Magnetotelluric impedance tensor analysis for identification of transverse tectonic feature in the Wagad uplift, Kachchh, northwest India

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The 2001 Bhuj earthquake (Mw 7.7) occurred in northwestern region of Indian peninsula has reactivated a couple of transverse faults to its surroundings. Intermediate to moderate magnitude earthquakes are occurring along these faults which includes recent Dholavira earthquake (Mw 5.1, 2012) suggesting distinct tectonic scenario in the region. We present the results of magnetotelluric (MT) impedance tensors analyses of 18 sites located along a profile cutting various faults in the uplifted Wagad block of the Kachchh basin. The MT time series of 4–5 days recording duration have been processed and the earth response functions are estimated in broad frequency range (0.01–1000 s). The observed impedance tensors are analyzed by using three decomposition techniques as well as by the phase tensor method constraining with the induction arrows. The analyses suggest distinct tectonic feature within the block bounded by the South Wagad Fault (SWF) and the North Wagad Fault (NWF) particularly in the period band of 1–10 s. In the south of NWF, the telluric vectors and the major axes of the phase ellipses are aligned in the NNW–SSE to NW–SE direction where as a dominant E–W strike is obtained for northern side of the NWF. The transverse geo-electric strike coincides with the prominent clustering of seismicity after the Bhuj earthquake and trend of the Manfara transverse fault is located in close vicinity of the study area. We therefore suggest the presence NNW–SSE trending transverse structural feature in the Wagad uplift of the basin appears to play significant role in the current seismicity of the active intraplate region.

Keywords. Magnetotellurics; Kachchh; intraplate seismicity; transverse tectonics.

1. Introduction

The Kachchh basin is an east–west oriented pericratonic basin and is a part of the network of rifts developed along the western margin of India following the breakup of Gondwanaland (Biswas 1987; Biswas and Khattri 2002; Roy 2003). The devastating Bhuj earthquake (Mw 7.7) occurred in this intraplate region with an intensity XI close to the epicenter (Hough *et al.* 2002) has killed about

20,000 people in the region (Rastogi 2004). The aftershock activity of the earthquake is still continuing (Mandal 2016; Singh *et al.* 2016) showing active seismic nature of the intraplate region.

A number of geophysical studies have been carried out in the region to understand the nature of the subsurface and its possible linkage with the intraplate seismicity of the region (Kayal *et al.* 2002; Mishra and Zhao 2003; Mandal *et al.* 2004; Mandal and Pujol 2006; Chandrasekhar *et al.* 2009;

Naganjaneyulu *et al.* 2010; Singh *et al.* 2011, 2016; Chandrasekhar *et al.* 2012). These studies suggested the presence of large scale crustal intrusive bodies and underplated magma at lower-to-mid crustal levels in the region. The epicentral zone of the Bhuj earthquake is characterized as fractured fluid filled rock matrix which weakens the strength of the lower crust (Kayal *et al.* 2002; Chandrasekhar and Mishra 2002; Mandal *et al.* 2004; Reddy 2005; Mandal *et al.* 2007; Mandal and Pandey 2010). Further, it has been observed that the eastern part of Kachchh is a highly accumulated strain zone which is able to produce large magnitude earthquakes in near future (Rastogi 2004; Biswas and Khattri 2002; Mandal *et al.* 2004; Mathew *et al.* 2006). The large stress drops are observed for the events occurred on the North Wagad Fault and Gedi Fault (GF) (figure 1) and clustering of earthquakes in the eastern part of the region are reported. These stress drops were attributed to the presence of high fluid pressure and the mafic intrusive bodies beneath these two fault zones (Biswas and Khattri 2002; Mandal and Rapolu 2014).

