# Inversion of GDS data of northwest Himalaya using EM2INV

ANUPMA RASTOGI[1], P K GUPTA[2] and SRI NIWAS[1]

[1]*Department of Earth Sciences, University of Roorkee, Roorkee 247 667, India*
[2]*Western Atlas Logging Services, Houston, USA*

This paper reviews the validity of earlier models obtained after quantitative interpretation of GDS data and presents a fresh model using the inversion scheme EM2INV. The 2-D inversion of data is more objective than the earlier interpretation performed by using trial and error method. The inversion results indicate that the present model differs from the earlier ones. The reason could be that available GDS data are sufficient only for deriving the horizontal variation of subsurface resistivity. In order to study the vertical resistivity variation additional MT sounding data would be required. It would therefore be desirable to carry out MT survey in the specified area. A more comprehensive/appropriate model could be derived from joint inversion of GDS and MT data.

## 1. Introduction

A magnetometer array study was planned and carried out in 1979 to study the subduction of the Indian plate under the Tibetan Plateau (Lilley *et al* 1981). The discovery of a large and distinctive geomagnetic induction anomaly in northwest India was reported. The reversal of vertical magnetic field led to this anomaly which indicated a high electrical conductivity structure striking across the Ganga basin into the foothills of the Himalayas.

Arora & Mahashabde (1987) attempted quantitative interpretation of the observed GDS data and proposed a ridge model of a conductive structure for the causative anomalous source. Singh and Pedersen (1988) claimed that the computed response of the model proposed by Arora and Mahashabde is not compatible with the data. It is interesting to note that this fact was accepted by Arora (1990) wherein he attributed this incompatibility to improperly chosen grid dimensions, large inter-station spacing etc. Keeping these facts in mind and on the basis of more field data and forward modelling, Arora (1990) modified his earlier model for this structure. Being aligned transverse to the Himalayan mountains, the conductive structure has been named the 'Trans Himalayan' conductor.

All the models so far derived were based on traditional trial and error methods of forward modelling. In order to check the validity of these models, a new 2-D inversion of GDS data has been attempted using the finite difference based inversion algorithm EM2INV (Rastogi 1997).

## 2. EM2INV, 2-D inversion algorithm

The inversion algorithm, EM2INV, is an efficient and reliable software package for 2-D inversion of geoelectromagnetic data (Rastogi 1997). Its validity and applicability are established through various theoretical experiment design exercises. The algorithm has been vigorously tested on a number of synthetic and numerical data sets.

The base of this finite difference algorithm is the formulation of the forward EM problem given by Brewitt-Taylor and Weaver (1976). In the finite difference method, the domain of study is discretized into a rectangular grid with blocks of constant resistivity. The Helmholtz equation is translated into a difference equation for each node. Special finite domain, integral and asymptotic, boundary conditions are designed to restrict the large extent of study domain (Weaver 1994). The asymptotic boundary

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conditions account for the asymptotic behaviour of field and restrict the horizontal extent of the grid. On the other hand, the integral boundary conditions restrict the vertical extent of the grid by transferring the integrated effect of overlying/underlying half-space at the respective horizontal boundary. These boundary conditions result in grid economy but perturb the sparsity structure of typical pentadiagonal finite difference coefficient matrix which gets transformed to block tridiagonal. The boundary conditions are used to set up the algebraic equations for internal nodes. The resulting matrix equation has been solved for field values using the Gaussian elimination matrix solver that exploits the special structure of the coefficient matrix.

The non-linear EM inverse problem is quasi-linearized and solved. The initial guess is made on the basis of observed anomaly and other *a priori* knowledge about the subsurface. Quasi-linearization results in a matrix equation with Jacobian matrix as the coefficient matrix, the parameter correction vector as the unknown vector and the difference between the observed and computed response as the known right hand side vector. The Jacobian matrix, comprising partial derivatives of observed response values with respect to block resistivities, is derived by differentiating the forward matrix equation with respect to block resistivities. The inverse problem equation is now solved for correction vector using Ridge regression (least square/minimum norm) estimator. After each iteration, the solution is checked for convergence. If it is not achieved, the next iteration starts with the updated resistivity values as the initial model. For confined targets, a region encompassing the anticipated target is chosen as inversion domain and its block resistivities as unknown parameters.

