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Deep crustal electromagnetic structure of Bhuj earthquake region (India) and its implications

K. NAGANJANEYULU [1] [2] [*] **J. J. LEDO** [2] **and P. QUERALT** [2]

[1] **National Geophysical Research Institute, Council of Scientific and Industrial research (CSIR)**
Hyderabad-500 007, India

[2] **Departament de Geodinàmica i Geofísica, Universitat de Barcelona**
C/Martí i Franques s/n, Barcelona 08028, Spain

* corresponding author E-mail: kasturi_kasturi@rediffmail.com

ABSTRACT

The existence of fluids and partial melt in the lower crust of the seismically active Kutch rift basin (on the western continental margin of India) owing to underplating has been proposed in previous geological and geophysical studies. This hypothesis is examined using magnetotelluric (MT) data acquired at 23 stations along two profiles across Kutch Mainland Uplift and Wagad Uplift. A detailed upper crustal structure is also presented using two-dimensional inversion of MT data in the Bhuj earthquake (2001) area. The prominent boundaries of reflection in the upper crust at 5, 10 and 20 km obtained in previous seismic reflection profiles correlate with conductive structures in our models. The MT study reveals 1-2 km thick Mesozoic sediments under the Deccan trap cover. The Deccan trap thickness in this region varies from a few meters to 1.5 km. The basement is shallow on the northern side compared to the south and is in good agreement with geological models as well as drilling information. The models for these profiles indicate that the thickness of sediments would further increase southwards into the Gulf of Kutch. Significant findings of the present study indicate 1) the hypocentre region of the earthquake is devoid of fluids, 2) absence of melt (that is emplaced during rifting as suggested from the passive seismological studies) in the lower crust and 3) a low resistive zone in the depth range of 5-20 km. The present MT study rules out fluids and melt (magma) as the causative factors that triggered the Bhuj earthquake. The estimated porosity value of 0.02% will explain 100-500 ohm·m resistivity values observed in the lower crust. Based on the seismic velocities and geochemical studies, presence of garnet is inferred. The lower crust consists of basalts - probably generated by partial melting of metasomatised garnet peridotite at deeper depths in the lithosphere - and their composition might be modified by reaction with the spinel peridotites.

KEYWORDS | **Electrical resistivity. Mesozoic sediments. Fluids. Bhuj earthquake. Intraplate seismicity.**

INTRODUCTION

The major part of the Indian shield region is covered by the Deccan Traps. Detection of Mesozoic sediments under the Deccan Traps has attained major importance over the last two decades as they are considered to be potential targets for hydrocarbon exploration. The Kutch basin (Fig.1A), with Deccan Trap cover in the middle, on the western continental margin of India, is a large scale rift basin (Biswas, 1987) having hydrocarbon potential. The Kutch region lies adjacent to the Indus basin of Pakistan where hydrocarbon reserves are found.

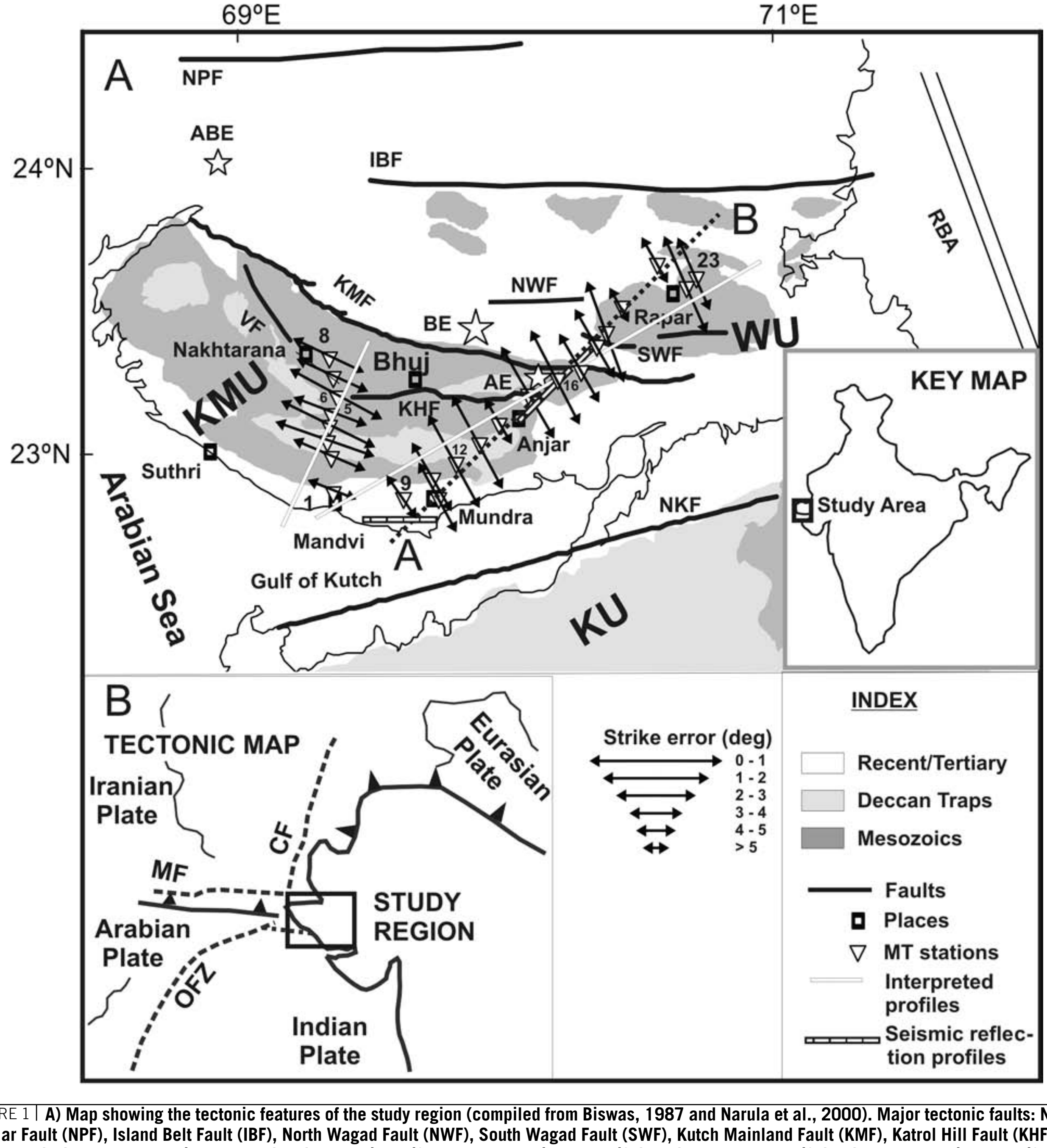

FIGURE 1 | **A) Map showing the tectonic features of the study region (compiled from Biswas, 1987 and Narula et al., 2000). Major tectonic faults: Nagar Park ar Fault (NPF), Island Belt Fault (IBF), North Wagad Fault (NWF), South Wagad Fault (SWF), Kutch Mainland Fault (KMF), Katrol Hill Fault (KHF), Vigodi Fault (VF) and North Kathiawar Fault (NKF). Tectonic uplifts: the Kutch Mainland Uplift (KMU), the Wagad Uplift (WU) and the Kathiawar Uplift (KU). Major earthquakes in the region viz. ABE-Allahbund earthquake, AE-Anjar earthquake and BE-Bhuj earthquake are marked by a star. Locations of MT stations are indicated by inverted triangles. Strike directions and misfits (indicated by arrows) for all the stations are also shown. Geologic section along line AB is shown in Fig. 2. Results from seismic reflection profiles near Mundra and between Anjar and Rapar are shown in Fig. 6. B) Broader tectonic map showing location of various plates. CF : Chaman Fault, MF : Makaran Fault and OFZ : Owen Fracture Zone (modified after Mishra et al., 2005).**

The region is known for hazardous earthquakes too. The eastern part is highly strained under the NNE-SSW directed compressive stress and is seismically active (Biswas, 2005). The Kutch region witnessed three devastating earthquakes - the Allahbund earthquake in 1819, Anjar earthquake in 1956 and the other recent Bhuj earthquake in 2001- with magnitudes over M_w 7. Regional and teleseismic earthquake studies (Kayal et al., 2002; Mandal et al., 2004a, b; Mandal, 2006; Mishra and Zhao, 2003) were carried out in the region after the Bhuj earthquake of 2001. These passive seismological studies estimated that the hypocentre is at a depth of around 25 km (Kayal et al., 2002). The Allahbund earthquake and the recent Bhuj earthquake were grouped under stable continental region earthquakes and compared with the New Madrid earthquakes (Reelfoot rift, US). Analogies were drawn based on their occurrence in intraplate regions and seismic velocities (see Johnston and Kanter, 1990; Ellis et al., 2001; Sarkar et al., 2007).

