# Magnetotelluric study to characterize sediment thickness across Kachchh and Cambay rift basins, western India

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**The Kachchh and Cambay rift basins are two pericontinental rift basins at the western continental margin of India (WCMI), which evolved during different stages of the Mesozoic era. Magnetotelluric measurements were carried out at 68 stations along four east–west trending profiles across these basins with an aim to infer basement configuration and sediment thickness. The data were analysed for galvanic distortions and decomposed into transverse electric (TE) and transverse magnetic (TM)-modes by rotating the impedance tensor into corresponding geoelectric strike directions of the four profiles. The decomposed data responses were then inverted using a nonlinear conjugate gradient algorithm. The top conductive layers (~2500–7500 S) across the Kachchh and Cambay rift basins indicate the presence of Cenozoic sediments and Deccan traps, which corroborates the results of earlier geophysical studies across these basins. The sediment thickness is low across Diyodar and Tharad ridges compared to the Sanchore, Patan and Mehsana sub-basins. A high conductive zone near Mehsana may support the evidence for the presence of Mesozoic sediments beneath traps as inferred from a deep seismic sounding (DSS) study. Even though the Oil and Natural Gas Corporation Limited (ONGC) drilled wells and DSS study reported the presence of Mesozoic sediments beneath the traps near Tharad ridge, their presence here is not clear from this study. Igneous intrusives and a Precambrian Aravalli–Delhi fold belt are delineated on either side of the Cambay rift basin. The electrical resistivity variations across these basins lead to the inference that the subsurface structure is highly heterogeneous in nature due to faults within the rift basins.**

**Keywords:** Cambay rift, Deccan traps, Kachchh rift, magnetotellurics, sediment thickness.

MAGNETOTELLURICS (MT) is a natural source electromagnetic method, which utilizes measurements of the earth's electric and magnetic field variations in orthogonal directions. These measurements can then be used to characterize the crust and mantle structures in terms of electrical resistivity/conductivity variations. The MT method has been effectively used in various parts of the world for shallow resource exploration, imaging the imprints of tectonic and geodynamic processes, geological evolution and also subsurface structures beneath resistant layers such as traps[1].

The western continental margin of India (WCMI) is a tectonic unit that contains three marginal rift basins, namely, the Kachchh, Cambay and Narmada basins respectively, referred to as KRB, CRB and NRB hereafter. This region has undergone two major geodynamic events, namely, the interaction of the lithosphere with Reunion plume and the Indo-Eurasian continental plate collision. The plume–lithospheric interactions have resulted in significant basaltic eruptions, which are popularly known as the Deccan volcanic province (DVP) and subdued initial rifting effects. Quaternary and Tertiary sediments were deposited on top of the Deccan traps through various transgressive and regressive cycles[2]. The stratigraphy of the basins thus consists of Cenozoic (Quaternary and Tertiary) sediments at the top, Deccan traps, Mesozoic sediments in the middle and Precambrian crystalline basement at the bottom[3].

Deep seismic sounding (DSS)[4] studies were carried out along North Cambay and Sanchore sub-basins of CRB to map the basement and its crustal structure. These studies revealed details about the thickness of Tertiary sediments and Deccan traps, and positive evidence for the occurrence of Mesozoic sediments beneath the traps. In addition, gravity and magnetic studies[5] were carried out along CRB and integrated with DSS studies[4] to further image its crustal structure. The crustal structure of CRB comprises various sub-basins within CRB, bounded by the fault controlled ridges and depressions. Previous MT studies were conducted across KRB[6] and Sanchore sub-basin of CRB[7] to study the impact of Reunion plume on lithospheric structures and source mechanisms involved in the generation of earthquakes within the rift basins.

Although a number of geophysical studies were carried out across CRB and KRB, there has been no proper attempt to study the basement configuration and sediment thickness through electromagnetic studies. We have carried out a detailed MT study across KRB and CRB along the four east–west (E–W) trending traverses as shown in Figure 1 and the collected data from 68 stations were processed and modelled to characterize basement configuration and sediment thickness. This study also provides some insights regarding the presence of Mesozoic sediments beneath the Deccan traps.

