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What to trust in a Magnetotelluric Model?

K.K.Roy, S.Dey[1], S.Srivastava[2], S.Biswas[3]
Department of Geological Sciences, Jadavpur University, Kolkata - 700 032
[1]Department of Geology and Geophysics, I.I.T., Kharagpur – 721 302
[2]AFPRO, Ashok Nagar, Ranchi – 834 006
[3]Schlumberger Asia, Mumbai – 400 086

Already more than 500 two-dimensional electrical conductivity maps of the subsurface have been published globally using magnetotelluric sounding data. In this note we have tried to make a subjective assessment about the trustworthiness of these models and the credibility of MT as a tool to map the crust and upper mantle. Since many of the readers are apprehensive about the scientific viability of these models, the responsibility lies with the MT community to defend the scientific contents of these models. The authors highlight the following points to address the topic.

(A) Differences in the TE and TM mode models
(B) Common features in these models
(C) Repeatability of observation
(D) Use of rotation invariant parameters
(E) Data quality and signal strength
(F) Purpose of investigation
(G) Constraints from auxiliary geophysical tools

The authors have tried to address on these topics based on their own field and mathematical modeling data to extract the quantum of truth from these exercises.

Differences in the models came from the magnetotelluric plane wave electromagnetic theory

Helmholtz electromagnetic wave equation

$$\nabla^2 \frac{E}{H} = \nu^2 \frac{E}{H}$$

derived from Maxwell's equations decouples into two different sets of electromagnetic wave equations after mathematical rotation (Swift 1967; Vozoff 1972) for two-dimensional structures. Here ν is the propagation constant ($\nu = \sqrt{i\omega\mu(\sigma+i\omega\varepsilon)}$ for harmonic field), ∇^2 are the mathematical operator ($\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$), and **E** and **H** are respectively the electric and magnetic fields in volt/ meter and ampere turn/meter. ω, μ, σ & ε are respectively the angular frequency ($\omega = 2\pi f$ where f is the frequency of the signal in cycles/ second or Hertz), magnetic permeability (in henry/ meter), electrical conductivity (in mho/meter or seimens) and electrical permittivity (in farad/meter). In E-polarization, electric field is parallel to the strike direction (transverse electric (TE) or $E_{\parallel}$ mode) and in H- polarization magnetic field is parallel to the strike direction (transverse magnetic (TM) or $E_{\perp}$ mode). These two sets of wave equations generate two very much different earth models, although the same set of data collected from a particular field spot are analyzed. Figure 1(b) and (c) show the rotated TE and TM mode field apparent resistivities and phases collected from the field station Baxi Barigah (Fig.1a) over the Singhbhum granite batholith. Fig.1 (b) shows that rotated ρ_{axy} and ρ_{ayx} are widely different. The discrepancies in apparent resistivity values are more than an order of magnitude. 1D interpretation will naturally give two completely different resistivity depth sections.

D'Erceville & Kunetz (1962) and Rankin (1962) have shown analytically that there will be significant difference in apparent resistivities (ρ_a) and phase (ϕ) in TE and TM mode MT responses near a vertical contact and a vertical dyke. Figs 2(a), (b), (c), (d), (e) show respectively the 2D model and TE and TM mode apparent resistivity and phase profiles across a vertical contact obtained by the authors using three dimensional finite difference source code of Mackie, Madden & Wannamaker (1993) modified by John Booker of the University of Washington at Seattle, USA.Nature of the apparent resistivity and phase curves are widely different. This fact is well known to the MT community. Except for a perfectly one-dimensional earth, where $\rho_{axy} = \rho_{ayx}$ ($\rho_{axy} = 1/\omega\mu_0 |E_x/H_y|^2$ and $\rho_{ayx} = 1/\omega\mu_0 |E_y/H_x|^2$), all the field apparent resistivities and their phases will be different. Here μ_0 is the free space magnetic permeability.

Fig.3 (a) shows the location map of the Khandwa-Ujjain traverse in central India. Figures 3(b), (c), (d) show the three 2D models for TE, TM and TE+TM mode taken along the Khandwa-Ujjain traverse across Narmada-Son lineament in Madhya Pradesh, Central India. These models are generated using 2D Rapid Relaxation Inversion algorithm of Smith & Booker (1991) and are significantly different models. These differences will always be there in MT field data