It has also been observed that in continental rift regions like the Reelfoot rift (US), the Kenya rift (Kenya and Tanzania), the Amazonas rift (Brazil), the Narmada rift (India) and the region of present study, the Kutch rift, hypocentres of earthquakes have been located in the lower crust. This deep crustal intraplate seismicity is attributed to the accumulation of strain associated with the mafic intrusive or rift pillows in the lower crust for the Reelfoot rift (Pollitz et al., 2002), the Amazonas rift (Zoback and Richardson, 1996) and the Narmada Rift (Ramalingeswara Rao and Rao, 2006). Lower crustal earthquakes in the Kenya Rift are attributed to melt movements (Young et al., 1991). In the case of the present study of the Bhuj region, passive seismological studies (Mandal et al., 2004a, b; Mandal, 2006) indicated the presence of a mafic body (intrusive) / rift pillow in the range of 10-40 km depth based on the observed higher seismic velocities (Vp: 7.0-8.5 km/s) and suggested underplating. The other interesting finding from the studies of passive seismology are the presence of fluids in the lower crustal depths (20-30 km) (Mishra and Zhao, 2003; Mandal et al., 2004a, b; Mandal, 2006). The causative factor for triggering the Bhuj earthquake derived from these studies is hypothesized to be fluids. The logic behind this argument is associated with the high fluid pressure in the fault zone acting as an agent to reduce the frictional strength of the fault zone and that time variations in fluid pressure controls the triggering of the earthquake (Biswas, 2005). Fluids play a vital role in the generation of earthquakes as observed from the Parkfield earthquake region, U.S. (Unsworth et al., 1997, 1999; Bedrosian et al., 2004), the Kobe earthquake region, Japan (Goto et al., 2005) and the Latur earthquake region, India (Gupta et al., 1998).

The magnetotelluric (MT) method allows detailed imaging from shallow to deep crustal structures (for a review, Jones (1992)). MT is a successful tool in imaging the fluids in the earthquake prone zones such as the Parkfield region (Unsworth et al., 1997, 1999; Bedrosian et al., 2004), Kobe (Goto et al., 2005) and Latur (Gupta et al., 1998). The method is also successful in imaging partial melt and magmatic underplating in the deep crustal depths at several places like in Southern Tibet (Unsworth et al., 2005), the Great Basin (Wannamaker et al., 2001, 2008) and also under the Deccan Traps in Central India (Patro et al., 2005).

In the present study, 2-D modeling has been carried by including additional data (stations 16-23, Fig.1A) on the northern side of the Kutch Mainland Fault region to obtain a deep crustal resistivity picture related to the Bhuj earthquake region, so far unknown. With the aid of this new data, the available geological models were examined in the present study along the 150 km long Mundra-Rapar profile (Fig. 1). For a comparison and to have a check on the features obtained, data along the 60 km long Mandvi-Nakhtarana profile are also considered. The results are discussed in terms of: 1) basement undulations and upper crustal fluids, 2) Fluid content in the lower crust, 3) presence (or lack) of magma and, finally, 4) an attempt is made to explain (or reject) the possible causative factors that triggered the Bhuj earthquake.

GEOLOGICAL AND TECTONIC SETTING

The existing compressive stress regime owing to northward movement of the Indian plate is considered to be one of the components responsible for the accumulation of higher stress in the Indian shield region (Biswas, 2005; Rao et al., 2006). The Kutch rift basin is located to the east of the junction of the Indian, the Arabian and the Iranian plates in the Arabian Sea along the Owen fracture zone, the Makaran and the Chaman faults (Fig.1B). The Kutch basin (Fig. 1A) is an east-west oriented pericratonic continental scale rift basin on the western margin of the Indian shield (Biswas, 1987). It is bounded by the Nagar Parkar Fault (NPF) to the north, the Radhanpur-Barmer arch to the east, the Kathiawar uplift to the south and the Arabian Sea to the west (Fig. 1A). Several regional faults, viz. the Nagar Parkar Fault, the Island Belt Fault, the Kutch Mainland Fault (KMF), the South Wagad Fault (SWF) and the North Kathiawar fault (NKF) in the region bound various uplifted blocks (Biswas, 1980). For example, the Kutch Mainland Fault is the northern marginal limit for the Kutch Mainland Uplift (KMU). The thickness of the sediment estimated is more than 3 km in the southern part of the basin and 1.5 km in the northern part (Srinivasan and Khar, 1995). ONGC (Oil and Natural Gas Corporation Ltd.) data show the thickness of the sediment to be about 2.2 km near the Kutch Mainland Fault (Biswas, 2005).

The intrusive rock composition will be mafic or ultramafic when partial melting affects the upper mantle (Rudnick and Gao, 2004). The crustal thinning of about 10 km and the high velocities (> 7.3 km/s) can be explained by lithospheric scale shear rifting and this process results in melt production and underplating (Korenaga et al., 2002 and references therein). The cause for these high velocities is explained by Biswas (2005) in terms of regional tectonics and a geological model is constructed with a magma chamber owing to underplating in the range of 20-40 km depth between the Katrol Hill Fault and northern end of the Wagad uplift (Fig. 2). If this hypothesis is true, huge conductive anomalies owing to presence of partial melt can be expected. This is possible if there is active upwelling of upper mantle material of high temperature in the pre-rift or syn-rift magma stages at continental margins (see Menzies et al., 2002). The present MT study would examine the geological model and also passive seismology models in view of reported thick underplating, deep crustal fluids and partial melts.

RECENT GEOLOGICAL AND GEOPHYSICAL STUDIES

The central and southwestern parts of the Indian shield region covered by the Deccan Traps have been well studied by several MT surveys (Gokarn et al., 1992, 2001; Rao et al., 2004; Patro, 2002; Patro et al., 2005) and the trap thickness has also been recently compiled (Harinarayana et al., 2007; Patro and Sarma, 2007). Significant variation in the sedimentary thickness from north (0.5 km) to south (4 km) was observed from the wells drilled in the Kutch region (Biswas, 2005). Integrated surveys carried out earlier along the Mundra – Bachau (20 km NE of Anjar, Fig.1A) segment inferred 3-5 km thick sediments (Gupta et al., 2001; Sastry et al., 2008). The refined gravity models have shown sediments of 5 km thickness (Chandrasekhar and Mishra, 2002; Mishra et al., 2005). Recent studies of passive seismology indicated that the thickness of low velocity (Vp: 1.8-2.5 km/s) sediments in the Kutch basin varies from 1 to 3 km (Mandal, 2006).