Couple of magnetotelluric (MT) studies (Sastry *et al.* 2008; Naganjaneyulu *et al.* 2010; Chandrasekhar *et al.* 2012) were carried out around the epicentral zone and at western part of the Bhuj. MT investigations by Sastry *et al.* (2008) in the western Kachchh suggested a mosaic of high resistive crustal blocks separated by deep-rooted conductive features that spatially correlate with the known tectonic features, viz., the Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF). MT survey by Naganjaneyulu *et al.* (2010) ruled out the presence of fluids and melt (magma) as the causative factors that triggered the Bhuj earthquake. The estimated porosity value of 0.02% will explain 100–500 $\Omega \cdot \text{m}$ resistivity values observed in the lower crust. They inferred that the lower crust consists of basalts – probably generated by partial melting of metasomatised garnet peridotite at deeper depths in the lithosphere. 2-D inversion of broadband MT data by Chandrasekhar *et al.* (2012) revealed a thick (~ 3 km) highly conductive (1–4 $\Omega\text{-m}$) surface layer of fluvio marine Mesozoic–Cenozoic sediments. The model delineates the hypocentre zone located at ~ 20 –25 km depth that manifests the high resistivity–conductivity transition zone.

These MT studies are mainly carried out in and around the Bhuj epicentral region aimed to understand the seismogenesis of the region and crustal

structure. Since the recent geophysical studies infer the accumulation of the large strain in eastern part of the Kachchh and migration of seismicity from the Bhuj epicentral zone (Rastogi *et al.* 2013) necessitate detailed studies in eastern Kachchh basin mainly in the Wagad region. In addition, the tectonic evolution and seismic phenomenon of Kachchh region is due to differential movement along the major E–W trending faults (Biswas and Khattri 2002). However, couple of NW–SE to NE–SW transverse faults which cuts across the E–W tectonic setting of the region are also present in the region (Rastogi 2004; Biswas and Khattri 2002; Rastogi *et al.* 2013; Rajendran and Rajendran 2001). These faults are suggested to be reactivated after the 2001 Bhuj earthquake (Rajendran and Rajendran 2001; Rastogi *et al.* 2013). It is inferred that a part of the stresses being accumulated on the major faults is being possibly transmitted to these transverse faults, which may account for the present seismic phenomenon in the Kachchh (Mau-rya *et al.* 2005). In the present study, we analyze the impedance tensors obtained from the magnetotelluric investigation along an approximately NNE–SSW profile in uplifted Wagad region cutting various faults for identification and subsurface nature of these transverse tectonics features in terms of MT geoelectric strikes.

2. Geology and tectonic setting of the Kachchh basin

The Kachchh basin is bounded by the Nagar Parkar Fault (NPF) in the north and Saurashtra horst in the south, the Radhanpur–Barmer arch to the east and the Arabian Sea to the west. The regional geotectonic setting of the Kachchh basin is shown in figure 1. The Quaternary/Tertiary sediments, Deccan volcanic rocks and Jurassic sandstones resting on Archean basement characterize the geological sequence of the Kachchh region (Biswas and Deshpande 1970). The Mesozoic rocks are exposed in the uplifted land masses while Tertiary rocks have occupied the structure lows within the basin (figure 1). The uplifted hilly region of Kachchh consists of three uplifts: (1) the Island Belt Fault Zone; (2) the Kachchh Mainland uplift, and (3) the Wagad uplift (figure 1). The Island Belt Fault Zone comprises of four islands, viz., Pachchham, Khadir, Bela and Chorar, controlled and separated by the right-lateral transverse and strike-slip faults (figure 1) (Biswas 1987). The Wagad upland is

Figure 1. General geological scenario of the Kachchh superimposed on elevation map (modified after Biswas 2005). MF/MKF: Manfara Kharoi fault (Rajendran *et al.* 2008 and GSI portal); BWF: Bela-Wagad fault (GSI). NWF from Mandal and Pujol (2006). MT sites are shown with blue symbols. The stars are the locations of 2001 Bhuj earthquake (red colour) and 2012 Dholavira earthquake (magenta colour) and 1819 Allah Bund earthquake (red colour). Focal mechanisms are taken from Mandal and Pujol (2006) and Singh *et al.* (2016).

the second largest upland area next to Kachchh mainland in the basin dominated by Jurassic and Cretaceous sandstone, shale and limestone with some out crop of Tertiary limestone and sandstone in the north and southeast of the Wagad (Biswas and Deshpande 1970). The elevation of the Wagad uplift ranges between 20 and 200 m with maximum elevation between the South Wagad Fault and the North Wagad Fault (figure 1).

