

UNIVERSITÉ DE MONTRÉAL

MAGNETOTELLURIC
INTERPRETATION OF THE
SUBDUCTING COCOS PLATE IN
OAXACA'S CONTINENTAL MARGIN

par

Jorge Arturo Arzate-Flores
Département de Génie Minéral
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Thèse présentée en vue de l'obtention
du grade de philosophiae doctor (Ph.D.)

(Génie Minéral)

Avril, 1994

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Cette thèse intitulé:

MAGNETOTELLURIC INTERPRETATION OF THE SUBDUCTING COCOS
PLATE IN OAXACA'S CONTINENTAL MARGIN

présenté par: Jorge Arturo Arzate-Flores

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Mme MARESCHAL Marianne, Ph.D., membre et directrice de recherche

M. STIX John, Ph.D., membre

*...A mi querida Abuela,
quien a sus casi 100 años
sigue teniendo la 'chispa'
que le conocí siendo un niño...*

Sommaire

Dans le cadre des efforts pour comprendre les processus associés aux zones de subduction, la thèse présentée ici a été conçue pour étudier la portion de la Plaque du Cocos dans l'État d'Oaxaca, au sud du Mexique. L'étude fait partie d'un projet scientifique international (GEOLIMEX) pour étudier la lithosphère sous le territoire mexicain.

Pour évaluer les caractéristiques de la subduction dans la fosse de l'Amérique du sud où la plaque de Cocos disparaît sous la marge continentale de Oaxaca (96 à 98° O), nous avons complété une étude magnétotellurique (MT) pour évaluer la profondeur et l'angle de descente de l'anomalie conductrice associée à la plaque plongeante. Pour évaluer si la zone de conductivité anormale correspond au sommet de la plaque de subduction ou à l'isotherme de 300-400 °C, où la précipitation de silicate forme une couche imperméable retenant les fluides, le modèle électrique obtenu par l'interprétation des données MT est comparé au modèle thermique de la région. De plus, les résultats d'autres études géophysiques dans la région, comme la réfraction sismique et la gravité, sont utilisés pour contraindre le résultat des études électriques et thermiques. Ces résultats vont permettre d'évaluer les types des processus physiques existants dans les régions de subduction active.

Plusieurs études MT ont montré qu'une zone de haute conductivité électrique était présente dans beaucoup de parties du globe (*par exemple* Haak et Hutton, 1986; Jones, 1992) à des profondeurs intermédiaires (10 à 20 km sous la surface).

Bien que l'origine de ce conducteur dans les vieilles croûtes continentales est encore un sujet de discussion (*par exemple* Duba et al., 1994) et peut être différent d'un environnement tectonique à un autre, il est clair que dans les marges continentales sous régime de subduction, les fluides mineralisés à haute pression compris dans les pores causent de la zone de conductivité. C'est la subduction de sédiments entraînés par la plaque en structures de 'grabens' (Hilde, 1983) que la MT perçoit. Les plaques de subduction sont typiquement brisées par des failles normales quand elles se courbent en descendant sous la croûte continentale et créent aussi les patrons typiques de grabens.

Des porosités de l'ordre de 0.5 à 3% peuvent expliquer la faible resistivité électrique observée si on suppose que la salinité du fluide se rapproche de celle de l'eau de mer (Hyndman et Tondeur, 1989). D'autres explications de la conductivité électrique comme la présence de graphite ou de sulphides (Jones, 1992), ou de roches partiellement fondues (*par exemple* Paon, 1990) ne s'appliquent pas à la zone de subduction de Oaxaca. En effet, les faibles porosités nécessaires pour expliquer le conducteur observé, aussi que les grandes quantités de sédiments entraînés dans le Pacifique est (Hilde, 1983), expliquent à eux seuls la signature électrique des zones de subduction active.

Seules quelques études MT dans des régimes de subduction active sont documentées. Les plus récentes, qui sont concentrées dans la côte ouest d'Amérique du nord (*par exemple* Kurtz, 1986a, 1990; Projet EMSLAB: Waff et al., 1988; Wanamaker et al., 1989), ont visé à étudier la plaque de Juan de Fuca en Colombie Britannique, Oregon et Washington. Par exemple, la structure interprétée sous l'île de Vancouver est une zone conductrice descendante ($\rho \approx 30$ ohm-m) épaisse d'environ

6 km (Kurtz, 1986a) qui est virtuellement identique à la géométrie du dessus de la plaque Juan de Fuca sous les Cascades (Wannamaker et al., 1989). Ces zones conductrices sont intimement apparentées à la croûte océanique en subduction, mais ne correspondent pas toujours au sommet de la plaque (*par exemple* Jones, 1992).

Dans le cas particulier de la zone conductrice sous l'Île de Vancouver, qui coïncide avec un horizon réflecteur (le réflecteur 'E'; Green et al., 1987), l'interprétation initiale a suggéré que ce réflecteur/conducteur représentait le sommet de la plaque Juan de Fuca. Des études plus récentes (*par exemple* Hyndman, 1988; Cassidy et Ellis, 1991) ont trouvé que l'interface conductrice et réflective n'était pas le sommet de la plaque océanique mais représente une limite thermique-métamorphique. En dessous de cette limite, les fluides (qui peuvent provenir de l'entraînement des sédiments ou de réactions de dévolatilization) sont pris au piège (Jones, 1987,1992; Hyndman, 1988). De plus, l'étude de l'amplitude des réflexions sismiques, a montré que les hauts coefficients de réflexion observés (jusqu'à 0.2) ne peuvent pas être causés par des fluides seuls mais doivent être produits par du cisaillement (Calvert et Clowes, 1990). Cette interprétation suggère un mécanisme du piégeage des fluides qui prend place sur le plan de faille entre le sommet de la plaque en subduction et la croûte continentale. Dans le cas où les fluides restent au sommet de la plaque qui s'enfonce, il est probable que les mécanismes vraisemblables qui gardent les pores et fractures sur le dessous de la plaque supérieure sont bouchés par les résidus d'érosion abrasive.

Dans la zone de subduction mexicaine, qui fait partie de la fosse de l'Amérique moyenne, aucune étude n'a été complétée avant celle-ci. L'étude magnétotellurique

a été inspirée en partie par les résultats obtenus dans le marge Pacifique d'Amerique du nord, où les données MT de période intermédiaire (10-500 secondes) ont découvert un conducteur associé à la subduction de la plaque océanique. La première question qui nous avons tenté de résoudre consiste à savoir si le même conducteur se trouve au Mexique. La réponse fut affirmative, qui a confirmé les ressemblances dans la forme générale de l'anomalie électrique. Cependant, la tâche la plus importante était de savoir si la subduction de la plaque de Cocos dans le sud-ouest mexicain partageait d'autres aspects avec le système de subduction contemporain de Juan de Fuca tels que les processus physiques et tectoniques impliqués pendant la subduction. Une réponse affirmative tendrait à suggérer des règles standards pour toute autre région de subduction en Amerique. Une réponse négative dénoncerait le caractère spécifique des différentes régions basé sur des facteurs contrôlant la subduction localement. Pour cette tâche qui consiste à interpréter les résultats MT en fonction de mécanismes physiques impliqués à la marge de convergence, nous nous sommes appuyés sur d'autres études géophysiques complétées dans ou près de notre région d'étude. L'études de sismicité dans cette région suggèrent que la subduction de la croûte océanique suit une trajectoire approximativement horizontale sous le continent dans la partie sud-ouest du Mexique (Lomnitz, 1982; Valdés et al., 1982; Suarez, 1990). L'interprétation de données de réfraction sismique exige l'incorporation d'une couche de faible vitesse à la base de la croûte. Ce modèle supporte bien d'autres données sismiques et gravimétriques (Valdés et al., 1986). Cette couche, qui peut être associée avec des sédiments saturés, correspond aussi aux résultats d'autres études géophysiques disponibles dans la région (Divan et Woodcock, 1981; Nava et al., 1988; Arzate et al., 1993).

Bien que les données de flux de chaleur ne sont pas très abondantes dans le sud du Mexique (voir la compilation de Prol-Ledesma, 1991), les résultats des études thermiques dans le état voisin de Guerrero (par exemple Ziagos et al., 1985) peuvent être appliqués à la région d'Oaxaca qui possède des ressemblances structurales et thermiques associées avec la subduction. La notion d'une province régionale thermique avec courants de la chaleur semblables parallèles à la fosse a été suggéré précédemment (Ziagos et al., 1985) et a été partialement confirmée par des données thermiques le long des profils MT (Urrutia-Fucugauchi, 1992).

Les mesure MT obtenues tout au long de deux profils, aproximativement perpendiculaires à la côte de Oaxaca, au Mexique, ont été prélevées afin d'étudier la subduction active de la plaque Cocos par rapport au continent dans cette région. Les données ont montré une structure à inclinaison douce et à haute conductivité qui pourrait être reliée au dessus de la plaque de subduction.

Nous avons effectué une rigoureuse sélection des sondages MT qui ne sont pas affectés par les anomalies régionales 3-dimensionnelles, afin d'exclure les emplacements qui ne présentent pas un tenseur d'impédance 2-D. La sélection a été effectuée pour des périodes suffisamment longues et selon les critères suivants: (a) exclusion des sondages dont les paramètres de distorsion de Bahr indiquaient une structure régionale 3-D, (b) l'imposition des contraintes sur l'azimut 2-D calculé au moyen de la composante verticale du champ magnétique, de même que l'observation de la réponse du vecteur d'induction aux effets galvaniques par rapport à l'induction.

L'exclusion des sondages 3-D a produit une inversion 2-D significative, effectuée avec un poids haut sur les phases et un poids léger sur les résistivités, à cause du

deplacement statique qui a sévèrement affecté la plupart des mesures MT. Cependant, nous avons utilisé la résistivité de sondages qui montraient un comportement 1-D non altéré à hautes fréquences pour contraindre la résistivité superficielle de chacun des profils. Ceci a donné comme résultat une estimation robuste de la structure électrique dans des modèles pseudo 1-D. La profondeur du conducteur varie de 8 km sur la côte à plus de 30 km sous la Vallée de Oaxaca.

La géométrie de l'anomalie conductrice suggère qu'elle est étroitement reliée à la couche océanique en subduction. La position du conducteur corrèle bien avec une couche à faible vitesse, interprétée indépendamment par deux levés de sismique de refraction dans la région.

Le manque de corrélation du dessus du conducteur avec l'isotherme de 300-400 °C obtenu à partir d'un modèle thermique 1-D semble exclure la possibilité que la zone conductrice soit en produite par une couche de fluides provenant du dégazage de la plaque et se trouvant au-dessus de la plaque elle-même. De ce fait, on peut affirmer que l'étude MT dans la région de Oaxaca a permis de mettre en évidence les paramètres géométriques de la subduction elle même. Dans ce sens, elle s'oppose aux résultats obtenus pour la plaque Juan de Fuca en Amérique du Nord. Il est donc clair qu'on ne peut pas définir une subduction type pour toute la côte américaine.

Abstract

Magnetotelluric (MT) measurements along two profiles approximately perpendicular to the continental margin of Oaxaca, Mexico, were carried out to study the interaction of the active subducting Cocos Plate with the continent in this region. The results reveal a highly conductive gently dipping structure which could be associated with the top of the subducting slab. A rigorous selection of MT sites that are not influenced by 3-dimensional regional anomalies was performed in order to exclude sites which would not be characterized by a 2-D impedance tensor. The selection was performed based upon the following criteria applied at sufficiently long periods: a) exclusion of those sites whose Bahr's distortion parameters indicated a 3-D regional structure; b) imposing constraints on the calculated 2-D strike using the vertical magnetic field component by observing the tipper response to galvanic (or channeling) effects versus induction.

The exclusion of 3-D sites insured a meaningful 2-D inversion that was performed mainly on the phases because of the static shift that severely affected most of the resistivity measurements. However, we inverted also the resistivity of several sites which showed an undistorted 1-D behavior at high frequencies to constrain the shallow resistivity for each profile and tentatively fix the static shift in pseudo 1-D models. This resulted in a robust estimation of a resistivity structure. The TE polarization mode was found to represent the correct structure of the region and is the base of our interpretation. The depth to the conductor is found to vary from about 8 km at the coast to more than 30 km under the Valley of Oaxaca. The geometry of the conducting anomaly suggests that it is directly associated to the downgoing subducting slab. The conductor correlates well with a low velocity layer independently interpreted from two seismic refraction studies in the region. The lack of correlation of the top of the conductor with the 300 – 400°C isotherm obtained from a 1-D

thermal model seems to rule out the possibility that the conductive zone is related to a layer of fluids produced by degazing and trapped at some level above the plate boundary. According to our results, fluids remain on top of the subducting slab for at least 20 m.y. after being subducted. A possible mechanism that keep fluids on top of the oceanic slab is through the sealing of pores and fractures on the underside of the overriding plate with desegregated material from abrasive erosion. The absence of shallow seismic activity can be explained in terms of smooth and continuous slip along the contact between the continental crust and the downgoing oceanic crust, which may be made possible by the presence of a fluid phase on top of the subducting plate.

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CHAPTER 1

INTRODUCTION

1.1) Objectives

The theory of plate tectonics says that there is an outer shell on the Earth that acts as a system of rigid plates. In the geophysical sense, 'rigid' means that no major deformation occurs except at plate boundaries, and that plate motions have to follow a relative simple set of rules since these are restricted to move along the surface of a sphere. The link of the observations with the prediction capabilities of the theory are provided by two quantitative elements: *geometrical precision* and *accurate timing* (Cox and Hart, 1986). The geometrical precision is the result of several key ideas that lie at the core of the hypothesis. Notably, a critical step in plate tectonics was the recognition that boundaries between rigid plates can be divided into *exactly* three classes: *Ridges*, which are the boundaries where two plates diverge; *Trenches*, the boundaries where two plates converge; *Transforms*, the boundaries where two plates are moving tangentially past each other. The rheological contrast between a rigid lithosphere and a ductile asthenosphere allows stress to be transmitted long distances through the lithosphere and therefore the generation of these boundaries is possible. After the introduction of these (and other) geometrical concepts and accurate time measurements using magnetic isochrones recorded on the sea floor, the plate tectonic

pile of 'loose' observations became a predictive theory.

Following the postulation of the plate tectonics theory in the late 60's as a truly quantitative science, a large number of geological and geophysical studies have been completed at or near plate boundaries aiming to explain their physical and kinematic development. In the specific case of convergent plate margins, which often correspond to continent-ocean collision zones, it is becoming apparent that there is a wide diversity of tectonic processes involved in the subduction of the oceanic lithosphere under the continental plate (e.g. von Huene, 1985). Several factors are reported to control the variation in geometry and dipping angle of the subducted oceanic lithosphere, among them are the age of the lithosphere, the relative motion of converging plates, the convergence rate, the amount of sediments, the subduction of aseismic ridges or sea mounts, etc. (Cross and Pilger, 1982; Hilde, 1983; Shipley and Moore, 1985). Such diversity in the controlling factors at the trenches prevents the extrapolation of the tectonic models that work in a region to other areas, even within the same trench, without properly evaluating the local conditions. The specific character of subduction in the Middle America Trench (Fig. 1) has been previously reported (e.g. Singh et al., 1981; Burbach et al., 1984; Nishenko and Singh, 1991). The subduction of the Tehuantepec Ridge along with the Cocos plate, the oblique convergence and hence the difference in age and consumption rate as well as a relatively large amount of marine sediments dragged on top of the oceanic layer, seem to be responsible for controlling the process of subduction along the Mexican portion of the Middle America Trench (MAT).

Several geophysical methods are normally used for crustal studies, among

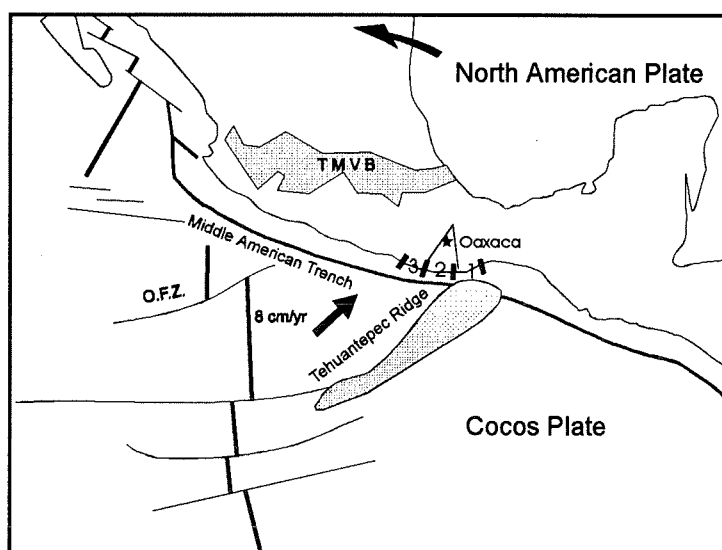


Fig. 1.- The Middle America Trench in southern Mexico and related tectonic elements (modified from Aubouin et al., 1985). Also shown (heavy lines) is the segmentation of the Oaxacan margin according to lateral extent of large earthquakes (Nishenko and Singh, 1987); eastern (1), central (2), and western Oaxaca (3) segments.

which the seismic methods have been widely favored. However, since it was first suggested that enhanced conductivity zones under the continental crust in convergence zones are related to the subduction processes (Law and Riddihough, 1971), electromagnetic (EM) sounding methods have been used in the study of subduction zones. The region of enhanced conductivity have been correlated with zones of high reflectivity (e.g. Jones, 1987). The combined cause of enhanced conductivity and high reflectivity associated with young subduction processes is assumed to be produced by mineralized fluids dragged with the subducting oceanic slab. Whether these fluids follow the top of the oceanic plate or migrate upwards to some level in the continental crust before being trapped, is one of the questions that we attempt to answer

in this work. Previous results in the Vancouver area where the Juan de Fuca plate is subducted, associate the enhanced conductive-reflective zone with trapped fluids above the top of the downgoing plate (Hyndman et al., 1990). As part of the ongoing efforts to understand the processes involved in subduction zones, the present thesis was designed to study the portion of the Middle America Trench in the Mexican state of Oaxaca, in southern Mexico. The present study is part of a multidisciplinary international scientific project (GEOLIMEX) to study the lithosphere under Mexican territory.

In order to evaluate the characteristics of subduction in the MAT where the Cocos plate is consumed under the Oaxacan continental margin (96 to 98° W), we have completed a magnetotelluric (MT) survey which has been used to assess the depth and dipping angle of the conducting slab. To try to evaluate whether the zone of enhanced conductivity correlates with the top of the subducting plate or with the 300-400 °C isotherm, where it is expected that silica precipitation forms an impermeable layer that traps upward migration of fluids above the subducted oceanic crust (Hyndman and Shearer, 1989), the electric model obtained from the interpreted MT data is correlated with a thermal model for this region. In addition, the results of other geophysical studies, namely seismic refraction and gravity models in the neighborhood of the studied area, are used to support the outcome of the electric and thermal studies. The results are expected to give insight on the character of the physical processes that occur in regions under active subduction.