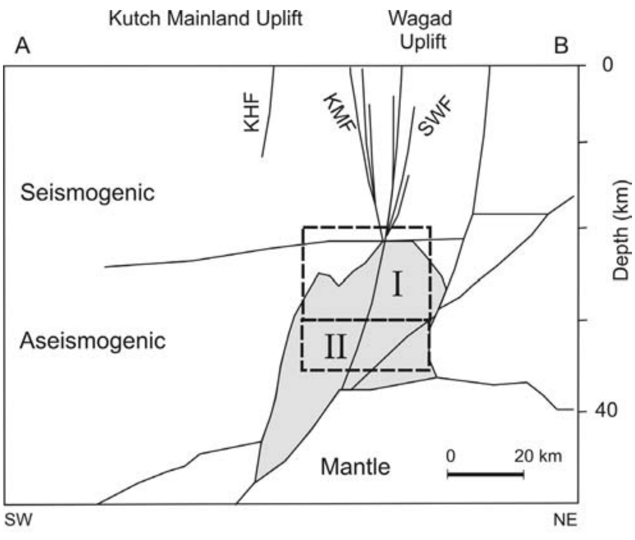

FIGURE 2 | **Simplified geological section across the Kutch rift basin along line A-B in Fig. 1 (After Biswas, 2005). Grey shaded region is interpreted as magma chamber. Region I (imaged by passive seismological tomography studies as a zone with presence of fluids) is tested with 4 km and 6 km thick conductors starting from 20 km and 24 km, respectively, and the results are shown in Fig. 10. In the region II, at a depth of 30-36 km, conductors with varying conductivity are placed to test the presence of magma chamber and the fit is shown in Fig. 11. See text for more details.**

Apart from the hydrocarbon prospects, the interest in this zone lies with its seismic activity. The Bhuj earthquake in 2001, with a magnitude of M_W 7.7, caused over 20,000 deaths (Rajendran et al., 2001). High crack density and saturation rate is estimated in the Bhuj earthquake hypocentre zone and the presence of fluids is indicated (Mishra and Zhao, 2003). In the range of 20–30 km depth, presence of numerous fractures was suggested and the nucleation process that triggered the earthquake was inferred in this zone (Mandal et al., 2004a, b). Mandal (2006) also observed that the heat flow values measured in Cambay and Rajasthan (Roy, 2003) suggest high heat flow (53-90 mW/m^2) values for the Kutch area and indicated that the source for these fluids could be of deeper origin that were released during metamorphism/partial melt intruded in the crust during Reunion plume activity at 64-68 Ma. Pandey and Agarwal (2000) estimated temperatures of about 600-1200^{o}C in the range of 20-40 km depth. A 1-D model of one long period MT station data on the northern side of the Kutch Mainland Fault (Arora et al., 2002) shows a conductor in the upper crust and is devoid of any conductor in the lower crust. Passive seismological studies also imaged a mafic intrusion/rift pillow of 60 km length (N-S), 40 km width (E-W) and 35 km thickness placed during rifting based on high seismic velocities (Mandal et al., 2004a, b; Mandal, 2006). Also, passive seismological studies have shown a thin crust near the Bhuj earthquake region (38 km). The crustal thickness variations are large (from 38-49 km). However, seismic reflection studies have inferred a crust of 45 km thickness near the epicentral zone (Sarkar et al., 2007).

MAGNETOTELLURIC DATA AND METHODOLOGY

Data

MT data were collected in the Bhuj earthquake zone to identify the electrical resistivity structure of the region and its significance in terms of known tectonic features covering the Kutch Mainland Uplift and the Wagad Uplift using wide band digital MT systems in two field campaigns. The MT data were acquired in the period range of 0.0001-1,000 s. Magnetic field components were measured using induction coil magnetometers and a set of Cd - $CdCl_2$ porous pots were used as electrodes for telluric field measurements. The time series data were processed to obtain the impedance tensors and induction vectors using a robust processing code (Ellinghaus, 1997). The data in the period range 0.0001-0.01 s are found to be noisy at few stations and also the induction vector data is not of high quality at several periods. Good quality impedance tensor data in the period range 0.01-1,000 s is considered in the present study (Fig.3). As can be seen from Fig. 3, data have small error bars indicating better quality.

Dimensionality and Two-dimensional Inversion

The observed MT data can be affected by local distortions owing to surface heterogeneities. The data along the two

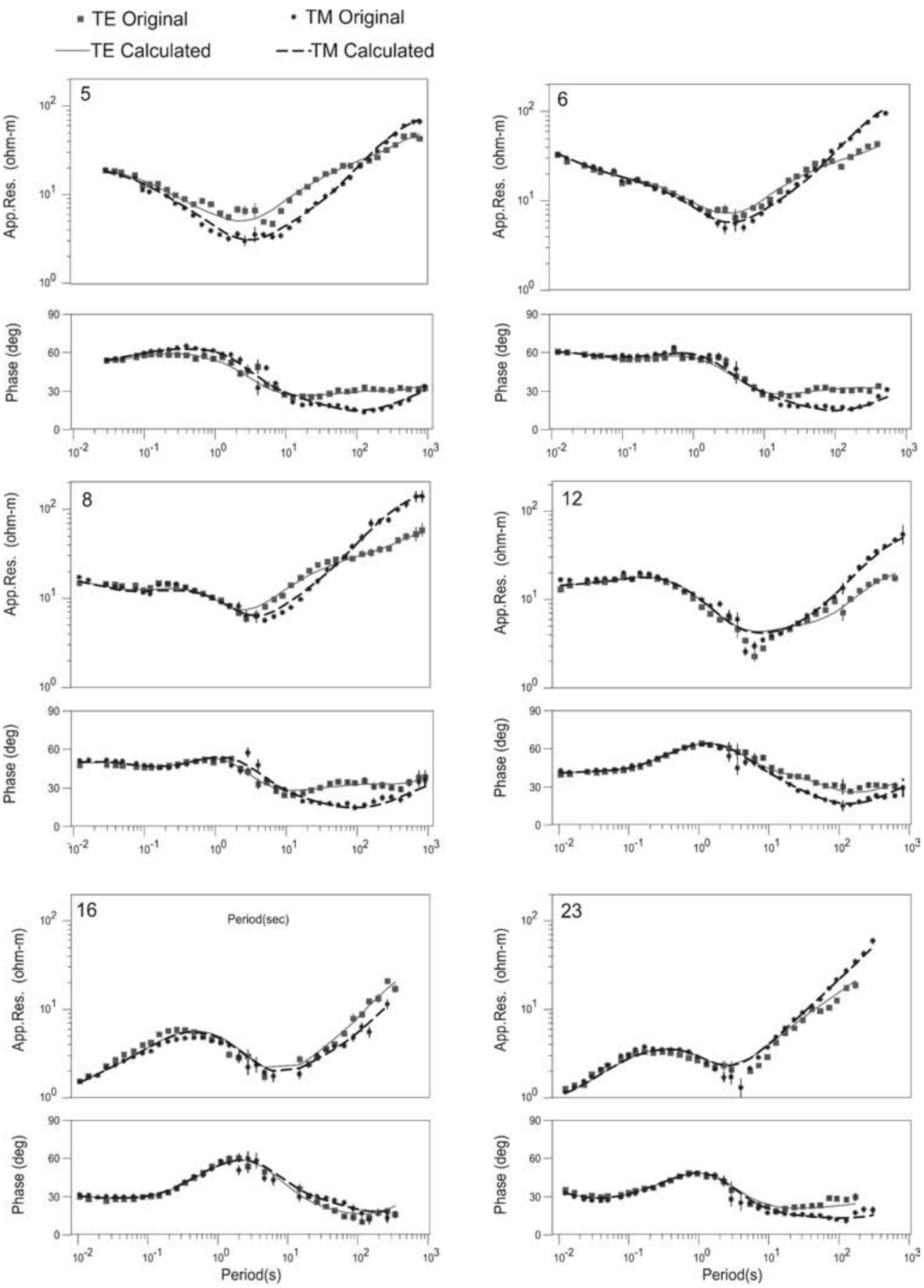

FIGURE 3 | **Plots of the observed data and computed responses at selected stations. The responses correspond to the models shown in Figures 5 and 6.**