Rifting at the western margin of the Indian plate was controlled by the NE–SW trend of the Delhi (Pre-Cambrian) fold belt that swings to E–W in Kachchh. The E–W striking master faults are resurgent basement faults (Biswas 1987; McCaig and Thakkar 2003) that controlled the structural style of the basin. The major structural features of the region are bounded by the south-dipping NPF and the north-dipping North Kathiawar Fault (NKF) (figure 1). Other major faults in this region are the Allah Bund Fault (ABF), Kachchh Mainland Fault (KMF), Katrol Hill Fault (KHF), Banni fault (BF), Vigodi fault (VF), South Wagad Fault (SWF), Gedi fault (GF) and North Wagad Fault (NWF) (Biswas and Khattri 2002; Rastogi *et al.* 2013; Mandal *et al.* 2004). These fault zones are the source of many moderate to large intraplate earthquakes in this region. In addition to

these major faults and the uplifts (figure 1), some minor NE/NW trending faults/lineaments extensively affect the tectonic setting in the Kachchh region, e.g., Manfara fault, Bharodia fault, etc. (Biswas 1987; Rastogi 2004; Maurya *et al.* 2005; Rajendran *et al.* 2008; Bhattacharya *et al.* 2013). It is postulated that the squeezing of soft sediments between the Kachchh mainland and the Wagad blocks has resulted in right-lateral strike-slip fault near Manfara and left-lateral strike-slip fault near Shikra (Karanth 2004). A similar transverse fault trending NNW–SSE and showing lateral displacement is reported near Bharodia (Maurya *et al.* 2005). Regional scale geomorphic study by Maurya *et al.* (2005) suggest the significant role of these transverse fault systems on evolution and tectonics of Kachchh mainland by transferring of part of stress to the transverse faults from the major E–W faults (figure 1).

3. Magnetotelluric field survey and data processing

MT survey has been carried out during November 2015–January 2016 in the Wagad uplift along 60 km approximately NNE–SSW profile cutting various faults. MT time series of four days' duration

Figure 2. Unrotated apparent resistivity and phase curves for four sites along the profile.

at 18 sites are recorded using ADU-07e [Metronix, Germany] recording system. Pb–PbCl₂ electrodes and induction coil magnetic field sensor (MFS-06e) are respectively used for measuring electric and magnetic components of the secondary electromagnetic (EM) fields. MT impedance tensors of broad frequency range (0.001–1000 s) are computed after processing the data using MT processing package MAPROS (M/s Metronix GmbH). After quality check, we finally chose impedance tensors of all sites for detailed geoelectric strike analysis. Off diagonal components of the impedance tensor and respective phase values as a function of period for some sites (sites 4, 8, 12 and 18) along the profile are shown in figure 2.

4. Induction arrows

We first analyze the geoelectric strike direction using geomagnetic transfer functions (Tipper vectors). Direction of induction arrows represented as rose diagram for the period band of 1–1000, 100–1000 and 1–100 s are shown in figure 3. For the period of 0.1–1000 and 100–1000 s, the petals of rose diagram represent the dominant E–W conductive feature in the region. The trend coincides with Precambrian trend of northwestern India and E–W trending faults in the region. However, for the period band of 1–10 s, the estimated conductive direction deviates from the regional structural trend (figure 3) suggesting presence of transverse

Figure 3. Rose diagram showing direction of Induction arrows at various frequency bands.

Figure 4. RMS error for different sites after SSMF analysis and MSMF analysis by fixing the regional strike to N65°E and N40°E/N50°W, respectively.

and oblique structures. From the figure, we observe that the strike variations in the moderate depths deviate from the regional tectonic trend of the Kachchh basin.