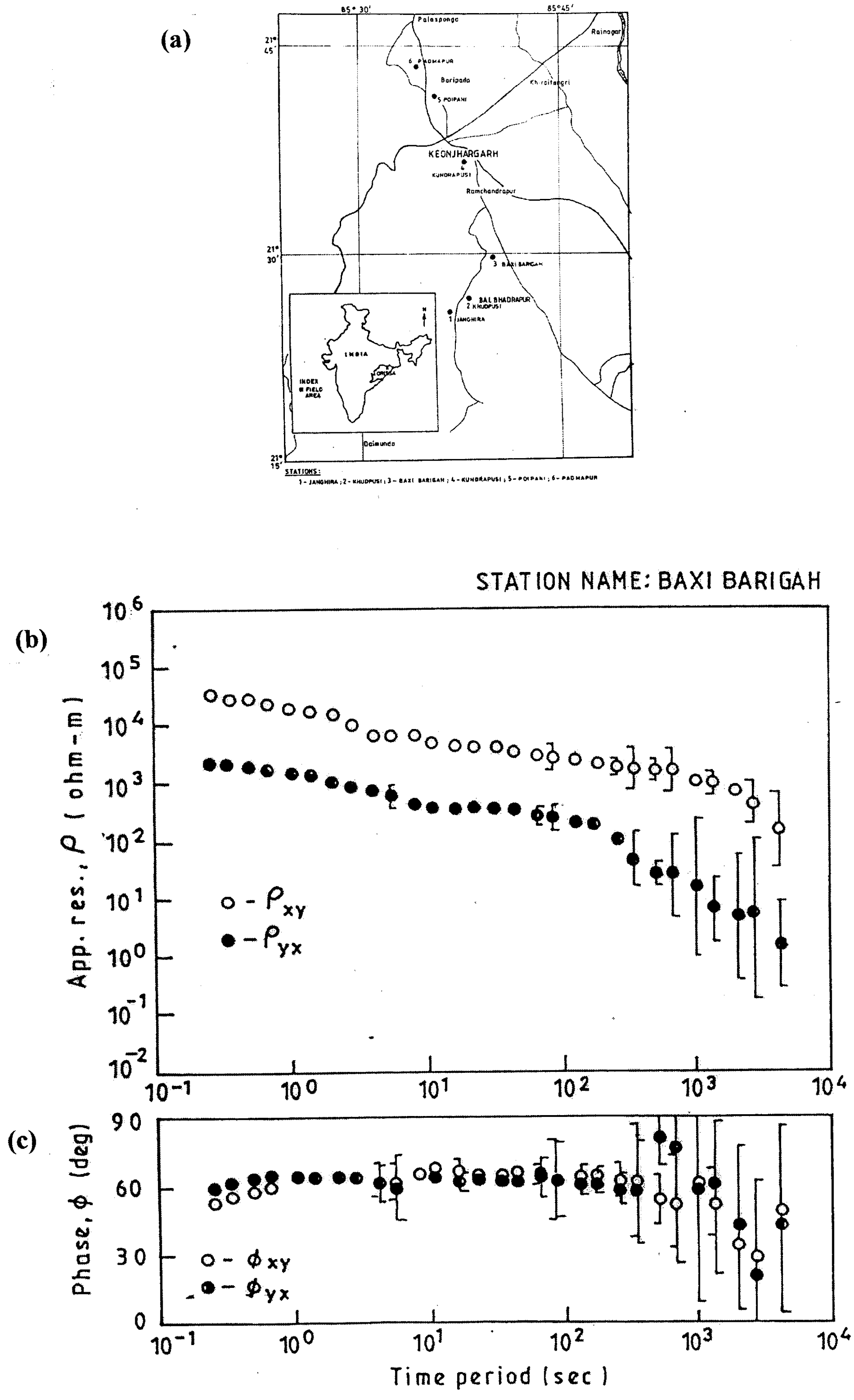


Figure 1. (a) Shows the location of the MT site Baxi Barigah in North-South Keonjhargarh profile, eastern India, (b) and (c) are respectively the magnetotelluric rotated TE and TM mode apparent resistivities and phases; apparent resistivity curves are showing more than an order of magnitude difference.

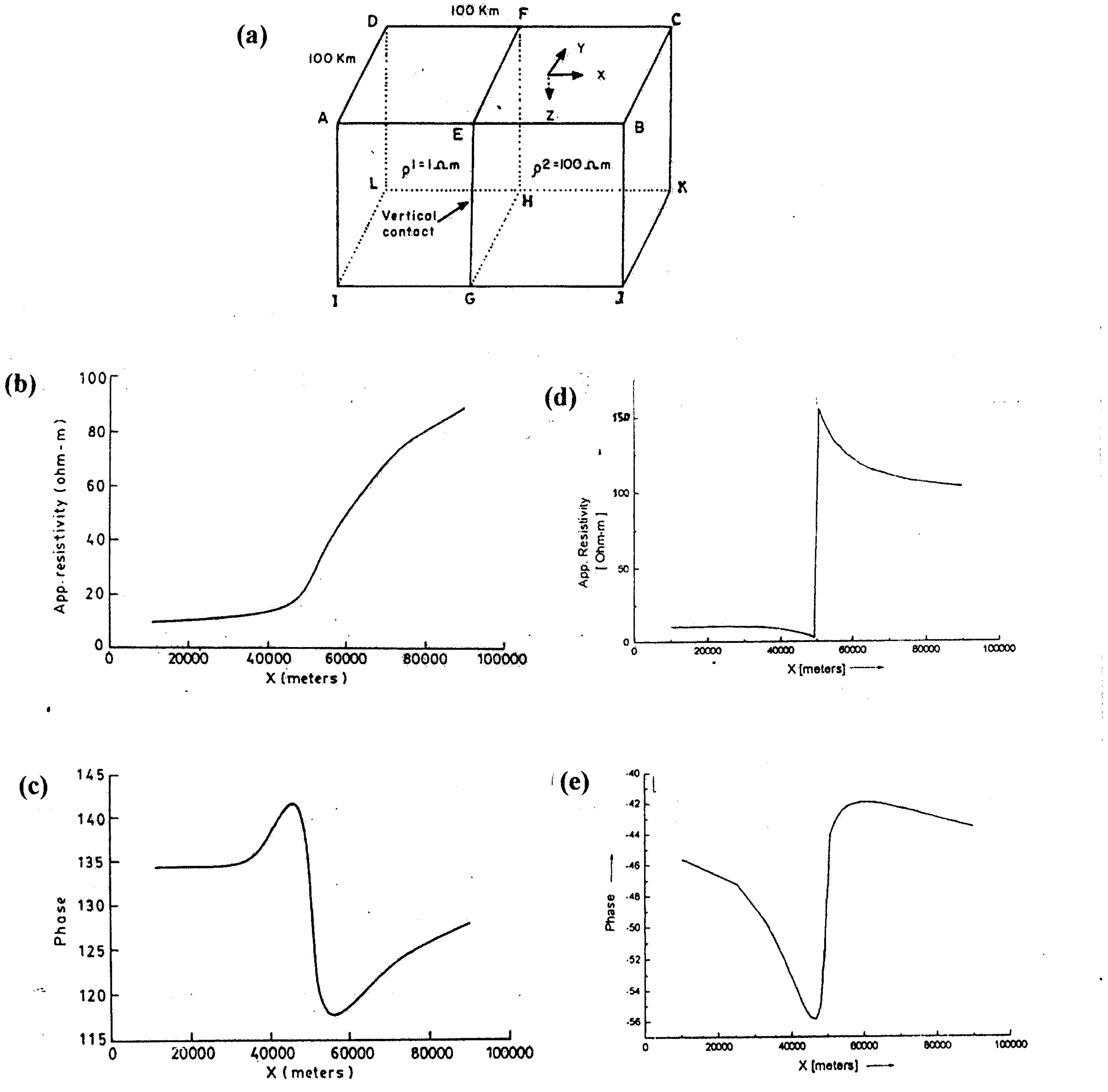


Figure 2 (a). Shows an earth model having the vertical contact EFHG parallel to the y-direction, the block ADFEILHG is having resistivity of 1 ohm-m., the block EBCFGJKH is having resistivity of 100 ohm-m, (b) and (c) show respectively the MT apparent resistivities and phases in TE mode across the vertical contact, (d) and (e) show respectively the MT apparent resistivities and phases in TM mode across the vertical contact.

interpretation. We cannot choose one of these models as a true representative of the subsurface structure.

Mathematical ModeL EXPERIMENT

Model 1: Fig.4(a) shows a 3D model of a 100 km. cube of resistivity 5000 ohm-m. with 3 graben type of structures. The dimensions of these three structures are respectively given by (i) left graben : width 2km., depth 40 km., resistivity of the rock filling the graben 50 ohm.m, (ii) central graben : width 20 km. and depth 25 km., resistivity of the rocks fiing the graben is assumed to be 200 ohm-m. and (iii) right graben : width 1 km. and depth 30 km., resistivity of the material filling the graben is 10 ohm-m.

Figs 4(b) and (c) show the TM and TE mode apparent resistivity pseudosections obtained from 3D finite difference source code of Mackie, Madden & Wannamaker (1993). The ordinate, time period, is in log to the base 10 scale. The abscissa is distance in kilometer. The two apparent resistivity pseudosections show that the TM mode apparent resistivities are superior to the TE mode apparent resistivities in resolving vertical faults, dykes etc.

Model 2: Fig.5 (a) shows a model of a 100 km. cube of resistivity 5000 ohm-m. Four dykes of width 100 meters, depth extent 10 km. and mutual separation of 2km. between these dykes are assumed. These dykes are assumed at a depth of 500 meters from the surface. Resistivity of the rocks filling the graben structures is assumed to be 20 ohm-m.

Figs 5(b) and (c) show respectively the TE mode apparent resistivity and phase profile across these dykes. Figs. 5(d) and (e) show the TM mode apparent resistivity and phase profiles across these dykes. Figs 5(d) and (e) show that both TM mode apparent resistivity and phase profiles could resolve all the dykes separately. TE mode apparent resistivity and phase profiles failed to resolve the presence of the four dykes.