1.2) Previous studies

The magnetotelluric method has been used to explore the continental lithosphere systematically since the early fifties. The method has evolved ever since in both the technical and theoretical aspects. The progress done in the geophysical instrumentation used to measure the EM fields has resulted in crustal studies supported by quality data. A number of MT studies have shown that a high electrical conductivity zone is present in many parts of the globe (e.g. Haak and Hutton, 1986; Jones, 1992) in Phanerozoic and Precambrian crust at intermediate depths (10 to 20 km below the surface). Although the origin of this anomalous conductor in old continental crust is still a subject of discussion (e.g. Duba et al., 1994) and could differ from a tectonic environment to another, it is widely accepted that in younger crust, and particularly in continental margins under subduction regimes, high pore pressure mineralized fluids are the cause of the zone of enhanced conductivity. Sediment subduction is known to occur by inclusion in subducting plate graben structures (Hilde, 1983). Subducting plates are typically broken by normal faults as they bend downwards below the continental crust forming regular patterns of grabens. Although it is known that fluid expulsion occurs at accretionary prisms (Moore and Vrolijk, 1992), underthrust saturated sediments may be completely subducted and transported to subcrustal depths for tens of kilometers (von Huene and Scholl, 1991). It has been estimated that porosities in the range 0.5 to 3 % can explain the low electrical resistivity observed assuming a fluid salinity close to that of sea-water (Hyndman and Shearer, 1989). Alternative explanations of enhanced electrical conductivity associated with subduction zones include highly conducting mineral phases, such as

graphite or sulphides in underplated sediments (Jones, 1992), and partial melting (e.g. Peacock, 1990). However, because of the relatively low porosities needed to explain the observed conductor as well as the large amounts of subducted sediments in the eastern Pacific (Hilde, 1983), it is probable that conducting fluids are the cause of the anomalous conductivity associated with young subducting zones.

Unfortunately, only few EM studies in active subduction regimes have been documented. Some of the more recent ones, which are concentrated in the west coast of North America (e.g. Kurtz, 1986a, 1990; EMSLAB project: Waff et al., 1988; Wannamaker et al., 1989, etc.), were aimed at imaging the Juan de Fuca plate beneath British Columbia, Oregon and Washington. The interpreted feature under Vancouver Island is a landward dipping conductive zone ($\rho \approx 30$ ohm-m) about 6 km thick (Kurtz, 1986a) which is virtually identical to the geometry of the subducted Juan de Fuca plate under the Cascades (Wannamaker et al., 1989). These conductive zones are regarded to be intimately related to the subducting oceanic crust but not necessarily to correspond to the top of the plate (e.g. Jones, 1992). In the particular case of the conductive zone beneath Vancouver Island, which is coincident with a reflecting horizon known as the 'E' reflector (Green et al., 1987), the initial interpretation suggested that it represented the top of the subducting Juan de Fuca plate. However, more recent studies (e.g. Hyndman, 1988; Cassidy and Ellis, 1991) assume that this conductive and reflective interphase is not the top of the oceanic plate but represents a thermal-metamorphic boundary below which fluids, originating either from the dragged sediments or from devolatilization reactions, are trapped (Jones, 1987, 1992; Hyndman, 1988). Other results obtained from the interpretation of the amplitude of seismic reflections, determined that the high reflection coefficients observed (up to

0.2) cannot be caused by fluids alone and that the reflections may be generated by shear zones (Calvert and Clowes, 1990). This interpretation suggests an alternative fluid trapping mechanism which takes place along the fault plane between the top of the downgoing plate and the continental crust. A probable mechanism to keep fluids on top of the lower plate is through the sealing of pores and fractures on the underside of the upper plate with desegregated material from abrasive erosion. Although the observed temperatures in the Vancouver Island region supports the hypothesis of silicate precipitation to keep conductive fluids trapped above the subducting oceanic crust, the 'shear-sealing' hypothesis should not be ruled out.

The EM work in Central and South America is more scarce and difficult to track down. Schwartz (1988) cites as the earlier EM investigation in this region a survey done by Schmucker and colleagues (1964) in southern Peru and Bolivia which resulted in the detection of a conductive anomaly about 20 km deep beneath the continental margin and traceable for about 400 km landwards. This enhanced conductor was first interpreted as a zone of vast magma chambers rising from the Benioff plane to the surface. Reinterpretation of the data have not changed substantially the general shape of the conductor (Schwarz, 1988) nor its possible origin. The possible extension of what is now known as the 'Schmucker anomaly' under northwestern Argentina was also investigated (Baldi et al., 1985) as was its continuation to northern Chile (Schwarz et al., 1984). There is no clear evidence though of a dipping continuous conductor as has been observed in western North America. However, none of these data were corrected for near-surface distortion. The sharp jumps in resistivity along profiles from the Pacific Coast across the Andean Cordillera to the Altiplano and beyond (Schwarz et al., 1984) are, most probably, the result of static shifts (e.g.

Sternberg, 1988) due to remarkable differences in surface resistivities. The source of the enhanced conductivity anomaly related to the subduction of the Nazca plate has been generally attributed to melted material but because of its large extension, this may explain only part of the anomaly.

In the Mexican subduction zone, which is part of what is known as the Middle America Trench, no MT work has been done before the present study. The present magnetotelluric work has been partly inspired by the results obtained in the North America Pacific margin where intermediate-period MT measurements (10-500 seconds) were able to follow a conductive anomaly closely linked to the subduction of the oceanic plate. The first question we have asked ourselves was if we were going to be able to 'see' the same conductive feature. The answer, as expected, was yes, which confirmed our initial guess with regard to possible similarities (at least) in the general shape of the anomaly. However, the more important and challenging task ahead was to determine whether the subduction of the Cocos plate in southwestern Mexico had other aspects in common with the contemporary Juan de Fuca subduction system relative to the physical and tectonic processes involved during subduction. An affirmative answer would allow us to argue in favor of standard 'rules' for other areas with similar subduction regimes in Central and South America, whereas a negative one would intrinsically recognize the specific character of various regions based on the particular factors that control subduction locally. In the task of interpreting the MT results in terms of the physical mechanisms involved at the convergence margin, we have taken advantage of other geophysical studies that have been completed in or nearby our area of study. Seismicity studies in this region have suggested that the subducting oceanic crust follows a near horizontal trajectory beneath southwestern

continental Mexico (Lomnitz, 1982; Valdés et al., 1982; Suarez, 1990). Refraction results require the incorporation of a low velocity layer to match satisfactorily the observed seismic and coincident gravity data (Valdés et al., 1986). This layer, that could be associated with saturated sediments, also correlates well with the results of other geophysical studies available in the area (Couch and Woodcock, 1981; Nava et al., 1988; Arzate et al., 1993). Although heat flow data are not very abundant in southern Mexico (for a compilation see Prol-Ledesma, 1991), results from nearby thermal studies in the neighboring State of Guerrero (e.g. Ziagos et al., 1985) can be applied to the Oaxaca region which bear structural, and hence, thermal similarities associated with the subduction. The notion of a regional thermal province with similar heat flows parallel to the trench has been previously suggested (Ziagos et al., 1985) and partially confirmed by heat flow measurements along the MT profiles (Urrutia-Fucugauchi, 1992).

The relevance of these and other results will be discussed throughout this document as the work progresses. In the following section, an account is given of the methodology followed in the elaboration of this thesis, as well as a brief description of the material content in each chapter.

1.3) Outline of the thesis

After the previous introductory sections, we begin in Chapter 2 with a description of the main geological features that dominate the landscape in southwestern Mexico, but particularly in the western and central parts of Oaxaca State. Based

upon relevant published material, a review is done of the distribution and age of accreted suspect terranes in the surroundings of the MT study. The extension of the terranes as well as the location of their boundaries will be important when we process the MT field data. It is expected that the geological differences in age and composition must affect the EM response of the inductive structure associated to the oceanic slab. Also in this chapter, significant aspects of the convergence of the Cocos plate with the continental margin in southwestern Mexico are described in an attempt to understand what physical parameters control the subduction pattern. In the last section we present the general characteristics of the magnetotelluric field campaign carried out in the autumn of 1991.

In Chapter 3, the diverse processing stages of the MT data before performing a precise modeling are described. These steps include the determination of the period band in which the MT response is of purely 2-D or 3-D inductive character (Zhang et al., 1992) with no current galvanic component. However, the inductive response of the conductor related to the subducting plate could be mixed up with other inductive responses of near surface conductive structures. The next step deals with the calculation of the regional strike of the principal conductive structure within the induction band as well as the estimation of several dimensionality indicators (Bahr, 1991) used in a later stage to discriminate distorted soundings. The three different approaches used in this task are justified in that the first (section 3.3.1; Chakridi et al., 1991) gives us insight on the dimensionality of the individual soundings, which in turn allows us to apply wisely the other methods of strike determination. The other approach (section 3.3.2; Bahr, 1988,1991) is a robust analytical method that assumes small perturbations to the ideal two-dimensional impedance, whereas the

last (section 3.3.3; Groom and Bailey, 1991) is a numerical approach based on the decomposition of the impedance tensor. The simultaneous use of these methods provides a robust estimation of the regional strike when it does exist. In the following sections of Chapter 3, a preliminary one-dimensional model is computed after proper considerations were given to attenuate the static shift effects produced by differences in surface resistivity along the MT profiles, while in the last part of this chapter the pseudosections of both MT profiles in the TE and TM polarization modes, calculated using the ‘true’ regional strike, are discussed.

In Chapter 4 we start by analyzing the ability of the MT data to resolve physical parameters such as resistivity and thickness of the conductive anomaly as well as the depth to its top using a singular value decomposition algorithm. Selection criteria are presented in a following section to discriminate soundings that do not conform a 2-D impedance tensor in the induction band of the principal structure. The given criteria are based on the dimensionality parameters, the dispersion from the regional strike and the scatter of the tipper without the galvanic component. We arrive then at the discussion of the two polarization modes of the field in the studied area, the inversion algorithm used with the data (Smith and Booker, 1991), and the general inversion strategy. The following section deals with the stability of the resulting electrical model. Here, the forward response of the perturbed electrical model at selected locations is estimated to assess its sensitivity to changes and hence the robustness of the model. In the last part of this chapter, the tipper magnitude of the model is compared with a tipper free of galvanic component at selected sites, which is useful to constrain the model.

In Chapter 5 the results of the 2-D modeling are discussed, and in subsequent sections the resulting electrical model is correlated with other existing geophysical models, based on earthquake, seismic refraction and gravity data. In the last section of the chapter, a time independent 1-D thermal model of the region is computed and correlated with the electric model to investigate a possible resemblance with the responses observed in the western coast of North America, particularly in regard to the temperature at which conductive fluids are trapped. Chapter 6, the last of this thesis, is a chapter of discussion and conclusions in which we stress both the weakness and strengths of the results of the present study.

CHAPTER 2

GEOLOGY AND TECTONICS OF SOUTHERN MEXICO

2.1) Suspect terranes in southern Mexico

The terrane concept (Coney et al., 1980; Coney, 1989) is applied to geological units of regional extent whose lithology and deformation patterns cannot be associated with the adjacent geology. The distribution analysis of suspect terranes has been used to interpret the tectonic evolution of continental margins and to the assessment of the genesis and distribution of mineral resources. Campa and Coney (1983) have suggested that about 80 % of the Mexican territory is made up of suspect terranes. They inferred that western and southwestern Mexico are an assemblage of several distinct submarine magmatic late Jurassic (140 m.y.) to late Cretaceous (70 m.y.) arc terranes accreted to the North American margin in the early Tertiary (60 to 70 m.y.). However, Ruiz et al. (1988), basing their argument on isotopic studies of exposed Precambrian crystalline rocks and lower crustal xenoliths emplaced in Mesozoic times, suggested that much of southern Mexico could be related to North America as part of the Grenville and later Appalachian-Caledonian orogenic belts. In this model, the Paleozoic Acatlán (also Mixteca) and Grenvillian Oaxacan complexes

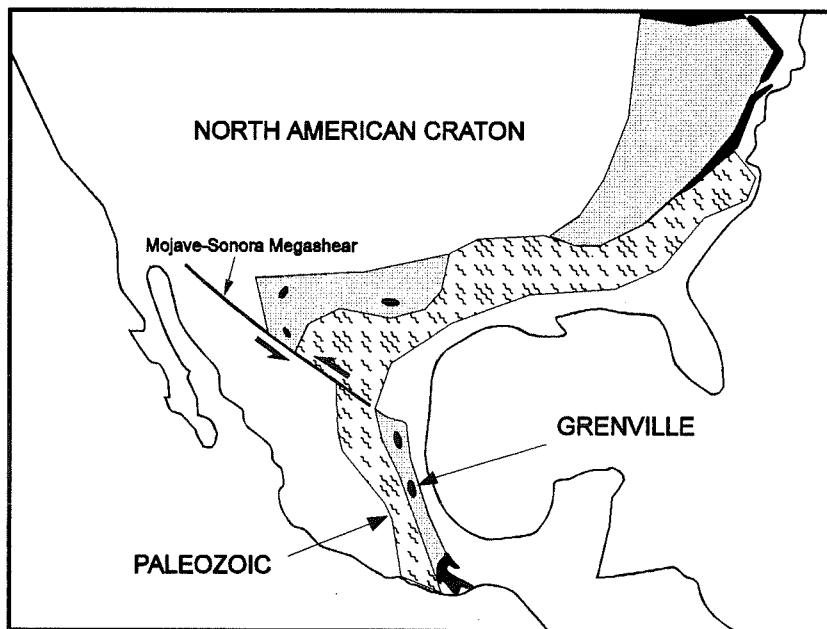


Fig. 2.- Ruiz et al. (1988) Appalachian-Caledonian tectonic model explaining the evolution of southern Mexico. Grenville rocks are shown in black. Stippled pattern is thought to be underlain by Grenville rocks. Ruled pattern is Appalachian-Caledonian terrane. Both the Grenville and Appalachian orogenic trends are displaced by the Mojave-Sonora megashear.

are not accreted terranes in the classical sense but are the continuation of the North American orogenic systems (Fig. 2). However, a critical problem of this tectonic model is that the Appalachian belt is to the west of the Grenville which is opposite to the configuration for the rest of North America. Because of this reversed geometry, it is impossible for both of these belts to be directly continuous into North America. A model proposed by Yañez et al. (1991) envisages the Appalachian suture as having cut across the Grenville belt in northern Mexico, such that the Oaxaca terrane lay on the opposite side of the Paleozoic ocean to most of North America. The paleomagnetic reconstruction of the Atlantic-bordering continents by Kent and Van

der Voo (1990) explains this discrepancy in terms of break-up/collision/break-up of the proto-Atlantic ocean. The modified Appalachian-Caledonian model similar to that of Ruiz et al. (1988) consistent with the Paleozoic reconstruction proposed by Yañez et al. (1991) was also based on isotopic studies. The authors found similar age (~ 1 Ga) and characteristics between the Oaxaca terrane and typical Grenville belt rocks. Similarly, the Paleozoic Acatlán complex, which consists of multiple deformed metasedimentary rocks, schists, granitoids, and eclogites, has been found to match chronologically and compositionally typical rocks of the Appalachian belt, supporting the interpretation of the evolution of parts of southern Mexico basement synchronized to the North American orogenic evolution.

In this scheme, the Guerrero, Juarez and Xolapa terranes (Fig. 3) are still regarded as island-arc accreted materials as described by Campa and Coney (1982). However, while the authors inferred an early Tertiary age of terrane accretion against the North American margin, measured paleolatitudes by Böhnel et al. (1989) suggest similar late Cenozoic ages of the Guerrero and Xolapa terranes. The Guerrero is a vast, composite terrane which is best known in the Sierra Madre del Sur, south of the trans-Mexican volcanic belt (TMVB). It is mid-Cretaceous in age and composed of submarine volcanic and sedimentary sequences (Campa and Coney, 1982). The Juarez terrane is the most easterly of the upper Mesozoic submarine volcanic and sedimentary assemblages. It is also distinctive in that it lies east of the Oaxaca Precambrian terrane. Deformation is very severe and mainly represents Upper Jurassic calcareous shale and sandstones, thin beds of cherty limestone and pillowed and andesitic volcanic rocks (Carfanten, 1981) although ultramafic occurrences are also reported (Campa and Coney, 1982). The Xolapa terrane occurs as a narrow belt

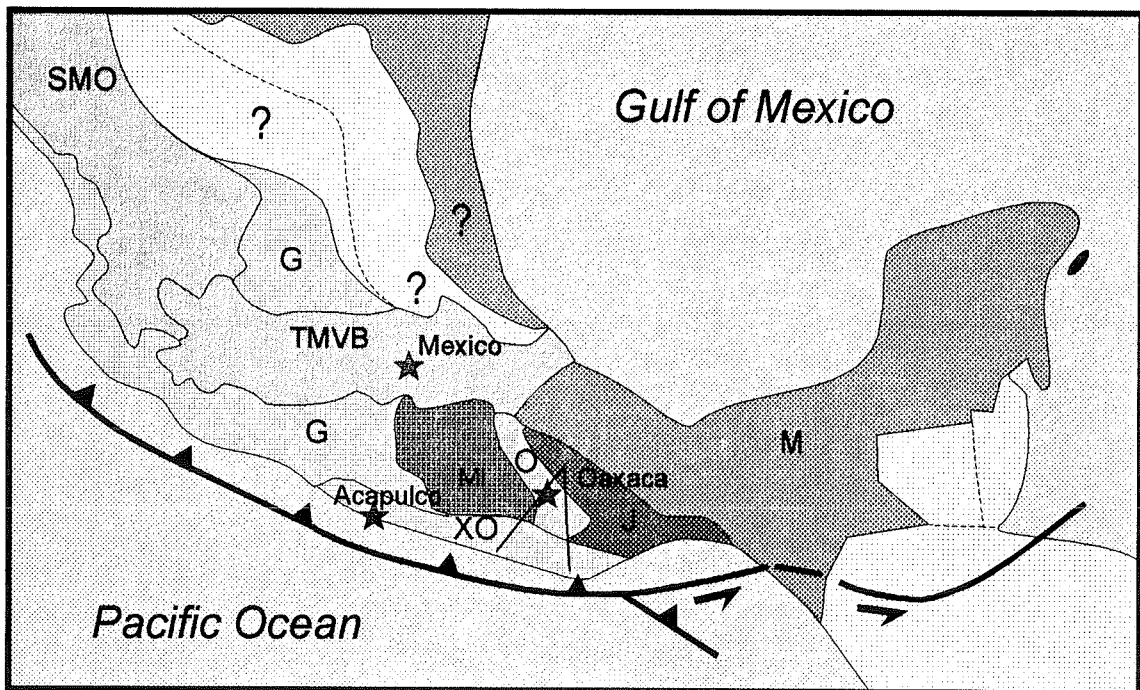


Fig. 3.- Terrane distribution in southern Mexico (modified after Campa and Conet, 1982). TMVB is the trans-Mexican Volcanic Belt, G, MI, O, J, M, and XO are the Guerrero, Mixteca, Oaxaca, Juarez, Maya and Xolapa terranes respectively. The magnetotelluric survey was carried out mainly over the Xolapa, Oaxaca and Juarez terranes. Their structural and geological differences produced 'near surface' distortion of the electromagnetic fields at some MT soundings.

along the southern coast of the states of Oaxaca and Guerrero. Isotopic ages given for this terrane range from Jurassic to Tertiary (Campa and Coney, 1982). Ratschbacher et al. (1991) used structural analysis to study the Xolapa terrane and proposed that it represents a late Mesozoic-early Tertiary magmatic arc built near the North American continental crust. They also observe that the boundaries between the Xolapa, Mixteca and Juarez terranes are zones of normal faulting indicating north-south sub-horizontal extension. They suggest that the timing and mechanism of Xolapa uplift,

extension and shear, depended on the regional plate tectonic framework, discussed in the following section.

Figure 3 depicts the terrane distribution in the area under study where the location of the MT profiles is also shown. The MT survey was carried out mainly over the Xolapa and Oaxaca terranes, although the southern narrow portion of the Juarez terrane, which lies between these two, was also crossed by both profiles. The structural and geological differences of the terranes could give rise to different electrical properties, the contact zones occasionally producing sharp electromagnetic (EM) responses. The data processing steps outlined in Chapter 3 were designed to remove the effects of galvanic distortion and current channelling through the different terranes encountered by the MT survey. The distortion are regarded as 'near surface' compared with the deeper, more homogeneous, inductive response of the subducting plate below the whole ensamblage of terranes. Thus, the removal of soundings too biased by near surface distortion or 3-D induction will allow us to provide a robust model of the subducting oceanic crust.

