Crustal variations and terrane boundaries in southern Mexico as imaged by magnetotelluric transfer functions

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Abstract

To investigate the complex crustal structure of southern Mexico magnetotelluric (MT) data were acquired at 75 stations along two north–south profiles, 200–250 km apart, crossing several terrane boundaries whose interpretation has been controversial in the literature. Resulting sounding curves can be grouped, according to their shapes, into 10 different sets. Each of them may represent a crustal unit with a characteristic depth dependent electrical conductivity distribution. Often, the spatial extent of such a crustal unit matches well with a geological terrane. However, we also observed transition zones or sharp contrasts in crustal electrical properties which do not correspond to any defined terrane boundary. Transition zones are associated with low angle crustal structures (regional thrust faults or mylonitic zones) and/or with areas of plutonism, which are adding heterogeneities to the crust. In other cases our data suggest that terrane boundaries proposed on the basis of surface geology are probably shallow structures, which may not continue at depth. The comparison of apparent resistivity profiles with the available geologic information indicates that the MT method is capable of clearly defining zones affected by recent and active volcanism and tectonics as well as the part of the crust with Paleozoic and Precambrian metamorphic rock assemblages. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The terrane concept refers to geological entities of regional extent characterized by a coherent stratigraphic sequence and bounded by major tectonic discontinuities (Coney, 1989). The first application of terrane analysis in Mexico by Campa and Coney (1983) led to the definition of 14 terranes (Fig. 1).

According to their work most of western and southern Mexico would have been aggregated by exotic blocks formed in oceanic environment and successively accreted to the North America plate in Mesozoic times. Since then new terranes were proposed and the nature and boundaries of others were redefined (e.g. Grajales-Nishimura, 1988; Ratschbacher et al., 1991; Sedlock et al., 1993; Lang et al., 1996). However, the substance of the Campa and Coney (1983) classification has remained.

The location of terrane boundaries as well as their
Fig. 1. Map of southern Mexico with terrane boundaries according to Campa and Coney (1983) with MT profiles A-A', B-B'.
kinematics and their geometry at depth has been especially controversial in southern Mexico. The boundaries of the Guerrero, Mixteca, Oaxaca, Juárez and Xolapa terranes have been modified (e.g. in Sedlock et al., 1993) and the mere existence of some of them has been questioned (Ratschbacher et al., 1991; Herrmann et al., 1994; Lang et al., 1996). Part of the discussion probably arose because terrane definition often is based on relatively scarce surface geologic information and because published borehole and seismic reflection data are not available.

The magnetotelluric (MT) method involves the measurement of orthogonal components of natural electric and magnetic fields, which by inductive coupling contain information about the electrical conductivity distribution at crustal and upper mantle depths. This electromagnetic method is particularly well suited for studying regional structures and may help in defining crustal variations and terrane boundaries based on lateral changes of conductivity. We present the results of a total of 75 long period MT soundings at stations aligned in two north–south trending, coast-to-coast profiles, which cross some of the most debated terranes in southern Mexico.

2. Crustal structure of terranes in southern Mexico

In the studied region (Fig. 1), the cratonic block represented by the Paleozoic and Precambrian complexes of the Mixteca and Oaxaca terranes is bounded to the west and to the east by volcanic and sedimentary assemblages of Mesozoic age belonging to the Guerrero and Juárez terranes, respectively (the original terrane names of Campa and Coney, 1983, are used throughout the text). These four terranes are in turn bounded to the south by the high grade metamorphic rocks of the Xolapa terrane, which is intruded by Tertiary plutons. Terrane boundaries are obscured to the north by the Trans-Mexican Volcanic Belt (TMVB), the volcanic arc formed as a result of the subduction of the Cocos and Rivera plates since the late Miocene (Ferrari et al., 1999). North of the TMVB the Late Jurassic to Cretaceous carbonate and shallow marine clastic rocks of the Sierra Madre Oriental fold-thrust belt and the late Tertiary and Quaternary sediments of the coastal plain of the Gulf of Mexico mostly cover the Precambrian and Paleozoic basement of the Sierra Madre and Coahuila terranes.