Model 3: Fig.6 (a) shows a 100 km. cube of resistivity 5000 ohm-m. in which a conducting dyke of width 15 meter is assumed. Resistivity of the materials filling the dyke is taken to be 10 ohm-m. and the depth of the dyke was varied from 15 m. to 1 km. Figs 6(b) and (c) show the TM and TE mode profiles across the dyke. The two figures clearly show that TM mode MT has immensely superior resolving power than the TE mode MT. TE mode MT sees the target from a greater distance. As a result bigger volume of earth materials are involved in generating the TE mode response.

These three sets of model experiments clearly show that the resolving power of the TM mode response is very much different from that of the TE mode response. Electric and magnetic fields parallel and perpendicular to the strike direction of the structures reflect very much different physical properties of the earth. Discrepancies in these models partly come from theory and partly come from the inhomogeneities and anisotropies of the subsurface.

Common features in the models

Strong data with minimum noise content will always show some common features in all the models even after using different inversion source codes and different MT parameters. Geometrical shapes of these major features may be different. Some of the minor signatures may be different in different models obtained from different magnetotelluric parameters. 2D quantitative models should be accepted in a semiquantitative way and the broad features, which are common in all the models, should be taken with greater degree of confidence. If several earth models have something common, then earth must have that property (Bachus & Gilbert 1967). All the three TE, TM and (TE+TM) models presented in the Figs 3b, c and d show the blackish high conductivity zone. The geometrical shapes of these zones are different in different models. All the three models show that the continent is rifted in this area. These parts are common in all the three models and can be accepted

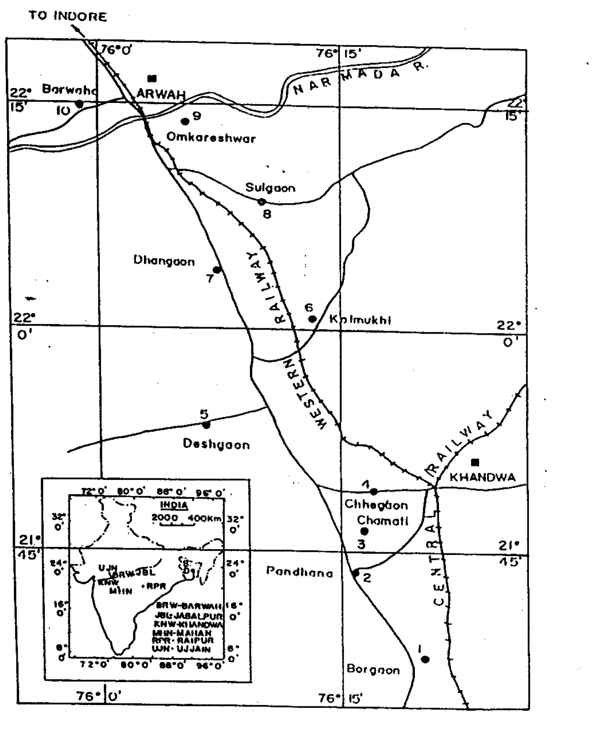


Figure 3(a). Shows the location map of the Khandwa-Ujjain traverse.

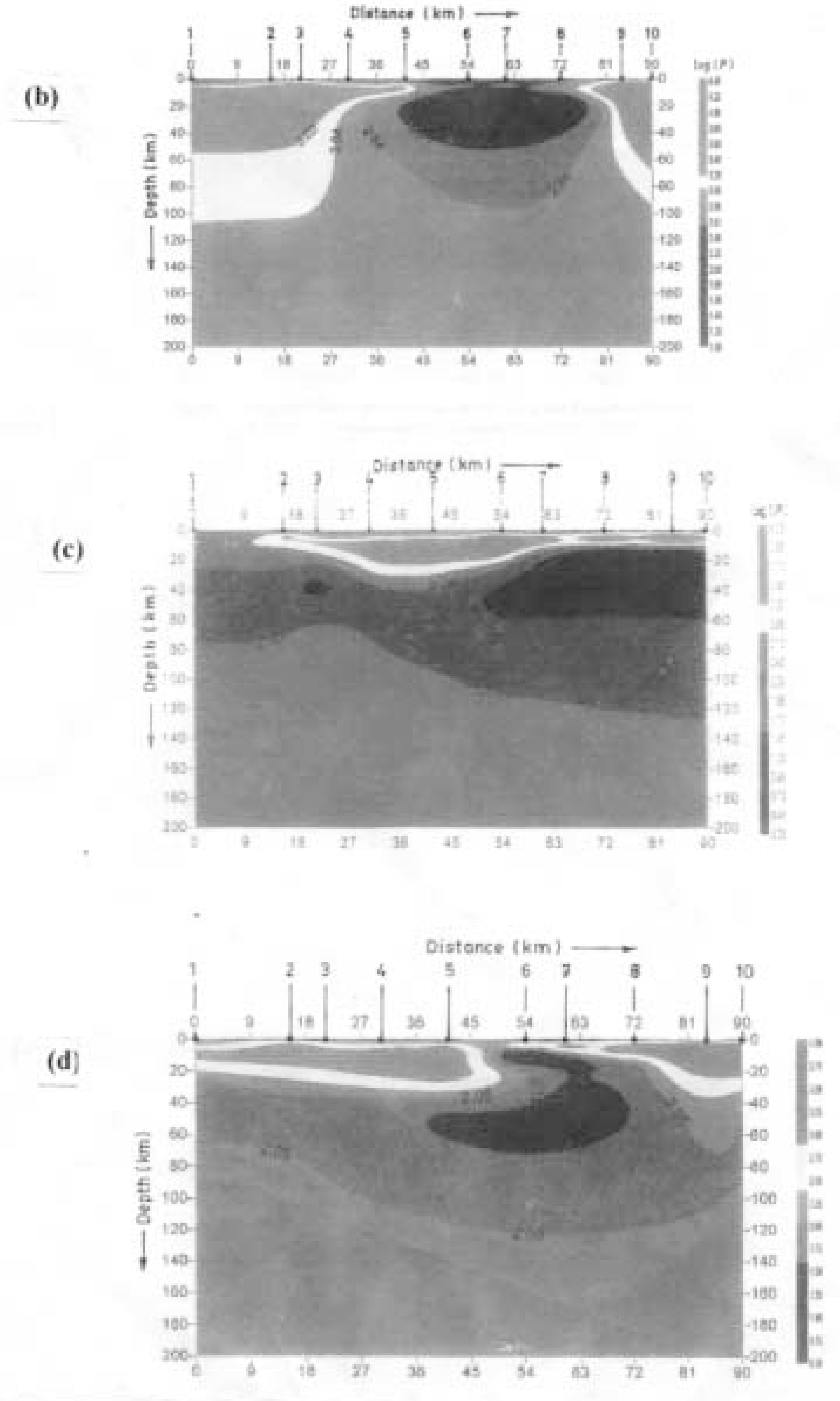


Figure 3(b), (c) and (d) show respectively the TE, TM and TE+TM mode models of the Khandwa-Ujjain traverse.