2.2) The Middle America Trench tectonic framework

Pindell et al. (1988) suggested that the Cretaceous-Cenozoic tectonics of southern Mexico was shaped by the evolution of the Caribbean region and the Pacific margin, reaching their present relative positions in approximately the early Campanian (~ 85 m.y. ago). It is assumed that large-scale sinistral strike-slip tectonic displacements followed, leading to the deformation of Central America and southern

Mexico. Along the North American Cordillera contractional tectonics of the Laramide orogeny (~ 60 to 80 m.y. ago) dominated the Late Cretaceous (Ratschbacher et al., 1991). According to Engebretson et al. (1985), the shortening of the Laramide orogeny was coeval with subduction of the Farallon plate as well as with an increase in rate of Farallon-North America plate convergence with a subsequent change in convergence direction from mainly frontal to more left lateral. Nixon (1982) assumes that the Cocos plate began to form from the Farallon plate about 12 to 17 m.y. ago. A plate reconstruction of the oceanic lithosphere for the last 74 m.y. by Whitman et al. (1983) suggests a splitting of the Farallon plate into the smaller Juan de Fuca, Cocos and Nazca plates around 10 m.y. ago. The Cocos plate is subducting along the Middle America region, which includes southern Mexico and Guatemala, beneath the North America plate at a rate of 5 to 8 cm/y in a SW-NE direction. Based on IPOD drillings, Aubouin et al. (1985) argue that all the pre-Lower Miocene (*i.e.* > 25 m.y. ago) structure in the continental margin basement are unrelated with the present Middle America Arc and Trench which were created in Lower Miocene time. This is supported with the fact that the Middle America Trench cuts off all structures of the Sierra Madre and that the first substantial layers of volcanic ashes, indicating development of the present Arc-Trench system, appeared only in the lower Miocene (Aubouin et al., 1985).

The subduction of the Cocos plate along the Middle America trench is polyphased and relatively complex. It has been suggested based on seismicity data that the subducting plate along the MAT is broken into three separate segments bounded by transform faults which are related to structural lineaments in the ocean floor (Molnar and Sykes, 1969; McNally and Minster, 1981; Singh et al., 1981; Bur-

bach et. al, 1984). These fault zones that coincide with topographic highs, are associated with the Orozco Fracture Zone (O.F.Z.) and the Tehuantepec Ridge (Fig. 1) and are regions where the subduction of the Cocos plate changes abruptly its dipping angle and convergence rate (e.g. Burbach et al., 1984). In the segment bounded by the Tehuantepec Ridge and the O.F.Z., the subduction angle of the Cocos plate, according to teleseismic data (Burbach et al, 1984; Suarez et al., 1990), is about 12 degrees while southeast of the Tehuantepec Ridge it changes abruptly to more than 25 degrees (e.g. Burbach et al, 1984). Among the factors that influence the change in dipping angle of the slab are the contrasting age of the ocean crust across the Tehuantepec Ridge (12 to 28 m.y. at the trench according to Nixon, 1982). A low subducting angle is anticipated for fast spreading young oceanic crust because of the relative low-density and buoyancy (Cross and Pilger, 1982; Cox and Hart, 1986). The anomalous arc-trench distance in this area has been also attributed to the high convergence rate; active volcanism is not only farther than expected from the trench, but it is aligned with the TMVB which makes an angle of approximately 20° to 25° with the axis of the trench (Fig. 1). The origin of this enigmatic distribution of the TMVB remains a controversial subject to date. Based on the analysis of earthquake seismic wave moments, Singh and Mortera (1991) observed a sharp change in plate interphase characteristics at the intersection of the O'Gorman Fracture Zone with the trench (99° W), supporting the existence of another possible segmentation of the Cocos plate at this point, which they explain also in terms of different ages of the subducting slab.

A more detailed segmentation was proposed by Nishenko and Singh (1987) based on the rupture zones of recent earthquakes which occurred in the area. Their

estimated recurrence probabilities for plate rupture along the MAT suggest that the plate portion along Oaxaca's continental margin is fragmented into several separate rupture zones. According to their estimated boundaries, the magnetotelluric field survey was carried out mainly over the Central Oaxaca segment (96.4° to 97.7° W), a zone that presents simple earthquake rupture (*i.e.* long-period body waveforms can be modeled as point sources). A simple rupture process indicates relative homogeneity on the subducting fault plane as well as little interaction between adjacent asperities. We will see in the next chapter that the relatively uncomplicated tectonic structure of the Oaxaca block inferred from seismicity is also reflected in the simplicity of the conductor defined by the MT method at intermediate depths.

2.3) The Magnetotelluric field study

A total of 14 MT soundings were carried out mainly south of Oaxaca city along two profiles that crossed three different suspect terrane boundaries (Fig. 4). The location of the MT soundings was chosen according to the availability of relatively noise-free soundings which were tested for AC and DC noise prior to a definite measurement. Thus some of the soundings had to be located in roughed areas which in some cases resulted in distorted field curves. Sounding 6, the most inland one, was located north of Oaxaca City in the Sierra de Juarez that belongs to the Juarez terrane. Soundings 1, 2, 3, 7 and 8 were distributed in the Valley of Oaxaca (Oaxaca Terrane); soundings 4, 5, 9 and 10 were located south of the valley in what appears to be the southern portion of the Juarez terrane. The remaining soundings, *i.e.* 11, 12, 13, and 14 were done entirely within the Xolapa terrane, however, soundings 11,

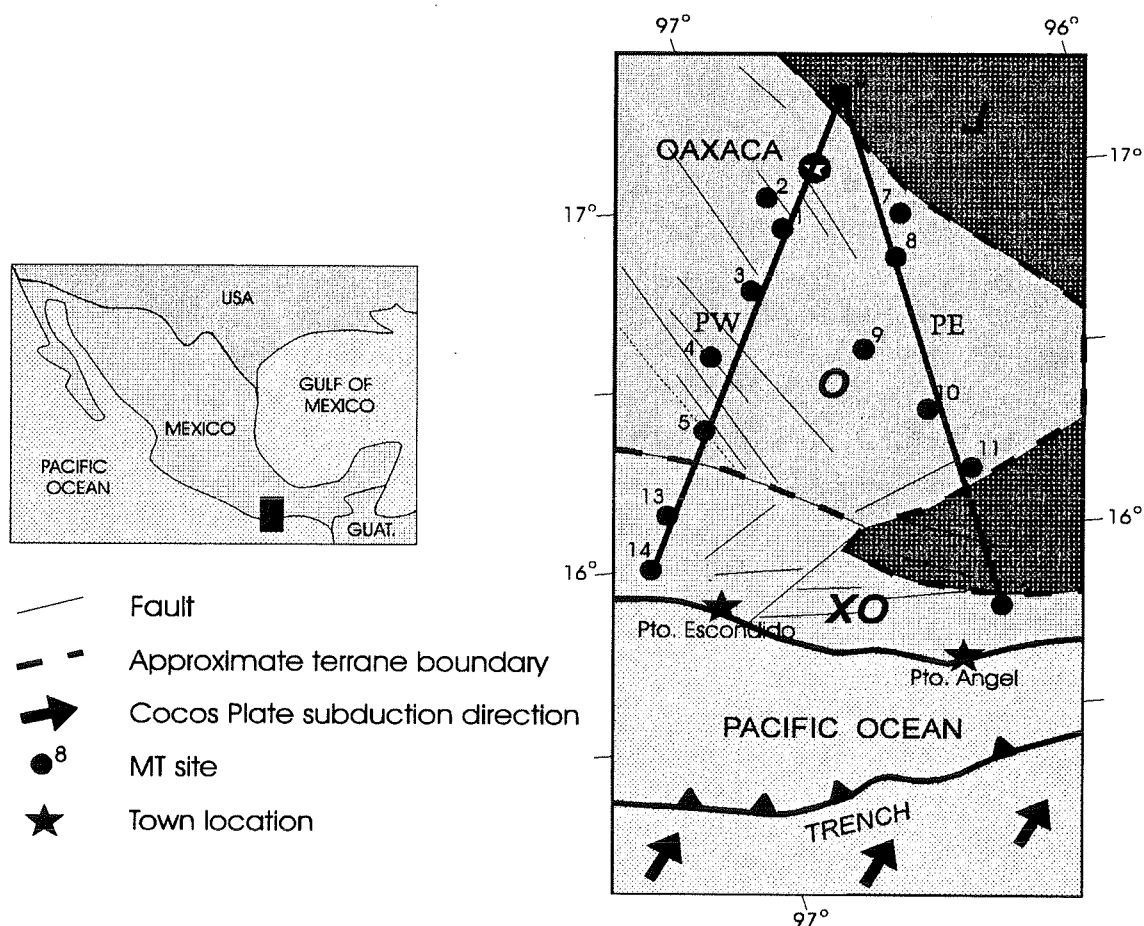


Fig. 4.- Location map of the survey area in southern Mexico. The distribution of the fourteen magnetotelluric soundings is shown as well as the approximate terrane boundaries.

and 13 are located in the high lands of the Sierra Madre del Sur while soundings 12 and 14 were completed in the coastal plain, between 10 to 15 km away from the Pacific Ocean. Including sounding 6, a total of eight MT soundings constitute the western profile (PW) that runs from the towns of Santa Catarina Ixtepeji in the Sierra de Juarez to Puerto Escondido in the coastal plain. The eastern profile (PE) which shares sounding 6 with PW runs from Santa Catarina Ixtepeji to the port town of

Puerto Angel (Fig. 4) and contains a total of seven soundings.

The electromagnetic field measurements were done using a MT Phoenix V-5 data acquisition system in the frequency range between 384 and 6.7×10^{-4} Hz (or in terms of period, 2.6×10^{-3} to 2000 s). The three orthogonal components of the magnetic field H_x , H_y , and H_z were recorded using Metronix coil magnetometers (MFS 05) while the horizontal components of the electric field E_x and E_y were measured with electrical dipoles 75 to 100 m long. Real time calculations of apparent resistivity, impedance phase, signal coherency as well as other physical parameters allowed us to judge the quality of the measurements in the field and to take appropriate action whenever it was required. A remote reference station (Gamble et al., 1979) located between 0.5 to 1 km apart from the sounding was used. The horizontal components of the magnetic field were recorded in the remote sounding so that local inhomogeneities at the sounding location or cultural noise could be monitored and accounted for. In general, the standard deviation associated with the resistivity and phase measurements was less than or equal to 2 % in the period interval between 2.6×10^{-3} to 500 s. This corresponds to an error of less than 4 ohm-m for an average resistivity of 100 ohm-m and to less than 2° for an average phase angle of 45° . For periods greater than 500 s the associated standard deviation is typically around 15 %, and in few cases is larger than this. Despite the wide variety of geological settings along the survey lines the surface resistivity varies between 10 to 200 ohm-m with the sole exception of sounding 13 where larger values are observed (~ 1000 ohm-m). In the next chapter we will deal with the static shift and other distortion problems that result from the diverse structural and geological environments in which the soundings were located.

CHAPTER 3

DATA PROCESSING

3.1) Introduction

The magnetotelluric method takes advantage of the natural time-varying electromagnetic fields due to electric storms ($f > 1$ Hz) and solar activity ($f < 1$ Hz). When the external electromagnetic field interacts with the ground, secondary electric and magnetic fields are induced. Usually, the three components h_x, h_y and h_z of the total magnetic field and the horizontal components e_x and e_y of the total electric field are recorded. In the conventional reference frame used in MT work, $\hat{x}$ points to the geomagnetic north (or along strike in a 2-D earth), $\hat{y}$ points to the east (or perpendicular to strike), and $\hat{z}$ vertically downwards. The field components measured in the form of individual time series are transformed using either Fourier or other transformation algorithms into the frequency domain. Then the cross-spectra are computed from which the MT response function $\mathbf{Z}$ is estimated. The Phoenix V-5 system performs these preprocessing steps.

The transformed horizontal components of the measured magnetic (H_x, H_y) and electric fields (E_x, E_y) are related through the expression (e.g. Vozoff, 1989)

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \quad (1)$$

where Z_{ij} ($i, j = x, y$) are the components of the surface impedance tensor. Maxwell's equations separate into two distinct cases if the induction problem is two dimensional. Z_{xy} and Z_{yx} , which are known as the principal impedances, represent these independent modes of polarization called transverse electric (TE) and transverse magnetic (TM) modes respectively (also referred as polarization E and polarization B). The TE mode is defined as having the electric currents parallel to the strike, while the TM mode has the currents across strike. The apparent resistivities ρ_{xy} and ρ_{yx} and the impedance phases ϕ_{xy} and ϕ_{yx} are calculated from the complex elements for subsequent interpretation. These have the form (e.g. Vozoff, 1989)

$$\rho_{xy}(\omega) = \frac{1}{\omega\mu_o} |Z_{xy}(\omega)|^2, \quad (2)$$

$$\rho_{yx}(\omega) = \frac{1}{\omega\mu_o} |Z_{yx}(\omega)|^2 \quad (3)$$

and

$$\phi_{xy}(\omega) = \tan^{-1} \frac{\text{Im } Z_{xy}(\omega)}{\text{Re } Z_{xy}(\omega)}, \quad (4)$$

$$\phi_{yx}(\omega) = \tan^{-1} \frac{\text{Im } Z_{yx}(\omega)}{\text{Re } Z_{yx}(\omega)}. \quad (5)$$

Here μ_o is the permeability of free space and ω the angular frequency $\omega = 2\pi f$.

In the absense of lateral variations in the earth's conductivity the vertical magnetic field H_z is approximately zero. Close to conductors however, $\nabla \times \vec{E}$ has a

vertical component which could be related to the two horizontal components of the magnetic field by (Schmucker, 1970)

$$H_z = (A \ B) \begin{pmatrix} H_x \\ H_y \end{pmatrix} \quad (6)$$

where the complex transfer response functions A and B are often displayed as induction arrows. When reversed, the real arrows generally point toward the zones of enhanced conductivity (Jones, 1986), and their magnitude gives an indication of the strength of the anomalous conductivity structure.

Equations (1) and (6) form the basis of the data processing that follows in this chapter. In the next section a recently developed technique (Zhang et al., 1992) to separate locally induced $H_z(\omega)$ components from those responding to current channelling is applied to the vertical components of the recorded magnetic fields. This is done to define a frequency band in which induction caused by 2-D subduction and/or other buried 3-D structures dominates over current channelling. This will help to assess a valid frequency interval in which the subducting plate could be regarded as a 2-D feature.

3.2) Induction band of the regional structure

Distortion of the electromagnetic (EM) field may occur at different scales within the earth due to electric inhomogeneities. Depending on the size of the target and the frequency range used, distortion by local structures of different sizes can occur. A rule of thumb often applied is that local distortion exists if the thickness of

the anomalous body that alters the regional current pattern is less than the inductive scale length, which is usually given in terms of the skin depth

$$\delta(\omega) = \left[\frac{2\rho_{app}}{\omega\mu_o} \right]^{\frac{1}{2}} \approx 503[\rho_{app}T]^{\frac{1}{2}}. \quad (7)$$

In magnetotelluric work directed to crustal studies, near surface inhomogeneities are among the main sources of distortion affecting the regional features. It is normally assumed that near surface structures produce only galvanic distortion due to the accumulation of charges at the boundary of the anomalous body. However, if the frequency band of the ‘local’ anomaly is broad enough it may overlap with the inductive scale of the larger structures, which may produce 3-D inductive responses that are often difficult to interpret. Using some properties of the vertical component of the magnetic field H_z , Zhang et al. (1992) developed a technique to qualitatively estimate the frequency intervals where induction in 2 or 3-D bodies dominates over channelling (a 1-D body does not produce any vertical field). Their approach is based on the assumption that the measured electric and magnetic fields E and H , can be written in terms of the galvanic distortion operators $\mathbf{P}$ and $\mathbf{Q}$ which are independent of frequency in the long period limit. Both distortion tensors act on the regional electric field, but $\mathbf{Q}$ represents the effect on the horizontal magnetic field. These are written as follows

$$E = E^o + \mathbf{P}E^o \quad (8)$$

$$H = H^o + \mathbf{Q}E^o$$

From these expressions the distorted impedance tensor $\mathbf{Z} = E_h/H_h$ can be given in terms of the undistorted impedance $\mathbf{Z}^o = E_h^o/H_h^o$ as (Zhang et al., 1987):

$$\mathbf{Z} = \frac{(\mathbf{I} + \mathbf{P}_h)\mathbf{Z}^o}{\mathbf{I} + \mathbf{Q}_h\mathbf{Z}^o} \quad (9)$$

where $\mathbf{P}_h$ is the galvanic distorter acting on the regional horizontal electric field whereas $\mathbf{Q}_h$, which also acts on the regional horizontal electric field, represents the current channelling effect on the horizontal magnetic field. The relation of the distorted impedance to the vertical magnetic field is through the magnetic transverse function (eq. 6)

$$H_z = AH_x + BH_y = (A \ B)H_h \quad (10)$$

that results in the following expression for the induction vector or tipper vector, when H_h is substituted (Zhang et al., 1987) in it

$$(A, B) = \frac{(A^o, B^o) + (Q_{zx}, Q_{zy})\mathbf{Z}^o}{(\mathbf{I} + \mathbf{Q}_h\mathbf{Z}^o)}. \quad (11)$$

Here, (A, B) and (A^o, B^o) are the total and regional tipper vectors. (Q_{zx}, Q_{zy}) is the distortion vector acting on the regional horizontal electric field which produces galvanic effects on the vertical magnetic field. Separating this equation into the local and regional parts gives

$$\begin{aligned} (A, B) &= [(A^o, B^o)(\mathbf{I} + \mathbf{Q}_h\mathbf{Z}^o)^{-1}] + [(Q_{zx}, Q_{zy})(\mathbf{I} + \mathbf{P}_h)^{-1}\mathbf{Z}] \\ &= (A_r, B_r) + (A_l, B_l). \end{aligned} \quad (12)$$

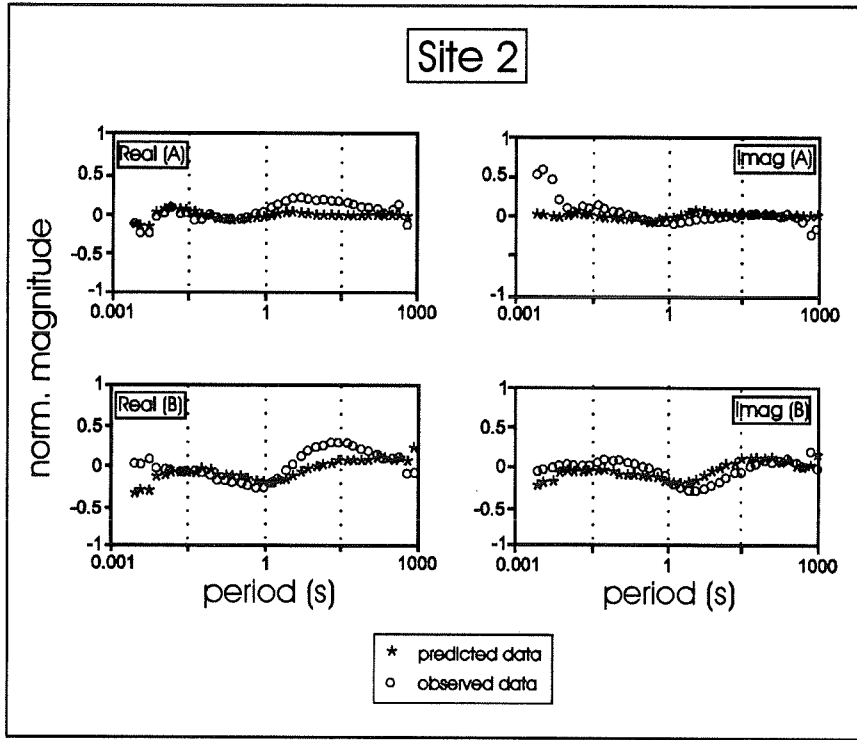


Fig. 5.- Calculated tipper component elements for sounding 2. The inductive response is observed between the measured (o) and galvanic I^* tipper particularly in the real components. In the period band [0.1, 250] s approximately, the tipper is dominated by induction rather than channelling.