In recent years, several works shed light into the structure of the basement of this region. One of the main advances of the past decade was the recognition that much of eastern and southern Mexico is underlain by a Grenvillian-type basement which was part of an ancient microcontinent named “Oaxaquia” (Ortega-Gutiérrez et al., 1995; Lawlor et al., 1999). This Precambrian basement is thought to underlie the Mixteca, Oaxaca, Maya, Sierra Madre and Coahuila terranes. In addition, lower crust xenoliths and Nd model ages of magmatic rocks permit the inference of a similar Precambrian basement to the west of the Mixteca terrane at least up to longitude 100°30' (Centeno-García et al., 1993; Elias-Herrera and Ortega-Gutiérrez, 1998; and references therein). To the east of the Oaxaca terrane Carfantan (1986) speculated on the existence of a Jurassic and Cretaceous times (Cuicatecan basin). However, this hypothesis has never been convincingly demonstrated (e.g. Delgado-Argote et al., 1992) and is not confirmed by published paleo-plate reconstructions for this period (Pindell, 1994; Meschede and Frisch, 1998).

According to recent field works, between Oaxaca and Cuicatlán there is neither evidence of an oceanic basin nor has a volcanic arc of Late Jurassic–Early Cretaceous age been evidenced but rather an intracontinental basin with terrigenous and carbonate sedimentation which covered unconformably both the Oaxaca and the Juárez terrane (Ferrari and Solari, 2000).

The southernmost slice of southern Mexico is occupied by the Xolapa terrane (Fig. 1). Several works have shown that the continental margin of southern Mexico has been truncated and uplifted during mid- to late Tertiary times. Particularly, geochronologic, paleotectonic and geobarometric studies demonstrated that the Xolapa terrane represents portions of lower continental crust exhumed and deformed by left-lateral shear since the Oligocene as a result of the eastward migration of the North America–Cocos–Chortis triple junction (Herrmann et al., 1994; Schaaf et al., 1995; Morán-Zenteno et al., 1996; Tolson, 1998). The boundary of the Xolapa terrane with the Mixteca and Oaxaca terranes is a dominantly left-lateral mylonitic zone, named the
Tierra Colorada, Juchatengo, and Chacalapa fault zone (Ortega-Gutiérrez et al., 1990; Ratschbacher et al., 1991; Meschede et al., 1996).

Seismic refraction data and gravimetric studies indicate that the crustal thickness reaches a maximum of 45 km beneath the cratonic block formed by the Oaxaca and Mixteca terranes (Valdez et al., 1986; GEOLIMEX Working Group, 1994; Urrutia-Fucugauchi and Flores-Ruiz, 1996) and in the western part of the Sierra Madre terrane (Steinhart and Meyer, 1961). It decreases by over 10 km in the central part of the Guerrero terrane (Zihuatanejo sub-terrane) and in the southern Juárez terrane (Ortega-Gutiérrez et al., 1990; GEOLIMEX Working Group, 1994; Urrutia-Fucugauchi and Flores-Ruiz, 1996; García-Perez and Urrutia-Fucugauchi, 1997). Based on these data, it can be inferred that the western part of the Guerrero terrane as well as the Juárez terrane are constituted by a thinned continental crust.

3. Magnetotelluric measurements and transfer functions

Our MT measurements were carried out along two profiles A-A’ and B-B’ (Fig. 1). On line A-A’, which is part of the multidisciplinary project of the GEOLIMEX transect (GEOLIMEX Working Group, 1994), the MT sites had a separation of 10–12 km and on line B-B’ of 10–15 km. The period range covers 0.25–4096 s and the recording time was 2–3 days to ensure sufficient data quality at long periods. The MT study was, primarily, aimed at the detection of conductivity signatures related to the subducting Cocos plate together with a general comprehension of the conductivity distribution of the deep subsurface. The first results were presented by Arzate et al. (1995) and Pareja-López et al. (2000), but here we discuss our observation that the various terranes and their boundaries, as crossed by the two profiles (Fig. 1), are distinguishable by means of basic MT transfer functions, which describe amplitude and phase relations between magnetic and electric fields. These transfer functions were calculated using Fourier transforms of time variations of the horizontal electric field $E = (E_x, E_y)$ (in mV/km) and the horizontal magnetic induction $B = (B_x, B_y)$ (in nT) through the linear bivariate equations:

