Geoelectric directionality analysis of a magnetotelluric (MT) survey in Parecis Basin (States of Mato Grosso and Rondônia), Brazil.

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Abstract

Eighty eight broadband (.001 – 1000 sec) magnetotelluric (MT) soundings have been made along a profile crossing the Parecis Basin (Mato Grosso and Rondônia) in a direction almost perpendicular to the main geological lineaments. The two-dimensional inversion (2-D) of MT data (constrained to well-log resistivity data) allowed to estimate the distribution of conductivity in subsurface. For the inversion procedure, the impedance tensors were rotated by an angle of 140° (± 10°) measured clockwise from the geographic north (E30°S – E50°S direction range) corresponding to the regional geological lineaments suggested by the main aeromagnetic data trend. An accurate interpretation of MT data requires an understanding of the dimensionality and directionality conditions that must be satisfied by the properties of impedance tensor. However, due to the usual presence of shallow, small-scale galvanic bodies which distort the responses, the regional scale structures can be masked. In order to verify if a geoelectric strike compatible with the previous choice for the geological strike can be found, we apply a tensor decomposition of MT data procedure (McNeice and Jones, 2001) for a set of 36 MT soundings in the profile. The results show that the distribution of strike angles is not uniform as expected, but the strike direction assumed *a priori* is compatible with the mean strike angle directions. The observed departures from an average angle value are investigated in terms of geotectonic structures of Parecis Basin and their influences in the geoelectric anisotropy. From a three-dimensional model of the basement topography based on downward continuation of gravity field constrained by spectral estimates of depth to magnetic sources (Braga et al, 1995), it is shown that the most regular strike angle distributions corresponds to the deepest sedimentary structures: Caiabís, Pimenta Bueno and Colorado Grabens. In the interface regions we expect anisotropy distorting strongly the regional impedance tensor.

Introduction

Parecis' Basin, one of the Brazilian intracratonic basins, is located in the center-west Region, covering an area of about 400.000 km^2 in Mato Grosso and Rondônia states (Fig. 1). Presently, Parecis' Basin is almost entirely covered by airborne (magnetics and gravity) and terrestrial (gravity) geophysical surveys. Recently, we perform a very long magnetotelluric (MT) sounding profile crossing the Basin in the direction almost N-S. It was assumed a 2-D dimensionality condition with a geoelectric strike suggested by the magnetic trend exhibited by the aeromagnetic surveys (Fig.2). The 2-D inversion of the MT profile was performed using a routine developed by Randi and Mackie (2001) which finds regularized solutions (Tikhonov regularization) to the two-dimensional inverse problem for MT data using the method of nonlinear conjugate gradients. The forward model simulations were computed using finite difference equations generated by network analogs to Maxwell's equations. The algorithm inverts for a user-defined 2D mesh of resistivity blocks, extending laterally and downwards beyond the central detailed zone, and incorporating topography (Fig.3). This inversion procedure was constrained by using well-logging resistivity data (exploratory well 2-SM-1-MT, Fig.5).

Method

The magnetotelluric (MT) method uses natural EM fields measured at Earth's surface to estimates the subsurface electrical resistivity. Amplitude, phase and directional relations between the electric field **E** and the magnetic induction **B** are connected by the 2x2 response impedance tensor $\underline{\mathbf{Z}}$: $\mathbf{E}=\underline{\mathbf{Z}}.\mathbf{B}$, but actual measurements of **E** and **B** are noisy so $\mathbf{E}=\underline{\mathbf{Z}}.\mathbf{B}+\varepsilon$. $\underline{\mathbf{Z}}$ is robust estimated from the recorded time series of **E** and **B** in the Fourier domain:

$$\left\langle \mathbf{Z}(\omega)\right\rangle = \left\langle \left(\mathbf{E}(\omega)\mathbf{B}(\omega)^{\mathsf{T}}\right)\right\rangle \left\langle \left(\mathbf{B}(\omega)\mathbf{B}(\omega)^{\mathsf{T}}\right)^{-1}\right\rangle \quad (1)$$