The inversion matrix equation is solved using Bi-Conjugate Gradient Method (BCGM), a semi-iterative matrix solver (Jacobs 1986; Sarkar 1991). It dispenses with the necessity of explicit computation of Jacobian matrix. For each BCGM iteration the forward matrix equation is solved twice with new right hand sides, it would score over direct matrix solver as long as the number of iterations needed for convergence of BCGM is less than half the number of blocks in inversion domain. In order to fix the number of unknown block resistivities for all frequencies and throughout the inversion process, a superblock notion has been developed. To ensure the positive value of resistivity, the logarithm of resistivity has been used in the algorithm.

EM2INV has been developed on an IBM compatible EISA based PC-486 machine with 32 MB RAM and 383 MB hard disk, using the SVR 4.0 version of Unix operating system and the F78 FORTRAN compiler. For a typical model, having 31 × 15 grid and needing 10 inversion iterations, the algorithm takes about 3 minutes.

Being an iterative one, EM2INV needs an educated guess of the model parameters to start the inversion process. The closer the initial guess to the true model, the faster is the convergence. For EM2INV, apart from using the *a priori* information about 1-D layered earth models, the better initial guess models which provide a rough idea about the body, are constructed on the basis of forward anomalies.

## 3. Numerical modelling

### 3.1 *Original model*

Arora and Mahashabde (1987) modelled the conductive structure using the 2-D formulation of Jones and Pascoe (1971). On the basis of numerical modelling results, they found that the observed induction pattern for period 46 min along the lesser Himalayas belt, could be explained by asthenospheric ridge, about 45 km wide with its top at a depth of 15 km and a resistivity of 2 ohm-m (figure 1a). The profile with station locations is displayed on top of the model.

The validity of the model has been established by comparing the observed and computed model responses. The observations for the period 46 min are shown in figure 1(b) using EM2INV. The computed results differ considerably from the observed ones (figure 1c). Singh and Pedersen (1988) also pointed towards this significant difference. It appears that there was something inherently wrong with the response computations carried out by Arora and Mahashabde (1987) otherwise such a drastic difference in forward response is not possible at all. This implies that the interpreted model is not appropriate.

The possible changes in the model by keeping the forward response unchanged have also been attempted. The change in lithosphere resistivity, from 10,000 ohm-m to 1,000 ohm-m, resulted in almost the same anomaly. Even when the top layer resistivity is reduced to 100 ohm-m the results do not seem to be affected much.

