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Publication Date
1980-05-01
Materials & Molecular Research Division

Submitted to Geophysics

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May 1980.

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Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48
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MAGNETOTELLURIC REGIONAL STRIKE

T. D. Gamble*,† W. M. Goubau*, R. Miracky** and J. Clarke**

ABSTRACT

A new method of choosing the coordinates for the magnetotelluric impedance tensor, \( Z \), and tipper, \( \tilde{T} \), involves the minimization of weighted sums of the squared magnitudes of elements of \( Z \) or \( \tilde{T} \) over all frequencies and all stations of interest. When applied to data from the area at the geothermal field at Cerro Prieto, Mexico, the method yielded orientations that agreed to within \( \pm 3.4^\circ \) for three lines of stations, and for a wide range of weighting functions.

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A magnetotelluric survey measures the relationship between the naturally occurring electromagnetic fields at the surface of the earth. These relationships are usually described in terms of the impedance tensor, $Z$, that relates the horizontal components of the electric field $\mathbf{E}$ to the horizontal components of the magnetic field $\mathbf{H}$ by $\mathbf{E}(\omega) = Z(\omega) \mathbf{H}(\omega)$, and the tipper $\mathbf{T}$ that relates the vertical magnetic field $H_z$ to $\mathbf{H}$ by $H_z(\omega) = T(\omega) \cdot \mathbf{H}(\omega)$.

A coordinate system must be chosen for the description of $Z$ and $T$. If the earth were one dimensional, i.e. horizontally layered, the elements of $Z$ and $T$ would be rotationally invariant so the choice of the coordinate orientation would be irrelevant. For many geological situations the earth is approximately two dimensional, that is, there is a horizontal direction in which the earth is approximately translationally invariant. If the earth were exactly two dimensional, the diagonal components of $Z$ and $T_x$ would be zero in a coordinate system with the x-axis aligned with the direction of translational invariance. A large number of criteria could be used to align the coordinates, for example, the minimization of $|Z_{xx}|$, $|Z_{yy}|$, $|Z_{xx}|^2 + |Z_{yy}|^2$, or $|T_x|^2$ or the maximization of $|Z_{xy}|$, $|Z_{yx}|$, $|Z_{xy}|^2 + |Z_{yx}|^2$ or $|T_y|^2$ (Sims and Bostick, 1969). Within the errors of measurement, all these criteria would determine the same orientation at all frequencies. There is, however, one important difference between the criteria involving $Z$ and those using $T$. The orientation determined from $T$ is unambiguous, while the criteria involving $Z$ may be satisfied with either the x or y axis aligned so that the orientation is always ambiguous by $\pm 90^0$.

The real earth is always three dimensional to some extent. There is no direction of translational invariance and all of the criteria designed to determine such a direction from the data yield different results which...
all vary with position and frequency. A large number of geological situations, however, contain, to a good approximation, only structures that are parallel or perpendicular to a regional strike direction. Examples of such structure are any two dimensional structure terminated by transverse faults, ridges with lateral erosion topology, or any structure limited to a narrow fault zone. Alignment of the coordinates so that most of the structure is either parallel or perpendicular to the axes will greatly simplify the description of such structure.

Any satisfactory method for orienting the coordinate system should satisfy three criteria: (1) It must in any event yield a fixed coordinate system for the description of all the results under consideration. It has become the custom to optimize one of the above criteria for each separate determination of Z or T, thus producing orientations that vary with frequency and position. Elements of Z or T are then presented as sounding curves or pseudosections but it makes no sense whatsoever to compare the results from different frequencies and/or positions that are referred to different coordinate orientations. Any quantitative inversion of magnetotelluric measurements obviously requires a fixed coordinate system. (2) If there is a direction for which the electrical structure is approximately translationally invariant, the method should align the coordinates with it and indicate which axis is along the strike. (3) In general, the method should align the axes so that as much of the structure as possible is either parallel or perpendicular to a given axis. This alignment must be stable, that is, it must not depend heavily on the particular sounding site or the range of measurement frequencies.