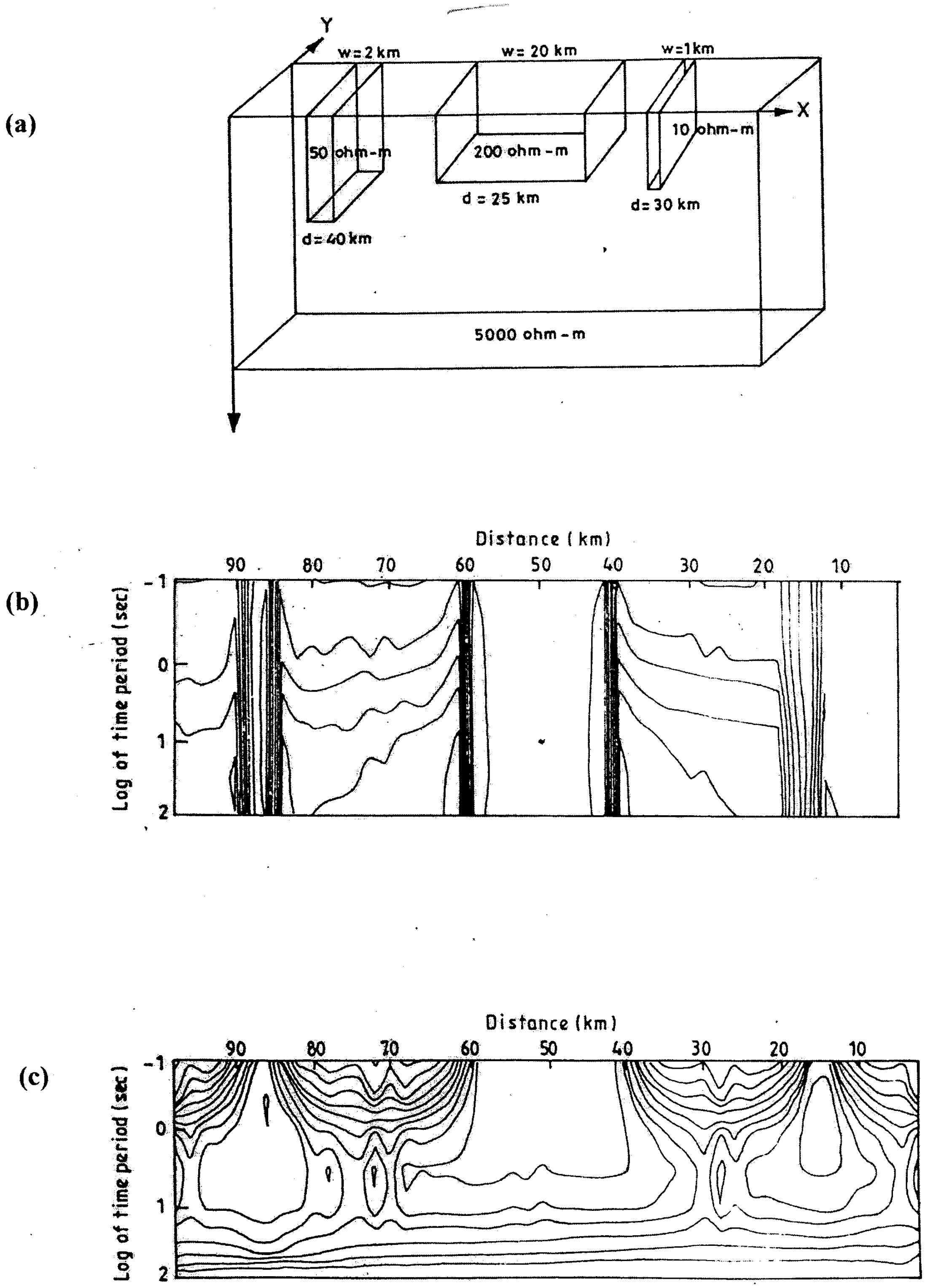


Figure 4(a). Shows three assumed grabens with different dimensions in a 100km. cube (not to scale) of resistivity 5000 ohm-m.: (i) left graben is having a width of 2km., depth 40km. and filling material of resisitivity 50 ohm-m, (ii) central graben is having a width of 20km., depth 25km. and filling material of resistivity 200 ohm-m and (iii) right graben is having a width of 1km. depth 30km. and filling material of resistivity 10 ohm-m, (b) and (c) are respectively the TM and TE mode apparent resistivity pseudosections across the three assumed grabens in the model.

as reliable information. Other MT group (viz. NGRI, India group) who worked in this area also mapped this high conductivity zone with different geometrical shapes. Fig 7(a), (b) and (c) show the TE, TM and TE+TM mode models over the Singhbhum granite batholith along the north-south traverse over Keonjhargarh, Orissa. All the three models are showing black highly resistive Singhbhum granite batholith. These parts can be trusted with greater level of confidence. Whoever will run an MT traverse over the Singhbhum granite batholith will map this highly resistive batholith. A highly conducting zone, delineated in TM and TE+TM mode models just below the resistive cover, is absent in TE mode model. We have seen in the previous section that vertical resolution in TM mode model is much better than that in TE mode model. Therefore some weightage is attached to the TM mode model but further verification from deep seismic sounding is necessary before we can confirm that it is a case of magmatic underplating.

Repeatability of observations

If two interpretations are found to be more or less same from two independent field observations taken in different time, then one can trust those models. As for example, the authors found from two independent field studies that Singhbhum granite batholith near Keonjhargarh is deep rooted; the depth extent of the batholith is 20km. or more and the granite body (Roy, Singh & Rao 1998a), (SBGA Saha 1994) is highly resistive. Roy, Singh & Rao (1998a), Roy, Mukherjee & Naskar (1996) have already mentioned that most highly resistive rocks in the Archaean craton of Singhbhum are Singhbhum granite phase II near Keonjhargarh and Older Metamorphics near Champua (oldest rock of India). Therefore repeatability of observation enhances the credibility of models.

Use of rotation invariant magnetotelluric tensors

Magnetotelluric rotation invariant tensors are those whose amplitude remains constant after 360^0 mathematical rotation (Vozoff 1972), (Swift 1967). The four-tensor elements in MT, viz, Zxx (=Ex/Hx), Zxy (=Ex/Hy), Zyx (=Ey/Hx) and Zyy (=Ey/Hy) describe ellipses of the same size and ellipticity not only theoretically (Eggers 1982) but field observations also show the same property (Fig 8a). Berdichevskii & Dmitriev (1976); Eggers (1982); Szarka & Menville (1997); Lilley (1993), Roy, Srivastava & Singh (1998b) have discussed about the properties of these rotation invariant tensors. The authors have chosen only three pairs of these rotation invariant tensors and their phases to propose that they generate much more trustworthy models. The three pairs of rotation invariant apparent resistivities and phases are respectively given by:

a) (i) $\rho_D = |Z_{XX}Z_{YY} - Z_{XY}Z_{YX}|/\omega\mu$

(ii) ϕ_D = phase of $[Z_{XX}Z_{YY} - Z_{XY}Z_{YX}]$

b) (i) $\rho_B = |Z_B|^2/\omega\mu$

where $Z_B = (Z_{xy} - Z_{YX})/2$

(ii) ϕ_B = phase of $(Z_{xy} - Z_{YX})/2$

c) (i) $\rho_C = |Z_C|^2/\omega\mu$

(ii) $\phi_C = \tan^{-1}(Y/X)$

where

$$Z_C = [X + iY]$$
$$X = [(Zxx_r+Zyy_r)^2 + (Zxy_r-Zyx_r)^2]^{1/2}/ 2$$
$$Y = [(Zxx_i+Zyy_i)^2 + (Zxy_i-Zyx_i)^2]^{1/2} / 2$$

r and i stands for the real and imaginary components of the impedance tensor element Z respectively.