$$E_x = Z_{xx}B_x + Z_{xy}B_y$$
$$E_y = Z_{yx}B_x + Z_{yy}B_y$$

with elements of $Z$ denoting the transfer tensor which for different periods, depending on the penetration depth of the electromagnetic fields (“skin depth”), characterizes the change of conductivity versus depth at a specific site. Estimation of $Z$ has been performed using well-known multiple regression techniques (e.g. Sims et al., 1971), and can be written as, e.g.:

$$Z_{xy} = \frac{[B_xB'_x][E_yE'_y] - [E_xB'_x][B_yE'_y]}{[B_xB'_x][B_yE'_y] - [B_xE'_x][B_yB'_y]}$$

where $[B_xB'_x]$ denotes Gaussian summation.

In case of low energy in the magnetic channels or of correlated artificial noise in the time series the data quality of the tensor elements had to be improved. Data selection after careful visual inspection of time series was the most powerful tool for data improvement but multiple coherency based rejection or weighting of spectra (Jenkins and Watts, 1968) were also applied. As the last step, the more illustrative apparent resistivity and phase curves (“sounding curves”) were derived from off-diagonal tensor elements at logarithmically equidistant periods $T$ using the expressions:

$$\rho_{ij}(T) = 0.2T|Z_{ij}|^2, \quad ij = xy, yx$$
$$\varphi_{ij}(T) = \arctan \left( \frac{\text{Im} Z_{ij}}{\text{Re} Z_{ij}} \right)$$

4. Rotation to strike direction and grouping of data

For further analysis, the transfer tensors had to be rotated to the electrical strike direction. Standard dimensionality criteria (e.g. Swift, 1967; Bahr, 1988) suggested that two-dimensional conductivity structure predominates so that rotation to the principal axes will result in coordinate systems of decoupled pairs of off-diagonal E- and B-components with the orientation of the E-components parallel (E-polarization) or perpendicular (B-polarization) to strike. Due
to the electrical boundary conditions, the E-polarization curves are continuous when crossing lateral boundaries while B-polarization curves can change discontinuously. Two different techniques to determine rotation angles have been examined, which are Swift’s (1967) and Bahr’s (1988, 1991) methods.

Swift’s angle $\alpha_s$ which is simply defined by the minimization of the squared sum of the diagonal elements of the transfer tensor $Z$, mainly reflects upper crustal structures. For most of our MT sites $\alpha_s$ turned out to be significantly stable and almost frequency independent. Problems will occur in the presence of static shift distortion, caused by galvanic effects due to charge accumulations at boundaries of near surface heterogeneities (Bahr, 1988; Groom and Bailey, 1989). In such cases $\alpha_s$ will likewise be distorted. To achieve rotation angles not being affected by static shift distortion, Bahr’s (1988) phase based angle $\alpha_B$ was used. In the majority of our cases, some frequency dependency of $\alpha_B$ over the whole MT period range appeared to be a characteristic complication the adoption of a mean or representative angle needed for two-dimensional analysis. Generally, differences between $\alpha_s$ and $\alpha_B$ are taken as an indication of the presence of static shift distortions in the data set.

Rotation of all transfer functions to principal axes following Swift’s criterion readily revealed that the sites may be grouped, mainly according to the shapes of the B-polarization curves. These shapes suggest the existence of 10 different electrical crustal units, 4 on profile A-A’ and 6 on profile B-B’, indicating a characteristic depth dependent conductivity distribution for each. Corroborating this result, Bahr’s angles used for rotation led to the same grouping. Thus, the grouping appears to be strikingly robust and, in particular, largely unaffected by static shift distortions. Fig. 2 gives an example from profile A-A’ of grouped stations considered to represent the “South Maya” electrical crustal unit. The similarity of the shapes of the phase curves as well as of the apparent resistivity curves is evident. At sites CHIL and SEBA, the shift of the resistivity curves to higher values in the B-polarization may be interpreted as static distortion in this case (cf. Jones, 1987, 1988). Fig. 3 gives another example of grouped stations for profile B-B’ representing the electrical crustal unit “Guerrero”. The curves are more widely scattered in their amplitudes but similarities are still quite obvious. The electrical crustal units are named here according to the tectonostratigraphic terranes.