The rift basins (KRB, CRB and NRB) of WCMI evolved during the northward drift of the Indian subcontinent through various stages during Mesozoic. These basins are bound by a number of intersecting faults controlled by three Precambrian tectonic trends-forming horsts and grabens within the basins. As a result, WCMI exhibits a complex structural fabric[8]. These rift basins show varying thickness of Mesozoic sediments. Among these basins, KRB has the longest record of sedimentation during Mesozoic era starting from Late Triassic to Lower Cretaceous. Thick accumulation of sediments

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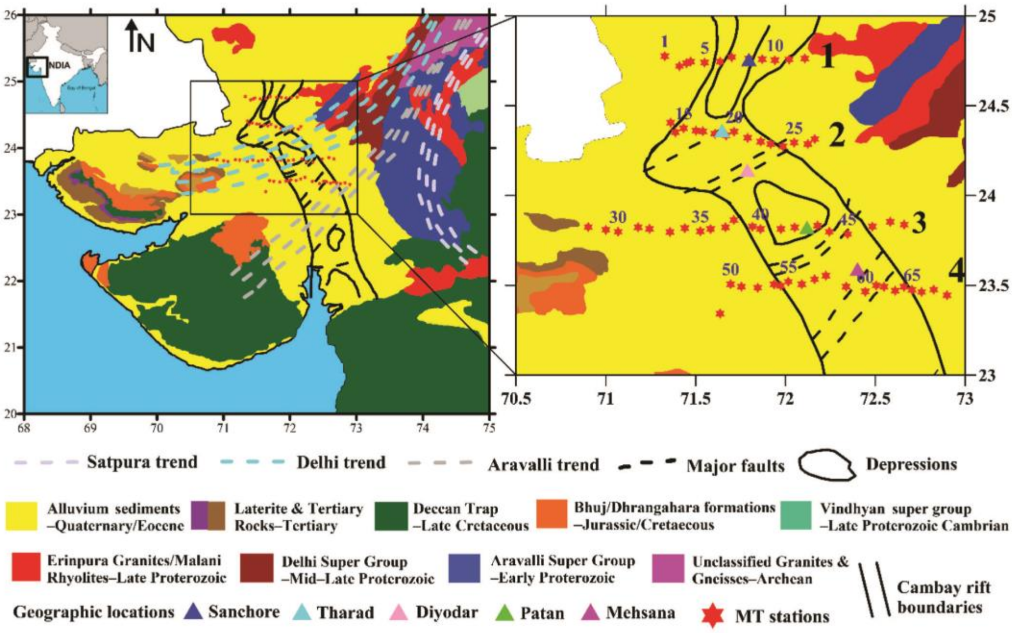


**Figure 1.** A regional geological map of western continental margin of India (WCMI). In the inset, it shows MT profiles indicated with numbers 1–4. Coloured triangles indicate geographical locations within CRB. The MT stations are denoted using red stars.

deposited through major transgressive and regressive cycles are observed here[2,8]. Carbonates and shales were deposited during transgressive cycle, whereas deltaic clastics were deposited during the regressive cycle[2]. The Mesozoic sediments were folded, intruded and uplifted during a Deccan trap eruption in the Late Cretaceous–Early Palaeocene, at which period volcano-clastic sediments accumulated[2,3]. Adjacent to and between Mesozoic highs and lows of the basin, Early Eocene tectonic movements, transgression and Tertiary deposition, occurred as confirmed by unconformities in the stratigraphic column.

Several drilled wells in CRB have penetrated the fluvio-deltaic sedimentary sequence of Lower Cretaceous age[2]. At the initial stages of rifting, thick volcano-clastic sediments were deposited in the Tertiary sequence[2,3]. Dark shales were deposited through marine sedimentation during an Early Eocene transgressive cycle at the subsidence stage of the basin and was followed by deltaic and lagoonal sedimentation in intra-basinal lows during oscillatory stages. In the Miocene, the rocks of CRB were covered by thick alluvial sedimentary deposits deposited during extensive marine transgression event. Based on the seismic studies across CRB, some researchers[2] conclude that Mesozoic sediments of thickness up to ~1.2 km may possibly be present beneath Deccan traps which form the floor of a thick Tertiary sedimentary sequence of ~5 km.