where T is the Hermitian transpose and the quantities in brackets are cross- and auto-powers of **E** and **B**. A 2-D dimensionality condition (i.e. the existence of a geoelectric strike) is described by the rotation relations for the impedance tensor

$$\mathbf{Z}_{\mathbf{obs}}(\theta_0) = \mathbf{R}(\theta_0)\,\mathbf{Z}_{\mathbf{2D}}\mathbf{R}^{\mathsf{T}}(\theta_0) = \begin{pmatrix}\cos\theta_0 & -\sin\theta_0\\ \sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}0 & Z_{xy}\\ Z_{yx} & 0\end{pmatrix}\begin{pmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{pmatrix} \quad (2)$$

where $\mathbf{Z}_{obs}$ is the observed impedance at the sounding station, **R** is a rotation tensor and $\mathbf{Z}_{2D}$ is the impedance rotated to the strike direction θ_0 measured from the geographic north. The corresponding field rotations are given by

$$\begin{cases} B_x(\theta)=Z_{xy}H_y(\theta), & \text{TE mode}\\ B_y(\theta)=Z_{yx}H_x(\theta), & \text{TM mode}\end{cases} \quad (3)$$

The strike direction θ_0 can be found by differentiating **Z** with respect to θ in order to give an angle θ_0 which maximizes or minimizes $\left|Z'_{xy}(\theta_0)\right|^2 + \left|Z'_{yx}(\theta_0)\right|^2$ for all frequencies giving: $4\theta_0 = \tan^{-1}$

$$\frac{\left[(\mathbf{Z_{xx}} - \mathbf{Z_{yy}})(\mathbf{Z_{xy}} + Z_{yx})^* + (\mathbf{Z_{xx}} - \mathbf{Z_{yy}})^*(\mathbf{Z_{xy}} + \mathbf{Z_{yx}})\right]}{\left|\mathbf{Z_{xx}} - \mathbf{Z_{yy}}\right|^2 - \left|\mathbf{Z_{xy}} + \mathbf{Z_{yx}}\right|^2} \quad (4)$$

This leaves four possible solutions or two strike directions with a $\pi/2$ ambiguity which can be solved from independent information (vertical magnetic data - tipper strike) or from geologic insights. The tipper is a MT quantity which depends on the vertical component of magnetic induction $\boldsymbol{B}_z$. This component is ≈ 0 except near lateral conductivity changes (2-D situations). The tipper $\boldsymbol{T}$ gives a relationship between $\boldsymbol{B}_z$ and the horizontal magnetic induction components: $\boldsymbol{B}_z=\boldsymbol{T}_x\boldsymbol{B}_x+\boldsymbol{T}_y\boldsymbol{B}_y$. For a 2-D structure with strike in the *x'* direction, in those coordinates, the tipper $\boldsymbol{T}$ reduces to $\boldsymbol{B}_z=\boldsymbol{T}_{y'}\boldsymbol{B}_{y'}$ (4a). This *x'* direction corresponds to the tipper strike angle (Vozoff, 1991).

Decomposition of MT impedance tensor.

A true 2-D conductive structure has an impedance tensor described by eq. (2). However, small local inhomogeneities will produce a galvanic, frequency independent distortion of the regional telluric currents. In this case, the observed impedance tensor is written as

$$\mathbf{Z_{obs}} = \mathbf{RCZ_{2D}R^T} \quad (5)$$

where **C** is a real telluric distortion tensor which can be factorized as a product of modified Pauli spin matrices:

$$\mathbf{C} = g\mathbf{TSA} \quad (6)$$

g is a scaling factor ("site gain"), **T, S** and **A** are tensors, called *twist*, *shear* and *anisotropy*, respectively. The factor *g* and anisotropy **A** form together the indeterminable part of **C** which is absorbed into the regional impedance, $\mathbf{Z}_{regional}=g\mathbf{AZ}_{2D}$. The *twist* tensor, **T**, and the *shear* tensor, **S**, are the determinable parts of **C**. **T** rotates clockwise the electric field produced by $\mathbf{SAZ}_{2D}$ through the *twist* angle *atan*(*t*) and **S** develops anisotropy on an axis which bisects the regional induction principal axes, rotating a vector by the *shear* angle, *atan*(*e*). The observed impedance expressed with the Groom-Bailey (1989) factorization becomes

$$\mathbf{Z_{obs}}(\theta_0) = \mathbf{RTSZ}_{regional}\mathbf{R^T}$$
$$= \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} 1-te & e-t \\ e+t & 1+te \end{pmatrix}$$
$$\text{x} \begin{pmatrix} 0 & A \\ -B & 0 \end{pmatrix}\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad (7)$$

Determination of the strike angle.

Following the above procedures, we have obtained frequency independent estimates of the *twist*, *shear* and regional *strike* for a set of 36 soundings stations from the MT profile using the *strike4.1* program of McNeice and Jones (2001, op.cit.). This can be done if these estimates can be found over a sufficiently wide band of frequencies. This is done by constraining iteratively the *twist*, *shear* and *strike* in order to find a frequency band where the misfit error is acceptable. We apply a four steps procedure: i) an unconstrained decomposition, were the distortion parameters were allowed to vary freely (-45^o < *shear* < 45^o), (-60^o < *twist* <60^o) and (-360^o <*strike*< 360^o); ii) we constrain the *twist* angle to its median value for a representative frequency range and we repeat the decomposition procedure; iii) the *twist* constrained data shows generally an improved stability in *shear*, then we constrain the *shear* angle at its median value over a representative frequency range and we repeat the decomposition procedure; iv) if the *twist* and *shear* constrained data results in a stability in *strike* angle over a representative period range, now we constrain the *strike* angle at its median value and we repeat the decomposition procedure, obtaining, finally, individual *strike* angles for each MT station. The strike angles obtained for each of the MT stations and an elucidating histogram with the angle distribution are shown schematically in Fig. 4 and Fig.5.

Discussion and conclusions.

The determination of regional strike in the presence of noise and galvanic distortion can leads to instability in decomposition procedures. This occurs for the sounding stations 02mt46, 02mt61, 03mt12 and 02mt15 when the decomposition analysis failed because the shear angles were very near to ± 45^o. In these cases the decomposition models becomes underdetermined. In order to recover the regional impedances, we use the strike found in adjacent stations or other independent information (like geological strike). The inherent $\pi/2$ ambiguity of the strike determination (Eq.4) was solved by using the tipper strike (Eq.4a). For most soundings, the average period range adopted as representative of stability in strike angle was 0.05 – 10 sec. The behavior of strike angle along the profile is not uniform as expected. The strike direction assumed *a priori* before the decomposition of MT impedance tensor is compatible with the mean calculated strike directions (Fig. 5). Our knowledge of the tectonic features of Parecis Basin comes from a three-dimensional model of the basement topography based on downward continuation of gravity field constrained by spectral estimates of depth to magnetic sources (Braga et al, 1995). The observed departures from an average strike angle value can be explained from the geotectonic structures of Parecis Basin and their influences in the geoelectric anisotropy. The most regular strike angles distributions correspond to the deepest sedimentary structures: Caiabís, Pimenta Bueno and Colorado Grabens (Fig.6). In the interface regions we can expect a geoelectric anisotropy which distorts strongly the regional impedance tensor.