Next, 2-D inversion of the proposed model response using EM2INV has been performed. The extent of the grid for period 46 min ranges from −14,000 km to 11,300 km, whereas the sites are located from −90 to 130 km (figure 1a). Since the 7 station data have been used in deriving the field model the GDS response of initial guess model has also been computed at these points. The inversion domain has been identified from −40 to 40 km and 15 to 100 km in horizontal and vertical directions respectively. The attempts to invert data with 7 observation points and single frequency failed miserably and the convergence is not achieved for any of the models tried. This means that the data are insufficient for unconstrained 2-D inversion. To overcome this problem of limited *a priori* information, inversion has been attempted by increasing the number of
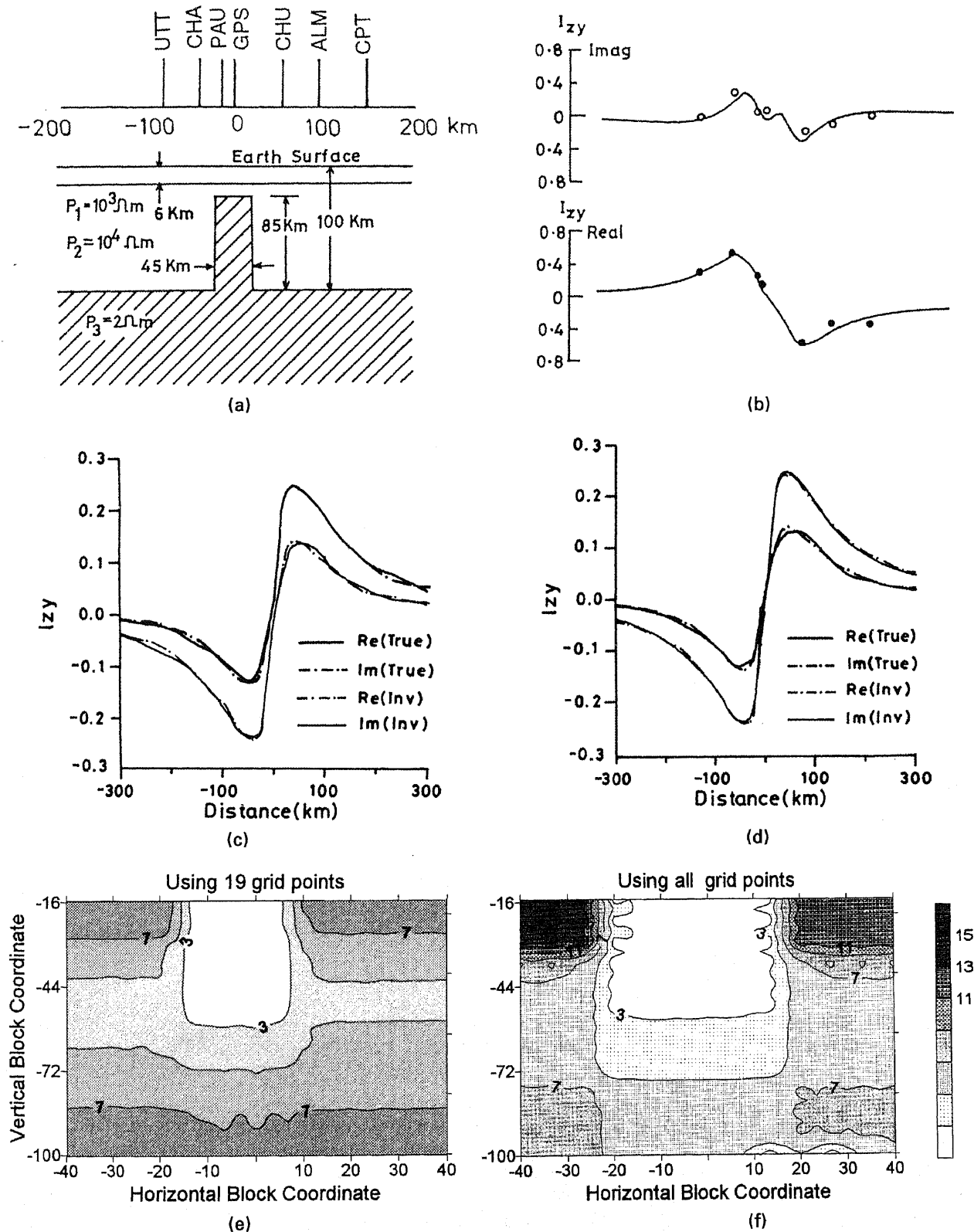
Figure 1(a–f).   (a) Proposed model for the conductor striking across the Himalayas (after Arora and Mahashabde 1987). (b) The real and imaginary parts of the observed GDS response. (c) and (d) The real and imaginary parts of GDS responses for two cases are compared with the computed model response. (e) and (f) The resistivity contours of inverted model within the inversion domain for the two cases.

synthetic observation points by adding points gradually on the left and right flanks of the profile till the convergence is achieved.