Here, the term (A_r, B_r) is defined as the regional tipper due to structures whose induction lengths are sufficiently large compared with those at the surface and therefore could be regarded as uncorrelated, while the term (A_l, B_l) is the local tipper mostly due to galvanic effects. If they are uncorrelated then the local tipper could be predicted by means of a least square estimation by minimizing a function of the form

$$F = |A - A_l|^2 + |B - B_l|^2, \quad (13)$$

however, the error measurements in the impedance tensor $\mathbf{Z}$ as well as possible corre-

lations of the regional and local terms of the tipper, can prevent an exact estimation of the later. Yet, the parametrization of the tipper components given by

$$A_l = T_{zx}Z_{xx} + T_{zy}Z_{yx} \quad (14)$$

$$B_l = T_{zx}Z_{xy} + T_{zy}Z_{yy}.$$

allows to distinguish at least qualitatively period bands for which the local tipper

Table1.- Estimated multidimensional induction band (in seconds) for all MT soundings

Profile West

SITE	IND. BAND
2	0.1-250
1	0.1-500
3	1-500
4	0.1-250
5	10-500
13	1-1000
14	10-500

Profile East

6	10-500
7	10-500
8	10-500
9	10-500
10	10-500
11	10-1000
12	10-1000

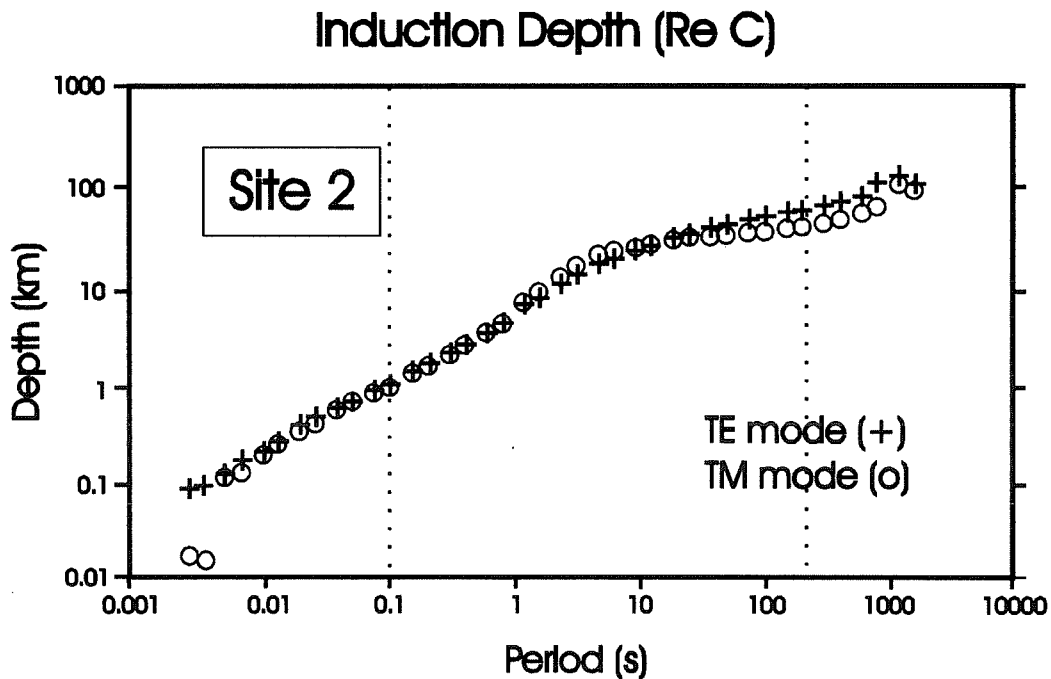


Fig. 6.- Schmucker C function for sounding 2. According to the assumed induction band (0.1 to 250 s for this particular site) channelling would occur either at depths shallower than 1 km or at depths greater than 20 km.

is due predominantly to current channelling versus induction. This can be done by observing the stability of the parameters T_{zx} and T_{zy} as a function of period. If they are approximately constant, then the local tipper is regarded as due to channelling. However, because of scaling problems, plots of T_{zx} and T_{zy} are usually not very telling. Then it is easier to compare the misfit between the 'predicted' tipper (due to channelling) and observed tipper. The tipper misfit

$$\epsilon^2 = \frac{F_{min}}{N - 2} \quad (15)$$

were F_{min} is the minimum of the equation (13), and N is the number of degrees of freedom in a particular period band, provides the means to evaluate how good the prediction of the local tipper is. Figure 5 shows the total (measured) and local (galvanic) tipper elements for sounding 2. However, the misfit (as observed for each individual component) is clearly useful. The tipper misfit is relatively small for periods lower than approximately 10^{-1} s, but it rises to higher values after this point. It stays that way up to about 250 s when it start decreasing until reaching a very good fit at the longer periods. In other words, in the period bands $[10^{-3}, 10^{-1}]$ s the anomalous vertical field is due to current channelling (galvanic effects), whereas in the period band $[10^{-1}, 2.5 \times 10^2]$ s approximately the tipper is dominated by induction in 2 or 3-D bodies. For periods longer that 250 s, the misfit reduces again. This may indicate channelling but it may also be representative of larger error bars in the data. Roughly, the channelling assumed at periods larger than 250 s corresponds to depths in the order or larger than 20 km according to the computed Schmucker (1970) C functions (Fig. 6). Although not all of the soundings show a clearly defined period interval (in fact some of them show an erratic behavior) where channelling occurs at the longer periods, for most of them the misfit tend to minimum values and T_{zx} and T_{zy} seem to stabilize at the larger periods (see Appendix A). However, it is important to remember that the error on the data becomes larger at the longer periods (> 500 s), therefore the small misfit may simply correspond to the fact that the data are not well constrained. Table 1 gives the approximate interval for each sounding at

which the tipper is thought to be associated with induction of the subducting plate. In the following section, the quantitative inspection of the impedance tensor through Bahr's dimensionality analysis will allow us to constrain reasonably well the strike angle of the main inductive structure at depth that we suggest is mainly associated with induction in the period band [1,500] s roughly.

3.3) Definition of a "true" 2D strike

It is well known that electromagnetic (EM) fields are galvanically distorted in the presence of conductors whose dimensions are small compared to the wavelengths of the fields. Unless the EM fields are measured in sedimentary basins or a similar geological environment, the electric field (and the magnetic fields to a lesser extent) are expected to undergo some kind of distortion by near surface inhomogeneities. As we discussed earlier in this chapter, the size and depth of the distorting bodies will determine what frequencies are more likely to be affected, whereas the conductivity contrast will reflect how strong the distortion is. In practice though, the problem is not simple. First because we normally do not know the dimensionality and conductivity of the distorters, and second because they may be coupled with other structures. Thus, telluric distortion may be a combination of both static shifts and angular deviations of the induced EM fields.

A structure can be characterized as local or regional depending on the scale of a particular survey. Obviously a regional structure has a different connotation in magnetotellurics, where the frequency band used is in the range 10^2 to 10^{-4} Hz, than

in audio magnetotellurics (AMT) where the working frequency band is often in the range 10^4 to 10^0 Hz. For example, in MT a regional structure may correspond to large scale tectonic features such as a mega-shear zone or a subduction zone, whereas in AMT the scale of a regional structure can be that of a very local fault or a similar geologic feature. In either case, we have to know the strike of the structure (if it is 2-D) in order to model the inductive response of the earth at the respective scales. Failing to determine accurately the azimuthal orientation of the principal structure may lead to models that do not represent the 'true' geoelectrical structure of the earth.

MT field measurements are used to survey at depths up to several tens of kilometers depending on the regional conductivity. Local structures are in general good conductors that may produce two types of distortion in the electric field: 1) that due to accumulation of charges in the boundary of a conductor (called galvanic distortion) which only affect the measured electrical field by multiplying it by a frequency independent (normally unknown) constant, and 2) that due to the circulation of currents or induction that makes appear the body as a source of currents that distorts locally the primary field. This second effect can be modeled using 2-D or 3-D induction algorithms if the structure considered is large. Models that account for the distortion effects of near surface heterogeneities normally exclude induction effects.

The simplest type of galvanic distortion is known as static shift, because it is observed as a vertical displacement of the resistivity curves in a logarithmic resistivity ($\log \rho$) versus period ($\log T$) plot. However, in many cases distortion involves phase impedance mixing and therefore fundamentally disturbs the regional

inductive response, leading to 2-D strikes that do not correspond to true 2-D regional structures. A number of techniques to remove the effects of galvanic distortion, except the static shift, already exist. We have chosen Groom and Bailey decomposition (1989) method as well as Bahr's robust approach that are reported to give stable results even under relatively strong near surface distortion. From these, the distortion parameters of a specific model, including the regional strike when the earth is 2-D, are extracted using the four complex elements of the impedance tensor. A simpler but less robust approach was developed recently by Chakridi et al. (1992) that allows qualitative inspection of the galvanic distortion occurring at the MT soundings will also be tested on the data. Although these overlap conceptually, they have different approaches to find the regional strike and to deal with distortion effects. The main goal in applying them is to define the strike angle for the 2-D tectonic feature that controls the induction of the regional electromagnetic fields in the area of study. In what follows, the fundamentals of the three methods used are outlined and, at the end of each subsection, the results of their application to the field data collected in Oaxaca are discussed.

3.3.1) The rotation method

The rotation analysis of Chakridi et al. (1992) takes advantage of the form of individual components of the impedance tensor. This gives a rapid insight of the dimension of the regional structure, which is important because if the earth is either 1-D or 2-D, distortion effects can easily be reduced to their simpler form of static shift. Thus, by observing each of the individual components of the measured regional

tensor $\mathbf{Z}_m$, given by

$$\mathbf{Z}_m = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}, \quad (16)$$

it is possible to recognize the true dimension of the regional structure if the data quality is reasonably good. For a 1-D regional earth for example, the impedance at the surface in the presence of shallow distorters can be expressed in terms of a distortion operator $\mathbf{A}$ as (Larsen, 1977)

$$\begin{aligned} \mathbf{Z}_m &= \mathbf{A}\mathbf{Z}_{1D} \\ &= \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} 0 & Z \\ -Z & 0 \end{pmatrix} \\ &= \begin{pmatrix} -a_{12}Z & a_{11}Z \\ -a_{22}Z & a_{21}Z \end{pmatrix}. \end{aligned} \quad (17)$$

Here the matrix elements of $\mathbf{A}$ are independent of frequency, and the tensor $\mathbf{Z}_{1D}$ represents the undistorted 1-D earth. The individual resistivity curves computed from equation 3.1.2 are shifted by different factors a_{ij} ($i, j = 1, 2$), but their shape remains the same within the experimental errors. The individual phases, computed from the measured impedance components are all the same and identical to the exact 1-D phase. Sounding 7 is a typical example of this particular case (see Fig. 7) for the higher frequencies.

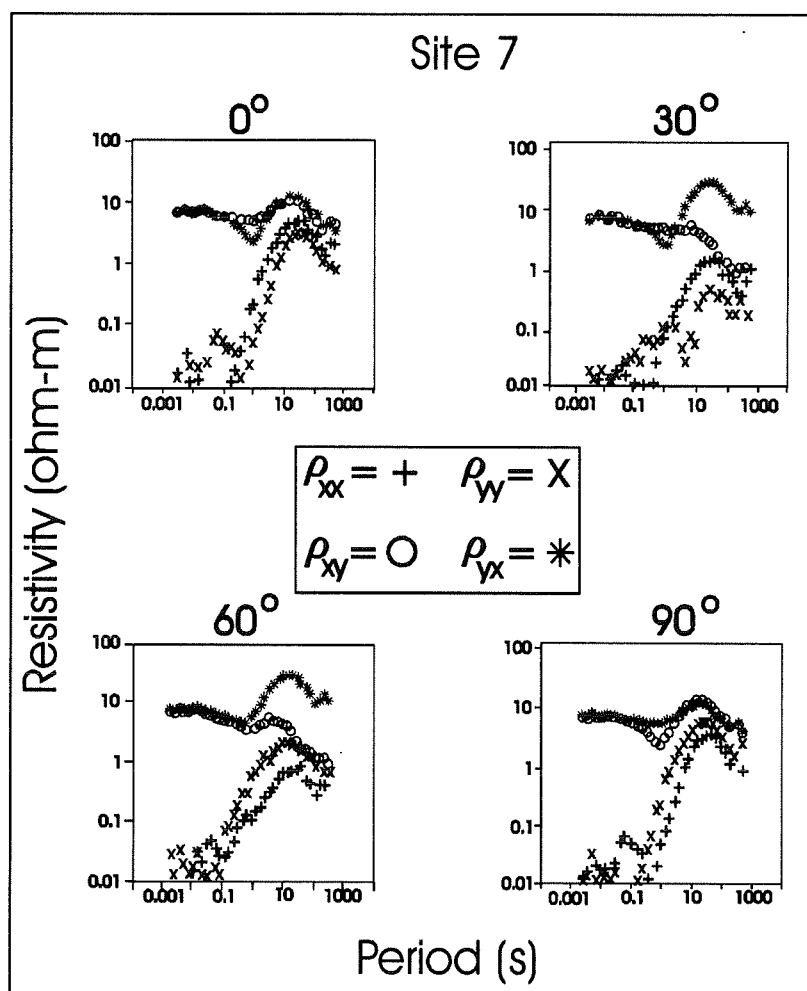


Fig. 7.- Sounding 7 is a typical example of undistorted one-dimensional impedance in the period band [0.01, 0.1] s. The resistivities of the off diagonal elements (symbols '*' and 'o') are on top of each other, whereas for the diagonal elements (symbols '+' and 'x') are close to zero. The phase curves are identical (shifted 180 degrees though) for the off diagonal elements and undefined for the diagonal elements of the impedance. Neither the resistivity nor the phase curves change significantly with rotation of the impedance (0, 30, and 60 degrees from top to bottom).

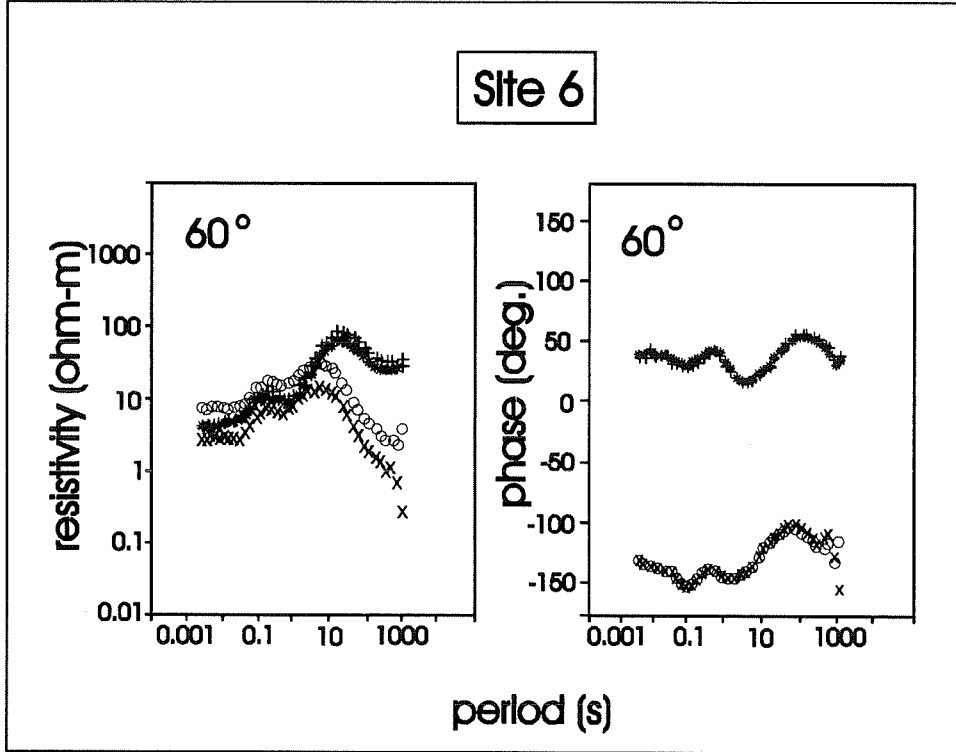


Fig. 8.- Sounding 6 is an example of a two dimensional impedance measured off the regional axis for $T > 1$ s. A rotation of $\theta = 60^\circ$ has the effect of grouping the resistivity curves by pairs (ρ_{xx} (+) is approximately parallel to ρ_{yx} (*), and ρ_{xy} (o) to ρ_{yy} (x)) and brings the phases to identical values for the elements of each column of the impedance ($\phi_{xx} = \phi_{yx}$, and $\phi_{xy} = \phi_{yy}$).

For a 2-D regional earth (where the impedance is represented by Z_{2D}) two cases may occur, depending on whether or not the regional axes coincide with the measuring axes. When the measurements are taken parallel to the regional structure Z_m is expressed as (Bahr, 1988)

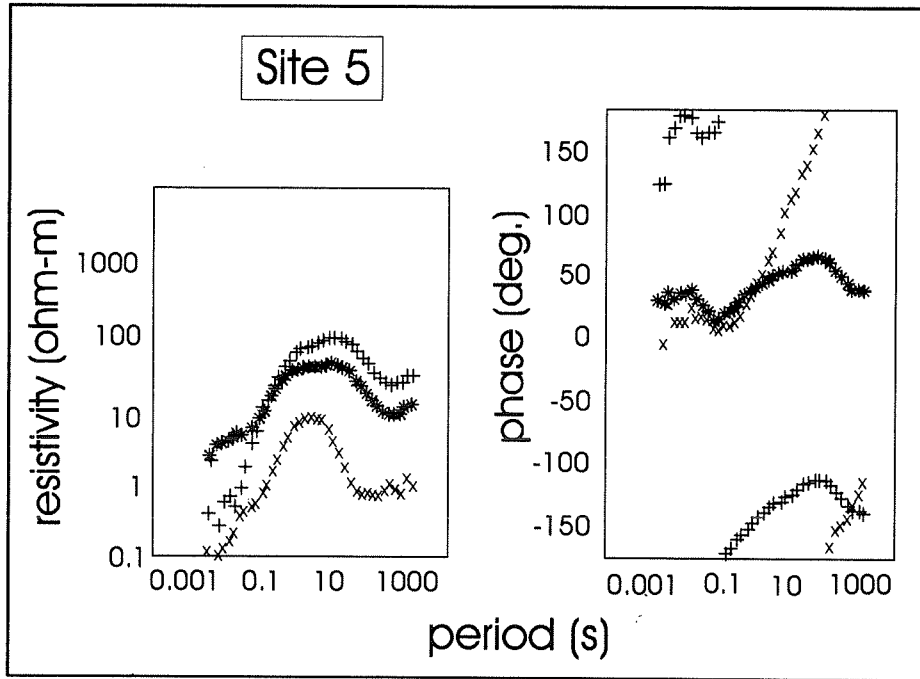


Fig. 9.- For sounding 5 all the phases and resistivities are mixed. No rotation exist that could unmix the components of the impedance. Thus, this sounding is 3-D. Symbols are as in figures 7 and 8.

$$\begin{aligned}
 \mathbf{Z}_m &= \mathbf{A} \mathbf{Z}_{2D} \\
 &= \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} 0 & Z_1 \\ -Z_2 & 0 \end{pmatrix} \\
 &= \begin{pmatrix} -a_{12}Z_2 & a_{11}Z_1 \\ -a_{22}Z_2 & a_{21}Z_1 \end{pmatrix} \\
 &= \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix},
 \end{aligned} \tag{18}$$

In this case, the resistivity plots are grouped by pairs. Z_{xx} and Z_{yx} , define a pair of curves having the same shape but displaced vertically by a factor a_{12}/a_{22} . Similarly, Z_{xy} and Z_{yy} define two other parallel curves displaced by a factor a_{11}/a_{21} . The phases on the other hand, are identical for the elements of each column of the impedance tensor and correspond to the true 2-D phases. When the measurements are taken in any other orientation but that of the regional axes, all phases and apparent resistivity curves differ with respect to each other. When this is the case, a rotation to the principal axes can be performed on the impedance, namely

$$\mathbf{Z}'_m = \mathbf{R}^T \mathbf{Z}_m \mathbf{R}, \quad (19)$$

where

$$\mathbf{R} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad (20)$$

is the rotation operator and $\mathbf{R}^T$ is its transpose and θ refers to the regional strike angle. Sounding 6 illustrates this case (Fig. 8). It is easy to determine θ since it will be the angle for which the elements of the tensor group by columns as in (18).