The DSS[4], gravity and magnetic[5] studies report that the thickness of Tertiary sediments varies from 2 to 3 km over the ridges and 5 to 6 km in the trough zones and are underlain by Deccan traps and Mesozoic sediments in some parts of CRB. A previous MT study[6] inferred the presence of thick (~2–4 km) Cenozoic and Mesozoic sediments and emphasized the role of deep crustal fluids in the generation of intraplate earthquakes within the fault systems of KRB. Another MT study[7] across CRB inferred the presence of thick (~1–5 km) Tertiary and Quaternary sediments, as well as evidence for magmatic underplating and partial melting.

A total of 68 stations of broadband MT data (period range of 0.003–3000 s) were acquired along four profiles across KRB and CRB in order to characterize the sediment thickness (Figure 1). The electric and magnetic field variations were measured using 60 m orthogonal dipoles with nonpolarizable Pb/PbCl electrodes and induction coil magnetometers respectively. The time series data were processed using robust remote reference techniques[9,10] to estimate impedance transfer functions. The period range of this study was 0.001–10 sec.

The multisite and multifrequency algorithm of McNeice and Jones[11] was applied for estimating appropriate geoelectric strike direction for the four individual profiles. The geoelectric strike directions obtained for the profiles 1 to 4 are N5°E, N12°W, N0°E and N59°E respectively. The pseudo sections obtained from the original data of the four profiles are shown in Supplementary Figures 1 and 2. At majority of the stations, the maximum phase split between *XY* and *YX* directions of impedance data was less than 10° for the period range of this study. This indicates that at these stations the subsurface appears to be one dimensional (1D) in nature, and thus

