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

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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, $\underset{\approx}{Z}$, and tipper, $\vec{T}$, involves the minimization of weighted sums of the squared magnitudes of elements of $\underset{\approx}{Z}$ or $\vec{T}$ 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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* Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley, California, 94720

** Department of Physics and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720.

† Present address: Ensco, Inc., 5408A Port Royal Road, Springfield, VA 22151.

INTRODUCTION

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

A coordinate system must be chosen for the description of $\underset{\approx}{Z}$ and $\vec{T}$. If the earth were one dimensional, i.e. horizontally layered, the elements of $\underset{\approx}{Z}$ and $\vec{T}$ 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 $\underset{\approx}{Z}$ 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 $\underset{\approx}{Z}$ and those using $\vec{T}$. The orientation determined from $\vec{T}$ is unambiguous, while the criteria involving $\underset{\approx}{Z}$ may be satisfied with either the x or y axis aligned so that the orientation is always ambiguous by $\pm 90^{\circ}$.

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 $\underset{\approx}{Z}$ or $\vec{T}$, thus producing orientations that vary with frequency and position. Elements of $\underset{\approx}{Z}$ or $\vec{T}$ 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 $\underset{\approx}{Z}$ or $\vec{T}$ 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 $\pm 3.4^{\circ}$ 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 $\underset{\approx}{Z}$ and $\vec{T}$, 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 $\vec{T}$ near the ends of the linear structures would indicate a strike that deviates widely from a. Determinations from $\underset{\approx}{Z}$, however, since they are always ambiguous by $\pm 90^{\circ}$, would indicate that the strike is roughly parallel or perpendicular to a for all stations. Thus, any regional strike determination from $\underset{\approx}{Z}$ involving a reasonable distribution of stations would be roughly aligned with a while that from $\vec{T}$ 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 $\underset{\approx}{Z}$ (with a $\pm 90^{\circ}$ ambiguity). On the other hand, the two dimensional modeler would require the direction of maximum translational invariance, b, that is indicated by the tipper $\vec{T}$.

THE ORIENTATION OF MAGNETOTELLURIC COORDINATES

Separate determinations of the orientation from each value of $\underset{\approx}{Z}$ or $\vec{T}$ at each frequency and 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 $\underset{\approx}{Z}$ 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

$$A(\Theta) = \sum_i W_i \, |T_{xi}(\Theta)|^2, \tag{1}$$

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 $\vec{T}_i$ (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 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

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

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

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

$$\eta_T = H_z - \vec{T}\cdot\vec{H}, \tag{3}$$

and $\vec{U} = \vec{R}[HR]^{-1}$. (4)

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

$$\Theta_T = \frac{1}{2}\arctan\left[\frac{\sum_i \mathrm{Real}(T_{xi}T^*_{yi})W_i}{\sum_i (|T_{xi}|^2-|T_{yi}|^2)W_i}\right]. \tag{5}$$

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

$$\frac{\partial^2 A}{\partial\Theta^2} = \cos(2\Theta_T)\sum_i (|T_{yi}|^2-|T_{xi}|^2)W_i - 2\sin(2\Theta_T)\sum_i \mathrm{Real}(T_{xi}T^*_{yi})W_i > 0\,. \tag{6}$$

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 $\underset{\approx}{Z}$ to find a rotation Θ_Z that is within 45^0 of Θ_T, and that defines the regional magnetotelluric strike unambiguously. Specifically, we find the angle Θ_Z that minimizes

$$B(\Theta) = \sum_i (|Z_{xxi}|^2+|Z_{yyi}|^2)W_i' \tag{7}$$

where

$$W_i' = f(t)N_i/(\overline{|\vec{n}_Z|^2}\,\overline{|\vec{U}|^2}), \tag{8}$$

and

$$\vec{n}_Z = \vec{E}-Z\vec{H}. \tag{9}$$

The extreme values of $B(\Theta)$ are obtained at

$$\Theta_Z = \frac{1}{4}\arctan\left[2\,\frac{\sum_i \mathrm{Real}(Z_{xyi}+Z_{yxi})(Z^*_{yyi}-Z^*_{xxi})W_i'}{\sum_i (|Z_{xyi}+Z_{yxi}|^2-|Z_{yyi}-Z_{xxi}|^2)W_i'}\right]. \tag{10}$$

One must check that a minimum rather than a maximum has been found, and add an integral multiple of 90^0 to find a Θ_Z within 45^0 of Θ_T. This orientation also maximizes the sum of the squared magnitudes of the off-diagonal elements of $\underset{\approx}{Z}$, with the same weights.