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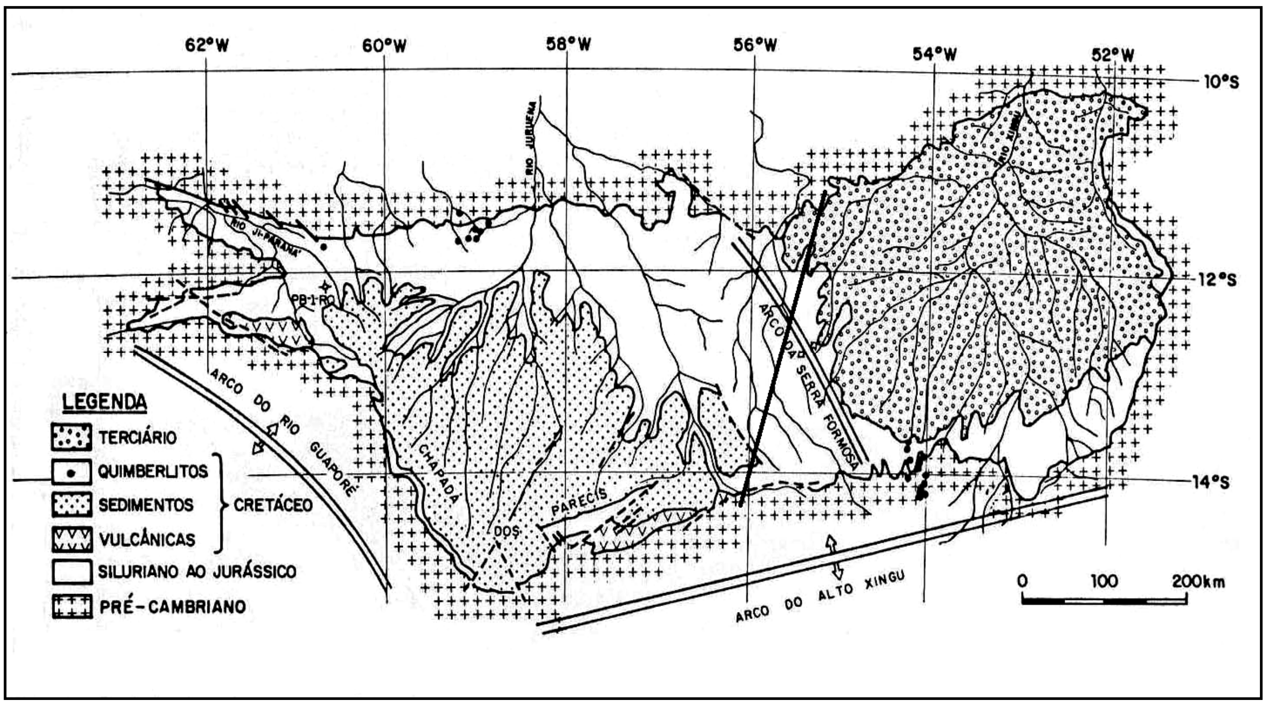

Fig.1 Geological map of Parecis Basin (simplified from Siqueira, 1989)

