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Short communication

Deep crustal electromagnetic structure of central India tectonic zone and its implications

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ABSTRACT

Magnetotelluric data at 45 locations along the Mahan–Khajuria Kalan profile in the central India tectonic zone are analysed. This 290 km long profile yields data in the period range 0.001–1000 s across the tectonic elements of the study region bounded by Purna fault, Gavligarh fault, Tapti fault, Narmada South fault and Narmada North fault. Multi-site, multi-frequency analysis suggests N70°E as the geo-electric strike direction. Data rotated into the N70°E strike direction are modelled using a non-linear conjugate gradient scheme with error floors of 10% for both apparent resistivity and phase components. Two-dimensional magnetotelluric model yields conductors that correlate with known faults in the study region and regional seismicity. Presence of a −30 mgal gravity high together with the observed conductive bodies (less than 20 ohm m) in the deep crust beneath the Purna graben and Tapti valley is explained by the process of magmatic underplating. The conductive bodies beneath the Mahakoshal rift belt and Vindhyans accompanied by regional gravity lows of the order −70 mgal are attributed to the presence of deep crustal fluids. Following the re-activation model proposed for the entire region, the conductors (20 ohm m) at various depth levels correspond to mafic magmatic and/or fluid intrusions controlled by deep-seated faults that seem to tap reservoirs beyond the crust–mantle boundary. The shallow depth localized faults also seem to have facilitated further upward movement of these underplated material and fluids release during this process.

1. Introduction

The central India tectonic zone consists of Purna graben, Tapti valley, Satpura mobile belt, Mahakoshal rift belt and Vindhyans among other litho units (Fig. 1). The region north of central India tectonic zone is known as the Bundelkhand craton while that lying to the south consists of the Dharwar–Bhandara cratons (Radhakrishna and Naqvi, 1986). The central India tectonic zone has several deep-seated faults; prominent among them are the Purna fault, Gavligarh fault, Tapti fault, Narmada South fault and Narmada North fault (Fig. 1) oriented in almost E–W to ENE–WSW directions. Several geological and geophysical investigations are carried out in the central India tectonic zone. Of these, the Mahan–Khajuria Kalan traverse that opportunistically cuts across the major litho-geologic units of the central India tectonic zone is also incidentally covered by a wide variety of other geophysical studies focusing on the deep structure. To further strengthen and constrain the available information along Mahan–Khajuria Kalan profile, we conducted broadband magnetotelluric sounding studies with an emphasis on issues related to the nature of the crust beneath the central India tectonic zone in general and this segment in particular (Fig. 1). A brief overview of earlier geophysical studies related to various segments of the central India tectonic zone and the Mahan–Khajuria Kalan is presented in the following.

1.1. Deep crustal seismic studies

Deep crustal seismic velocity signatures across the central India tectonic zone are obtained along six profiles by various researchers (Kaila et al., 1985; Kaila and Krishna, 1992; Mall et al., 2008). Seismic studies were carried out from west coast of India up to Jabalpur in approximately N–S direction covering the central India tectonic zone (Fig. 1). These studies identified several deep-seated faults reaching Moho depths (e.g., Tapti fault and Narmada South fault). Based on the observed seismicity, it is inferred that these faults are active (see Kaila and Krishna, 1992 for a review). These deep-seated faults mark the boundaries of various blocks. For example, Narmada South fault and the Narmada North fault limit the boundary of the Mahakoshal rift belt (Acharyya, 2003). Seismic studies indicate that the average crustal thickness in this zone is about 40 km. In the

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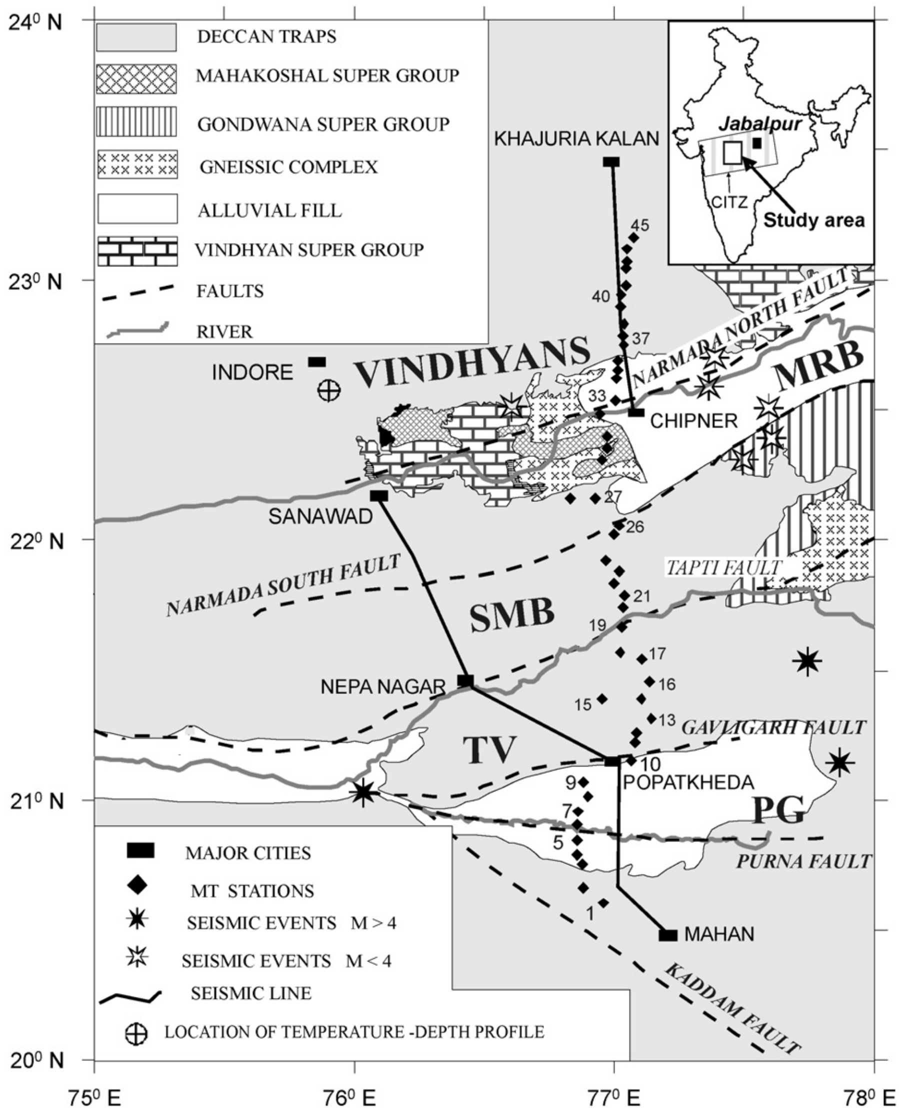