In fact, W_i' 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_{xi} 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 Θ_Z and Θ_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 Θ_Z and Θ_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° west of north. (We define all directions relative to magnetic north which is 14° 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° 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° 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° west of north, while the tipper strike averages about 48° west of north, varying from 61° to 29° 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 $\underset{\approx}{Z}$ and $\vec{T}$ 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 $\pm 0.4^{\circ}$ while the impedance strike varies by $\pm 2.3^{\circ}$. The mean disagreement between the impedance and tipper strikes is 1.4°. This is comparable to the uncertainty in the orientation of the telluric lines.

This agreement between the $\underset{\approx}{Z}$ and $\vec{T}$ 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 $\vec{T}$ in the strike direction and the diagonal components of $\underset{\approx}{Z}$ 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 $\underset{\approx}{Z}$ 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 $\underset{\approx}{Z}$ and $\vec{T}$ strikes disagree by more than 10^0 and on FF' by 3.2^0. 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 $\underset{\approx}{Z}$ and $\vec{T}$ 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 $\underset{\approx}{Z}$ is essentially identical on all three lines: $-27.0^0 \pm 1.5^0$. All of the regional strikes determined from the impedance with the different weights and station locations fall in the range $28.9^0 \pm 3.4^0$. This both confirms our impression that there is a relatively well defined regional strike in the Cerro Prieto area and confirms our assertion that a stable regional strike can be determined by a regional calculation based on the measured values of $\underset{\approx}{Z}$ 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 $\underset{\approx}{Z}$ and $\vec{T}$ 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 <u>and</u> the diagonal components of the impedance tensor are small at all frequencies and stations.

ACKNOWLEDGEMENTS

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

Function of Period	Strike from Z	Strike from T
t^0	-32.3^o	-30.6^o
$t^{1/2}$	-30.0^o	-30.1^o
t	-28.4^o	-29.8^o
$t^{3/2}$	-27.8^o	-30.2^o

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

Line	Z strike	T strike
DD'	-28.4^o	-29.8^o
EE'	-27.9^o	-17.3^o
FF'	-25.5^o	-22.3^o

APPENDIX I

DERIVATION OF THE VARIANCE OF $\vec{T}$

In the notation of Gamble et al. (1979), the referenced estimate for the tipper is $T = [H_z R]\,[HR]^{-1}$ where $[H_z R] = (\overline{H_z R_x^*}, \overline{H_z R_y^*})$. The error in this estimate of $\vec{T}$ is $\Delta_T = [\eta R]\,[HR]^{-1}$, where η 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 $\mathrm{var}\,(T_j) = \overline{|\eta|^2}\,\overline{|A_j|^2}/(N|D|^2)$, $(j = x,y)$ where $A_x^* = R_x^*\overline{H_y R_y^*} - R_y^*\overline{H_y R_y^*}$, $A_y^* = R_y^*\overline{H_x R_x^*} - R_x^*\overline{H_x R_y^*}$, and $D = \overline{H_x R_x^*}\,\overline{H_y R_y^*} - \overline{H_x R_y^*}\,\overline{H_y R_x^*}$. Equation (2) includes the inverse of the sum of the expected variance T_x and T_y with the definition $\overline{|\vec{U}|^2} = (\overline{|A_x|^2} + \overline{|A_y|^2})/|D|^2$.

```
      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).
      COMPLEX  Z,TX,TY,ZB,ZS,ZD
      DIMENSION NW(25),T(20,25),Z(4,20,25),E(2,20,25),A(2,20,25),EX1(20,
     C25),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
     CX1(J,K),EX2(J,K),AX1(J,K),AX2(J,K),J=1,NWI)
C         K IS THE DATA BLOCK INDEX, J THE FREQUENCY INDEX AND T THE PERIOD.
C  THE MEAN SQUARED MAGNITUDE OF THE VECTOR ETA IN EQ. 8 IS E(1,J,K)+E(2,J,K).
C  THE MEAN SQUARED MAGNITUDE OF U DEVIDED BY N IS A(1,J,K)+A(2,J,K).
C  TX AND TY ARE THE COMPONENTS OF THE TIPPER. ZN(J,K) IS THE MEAN SQUARED
C  MAGNITUDE OF THE SCALAR ETA IN EQUATION 2.
      IF(EOF(3).NE.0) GOTO100
      READ(3) (TX(J,K),TY(J,K),ZN(J,K),J=1,NWI  )
  1   NW(K)=NWI
  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= 1. /ZN(J,K)/(A(1,J,K)+A(2,J,K))
      W=W*SQRT(T(J,K))
      BOT=BOT+W*(TX(J,K)*CONJG(TX(J,K))-TY(J,K)*CONJG(TY(J,K)))
      TOP=TOP+REAL(TX(J,K)*CONJG(TY(J,K)))*W
  2   CONTINUE
      TANG=ATAN(2*TOP/BOT)/2
      IF(BOT*COS(TANG*2)+2*TOP*SIN(TANG*2).GT.0.)TANG=TANG-PI2
      PRINT500,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=1.    /(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))
  3   CONTINUE
      ZANG=ATAN(2*TOP/BOT)/4
      IF(BOT*COS(4*ZANG)+2*TOP*SIN(4*ZANG).LT.0.)ZANG=ZANG-PI4
      N=INT((ZANG-TANG)/PI4)
      ZANG=ZANG-((N+ISIGN(1,N))/2)*PI2
      PRINT 502,ZANG*90/PI2
  502 FORMAT(* REGIONAL STRIKE FROM IMPEDANCE,*F8.2* DEGREES*)
      END
```