Fig.8 (b) shows the plots of field TE, TM and the rotation invariant determinant, central and average apparent resistivities. Whatever be the discrepancy or separation between the TE and TM mode apparent resistivities, the rotation invariant $\rho_{determinant}$ (ρ_D), $\rho_{central}$ (ρ_C) and $\rho_{average}$ (ρ_B) values are very close to each other at all the periods. So the models they generate after inversion are also very close to each other. Rotation invariant apparent resistivities are approximately treated as 1D apparent resistivities. Therefore 2D model based on 1D inversion should be done. In (ρ_D,ϕ_D) and (ρ_C,ϕ_C) pairs, information from real and imaginary components of all the four tensor elements are present. The information content is more in these parameters. Therefore they will generate more trustworthy models in 1D, 2D and 3D domains. For 2D however, TE and TM mode electromagnetic wave equations cannot be used for rotation invariant parameters. Therefore 2D model may be made based on 1D inversion information.

The idea of bringing rotation invariant parameters in modeling came from increasing the quantum of information in the input data by introducing the diagonal elements of the impedance tensor. Routine TE and TM mode impedances deal only with one off diagonal element Zxy or Zyx. Increase in information content reduces the differences between the basic data and therefore reduces the discrepancies in the models. As a result reliability or confidence level of the models will increase in rotation invariance domain. Figs 9(a), (b) and (c) show the 2D models obtained from (ρ_D,ϕ_D),

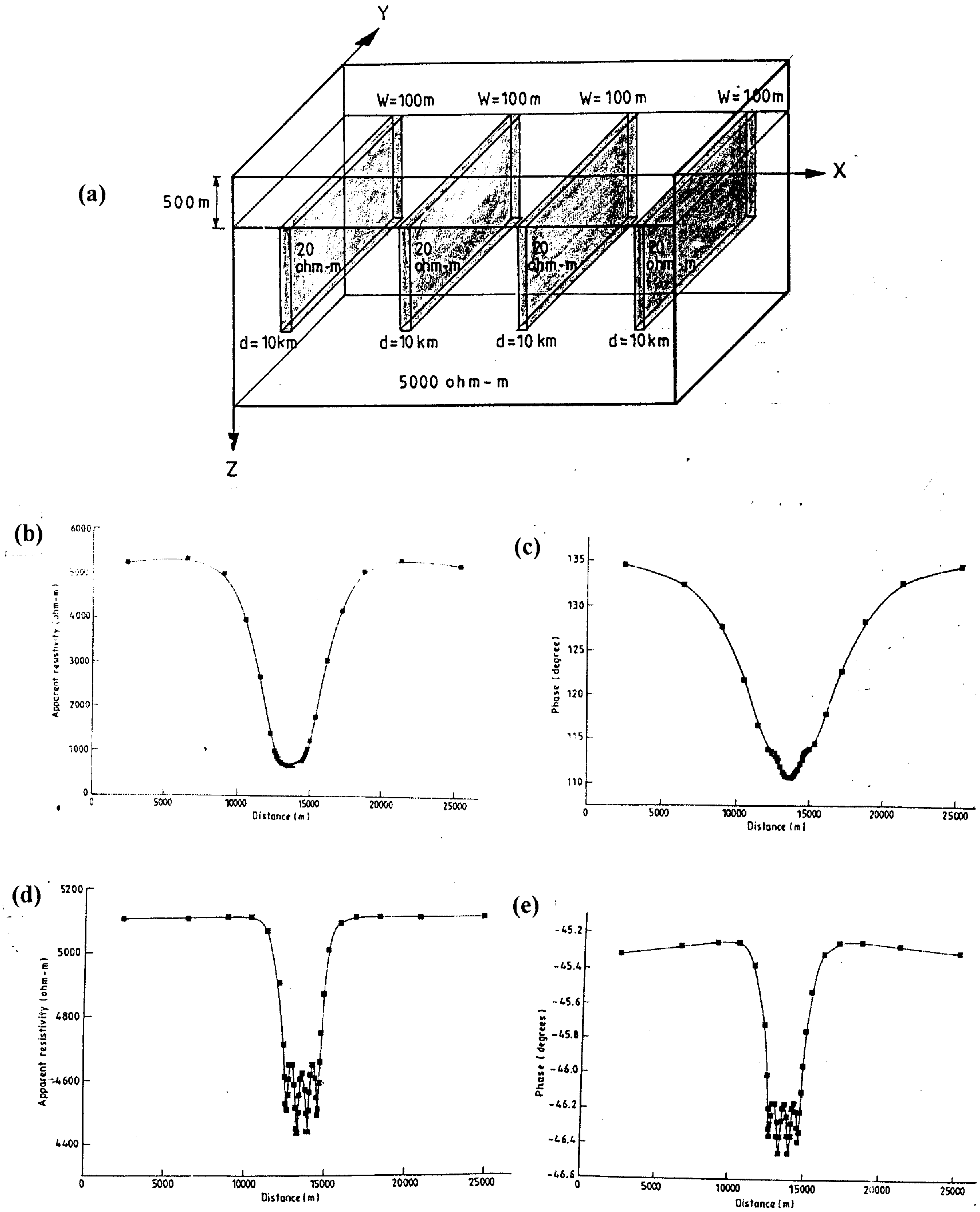
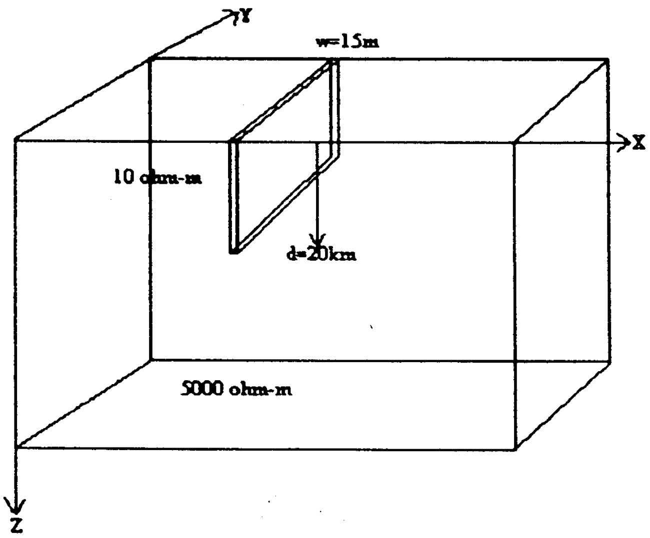
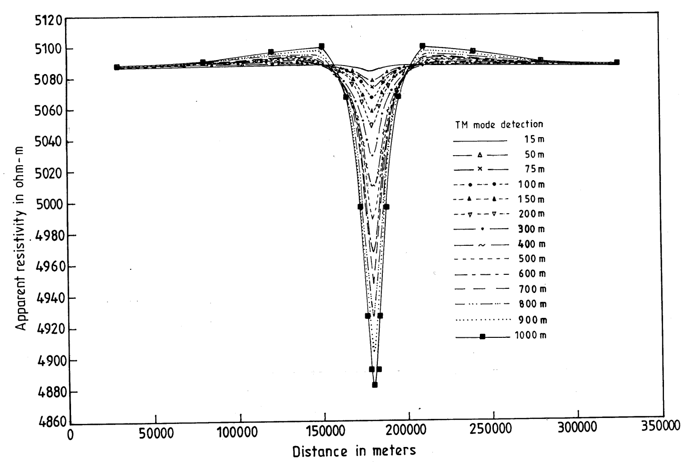