Fig. 1. Detailed geologic map of the study region showing: major tectonic features, faults, earthquake epicentres, profiles of deep seismic sounding (DSS) studies along with magnetotelluric (MT) station locations. Major tectonic features are: Purna Graben (PG), Tapti Valley (TV), Satpura Mobile Belt (SMB) and Mahkoshal Rift Belt (MRB).

Mahan–Sanawad region, the Moho boundary is delineated in the depth range of 37–42 km. Near Mahan region the seismic studies do not provide much deep crustal information. Seismic studies in the Chipner–Khajuria Kalan section indicate Moho in the depth range 35–40 km. The upper mantle velocity is in the range 7.8–8.1 km/s (Kaila and Rao, 1986). The estimated crustal thickness south of Jabalpur is between 41 km and 46 km (Mall et al., 2008). Seismic studies indicate low seismic velocities 6.3–7.2 km/s for middle and lower crustal rocks beneath the study region when compared to global average 7.17–7.34 km/s (Rudnick and Fountain, 1995) for mafic granulite–facies rocks.

1.2. Gravity signatures

Gravity models (Verma and Banerjee, 1992; Singh and Meissner, 1995) for the central India tectonic zone suggest that extensive tectonic underplating visited this region. These studies indicate the region south of Narmada River is characterised by high density crust in comparison to its northern counterpart (Verma and Banerjee, 1992). The thickness of the underplated material south of Narmada River is about 20 km near the west coast thinning eastwards to 5 km near Chipner. A density of 3.02 g/cc is inferred for this material (Singh and Meissner, 1995). Based on the inferred higher density of the crust Verma and Banerjee (1992) suggest that the central India tectonic zone although possesses features of a rift valley, may not be a typical rift zone. Presence of a thick crust and absence of rift pillows in this region are in support of non-rift model. Several others believe that central India tectonic zone is indeed a classic rift zone (e.g., Biswas, 1987; Ravi Shanker, 1991). Thus classification of central India tectonic zone is highly debated (for a review, Mahadevan, 1994).

1.3. Heat flow and models of re-activation

The heat flow studies indicate that the central India tectonic zone records comparatively high values when compared to both south and north of central India tectonic zone (Ravi Shanker, 1988). The region is also associated with several thermal springs (Krishnaswamy and Ravi Shanker, 1980). Within the central India tectonic zone, the heat flow values in Purna graben and Tapti valley are about 50 mW/m^2, whereas near north-east of Chipner the values are close to 55–70 mW/m^2 (Ravi Shanker, 1988). In the

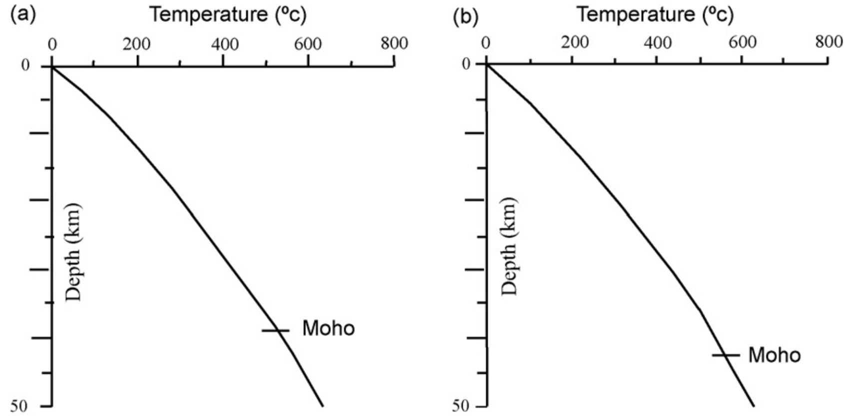

Fig. 2. Calculated temperature-depth distribution (a) near Indore and (b) near Multai (modified after Rai and Thiagarajan, 2006).

Mahan–Khajuria Kalan region, numerical modeling results indicate that temperatures near the Moho are in the range 500–580 °C (Fig. 2) (see Rai and Thiagarajan, 2006). Moreover the temperature depth profiles indicate that there is a uniform thermal regime in the present study region without any noticeable gradients that can be tied to the presence of partial melt in the crust.

The central India tectonic zone is believed to have been re-activated several times since the Precambrian (West, 1962; Choubey, 1971). The region witnessed several intense earthquakes in the past. The 1938 Satpura earthquake and the recent 1998 Jabalpur earthquakes occur in the deep crust. Their hypocentres are estimated at crust–mantle boundary (Rao et al., 2002). In several other rift regions, e.g., the Reelfoot rift, the Kenya rift, the Amazon rift, hypocentres of earthquakes have been located in the lower crust (see Young et al., 1991; Zoback and Richardson, 1996; Pollitz et al., 2002). The central India tectonic zone is slightly different from other regions due to the fact that in its western part, earthquake hypocentres are located at shallow depths (less than 20 km) as opposed to deep-seated (close to the Moho) hypocentres in the eastern parts (Fig. 3). Rao et al. (2002) infer that a serpentinized mafic intrusive in the lower crust is the causative of Jabalpur earthquake, whereas Rao and Rao (2006) attribute fluids released by the process of serpentinization as the chief reason for this earthquake. Repeated occurrence of deep crustal earthquakes in the central India tectonic zone is explained invoking the model of re-activation of pre-existing faults (Rao et al., 2002) giving rise to the possibility of the presence of fluid rich regimes in the deep crust of the study region.