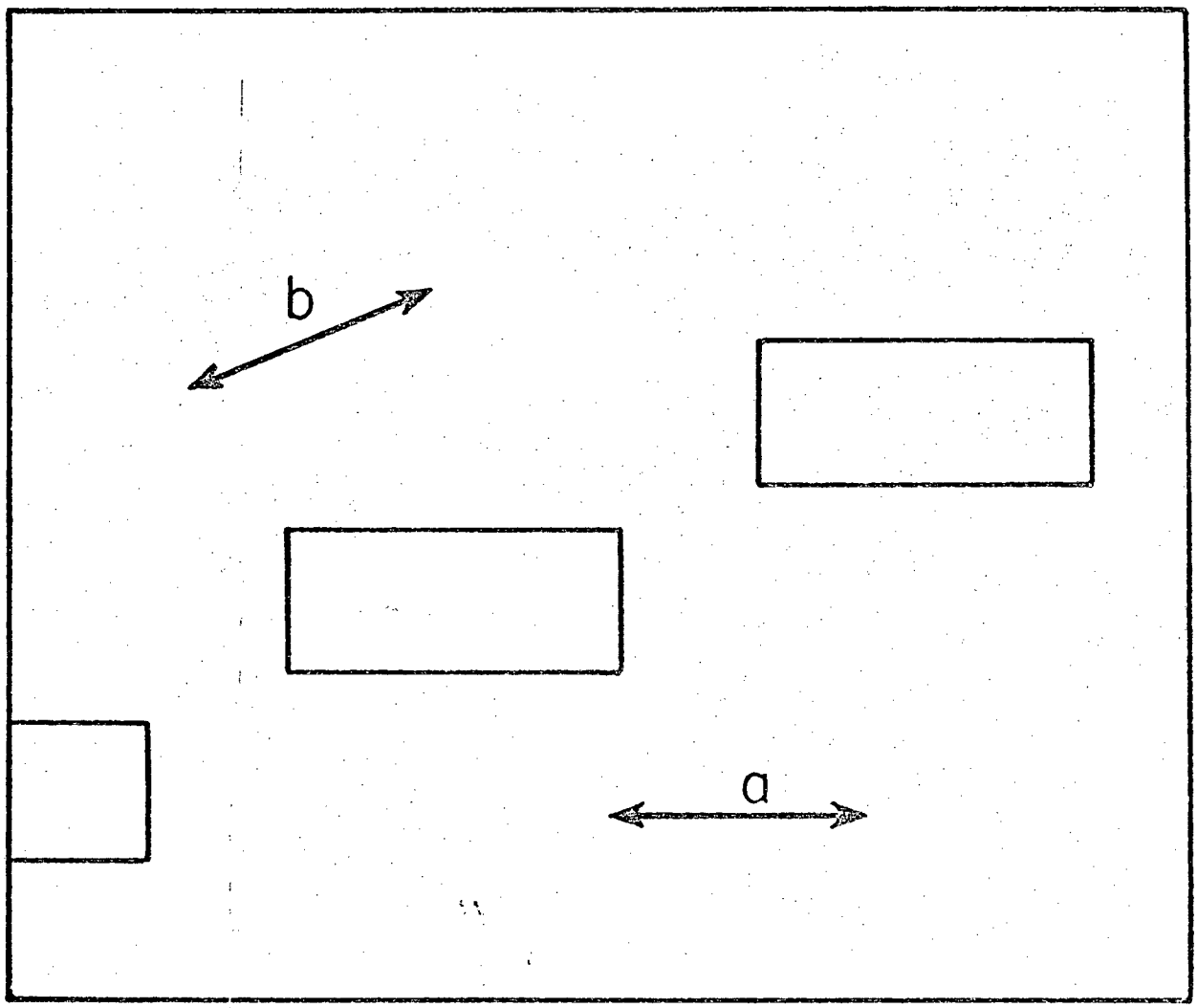
FIGURE CAPTIONS

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 $|T_x|^2$.