We propose a method of orienting the coordinates which satisfies these criteria. It involves the minimization of weighted sums of the squared
magnitudes of elements of $Z$ or $\hat{T}$ over all frequencies and positions of interest. This method is tested on real data from the area of the geothermal field at Cerro Prieto, Mexico. The geological strike for this region is fairly clear, but the three dimensional effects of the conductivity structure of the geothermal field cause the usual orientation of the coordinates to vary widely, often with no apparent relation between the tipper and impedance orientations. In contrast, the orientations from the new method are identical within $+3.4^\circ$ for three lines of stations and for a wide range of weighting functions.

REGIONAL STRIKE

The strike of a linear structure is simply the horizontal component of its direction. Obviously, for a two dimensional earth the strike is identical to the direction of translational variance. It is often assumed that for a more complex structure the direction of maximum translational invariance is the same as the regional strike. In fact, this is not the case and the relationships between the orientations from $Z$ and $\hat{T}$, the direction of maximum translational invariance, and the regional strike must be considered carefully.

Consider the relatively simple case (Fig. 1) of linear structures with uniform offsets. If we follow the structural geologist and define the strike as the axis of the linear structure (Hobbs et al., 1976), clearly this is the direction $a$. This is also the orientation of the rectilinear coordinate system that would be most appropriate for the description of this three dimensional structure. However, the direction for which the structure is most nearly translationally invariant is clearly $b$, since the blocks can be translated into each other along this direction. If we were forced to
match this structure by a two dimensional model, the best fit would be obtained with the direction of translational invariance in the direction b, but clearly, no two dimensional model could match the structure of the individual blocks. Strike determinations from T near the ends of the linear structures would indicate a strike that deviates widely from a. Determinations from Z, however, since they are always ambiguous by ±90°, would indicate that the strike is roughly parallel or perpendicular to a for all stations. Thus, any regional strike determination from Z involving a reasonable distribution of stations would be roughly aligned with a while that from T would be closer to the direction b.

Thus, the structural geologist and the three dimensional modeler would agree that the regional strike is in the direction a, close to the direction determined from a regional calculation involving Z (with a ±90° ambiguity). On the other hand, the two dimensional modeler would require the direction of maximum translational invariance, b, that is indicated by the tipper T.

THE ORIENTATION OF MAGNETOTELLURIC COORDINATES

Separate determinations of the orientation from each value of Z or T and at each frequency/station certainly do not provide an estimate for the best fixed coordinate system. One might consider taking some average of these individual angle determinations, but it is impossible to do so unambiguously because of the 90° ambiguity of the determination from Z or the 180° ambiguity in the definition of strike. The individual orientations often vary smoothly with frequency over a range of 90° or even more than 180°, forcing one to introduce arbitrary jumps of 90° or 180° between orientations at adjacent frequencies to maintain a sensible range of angles. One might simply present the results in a fixed coordinate system aligned with the regional strike as determined from other information. In our experience this would usually
be preferable to the usual varying orientations but such additional information 
may not be available. If the strike is misidentified it will make a relatively 
simple two dimensional geology appear totally uninterpretable. One would 
like to know that the orientation is in some sense optimum for the electrical 
structure. We have adopted the following procedure for determining the 
regional strike from magnetotelluric data.

First, we minimize the weighted mean squared value of the \( x \) component of the tipper, by minimizing

\[
A(o) = \sum_i W_i |T_{xi}(o)|^2,
\]

(1)

where the summation is over all stations and all frequencies under consideration.
The \( W_i \) are rotationally invariant weights that include as a factor the inverse of the expected variance of \( T_{xi} \). (Appendix I). We may also wish to weight the measurements from longer periods more heavily since they are sensitive to the structure in a larger volume of the earth. However, it is not clear \textit{a priori} just how strong this factor should be. It would seem that at least a factor \( t^{1/2} \) (\( t \) is the period) should be included to recognize the greater depth of penetration of the longer periods. If the earth were two dimensional, a weighting of \( t \) might be appropriate since this would be roughly proportional to the cross sectional area which affects each measurement. Weighting proportional to \( t^{3/2} \) would be roughly proportional to the volume to which each measurement is sensitive. An additional factor of \( t^{1/2} \) might be included in calculations involving \( Z \) since \(|Z|\) is proportional to \( t^{-1/2} \) for a homogeneous earth. However, the central idea of this approach to determine the strike direction is that any regional calculation involving a quantity with appropriate behavior under rotation will serve to determine the strike, if such a direction exists. Thus, weighting should not be important. The
The most important reason for our including a function of the period as a weight is to test whether the strike determination is in fact insensitive to the choice of weights. Thus, we take as the weighting function in the tipper calculation