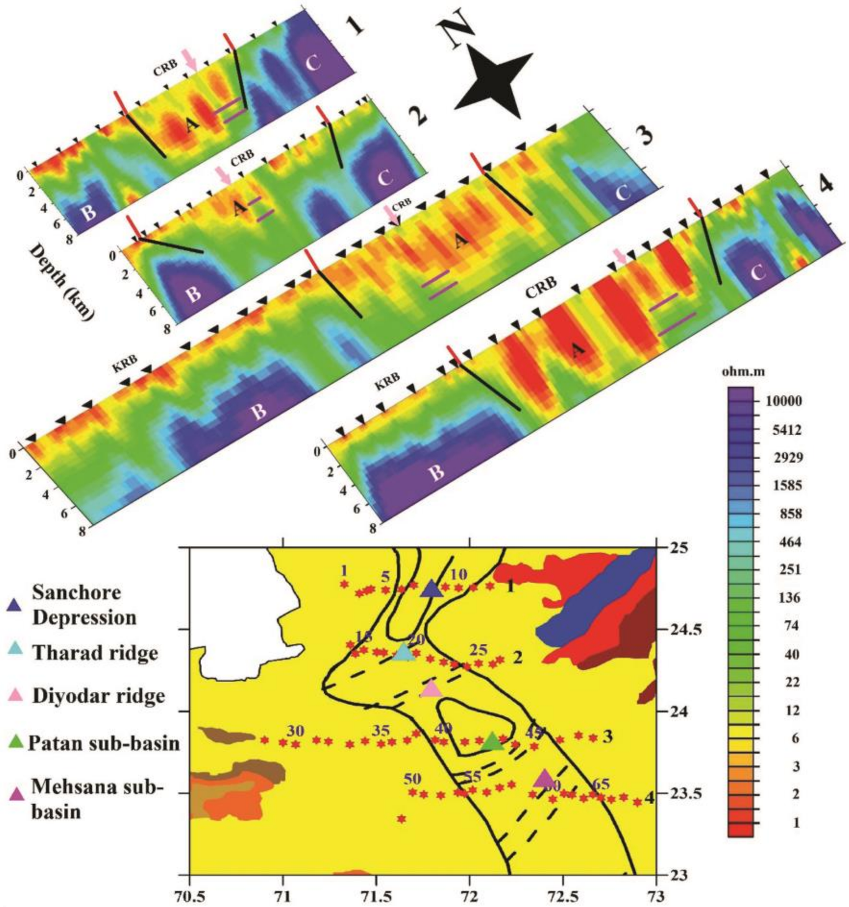


**Figure 2.** Geoelectric models obtained from 2D inversion along the four profiles of west–east direction. Major conductive and resistive blocks are marked with letters A, B and C. In the bottom part, a geological map is shown with MT profiles and major geographic locations of the study area are indicated with triangles (see Figure 1 for legend of a geological map). The red lines indicate margins of rift basins, black solid lines on the inversion models indicate the extension of marginal faults of CRB. The rose arrows indicate coincident locations of DSS and present MT study. The two purple horizontal lines indicate thickness of the Deccan traps obtained from DSS study[4].

the scatter of the estimated geoelectric strike angle does not play any significant role in the impedance rotation at these stations[12]. Maximum phase splits are observed at few stations in the eastern part of the profiles (which can be seen in pseudo sections shown in supplementary figures), where the geoelectric strike angle may be controlled by regional structural discontinuities, for example, large scale faulting. The large difference in the strike angles estimated from profile 2 (N12°W) and profile 4 (N59°E) could be due to the northwestward turn of CRB at Tharad ridge and a major deep-seated NE–SW fault near Mehsana respectively. The depressions of Sanchore and Patan basins resulted in similar strike angles (N5°E and N0°E) obtained for profiles 1 and 3. Though data at majority of the stations are 1D in nature, the two dimensional (2D) nature of the data at the remaining stations may have an effect on the results obtained by 1D inversion/modelling. To avoid these effects, we have opted for a 2D inversion scheme. The individual impedance tensor data for each of the profiles were rotated into corresponding geoelectric strike directions by assuming that the response functions parallel and perpendicular to strike directions represent TE- and TM-modes respectively. The decomposed TE- and TM-mode responses were inverted using a nonlinear conjugate gradient algorithm[13]. The inversions were carried out with a 100 Ωm homogeneous half-space as an initial model and 7 as the appropriate regularization parameter. The apparent resistivity and phase error floors used in the inversion scheme were 15% and 10% for TE-mode and 10% and 5% for TM-mode respectively, to obtain the geoelectric models shown in Figure 2. Since TE-mode data was more sensitive to three dimensional (3D) effects than TM-mode data, more emphasis was given to TM-mode. The higher weighting for phase-over resistivity data helps to overcome possible static shift effects in the data, if any[14]. Vertical magnetic field (Hz) data were included in the inversion process after 70 iterations and an absolute error floor of 0.025 was fixed in the inversion scheme. The data fit at a few stations are shown in Figure 3.