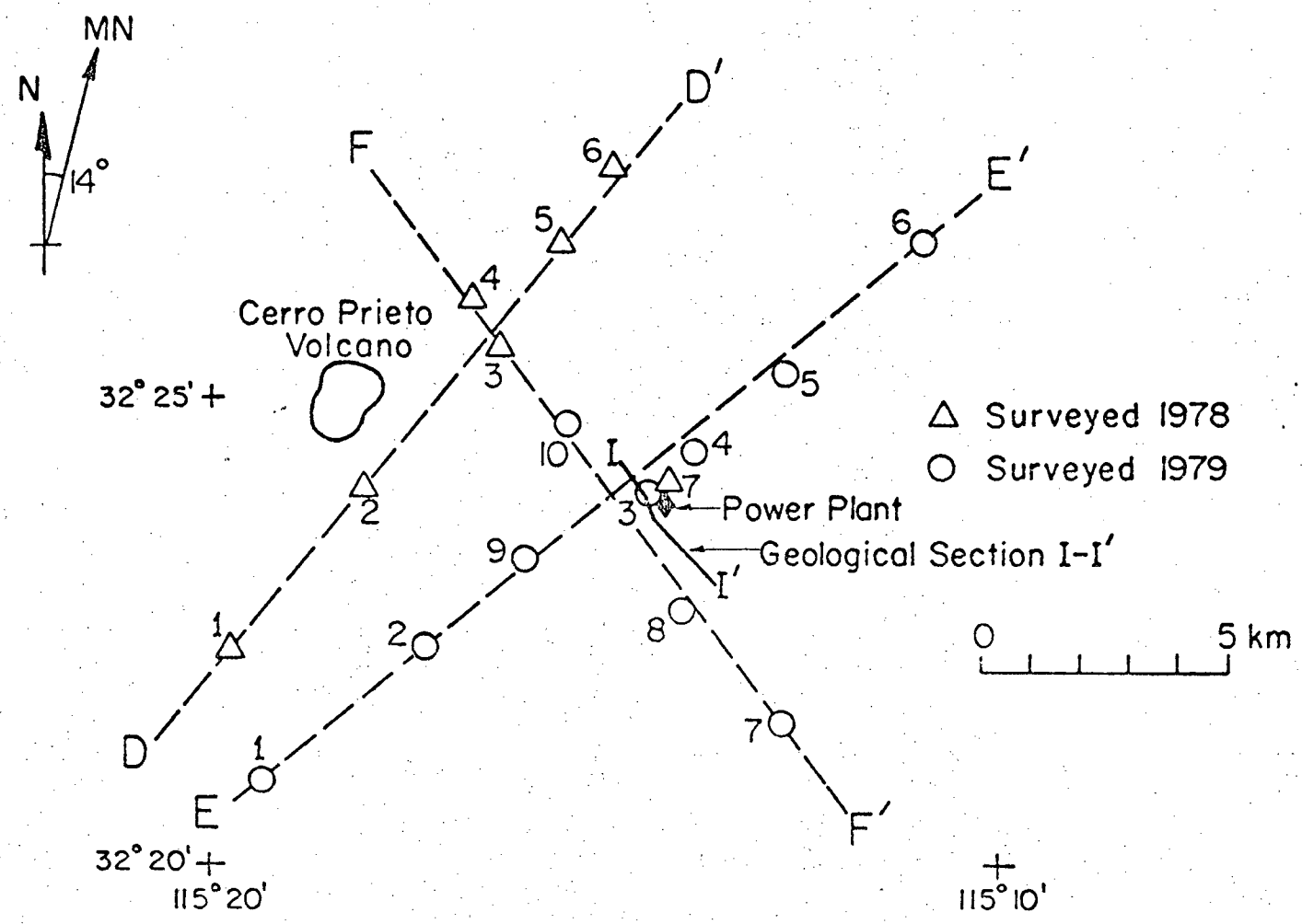
Fig. 4. Strike angle relative to magnetic north at station 5 obtained by minimization of $|Z_{xx}|^2 + |Z_{yy}|^2$.