1.4. Magnetotelluric images

A few magnetotelluric surveys were also carried out in central India tectonic zone (Gokarn et al., 2001; Rao et al., 2004; Patro et al., 2005). The magnetotelluric survey near Jabalpur earthquake region reveals the presence of a very low resistive body (30 ohm m) between 10 and 30 km depth. This anomalous high conductivity is due to fluids at these depths (Gokarn et al., 2001). Magnetotelluric studies carried out the south of Narmada South fault and the west of Nepanagar infer underplating in this region (Patro et al., 2005). Earlier studies by Rao et al. (2004) on the same profile delineate conductive bodies in the northern and southern parts of the traverse. These conductive zones are interpreted as suggestive of partial melt conditions in the deeper crust leading to emplacement of magma in the shallow crust. These three studies have profile lengths of less than 200 km. The studies by Rao et al. (2004) and Patro et al. (2005) imaged only the southern part of the Narmada River. Although Gokarn et al. (2001) imaged both southern and northern parts of the Narmada River, their profile is about 200 km away from the present study on the eastern side, near Jabalpur (Fig. 1). Gokarn et al. (2001) not sampled features like Purna fault, Tapti fault and Gavligarh fault as they are not extending that far on the east. The present profile is relatively long (290 km) and images both southern and northern parts of the Narmada River (Fig. 1). In addition, it covers all the major faults in the zone with less station spacing and thus provides high lateral resolution. It is well known that better lateral resolution can be achieved through decreasing the station interval in some of the geophysical studies like resistivity, gravity, magnetic and magnetotelluric.

In summary, seismic and gravity surveys in the study region reveal the presence of anomalously low velocity deep crust accompanied with low density when compared to global averages. The gravity models bring out high density anomalies in some parts of the deep crust and do not discriminate between rift and non-rift models. On the contrary, seismogenesis models strongly favour a re-activated lower crust with high surface heat flow values and envisage role of fluids in earthquake genesis at lower crustal depths. The magnetotelluric studies in the region support the presence of fluids in the deep crust and partial melt conditions in the shallow crust besides underplating.

From the above, though not definitive, one can infer that there are indications of underplated material and fluids besides partial melt at lower crust perhaps beneath various segments of the central India tectonic zone.

Magnetotelluric method is considered as one of the best methods to image models that envisage the presence of fluids, underplated material and melt at the deep crustal depths (for a review, Jones, 1992; Wannamaker et al., 2001; Bedrosian et al., 2004; Unsworth et al., 2005). We therefore image the electrical properties of the upper crust and map the lower crustal features

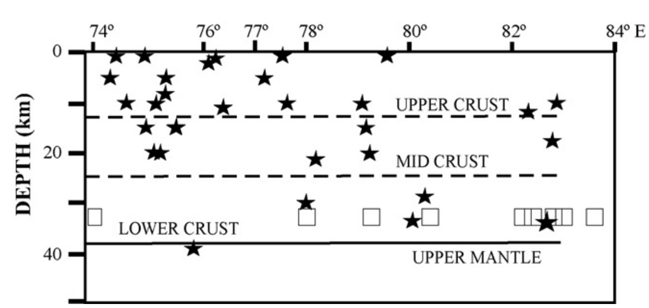

Fig. 3. ISC reported depth distribution of earthquakes (1967–1999) in the NSL zone (modified after Gahalaut et al., 2004). Unfilled squares represent the restricted focal depths at 33 km. The map indicates in the western part seismicity is confined mainly up to mid crustal depths, whereas on the eastern part it extends to lower crustal depths also.

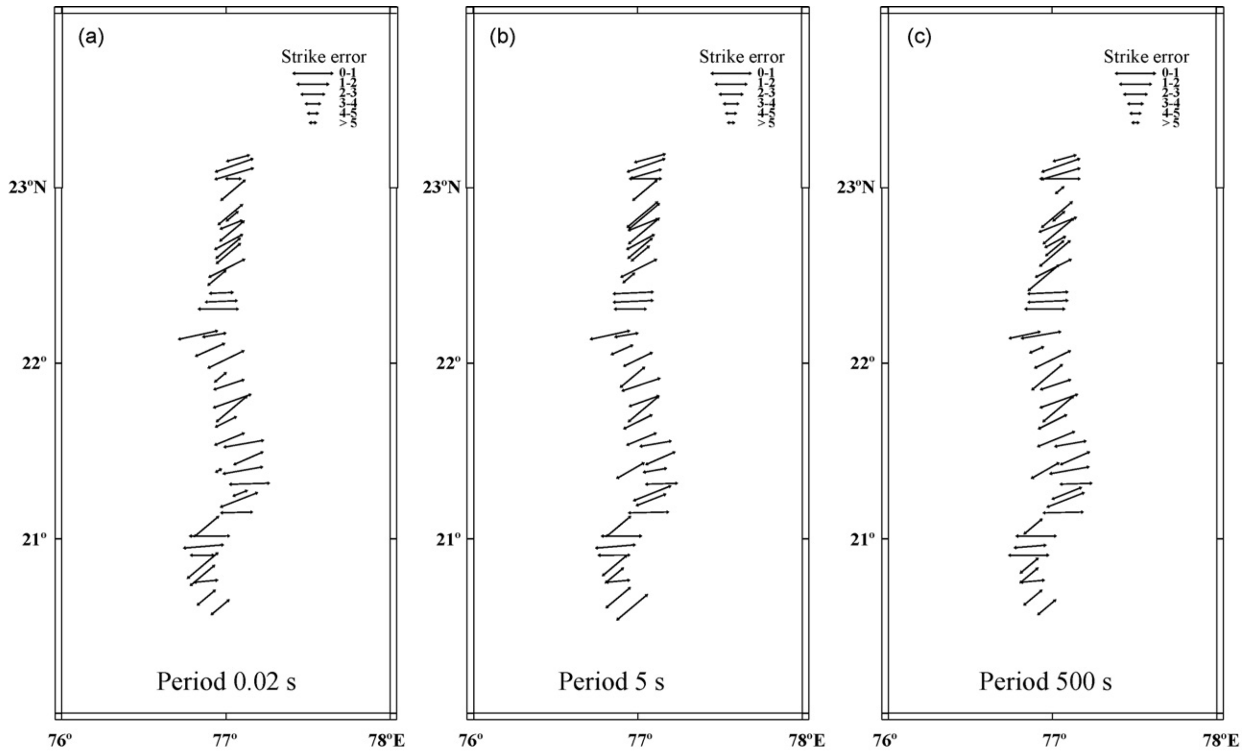

Fig. 4. Strike direction and misfit for period(s) (a) 0.02 s, (b) 5 s and (c) 500 s.

to identify and evaluate the spatial and vertical dominance of the diverse processes of underplating, fluid rich regimes and zones of partial melt, if any, along the Mahan–Khajuria Kalan profile.

