Tundav, b) Sakri–Devgadh Baria, c) Erandol–Barwani, d) Balapur–Andharwadi and e) Darwha–Hoshangabad profiles. In the upper panel fit between the observed Bouguer gravity anomaly (BGA) and modeled BGA is shown. In the lower panel derived crustal structure is shown. Densities: Upper Crust: 2.70 g/cm^3; Middle Crust: 2.80 g/cm^3; Lower Crust: 2.90 g/cm^3; Upper Mantle: 3.30 g/cm^3. The figure shows correlation of high-density and low-density features with conductors (white dashed regions).

modeling exercise, we noted several similarities between our models and seismic models proposed by Tewari and Kumar (2003). By substituting high density to high velocity and low density to low velocity, the crustal structural obtained along the Valod–Tundav profile can be redrawn as shown in Fig. 9. This model shows a high velocity layer trapped between two relatively low-velocity layers and domal upwarp in the northern side.

The important features in our final models are: 1) the upper crust is normally a 10 km thick layer with a density of 2.70 g/cm^3; 2) the mid crust is another 10 km thick layer with a density of 2.80 g/cm^3; 3) the lower crust is a 20 km thick layer with a density of 2.90 g/cm^3; and 4) the distribution of both high-density (2.95 g/cm^3) and low-density (2.65 g/cm^3) features generally extend to deep crust and is not confined to the middle or lower crust.

5. Discussion

5.1. Precambrian suture zone as a deep crustal fluid reservoir

Detailed analysis of the conductive features from the CITZ – a major Paleo-Mesoproterozoic collisional suture in Peninsular India that witnessed younger plume-related volcanic activity and that also hosts seismically active deep-seated younger faults – shows that some of these anomalies can be associated with high density and the others with low-density features (Fig. 8). Deciphering the causes for such anomalies is not straightforward. In general, elevated conductive zones can be explained by the presence of partial melts, mineral films (graphite, sulphide and magnetite) and fluids (Jones, 1992 for a review). Within the CITZ the temperature at

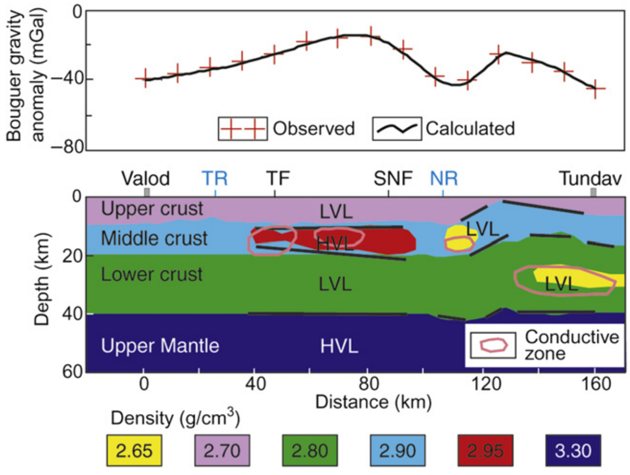

Figure 9 Simplified model along Valod–Tundav profile showing low-velocity layer (LVL) and high velocity layers (HVL) based on density values shown in Fig. 8. LVL and HVL are indicative only. SNF: Son Narmada Fault; TF: Tapti Fault; NR: Narmada River; TR: Tapti River.

Moho depth estimated from heat flow studies is around 600 °C. Partial melting of felsic (TTG) crust generally requires temperatures over 700 °C (Thompson, 1992) and is reflected through low-density and low-velocity features. Even though some of the conductive zones are associated with low-density (2.65 g/cm^3) anomalies (Fig. 8), the temperature−depth profiles in this region do not support presence of any large volume of partial melts.