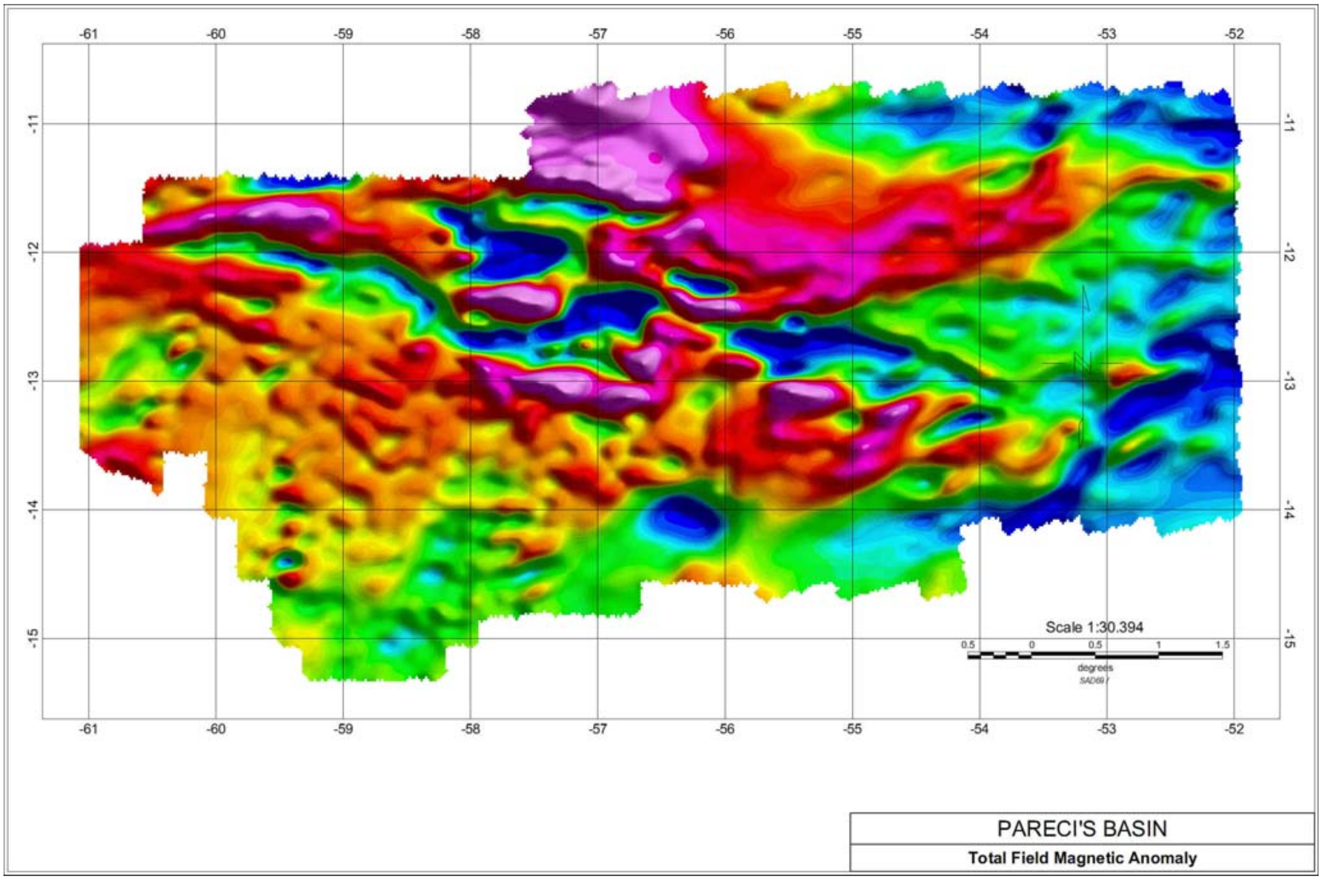

Fig. 2. The trend of the total field magnetic anomaly map suggest a geological strike in a direction (~E40^{o} – 50^{o}S). This direction was used to rotates the MT impedance tensors for the 2-D inversion (fig.3).