In a compilation of all our data, curves of apparent resistivity for E- and B-polarization along profiles A-A’ and B-B’ are presented in form of “pseudosections”, i.e., in form of isolines of apparent resistivity in a diagram of period $T$ versus profile length (Figs. 4 and 5). The various electrical crustal units resulting from different curve types are marked. In addition, apparent resistivity curves of representative sites from each crustal unit are shown on top of the pseudosections. Such pseudosections may easily be converted into a simplified apparent resistivity versus depth section, however, we expressly want to restrict ourselves to the most basic MT data presentation. As a rule, short MT periods provide information about upper crustal resistivities while long periods probe the whole crust and the uppermost mantle in case of moderate to high resistivities. In case of near surface good conducting layers, like in the Veracruz sedimentary basin, the penetration depth of the longest periods is restricted to a few kilometers because of shielding effects. Different types of apparent resistivity curves reflect different conductivity distributions of larger depths rather than small scale near surface anomalies.

The grouping of sites is quite clear in the B-polarization pseudosection but becomes, in part, visible also in the laterally more homogeneous E-polarization curves. For this presentation, the niveau of apparent resistivity curves has been smoothed in order to avoid local unsteadiness of the isolines. This smoothing means a mere shift correction of a resistivity curve at some sites without changing its shape and, thus, not affecting the grouping criteria.

5. Geological Interpretation of Results

Fig. 6 displays the boundaries of grouped data as deduced from our MT measurements. In general, the distribution of these electrical conductivity crustal units matches well with geological terranes as defined by Campa and Coney (1983), but the boundaries appear to be shifted in many cases.

By comparing the mean individual Swift’s angle of each single MT site with the dominant trend of regional tectonic structures, correspondence to surface geology becomes obvious: At many MT sites the
orientation of the E-polarization component parallels near surface geological structures or major tectonic elements. In particular, MT strike directions are related to the azimuths of the geological terrane boundaries. On the whole, the directions of the E-polarization components may coincide with the strike of the subducting plate. We have further tried to correlate geologic structure and apparent resistivities along the profiles.

Profile A-A' crosses the Xolapa (XO), Oaxaca (O), Juárez (J) and Maya (M) terranes as defined by Campa and Coney (1983). Along this transect we observed four groups of sounding curves (Figs. 4 and 6). The “Xolapa” electrical crustal unit, which is almost identical with the Xolapa terrane, is characterized by a high apparent resistivity in the B polarization (Fig. 4), and is separated from the “Oaxaca” crustal unit by a wide transition zone observed between stations CERR and AGUA (Fig. 6). A transition zone is understood as a region where one or two sounding curves do not fit with the preceding or following set of sites. Here it corresponds to the Juchatengo mylonitic zone (Meschede et al., 1996) and the Honduras batholith (Grajales-Nishimura, 1988). The existence of the transition zone suggests that the Juchatengo mylonitic zone, which bounds the Xolapa terrane to the north is not vertical, but, rather, dips at a relatively low angle to the north also at depth. On the other hand, the Honduras batholith constitutes a crustal unit with electric properties different from the Xolapa and
Oaxaca terranes, and could also be responsible for the observed transition zone.