5. Impedance tensor analysis

Impedance tensor of all 18 sites are used to investigate the geoelectric directionality of the region. We initially performed multi-site multi-frequency and single-site multi-frequency analysis in broad frequency range using physical decomposition (Groom–Bailey decomposition (Groom and Bailey 1989) (GB technique)), mathematical decomposition (LaTorraca decomposition method (LaTorraca *et al.* 1986) LT method) and mixed decomposition methods [Caldwell *et al.* (2004) (Phase tensor-PT method) and Becken and Burkhardt 2004 (BB-method)], next investigated the period-wise variations in the MT geo-electric strike.

5.1 GB approach

In GB decomposition technique, the observed impedance tensor is written as: $\bar{\mathbf{Z}} = \mathbf{RCZ}_{2D}\mathbf{R}^T$,

where $\mathbf{Z}_{2D}$ is the regional impedance tensor, $\mathbf{R}$ is the rotation matrix and $\mathbf{C}$ is a real tensor of rank 2, known as channeling tensor or telluric distortion tensor which itself is the product of three distortion tensors: shear (S), twist (T) and anisotropy (A). McNeice and Jones (2001) extended this approach to multi-site multi-frequency (MSMF) analysis for the determination of the most consistent 2-D parameters for a set of sites and the optimum regional strike direction.

First, the impedance tensors of all sites are used to perform MSMF decomposition analysis to obtain regional impedance tensor and estimate regional geoelectric strike in broad period (0.01–1000 s) range. An impedance noise floor of 1.75% (predefined/optimal noise floor specified in strike code) was used for decomposition analysis. The twist and shear values after the analysis in broad frequency range (0.01–1000 s) at each station are listed in table 1. The obtained shear and twist values are well below the maximum shear and twist limit (± 45) suggesting 2-D subsurface structure. The RMS misfit values estimated from the MSMF decomposition are shown in figure 4. The RMS errors for most of the sites located in south of the NWF (1–10) are below 2. However, for the

Table 1. *RMS errors after MSMF analysis using GB technique and corresponding shear and the twist values.*

Site no.	RMS error	Shear	Twist
1	2.22	−5.02	10.23
2	2.21	−6.09	11.27
3	0.35	−8.39	1.63
4	1.06	−1.49	−9.02
5	0.68	8.46	0.16
6	0.80	−6.18	1.65
7	1.90	−0.15	−5.70
8	1.97	8.32	−1.74
9	0.81	−0.72	2.02
10	0.58	0.22	0.47
11	2.43	−1.66	−0.88
12	2.39	6.77	−1.15
13	2.23	5.03	0.13
14	1.96	0.95	−3.86
15	2.81	1.59	−5.15
16	3.44	−0.31	−1.55
17	6.33	−1.91	−4.46
18	1.14	−3.19	−3.86

sites located north of NWF (11–18) shows considerable increase in RMS misfits except site 18. The MSMF analysis yielded a tensor principle direction of N65°E with 90° ambiguity for the entire profile. We further performed single site multi-frequency (SSMF) analysis using all sites in the broad frequency range (0.01–1000 s). Rose diagram

showing dominant strike direction from the analysis is shown in figure 5. The strike direction of each site is shown as bars in figure 6. The estimated value from the MSMF analyses leads to slight deviation from E–W Precambrian trend of the western India (Delhi Super group). The SSMF analysis leads almost E–W strike considering 90° ambiguity in the estimation of the MT strike (figure 5a). The geoelectric strikes estimated from SSMF analysis in broad frequency range (0.01–1000 s) at each site suggest broadly E–W trend for the sites located in north of the NWF; however, significant variation in the trend is seen for the sites located in the south of NWF (figure 6). The bars are oriented in NNW–SSE (or its conjugate) direction suggesting transverse-oblique strike for these sites.