$$W_i = f(t)N_i /(|\eta_T|^2|\vec{U}|^2),$$

where \(f(t)\) is some function of \(t\), \(N_i\) is the number of degrees of freedom in the estimate of \(T_{\xi_i}\),

$$\eta_T = H_z - \hat{T} \cdot \hat{H},$$

and \(\vec{U} = R[HR]^{-1}\).

In Eq(4), \([HR]\) is the crosspower spectral density matrix between \(\hat{H}\) and the reference field \(\vec{R}\). (Gamble (1978) and Gamble et al. (1979)). The extreme values of \(A(\phi)\) are obtained at angle

$$\phi_T = \frac{1}{2} \arctan \left[ \frac{\sum_i \text{Re}(T_{\xi_i}T_{\xi_i}^*)W_i}{\sum_i (|T_{\xi_i}|^2 - |T_{\eta_i}|^2)W_i} \right].$$

One can verify that a minimum rather than a maximum has been found by checking that

$$\frac{\partial^2 A}{\partial \phi^2} = \cos(2\phi_T) \sum_i (|T_{\eta_i}|^2 - |T_{\xi_i}|^2)W_i - 2\sin(2\phi_T) \sum_i \text{Re}(T_{\xi_i}T_{\xi_i}^*)W_i > 0.$$ (6)

From our discussion of regional strike, Eq.(5) should determine the direction of maximum translational invariance, which is the orientation of strike that should be used for a two dimensional model. The calculation is unambiguous. However, a structural geologist would not pick this direction for the regional strike, nor is this direction the optimum orientation for the description of the structure in rectilinear coordinates if the structure is not nearly two dimensional. To determine this direction we perform a
second calculation using \(Z_r\) to find a rotation \(\theta_Z\) that is within 45° of \(\theta_T\), and that defines the regional magnetotelluric strike unambiguously. Specifically, we find the angle \(\theta_Z\) that minimizes

\[
B(\theta) = \sum_i \left( |Z_{xxi}|^2 + |Z_{yyi}|^2 \right) W'_i
\]

where

\[
W'_i = f(t) N_i / \left( |\eta_Z| |\bar{Z}|^2 \right),
\]

and

\[
\eta_Z = \bar{Z} - Z H.
\]

The extreme values of \(B(\theta)\) are obtained at

\[
\theta_Z = \frac{1}{4} \arctan \left[ \frac{\sum_i \text{Real}(Z_{xyi} + Z_{yyi}) (Z_{xyi}^* - Z_{yyi}^*) W'_i}{\sum_i (|Z_{xyi}|^2 + |Z_{yyi}|^2) W'_i} \right].
\]

One must check that a minimum rather than a maximum has been found, and add an integral multiple of 90° to find a \(\theta_Z\) within 45° of \(\theta_T\). This orientation also maximizes the sum of the squared magnitudes of the off-diagonal elements of \(Z\), with the same weights.

In fact, \(W'\) is inversely proportional to the sum of the variances of all four impedance tensor elements while \(W_i\) is inversely proportional to the sum of the variances of \(T_{xyi}\) and \(T_{yi}\). Exact statistics would demand that each term in the sum be weighted by the inverse of its own variance. Unfortunately, the variances of the individual elements are functions of the orientation, and an exact statistical treatment leads to very complicated transcendental equations for \(\theta_Z\) and \(\theta_T\). However, if the concept of a regional strike is valid the angles should not depend strongly on the weights, and we feel that the tedious exact weighting is unnecessary.