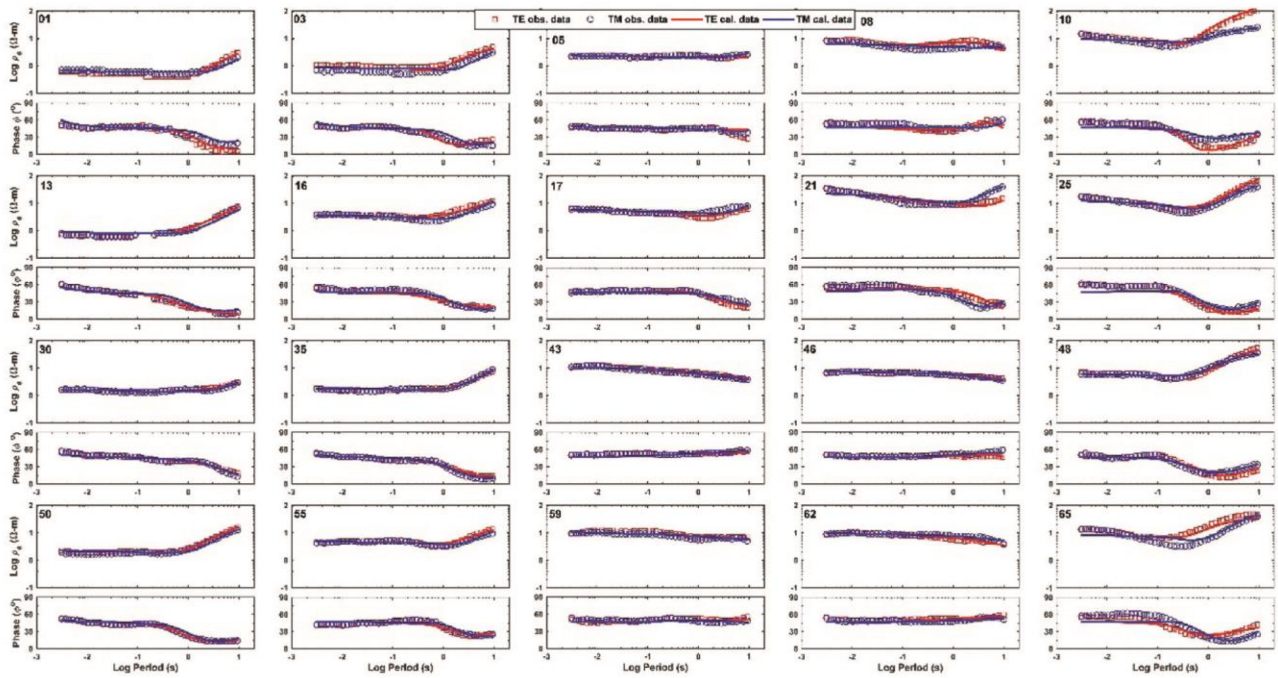


**Figure 3.** 2D inversion data fit between the observed and modelled responses for a few stations. The station numbers are given on the top left side of the resistivity plot panel.

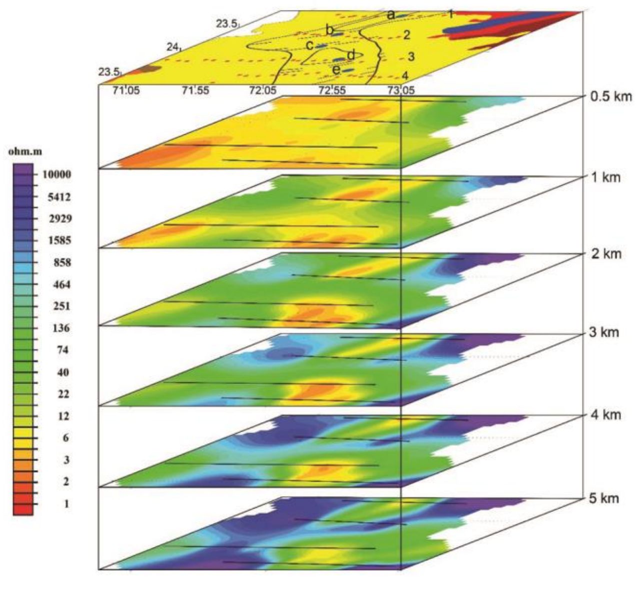


**Figure 4.** The depth slices (depths are given at the left side of each slice) obtained from inversion models are shown here. The geological map of the four profiles is marked on the top side. The letters a, b, c, d and e indicate Sanchore depression, Tharad ridge, Diyodar ridge, Patan and Mehsana sub-basins respectively.

Using the geoelectric models (Figure 2), the resistivity variations were contoured at various depths over the study area. The contour maps at 0.5–5 km depths are stacked together to infer the varying sediment thicknesses of the rift basins as shown in Figure 4.