If there do not exist a rotation angle θ for which $\mathbf{Z}_m$ can be represented by equation (18), then the regional structure is 3D (Fig. 9). In such a case

$$\begin{aligned} \mathbf{Z}_m &= \mathbf{A} \mathbf{Z}_{3D} \\ &= \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} Z_1 & Z_2 \\ Z_3 & Z_4 \end{pmatrix} \end{aligned}$$

$$= \begin{pmatrix} a_{11}Z_1 + a_{12}Z_3 & a_{11}Z_2 + a_{12}Z_4 \\ a_{21}Z_1 + a_{22}Z_3 & a_{21}Z_2 + a_{22}Z_4 \end{pmatrix}, \quad (21)$$

which means all phases and apparent resistivity curves result from a mix of the distortion and impedance tensor components. Here the elements of the measured impedance Z_{ij} bear no relation among them even after any rotation (see Fig. 9) and it is impossible to retrieve any element of the regional 3-D tensor.

A qualitative analysis of the collected MT soundings was done using this approach to classify them according to the previous criteria, although very often MT soundings showed different dimensionalities depending on the observed frequency range. Some soundings had a 2-D behavior after rotation to the principal axis for a given period band while in other bands their behavior was mainly 3-D. It was useful however, to determine period bands in which the earth could be approximated by (18). Many of the soundings could be considered as 2-D for longer periods (10 to 500 s). Therefore, a meaningful strike angle θ for the regional structure can, in principle, be obtained. In the remaining of this section two methods to quantify θ are used, and later on the results are discussed.

3.3.2) Bahr's robust strike method and distortion indicators

The model of equation (18) represents a layered earth with a local 3-D anomalous body located on top of the sequence. The elements of the distortion tensor $\mathbf{A}$ are independent of frequency at periods for which the top structure is

small compared with the penetration depth. As mentioned before, in the ideal 1-D case all the elements of the impedance $\mathbf{Z}_m$ have the same phase. With real data however, this is seldom the case. A parameter that measures phase differences in the impedance tensor to evaluate departure from this model (and therefore a measure of one-dimensionality) which is rotationally invariant was defined by Bahr (1988) as

$$\mu = \frac{(|[D_1, S_2]| + |[S_1, D_2]|)^{\frac{1}{2}}}{|D_2|} \quad (22)$$

where

$$\begin{aligned} S_1 &= Z_{xx} + Z_{yy} \\ S_2 &= Z_{xy} + Z_{yx} \\ D_1 &= Z_{xx} - Z_{yy} \\ D_2 &= Z_{xy} - Z_{yx} \end{aligned} \quad (23)$$

with $[D_1, S_2]$, the phase difference between two complex numbers given by

$$[D_1, S_2] = \text{Re } D_1 \text{Im } S_2 - \text{Re } S_2 \text{Im } D_1. \quad (24)$$

and similarly for $[S_1, D_2]$. Equation (18), also referred as the ‘superimposition model’, represents a 2-D earth on top of which a thin layer of varying conductance is located. Bahr’s method uses the four complex elements of the impedance tensor to find an analytical solution of the strike angle θ for this case. By using the condition discussed before that the two elements in the same column of the impedance tensor have the

same phase, it is possible to show that the strike angle of the regional structure is given by

$$\theta = \frac{1}{2} \tan^{-1} \frac{[S_1, S_2] - [D_1, D_2]}{[S_1, D_1] + [S_2, D_2]} \quad (25)$$

with S_1, S_2, D_1 and D_2 as in (23) and $[S_1, S_2], [D_1, D_2], [S_1, D_1]$ and $[S_2, D_2]$ having the same form as in (24). There may be however deviations from this model. A measure of the phase difference resulting from the departure of this model is given by the also rotationally invariant parameter η , or regional skew, obtained by Bahr (1991) from the condition that in the coordinate system of the regional 2-D structure the two elements of the tensor in each column have the same phase. Any departure from these conditions ($\phi_1 = \arg Z_{xx} = \arg Z_{yx}$ and $\phi_2 = \arg Z_{xy} = \arg Z_{yy}$) results in a regional skew larger than zero, therefore η is a measure of two-dimensionality. Thus, the explicit form for η is written as

$$\eta = \frac{(|[D_1, S_2]| - |[S_1, D_2]|)^{\frac{1}{2}}}{|D_2|}. \quad (26)$$

When the model departs from the principal superimposition model, then there is no coordinate system in which the impedance tensor takes the form of equation (18). If the departure is moderated, a phase deviation δ can be introduced such that the phases in each column of the tensor differ slightly. The key assumption Bahr does here is that the same phase deviation must occur in the two columns of the tensor. Thus, by introducing the phase perturbation as $e^{\pm i\delta}$, the impedance tensor of the principal model (18) in the coordinate frame of the regional strike is given by

$$\begin{aligned}
\mathbf{Z}_m &= \mathbf{A} \mathbf{Z}_{2D} \\
&= \begin{pmatrix} a_{11} & a_{12}e^{i\delta} \\ a_{21}e^{-i\delta} & a_{22} \end{pmatrix} \begin{pmatrix} 0 & Z_1 \\ -Z_2 & 0 \end{pmatrix} \\
&= \begin{pmatrix} -a_{12}Z_2e^{i\delta} & a_{11}Z_1 \\ -a_{22}Z_2 & a_{21}Z_1e^{-i\delta} \end{pmatrix} \\
&= \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}.
\end{aligned} \tag{27}$$

It can be proven that the transformation of these modified impedance tensor elements using an expression of the form of equation (19) into the coordinate system of the regional strike when the measurements were taken in an arbitrary orientation yields the following equation for θ :

$$\begin{aligned}
\theta &= \frac{1}{2} \tan^{-1} \frac{(B_1A_2 + A_1B_2 + C_1E_2)}{(A_1A_2 - C_1C_2)} \\
&\pm \left[\frac{1}{4} \frac{(B_1A_2 + A_1B_2 + C_1E_2)^2}{(A_1A_2 - C_1C_2)^2} - \frac{(B_1B_2 - C_1C_2)}{(A_1A_2 - C_1C_2)} \right]^{\frac{1}{2}},
\end{aligned} \tag{28}$$

where the coefficients $A_1, A_2, B_1, \dots$ etc, are combinations of the modified impedances in equations (23). In terms of these coefficients the phase deviation angle δ , a measure of departure from a 2-D earth, is expressed by

$$\delta = \tan^{-1} \frac{C_1}{-A_2 \sin(2\theta) + B_2 \cos(2\theta)} \tag{29}$$

Equation (28) is Bahr's robust method to calculate the strike θ when there is a moderate departure from the 2-D case. It describes two different coordinate systems

in which η (eq. 26) is converted either to a minimal or maximal phase deviation. For physical reasons the minimal δ is chosen, although both are equally valid.

Figure 10a and 10b show the plotted values of θ obtained for the eastern (PE) and western (PW) profiles respectively by applying equation (28) to the collected MT data. Filled squares represent the strike angle θ_{500} corresponding to a period $T = 500$ s. This period was suggested partly by Zhang's et al. (1992) tipper separation approach that indicate that 500 seconds was the maximum period for most soundings at which the tipper responded to induction (Table 1), presumably due to the subducting plate. The scatter of θ at relatively short periods supports our choice (see Table 2). This scatter is probably due to the fact that the problem is almost 1-D, the subduction angle being relatively small. A safe choice to estimate the true strike of the plate is therefore $T = 500$ s where more stable results were observed even though we may be reaching, in the inductive sense, the lower boundary of the conductor. Open circles in Figure 10 represent the average strike angle θ_{avg} and the vertical bars their corresponding deviation calculated within the induction band 100 to 500 s. This band was found to be unusable for a number of soundings, particularly those belonging to PE. Neither θ_{500} nor θ_{avg} have the expected trend of clustering along a line of constant value. However, the larger scatter seems to be introduced particularly by the values computed for soundings 9, 10 and 11. Profile PW shows a more stable strike value, although some scatter along the average value is still observed (dashed line in Fig. 10b). The values of Bahr's regional strike assumed to be more reliable and used in subsequent discussions are $\bar{\theta}_{500} = -1^\circ$ and 4° degrees for PE and PW respectively. These will be compared with those obtained using Groom and Bailey's decomposition method outlined in the following section.

Table 2.- Regional strike estimation for several periods using Groom and Bailey (G&B) and Bahr (B) methods for PW (top) and PE (bottom). Periods for which the strike value was more stable are shown with a grey background. AVG and SD in the last two columns are the standard deviation and average of the strike calculated using the values for all the periods shown (10 to 1500 s). The last two lines in each of the tables show also the average and standard deviation at that particular period.

GROOM AND BAILEY (G&B) AND BAH'S (B) STRIKE ANGLE

WEST PROFILE

SITE	Meth.	PERIOD (s)								AVG	SD
		10	50	100	250	500	750	1000	1500		
2	G&B	-4.80	13.10	16.80	19.30	16.70	13.40	15.00		17.60	1.47
	B	-4.80	13.10	17.50	19.90	19.40	21.10	20.00		18.93	1.27
1	G&B	7.50	39.80	10.20	17.80	17.20	51.30	22.20	0.30	15.07	4.23
	B	7.30	43.00	10.20	17.50	16.40	44.50	24.30	0.30	14.70	3.94
3	G&B	25.60	13.50	9.00	-22.70	3.50	0.30	8.80		-3.40	16.94
	B	24.20	2.30	-3.10	-3.50	0.80	1.50	8.70		-1.93	2.38
4	G&B	-57.20	-63.40	-65.60	-66.80	-16.70	-9.30	-0.50	7.60	-49.70	28.59
	B	-43.90	-49.10	-50.50	-50.20	-17.20	-11.10	-0.50	10.10	-39.30	19.14
5	G&B	7.50	39.40	-6.60	2.70	-4.50	-41.50	-11.00		-5.55	1.48
	B	-10.80	-7.20	-14.80	-9.80	-4.40	2.20	10.50		-9.67	5.20
13	G&B	54.70	69.30	1.40	5.10	11.70	5.90			6.07	5.22
	B	33.10	49.40	-1.30	4.20	11.70	5.90			4.87	6.53
14	G&B	10.90	2.70	7.30	10.40	17.50	-12.70	-10.30		11.73	5.23
	B	10.90	5.20	-0.90	-1.60	0.90	-5.50	-8.80		-0.53	1.29
G&B avg.		6.31	16.34	-3.93	-4.89	6.49	1.06	4.03	3.95		
B avg.		2.29	8.10	-6.13	-3.36	3.94	8.37	9.03	5.20		
G&B sd.		33.90	41.73	28.17	30.66	13.13	28.31	13.60	5.16		
B sd.		25.44	32.91	22.09	23.35	12.85	18.84	12.37	6.93		

EAST PROFILE

6	G&B	-28.50	-7.70	-14.50	5.70	7.00	6.10	-41.30		-0.60	12.06
	B	-28.80	-7.10	-14.30	7.20	5.50	15.40	-38.30		-0.53	11.95
7	G&B	35.00	45.40	39.00	8.90	30.70				26.20	15.55
	B	37.60	47.20	38.10	9.00	***				23.55	20.58
8	G&B	0.00	39.50	23.50	34.10	9.00				22.20	12.60
	B	-0.20	14.10	15.60	6.00	15.40				12.33	5.49
9	G&B	6.00	11.70	20.70	6.90	-26.30	30.50	35.10		0.43	24.16
	B	-40.40	44.10	31.70	21.70	-15.30	32.30	12.10		12.70	24.76
10	G&B	28.00	-44.00	-29.40	-49.50	-34.40	33.70	47.90	21.40	-37.77	10.46
	B	29.10	-43.70	-45.40	-57.30	-45.90	33.50	41.20	32.70	-49.53	6.73
11	G&B	16.60	38.70	16.40	38.00	-6.70				15.90	22.35
	B	17.80	38.80	16.50	40.30	-33.40				7.80	37.61
12	G&B	-54.70	-9.70	0.60	4.30	9.50	-36.30	-19.10		4.80	4.47
	B	-6.30	-6.60	0.60	4.30	9.60	-6.80	-6.00		4.83	4.52
G&B avg.		0.34	10.56	8.04	11.98	4.70	8.50	5.65	21.40		
B avg.		1.26	12.40	6.11	9.64	-0.73	18.60	2.25	32.70		
G&B sd.		31.95	33.08	23.78	12.48	7.68	32.31	42.70	***		
B sd.		29.06	33.68	28.80	6.96	22.16	18.84	33.30	***		

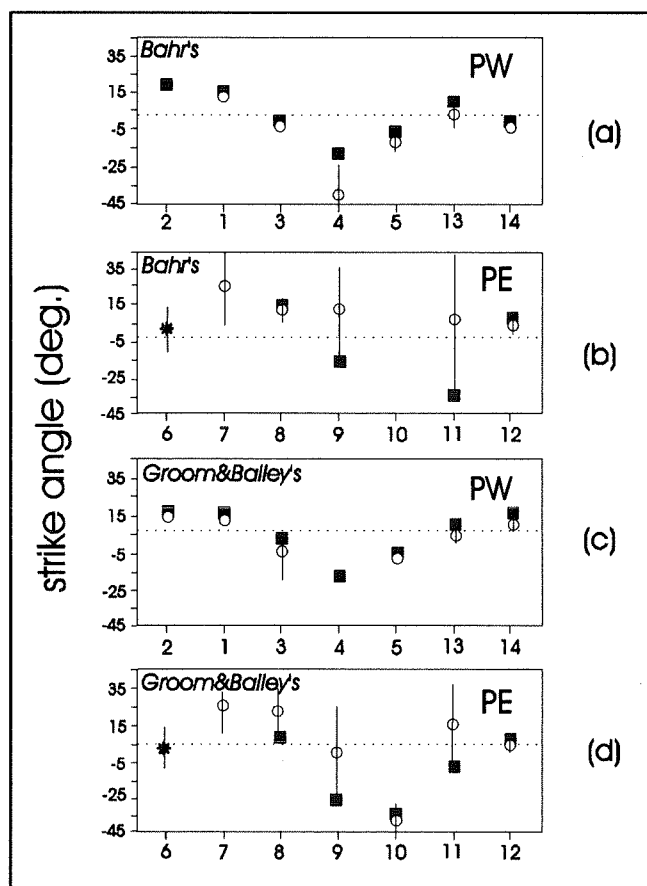


Fig. 10.- Calculated strike angle using Bahr's robust method (PW (a), PE (b)) and Groom and Bailey decomposition method (PW (c), PE (d)). Filled squares represent the strike angle at $T=500$ s, whereas open circles represent the average strike within the induction band $[100, 500]$ s. Vertical bars are the calculated standard deviation. The dashed lines represent the average strike. The asterisk corresponds to the strike angle calculated for sounding 6 which contradicts that found through the rotation of Z (60°).

Bahr's (1991) dimensionality indicators (eqs. 22, 26 and 29) were also applied to the data to further constrain the regional strike. Figure 11 shows the variation of the phase differences μ in the impedance tensor. As observed before, this parameter is an indicator of regional one-dimensionality: when $\mu \approx 0$ it indicates a 1-D earth, whereas large values imply a more complex earth model (2 or 3-D). In profile PW (Fig. 11a), most of the soundings differ from the ideal 1-D model represented by equation (17), except probably sounding 2 which has a relatively small phase

Phase Difference

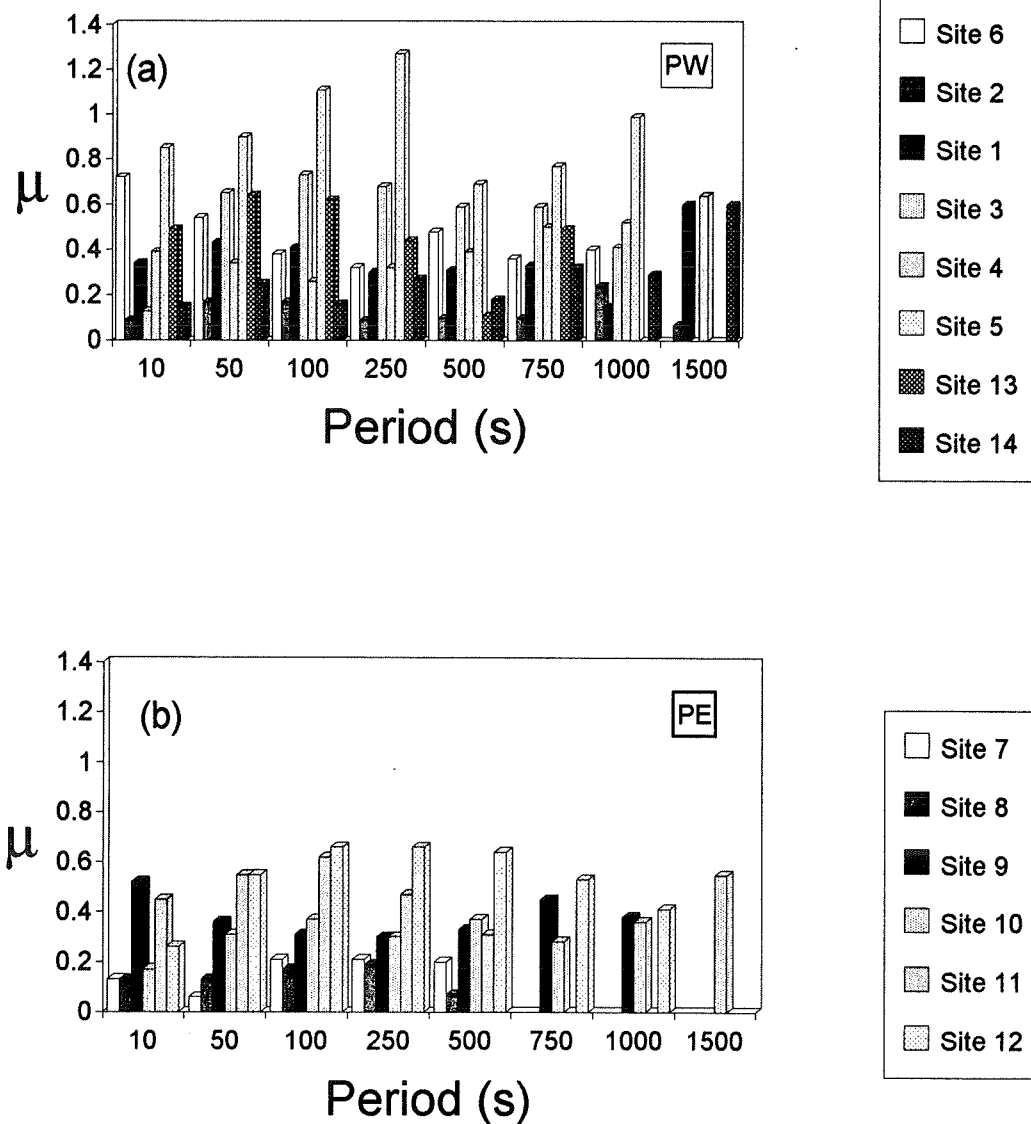


Fig. 11.- Variation of phase differences (μ) in the impedance tensor for PW (a) and PE (b) respectively. μ close to zero indicates a 1-D earth. Soundings 2 (PW), 7, and 8 (both from PE) behave as 1-D soundings.

difference in the period band shown. In contrast, sounding 5 has the larger phase differences in the same period band. Two soundings (7 and 8) in profile PE (Fig. 11b) also present small values of μ . The magnitude of the regional skew η on the other hand, determines whether or not a sounding is 2-D. If $\eta = 0$, then the impedance tensor can be represented by equation (18). Moderate departures from this model are considered to be within the range $0 < \eta < 0.3$; values larger than 0.4 are definitely regarded as 3-D. In Fig. 12a and b are plotted the results for the regional skew for PW and PE respectively. It can be observed that the larger values of η appear at shorter periods and that it tends to decrease as the period increases. This is approximately the general trend except for the soundings 5 from PW, and 9 and 10 from PE where η increases at larger periods, which is particularly true for sounding 5. Thus, these soundings can be regarded as being 3-D in this period band. The phase deviation angle (eq. 29) is not strictly a dimensionality indicator but a measure of departure from a 2-D earth that results from the regional skew. The calculated values for δ are shown in Fig. 13a and b, corresponding to PW and PE respectively. For PW δ has a low variability in the period band of 100 to 1000 s and relatively small values for long periods. Sounding 6 is, according to these results, close to the 2-D ideal model for the impedance tensor, whereas the increasing δ at long periods at sounding 5, suggests it is a 3-D sounding. The phase deviation for PE in contrast, shows a great variability within the same period band. The significance of this and other results shown here, will be summarized at the end of this section.