2. Magnetotelluric data and methodology

2.1. Data acquisition

Major sections of the 290 km long Mahan–Khajuria Kalan profile (Fig. 2) are covered by thick forests with limited access. Therefore, selection of suitable sites in the study region becomes rather difficult. However, we strived to site our instruments on farms/fields ready for cultivation. This ensures better porous pot contact with the underlying medium. The data are collected at 55 locations deploying wide band digital magnetotelluric systems in single site mode with an operational time period range 0.0001–1000 s. All the three (two horizontal and one vertical) magnetic field components are measured using induction coil magnetometers while the two telluric fields are recorded employing paired sets of $Cd–CdCl_2$ porous pots. Quality checks and overlap criteria reduce the number of usable stations to 45 with an inter-station spacing of 4–7 km. The profile traverses through Purna fault, Gavligarh fault, Tapti fault, Narmada South fault and Narmada North fault (Fig. 1) and ensures delineation of the deep electrical resistivity structure sampling the Gondwanas, Mahakoshal rift belt and Vindhyan tectonic settings.

2.2. Analysis and modeling

The time series data are processed using robust processing schemes (Ellinghaus, 1997) to get the impedance tensors and induction vectors. Data in the period range 0.01–1000 s were found to be of good quality and hence utilised for further analyses. Also, we found that the induction vector data are of relatively poor quality at several stations for various periods. For these reasons, we used only two sets of orthogonally perpendicular electric and magnetic field component data.

The data are investigated for strike estimation using the widely popular multi-site, multi-frequency magnetotelluric tensor decomposition scheme (McNeice and Jones, 2001). This scheme is based on the galvanic distortion decomposition of Groom and Bailey (1989). The strike direction is obtained for individual stations in the period range 0.01–1000 s and the results are shown (in Fig. 4) for 3 representative periods. The lengths of the arrows (in Fig. 4) are scaled by average error in strike estimation for each site. The observed consistency in the strike direction with low chi-square errors (Fig. 4) suggests a mean value of 70° as the geo-electric strike direction for the study region. This strike direction is coincident with the major strike direction of tectonic features in the central India tectonic zone region. Rao et al. (2004) reported N70°E and Patro et al. (2005) obtained N75°E as the strike directions in central India tectonic zone. Our strike direction is close to the above reported values and hence our data are rotated to 70° in such a way that one component is parallel while the other component remains perpendicular to the estimated strike direction. The data of the component parallel to the strike direction are known as TE mode data while those perpendicular to the strike are referred to as TM mode data (for a review Jones, 1992). The data at few stations indeed exhibited distortions of the order of less than half a decade indicative of static shift effects (see Jones, 1988 for a review over static shift effects). This resulted in the shift of apparent resistivity curves from a normal position. As shifts in apparent resistivity curves result in erroneous estimates of subsurface parameters, various procedures are suggested in literature to overcome this problem (Jones, 1988).

It is important to note that two common practices are in vogue in application of corrections to the observed static shift effects. In some studies the correction is applied prior to inversion of data and in few others it is done after preliminary inversion. We followed the latter scheme. We used both apparent resistivity and phase data of TE mode and TM mode. The data are inverted using the non-linear conjugate gradient inversion algorithm of Rodi and Mackie (2001).