profiles were investigated for strike estimation using the multisite, multifrequency MT tensor decomposition code (McNeice and Jones, 2001). This code is based on the galvanic distortion decomposition of Groom and Bailey (1989). Initially, the strike direction was obtained for individual stations in the period range 0.01 – 1,000 s and the results are shown in Fig. 1A. The lengths of the arrows (in Fig. 1A) are scaled by the average error in strike estimation for each site in the range of 0.01 – 1,000 s. The consistency in the strike direction with low chi-square errors (Fig. 1A) allowed a mean value of -65° for the Mandvi-Nakhtarana profile, whereas for the Mundra-Rapar profile, a strike of -30° was obtained. Strike directions are coincident with the dominant structural trends in the Kutch region, i.e., NW-SE. Hence, the data were rotated to -65° and -30°. The resulting responses are shown in Fig. 4 in the form of pseudosections. These responses were inverted using the non-linear conjugate 2-D inversion algorithm of Rodi and Mackie (2001). This algorithm provides a minimum structure model required for the observed data, i.e., a more complicated model can also justify the given data. Mesh sizes are 109 horizontal and 120 vertical elements for the Mundra-Rapar profile and 123 horizontal and 150 vertical elements for the Mandvi-Nakhtarana profiles, respectively. The initial model was obtained from 1-D modeling of TM mode data. The Gulf of Kutch was considered in the models during the inversion process. Both modes, TE (electric field parallel to the strike) and TM (electric field perpendicular to the strike), were taken into consideration. The same inversion parameters were used to obtain both

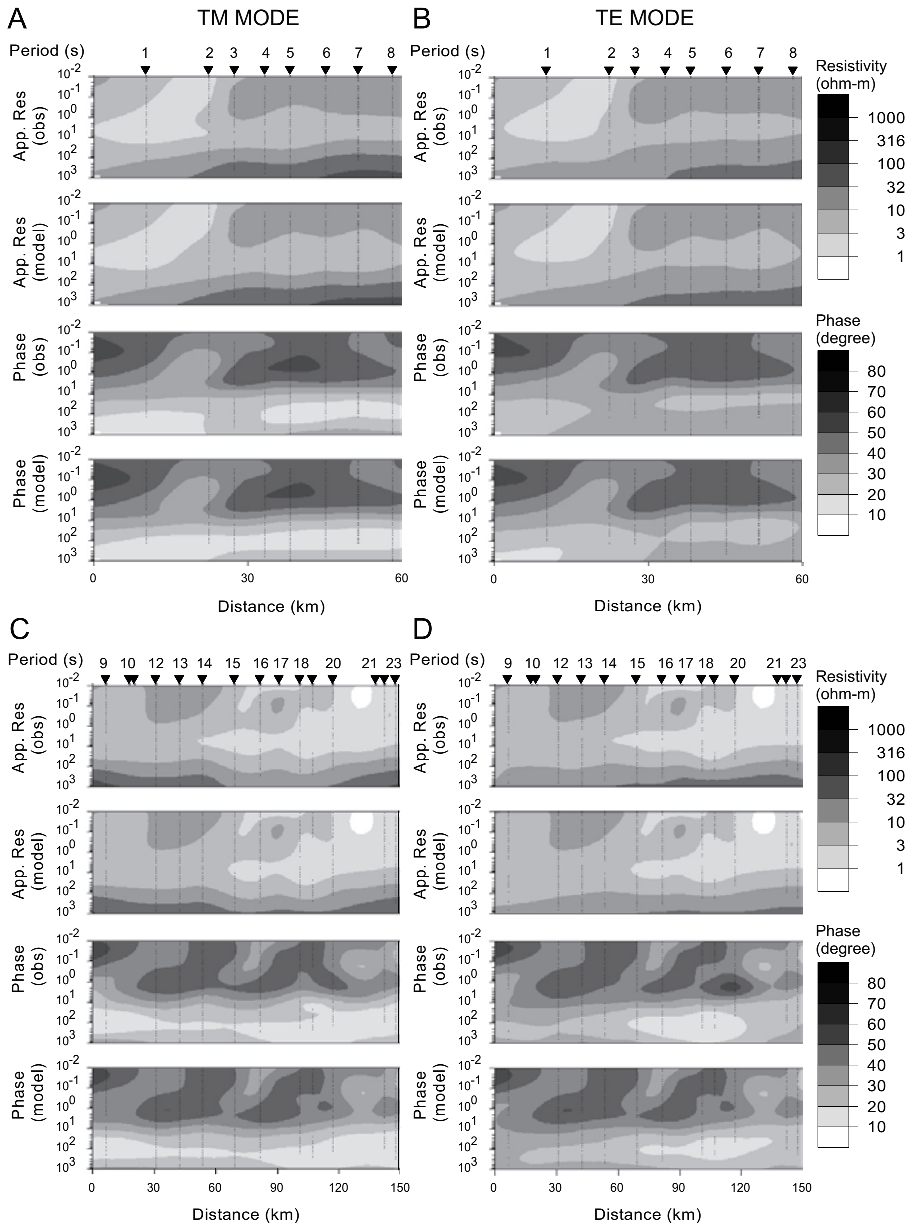

FIGURE 4 **Pseudosections of data and model responses for both profiles. The responses correspond to the models shown in Figures 5 and 6. Responses for Mandvi-Nakhatarana profile in both A) TM mode and B) TE mode and for Mundra-Rapar in both C) TM mode and D) TE mode are presented.**

models (apparent resistivity error floor of 10% and phase error floor of 10%). A few stations showed small scale static shifts of less than half a decade. The static shift correction was carried out using the coefficients achieved in the inversion. One of the other alternatives of giving more weight to phase data in the inversion was also tried and gave similar results. A good fit was found between the observed data and the model response (Figs. 3 and 4). The fit for the data at representative stations on both the profiles are shown in Fig. 3. The RMS errors are 1.27 for the Mandvi-Nakhtarana profile and 1.38 for the Mundra-Rapar profile.

The common major features visible in the models (Figs. 5 and 6) are a 4 km thick low resistive sedimentary section (along with traps) of less than 50 ohm·m underlain by a high resistive (> 200-1,000 ohm·m) structure in the upper crust to a depth of about 8 to 10 km. This layer is underlain by an upper crustal resistivity structure (< 85 ohm·m) to a depth of about 20 km which is likewise underlain by a 100-500 ohm·m lower crust.

