Anisotropy estimation using 1D joint inversion of DC resistivity and CSRMT methods in the granite-gneiss terrains of Eastern Ghats, India

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SUMMARY

The joint inversion of a galvanic and an inductive method is a standard procedure for the estimation of resistivity anisotropy of the subsurface. Other advantages of the joint inversion include the enhancement in the resolution and the *importances* of the model parameters obtained after the joint inversion. The joint inversion of the DC resistivity method and far-field CSRMT method is utilized to evaluate the resistivity anisotropy in the fractured granite-gneissic terrains of Eastern Ghats, Odisha, India. A table depicting the *importances* justifies the accuracy of the joint inversion. The interpreted results validate the inferences made from a borehole lithology in the area. The anisotropy in the subsurface is found to increase with depth and is more pronounced near the fractured horizons. Also, the magnitude of the anisotropy varies up to 15.

Keywords: Anisotropy, joint-inversion, DC resistivity, CSRMT

Introduction

Geophysical interpretation is always susceptible to ambiguity, which can be resolved to a degree by taking various measures like the inclusion of apriori information or resorting to a combination of several geophysical techniques. A good possibility for the joint usage of more than one technique is by concatenating the parameter, data, and the parameter sensitivity (Jacobian) matrices to utilize the advantages of all the individual methods involved.

In the standard DC resistivity surveys, the individual consecutive layers are assumed isotropic and homogeneous. However, in a scenario where multiple thin layers coexist inside a thicker stratum, the assumption of an isotropic layer no longer holds. The terminology macro- and micro-anisotropy are worth considering at this point. Maillet (1947) referred to the single electrical equivalent of a set of thin distinct resistive layers as a macro-anisotropic layer and termed the phenomenon macro-anisotropy. Nevertheless, the individual thin layers are quite discernible in the well-logging measurements (Shlykov et al. 2018). The other type of anisotropy, which originates from the preferential orientation of mineral grains (crystals) in the layer matrix, is called micro-anisotropy. This may also be due to the presence of certain flaky and platy minerals like biotite and amphiboles respectively.

Jupp and Vozoff (1977) first elucidated anisotropy estimation using the joint inversion of a resistive and an inductive method. They used a set of four coupled equations as shown below (Equations 1-4):

$$\rho_{DC} = \sqrt{\rho_V * \rho_H} \tag{1}$$

$$h_{DC} = h * \sqrt{\rho_V / \rho_H} \tag{2}$$

$$\rho_{MT} = \rho_H \tag{3}$$

$$h_{MT} = h \tag{4}$$

where, ρ_{DC}, ρ_{MT} and h_{DC}, h_{MT} are the resistivity and thickness detected by the DC and MT methods. ρ_V and ρ_H are the actual vertical and horizontal resistivity while h is the actual thickness.

These equations clearly show that the resistivity perceived by the DC resistivity method is the product of the vertical and the horizontal resistivities, while resistivity measured by the MT method (present case: CSRMT in a far-field zone) is purely horizontal. Also, the thickness is over-estimated in the resistivity method by a factor of the anisotropy coefficient $\left(= \sqrt{\rho_V / \rho_H}\right)$ of the layer while the thickness estimated by the CSRMT method corresponds to the true (geological) thickness.

The accuracy of the Marquardt inverted model parameters can be evaluated in terms of their *importances* (Jupp and Vozoff, 1975) which is presented at the end, for all the soundings. Sudha et al. (2014) defined *importances* for model parameter (m_i) as shown in equation (5)

$$Imp(m_i) = \sqrt{[(\boldsymbol{VT})(\boldsymbol{VT})^T]_{ii}} \tag{5}$$

where V is the parameter eigen vector matrix (or V-matrix) obtained from the singular value decomposition of the Jacobian matrix. T is the diagonal matrix having damping factors as its elements. *Importances* are a measure, of how well the parameters are resolved. Their high values imply a major influence on the modeled data. (Vozoff and Jupp, 1975).

Geology of the study area

High-grade metamorphosed rocks of the Eastern Ghats Mobile belt (EGMB) are found in the study area. The area lies in the Archean-aged Charnockite-Migmatites-Khondalite province (figure 1). Due to the intense shearing and metamorphism, the rocks were highly fractured. The borehole (figure 2) displays fractured granite gneiss in the depth interval of 12-13 m. The successive layers were mostly coarse-grained granite-gneiss with the presence of feldspar veins for an interval of 1 m at 30.5 m depth and then the same rock without veins.