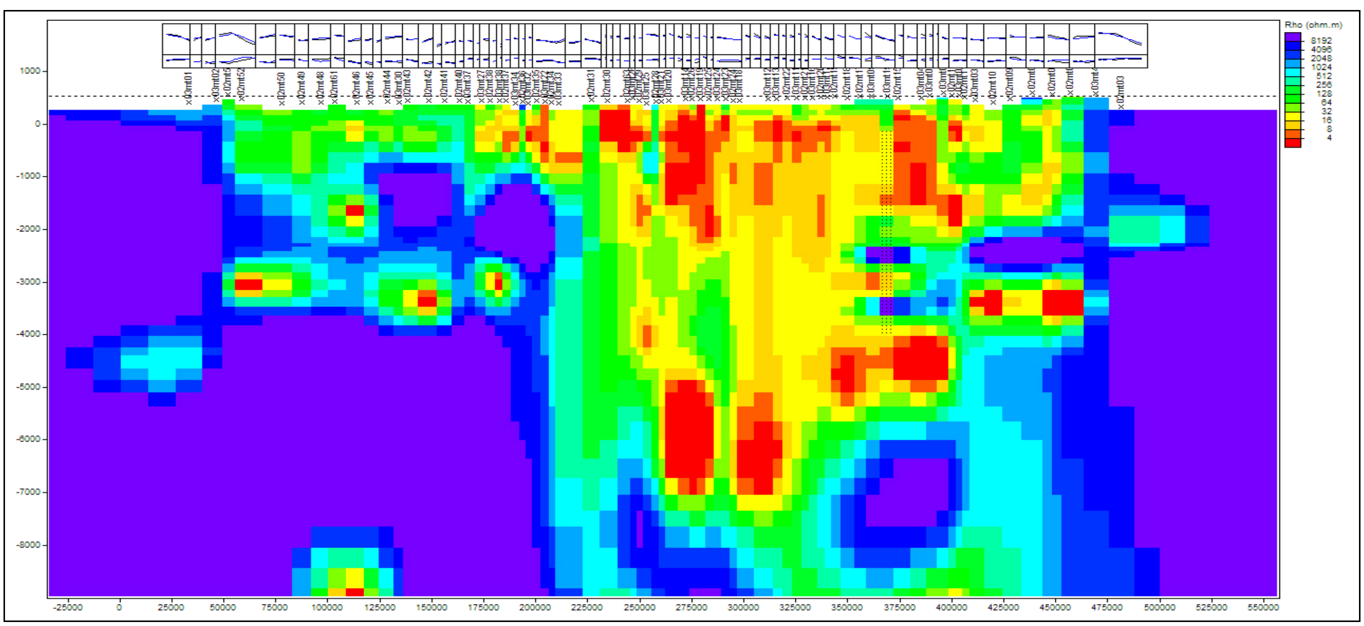

Fig 3. 2-D inversion of MT data of the Pareci's Basin profile (Flexor and Fontes, 2004)