In the shallow section, on the Mandvi-Nakhtarana profile (Fig. 5A), between stations 3 and 6, a resistivity value of 40-60 ohm·m up to a depth of 0.5-1 km can be observed. Southward dipping conducting features of about 5 ohm·m underlain by a well characterised undulating high resistive (> 200-1,000 ohm·m) layer at a depth of 3.5 km in the middle of the profile to 4.5 km on the southern end of the profile are evident. The Mundra-Rapar profile is characterised by 20-40 ohm·m (top layer) from station 18 in the centre of the profile to the southern end of the profile with thickness varying from 0.1-1 km (Fig. 5B). The distinct feature of this profile is a conducting layer of approximately 1-2 km thickness of less than 5 ohm·m almost all along the profile underlain by a 200-1,000 ohm·m resistive layer. This layer is almost flat to gentle and southern dipping starting from approximately 2 km on the northern side to 3 km on the southern side. Another

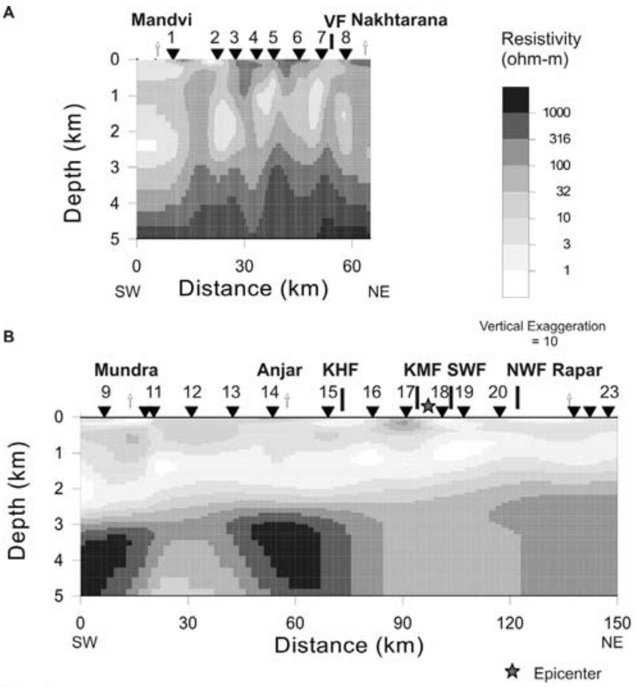

FIGURE 5 | **Shallow upper crustal structure (< 5 km) obtained for both profiles from 2-D inversion of magnetotelluric data using the non-linear conjugate gradient algorithm of Rodi and Mackie (2001) shown along with geological faults.**

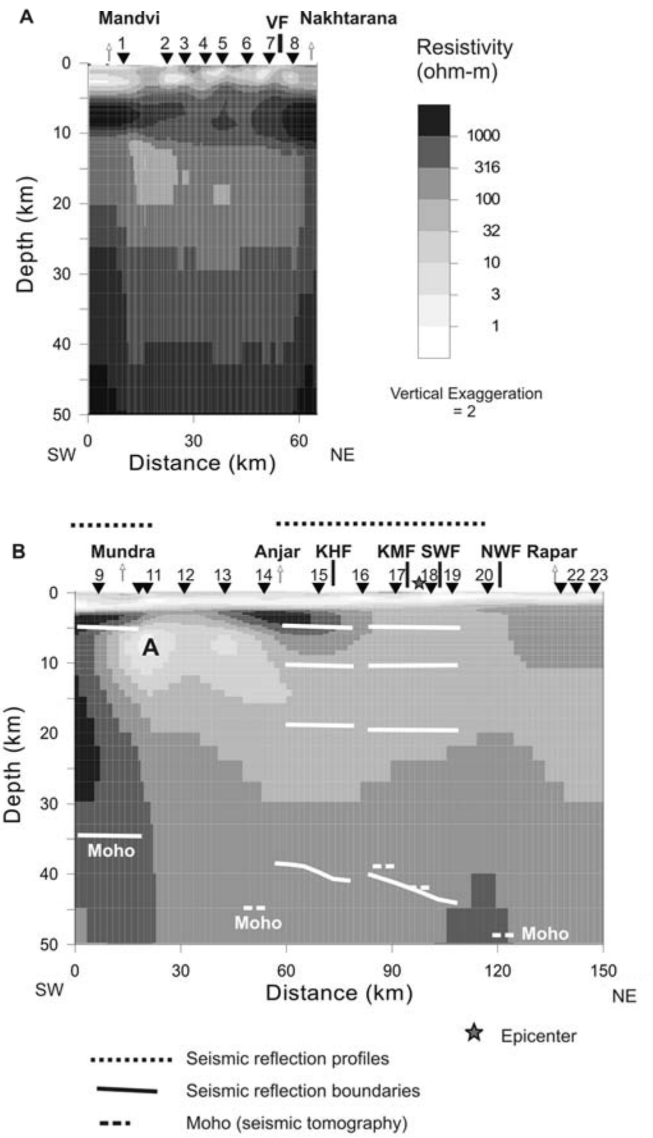

FIGURE 6 | **Geoelectric structure obtained for both the profiles from 2-D inversion of magnetotelluric data using the non-linear conjugate gradient algorithm of Rodi and Mackie (2001) shown along with geological faults. Prominent reflection boundaries as well as Moho obtained from passive seismological tomography studies are plotted.**

prominent feature ('A' in Fig. 6) is a 2-5 ohm·m conductor near stations 10-12 in the range of 6-10 km depth. The relevance and interpretation of these features is presented in the following sections.

Modeling and sensitivity analysis

Robustness of the MT models presented

The sensitivity analysis gives the required confidence over the features that were obtained in the inversion. The sensitivity values (Fig. 7) represent the sensitivity to small changes of resistivity. The sensitivity of the features in the models (Figs. 5 and 6) was tested with both linear and non-linear approaches. Values obtained by the linear sensitivity matrix were calculated using the code of Mackie et al. (1997) and are shown in Fig. 7 for both profiles. The structures with sensitivity matrix values of above 0.0001 are considered to be resolved features here following several other works like Brasse et al. (2002) and Ledo and Jones (2004).

Most of the Mandvi-Nakhtarana profile has sensitivity matrix values (Fig. 7A) above 0.0001 in the range of 0-35 km depth. The first 4 km layer has sensitivity values of more than 0.01. Between 5 and 10 km and below 35 km, the model presents lower sensitivity values, as expected, because these are resistive zones (Fig. 6A). The Mundra-Rapar profile has sensitivity matrix values above 0.0001 up to 50 km, in general. The top 3 km layer presents sensitivity values of more than 0.01. The conductor in the upper crust (Fig. 6) at 5-20 km depth is another resolved feature with sensitivity values in the range of 0.01-1. Less sensitive features are noticed for the high resistive zones, just below the basement at depths 3-6 km between stations 14 and 23 and also below 15 km depth near stations 9 and 10 (Fig. 7b) with values below 0.0001.

Non-linear sensitivity analysis was carried out to check the need for a conductive upper crust of 10 km thickness starting from 10 km depth in both profiles, as well as the need for feature 'A' (Fig. 6B). The procedure adopted for non-linear sensitivity and the results are briefly explained here. In this analysis, a value of 300 ohm·m was used, as this is a general representative value of the basement resistivity (Figs. 5 and 6). In the first step, in the Mandvi-Nakhtarana profile, the zone between 8 km and 36 km depth (Fig. 6A) was replaced with a 300 ohm·m layer whereas in the Mundra-Rapar profile, the zone between 4 km to 36 km depth (Figs. 5B and 6) was replaced with 300 ohm·m, and then forward modeling was carried out. Deviations from the responses of this model are observed in resistivity and phase data for both TE and TM modes. As an example, the results for TE phase for stations 5 and 12 are shown in Fig. 8 where the responses observed clearly indicate the conductive nature of the upper crust. In the next steps, the zones between 20 km and 36 km depth and between 10 km and 36 km depth were replaced successively with a 300 ohm·m layer for both profiles, and forward modeling was carried out. It is observed (Fig. 8) that when the zone between 20 km to 36 km is replaced with a resistivity value of 300 ohm·m, the deviation is minimal. Hence, it is concluded that the bottom depth of these conductors is around 20 km as observed in Fig. 6. Placing the 300 ohm·m layer at even deeper depths, i.e., from 24 km to 36 km resulted in minimum deviations again, but the objective here is to check if the model(s) obtained in the inversion are valid or not on a regional scale. Similar tests were carried out for feature 'A'. In the first step, all the cells with resistivity values of less than 10 ohm·m near feature 'A' were replaced with 10 ohm·m and forward modeling was carried out. The sensitivity analysis results (shown for station 11, Fig. 9) clearly indicate the need of conductive feature 'A' (Fig. 6B). Hence, it is believed that the features in the models are robust.