We further analyzed the behaviour of regional strike with depth by carrying out SSMF and MSMF analyses of the impedance tensors for three different period bands of 1–10, 10–100 and 100–1000 s, respectively in order to test the pattern of regional strike with depth. The obtained strike directions from the MSMF analysis are listed in table 2. For the period band of 1–10 s, the MSMF analysis yields a principle strike direction of N42°E/N48°W whereas a dominant E–W strike is obtained for the remaining period bands (10–100 and 100–1000 s). Thus, the regional strike of the geoelectric structure contributing to the period range of 1–10 s within the Wagad region is transverse to the E–W Precambrian trend. Following

Figure 5. Rose diagrams after SSMF analysis in broad and three different period bands using (a) GB method and (b) BB approach.

Figure 6. Strike directions at various sites for entire period band (0.01–1000 s) obtained by BB and GB approaches.

Manglik *et al.* (2013), we performed GB analysis after fixing the regional strike to $N40^{\circ}E/N50^{\circ}W$ for the period band of 1–10 s. Now, the RMS errors (figure 4) for sites between SWF and NWF are below 2 except 7 and 8 suggesting that this particular strike value fits the data better compared to the $N65^{\circ}E$ direction. The RMS errors for sites 11–18 now deteriorate suggesting the dominance of the E–W strike of the Precambrian trend in this region. The local strike directions for three period bands obtained by SSMF analysis (figure 6) suggested that the trend of strike directions are approximately E–W for sites located in north of the NWF. A dominant NW–SE (or its conjugate) is observed for the sites south of the NWF for the period band of 1–10 s consistent with the regional strike estimated from MSMF analysis in this period band. The rose diagram showing dominant strike directions for these period bands are shown in figure 5. The rose diagram also infers dominant transverse strike in 1–10 s period and broadly E–W strike for remaining period bands (figure 5a).

From the RMS error and SSMF analyses, it has been seen that sites south of the NWF behaves

differently compared to the sites located in north of NWF. To understand the spatial-wise variations in the strike, we divided the data-set into two groups, one group comprises the sites 1–10 (between the SWF and NWF) and another 11–18 (north to the NWF). We performed MSMF analysis for these two groups in broad and as well as different period bands. The estimated strike values for broad and different frequency bands are listed in table 2. From the table it is evident that the transverse strike of the region is mainly contributed by sites lying between SWF and NWF. For the broad period range, the sites between NWF and SWF have the regional strike of $N55^{\circ}E/N45^{\circ}W$ whereas the sites situated north of NWF have consistent E–W trend ($N89^{\circ}E$). MSMF analysis for the first group in three different period bands (1–10, 10–100 and 100–1000 s) yields a strike of $N41^{\circ}E/N49^{\circ}W$ for the period band of 1–10 s and consistent E–W trend is obtained for remaining bands. Whereas for second group, consistent E–W strike is obtained. We therefore, conclude from the above analysis that transverse MT strike is mainly confined between the NWF and the SWF. A synthesis of these results indicates that the subsurface at 1–10 s period along the profile is structurally very complex, has different strike direction, and supports transverse/oblique tectonic nature within the Wagad uplift. These results are consistent with the inferences drawn about strike variations based on RMS error and the SSMF analyses.

5.2 BB approach

The dimensionality of the data was also analysed using the technique developed by Becken and Burkhardt (2004). This technique is an alternative physical parametrization which combines the SVD approach of La LaTorraca *et al.* (1986) and the distortion analysis. This technique examines the impedance tensor from the point of polarization states of the electric and magnetic fields. Analysing the ellipticities of polarization

Table 2. Strike values estimated from MSMF analysis using GB and BB methods.

Sl. no.	GB method				BB approach			
	0.01–1000 s	1–10 s	10–100 s	100–1000 s	0.01–1000 s	1–10 s	10–100 s	100–1000 s
1–18	65	42	0	13	–57	–40	–57	–4
1–10	55	41	75	17	34	48	–56	–4
11–18	89	11	4	12	85	–75	–9	–90

of the fields, the regional geoelectric strike direction can be identified even if the data are affected by galvanic distortions. When small scale inhomogeneities galvanically distort the electric fields at the surface, only field rotations and amplifications are observed, while the ellipticity remains unchanged. Thus, regional strike direction can be identified from vanishing ellipticities of the electric and magnetic fields even in the presence of distortion.