REGIONAL SKEW

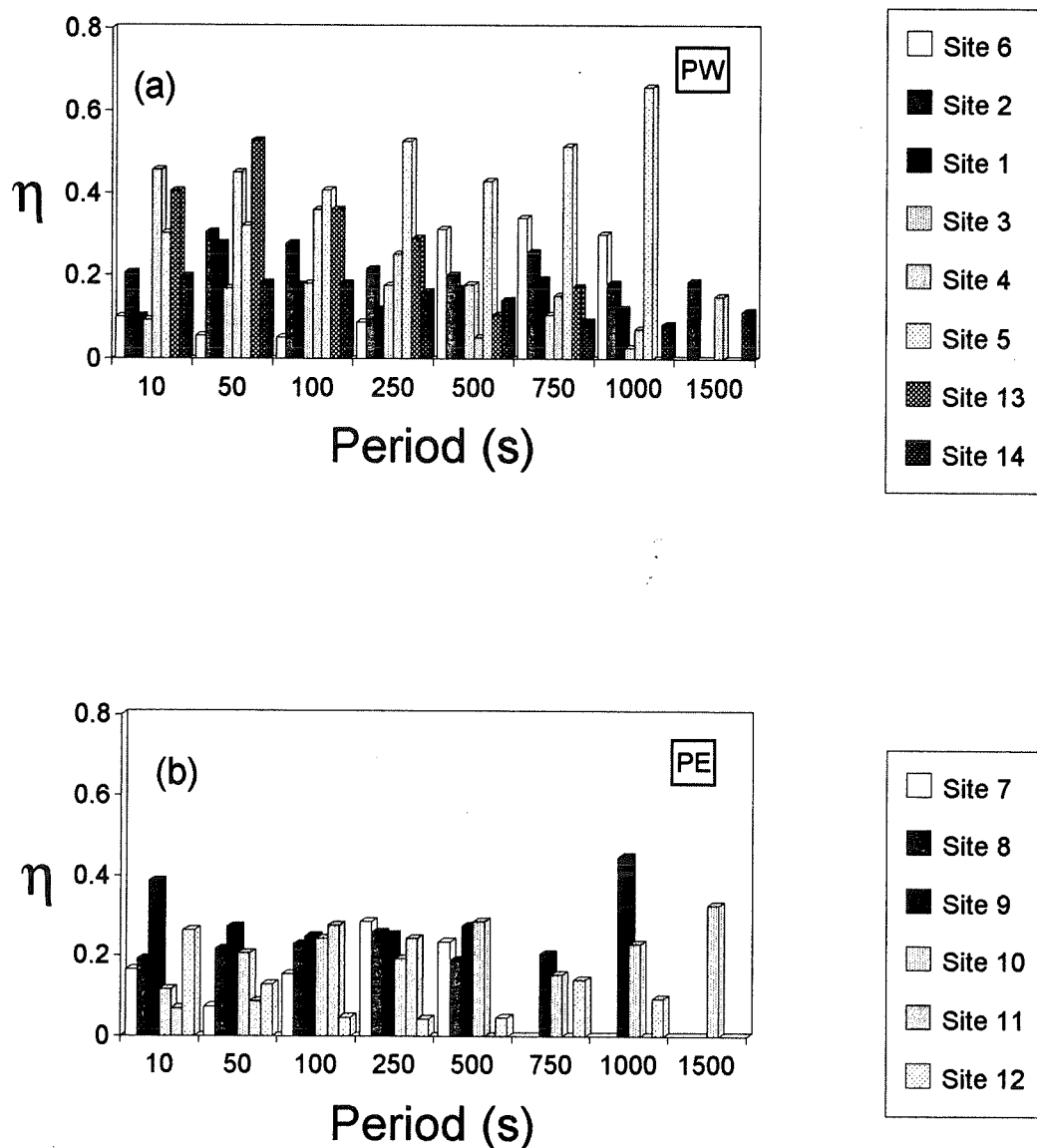


Fig. 12.- Regional skew for profiles PW (a) and PE (b). Values of η larger than 0.3 are regarded as due to 3-D structures. Sounding 5 of PW shows large values of η , this is regarded as a 3-D sounding. Sounding 9 (and perhaps 10) of PE show increasingly larger values of η as T increases.

PHASE DEVIATION ANGLE

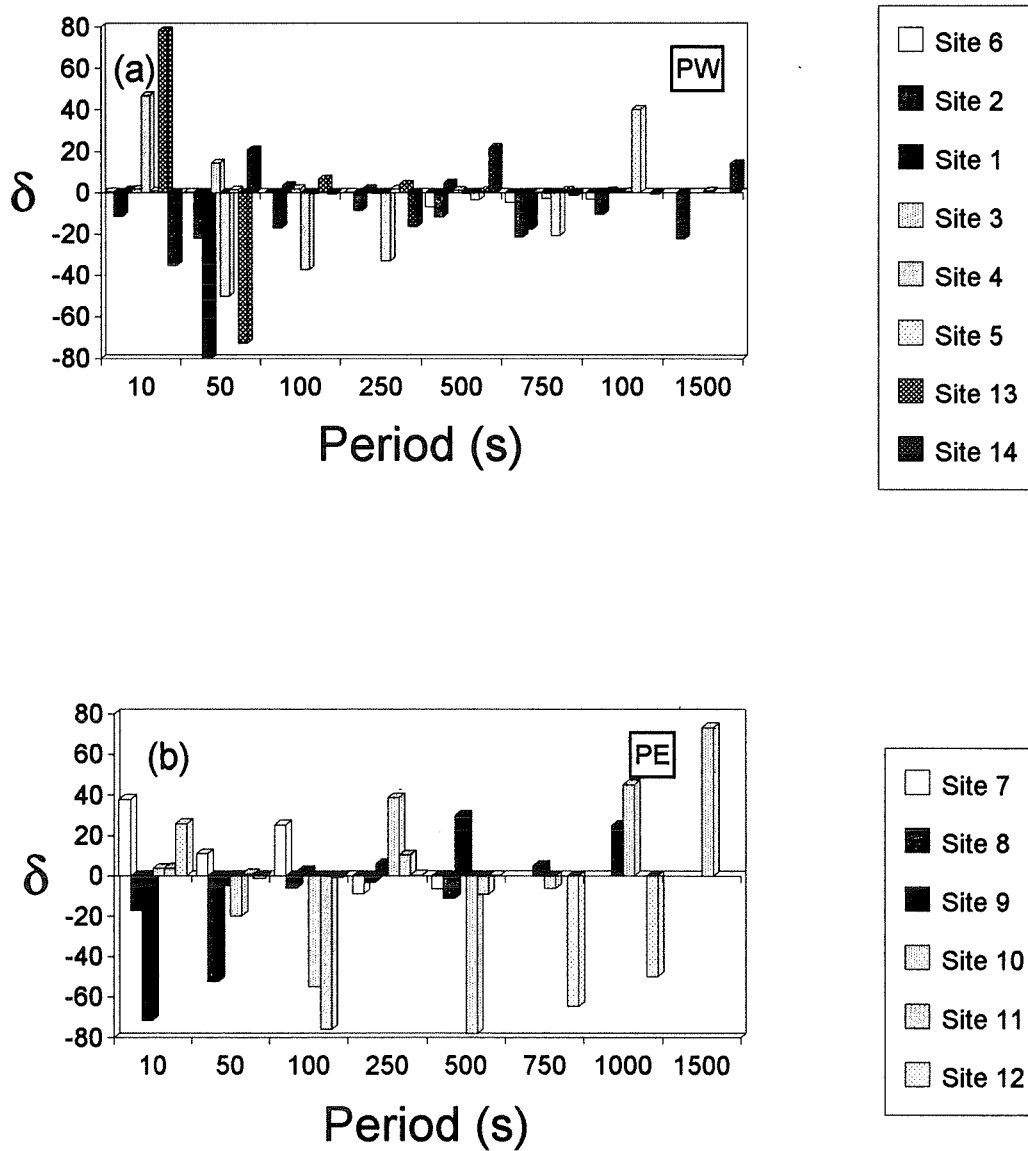


Fig. 13.- Phase deviation angle δ for PW (a) and PE (b). Phase deviation measures δ departure from a 2-D impedance that result from the regional skew. Many of the soundings along profile PE show relatively large deviation angles compared with those in profile PW.

3.3.3) Groom and Bailey's decomposition method

Groom and Bailey's (1989) decomposition method of the impedance tensor has also been developed to deal with a 2-D earth under the influence of a local 3-D distorter. Like the methods described above, it assumes that distortion on the measured impedance $\mathbf{Z}_m$ due to the near surface heterogeneity is caused by charge accumulation on its surface. This effect, called galvanic distortion, is represented by a distortion operator $\mathbf{C}$. Thus, for the principal superimposition model the measured impedance is

$$\mathbf{Z}_m = \mathbf{C}\mathbf{Z}_{2D}. \quad (30)$$

As with $\mathbf{A}$, the elements of $\mathbf{C}$ are real and frequency independent because it is assumed that the 3-D structure is inductively weak. In general, the distortion tensor $\mathbf{C}$ has diagonal and off-diagonal elements different from zero. Assuming that galvanic distortion does not destroy the information about an underlying regional 2-D induction process (Bahr, 1985), Groom and Bailey (1989) proposed a product factorization of the impedance tensor. Their decomposition is an explicit parametrization of the tensor that separates local and regional effects when the regional structure is at most two dimensional. The proposed factorization for the distortion tensor is given by

$$\mathbf{C} = g\mathbf{TSE} \quad (31)$$

where g is the sounding gain that includes the static shift and normalizing factors of

the tensors $\mathbf{T}$, $\mathbf{S}$ and $\mathbf{E}$, corresponding to the twist, shear, and anisotropy distortion operators respectively. Explicitly, these are expressed by

$$\mathbf{T} = \begin{pmatrix} 1 & -t \\ t & 1 \end{pmatrix} \quad (32)$$

$$\mathbf{S} = \begin{pmatrix} 1 & s \\ s & 1 \end{pmatrix} \quad (33)$$

$$\mathbf{E} = \begin{pmatrix} 1+e & 0 \\ 0 & 1-e \end{pmatrix}. \quad (34)$$

In a coordinate frame other than the regional axes system, the measured impedance tensor is

$$\mathbf{Z}_m = g \mathbf{R}^T \mathbf{T} \mathbf{S} \mathbf{E} \mathbf{Z}_{2D} \mathbf{R}, \quad (35)$$

with $\mathbf{R}$ is given by equation (20). If $g\mathbf{E}$ is absorbed into $\mathbf{Z}_{2D}$, which is only possible when the distortion is trully frequency independent, then

$$\mathbf{Z}_m = \mathbf{R}^T \mathbf{T} \mathbf{S} \mathbf{Z}'_{2D} \mathbf{R}. \quad (36)$$

This expression is Groom and Bailey's decomposition approach which constitutes a non linear system of eight equations with seven real unknowns in its explicit form. These are: the real and imaginary part of the 2-D impedance components Z_1 and Z_2 , the shear (s), the twist (t), and the strike angle of the regional strike θ . Groom and Bailey proved that if the physical model is correct for the impedance tensor, then there is a unique decomposition given by equation (36).

The twist and shear angles given by $\phi_t = \tan^{-1} t$ and $\phi_s = \tan^{-1} s$ respectively, are measures of deflection and rotation of the electric fields, thus it would be possible to characterize the strength and possibly the extension of the near surface 3-D structure that produces them. Except for the static shift, Groom and Bailey's

Table 3.- Induction band, regional strike and dimensionality indicators for the MT soundings for PW (top) and PE (bottom).

PROFILE WEST

SITE	IND. BAND(s)	θ (500)		DIST. INDIC.			SELECTED SITES
	No galvanic comp.	G&B	BAHR	Reg. 2D	$\eta > 0.25$	$\delta > 10 $	
MEX02	0.1-250	16.70	19.40	X			✓
MEX01	0.1-500	17.20	16.40	X			✓
MEX03	1-500	3.50	0.80	X			✓
MEX04	0.1-500	-16.70	-17.20	X			✓
MEX05	10-500	-4.50	-4.40		X	X	
MEX13	1-750	11.70	11.70	X			✓
MEX14	10-500	17.50	0.90	X			✓
Avg. Strike ==>		8.32	5.33				
SD ==>		13.37	13.48				

PROFILE EAST

MEX06	10-500	7.0(?)	5.5(?)		X		?
MEX07	10-500	30.70	---				
MEX08	10-500	9.00	15.40	X			✓
MEX09	10-500	-26.30	-15.30		X	X	
MEX10	10-500	-34.40	-45.90		X	X	
MEX11	10-250	-6.70	-33.40			X	
MEX12	10-1000	9.50	9.60	X			✓
Avg. Strike ==>		9.25	12.50				
SD ==>		0.35	4.10				

method can fully represent the sources of distortion using the parameters obtained when equation (36) is solved. However, here attention was paid only to the definition of θ which will be used in a subsequent chapter to model the regional structure in the Oaxacan continental margin. Indeed, if θ is defined properly for a 2-D problem, then the 2-D phases are exact and can be used for modeling.

Calculations of the strike angle θ were done using Groom and Bailey for all soundings. The results obtained are shown in Figure 10c and d for PW and PE respectively. Here too, a large deviation from a central value is observed at soundings 9 and 10 in PE, whereas soundings in PW show less scatter around a mean value of about 5 degrees. This value agrees well with that of PE when soundings 9 and 10 are excluded. Groom and Bailey's method provided results with slightly less scatter than Bahr's. However, the values of θ_{500} obtained with both methods are in general similar. Table 3 is a summary of results that includes the strike angle θ obtained from both Bahr's and Groom and Bailey's methods, the 2-D distortion indicators, and the period band where induction dominates the vertical field response. These results will be further discussed in Chapter 4 and used accordingly to model the subduction of the oceanic crust under the continent in this region.

3.4) Evaluation of static shift

3.4.1) Classification of soundings according to static shift

For the soundings at which we have managed to show that the MT tensor

is roughly 2-D, the only distortion effect that remains when the tensor is represented in the structural axes (along and perpendicular to strike) is the static shift. Several ways to correct MT soundings for static shift have been suggested. They include site-average or low-pass spatial filters of MT soundings (Warner et. al., 1983; Torres-Verdin, 1985; Bostik, 1986; Sternberg et al., 1988), theoretical calculations of near surface 3-D bodies (Wannamaker, 1984b), and theoretical calculations of topographic effects (Wannamaker, 1986). However, the application of the first two techniques requires a large amount of MT stations to be effective, whereas the later refers only to a particular type of problem affecting MT measurements; Sternberg et al. (1988) have shown that substantial static shifts can occur even in flat areas.

The simplest approach to correct static shift, if it can be assumed that one layer has roughly the same conductivity at all soundings, is to use the most 1-D sounding (without distortion) to correct all others. The site with least departure from a 1-D model is chosen to correct nearby sites by multiplying the resistivity curves by the required factor to bring them to the same level, usually the long period segment of the resistivity curve. When a sounding is truly 1-D, the diagonal elements of the tensor are zero and the off-diagonal elements are equal. In terms of the individual apparent resistivity curves computed from the tensor components Z_{xy} and Z_{yx} of the MT soundings this means that the ρ_{xy} and ρ_{yx} curves are the same as are their corresponding phases ϕ_{xy} and ϕ_{yx} . The ρ_{xx} and ρ_{yy} curves on the other hand, must be both close to zero, and it is expected that the calculated phases ϕ_{xx} and ϕ_{yy} will have unstable values (which results from the division by small quantities) that produce unusually scattered curves.

There are several sites that fulfill this pattern to a greater or lesser extent depending on the frequency interval chosen. Among them, sounding 7 shows a clearer 1-D behavior in a broader frequency band (Fig. 7) than other sites (Appendix A). Nevertheless sounding 2, which also behaves approximately as a 1-D earth in about the same frequency band, was preferred over sounding 7 because the latter had particularly low surface resistivities (~ 10 ohm-m), which is due to the presence of a shallow salty aquifer. Therefore, Site 2 was used to correct neighboring soundings. This was done by overlapping the set of all effective resistivity ρ_{eff} curves and selecting a frequency band in which the response was similar. ρ_{eff} is the resistivity value calculated from the value of the determinant of the impedance tensor (eq. 37 next section). The similarities of the curves for most of the sites are clearer at the long periods that correspond to deeper penetration depths. This is probably the level at which the conductive top of the subducting plate is observed at all soundings. A set of three representative frequencies for the reference sounding in the low frequency band (< 0.1 Hz) were selected (f_{25}, f_{27}, f_{29}) and their associated resistivity values averaged. This resistivity ρ_{ref} was used as a reference point to find the scaling factor for each of the resistivity curves with similar long period responses. With these scaling factors the resistivity curves from which they were derived are shifted vertically to the level of the reference site. By forcing the resistivity to be very close for each sounding, we did not impose any condition on the depth at which it appeared, therefore one can hope to retrieve a realistic slope for the top of the subducting plate. There are three assumptions that we have implicitly made: 1) that the regional structure changes smoothly from one sounding to the next, 2) that despite the static shift and other near surface distortion, the inductive response at middle and low frequencies is similar

for neighboring soundings, and 3) that phase curves do not experience static shifts, as was shown in the previous sections of this chapter.