Testing the tomography hypothesis and geological models

As mentioned earlier, passive seismological studies inferred fluids in the range of 20-30 km depth and also a magma chamber between 20 and 40 km between the Katrol Hill Fault and the North Wagad Fault (Fig. 2). The existence of fluids and melt has been tested using non-linear sensitivity analysis with the following inputs:

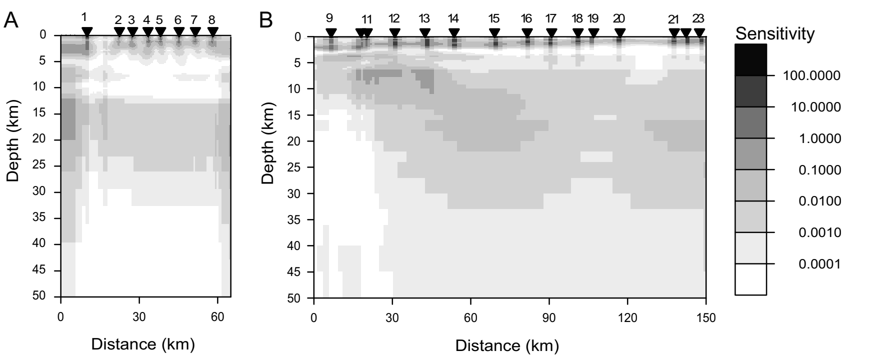

FIGURE 7 | **Contour of the normalized weighted columnwise sums of the sensitivity matrix for A) Mandvi-Nakhtarana and B) Mundra-Rapar profiles. This graphic represents the influence on the data to small perturbations of the logarithm of resistivity in each model cell.**

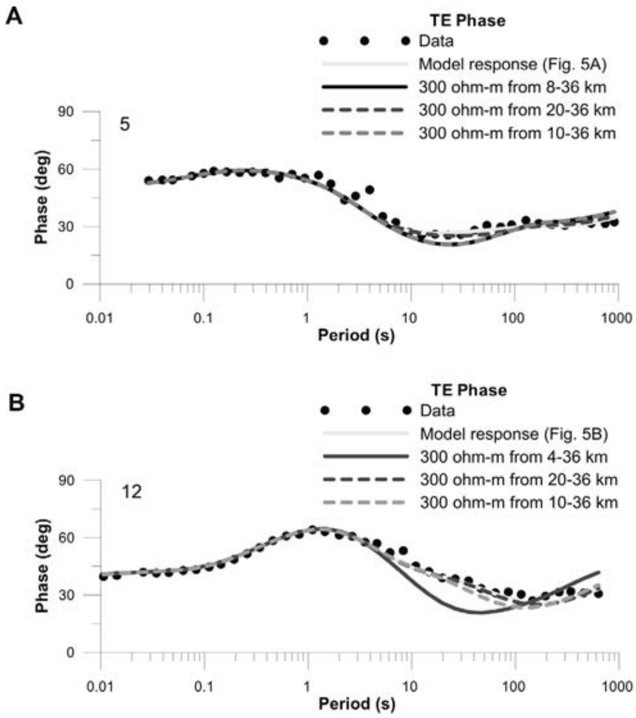

FIGURE 8 | **Comparison of TE phase between our final model (Fig. 6A) and alternative models with electrical resistivity of 300 ohm·m at various depth levels and varying thicknesses for A) station 5 on the Mandvi-Nakhtarana profile and B) station 12 on the Mundra-Rapar profile.**

Experimental studies showed that the maximum bulk resistivity of rocks containing fluids will be in the range of 1-10 ohm·m depending on the brine concentration and pressure conditions (Hyndman and Shearer, 1989). At deep crustal depths, with the temperatures around 500°C for normal magmatic salinities of 25 wt% or greater, brine conductivity is roughly 0.01 ohm·m (Nesbitt, 1993). Also, passive seismological studies have estimated that most parts of the study region have high porosity values (Mishra and Zhao, 2003). This implies that resistivity values in a range 1-10 ohm·m are suitable to explain the presence of fluids and melt, if exists.

Resistivity blocks with 1, 5 and 10 ohm·m were introduced in the final model obtained for the Mundra–Rapar profile at various depths (20-50 km) with varying thicknesses (4, 6 and 10 km) along the profile (Fig. 2). Several sensitivity analyses by forward modeling were done to determine whether data are compatible with the presence of these conductors or not. In Fig. 10, the TE phase data responses for conducting bodies of 10 ohm·m with thicknesses of 4 km and 6 km starting from 20 km and 24 km, respectively, are shown. The results of these tests indicate that no conductor at these depth levels is required. This can be seen in Fig. 10 where TE phases obtained from various model responses (Figs. 10B and C) misfit the data (Fig. 10B). Similarly, in Fig. 11, TE phase data responses for conducting bodies of 1, 5 and 10 ohm·m with a thickness of 6 km placed at a depth of 30 km are shown. The data do not support the presence of a conductor here either. A thicker block of about 20 km thickness as shown in the geological models with resistivity values ranging from 1

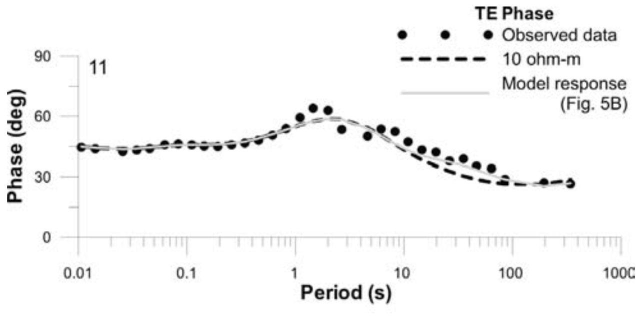

FIGURE 9 | **Comparison of TE phase between our final model (Fig. 6B) and alternative model with electrical resistivity of 10 ohm·m at feature 'A' on the Mundra-Rapar profile.**

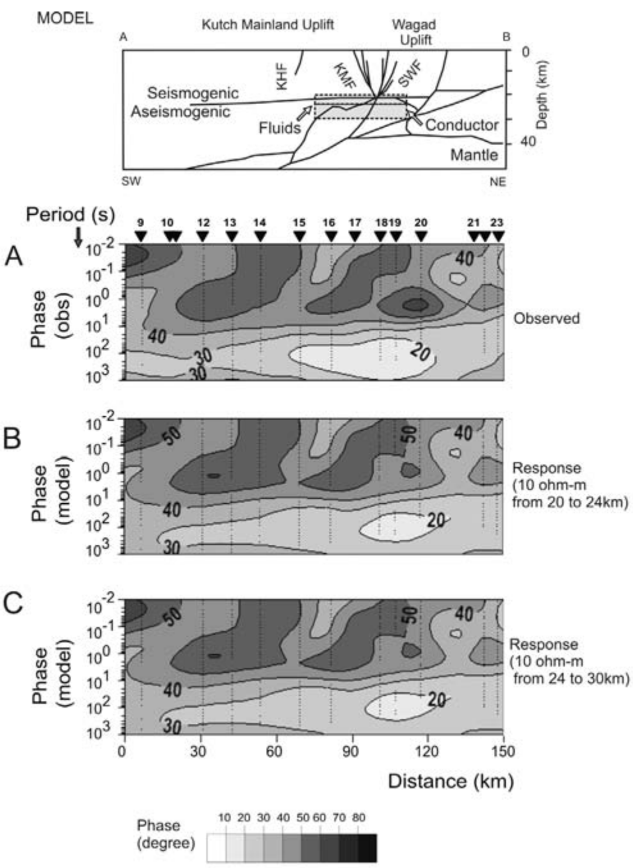

FIGURE 10 | **Observed phase (A)) and calculated TE mode phase responses (B) & C)) with conducting body of 10 ohm·m placed between B) 20-24 km zone and C) 24-30 km zone between the Katrol Hill Fault and the South Wagad Fault.**

to 10 ohm·m would make the fit much worse. Absence of a conductor at these depths is supported by 1-D models of a previous MT study (Arora et al., 2002) also, where it was observed that the region between 20 and 50 km depths has a resistivity of 200 - 2,000 ohm·m.