Similar to GB approach, we first estimate the regional geoelectric strike in broad frequency range as well as in the three period bands using the BB technique. The estimated strike values are listed in table 2. From the table it is evident that regional strike estimated from the BB approach are reasonably in agreement with the GB strikes. Period-wise analysis of the entire dataset yield N50°E (N40°W) and N33°E (N57°W) strike directions for the 1–10 and 10–100 s period bands, respectively. A N86E trend is obtained for 100–1000 s band. Thus, the analysis also suggests the

presence of NW–SE (or its conjugate) geoelectric at 1–10 s. Similar to GB analysis, we also performed MSMF analysis by dividing the dataset into two parts. The analysis yield N85E for the sites located in north of the NWF whereas N34°E/N56°W for the sites located in south of NWF (table 2). Dominant E–W trend is estimated in all three period bands for the sites located north of the NWF and transverse trend is suggested for the period bands of 1–10 and 10–100 s. A dominant E–W trend is obtained for higher periods (100–1000 s) even for the sites located in south of the NWF.

We carried out SSMF analysis in broad as well as three different period bands. The rose diagrams showing dominant geoelectric strike direction for the broad frequency and the three period bands are shown in figure 5(b). The strike directions for each site along the profile in broad frequency range as well as different period bands are displayed in figures 6 and 7, respectively. The BB approach also suggests the dominant NNW–SSE (or its conjugate ENE–SWW) strike direction of the MT

Figure 7. Strike directions at various sites for four different period bands obtained by GB (top panel), BB (bottom panel) (bars) and PT (ellipses) approaches. PT ellipses are also normalized so that major axes at all sites are of the same length.

sites between the SWF and the NWF signifying the transverse trend in the region. The findings are coinciding with the results obtained by GB analysis. All this analyses infer the presence of transverse strike between the SWF and the NWF in the Wagad region.

5.3 PT approach

The GB approach assumes the regional structure is 2-D in nature and attempts to recover regional impedance tensors. Caldwell *et al.* (2004) proposed a phase tensor approach (PT approach) $\Phi = XY^{-1}$, where X and Y are real and imaginary components of the impedance tensor, that does not invoke any assumption about the dimensionality of the regional conductivity structure. The analysis formulated through the phase relationship between the horizontal components of the electric and magnetic fields, which is unaffected by galvanic distortions. This scheme can also be applied in situations when both local heterogeneities and the regional conductivity structure are 3-D in nature (Caldwell *et al.* 2004).

We analyze data to test whether the local strikes obtained by this approach are consistent with the results obtained by the GB and BB approaches discussed above. The phase tensor ellipses for the three different periods are superimposed on the local strike obtained by GB and BB analysis are

shown in figure 7. It is to be noted that GB and BB strikes are for period bands whereas PT strikes are at a given period. The major axis values are normalized to keep the length of the major axis of ellipses same across all plots. The values of minor axis are also normalized accordingly. The colour of ellipses represents skew angle (β). High skew angles are observed for the period of 100 s at all sites along the profile (figure 7). Analysis of spatial behaviour of phase ellipses in the Wagad block suggest that the ellipticities also increase for the 100 s period suggesting complex subsurface nature at upper-mid crustal levels in the uplift. These major axes of the ellipses are aligned broadly in N–S direction at 100 s and 1000 s periods (figure 7) and consistent with the strike directions obtained by the GB and BB approaches. The NNW–SSE (or its conjugate) strike for the sites south of the NWF is also obtained by phase tensor analysis at 10 s period.