XBL 803-4931

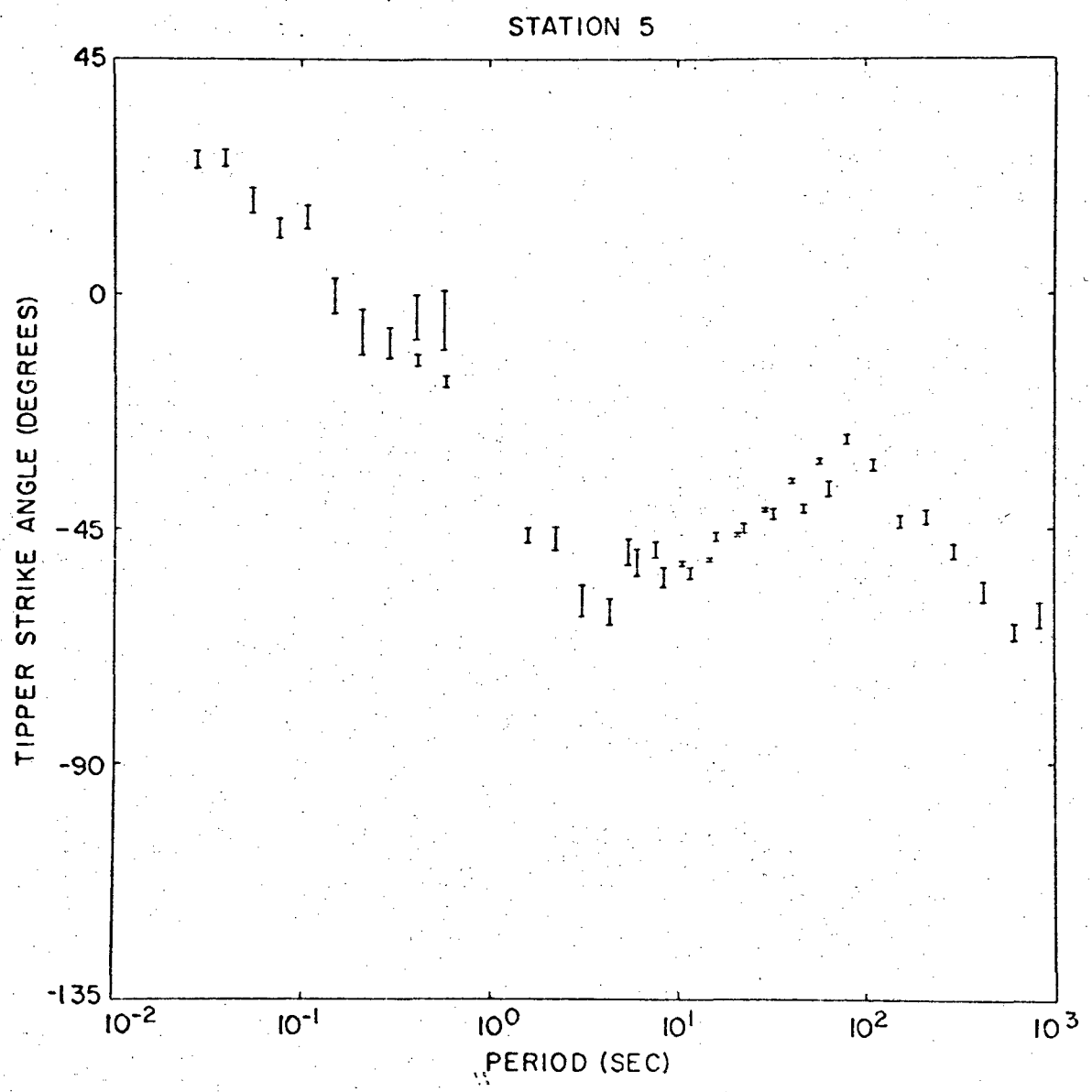
Fig. 1

LOCATION OF MAGNETOTELLURIC STATIONS
AT CERRO PRIETO, BAJA CALIFORNIA