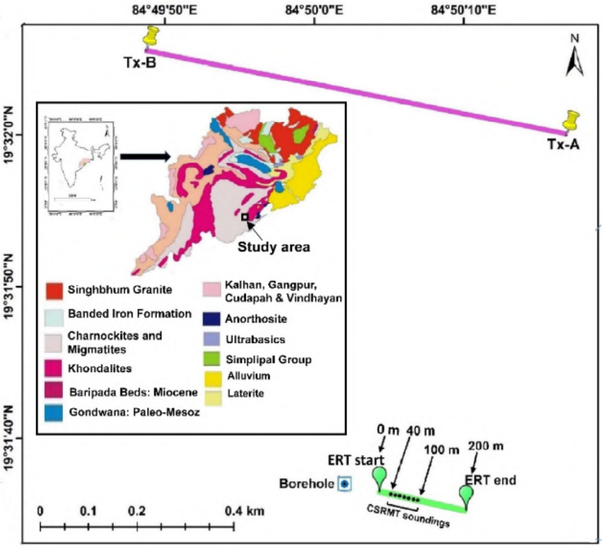

Figure 1. Study area map depicting the geology of Odisha (Mahalik, 1998) and the location of the DC resistivity and CSRMT soundings.

Instruments and Field experiment

The multi-electrode instrument ABEM Terrameter LS was used for 2D DC resistivity data acquisition in the Wenner-Schlumberger configuration using a 2x21-electrode protocol and 5 m inter-electrode spacing. The 1D data was extracted from the 2D acquired data at the profile distances (mid-points) from 40-100 m. Figure 1 depicts the location of the 2D resistivity profile and the CSRMT soundings.

SM-25 RMT-F receiver and a portable AC transmitter GTS-1 were used for CSRMT soundings (Saraev et al, 2017). The source was a grounded horizontal electrical dipole (HED) with 800 m length and a cluster electrode arrangement at each end. Two electric and three magnetic i.e. five channels were used in the receiver. A portable Gasoline generator powered the transmitter. The field experiment was carried out in the granite-gneissic terrains of the Eastern Ghats. Shallow clay layers provided good electrode connectivity. CSRMT data was acquired in the broadside configuration. The borehole was about 50 m WNW from the start of the ERT profile.

Frequency in the range of 1-1000 kHz was propagated from the transmitter. The data was recorded in the broadside direction of the HED. The far-field zone, which is least sensitive to vertical resistivity (Constable et al., 2010), lies in the broadside direction.

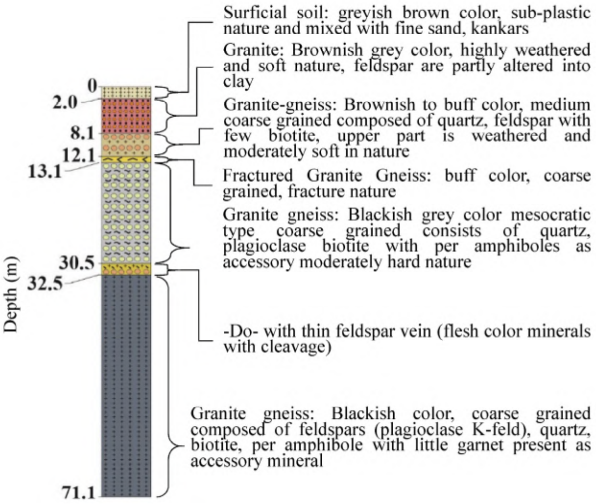

Figure 2. Borehole lithology from the study area.

Results

Single and joint inversion results of the sounding at a profile distance of 50 m have been displayed in table 1 and figure 4. The joint inversion results of seven CSRMT soundings coincident with 1-D DC resistivity soundings are shown in table 2 and figure 3. For the sounding at 50 m, the single DC resistivity inversion fitted most well for a three-layer model. For the DC method mean resistivity and the equivalent thickness are shown in table 1.