5.4 LT approach

We also analyzed the observed impedance tensor using singular value decomposition based technique proposed by LaTorraca *et al.* (1986). The technique considers the rotation of Z using two mutually orthogonal magnetic field (H) directions for which the associated electric fields (E) are orthogonal to

Figure 8. Rose diagram showing dominant strike direction at various sites for entire period band (0.01–1000 s) obtained by LT approach.

each other but not necessarily orthogonal to the magnetic fields.

The rotation angles obtained after LT approach at each site are shown in figure 8. From the figure it is seen that, the strike direction of sites located in north of the NWF (except for sites 18 and 17) are oriented in E–W direction representing the E–W trend of Delhi supergroup (considering 90° ambiguity in the estimated MT strike value). For the sites in south of the NWF, the geoelectric strikes are oriented in NNW–SSE direction highlighting the transverse MT strikes in the Wagad uplift suggested by previous three methods.

6. Discussion

A comparison of results from strike analyses by GB, BB, PT and LT approaches reveals that even though there are slight variations in the strike estimates from these methods, the strike directions are broadly in good agreement. At some sites and frequency bands, the GB and BB strike matches well with the PT strike when rotated by 90° and *vice versa*. The local and regional strike values estimated in different period bands using GB, BB and PT approaches support transverse strike (NNW–SSE) at 1–10 s periods. The presence of a transverse conductive feature is also seen from induction arrows in the period band of 1–10 s. Analysis of spatial variations in MT strikes concludes that the sites located between the SWF and NWF contribute to the transverse trend in the region. Combining the results drawn from the impedance tensor analyses and the geomagnetic transfer function, the presence of transverse to oblique MT strike directions between the SWF and the NWF at 1–10 s is seen, which is contrary to the general east–west Precambrian trend in the Kachchh basin. Similar type of variation of geoelectric strikes with respect to periods/depths are previously suggested in the Sikkim Himalaya through detailed MT strike analysis by Manglik *et al.* (2013), in the Garhwal Himalaya by Israil *et al.* (2016) and Ferguson *et al.* (1999) in Trans-Hudson orogeny, Canada. The strike variations in the electrical structure of the San Andreas Fault at Parkfield, California also reported by Unsworth *et al.* (2000), Becken and Ritter (2012).

Now, we integrate the geoelectric strike direction obtained from the analyses with the seismological observation and the focal mechanisms estimated for some events in the study region. Epicentral

map of relocated earthquakes (magnitude $M \geq 3$) occurred during 2007–2015 in the study region recorded by the network of Institute of Seismological Research (ISR) is shown in figure 9 along with focal mechanism solutions of some events (taken from Singh *et al.* 2016). These fault plane solutions suggest dominant strike-slip nature of faulting with some of the mechanisms, the p axis oriented in NNW–SSE direction. From the map, two prominent clustering of earthquakes, one in NE and another in NW direction can be seen. Kayal *et al.* (2002) have also shown two major fracture directions, one trending NE and the other NW from the relocated aftershocks. Another study by Rao *et al.* (2013) from the moment tensor inversion of earthquake waveform data in the Kachchh region suggests reverse and strike-slip type focal mechanism solutions for some events in the region. The inferred fault planes from strike-slip solutions of the earthquakes are well correlated with the local trends of geological faults and lineaments (figure 1). An Mw 5.1 earthquake occurred on 19 June 2012 (Dholavira), about 30 km north of the 2001 Bhuj main shock along the NE-trending Khadir transverse fault. The fault displaces the eastern part of Island Belt Fault and extends south to the western part of the NWF (Singh *et al.* 2016).