Interconnected graphite films are invoked in explaining the elevated high-conductivity zones in the lower crust in several studies (Duba and Shankland, 1982; Frost et al., 1989 among others). Subduction of organic graphite-bearing sediments in continental collision zones has also been suggested to explain the high-conductivity anomalies observed in the lower crust in some regions (e.g. Bologna et al., 2011). The precipitation of graphite even in small amounts proximal to the deep-seated faults and shears would significantly reduce the overall resistivity of the rock matrix. Moreover, presence of graphite at certain horizon would elevate the electrical conductivity locally at that depth. Graphite is stable at low oxygen fugacity and could occur as interconnected films (Gough, 1986; Frost et al., 1989; Jones, 1992). The presence of titanomagnetite and magnetite as recorded from xenolith samples from the CITZ (Dessai et al., 2010) can also account for the anomalous conductivity (Mareschal et al., 1992; Duba et al., 1994). However, accumulation of ore minerals like magnetite, titanomagnetite, pyrrhotite or other accessory minerals over few hundreds of km (from west coast to eastern part of CITZ) is difficult to envisage as there are no known major oxide or sulphide mineralization in the area, nor a feasible crustal or mantle rock composition and fractionation mechanism to explain such anomalous conductors (see Schilling et al., 1997). Furthermore, the CITZ region is known to have been reactivated several times since the Precambrian (West, 1962; Choubey, 1971), and also witnessed several intense earthquakes including the 1938 Satpura earthquake and the recent 1997 Jabalpur earthquake with hypocenters estimated around the crust−mantle boundary (Ramesh and Estabrook, 1998) (Fig. 2). Hence, even if it is assumed that the subducted continental margin sediments in this collisional suture carried biogenic material that was converted into graphite (e.g. Santosh and Wada, 1993), such graphite occurs only as a minor accessory and is restricted to specific horizons of metasedimentary units. Furthermore, it is difficult to maintain graphite interconnection in a tectonically disturbed zone.

Studies carried out in southern Africa proposed that the lower crust may contain serpentinized ultramafics, accumulated during the subduction-collision tectonics associated with the late Proterozoic assembly of Gondwana (De Beer et al., 1982). It is known that all the three crystalline forms of serpentine are porous and may contain pore water. Earlier view is that if there is adequate interconnectivity, presence of serpentine would cause elevated electrical conductivity. Based on the elevated electrical conductivity reported from MT studies (Gokarn et al., 2001) in the CITZ region, Rao and Rao (2006) proposed the presence of serpentinized peridotite in the lower crust. However, recent studies suggest that serpentinite is a poor conductor (Airo and Loukola-Ruskeeniemi, 2004; Bruhn et al., 2004). In spite of the experimental setup designed to retain water within the rock assembly, all the samples considered yielded a resistivity of about 100 Ω·m at about 560 °C (Bruhn et al., 2004). The temperatures employed in this experimental study and the modeled temperatures in CITZ from heat flow studies are similar. Furthermore, the elevated conductivity values (20−30 Ω·m) in the CITZ region preclude serpentinite as a major cause for the anomalous conductivity.

It is known that large volumes of basaltic magma were extracted into the crust from upper mantle during the Deccan flood basalt regime in the Mesozoic (Dessai et al., 2010, and references therein). One of the significant features reflected in the MT models is that the faults in this region are associated with highly conductive bodies, representing fault-controlled emplacement of basic/ultrabasic intrusions from a deeper reservoir of underplated basaltic magma. However, this magmatism cannot produce the present day high-conductivity anomalies as the basaltic rocks are no more in a molten state. The absence of ^{3}He degassing anomalies at two locations (Tattapani − 23°41′12″ N, 83°39′04 ″ E; Salbardi − 21°25′25″ N, 78°00′50″ E) preclude the presence of any ‘present day’ cooling of magma or a currently active magma chamber at depth (Minissale et al., 2000), the presence of which could have been accounted for high-density anomalies as observed in the gravity models. However, results from more samples in the region are required to clarify this aspect, since the formation of high-density rocks through the crystallization of mafic magmas at depth cannot be excluded as a cause for the observed high-density anomalies. Our preferred interpretation is that fluids that expelled from these magmas and trapped within mineral inclusions or structural pathways account for the high conductivity.

From broadband and long period magnetotelluric studies along a 560 km E−W profile along the Neoproterozoic suture zone in central Brazil, Bologna et al., (2011) recently investigated the continental collision signature in this region. The conductivity structures derived in their work show signatures of the past tectonomagmatic events that affected the region. A gravity-defined suture zone beneath the Paraná basin is detected in the models as a subvertical conductor extending from crustal to upper mantle depths, which strengthen the interpretation of a Neoproterozoic collision of the São Francisco craton and a continental block beneath the sedimentary basin. An increase in electrical conductivity along this zone was correlated to deep underthrusting of organic graphite-bearing metasedimentary rocks composing a fossil suture zone. A similar conductivity signature beneath the sedimentary covered region of the São Francisco craton was interpreted as another similar cryptic suture zone. Other isolated high-conductivity anomalies detected at mid crustal depths probably represent fossil residues indicating precipitated graphite and sulfide derived from percolating volatiles during the emplacement of Cretaceous mafic-ultramafic volcanics. A very high-conductivity wedge into the lower lithosphere imaged in the deep mantle is coincident with a zone of low velocity defined by seismic tomography. This is thought to be linked with the alkaline magmatism originating from a metasomatized upper mantle. The high conductivity observed in their study was thus correlated to interconnected carbonatite melts of low melting point and graphite in the lithospheric mantle. The conductivity anomalies at crustal and mantle depths in the southern segment of the São Francisco craton is in conformity with the several tectonomagmatic episodes experienced by this section of the lithosphere during its prolonged geological history. According to these authors, the enhanced conductivity in the lower crust would thus be genetically related to upwelling of volatile-rich intrusions; whereas the high conductivity in the mantle region might represent refertilization by infiltrations of low-degree carbonatitic melts from deeper-sourced metasomatic processes.