Appendix II contains our computer program for the calculation of \(\theta_Z\) and \(\theta_T\).
EXAMPLE OF REAL DATA

Figure 2 shows the three lines DD', EE', FF' of our magnetotelluric sounding sites near the geothermal field at Cerro Prieto. Cerro Prieto volcano is an inactive cinder cone. The current zone of production is near the intersection of lines EE' and FF'. The nearest edge of the Sierra Cucapa range lies about 10 km to the west and has a strike about $30^\circ$ west of north. (We define all directions relative to magnetic north which is $14^\circ$ east of true north). The southern end of the imperial valley fault is about 12 km to the east with the same strike. At the production zone itself dipole-dipole and magnetotelluric measurements indicate that there is a narrow resistive zone extending to the south-southeast and a narrow conductive zone near the surface to the north-northwest, all in a zone of faulting with roughly the same strike. Thus, there is a clear regional strike about $30^\circ$ west of north, roughly the direction of line FF', but the large contrast between the conductive zone to the north and the resistive zone to the south prevents the electrical structure from being even approximately translationally invariant.

For stations near the Cucapas the strike determined by the usual calculations for both the tipper and impedance at periods larger than 10 seconds is roughly $30^\circ$ west of north. For the other stations this is not true. The results from station 5, line DD', are shown as a typical example. Figure 3 is the strike direction versus period determined by minimizing $\|T_x\|^2$. Figure 4 is the strike determined by minimizing $|Z_{xx}|^2 + |Z_{yy}|^2$ which is equivalent to maximizing $|Z_{xy}|^2 + |Z_{yx}|^2$. The two determinations are obviously very different. For periods longer than 10 seconds the impedance strike is fairly well defined at $35^\circ$ west of north, while the tipper strike averages about $48^\circ$ west of north, varying from $61^\circ$ to $29^\circ$ west. As the period decreases, the tipper strike moves...
monotonically towards the east reaching 30° east of north, while the impedance strike, although less well defined, moves consistently to the west, reaching almost due west. Near the production zone, the orientations are even more variable. At station 3 on line EE' and 10 on line FF', the tipper strike at about 1 second period is unambiguously perpendicular to the regional strike due to the contrast in resistivities between the north and south. Because of its ambiguity, the impedance strike could be interpreted to be either parallel or perpendicular to the regional strike. There is no stable orientation over any large range of periods.

We investigated the stability of our regional magnetotelluric strike determination by comparing the orientations found with different functions of the period as weights and at the stations on different lines. We calculated the regional strike for the stations on line DD' with four different weighting functions: \( f(t) = 1, t^{1/2}, t, \) and \( t^{3/2} \). The strike determinations from \( Z \) and \( \hat{T} \) with these weights are given in Table 1. They are remarkably consistent. Despite the fact that the relative weights of the long and short periods are varied by more than \( 10^6 \), the variation in the tipper estimate of strike varies by only \( \pm 0.4^0 \) while the impedance strike varies by \( \pm 2.3^0 \). The mean disagreement between the impedance and tipper strikes is \( 1.4^0 \). This is comparable to the uncertainty in the orientation of the telluric lines.

This agreement between the \( Z \) and \( \hat{T} \) determinations of strike indicates that the structure along DD' might be well matched by a two dimensional model. However, to ensure that a two dimensional model is appropriate, one must confirm that the component of \( \hat{T} \) in the strike direction and the diagonal components of \( Z \) are small in the coordinate system aligned with the regional strike. This is the case for line DD', along which the magnitudes and phases of the off-diagonal components of \( Z \) and the magnitude
and phase of $T_y$ have been closely matched by a two dimensional model (Gamble et al., 1980).

For the other two lines a two dimensional model is not appropriate. Table II lists the strike determined along the three lines with the same arbitrary weighting function $f(t)=t$. On line EE' the $Z$ and $T$ strikes disagree by more than 10° and on FF' by 3.2°. While this may not seem to be a significant discrepancy when compared to the usual variation in directions as seen in Figs. 2 and 3, it is larger than any of the discrepancies on line DD' for any weight in Table 1. Thus, we feel that any discrepancy between the strikes as determined from $Z$ and $T$ which is unambiguously larger than the location of the telluric lines would indicate that a two dimensional model of the earth will be insufficient.