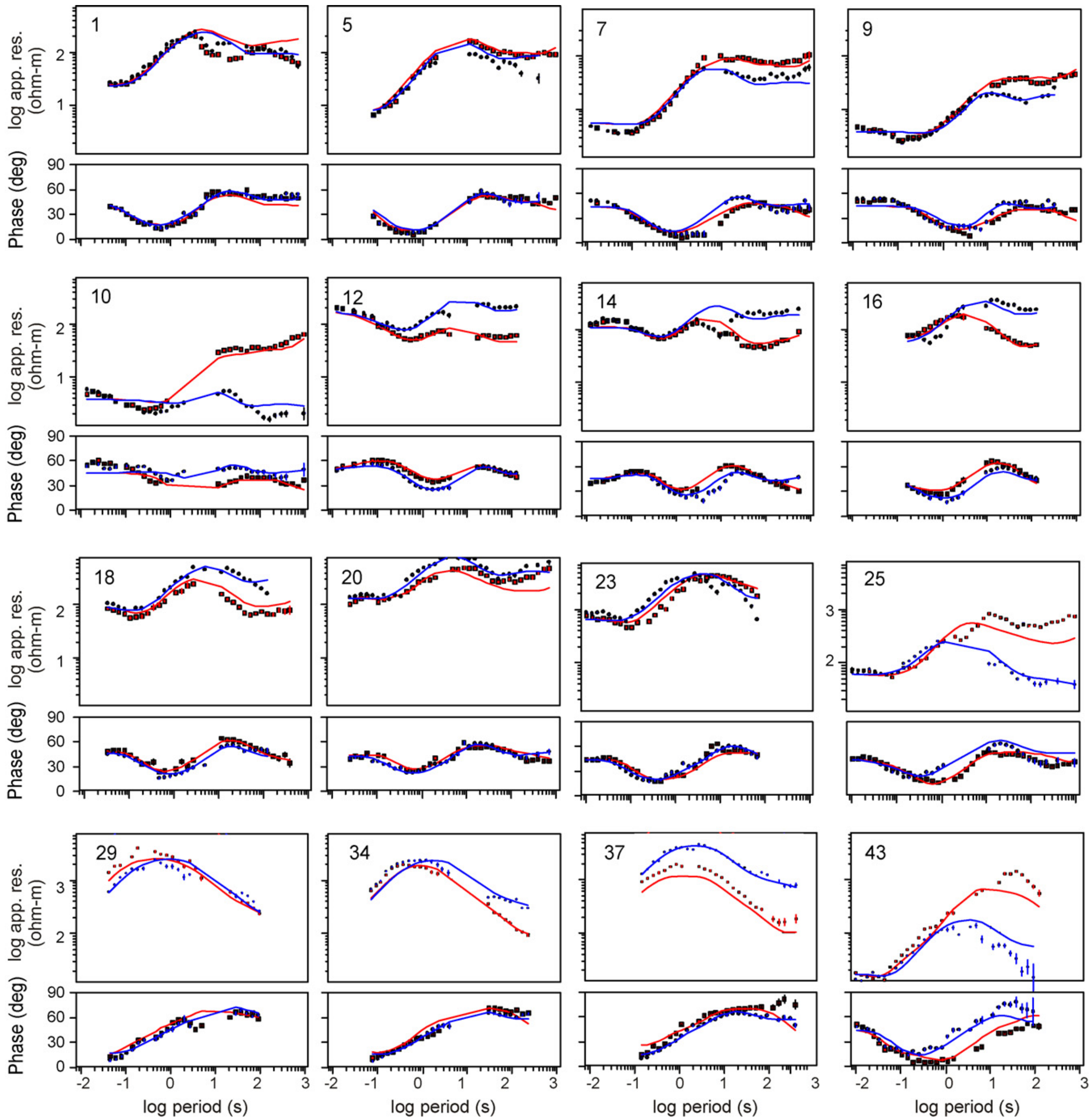

Fig. 5. Fit with the observed data and computed responses at few stations. The response corresponds to the models shown in Fig. 7.

This algorithm provides a minimum structured model required for the observed data. The model mesh consists of 120 horizontal and 150 vertical elements. The starting model is a homogeneous half space model of 100 ohm m. We used an apparent resistivity error floor of 10% and a phase error floor of 10% to arrive at an initial working model. The static shift correction is now carried out using the coefficients obtained for this initial working model. We present in Figs. 5 and 6, apparent resistivity, phase with respect to period and pseudo-sections respectively using data corrected for both strike direction (70° rotation) and static shift. Using the corrected data and already available initial working model, 30 more iterations were performed to obtain a two-dimensional final model through the mentioned non-linear inversion technique. The root mean square error for the final model (shown in Fig. 7) is 3.89. A good fit can be noticed between the observed data and the model response (Figs. 5 and 6). The fit to the data at several representative stations are also shown in Fig. 5. The major features visible in the model (Fig. 7) are a high resistive (3000–10,000 ohm m) upper and mid crust of about 20–25 km thickness underlain by a low resistive (100–300 ohm m) lower crust. Other distinct features are conductors with less than 20 ohm m coinciding with the well demarcated Purna, Gavligarh, Tapti and Narmada North faults (marked A–F in Fig. 7). However, we did not observe any prominent conductor beneath Purna fault, but a change in the apparent resistivity close to this place can be observed. Kaddam fault's signatures are recorded as conductor 'A' at the southern end of the profile (Figs. 1 and 7). The relevance of these conductors and their interpretation is presented in the following sections.

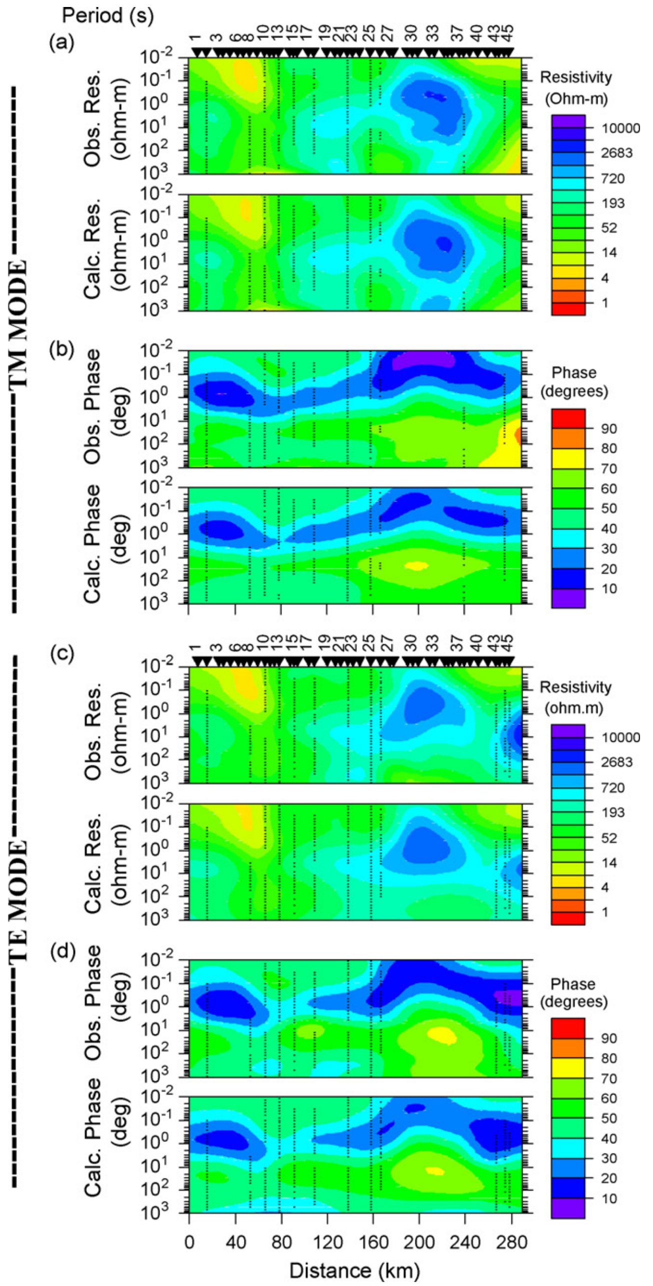

Fig. 6. Comparison of data and model responses in the form of pseudo-sections. The response corresponds to the model shown in Fig. 7. Data and response for (a) apparent resistivity in TM mode, (b) phase in TM mode, (c) apparent resistivity in TE mode and (d) phase TE mode are presented.