Although slightly disturbed and showing larger than normal scatter of rotation angles, MT soundings obtained at stations within most of the Oaxaca and Juárez terrane can be grouped together. The sites within these terranes are characterized by high apparent resistivities at short periods (Fig. 4) which could correlate, at least in part, with the presence of the Precambrian Oaxacan complex in the upper crust. High resistivity is in accordance with the dry granulite facies of this rock assemblage. Our data suggest that no real crustal boundary exists between these two terranes along the profile. The wide mylonitic zone of the Sierra de Juárez (Alaniz-Alvarez et al., 1994, 1996) thought to be the boundary between the two terranes, ends at the latitude of Oaxaca and is not crossed by our profile (Fig. 6). The pre-Mesozoic basement of the Juárez terrane along this part of the profile is poorly known (Sedlock et al., 1993) but metamorphic rocks of possible Paleozoic ages are reported at a number of locations (Consejo de Recursos Minerales, 1998; Martínez-Reyes, 2000). With respect to the relative similarity of MT soundings described above, it may not be excluded that the Oaxaca and the Juárez terranes could share a similar pre-Mesozoic basement at depth.

A clear change in MT curves is observed some tens
of kilometers to the south of the proposed boundary between Juárez and Maya terranes (sites MACU and ESPE). In the surface geology the boundary between these two terranes is the low angle southwest-dipping Vista Hermosa fault system, where the Mesozoic sedimentary cover of the Juárez terrane is thrust over the lower crustal Paleozoic metasediments of the Maya terrane (Ortega-Gutiérrez et al., 1990). In the pseudosection of Fig. 4 the mid- to lower crustal assemblage of the southern part of the Maya terrane (South Maya electrical crustal unit) is seen as a homogeneous block with a high apparent resistivity in the B polarization. The shifting of the conductivity boundary to the south with respect to the surface geology is consistent with the southwest dip of the Vista Hermosa fault system shown by Ortega-Gutiérrez et al. (1990). The observation of the pseudosections of Fig. 4 also indicates that this fault system extends to great depths. This confirms the results of the GEOLIMEX experiment, in which the Vista Hermosa fault appears to be the sole crustal structure clearly observed in the refraction seismic sections (Spranger, 1994).

Another sharp electrical boundary is observed in the northernmost part of the profile near the city of Tuxtepec, between sites SEBA and OTAT. Due to the young sedimentary cover of the Gulf of Mexico
coastal plain, no surface geological structures are revealed at this location. The boundary might correspond to the abrupt increase of the thickness of Tertiary sediments related to the Gulf of Mexico extensional basin which is characterized by a significant decrease in crustal thickness and an increase in heat flow. Because of this electrical boundary we divide the Maya terrane into a more resistive southern and a conductive northern part (South Maya and “North Maya”).

Profile B-B' crosses the Xolapa (XO), Guerrero (G), Mixteca (MI), Sierra Madre (SM), and Coahuila (COA) terranes as well as the TMVB. Our results show that a separate group of MT curves exists in the southernmost part of the profile (sites ACAP-TIER), followed to the north by a transition zone (sites CAJE, ACAH) which matches with the border of the Xolapa terrane as introduced by Campa and Coney (1983). This transition zone coincides broadly with the Oligocene Tierra Colorada pluton, which is bounded to the south by a north dipping mylonitic zone (Riller et al., 1992; Meschede et al., 1996). Likewise to profile A-A' the transition may originate from the northward inclination of the mylonitic zone and/or by the irregular shape and crosscutting of the intrusive bodies, which make the crust heterogeneous from the electrical point of view.

A boundary between the Guerrero and the Mixteca...
Fig. 6. Comparison between MT electrical crustal unit boundaries, terrane boundaries of Campa and Coney (1983) and main geologic structures presently thought to represent terrane boundaries, mainly based on Riller et al. (1992), Suter et al. (1997) and Ortega-Gutiérrez et al. (1992).

JMZ = Juchatengo mylonitic zone, VHFS = Vista Hermosa fault system, SJMC = Sierra de Juárez mylonitic complex; LCT = Lobo-Cienega thrust and IHF = Ixtlapala-Huiznopala fault.
terranes is not clearly detected along our profile. As summarized in Sedlock et al. (1993) its exact location is uncertain. Furthermore, Lang et al. (1996) argue that no terrane boundary should exist in this area. We note that a zone of high apparent resistivity north of station PLAO could roughly correspond to the Permian to early Triassic granitic rocks overlain by the pre-Jurassic Taxco schists (Elias-Herrera and Sanchez-Zavala, 1990). Therefore, the weak boundary seen in short periods between sites PLAO and BUEN could be associated with a lateral crustal variation inside the Guerrero terrane.