The presence of free fluids can potentially elevate conductivity. The existence of a widely extending free fluid zone is difficult to envisage over geologically longer periods, particularly as the mid crustal temperatures within the CITZ are well above 250 °C (roughly at 15 km depth, Fig. 6), because dehydration reactions would absorb the fluids rapidly (Frost and Bucher, 1994). Well-defined conductors in the depth range of 10–40 km within the CITZ, however, do indicate the presence of fluid reservoirs in the middle and lower crust in this region. Zhang et al. (2011) in an experimental study reported that the zones of high conductivity and low velocity in the mid crust are the direct result of the properties of fluids flowing in rocks and the reactions (e.g. the leaching of Si and the collapse rock structures at temperatures from 300 to 435 °C) of those fluids with surrounding rocks. The highest electric conductance of an aqueous solution is observed at temperatures from 374 °C to 450 °C. This indicates that the high-conductivity zones in the mid crust originate from the conductivity of fluids in the rocks at temperatures from 374 °C to 450 °C (Zhang et al., 2011). Such temperature conditions prevail in the CITZ (Fig. 6).

The role of fluids in contributing to geophysical anomalies in the deep continental crust has been addressed in previous studies (e.g., Frost and Bucher, 1994). The CITZ is a fossil suture zone that might have witnessed the activity of large volumes of fluids and melts at the time of its formation. The region has been subjected to major compressional regime associated with the Mesoproterozoic collision, as well as extensional regime in relation to the plume-generated Deccan activity and emplacement of voluminous mafic magmas. In addition, repeated faulting and shearing occurred in the recent times. Models on the distribution of fluids within the Earth propose a prominent stratification with water-rich fluids having variable concentration of salts (brines) dominating at shallow crustal regions, and CO_2-rich fluids dominating at depth (Touret, 1992, 2005; Santosh et al., 2009c). Mixtures of carbonic-aqueous fluids with traces of other gas species (such as methane, nitrogen etc.) occur at intermediate levels. The release of fluids and their upward migration accompany various processes such as magmatic underplating; asthenospheric upwelling, among other factors, and results in a lowering of the resistivity of rocks (Hyndman and Shearer, 1989).

Of particular importance in this context are the high grade metamorphic orogens in this continental suture zones. Several recent studies brought out the presence of abundant fluids trapped as fluid inclusions within various minerals in granulite facies high-temperature and ultrahigh-temperature rocks (e.g. Santosh and Omori, 2008 and references therein). In a recent study, Tsunogae and Santosh (in press) reported the petrographic and microthermometric features of fluid inclusions associated with high- to ultrahigh-temperature metamorphic rocks in three major Precambrian suture zones on the globe: (1) the Limpopo Complex of southern Africa, a Neoarchean granulite facies orogen formed by continent–continent collision; (2) The Palghat-Cauvery Suture Zone in southern India, a trace of the Late Neoproterozoic–Cambrian Gondwana suture; and (3) the Tonagh Island in the Neoarchean Napier Complex of East Antarctica. The rocks analyzed in their study form part of hot orogens developed along collisional plate boundaries and contain abundant CO_2-rich fluids trapped within inclusions with variable, but generally high densities (of up to 1.179 g/cm^3). Previous studies on carbonic inclusions in granulite facies rocks also reported the presence of graphite within carbonic inclusions (e.g., Satish-Kumar, 2005). In most cases, the primary CO_2 inclusions also contain traces of water as a thin film wetting the inner surface of the inclusion cavity. Most of the pseudo-secondary and secondary inclusions in high-grade metamorphic rocks also carry a hydrous phase, with or without variable concentration of salts. The markedly aqueous fluid composition, preserving the fossil fluids associated with retrograde metamorphism, is compatible with the stability of hydrous minerals like biotite and amphiboles in these rocks, as well as the widespread Barrovian hydration observed in many of the high grade metamorphic orogens. Therefore, the high-grade metamorphic rocks rooted in the lower crust and exhumed into the mid crust can be considered to carry substantial amounts of water, in addition to CO_2.