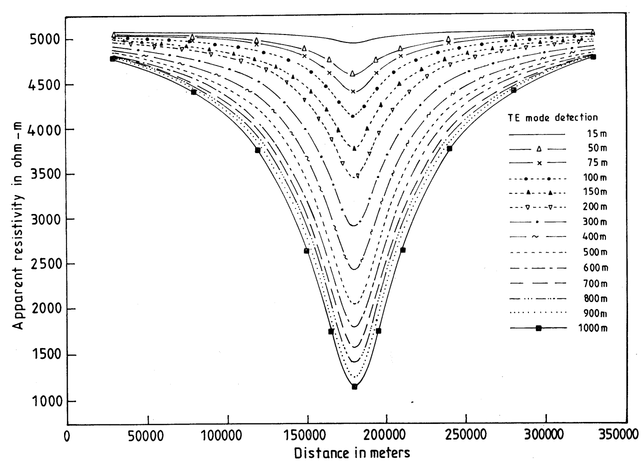
Figure 5(a). Shows a 100 km. cube (not to scale) of resistivity 5000 ohm-m. in which 4 dykes of width 100m. and depth extents of 10km. are placed at a mutual separation of 2km. The resistivity of the filling material is 20 ohm-m. in all the dykes. MT traverse is taken at right angles to these four dykes along the x-direction, (b) and (c) are respectively the TE mode apparent resistivity and phase profiles, (d) and (e) show respectively the TM mode apparent resistivity and phase profiles.



a)



b)



c)

Figure 6(a). Shows a 100 km. cube of resistivity 5000 ohm-m. in which a dyke of width 15m. and resistivity 10 ohm-m. is emplaced; depth extent of the dyke varies from 15m. to 1km, (b) and (c) show respectively the TM and TE mode apparent resistivity profiles across the assumed dyke in the model; the profile is at right angle to the strike direction.

(ρ_B, ϕ_B) and (ρ_C, ϕ_C) using the questionable and debatable TE mode part of 2D RRI. The models of the Khandwa- Ujjain traverse based on the rotation invariant parameters are quite similar and are more reliable. Since the rotation invariant apparent resistivities are quite close, the models generated out of them will be similar in whatever way the interpretation is done.

Strength of the Noise and Signal

To increase the reliability of the earth models the data quality should be good. The general guidelines the MT community follows are: (i) Avoid solar quiet days and try to choose solar disturbance days for MT survey when the signals are strong, (ii) Avoid areas full of cultural noise. Generally, high tension power lines, electrified railway tracks, defense installations, highways, underground cables destroy signals to a considerable extent at many places, (iii) Collection of data for extended periods i.e. for 15 to 30 days at a particular spot improves the longer period data quality and enhances the trustworthiness of the deeper part of the models and (iv) Strong signal improves the data quality. The days before and after the magnetic storms are preferable.

Purpose of investigation

Field planning is very important to improve quality of the models. Whether the investigation is for mapping (i) lithosphere-asthenosphere boundary (ii) magma chambers in a volcanic cone (iii) high heat flow areas or (iv) sediments below the flood basalts, will dictate the field planning, which will dictate the quality of interpretation. For mapping lithosphere-asthenosphere boundary with considerable clarities, granite batholiths or any hard rock areas should be chosen. Higher the resistivity of the upper crustal rocks, lesser will be the attenuation of the high frequency MT signals, better will be the resolution of the subsurface.

An MT station over Cambay basin in India where 3 to 4 kms. of Quaternary and Tertiary sediments overlie Deccan basalts, most of the high frequency MT signals will attenuate considerably in the highly conducting sediments and only long period signals with poorer resolving power will penetrate deep inside the earth. Geoelectrical models, for mapping the lithosphere will always be more trustworthy if the observations are taken over exposed granites/ granodiorites or any other high-grade metamorphic terrain. Even granite windows do not guarantee better models always. Higher conductivity of the lower crust can reduce the detectibility of the Lithosphere-Asthenosphere boundary considerably. For mapping horizontal boundaries TE and TM mode MT will behave more or less in the same way. For a perfect 1D structure the concept of TE and TM mode vanishes and ρ_{axy} becomes equal to ρ_{ayx} at all frequencies.

If the purpose of investigation is to reach beyond olivine-spinel transition zone, then the signals must be recorded with period of upto 30,000 to 40,000 seconds, if not more, with continuous observation of 30 to 40 days together at a stretch and at one spot. TE and TM mode signals should be interpreted together. Some geomagnetic signals from the permanent observatories should also be taken into account.

Electrical conductivity has very strong dependence on the degree of partial melts and temperature (Shankland & Waff 1977). Since degree of partial melt and temperature increases with depth, electrical conductivity of the upper mantle silicates (garnet lherzolite) increases rapidly. As a result attenuation of the EM signals will also increase at a faster pace. Therefore MT models will suffer from resolution problem and only some broad major features will be reflected in these models at a depth of 300 to 450 km. from the surface. At a greater depth geomagnetic depth sounding (GDS) from a permanent observatory and earthquake seismological data should be interpreted to increase the reliability of the earth models obtained from MT. At this depth TE and TM mode MT will behave in a similar way for horizontal or nearly horizontal boundaries.

Constraints from auxiliary geophysical tools

Information from complementary geophysical tools will always increase the reliability of the models. Therefore scientists attach more weightage on the integration of the geophysical methods. Authors tried to use the information from gravity, seismic reflection and heat flow survey to improve the quality of interpretation. Integration of information collected from different geophysical tools improves reliability and acceptability of the models.