On the other hand, we see that the regional strike as determined from $Z$ is essentially identical on all three lines: $-27.0° ± 1.5°$. All of the regional strikes determined from the impedance with the different weights and station locations fall in the range $28.9° ± 3.4°$. This both confirms our impression that there is a relatively well defined regional strike in the Cerro Prieto area and our assertion that a stable regional strike based can be determined by a regional calculation/on the measured values of $Z$ even though there are significant deviations from a two dimensional structure.

CONCLUSION

This method appears to yield a satisfactory quantitative determination of the regional strike direction from a group of magnetotelluric soundings. It provides a superior means of orienting the coordinates for the presentation of the measurements in that it defines a fixed coordinate system, it has shown itself to be extremely stable for real data; and it has determined a regional strike consistent with our knowledge of the
regional geology, even for lines of stations that traverse three dimensional structure.

Close agreement of the strikes determined from $Z$ and $T$ is a necessary but not sufficient condition for a two dimensional structure. They might be nearly identical simply by coincidence. A two-dimensional model is suitable only if the component of the tipper in the strike direction and the diagonal components of the impedance tensor are small at all frequencies and stations.
ACKNOWLEDGEMENTS

We are indebted to Professor K. Vozoff for impressing on us the importance of determining the strike direction properly. This work was supported by the Division of Materials Science, Office of Basic Energy Sciences, and Office of Geothermal Energy. U.S. Department of Energy.

REFERENCES


Table 1. Regional strike on line DD' estimated with different weighting functions

<table>
<thead>
<tr>
<th>Function of Period</th>
<th>Strike from Z</th>
<th>Strike from T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t^0$</td>
<td>-32.3°</td>
<td>-30.6°</td>
</tr>
<tr>
<td>$t^{1/2}$</td>
<td>-30.0°</td>
<td>-30.1°</td>
</tr>
<tr>
<td>$t$</td>
<td>-28.4°</td>
<td>-29.8°</td>
</tr>
<tr>
<td>$t^{3/2}$</td>
<td>-27.8°</td>
<td>-30.2°</td>
</tr>
</tbody>
</table>

Table 2. Regional strikes on different lines with $f(t)=t$

<table>
<thead>
<tr>
<th>Line</th>
<th>Z strike</th>
<th>T strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD'</td>
<td>-28.4°</td>
<td>-29.8°</td>
</tr>
<tr>
<td>EE'</td>
<td>-27.9°</td>
<td>-17.3°</td>
</tr>
<tr>
<td>FF'</td>
<td>-25.5°</td>
<td>-22.3°</td>
</tr>
</tbody>
</table>
APPENDIX I

DERIVATION OF THE VARIANCE OF $\hat{t}$

In the notation of Gamble et al. (1979), the referenced estimate for the tipper is $T = [H_z R] [HR]^{-1}$ where $[H_z R] = (H_z R_x^*, H_z R_y^*)$. The error in this estimate of $T$ is $\Delta T = [nR] [HR]^{-1}$, where $n$ is defined in Eq. (3).

Following the arguments of Gamble et al. (1979), under the conditions that the noises are stationary and independent of the signals, we find the expected variance of $T_j$ to be $\text{var}(T_j) = |\eta|^2 |A_j|^2 / (N|D|^2)$, $(j = x, y)$ where

$$A_x^* = R_x^* H_y R_x^* - R_x^* H_y R_y^*, \quad A_y^* = R_y^* H_y R_x^* - R_y^* H_y R_y^*, \quad \text{and} \quad D = H_x R_x H_y R_y - H_x R_y H_y R_x.$$

Equation (2) includes the inverse of the sum of the expected variance $T_x$ and $T_y$ with the definition $|\hat{\Omega}|^2 = (|A_x|^2 + |A_y|^2) / |D|^2$. 