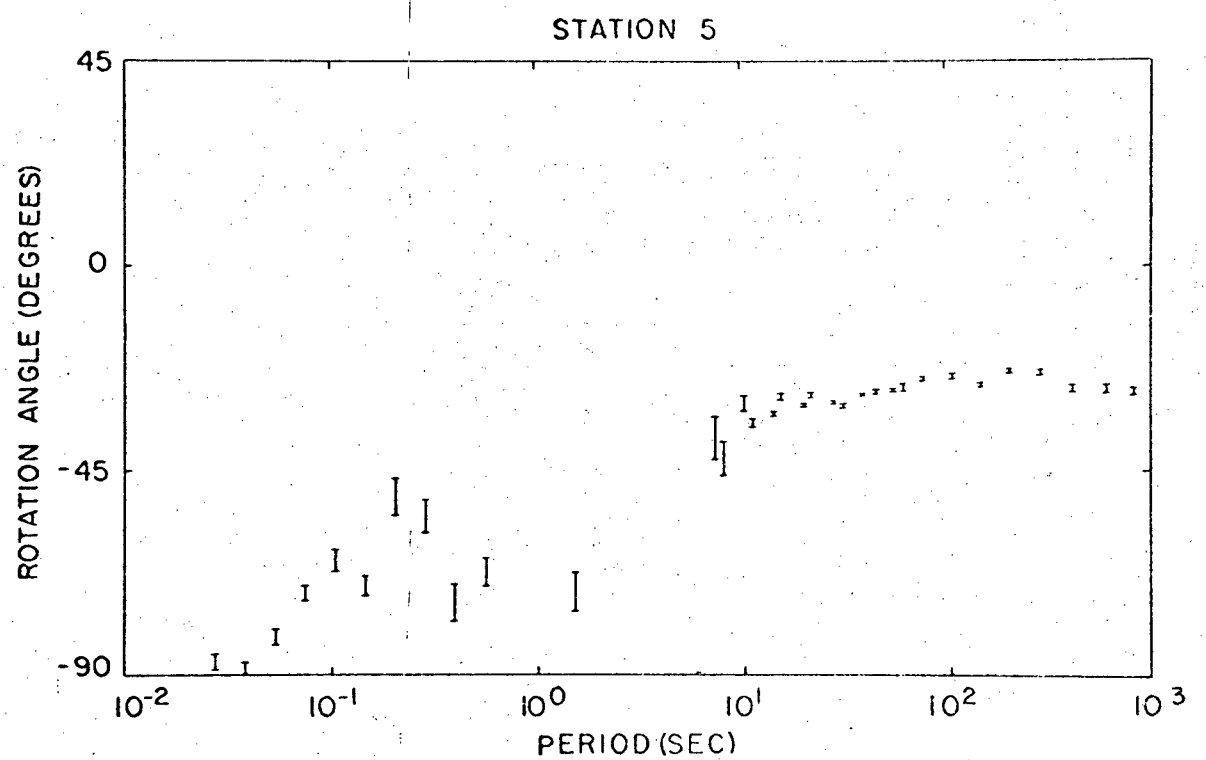
XBL 7911-12866

Fig. 2



XBL 791-5595

Fig. 3



XBL791-5593

Fig. 4

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