RESULTS AND INTERPRETATION

For the interpretation of the shallower section, earlier results (Gupta et al., 2001; Chandrasekhar and Mishra, 2002; Mishra et al., 2005; Sastry et al., 2008) and geology were taken into consideration which led to the following conclusions: The less resistive 20-60 ohm·m top layer on both profiles is interpreted as Deccan Traps and its thickness increases towards south up to 1.5 km (Fig. 5). Another resistive (200-1,000 ohm·m) layer at about 3-5 km depth corresponds to the basement. The conductive layer sandwiched between these layers is of Mesozoic sediments. The Mesozoic sediments are more conductive than the Tertiary sediments. The basement depth increases from north (about 2.5 km depth) to south (about 3 km depth) indicating thickening of the Mesozoic sediments in the southern direction. The basement along the Mundra-Rapar profile has less variation in terms of basement depth (2-3 km) and the Mesozoic sediment thickness is of about 1 km. The general basement trend is gentle dip towards the south (Fig. 5). These results have an excellent correlation with the known geology and passive seismological interpretation (Mandal, 2006) of low velocity (1.8-2.5 km/s) sediments in the shallow depths (< 4 km). The low resistive feature between 6 and 20 km depth (Fig. 6) is interpreted as fluids with some mineralization (discussed later). The lower crust (20-40 km) is less resistive (100-500 ohm·m). It should be noted here that earlier geochemical studies carried out by Karmalkar et al. (2005) on the primitive alkaline rocks from Kutch show that these rocks are similar to those of ocean-Island basalts. These alkaline rocks entrain spinel-peridotite xenoliths of mantle origin. Presence of garnet is also inferred. Hence, Karmalkar et al. (2005) suggest that rocks in the lower crust are basalts (generated from partial melting of metasomatised garnet peridotite at mantle/lithosphere depth) and their composition was modified by reaction with the spinel-peridotites of the overlying lithosphere. The increase in seismic velocity supports the presence of garnet, whereas the absence of a conductive anomaly in the lower crust indicates that the partial melting/magma chamber is probably situated at even deeper depths in the upper mantle.

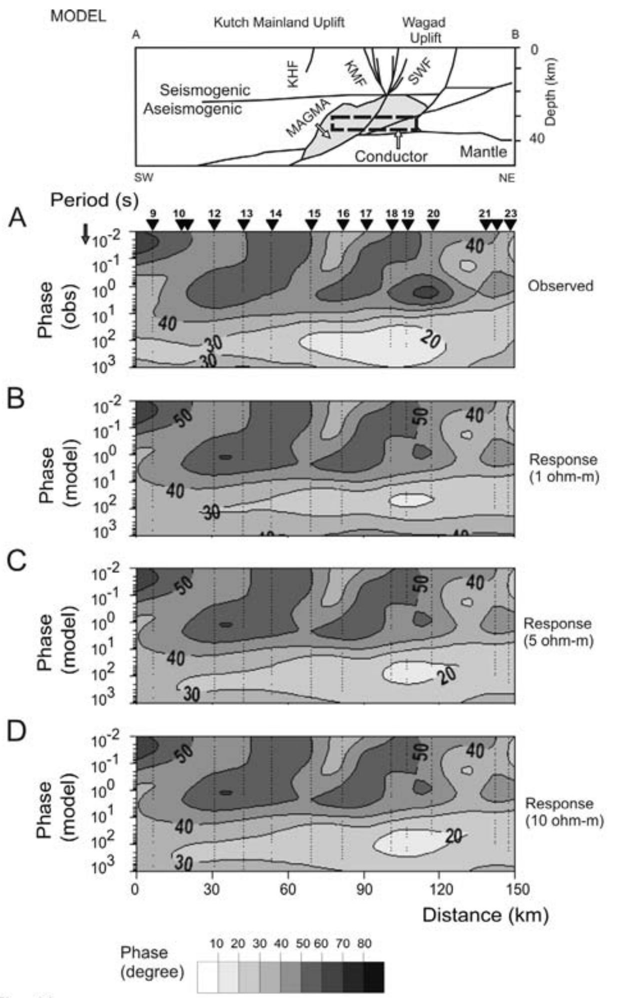

FIGURE 11 | **Observed A) and calculated TE mode phase responses of conducting bodies of B) 1, C) 5 and D) 10 ohm·m. The conductors are placed at a depth of 30-36 km between the Katrol Hill Fault and the South Wagad Fault.**

DISCUSSION AND CONCLUSIONS

Basement undulations and upper crustal fluids

The basic trend along these two profiles is that the basement becomes shallow northward (Fig. 5). The thickness of the Mesozoic sediments is about 1-2 km along both profiles. The resistivity and thickness of the Deccan Traps are in the range of 20-60 ohm·m and 0-1.5 km. Several undulations in the basement are observed in both profiles. The observed low resistivities are due to the fact that all the sediments – Mesozoic, Tertiary and Quaternary – are of marine origin (Biswas, 1987). The increase in basement depth from the Mundra-Rapar profile to the Mandvi-Nakhtarana profile in the southern part of the profiles indicates that the Kutch basin slopes towards the southwest. Well data (Srinivasan and Khar, 1995), geological model showing uplift of northern margin of KMU and a southward tilt (Biswas, 1987) and the present MT models indicate that the thickness of sediments should further increase southwards into the Gulf of Kutch up to North Kathiawar Fault (NKF).

Feature 'A' (Fig. 6B) on the Mundra-Rapar profile is a high conductivity body associated with a fault zone whose north-western extension is not observed on the Mandvi-Nakhatarana profile. Another significant aspect that needs an explanation is the presence of a low resistive (< 50 ohm·m) feature at depth levels between 10 and 20 km (Fig. 6). Other geophysical observations are: 1) a moderately high seismic Vp anomaly of 5.65-6.31 km/s between 6 km and 20 km depth (Mandal et al., 2004a), 2) low seismic activity/aftershocks (only 11% of total) below 20 km depth (Mandal et al., 2004a), 3) the temperature-depth profiles calculated from available heat flow data estimate temperatures of 150ºC at the top of the conductor (6 km) and 450ºC - 600ºC at its bottom (15-20 km) (see Pandey and Agarwal, 2000; Sharma et al., 2005), and 4) presence of several gravity highs in the Kutch region. All these observations were considered when interpreting the deep upper crustal structure in the depth levels of 5-20 km.