Several high temperature and high-pressure metamorphic rocks have been reported from the CITZ (e.g. Bhowmik and Roy, 2003; Bhowmik et al., 2005). Their formation and exhumation mechanism and extension at depth is interpreted from combined geological and geophysical models (Naganjaneyulu and Santosh, 2010). The high conductivity within the CITZ as observed in our present study is probably a reflection of the fluid-rich nature of the metamorphic orogens extending to depth. Any model linking the high conductors with fluids should also be able to explain the gravity anomalies. In view of the gravity highs associated with many of the conductive zones, we infer that the fluids occur either only in small quantities, or that the interconnectivity between the rock matrices is limited. Both these interpretations agree well with the model proposed above on the presence of carbonic-aqueous fluids (and graphite) trapped within minerals, rather than the presence of abundant free fluid phase. Where the conductive zones associate with gravity lows, an interconnected grain boundary network of fluids need to be present. We attribute this to the repeated reactivation along the deep-seated fault zones which might have released substantial quantities of the trapped fluids through rupture of the inclusion cavities and expulsion of the fluids.

5.2. Implications on the dynamics of earthquakes

The CITZ witnessed several major and minor earthquakes (Ramesh and Estabrook, 1998; Rao et al., 2002; Gahalaut et al., 2004) (Fig. 2). Most of these occurred proximal to the fault zones. Major earthquakes such as the Jabalpur earthquake of 1997, with magnitude five or above are associated with the Narmada North Fault and the Narmada South Fault (see Gahalaut et al., 2004). Seismological studies (Gahalaut et al., 2004; Rao and Rao, 2006) inferred high pore pressure in the lower crust in this zone. These studies observe a lower frictional coefficient possibly reflecting fractured rocks at depth. 2–D seismic forward modeling studies indicated a better fit when introducing a low-velocity (6.5 km/s) lower crust near Jabalpur (Kaila et al., 1987), which provides another compelling evidence for deep crustal inhomogenities and the presence of fluids.

Detailed geochemical and helium isotopic studies carried out near San Andreas Fault zone, California reveal that fluids derived from mantle, and passing through the lower crust when finally entered into brittle faults contribute directly to the weakening of the faults (Kennedy et al., 1997). It is widely observed that the trend of major intra-continental faults changes from vertical to near horizontal (e.g., Lemiszki and Brown, 1988) because at deeper and hotter conditions, the rocks are ductile (e.g., Burgmann and Dresen, 2008). In the present study, we infer the transfer of fluids from mantle into the lower crust – through younger plume-related Deccan volcanism, as well as the reactivation, fracturing and expulsion of fluids from the lower crustal granulites generated during Mesoproterozoic subduction-collision tectonics – thus accounting for the highly conductive lower crust in this region (<300 Ω·m; Naganjaneyulu et al., 2010). These fluids finally migrate into brittle fault zones like the Narmada North Fault and the Narmada South Fault, creating high pore pressures. As a result, the fault zones become weak leading to lower frictional coefficient. These processes better explain the observed seismicity near the Narmada North Fault and the Narmada South Fault. This inference is also generally well supported by gravity lows near these faults in the CITZ region (Fig. 8) and the low velocity of the lower crust, in particular at Jabalpur. But how deep into the crust these faults would extend is a mute question. As Hobbs et al. (1986) pointed that the occurrence of earthquakes in ductile lower crust is also possible as long as the temperature of particular rock types is below a certain critical threshold. However, no detailed information is currently available on the rock types and temperature–depth profile near Jabalpur.

Zhao et al. (2002, 2010) analyzed the role of fluids and magmas in the generation of large crustal earthquakes related to active convergent tectonics. Their study shows prominent anomalies of low-velocity and high Poisson's ratio in the crust and uppermost mantle beneath the main shock hypocenters, which might reflect arc magmas and fluids that are produced by a combination of the dehydration of subducting slab and corner flow in the mantle wedge. The distribution of 164 crustal earthquakes (magnitude ranging from 5.7 to 8.0) that occurred in Japan during 1885–2008 also show a correlation with the distribution of low-velocity zones in the crust and uppermost mantle confirming that the nucleation of large earthquakes closely related to the dynamics of the subduction zone, and the control exerted by the physical and chemical properties of materials in the deep crust and upper mantle, in particular, arc magma and fluids.