CONCLUSIONS

a) Magnetotelluric TE, TM and TE+TM models will have some difference. It is difficult to choose one of the three as the true representative of the subsurface. Models obtained after quantitative interpretation should be taken in a semiquantitative way. Common

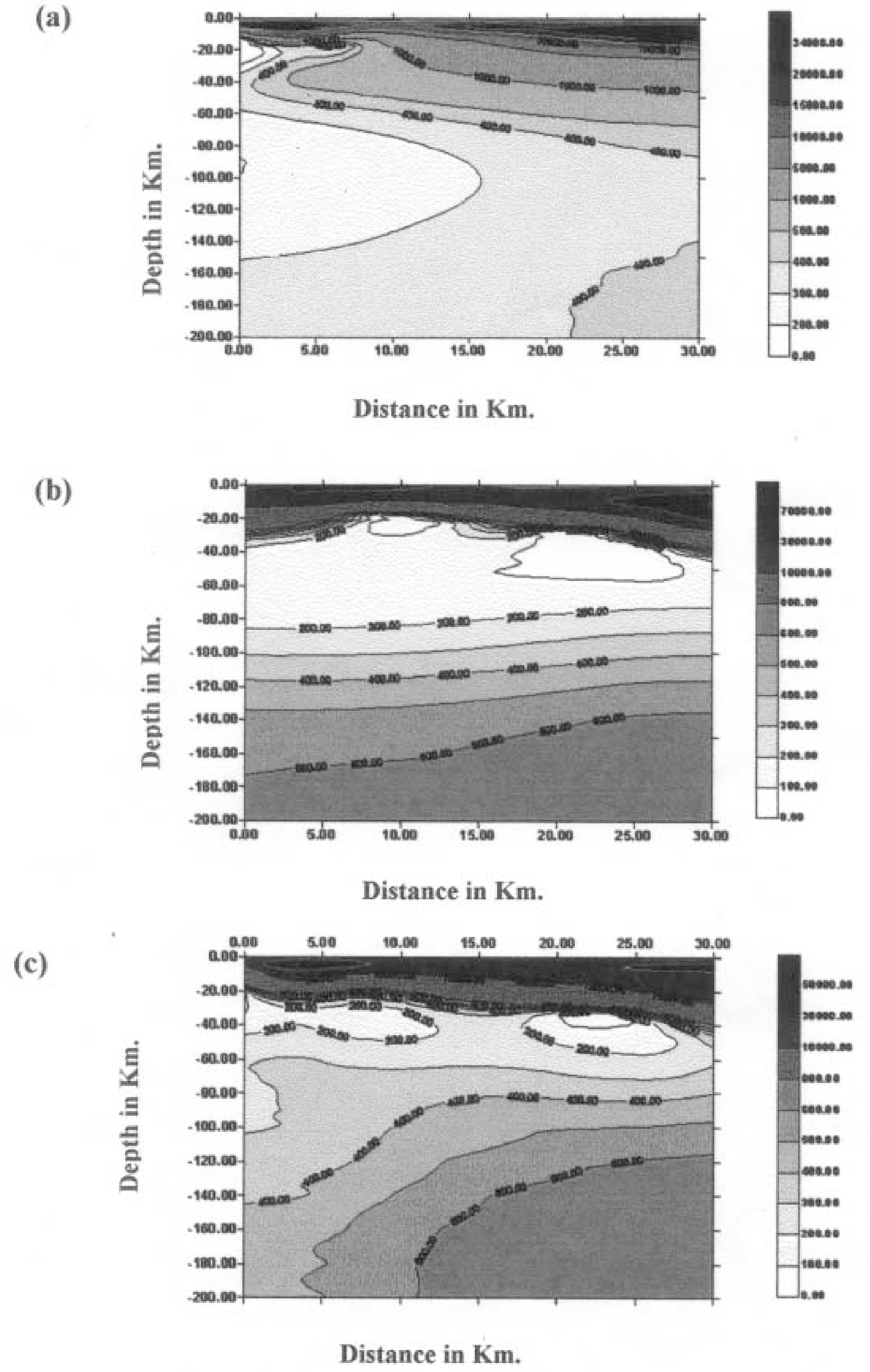
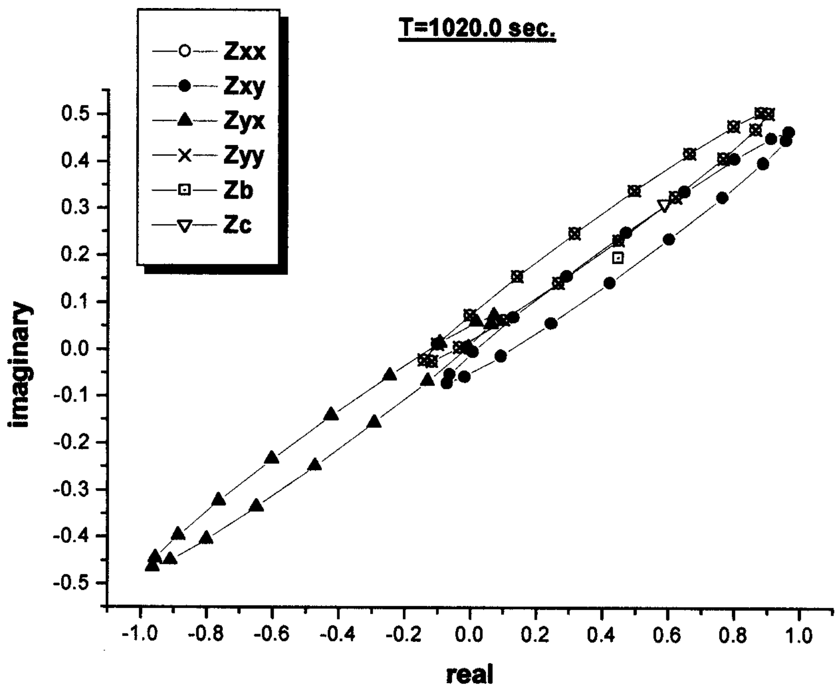


Figure 7(a), (b) and (c) Show respectively the TE, TM and TE+TM mode models over the Singhbhum granite batholith, along the north-south traverse over Keonjhargarh, Orissa.

(a)



(b)

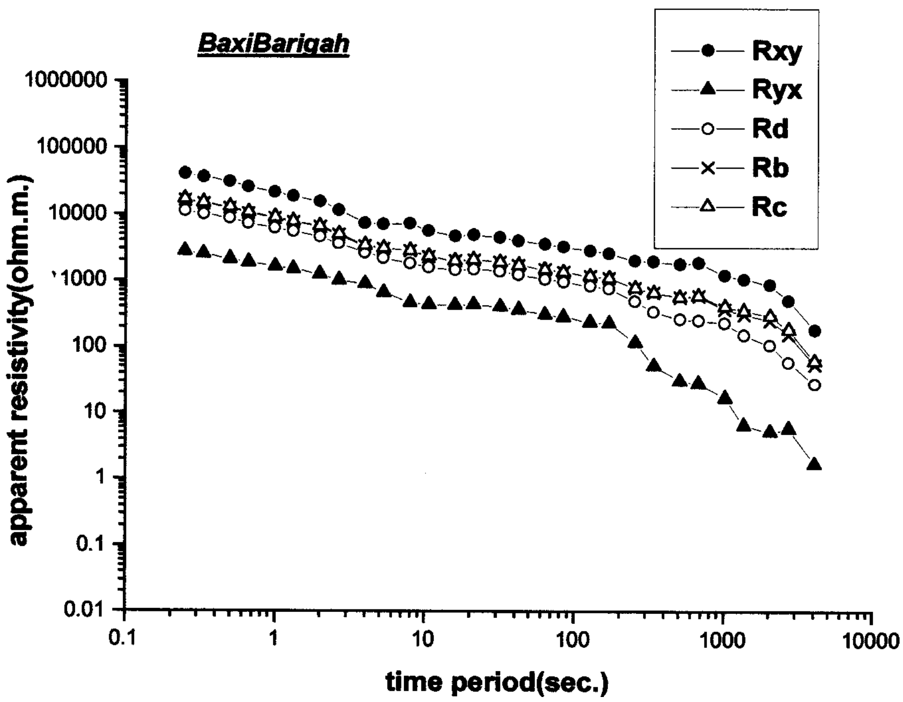


Figure 8(a). Shows the traces of Zxx, Zxy, Zyx, Zyy, Zb, Zc in the complex domain; Zb, Zc are respectively the average and central impedance tensors, (b) shows the TE and TM apparent resistivity curves along with the rotation invariant apparent resistivities over the station Baxi Barigah; Rd, Rb and Rc are respectively the determinant, average and central apparent resistivities.