The north–south compression in the Kachchh rift basin promotes reverse faulting on the east–west faults and strike-slip motion on the transfer faults (Talwani 2017). As a result, as mentioned in the previous sections the region consists primarily east–west striking moderately dipping faults bounding the uplifts, and a few NW–SE and NE–SW striking transfer faults (figure 1), some of which extend to large depths and area, dividing the region into discernible blocks (Talwani 2017). Paleoseismological studies in the region (Rajendran and Rajendran 2001; Rajendran *et al.* 2008) have reported a north–west striking fault at a location close to 23.46°N70.38°E which they refer to as the Manfara fault (MF). The MF displays a right-lateral strike-slip motion and was described as a ‘tear fault’ in the hanging wall block above the fault plane. Recent studies also suspect the presence of two large scale transverse faults in either side of the Wagad highland (GSI), namely Manfara–Kharoi fault (MKF) in west and Bela–Waga fault in east of the highland (figure 1). Interestingly, the trend Manfara fault (MF) in the close vicinity of the study area correlates with the trend of NW clustering of the events. It is also found based on absolute dates that, MF has been ruptured in the past

~4.1 ka (Rajendran *et al.* 2008) which passes parallel to the western bank of the Chang river from Manfara village to the mouth of it. They further opined that the NNW–SSE-oriented MF located in close vicinity could be an evidence of a major fault along this trend in the region and possibly suggesting a long standing structural feature. These structures are believed to be evolved as a transverse fault linking between the KMF and the SWF (McCalpin and Thakkar 2003). A similar fault trending NNW–SSE and showing lateral displacement is reported near Bharodia named as Bharodia fault (Rajendran and Rajendran 2001; Maurya *et al.* 2005; McCalpin and Thakkar 2003).

These set of strike-slip faults whose geometry and sense of movement are conformable with the near north–south compression postulated in the tectonic regime of the 2001 Bhuj earthquake. Thus, the constant volume of the deforming transtension zone associated with the strike-slip fault system might produce local extension, vertical shortening and surface depression in the study region. The transtension is possibly taking place because of the extensional component orthogonal to the deformation zone. The pull-apart area could be a locale for sedimentation, which might be correlated with the Samakhiali/Banni planes in the region. The

NE/NW orientation of the horizontal maximum compressive stress estimated in the region (Singh and Singh 2005) also indicate the dominance of current flow in the transverse to the general E–W trend of major faults.

A correlation between the NNW trend of the epicentral distribution of aftershocks (figure 9) and the NNW–SSW strike of geoelectric structures within the Wagad block supports the presence of a transverse conductive feature at upper crustal depths. This is well supported by dominant strike-slip movement along near vertical planes evident from focal mechanisms of the events in the region. The excavations and paleoseismological investigations in the vicinity of the epicentral region of the 2001 Bhuj earthquake near Manfara (Rajendran *et al.* 2008) suggesting a long standing transverse structural feature strengthen the results obtained from the present MT analyses. We therefore speculate that the transverse tectonic feature suggested from the MT impedance tensor analysis might be playing a key role in stress transfer from main E–W structural trend and leading moderate-small sized earthquakes. Due to significant neo tectonic activity of the inferred transverse faults (Maurya *et al.* 2005; Rajendran *et al.* 2008; Bhattacharya *et al.* 2013), the kinematics of the fault structures need to

Figure 9. Epicentral distribution of earthquakes in the study region. The focal mechanism solutions are taken from Singh *et al.* (2016).

be constrained through detailed shallow and deep geophysical models. Detailed geophysical studies including 3-D MT modelling needs to be carried out to further characterize/conforming the role of these faults and mechanism of the stress transfer in current seismic activity and deformations of the Kachchh intraplate region.

7. Conclusions

Analysis of magnetotelluric (MT) impedance tensors along with the induction arrows in various frequency bands at 18 sites located along a profile in the uplifted Wagad block of the Kachchh basin suggest transverse tectonic (NW–SE) feature between the SWF and NWF. The transverse geoelectric strike coincides with the current seismicity pattern and trend of the pre-existing reactivated transverse faults inferred from the paleoseismological studies as well as geomorphological investigations located in the vicinity of the study area. The strike-slip nature is also affirmed by the fault-plane solutions of a few moderate earthquakes in the region. We therefore, suggest the presence of a NNW–SSE trending transverse to oblique structural feature in the Wagad block of the Kachchh basin which might play a prominent role in the deformation and current seismicity of the active intraplate region.

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