2.3. Sensitivity analysis

To check the robustness of the model, we have done several tests. A wide range of error floors (3–40%) to both apparent resistivity and phase data were assigned to a starting model. Utilising the resultant static shift corrections followed by inversion we obtain 2D models similar to that shown in Fig. 7. Many variants of the starting models with homogeneous half space resistivities of 500 ohm m and 1000 ohm m are also found to converge towards the final model presented in Fig. 7. We also replaced the low resistivity features obtained in final model with 500 ohm m blocks and re-inverted the data. After a few iterations, the 500 ohm m features diminished and the original low resistive features of the final model started to emerge. These sensitivity analyses suggest that the models shown

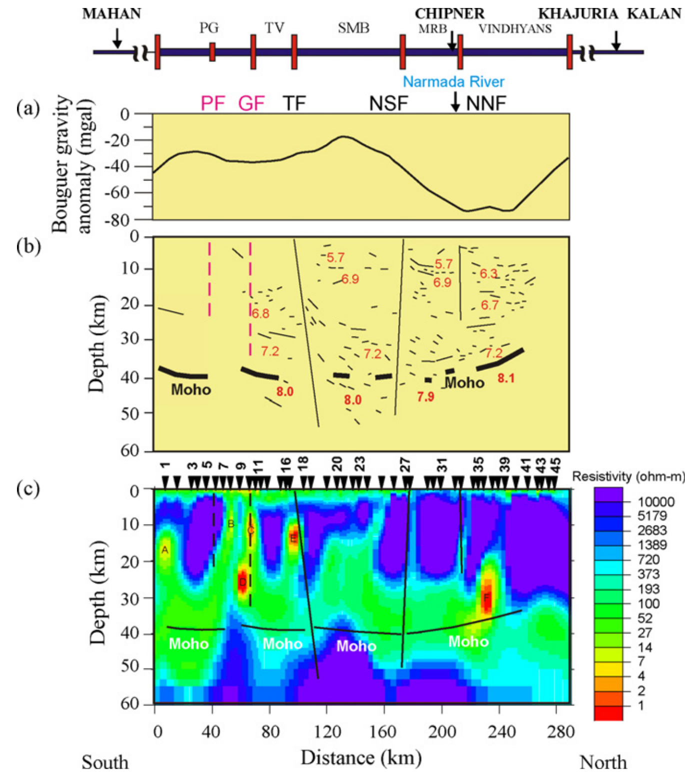

Fig. 7. Gravity anomaly (upper panel), seismic section (middle panel) and geo-electric section (lower panel) are shown. On the top boundaries of various geologic features are shown. The gravity anomaly is derived from available bouguer gravity map (Verma and Banerjee, 1992). The numbers in the DSS sections (middle panel) refer to seismic velocities in km/s (modified after, Kaila et al., 1985; Kaila and Rao, 1986). In the DSS section (middle panel) dashed lines in pink colour corresponds to Purna Fault and Gavligarh Fault inferred from geo-electric section (lower panel). The geo-electric structure is obtained from two-dimensional inversion of magnetotelluric data using non-linear conjugate gradient algorithm of Rodi and Mackie (2001). Moho is taken from seismic section. Features A–F are interpreted as conductors associated with faults in this region. Litho units are: Purna Graben (PG), Tapti Valley (TV), Satpura Mobile Belt (SMB) and Mahkoshal Rift Belt (MRB). Faults are: Purna fault (PF), Gavligarh fault (GF), Tapti fault (TF), Narmada South fault (NSF), and Narmada North fault (NNF). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

in Fig. 7 and the delineated features are indeed appropriate and optimal to explain the observed data in a qualitative manner.

In a more systematic approach both linear and non-linear sensitivity analyses are carried out for this model (Fig. 7). Values obtained by linear sensitivity matrix are calculated based on the code of Mackie et al. (1997) and are shown in Fig. 8. The sensitivity values represent the sensitivity to small changes in resistivity. The structures with sensitivity matrix values above 0.0001 are considered as resolved features following several other works like Brasse et al. (2002) and Ledo et al. (2004). Most part of the Mahan–Khajuria Kalan profile shows sensitivity matrix values above 0.0001 in the 5–20 km depth range. The conductors A–F delineated in the depth

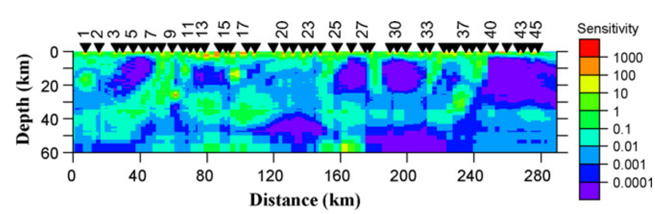

Fig. 8. Sensitivity matrix values for Mahan–Khajuria Kalan section. This figure represents the influence on the data to small perturbations of the logarithm of resistivity in each model cell.