Although the selected reference sounding seems to work for most of the sites, there are others that could not be corrected using station 2 mainly because they were located in a different geological environment which did not correspond to that of the reference. This is the case of the coastal and neighboring soundings (14, 13, 12 and 11) that had to be shifted using another reference. We choose sounding 14 to correct them as it was apparently least affected by lateral discontinuities at high frequencies. The discrepancy in other segments of the curves with respect to each other is assumed to represent structure. The set of all static shifted MT soundings was then used for 1-D modeling. This is outlined in the following section.

3.4.2) 1D inversion average

Unless there is evidence of complexity in the survey area, it is often convenient to perform a 1-D inversion of the data before trying a more elaborated model. This is specially useful to verify if the static shift corrections are reasonable, which is possible by looking at the smoothness of the resistivity structure obtained from the modeling. However, there is no warranty that the true resistivity value is found because there could still be a collective vertical shift in the modeled soundings. What is more important at this stage is that a 1-D inversion will suggest the type of regional variations to be expected in the resistivity section.

To attenuate lateral variations in the conductivity structure, the effective

impedance Z_{eff} (Berdichevsky and Dmitriv, 1976) given by

$$Z_{eff} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}} \quad (37)$$

is often chosen to obtain a first impression of the structural model. This parameter, which is rotationally invariant with respect to the measuring axes, averages the effects of lateral heterogeneities. The effective resistivity ρ_{eff} and corresponding phase ϕ_{eff} were computed for all soundings and inverted simultaneously using a Marquardt (1963) procedure. The Marquardt algorithm is based on a selection criterion which constrains the error between the observed data and the linear approximation for the observations. In addition, it restricts the deviation of the estimated parameters from a reference parameter (Keys, 1986). The inversion was done for all the soundings which were subsequently grouped into two profiles plotted in Figure 14. Basically, the interpreted resistivity structure shows a three layered earth in both the western (PW) and eastern (PE) profiles. A conductive layer, sandwiched between two more resistive layers, appears in both profiles and is shown to dip towards the continent (Fig. 14). Its resistivity varies approximately from 10 to 100 ohm-m with depths to the top ranging from about 5 to 30 km for PW and from about 10 to 30 km for PE. Although the approximate thickness h of the conductive layer was estimated, it is poorly resolved because the lower boundary is calculated using the longer period data, where the noise is larger. In the first section of Chapter 4 the significance of depths and resistivities of the interpreted 1-D parameters is discussed in more details. The conductive layer, whose average dipping angle is about 8° for the PE and 12° for the PW, is interpreted to be associated with the subduction slab of the Cocos plate which is known to be gently dipping landwards.

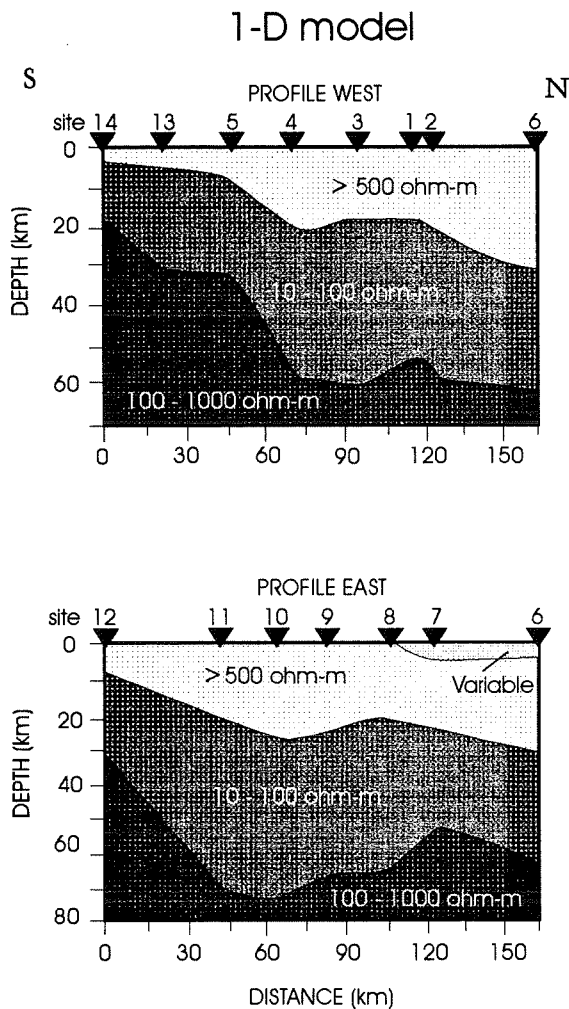


Fig. 14.- 1-D electrical structure obtained from the simultaneous resistivity and phase Marquardt inversion of the individual magnetotelluric soundings. Both profiles PW (top) and PE (bottom) suggest a gently dipping conductor. Note that the lower boundary of layer 2 is not resolved by the data.

Although a 1-D approach allows to visualize the regional electric features and their relative continuity, the calculated depths are likely to differ from the true depths from the surface to the top of the conductor. The reason of this is that in Z_{eff} are mixed 2-D and even 3-D responses of the earth that cannot be modeled with a simple 1-D approach. Because of the averaging, details hidden in the two perpendicular polarizations of the field curves, which emphasize the presence of good conductors,

are neglected and consequently there is information lost. In the next section, details of the E and H polarization pseudosections are discussed.

3.5) *TE* and *TM* polarization phase pseudo-sections

Contrary to what occurs with the apparent resistivity, the impedance phase is not affected by static shift. Recently Fisher et al. (1992), have emphasized the robustness of the phase with respect to the apparent resistivity computed from the measured impedance tensor. They observed that apparent resistivity can undergo drastic changes across electrical discontinuities while the phase variation remains stable and continuous. Thus, in this respect, the phase impedance is a reliable parameter that could provide more accurate information of regional 2-D structures, particularly in the presence of 3-D near surface distorters. This is illustrated for the collected field data in Figures 15 and 16 where the phase and resistivity pseudo-sections of the PW and PE profiles respectively are plotted, as well as the associated error. The relative variance of the resistivity errors were in general too small to be plotted. The pseudo-sections were obtained by rotating the soundings to the estimated regional strike in the area (Section 3.3) for each profile ($\bar{\theta}_{PW} \sim \bar{\theta}_{PE} \sim 5^\circ$). In profile PW it can be seen that for both TE and TM polarizations, the observed phase impedance reveals an elongated slightly tilted structure at frequencies ranging from 10 to about 0.01 Hz. Although 3-D effects are suggested at some sites (notably sounding 13), the high phase anomaly is well defined and corresponds to the frequency band for which we showed that H_z was certainly responding to induction. In contrast, the non-corrected apparent resistivity pseudo sections are strongly influenced by static

shifts which obscure the presence of the conductive structure. In profile PE, the phase pseudo-sections show similar phase anomalies as those revealed in PW whereas the apparent resistivity sections do not provide any information on the regional inductive structure. Even though this profile is particularly affected by other inductive processes (as noticed in Section 3.3), it is still possible to visualize a high phase anomaly at a similar frequency band as in PW confirming the relative stability of the impedance phase. However, a 2-D model including soundings that do not comply with the principal model would yield a wrong depth conductivity structure because they include three dimensional effects which require appropriate 3-D modeling.

It is well known that for an incident electromagnetic (EM) plane wave the phase of the electric field E leads the phase of the magnetic field H by $\phi = 45^\circ$ at the interface of a uniform conductor with the vacuum. If the conductor extends into the earth at large depths, this phase difference will prevail. However, when the earth differs from a uniform half space, a situation observed more often, there is a rule of thumb used to interpret MT phases which refers to a two layered model and states that $\phi > 45^\circ$ if the lower layer is a better conductor or $\phi < 45^\circ$ if the bottom layer is a poorer conductor than the top one.

The physical explanation of this behavior of the impedance phase has been given by Fisher (1985) in a 2-D environment for the TE polarization mode in terms of current distribution by showing that near-surface current increase leads to a phase reduction in the layer underneath and that a near-surface current reduction increases the phase. This can be illustrated for a horizontal dyke when the electric field component E_x is along the strike (*i.e.* TE polarization mode). When this is the case, there

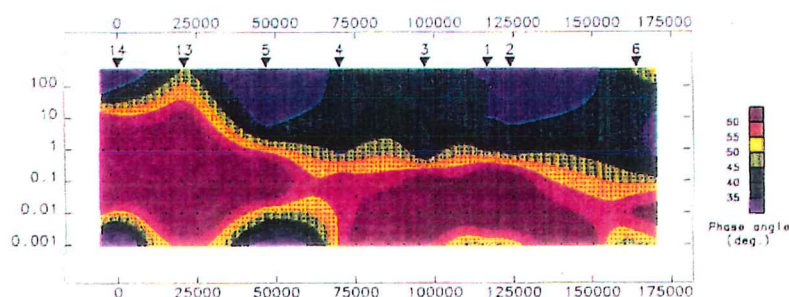
is a strong current flow j_x in phase with the local electric field which produces an anomalous magnetic field of magnitude H_{ay} around the dyke. To a first approximation this magnetic field is proportional to the electric field $E_x(z = 0)$ at the surface. Thus the surface impedance at the dyke center is

$$Z_{xy} = \frac{E_x(0)}{H_y + H_{ay}} \approx \frac{E_x(0)}{H_y + \alpha E_x(0)} \quad (38)$$

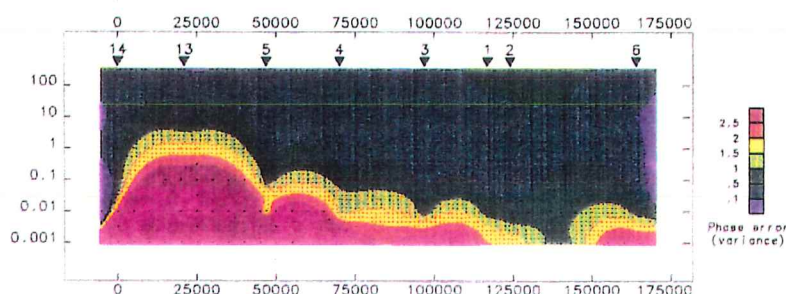
where $E_x(0)$ and H_y are the fields at the surface on the medium surrounding the dyke far away from it, and α is a real positive constant. The effect of adding a quantity with same argument as the numerator will be to reduce the argument of the ratio. Therefore, the phase of Z_{xy} will be reduced below 45° under the conductor. Conversely, if the dyke is more resistive than its surroundings the current will be reduced. In this case α is negative and therefore H_{ay} will be subtracted from the denominator of equation (38) which will increase the argument of the ratio. Thus the phase of Z_{xy} will rise above 45° for the conductive surroundings. Fisher et al. (1992) demonstrated that this behavior is also characteristic of a layered earth and that it is valid for the TM polarization mode as well.

The high phases anomaly observed in the pseudo-sections of Figures 15 and 16 are thus associated with a 2-D highly conductive structure that qualitatively matches the model obtained by the gathering of the 1-D inversions of the MT sites along profiles PW and PE (Fig. 14). The phase pseudo-sections and 1-D model for both profiles suggest that the conductor dips at a relatively small angle from the coast, where depths to the anomalous body are shallow, to the Oaxaca Valley and beyond, where the conductor is observed at larger depths. However, the distribution

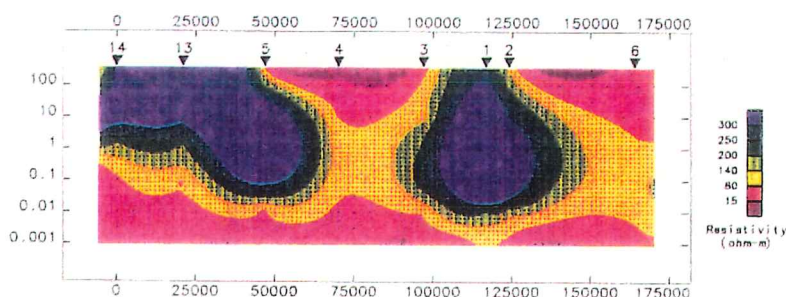
Frequency (Hz)



Observed phase



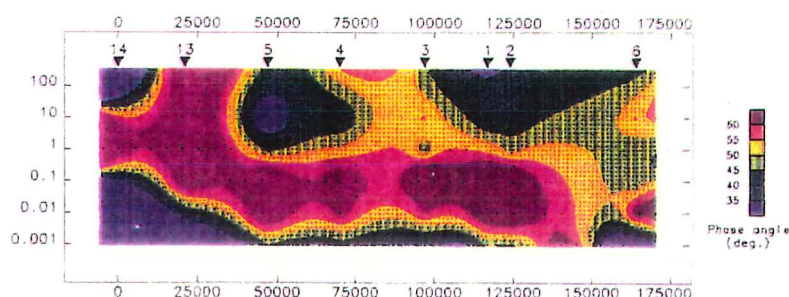
Observed phase error



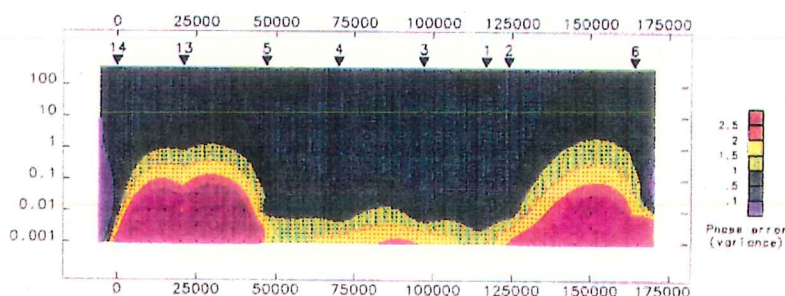
Observed resistivity

Fig. 15a.- TE observed phase (top), associated error (middle), and observed resistivity (bottom) pseudo-sections for profile PW. These were obtained by rotating the impedance to the regional strike estimated in Section 3.3 ($\theta=5^\circ$ was used). The observed high phases shows clearly a gently dipping conductor (top). The error is normalized to the standard deviation at each particular frequency (middle). The observed apparent resistivity is strongly affected by static shifts.

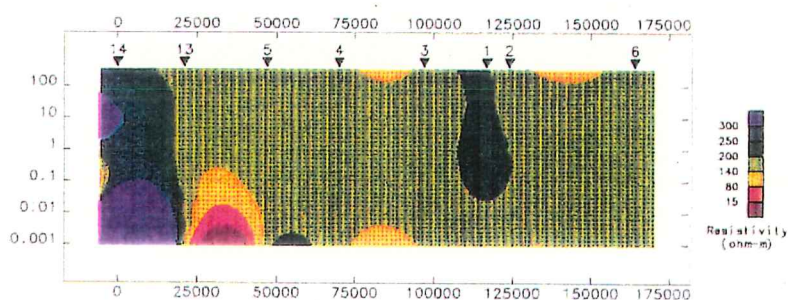
Frequency (Hz)



Observed phase



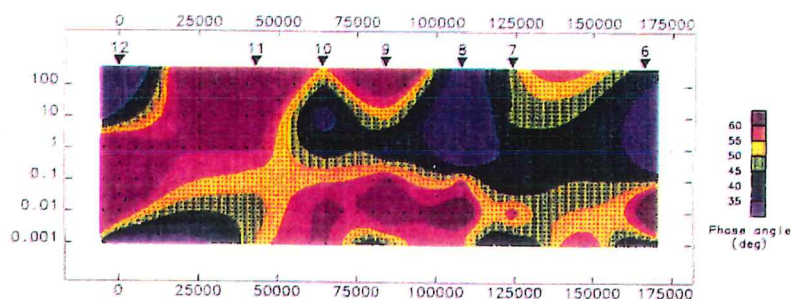
Observed phase error



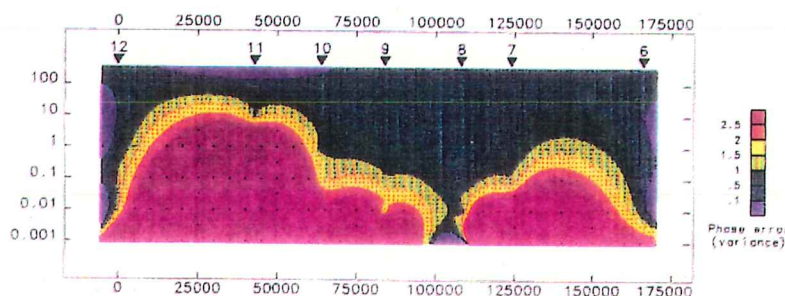
Observed resistivity

Fig. 15b.- TM observed phase (top), associated error (middle), and observed resistivity (bottom) pseudo-sections for profile PW. These were obtained by rotating the impedance to the regional strike estimated in Section 3.3 ($\theta=5^\circ$ was used). Although slightly more affected by surface distortion, the observed phases also show a gently dipping conductor (top). High errors are observed mainly at soundings 13 and 6. As for the TE mode the observed apparent resistivity is strongly affected by static shifts (bottom).

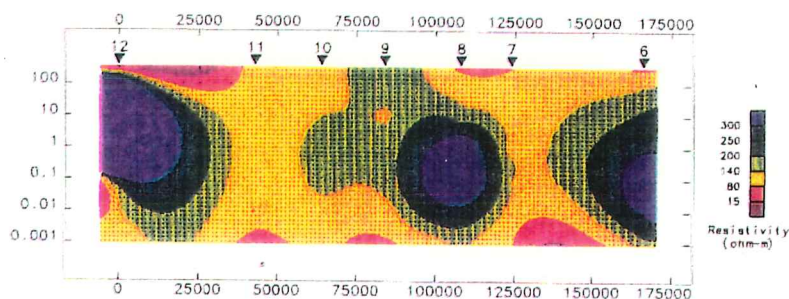
Frequency (Hz)



Observed phase



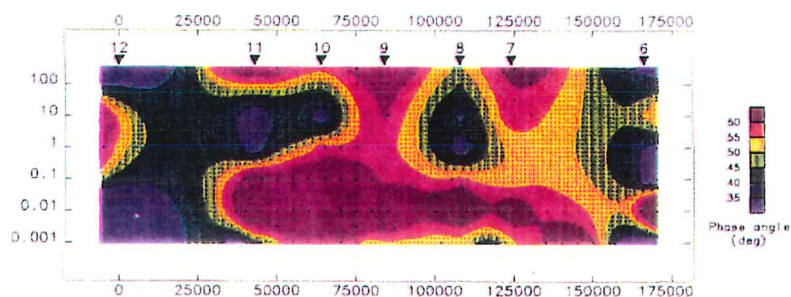
Observed phase error



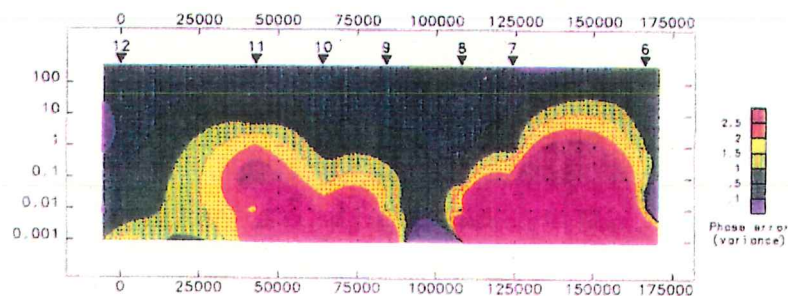
Observed resistivity

Fig. 16a.- TE observed phase (top), associated error (middle), and observed resistivity (bottom) pseudo-sections for profile PE obtained by rotating the impedance to the regional strike estimated in Section 3.3 ($\theta=5^\circ$ was used). The observed phases are considerably more affected by surface distortion (top) and their associated errors (middle) are larger, particularly at some soundings. Although the presence of the dipping conductor is obscured by distortion, there are indication at some sites of its existence (top). As for PW, the observed apparent resistivity is strongly affected by static shifts (bottom).