High electrical conductivity anomalies can be explained by the presence of fluids, partial melting and/or conductive mineral phases (Jones, 1992 for a review). High conductivity in mineral phases depends on their composition and interconnection level. Major faults in the Kutch region have exhibited repeated reactivation (Biswas and Khatri, 2002). The Kutch Mainland Fault and the Island Belt Fault are active faults and are associated with two previous major earthquakes in the region (Anjar and Allahbund earthquakes). The presence of fluids can be expected because of repeated reactivation of the faults in this region. However, fluids alone make it difficult to explain the large volume of the conductor because the upper crust contains nearly vertical and oblique faults in general. In such a case, fault tectonics cannot cause a significant effect on the overall electrical conductivity and result in a more complex block structure. Even if one considers fluid circulation along such faults, no interconnected conductive network can be created (Popov et al., 1999). The hypothesis of partial melting can be rejected, as it commonly needs a minimum temperature of 700ºC (Thompson, 1992). However, 700ºC is significantly higher than the values estimated from heat flow data (see Pandey and Agarwal, 2000; Sharma et al., 2005). Therefore, in such a scenario, the shallow and upper crustal electrical conductivity depends mainly on rock composition. In case of graphite, it forms thin films that are easily interconnected; whereas for other conducting minerals (e.g., pyrite and pyrrhotite) an additional mechanism is required to enable their interconnection. Fluids spread over the massive sulphurs would provide such an interconnection. Although these fluids are subsequently released, the interconnected matrix and, as a result, the high conductivity, can be present. High seismic velocities, several gravity highs in the Kutch region and associated low seismicity/aftershocks in this depth range indicate rocks hosting these conducting minerals must be basic or ultrabasic rocks, such as ophiolites (e.g., gabbro) or peridotites. The alkaline basaltic intrusions in the central Kutch region consist of peridotite xenoliths of mantle origin (De, 1964; Krishnamurthy et al., 1989; Karmalkar et al., 2005) which could produce gravity highs. Hence, this low resistivity can be attributed to fluids and conducting mineral phases. Since, in the upper crust, generally, porosity will be low and the grains will be rather poorly connected when compared to the lower crust, the existence of fluids and a conducting mineral phase may be justified with the observed resistivity values. Also, these depths are comparable to boundaries identified by seismic reflection studies (Sarkar et al., 2007). Our findings are consistent with the earlier MT surveys on the Kurduvadi rift feature in the Deccan Trap region (further south-eastern direction from the study region), where Gokarn et al. (1992) reported presence of fluids at a depth of 12-18 km.

Fluid content in the lower crust

Passive seismological studies (Mandal et al., 2004a) have observed high Vp, low Vs and high Poisson's ratio in the depth range of 20-30 km and explained this anomaly as a fractured and fluid filled (saturated rock) matrix. According to Mandal et al. (2004a, 2006) the source for these fluids could be aqueous fluids released from metamorphic dehydration reactions and/or trapped melts due to Deccan volcanism. This can be negated in two ways: 1) in high metamorphic grade rocks, fluids at temperatures greater than 500°C must be absorbed in mineral hydration reactions (Stevens and Clemens, 1993); 2) also, the data of the present study are not compatible with any conductor in the earthquake hypocentral zone, hence it is inferred that the hypocentral zone of the Bhuj earthquake is devoid of fluids. However, if the rock matrix interconnection is poor at these depth levels in the lower crust, then one cannot expect a decrease in electrical resistivity. In such a case, calculation using Hashin and Shtrikman (1963) approximation (for normal salinities of 25 wt % at temperatures greater than 500ºC and normal brine resistivity of 0.01 ohm·m) shows that less than 0.02 % porosity is required for the observed deep crustal electrical resistivity values of 100-500 ohm·m. Our results are coincident with the Kurduvadi rift feature results (Gokarn et al., 1992) where the lower crust and the upper mantle resistivity is about 100 – 1000 ohm·m. The estimated porosity values here are very low / negligible. Hence, we do not think that there are enough fluids in the lower crust to generate an earthquake or to produce electrical resistivity anomalies.

Absence of magma in the lower crust

Biswas (2005) advocated a magma chamber at lower crustal depths in the Kutch region. Mandal et al. (2004a,

b) suggest a regional high velocity body (Vp 7.0-8.5 km/s) at 10 - 45 km depth. The body is interpreted as a mafic intrusive/rift pillow structure (Mandal et al., 2004a, b). MT forward sensitivity tests indicated that the MT data do not require a conductor of 10 ohm·m in the deep crustal depths. Low phase values in the longer period data in the region between 60 km to 125 km on the Mundra-Rapar profile (Fig. 10A) indicate a deep high resistive body. One can infer the same from the 1-D models of Arora et al. (2002). It is also interesting to mention here that the passive seismological studies (Mandal, 2006) have shown a low velocity zone at depths of 18-37 km. This low velocity zone is present at 5 stations (3 in Kutch and 2 in Saurashtra) out of a total of 8 tomographic stations (5 in Kutch and 3 in Saurashtra). The absence of a conductor at these depths as shown in the present MT study indicates the absence of a magma chamber at lower crustal depths. Deccan volcanism took place in the time interval of 64-68 Ma. Hence, melts cannot exist in the partially molten state for several million years but must crystallize in a few thousand years. Besides, there is also evidence for passive mechanism of rifting over active type (see Biswas, 1987; Chand and Subrahmanyam, 2003). Passive rifting results in only thin underplating or even absence of underplating. Supporting results were obtained indicating absence of underplating near the western coast of the Indian continental margin (further SSE of the study region) using passive seismological studies (Mohan and Ravi Kumar, 2004). Also, seismic reflection studies (Sarkar et al., 2007) inferred that there are no offsets in the crust-mantle boundary associated with deep mantle faults. Presence of garnet should be required to increase seismic velocities for depths greater than 30 km (Wannamaker, 2003). Recent studies from the southern Rio Grande rift, New Mexico, showed that high seismic velocities (> 7.0 km/s) and heat flow anomalies can lead to a misleading interpretation of underplating when only geophysical data are taken into account. These anomalies can be explained by the lower crust containing meta-sedimentary rocks with alternating garnet-rich and garnet-poor rocks (Hamblock et al., 2007). They further advocated employing studies on xenoliths and regional geology (Hamblock et al., 2007) before any conclusions can be made on underplating. The same situation is not inferred here, but a similar situation may be possible. All these findings suggest that the interpretation of existence of magma chamber needs some other specific evidence.

The suggested plume activity, low seismic velocity in the upper mantle and high heat flow (see Mandal, 2006) may favour partial melting in the study region. The present study infers that if partial melt exists, it will not be in the crust, but in the upper mantle.

Possible causative factor(s) for the 2001 Bhuj earthquake

The focal depths of major earthquakes of magnitude over M_w 7 in the Kutch region are deeper than 15 km. Based on the model sensitivity tests explained in the previous section and available geological and geophysical information in the region, an attempt is made here to discuss some of the possible causative factors that might have triggered the 2001 Bhuj earthquake.

The occurrence of lower crustal intraplate earthquakes can be explained by one or a combination of the following factors which we assess in conjunction with our MT results:

1) Instability owing to magma (partial melt) movements (Young et al. 1991): Melts would, however, produce anomalous conductivity which is not compatible with the observed MT data.

2) Large crustal stress concentration or deepening of the base of the seismogenic depth due to mafic intrusives (Mackwell et al., 1998; Nyblade and Langston, 1995): This is similar to the model proposed by Mandal (2004a, b). This is explained by formation of a magma chamber (Fig. 2) in the geological model (Biswas, 2005). However, existence of magma chambers causes high conductivities, so this cause can be rejected too.

The other possibilities like a) strike-slip frictional failure on brittle crustal faults (Sibson, 1998), b) Ductile lower crust (Nyblade et al., 1996), c) reactivation of rift structures in response to present day plate tectonic forces (Johnston, 1996) and d) sudden movements along the existing faults due to changes in local stress regime (Sykes, 1978) etc., were not discussed as our data cannot provide relevant input.

Further, it is concluded that there could be similarities between (several) rift related deep continental earthquake prone zones – the Kutch, the Kenya and the Reelfoot rift – but the causes for the occurrence of earthquakes in these zones are not similar and may be case dependent. Since the region is active, further efforts should be made to obtain detailed electrical resistivity, seismic velocities, studies of mantle xenoliths etc. to better constrain the physical state of the crust and lithosphere/upper mantle.

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