The major conductive and resistive layers/structures across the MT profiles are denoted using letters (A, B and C) in Figure 2 and their details are discussed here. The conductive top layer A (1–10 Ωm) exhibits varying thickness beneath the four independent profiles. In general, the thickness of conductive layers and their individual conductivities may not be accurate from MT studies. In contrast, the conductance, i.e. the conductivity thickness product, of conductive layers and the bottom of resistive layers are well-determined parameters in MT studies. The conductance of layer A varies from ~400 to 2000 S on the west side, whereas beneath CRB it varies from ~1000 to 7500 S. Conductive layer A is overlain by a moderately resistive (~40–250 Ωm) layer. The high resistive (~5000–10000 Ωm) structures B and C are located on both sides of CRB.

The DSS[4] study along CRB delineated four sub-basins in its northern part, namely, North Sanchore, South Sanchore, Patan and Gandhinagar sub-basins. This study estimated trap thicknesses of ~0.5–1.5 km and basement depths of ~5–5.8 km, 6 km and 6.2–7.7 km beneath Sanchore, Patan and Gandhinagar sub-basins respectively. It also observed that very thin Mesozoic sediments existed beneath the traps in South Sanchore and Patan sub-basins of CRB. In the other sub-basins, chances of their occurrence were reported as affirmative, except in the northern part of Sanchore basin. Wells drilled by Oil and Natural Gas Corporation Limited (ONGC) in the Sanchore sub-basin near Tharad ridge showed the presence of Mesozoic sediments beneath Deccan traps and these observations were consistent with the results of DSS study[4]. The other wells between Diyodar and Mehsana terminated within the traps at a depth range of ~2–3 km and therefore could not confirm the presence of Mesozoic sediments beneath Deccan traps. However, gravity and magnetic studies[5] along CRB reported varying sediment thicknesses of 2–3 km over the ridges to 5–6 km in the troughs and supported the presence of Mesozoic sediments beneath the Deccan traps. Previous MT studies[6,7] have delineated a conductive layer (~100–500 S) beneath KRB and CRB indicating the presence of Cenozoic and Mesozoic sediments. MT method can give a reliable depth estimate regarding the top of a conductive layer, but it is not always possible to delineate its base. In such instances, it is hard to determine the thickness of Cenozoic sediments overlying the Deccan traps. Thin traps of moderate resistivity (~20–50 Ωm) may go undetected when the thick conductive (~1–5 Ωm) Cenozoic sediments overlie the traps[15,16]. If thin Mesozoic sediments are present beneath the traps, it will be difficult to estimate the thickness of individual sedimentary and trap formations. Due to insufficient conductance contrast between sediments and traps, our MT study may image these different layers as a single high conductance layer. The thickness of Cenozoic sediments and Deccan traps estimated from the DSS study along CRB is marked on the inversion models. The conductance of layer A (~1000–7500 S) in Sanchore depression and Patan and Mehsana sub-basins indicates thick Cenozoic sediments. The variations observed in the conductance of layer A from inversion models indicate that the thickness of the traps and sediments are not uniform beneath CRB. Discrimination between Deccan traps and Cenozoic sediments can be clearly seen in some parts of the profile, especially at locations where DSS[4] and the present MT profiles meet. At these coincident locations, the conductive layer A is followed by a layer with resistivities of ~20–40 Ωm at depths of 4–6 km, which in turn is underlain by a basement (~200–1000 Ωm). Conductive layer A represents Cenozoic sediments and a deeper moderately resistive (~20–40 Ωm) layer indicates Deccan traps. The delineated sediments and traps from the present study show good correspondence with DSS study[4] at the coincident locations of both studies. However, other parts of the profiles do not show such agreement, due to lack of adequate conductance contrast between these units. The Cenozoic sediments and Deccan traps are imaged beneath CRB as a single conductive layer A or two different layers depending on the conductance contrast between them. However, presence of Mesozoic sediments cannot be confirmed from the present study alone without the evidence from DSS study and drilling information. Our study infers that the thickness of Cenozoic sediments and Deccan traps are not uniform beneath the rift basins. The thickness of Cenozoic sediments and Deccan traps reported from our study corroborates with the estimates of earlier DSS[4], MT[6,7], gravity, and magnetic studies[5,17] carried out over CRB and KRB.