The parameter *importances* from the DC resistivity inversion are larger than 0.6. CSRMT method fitted better for the four-layer model and the horizontal resistivity and layer thickness parameters are found to be closer in magnitude to that obtained by the joint inversion. The *importances* obtained in the joint inversion are improved.

The variation of vertical and horizontal resistivity and anisotropy coefficient with depth for all soundings are shown in figure 3. The last layers in all the soundings are exhibiting a high anisotropy coefficient with the magnitude varying up to 10. However, the sounding at a profile distance of 90 m shows an anisotropy coefficient up to ~14 in the last two layers. The appearance of a high anisotropy coefficient (>4.0) below 10 m depth (figure 3c) conforms to the lithology (granite-gneiss) reported in the borehole.

Table 1. Inversion results along with the *importances* for the sounding at the profile distance of 50 m

method / param	DC Alone (ρ_{mean}, $h_{eq.}$)		CSRMT alone		Joint	
	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*
ρ_{v1}	3.5	0.76			6.8	0.73
ρ_{v2}	10.0	0.63			4.8	0.17
ρ_{v3}	12.0	0.70			293.5	0.87
ρ_{v4}					1.4e4	0.11
ρ_{h1}			6.8	1.00	6.8	1.00
ρ_{h2}			1.7	0.89	1.7	0.92
ρ_{h3}			10.1	0.91	9.5	0.95
ρ_{h4}			142.7	0.96	140.2	0.96
h_1	1.8	0.63	1.2	0.97	1.2	0.98
h_2	11.4	0.72	1.3	0.66	1.2	0.80
h_3			8.2	0.95	7.8	0.96
RMS (%)	3.1		2.6 (ρ) 4.3 (ϕ)		2.5	

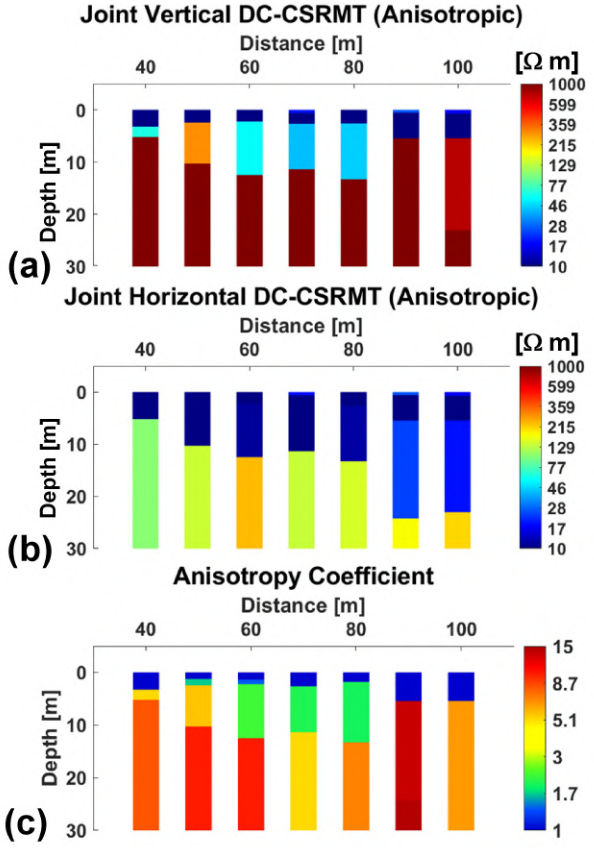

Figure 3. 1D joint inversion of DC and far-field CSRMT data: (a) vertical resistivity, (b) horizontal resistivity, and (c) Anisotropy coefficient.

Conclusions

Joint inversion of DC resistivity and far-field CSRMT data has successfully resolved the anisotropy present in the area. High anisotropy values (up to 15) have been observed in the deeper layers (>10 m). This might be due to the presence of fractured and foliated granite-gneiss rocks.