This exercise identified 19 observation points with the extent ranging from −250 to 200 km as the minimum number of data points needed for successful
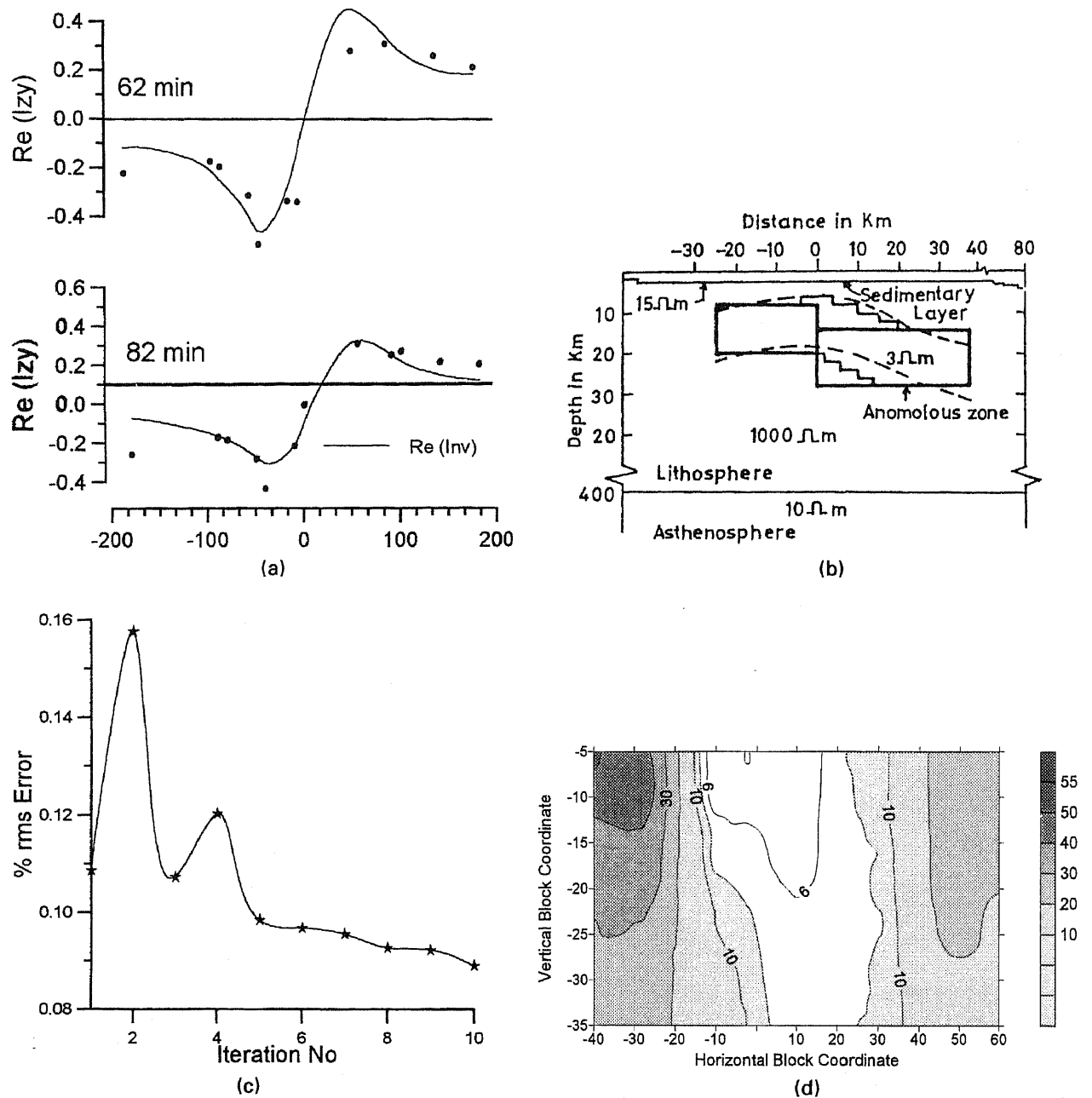
Figure 2(a–d).  (a) Comparison of the real part of inverted response of Trans Himalayan conductor model with the observations for three periods. (b) Modified geoelectrical model for the Trans-Himalayan conductor (after Arora 1990). (c) Convergence plot of % rms error of inversion. (d) The resistivity contours of the real part of GDS response of the inverted model within the inversion domain.

inversion. The inversion using the initial guess model with variable depth of burial could not succeed as it is difficult to derive vertical information from a single period data. As a result, the initial guess model with exact vertical extent has been taken. Besides, the inversion has also been performed using all the 40 grid points as observation points. The % relative rms error for 19 and 40 observation points are .015 and .01 respectively. Figures 1(c) and (d) indicate the excellent agreement between the observed and computed GDS response curves for both the real and imaginary components. Since the GDS responds to the lateral variations, the edges of the ridge have been recovered

in the resistivity contours within specified inversion domain. Increase in data points results in further refinement of the estimated model as is evident from figures 1(e) and (f) plotted, respectively, for 19 and 40 observation points.

### 3.2  Modified model

The highly differing responses, obtained by Arora and Mahashabde (1987) and Singh and Pedersen (1988) as well as EM2INV for a given model, may be an artifact of the inadequate choice of grid dimensions (Arora 1990). Furthermore, the accuracy of the computed

response depends on both the size and uniformity of the grid adopted in numerical modelling. Chamalaun *et al* (1987) have discussed about the factors contributing to the non-uniqueness of the Arora and Mahashabde (1987) models. The uncertainty, which arises due to the large station spacing, resulted in a poor definition of the observed response profile which ultimately determines the model parameters and their interpretation. The more realistic constraints on the best fitting model can be provided by comparing the responses over a wide range of frequencies. In addition, the denser network of observation stations need be utilized to define depth and boundaries of conductive bodies and the shape parameters of the conductor. The location sites of magnetometers together with the principal tectonic features of the region are discussed in detail by Arora (1990, 1993).