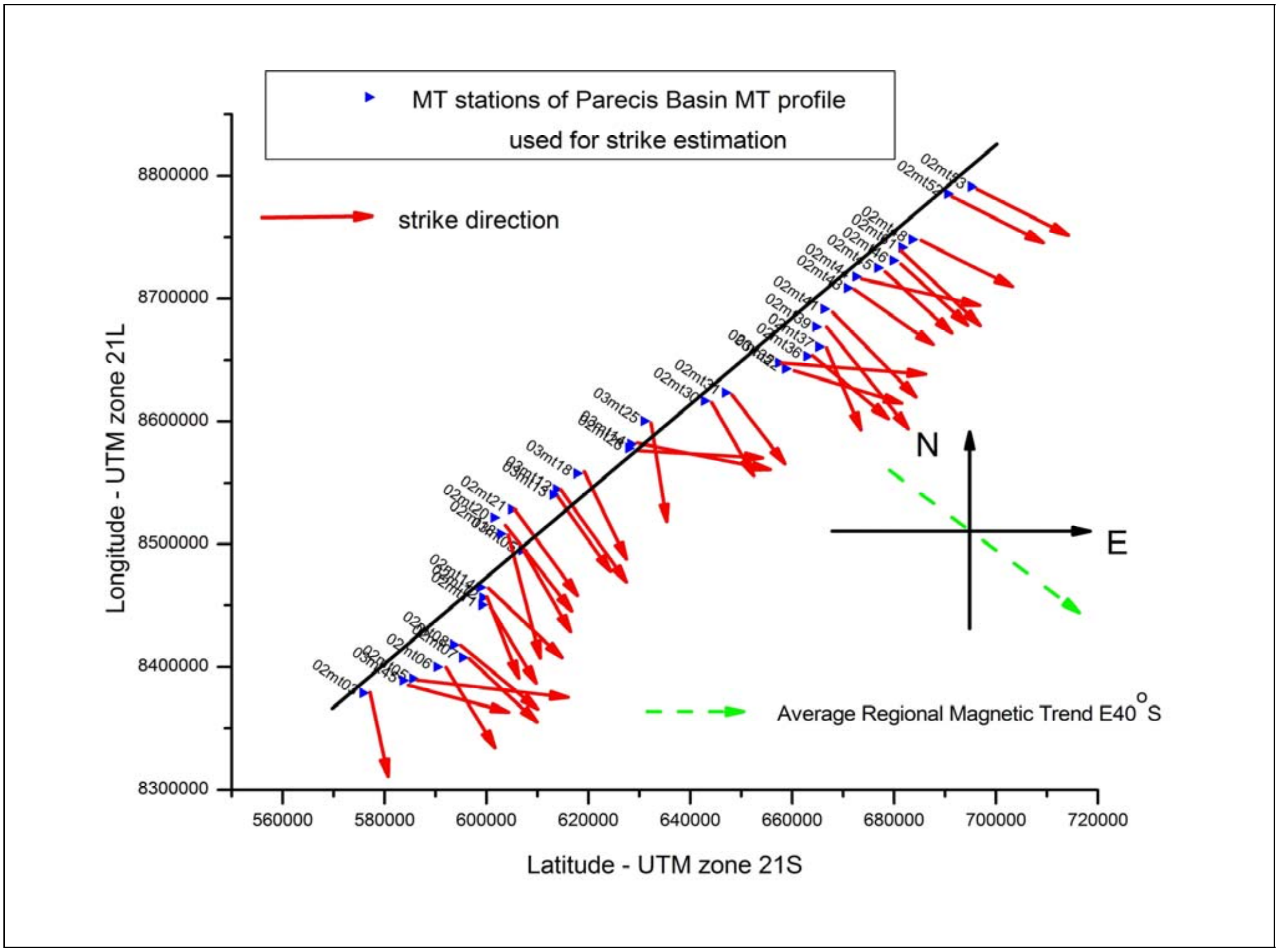

Fig.4. Geoelectric strike directions (red arrows) estimated at selected sounding stations of Parecis Basin MT profile.

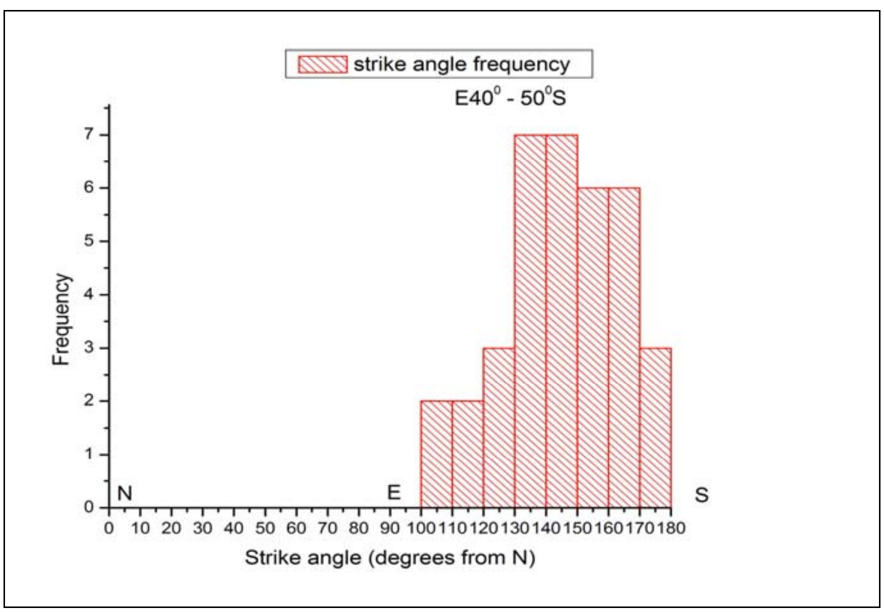

Fig.5 Histogram of the estimated geoelectric strike angles, showing the coherence with the *a priori* geological strike used for the 2-D inversion of MT data.