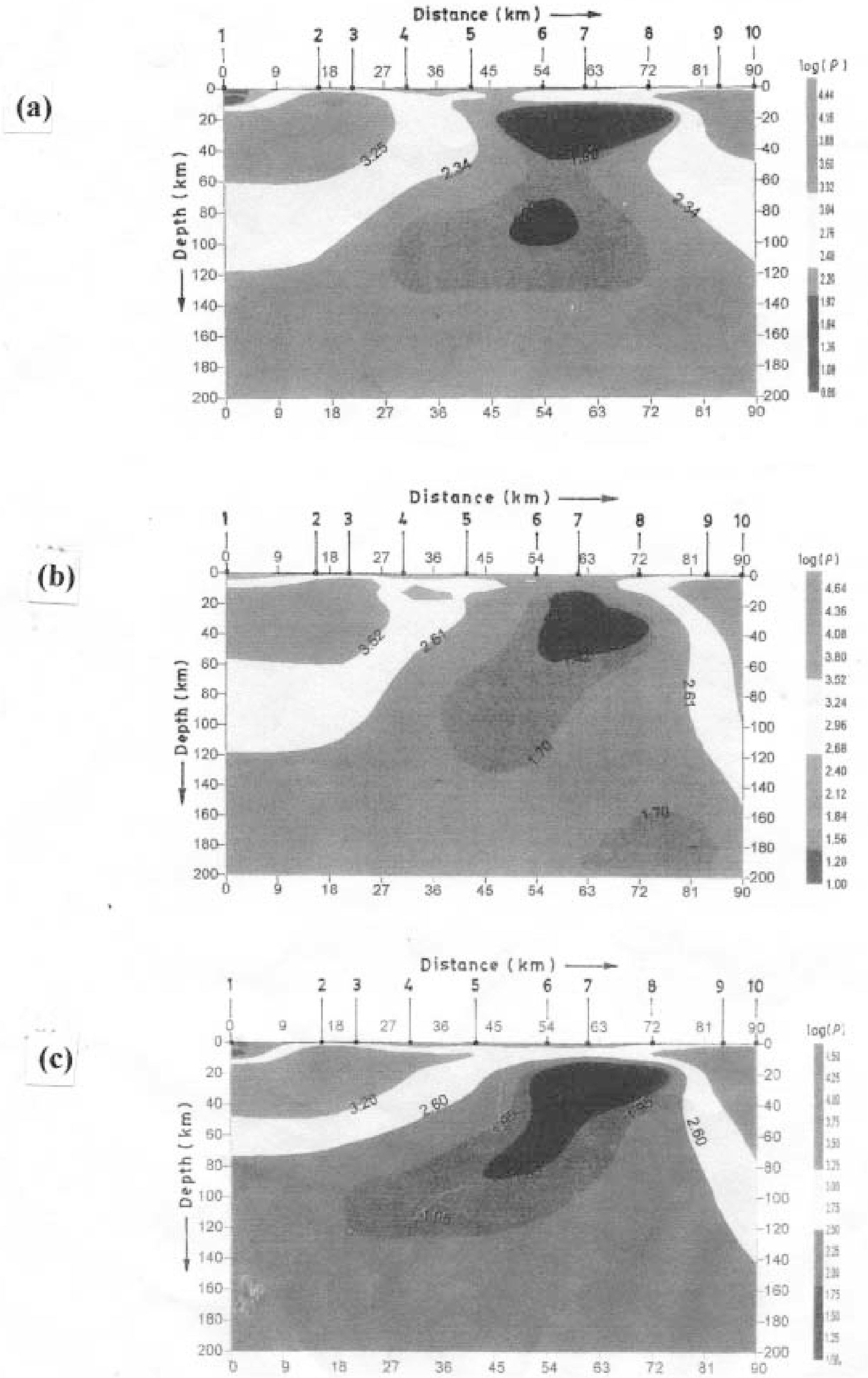


Figure 9(a), **(b)** and **(c)** show respectively the 2D models of the Khandwa-Ujjain traverse obtained using rotation invariant determinant, average and central apparent resistivity and phase and using the TE mode formulation of the 2D RRI.

features in all the models with different geometrical shapes should be accepted with greater level of confidence. Minor features which are not common in TE, TM and TE+TM mode models should preferably be ignored or attached some weightage after cross verification from other auxiliary geophysical or geological tools.

b) From model experiment it has been shown very clearly that for vertical inhomogeneities, viz., grabens, dykes, etc., TM mode MT anomalies are much more sharper than TE mode MT anomalies. Therefore, greater weightage can be attached to the TM mode models for mapping shear zones, suture zones, faults, fractures, lineaments, etc.

c) Rotation invariant apparent resistivities and their phases are very close to each other. Moreover, the information content will be more in (ρ_D,ϕ_D), (ρ_C,ϕ_C) and (ρ_B,ϕ_B) pairs. Therefore, models generated from rotation invariant parameters will be very close and more trustworthy. For 1D and 3D problems we can use these pairs as such for modeling. For 2D we have to make 2D stiched in models from 1D-inverted models because TE and TM mode electromagnetic wave equations cannot be used for rotation invariant parameters. Models generated using RITs and TE mode of RRI are presented just to show the readers how do they look like.

d) Routine do's and don'ts in MT, which are well known to the MT community, must be followed religiously to improve the trustworthiness of the models. These guidelines are (i) avoid cultural noise as far as practicable (ii) avoid solar quiet days as far as practicable for field measurements (iii) summer months are preferable for MT field data acquisition (iv) for deeper probing, hard rock terrain should be chosen so that high frequency MT signals also can penetrate to a considerable depth.

e) For interpretation of MT data collected over an Archaean or Proterozoic terrain, if we go for 1D inversion, we should over parameterize the models to increase the trustworthiness of the models. 3 to 4 layered earth model for a granite batholith or a highgrade granulitic terrain is not acceptable to the geologists. For 2 dimensional interpretation if we choose square or rectangular blocks of bigger size in finite difference or finite element forward models, square elements or blocks of different colors appear in the 2D models. Geologists are reluctant to accept the square blocks in the models. Either very fine finite difference cells should be taken with some increase in computation time or finite element method with isoparametric elements should be chosen to map the complicated subsurface geology.

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