The thick conductivity layer (~7500 S) near Mehsana in profile 4 may support the hypothesis for the presence of Mesozoic sediments as inferred from DSS study[4], but this needs further confirmation by drilling. Though DSS study[4] and ONGC wells drilled near Tharad ridge report the presence of Mesozoic sediments beneath the traps, their presence is not clear from the present study. In Figure 4, the conductive layer is extending up to 5 km beneath the profiles 3 and 4 indicating a depression in CRB, whereas the resistive layer beyond 3 km near profile 2, marks the Diyodar and Tharad ridges with basement uplift. Variations in sediment thickness and basement depth in Figure 4 indicate that the subsurface structure is heterogeneous due to the presence of faults and indicate ridges and troughs within CRB. The ridges and troughs delineated from the present MT study coincide with inferences from DSS[4], gravity and magnetic[5] studies. The conductive structures in CRB extend up to 5 km depth and on both sides of CRB they are limited to 2–2.5 km, below which are the resistive structures. The faults of CRB margins extend to basement depths beneath the four profiles as shown in Figure 4.

The resistive structure (B) on the west side of the profiles may be due to intrusive igneous rocks. Gravity and magnetic studies[18] reported the presence of igneous intrusives beneath the recent sediment cover in structural lows of the rift basins. Previous MT studies[6,7] across KRB and CRB reported the presence of igneous and alkali basaltic intrusive rocks which represent the distribution of polyphase metamorphic rocks and support the imaged resistive feature (B). They also suggested that these are the remnant signatures of earlier magmatic activities.

The resistive structure (C) on the eastern side of the profiles indicates Precambrian rock formations of the Proterozoic Aravalli–Delhi fold belt overlying Archean basement. Structure C represents one of the oldest orogenic cycles of fold belts in western India and has witnessed four major tectono-magmatic and metamorphic events between ~3000 and 750 Ma (ref. 19), which forms the eastern margin of CRB. The major fault systems of the rift basins were controlled by the reactivation of orogenic trends.

Our magnetotelluric study has identified a thick conductive layer (~2000–7500 S) across KRB and CRB which is followed by a basement layer with resistivity ~200–1000 Ωm. The thick conductive layer represents the presence of Cenozoic sediments and Deccan traps which corroborates previous geophysical studies across the rift basins. The thick conductive zone near Mehsana may support the hypothesis of the presence of Mesozoic sediments as inferred by an earlier DSS study. Though DSS study and the wells drilled by ONGC reported the presence of Mesozoic sediments beneath the traps near Tharad ridge, these have not been detected in the present

MT study. The sediments beneath Sanchore, Patan and Mehsana sub-basins are much thicker and comparatively less thicker over Diyodar and Tharad ridges. The resistive blocks on the western margin of CRB represent igneous intrusives whereas on eastern margin, they indicate the Precambrian formations of the Aravalli–Delhi fold belt. The electrical resistivity variations across these basins infer that the subsurface structure is highly heterogeneous in nature, due to the faults within the rift basins. Thus the results of our MT study together with other geophysical studies and well data, may further refine the sediment thickness estimates across the rift basins.


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# Retreating rate of Chaturangi glacier, Garhwal Himalaya, India derived from kinematic GPS survey and satellite data

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**The regular monitoring of glaciers is important to determine their retreating rate and mass balance for overall glacier health. Chaturangi glacier, a major inactive tributary of the Gangotri glacier system was selected for the present study due to its dynamic nature and also because there are no previous records of its retreating rates. In order to reconstruct past retreating rates, total area loss, volume change and shift in snout position were measured through multi-temporal satellite data from 1989 to 2016 and kinematic GPS survey from 2015 to 2016. The results obtained from satellite data indicate that in the last 27 years Chaturangi glacier snout has retreated 1172.57 ± 38.3 m (average = 45.07 ± 4.31 m/year) with a total area and volume loss of 0.626 ± 0.001 sq. km and 0.139 km$^3$ respectively. The field measurements through**

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