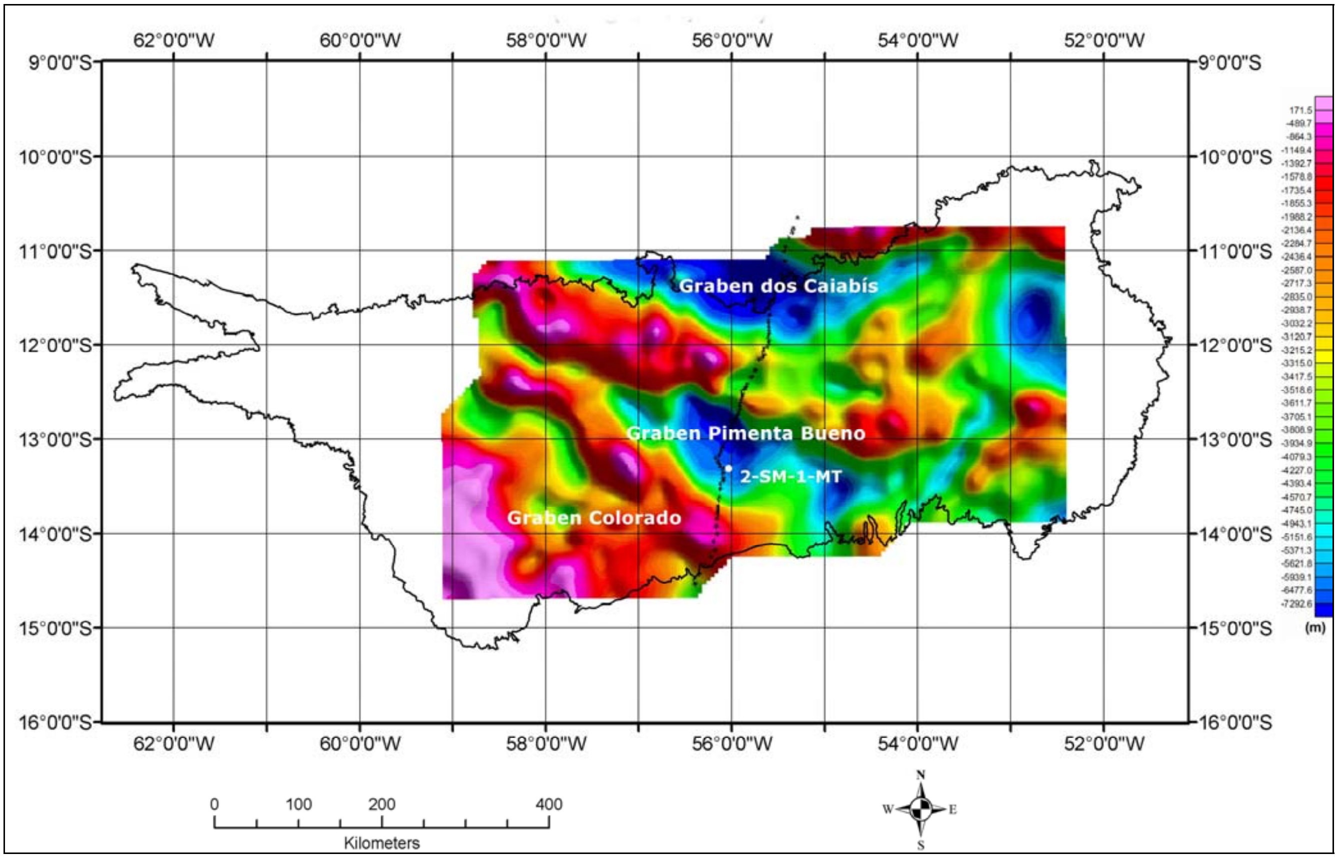

Fig. 6. 3-D gravity modeling of the basement topography beneath Parecis Basin and the main tectonic features. (Braga *et*. *al*. , 1995). The MT profile across the Basin and the exploratory well 2-SM-1-MT are shown.