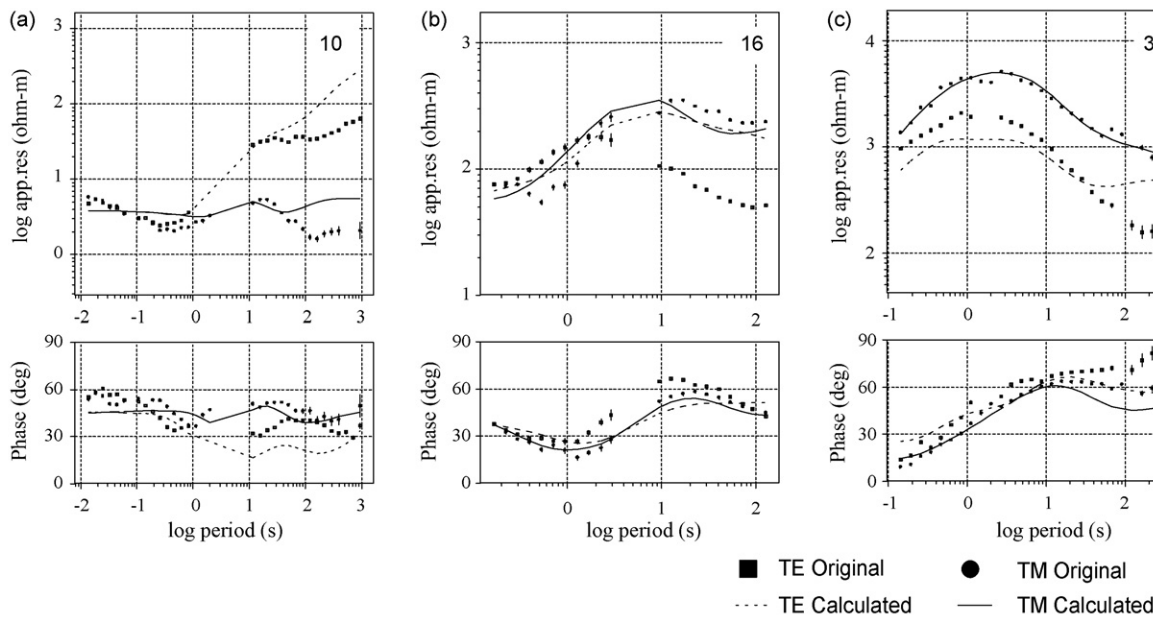

Fig. 9. Forward response calculated after replacing the conductors with 500 ohm m resistive bodies near (a) Gavligarh Fault, (b) Tapti Fault and (c) Narmada North Fault is shown. This forward modeling exercise indicates the conductors shown in Fig. 7 are required bodies in the model to explain the observed anomalies.

range 15–40 km are the best resolved features as their sensitivity values fall in the range 0.01–1. The relatively low sensitivity (around 0.0001) of features in the upper crust (5–20 km) is on expected lines due to their higher resistivity.

Non-linear sensitivity analysis is also carried out for the features A–F to make sure that they are not artefacts of inversion. These low resistive features (Fig. 7), A–F, are now assigned resistivity values of the order 500 ohm m in a sequential manner, i.e., value of only one feature is changed while others retain their original resistivity and the forward response of each such model is computed. Deviations are observed in the resistivity and phase data responses of both TE and TM modes for all the variants of these forward models. Representative results of the forward modeling response misfits for C–D (combined), E and F are shown in Fig. 9. The sensitivity analysis results presented in Figs. 8 and 9 clearly demonstrate that the low resistive nature of conductors A–F in the depth 15–40 km (Fig. 7) is indeed robust and real. Therefore, it is inferred that the features in the models are appropriate to represent the subsurface electric structure.

3. Results and discussion

Along the profile the upper crust in general is highly resistive with resistivity values reaching excess of 3000 ohm m. However significantly low resistive values of the order 20 ohm m are clearly observed near stations 1, 7–8, 10–11 and 16–18 that coincide with exposed geologic faults on the surface. Importantly the deep seismic sections do not trace the known geologic faults identified in our model at stations 1, 7–8 and 10–11 which are reflected as conductors at these locations. These are Kaddam, Purna and Gavligarh faults respectively. The fourth conductor mapped at stations 16–18 being the well known Tapti fault is also identified in deep seismic reflection data (Kaila et al., 1985).

The lower crust all along the Mahan–Khajuria Kalan profile exhibits low resistive values (50–300 ohm m). This low resistivity extends from about 18–25 km to 40–45 km. Anomalously low resistive features (<20 ohm m) can be observed in the vicinity of stations 9–12 and 35–39 (Fig. 7). These conductors are spatially correlated with Gavligarh Fault and Narmada North Fault. Our results indicate the clear presence of at least six conductors at varied depths with in the crust of the study region with apparent correlation with exposed surface geologic faults.

The magnetotelluric model (Fig. 7) reveals anomalous features near Kaddam fault, Purna fault, Gavligarh fault, Tapti fault and Narmada North fault. These are reflected as 6 distinct conductors, i.e., unconnected, with varied dimensions and resistivity values located at different depths. Low electrical conductivity anomalies, in general, can be explained invoking the presence of fluids (Hyndman and Shearer, 1989), partial melt conditions (Hermance, 1979; Schilling et al., 1997) and due to thin graphite films (Glover and Vine, 1992) or a combination of more than one of the above. In active regions connectivity between thin graphite films is unlikely and hence cannot generate any conductive zones (Jones, 1992; Wannamaker, 2000) as delineated in our study area which is also classified as a tectonically active region based on both geological (West, 1962; Choubey, 1971) and geophysical evidences (Rao et al., 2002). In general generation of partial melt needs a minimum temperature of 700 °C (Thompson, 1992), which is significantly higher than those estimated from heat flow data (Fig. 2) for the study region. As mentioned earlier, numerical modeling results suggest that the Moho temperatures in the study region do not exceed 500–580 °C (Fig. 2) and the temperature depth profiles are devoid of sharp gradients (Rai and Thiagarajan, 2006). This precludes the presence of partial melt in the crust of the study region. Therefore, the modelled conductive features along the Mahan–Khajuria Kalan profile cannot be explained by either presence of graphite films and/or by partial melt in this region.

Results from gravity modeling of data collected along two deep seismic reflection profiles; the Mahan–Ujjain and Pulgaon–Khajuria Kalan profiles, in the vicinity of our magnetotelluric profile, are discussed. Along the Mahan–Ujjain profile, in the southern segment (Mahan–Chipner), Verma and Banerjee (1992) delineate the presence of an anomalously high dense (2.95 g/cc) intrusive body in the upper crust underlain by an anomalous lower crust with density values reaching 3.00 g/cc at depths 35 km and beyond. The northern segment that reflects a clear gravity low is explained by a low dense upper crust intrusive at shallow depths (8–15 km). In another study along the same profile, a normal (density of 2.67 g/cc) upper crust followed by a lower crust with underplated material (density 3.03 g/cc) is inferred in the southern segment, while the northern counterpart is devoid of any underplated material (Singh and Meissner, 1995). Similar results from gravity modeling were also obtained along Pulgaon–Khajuria Kalan profile. Therefore, gravity models in the study region indicate the presence of high dense material in the crust south of the Narmada River related to tectonic/volcanic activity (probably underplated material), though their exact depth location remains ambiguous. The northern segment though shows clear gravity lows is not dealt with the desired rigour. Further, to authenticate the causative to explain the delineated conductors, we construct a 290 km long gravity profile along our interpreted magnetotelluric profile (Fig. 7) utilising available gravity map of Verma and Banerjee (1992).