Several studies show that fluids exist widely in the crust and upper mantle in active subduction zones (e.g. Tatsumi, 1989; Peacock, 1990; Iwamori, 1998; Zhao et al., 2002). Deep subduction of oceanic lithosphere is accompanied by metamorphic processes which lead to continuous fluid production, which in turn plays a key role in the genesis of magmas at convergent plate margins. Dehydration occurs continuously down to about 200 km through breakdown reactions of hydrous phases in the subducting slab, and fluid inclusion studies in minerals from deep subducted rocks indicate the production of aqueous fluids (e.g. Scambelluri and Philippot, 2001). So far many low-frequency micro earthquakes detected at a depth range of 22–47 km around the Moho discontinuity in northeast Japan found to occur in or around the low-velocity zones (see Hasegawa et al., 2009 for a recent review). From a synthesis of seismic data from Japan, Zhao et al. (2010) showed that the low-velocity zones in the uppermost mantle are the manifestation of mantle diapirs associated with the ascending flow of subduction-induced convection in the mantle wedge and dehydration reactions in the subducting slab. The upward migration of magmas raises the temperature and reduces the seismic velocity of crustal materials around them, causing the brittle seismogenic layer above them to become locally thinner and weaker. Contractive deformations will take place mainly in the low-velocity areas because of thinning of the brittle seismogenic layer and weakening of the crust and uppermost mantle due to higher temperature and the existence of magma- or fluid-filled, thin, inclined reflectors that are incapable of sustaining the applied shear stress. The edge portion of the low-velocity areas becomes the ideal locations to generate large crustal earthquakes and can produce faults reaching to the Earth's surface or blind faults within the brittle upper crust.

In a recent overview, Karato (2011) showed that electrical conductivity is highly sensitive to water content and only modestly sensitive to other factors such as temperature, oxygen fugacity and major element chemistry. Models of electrical conductivity–depth profiles show that water distribution even down to depths of 410 km in the mantle transition zone can be successfully imaged. Ichiki et al. (2009) reviewed the electrical conductivity structures of the oceanic upper mantle, subduction zones, and the mantle transition zone beneath the northwestern Pacific, the Japanese Islands, and continental East Asia. They noted that the location of a lower crustal conductor in a subduction zone changes according to the nature of subduction, which is a function of the dehydration from the subducting slab. High conductivity in the lower crust as imaged in magnetotelluric studies has also been attributed to fluid-filled porosity in the deep crust probably characterized by the presence of highly saline brines and predominantly grain-edge interconnection (Wannamaker et al., 1997). High porosities are consistent with fluid percolation models for ductile crustal rocks that witness fluid replenishment by basaltic underplating.

In ancient suture zones, the existence of fluids in the crust and uppermost mantle would affect the long-term structural and compositional evolution of fault zones, change the strength of the fault zone, and alter the local stress regime (Sibson, 1992; Hickman et al., 1995). These factors enhance the stress concentration in the seismogenic layer leading to mechanical failure. Spatial and temporal variations in the crustal stress field reported for the source areas of some earthquake associate with fluids in the fault zones (e.g. Katao et al., 1997; Zhao et al., 2007). In a recent study, Zhao et al. (2010) synthesized geophysical evidences that suggest the generation of a large earthquake is not a pure mechanical process, but is closely related to the physical and chemical properties of materials in the crust and upper mantle, particularly magmas and fluids. The rupture nucleation zone should have a three-dimensional spatial extent, with the source zone of magnitude of 6–8 earthquakes extending from about 10 km to over 100 km (Kanamori, 2004). The geophysical signatures observed in the CITZ and the recent history of major earthquakes in this region correlate with the above models (e.g., Katao et al., 1997; Zhao et al., 2007, 2010) that, emphasize the role played by fluids.

6. Conclusions

Seismic, gravity and magnetotelluric data from CITZ, a major Precambrian collision suture with repeated reactivation history, provide windows to the deep crustal structure. Gravity data from earlier studies identified both high-density and low-density bodies in the deep crust. A significant feature reflected from more recent magnetotelluric studies is the dominant distribution of a highly resistive TTG upper crust throughout the region, which is dissected by several deep-seated faults that yield high conductivity.

New gravity models presented in this study, in conjunction with recent magnetotelluric data, suggest the role of fluids to account for the geophysical anomalies of the deep crust in this region. We propose the lower crust beneath the CITZ carries several large pockets of fluid reservoirs, generated by the transfer of fluids from plume-related mantle-derived magmas associated with the Deccan volcanism, as well as through the reactivation, fracturing and expulsion of fluids from the metamorphic orogens extending into the middle and lower crust, and which were generated during Mesoproterozoic subduction-collision tectonics. Upward migration of the fluids through brittle fault zones like the Narmada North Fault and the Narmada South Fault cause high pore pressures. As a result, the fault zones become weak leading to lower frictional coefficient, which account for the observed seismicity along the Narmada North Fault and the Narmada South Fault. This inference is also well supported by gravity lows near these faults in the CITZ region as well as the low velocity of the lower crust.

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