PROGRAM STRIKE(INPUT,OUTPUT,TAPE3)
C    THIS PROGRAM READS THE IMPEDANCE, TIPPER AND ERROR INFORMATION FROM
C    TAPE3 AND CALCULATES THE MAGNETOTELLURIC REGIONAL STRIKE RELATIVE TO THE X
C    AXIS OF THE MEASUREMENT COORDINATE SYSTEM (RIGHT HANDED COORDINATE SYSTEM,
C    Z AXIS DOWN).
C
COMPLEX Z,TX,TY,ZB,ZS,ZD
DIMENSION NW(25),T(20,25),Z(4,29,25),E(2,20,25),A(2,20,25),EX1(20,
C29),EX2(20,25),AX1(20,25),AX2(20,25),TX(20,25),TY(20,25),ZN(20,25)
PI4=ATAN(1.) $ PI2=2*PI4
DO1 K=1,26
READ (3) NWI , (T(J,K), (Z(I,J,K), I=1,4), (E(I,J,K), A(I,J,K), I=1,2), E
C1(K), EX2(J,K), AX1(J,K), AX2(J,K), J=1,NWI)
K IS THE DATA BLOCK INDEX, J THE FREQUENCY INDEX AND T THE PERIOD.
C    THE MEAN SQUARE MAGNITUDE OF THE VECTOR ETA IN EQ. 8 IS|E(1,J,K)|^2 + |E(2,J,K)|^2.
C    THE MEAN SQUARE MAGNITUDE OF U DIVIDED BY N IS A(1,J,K)^2 + A(2,J,K)^2.
C    TX AND TY ARE THE COMPONENTS OF THE TIPPER. ZN(J,K) IS THE MEAN SQUARE
C    MAGNITUDE OF THE SCALAR ETA IN EQUATION 2.
IF (Z0F (3), NE, 0) GOTO 100
READ (3) (TX(J,K), TY(J,K),ZN(J,K), J=1,NWI )
1
NW(K)=NW1
100 NBLOK=K+1
CALCULATE TIPPER STRIKE (TANG) BETWEEN -135 AND 45 DEGREES
BOT=TOP=0.
DO2 K=1,NBLOK
NWIND=NW(K)
DO2 J=1,NWIND
W= ZN(J,K)/(A(1,J,K)+A(2,J,K))
W=W*SQRT(T(J,K))
BOT=BOT+W*(EX2(J,K)*CONJG(TX(J,K))-TY(J,K)*CONJG(TY(J,K)))+A
CONTINUE
TANG=ATAN(2*TOP/BOT)/2
IF (BOT*COS(TANG*2)+TOP*SIN(TANG*2)+0.1) TANG=TANG+PI2
PRINT 500,TANG*90/PI2
500 FORMAT(* DIRECTION OF MAXIMUM TRANSLATION INVARIANCE FROM TIPPER,*
CF8.2* DEGREES*)
TOP=BOT=0.
DO3 K=1,NBLOK
NWIND=NW(K)
DO3 J=1,NWIND
W= (E(1,J,K)*E(2,J,K))/(A(1,J,K)+A(2,J,K))
W=W*T(J,K)
ZS=Z(2,J,K)+Z(3,J,K)
ZD=Z(4,J,K)-Z(1,J,K)
TOP=TOP+W*REAL(ZS*CONJG(ZD))
BOT=BOT+W*(ZS*CONJG(ZS)-ZD*CONJG(ZD))
CONTINUE
ZANG=ATAN(2*TOP/BOT)/4
IF (BOT*COS(4*ZANG)+TOP*SIN(4*ZANG)+0.1) ZANG=ZANG+PI4
N=INT((ZANG-TANG)/PI4)
ZANG=ZANG+(N+SIGN(1,N))/2*PI2
PRINT 502,ZANG*90/PI2
502 FORMAT(* REGIONAL STRIKE FROM IMPEDANCE,*CF8.2* DEGREES*)
END
FIGURE CAPTIONS

Fig. 1. Simple example of linear structures with uniform offsets.

Fig. 2. Configuration of MT stations at Cerro Prieto, Mexico.

Fig. 3. Strike angle relative to magnetic north at station 5 obtained by minimization of $|T_x|^2$.

Fig. 4. Strike angle relative to magnetic north at station 5 obtained by minimization of $|Z_{xx}|^2 + |Z_{yy}|^2$. 
LOCATION OF MAGNETOTELLURIC STATIONS AT CERRO PRIETO, BAJA CALIFORNIA

Fig. 2
Fig. 3
Station 5

Rotation Angle (Degrees)

Period (Sec)

10^{-2} 10^{-1} 10^0 10^1 10^2 10^3

XBL791-5593

Fig. 4
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