The gravity anomaly along this profile reveals high gravity values of about −30 mgal in the southern part (Mahan–Chipner) roughly coinciding with the Purna, Tapti conductors (20 ohm m) located at 10 km to 20 km depth and the Gavligarh conductor situated at depths between 10 and 30 km. A relatively low seismic P-wave velocity of 6.7–7.2 km/s in the deep crust of Mahan–Chipner, compared to corresponding global average range of 7.17–7.34 km/s (Rudnick and Fountain, 1995), together with the observed high conductivity and high gravity anomaly can be explained mainly by magmatic bodies intruded into the crust due to underplating. Often, release of fluids that migrate upwards accompany underplating resulting in lowering the resistivities of rocks (Hyndman and Shearer, 1989). However, in view of gravity high, presence of fluids may be in small quantity or alternatively interconnectivity between the rock matrices could be small.

In the northern Chipner–Khajuria Kalan segment, our magnetotelluric model (Fig. 7) shows a very low resistive (less than 20 ohm m) body extending from a depth of 25–40 km below the stations 35–39. A gravity low anomaly of −70 mgal coincident with this conductor is revealed by our gravity profile. However, the gravity models in the near vicinity of the study region by Verma and Banerjee (1992) attributed the observed low to granitic rocks in the crystalline basement while Singh and Meissner (1995) argued that the low density sediments in the upper crust is the causative. The observed relatively low seismic P-wave velocity of 6.7–7.2 km/s in the deep crust of the southern segment continues into the northern segment too. Therefore, unlike in the southern counterpart of the profile, here we need to explain the presence of a conductor accompanied by similar low P-wave velocity but with a gravity low of the order −70 mgal. Hence the presence of underplated material like in southern part seems an unlikely candidate to explain our observations in the northern segment of the profile. Recognising that the delineated conductor has reasonable spatial correlation with the Narmada North fault, we realise that similar conductors in the deep crust at depth ranges 10–30 km and 20–35 km are reported further east of the study area near Jabalpur by Gokarn et al. (2001). The first conductor (10–30 km depth) is linked to the presence of fluids (Gokarn et al., 2001), a view shared by Rao and Rao (2006) who in addition interpret that these fluids originate from the serpentinized mafic/ultramafic bodies mapped as the other conductor (depth 20–35 km). However, the observed gravity low over the conductor in the northern segment of our study area does not support the presence of high dense serpentinized bodies to underlie this region. Therefore, the presence of fluids associated with deep-seated faults seems to be the most plausible reason to explain our observations in the northern part of the study area. Also, the presence of few earthquakes in this region with focal depths (Fig. 3) in the lower crust lends support to such an interpretation.

4. Implications and conclusions

We integrated our magnetotelluric results with available gravity, deep seismic sounding and heat flow studies along the Mahan–Khajuria Kalan profile in the central India tectonic zone. The study region witnessed tectonic re-activation and is manifested as two distinct processes. The region north of the Narmada River (northern segment of the profile) is characterised by the presence of fluids in the deep crust contrary to dominance of underplated material in the southern segment of the profile at similar depths. The implications of these new results are explained in the following.

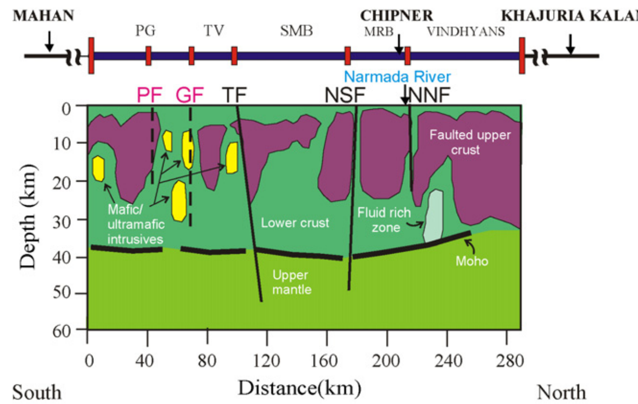

Fig. 10. Cartoon sketch showing possible interpretation. Re-activation of the region leading to registration of contrasting processes in the crust across the Narmada River. The conductors (20 ohm m) at various depth levels correspond to mafic magmatic and/or fluid intrusions controlled by deep-seated faults that seem to tap reservoirs beyond the crust–mantle boundary. Moho is taken from seismic section (Fig. 7b). Litho units are: Purna Graben (PG), Tapti Valley (TV), Satpura Mobile Belt (SMB) and Mahkoshal Rift Belt (MRB). Faults are: Purna fault (PF), Gavligarh fault (GF), Tapti fault (TF), Narmada South fault (NSF), and Narmada North fault (NNF).

Presence of deep-seated conductivity anomalies in the deep crust offers an opportunity to estimate possible anomalous concentration of fluids beneath the study region. It is well known that normal salinities of 25 wt% at 500 °C temperature results in 0.01 ohm m brine resistivity (see Nesbitt, 1993). Calculations based on Hashin and Shtrikman (1963) approximation for these above conditions yields less than 3% porosity to explain the normal deep crustal electrical resistivity values of 50–300 ohm m. The temperature in the lower crust relevant to our study area is roughly around 500 °C (Fig. 2). Based on the above we arrive at about 7–8% porosity to be associated with our delineated conductors (20 ohm m). Such inferred high porous fluid filled bodies (7–8% porosity) in the study together with a 3% background porosity deep crust would lead to decrease in P-wave velocity and density of the rock matrix as observed in this study region.

Following the re-activation model proposed for the entire region, the conductors (20 ohm m) at various depth levels correspond to mafic magmatic and/or fluid intrusions controlled by deep-seated faults that seem to tap reservoirs beyond the crust–mantle boundary. The shallow depth localized faults also seem to have facilitated further upward movement of these underplated material and fluids release during this process. Such a scenario is presented in the form of a cartoon sketch in Fig. 10.

The major outcome from our study is the recognition of re-activation of the region leading to registration of contrasting processes in the crust across the Narmada River deciphered with constraints from available geophysical information to explain apparently similar conductive bodies.

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