Arora (1990) found that the real part of GDS responses at periods 46, 62 and 82 min could be reproduced by the induction response of two tabular blocks of 3 ohm-m as shown in figure 2(a). The left block is approximated to have a width of 25 km, a thickness of 12 km with its top at a depth of 8 km. The right block with its top at a depth of 12 km is approximated to have a width of 38 km and thickness of 18 km. The inclusion of a surface conducting layer of thickness 2–3 km simulating conducting sediments of 15 ohm-m in the Indo-Gangetic plains, improves the fit for the real part of the anomaly (Arora 1993). The reliability of the modified model was tested by comparing the real part of the observed and calculated responses at three periods using 2-D FDM modelling approach of Brewitt-Taylor and Weaver (1976).

Field data were recorded only at 12 observation points (in km): −180, −90, −80, −50, −40, −10, 0, 55, 90, 100, 140 and 180 for periods 46, 62 and 82 min. Only the real component of observations, induction vector, is available. For EM2INV, the inversion domain has been identified as ranging from −40 to 60 km in horizontal and 5 to 35 km in vertical directions. The resistivity is assumed to be 10 ohm-m. The inversion has been performed using 12 sites as observation points.

The comparison of real components of the inverted model responses with observations is shown is figure 2(a) for 3 periods where observation sites are shown in bottom part of the figure. The error bars of the observations are marked by dots. Figure 2(b) presents % rms error of inversion (figure 2b). Though individual block boundaries are not clear, yet the side boundaries, which distinguish the block from the host are distinct in resistivity contours plotted for the inversion domain in figure 2(c).

The model obtained after inversion displays the presence of conductive structure at the centre of the anomaly ranging from −20 to 40 km. The boundaries of the two blocks are not clear. Thus, one can not say whether the model obtained by Arora (1990) is appro-

priate or not. Many other such models can give rise to the same response. Further, for demarcating vertical boundaries MT sounding data are needed. The joint inversion of the GDS and MT data, can yield a better picture of the subsurface resistivity distribution.

## 4. Conclusion

The GDS data of northwest Himalaya were analysed and a few models proposed for this conductivity structure. To establish the validity and accuracy of the modelling results the data have been inverted using 2-D inversion algorithm and the obtained model has been compared with the proposed model. It has been found that the inversion of GDS data can only decipher horizontal boundaries. For delineation of vertical boundaries MT sounding data are required. Further, the joint inversion of the two data sets can give detailed information about the structure.

## Acknowledgement

## References

Arora B R 1990 Magnetometer array studies in India: Present status, data interpretation and assessment of numerical modelling results; *Proc. Indian Acad. Sci. (Earth Planet Sci.)* **99** 693–716

Arora B R 1993 Implications of electrical conductivity structures in the tectonic framework of northwest India; *Curr. Sci.* **64** 848–855

Arora B R and Mahashabde M V 1987 A transverse conductive structure in the northwest Himalaya; *Phys. Earth Planet. Int.* **45** 119–127

Brewitt-Taylor C R and Weaver J T 1976 On the finite difference solution of two-dimensional induction problems; *Geophys. J. R. Astr. Soc.* **47** 375–396.

Chamalaun F H, Prasad S N, Lilley F E M, Srivastava B J, Singh B P and Arora B R 1987 On the interpretation of the distinctive pattern of geomagnetic induction in northwest India; *Tectonophysics* **140** 247–255

Jacobs D A H 1986 A generalization of the conjugate gradient method to solve complex system; *IMA. J. Numer. Anal.* **6** 447–452

Jones F W and Pascoe L T 1971 A general computer program to determine the perturbation of aternating electric currents in a two-dimensional model of a region of uniform conductivity with an embedded inhomogeneity; *J. R. Astr. Soc.* **24** 3–30

Lilley F E M, Singh B P, Arora B R, Srivastav B J, Prasad S N and Saloane M N 1981 A magnetometer array study in northwest India; *Phys. Earth Planet. Int.* 232–240

Rastogi A 1997 A finite difference algorithm for two-dimensional inversion of geoelectromagnetic data; *Ph.D thesis*, Department of Earth Sciences, University of Roorkee, Roorkee

Sarkar T K (ed) 1991 *Application of conjugate gradient method to electromagnetic and signal analysis*, Elsevier Science Publ. Co., Inc.

Singh R P and Pedersen L B 1988, A transverse conductive structure in the northwest Himalaya by B R Arora and M V Mahashabde; *Phys. Earth Planet. Int.* **53** 177–179

Weaver J T 1994 *Mathematical methods for geo-electromagnetic induction;* Research Studies Press, Taunton 316.