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Table 2. Summary of the joint Inversion results along with the *importances* of all the soundings

sounding / param	40m		50m		60m		70m		80m		90m		100m	
	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*	model parameters	*importances*
ρ_{v1}	3.9	0.37	6.8	0.73	8.2	0.81	19.0	0.71	8.5	0.93	26.3	0.87	17.0	0.41
ρ_{v2}	50.	0.14	4.8	0.17	3.4	0.09	3.1	0.24	6.3	0.13	3.6	0.43	3.9	0.25
ρ_{v3}	63.9	0.41	293.5	0.87	57.3	0.94	42.1	0.81	45.1	0.91	4356.9	0.36	786.7	0.83
ρ_{v4}	7326	0.13	14448	0.11	25147	0.09	3652	0.45	7310	0.27	37427	0.03	8771	0.11
ρ_{h1}	3.9	1.00	6.8	1.00	8.2	1.00	19.0	0.75	8.5	1.00	26.3	0.48	17.0	0.93
ρ_{h2}	5.0	0.75	1.7	0.92	1.8	0.83	3.0	0.98	1.6	0.80	3.6	1.00	3.9	1.00
ρ_{h3}	2.4	0.77	9.5	0.95	11.2	0.99	10.2	0.96	11.7	0.98	23.8	0.95	19.1	0.95
ρ_{h4}	106.3	0.99	140.2	0.96	241.6	0.96	137.3	0.94	149.4	0.97	173.8	0.71	212.4	0.71
h_1	1.9	0.76	1.2	0.98	1.4	0.98	0.6	0.93	1.8	0.99	0.5	0.97	0.7	0.98
h_2	1.4	0.60	1.2	0.80	0.8	0.65	2.1	0.91	0.8	0.64	4.9	1.00	4.8	0.99
h_3	2.0	0.78	7.8	0.96	10.2	0.99	8.7	0.97	10.7	0.98	18.7	0.90	17.6	0.94
RMS (%)	2.2		2.5		2.8		3.0		3.3		4.2		5.4	

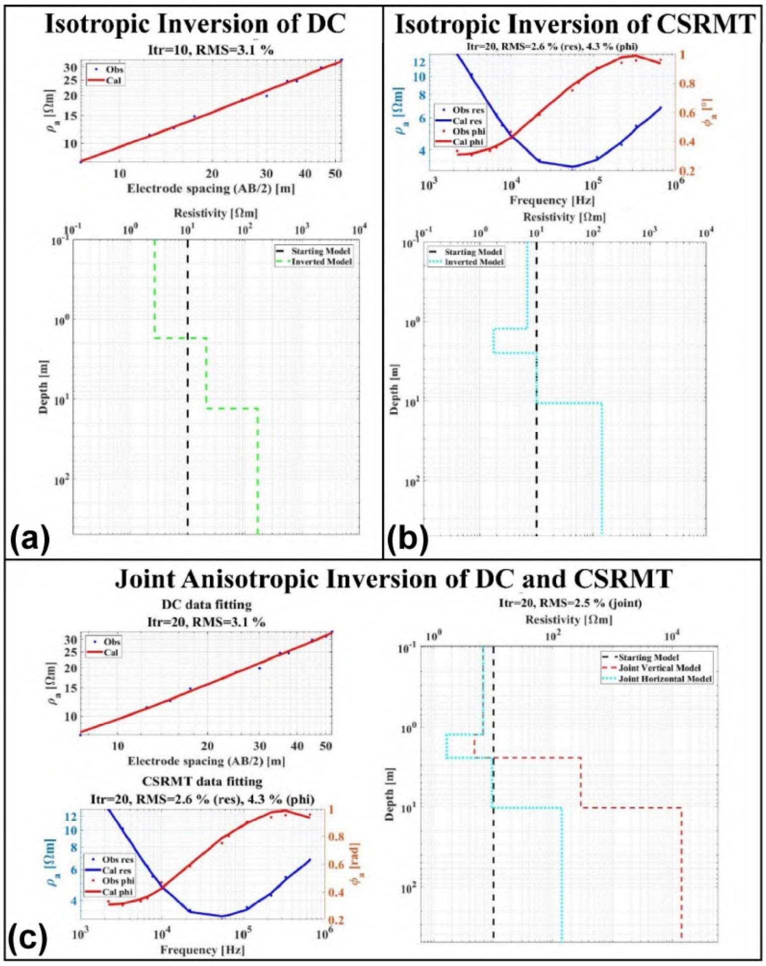

Figure 4. Single Isotropic inversion of (a) DC, (b) CSRMT. (c) Joint Anisotropic Inversion for sounding at 50 m.