The electrical boundaries between stations ANDR and ZAPA and stations ATOT and MONI match with the boundaries of the TMVB, characterized by recent volcanism and tectonics. Laboratory experiments and numerical models indicates that less than a 5% of partial melting is sufficient to induce a drastic increase in conductivity if the melt fraction is interconnected (Partzsch et al., 2000). In our cases MT soundings likely map the extent of an anomalous region where a thermal anomaly is associated with the volcanism (Fig. 5). Here, conductivity due to melts or hydrothermal fluids in the crust is enhanced by the active and recent extensional faulting which affect the upper crust (e.g. Suter et al., 1995).

The MONI-METZ transition zone corresponds broadly to the extent of the Valles-San Luis Potosí carbonate platform, a tectonic nappe bounded to the east by a basal detachment thrust (Suter et al., 1997). The last MT boundary along the profile is observed between IXTL and TLAN, close to the Sierra Madre-Coahuila terrane boundary. This boundary may actually reflect the topography of the Precambrian basement at depth, covered by conductive young sediments. Proterozoic gneisses of the Huiznopala Formation crop out at ~500 m just a few kilometers south–west of site TLAN (Ochoa-Camarillo, 1997; Lawlor et al., 1999) and disappear toward the north–east due to the Ixtlapala-Huiznopala fault (Fig. 6), which has a minimum displacement of 1600 m (Ochoa-Camarillo, 1997). Further to the east, in fact, rocks correlate with the Huiznopala gneisses were cored at a depth of 2600 m in the coastal plain of the Gulf of Mexico (Suter, 1990). These normal faults developed in Jurassic times during the opening of the Gulf of Mexico, and are part of the wide extensional fault system which affect this passive margin.

6. Summary and conclusions

To some extent it is commonplace for terranes to be intended as exotic crustal blocks separated from a continental nucleus by sub-vertical sutures. Although common, this is neither true for all terranes nor implicit in their definition. Some terranes, indeed, are just rootless nappes bounded by sub-horizontal fault zones or complex volcano-sedimentary assemblages separated by low angle thrust faults (e.g. Coney, 1989). Since long period MT data normally probe the whole crust down to the uppermost mantle, the observed changes in the shapes of the sounding curves reflect lateral variations in a large depth range rather than in the surface geology. In this respect, our results illuminate electrical boundaries which seem to cut through large parts of the crust separating various electrical units, each with largely homogeneous conductivity structures. In most cases, these boundaries coincide with geological terrane boundaries. Representative examples are the contact between the lower crust assemblage of the Xolapa terrane with the Mixteca and Oaxaca terranes along the Tierra Colorada-Juchatengo mylonitic zone, the contact of the mid to lower crust meta-sediments of the Maya terrane with the sedimentary cover of the Juárez terrane along the Vista Hermosa fault, and the lowering of the Precambrian basement of the Sierra Madre Oriental along the Ixtlapala-Huiznopala fault (Figs. 4 and 5). In all these cases, the resistivity contrast between different crustal levels and the geometry of the boundary may produce the observed variation in the MT curves.

The main implications for terrane geology in southern Mexico that can be deduced from the analysis of the MT profiles presented in this study are the following:

1. The Xolapa terrane is bounded to the north by a transition zone which corresponds to a north dipping mylonitic zone crossing large parts of the crust and which is complicated by Tertiary intrusions.

2. No boundary is observed between the Oaxaca and Juárez terranes, suggesting that they could share a similar basement in the area crossed by our profile.

3. The Vista Hermosa fault zone is a major crustal structure separating the Oaxaca/Juárez terrane and the Maya terrane.
(4) There are no clear indications of a boundary between the Mixteca and the Guerrero terranes along our profile.

We conclude that basic MT data without any elaborate model calculation may be used to map different crustal units and may help to define terranes and their boundaries in conjunction with geological observations.

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