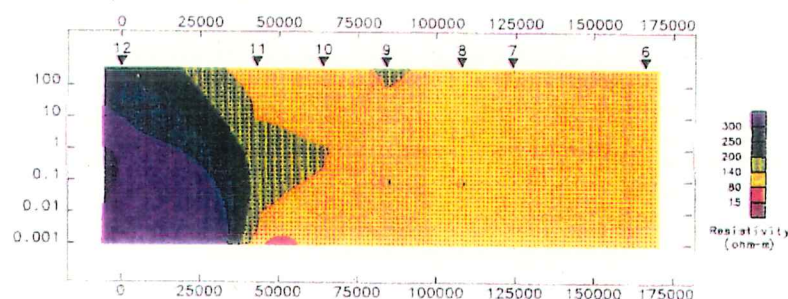
Frequency (Hz)



Observed phase



Observed phase error



Observed resistivity

Fig. 16b.- TM observed phase (top), associated error (middle), and observed resistivity (bottom) pseudo-sections for profile PE. These were obtained by rotating the impedance to the regional strike estimated in Section 3.3 ($\theta=5^\circ$ was used). Although with some near surface distortion effects, the observed phases reveal a sub-horizontal conductor (top). The errors are particularly important for soundings 7, 9, 10, and 11 (middle). The observed apparent resistivity is strongly affected by static shifts (bottom).

of high phases in TE mode seems to indicate that the conductor levels off at some point under the location of sounding 4 along the PW line. This is less obvious in line PE where distortion due to 3-D structures is blamed for the irregular pattern at several sites that prevents to distinguish a clear trend.

The elongated regional structure observed in both polarization modes at approximately the same frequency band, as well as the relatively stable strike angle previously obtained associated to the strike direction of the dipping subducting plate, indicate that a 2-D model would be appropriate to represent the resistivity structure in this area. The main objective of the following chapter is to perform a 2-D inversion on the MT soundings for this purpose. A meaningful inversion though, will be achievable only in the premise that the soundings included are not affected by 3-D induction processes. Also in the next chapter, the limits of validity for the preferred 2-D model are assessed through the analysis of the 1-D eigen-parameters of ρ_i and h_i and the stability of the model will be tested by direct calculation of the response for the perturbed model.

CHAPTER 4

2-D MODELING AND ROBUSTNESS OF MODEL PARAMETERS

4.1) Eigen-analysis of physical parameters from 1-D inversion

Before the observed conductivity zone can be attributed to the subducting oceanic crust, it is important to determine the limits within which depth and conductivity can be resolved with the MT method. One of the most useful tools in examining parameter resolution is the singular value decomposition (SVD) technique to perform an eigensolution analysis (Jackson, 1972; Wiggins, 1972). Edwards et al. (1981) used this approach to describe the inherent ambiguities of the model-fitting procedure of DC-resistivity, controlled source EM, MT and GDS data in terms of parameters connected with the physics of the problem instead of by means of statistical errors of model parameters as it is often done. Ilkisk and Jones (1984), and Mareschal and Cateland (1989) among others, had also applied eigenparameter analysis to bound the validity of their earth models obtained from MT data. In the eigensolution analysis, the model is allowed to determine for itself which independent parameter combinations are constrained by the data and to what degree (Edwards et al., 1981).

The theory behind the eigenvalue decomposition is relatively simple and is based on the factorisation of the sensitivity matrix $\mathbf{A}$ that relates small variations in the model parameters $d\mathbf{p}$ when changes in the observed data $d\mathbf{Y}$ are produced through

$$d\mathbf{Y} = \mathbf{A}d\mathbf{p}. \quad (39)$$

The matrix elements A_{ij} are the partial derivatives $\partial Y_i / \partial p_j$ of each one of the i_{th} data to be fitted with respect to the j_{th} model parameter. It is possible to choose linear combinations $\mathbf{p}'$ and $\mathbf{Y}'$ of $\mathbf{p}$ and $\mathbf{Y}$ respectively such that equation (39) is simplified for inversion. The factorisation that does this, also known as SVD decomposition expresses $\mathbf{A}$ as the product

$$\mathbf{A} = \mathbf{U} \times \mathbf{L} \times \mathbf{V}^T \quad (40)$$

where $\mathbf{L}$ is a diagonal matrix and the matrices $\mathbf{U}$ and $\mathbf{V}$ are uniquely defined by the fact that

$$\mathbf{U}\mathbf{U}^T = \mathbf{I} \quad (41)$$

$$\mathbf{V}\mathbf{V}^T = \mathbf{I}' \quad (42)$$

$\mathbf{I}$ and $\mathbf{I}'$ being identity matrices of different dimensionality. Furthermore, because

$$d\mathbf{Y}' = \mathbf{U}^T d\mathbf{Y} \quad (43)$$

and

$$\mathbf{d}p' = \mathbf{V}^T \mathbf{d}p \quad (44)$$

then (39) is written as

$$\mathbf{d}Y' = \mathbf{L} \mathbf{d}p'. \quad (45)$$

Here, the elements of $\mathbf{L}$ (only the terms L_{ii} are $\neq 0$) are the eigenvalues of $\mathbf{A}$ and the parameters $\mathbf{p}'$ are the eigenparameters of the system that are defined independently by a corresponding eigendata $\mathbf{Y}'$. Edwards et al. (1981) have shown that when each element $\partial Y_i / \partial p_j$ of matrix $\mathbf{A}$ is divided by the standard error e_i in Y_i before the SVD decomposition is performed, then the standard error in the eigenparameters p'_i is given by $1/L_{ii}$, which is the reciprocal of the corresponding eigenvalue. In addition to this scaling, a multiplication by p_j of each one of $\mathbf{A}$ elements allows to transform the model parameters into their logarithm, in other words

$$p_j \frac{\partial Y_i}{\partial p_j} = \frac{\partial Y_i}{\partial (\log p_j)}. \quad (46)$$

This has the advantage that the linear combination of the original parameters p_j , represented by logarithms of thicknesses and resistivities, are often combined into the logarithm of the conductance S (thickness $\times$ conductivity) or its reciprocal, which also leads to physically meaningful parameters.

Table 4.- Resolved model parameters for sounding 10. Each eigenvector $dp'(n)$ is expressed in terms of a set of eigenvalues (9 of them for a 5 layer earth). Their value is normalized so that the sum of their square will always give 1 (see text for further explanation)

Resolved model parameters for Site Mex10

	Eigenvectors									Mod. par.
	$dp'(1)$	$dp'(2)$	$dp'(3)$	$dp'(4)$	$dp'(5)$	$dp'(6)$	$dp'(7)$	$dp'(8)$	$dp'(9)$	
$\log p(1)$	-0.755	0.09	-0.641	0.082	0.004	0.058	0	0	0	$p(1)=10.5$
$\log H(1)$	0.608	-0.091	-0.666	0.25	0.02	0.342	-0.001	0	0	$H(1)=0.19$
$\log p(2)$	-0.225	-0.188	0.346	0.219	0.048	0.863	-0.004	0	0	$p(2)=105.2$
$\log H(2)$	-0.094	-0.923	-0.013	0.246	-0.014	-0.282	0.003	0	0	$H(2)=1.6$
$\log p(3)$	0.019	-0.312	-0.161	-0.907	0.019	0.231	-0.007	0	0	$p(3)=15.4$
$\log H(3)$	0	-0.004	-0.003	-0.006	-0.991	0.057	0.12	0	0	$H(3)=8.3$
$\log p(4)$	0	0	0	0.006	-0.12	0	-0.993	0	0	$p(4)=1.6$
$\log H(4)$	0	0	0	0	0	0	0	-1	0	$H(4)=58.4$
$\log p(5)$	0	0	0	0	0	0	0	0	-1	$p(5)=27.4$
$1/\lambda$	0.005	0.025	0.047	0.086	0.135	0.178	> 1	> 1	> 1	
Resolved param.	$H(1)\sigma(1)$	$H(2)$	$H(1)p(1)$	$p(3)$	$H(3)$	$p(2)$	--	--	--	

Table 4 is an example of the results obtained by applying the eigen-analysis to sounding 10 using an algorithm by Mareschal and Cateland (1989) (see Appendix B for the solution of all other stations). The initial models fed to the inversion algorithm were those obtained from the original inversion of static shifted soundings performed in Section 3.4, however several different initial models were tried subsequently with basically the same results. The first column in the table indicates the logarithm of the original parameters p whereas the following columns contain the weight given to each dp_i to make up the corresponding eigenparameter dp'_i (eq. 43). Each column represents an eigenvector that relates the logarithm of the original parameters with the newly defined eigenparameters. For example, the first eigenvector in table 4 defines the eigenparameter dp'_1 as

$$\begin{aligned}
dp'_1 &= V_{11}d(\log\rho_1) + V_{21}d(\log H_1) + \cdots + V_{91}d(\log\rho_5) \\
&\approx -0.755d(\log\rho_1) + 0.608d(\log H_1),
\end{aligned} \tag{47}$$

where ρ_1 is the resistivity of the top layer and H_1 its thickness. In other words, the eigenparameter is dominated by the weights for $d(\log\rho_1)$ and $d(\log H_1)$. In the ideal case, the weights should be equal to $1/\sqrt{2}$ or 0.717 and of opposite sign because of the condition given by equation (41). This condition is approximately true for dp'_1 , therefore

$$dp'_1 \approx (1/\sqrt{2})d(\log H_1) - d(\log\rho_1) \tag{48}$$

or

$$dp_1 = d[\log(H_1\sigma_1)] \tag{49}$$

Thus it is possible to identify the redefined p_1 as effectively describing the conductance (thickness $\times$ conductivity) of the first layer through its logarithm. According to Edwards et al. (1981), the standard error assigned to p_1 is the standard error of the logarithm of the thickness-conductivity product, which is equivalent to the fractional standard error in this product. The next eigenvectors define almost exclusively the other physical parameters of the layered earth ($H_2, \rho_2, \dots$) without ambiguity, but the large fractional errors (> 1) for the last three indicate that these parameters are not well constrained by the original data. The value we have taken as the threshold error to accept or reject the significance of a parameter is $1/L_{ii} = 1$;

Table 5.- Summary of the results of the eigen-analysis for all MT soundings. Numbers in bold type indicate well resolved physical parameters. Numbers in normal type mean that a (normally thin) layer above the conductor is fairly resolved. Italics denote fairly or poor defined model parameters. The asterisks indicate parameters that are not defined at all or whose fractional error is greater than 100 %. The error in depth to the conductor is the sum of the standard errors in percentage of each individual layer above it.

DEPTH TO THE CONDUCTOR

PROFILE W

Site	Depth(km)	Thick.(km)	Res.(ohm-m)	$\rho(t-1)/\rho(t)$
MEX02	7.4+/-0.2	***	8.7+/-0.9	<i>10.17</i>
MEX01	7.1+/-2.3	***	<i>5.2+/-5.1</i>	<i>18.40</i>
MEX03	<i>9.1+/-3.4</i>	***	<i>7.2+/-5.5</i>	<i>4.86</i>
MEX04	5.7+/-0.5	***	11.7+/-2.3	<i>8.45</i>
MEX05	9.6+/-1.2	<i>4.9+/-0.5</i>	***	<i>9.40</i>
MEX13	<i>6.5+/-8.2</i>	***	***	<i>7.3</i>
MEX14	5.9+/-0.2	<i>13.8+/-2.4</i>	<i>120+/-8</i>	<i>3.58</i>

PROFILE E

Site	Depth(km)	Thick.(km)	Res.(ohm-m)	$\rho(t-1)/\rho(t)$
MEX06	12.3+/-3.0	***	<i>1+/-0.5</i>	<i>> 1000</i>
MEX07	9.4+/-0.9	***	<i>4.1+/-2.6</i>	<i>61.93</i>
MEX08	7.3+/-0.2	<i>12.8+/-9.4</i>	<i>4.1+/-1.0</i>	<i>19.22</i>
MEX09	6.6+/-0.6	<i>16.1+/-12.0</i>	<i>5.6+/-2.1</i>	<i>11.70</i>
MEX10	10+/-1.6	***	***	<i>9.63</i>
MEX11	7.8+/-0.3	***	<i>3.2+/-0.5</i>	<i>42.78</i>
MEX12	<i>7.7+/-1.3</i>	***	<i>50+/-7</i>	<i>3.18</i>

the parameters that had associated a fractional error $1/L_{ii} > 1$ were assumed to be unresolved by the MT method.

From the application of the eigen-analysis to the collected MT data, we are interested in knowing if we resolve the depth, resistivity and thickness of the anomalous conductor observed in the phase pseudo-sections (see Figs. 15 and 16). This would allow us to significantly eliminate the ambiguity in the interpretation process that follows this section. The resolution of the depth to the top of the conductor is particularly important since it is from this parameter that we will extrapolate the source of the conductivity observed, *i.e.* the top of the subducting plate or a level of water concentration in the upper crust where fluids would have migrated. By inspecting the tables for the rest of the MT soundings (Appendix B) we were able to determine what parameters of the model could be realistically known assuming that the earth is quasi 1-D. Table 5 is a summary of the results. With the exception of few locations, the thickness of the conductor is a parameter that is not resolved. Despite an obvious problem of static shift, it can be observed that the depth to the conductor is a resolvable parameter if the depth to the layers on top of it can be resolved. This was the case for most of the soundings. However, its resistivity is only fairly or not resolved resolved except at two sites where it is well constrained.

The eigenanalysis of the 14 MT soundings therefore, shows that the depth to the conductor is the parameter best resolved by the data. The extrapolation of the 1-D eigenanalysis results to the 2-D case is justified because the algorithm used for the two dimensional model described in Section 4.3, calculates the conductivity perturbation beneath each measurement site by solving an inverse problem that is

closely related to the 1-D inverse problem (Smith and Booker, 1991). Further, as can be seen from the relatively small dipping angle of the conductor across the survey lines, the problem itself is ‘almost’ 1-D.

4.2) Selection of MT sites for 2-D modeling

At this point we have used several criteria to assess the dimensionality of the MT soundings as well as the physical parameters they can resolve. In order to perform a meaningful interpretation of the data it is necessary to exclude soundings that cannot be represented by equation (18) in the induction band of the principal structure. The criteria we followed consisted in selecting these soundings on the basis of A) their dimensionality given by Bahr’s analysis, B) their dispersion from an average regional strike obtained using both, Groom and Bailey and Bahr’s methods, and C) the scattered tipper calculated from the separation method of Zhang et al.

In profile west (PW) the observed scatter of the strike angle is relatively small and Bahr’s dimensionality parameters indicate that all soundings but sounding 5 can be regarded as 2-D in the induction band between 10 to 500 s. Although sounding 4 has a relatively large deviation from the average strike, the distortion indicators suggest that it is indeed a 2-D site for relatively longer periods. Sounding 5, on the other hand, shows strong 3-D effects suggested by an increasing regional skew η and phase deviation angle δ as the period increases. Sounding 6, located northeast of Oaxaca, satisfies the 2-D criteria. However, its best regional azimuth is 60° , thus quite different from that of the rest of the profile. We have included this

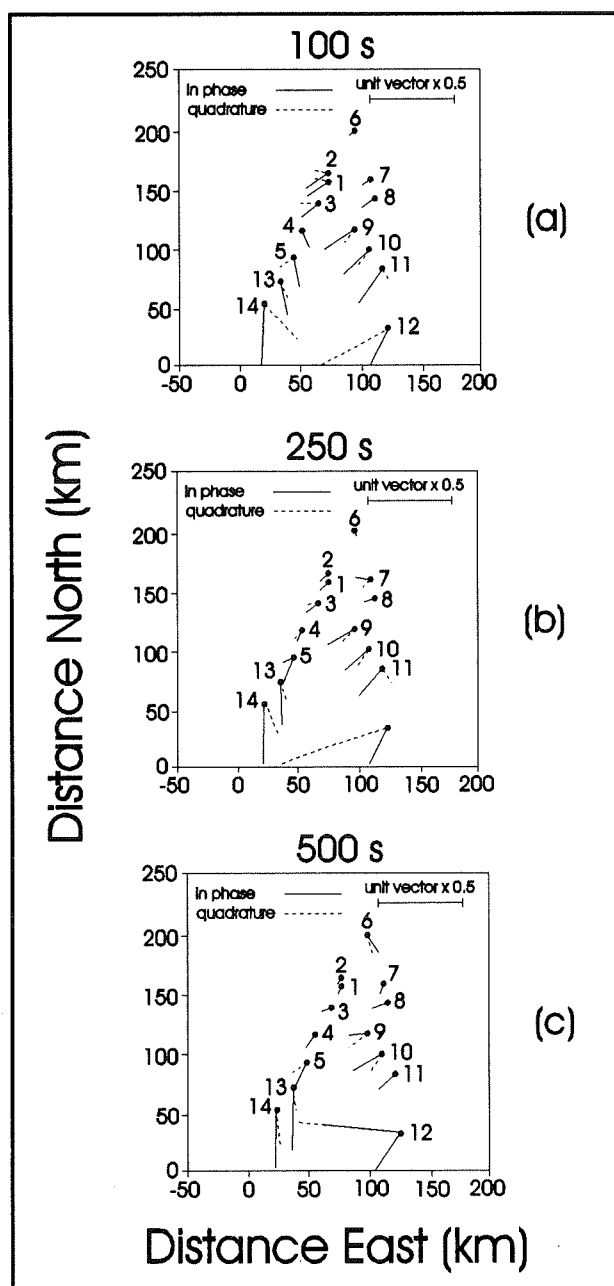


Fig. 17.- Tipper cleared of its galvanic component at $T=100$ (a), 250 (b), and 500 (c) seconds. At $T=100$ s all soundings but 4, 5, 13 and 14 appear to respond to the same conductive structure. At periods of 250 and 500 s all soundings along PW (except 6) are pointing roughly perpendicular to the strike of the conductivity structure ($\theta + \pi/2$).

sounding in the first step of the analysis because of its particular location (intersection of our two profiles). But it was left out the final interpretation. Thus, sounding 5 is

originally the only one excluded from PW for 2-D modeling.

The results obtained for the regional strike as well as the calculated dimensionality parameters indicate that the eastern profile (PE) is more affected by 3-D effects. This is particularly true for soundings 9 and 10 which show both, a large regional skew and large phase deviation angles. These soundings also present a large dispersion in their calculated values for the strike angle, therefore they are considered to be 3-D. Although soundings 7 and 11 do not appear as 3-D sites according to the regional skew indicator η (only sounding 11 has a large phase deviation), they have unstable values for the regional strike, which suggests they are also unsuitable for modeling of the plate. Although it is possible to find a solution for the regional strike of sounding 6 using both Bahr's and Groom and Bailey's methods (Fig. 10), this is not meaningful since there is little distortion and Swift's gives the correct strike in the first place. Thus, for profile PE we consider that only soundings 8 and 12 are acceptable for further modeling. However, we first included Site 6 (as well as 8 and 12) in the 2-D inversion as mentioned above. Table 3 is a summary of the selected soundings in both profiles according to their dimensionality and θ_{500} scatter. The average strike $\theta_{500} \approx 8^\circ$ for both profiles has been recalculated using only the selected soundings.

The induction vector or tipper can also be used to discriminate soundings which are not represented by the principal model of equation (18), *i.e.* which include 3-D structures. The visual display of these arrows in maps offers a comprehensive view of the changing anomalous behavior of H_z as a function of period and/or location. The real components of the reversed induction arrows point toward zones of high

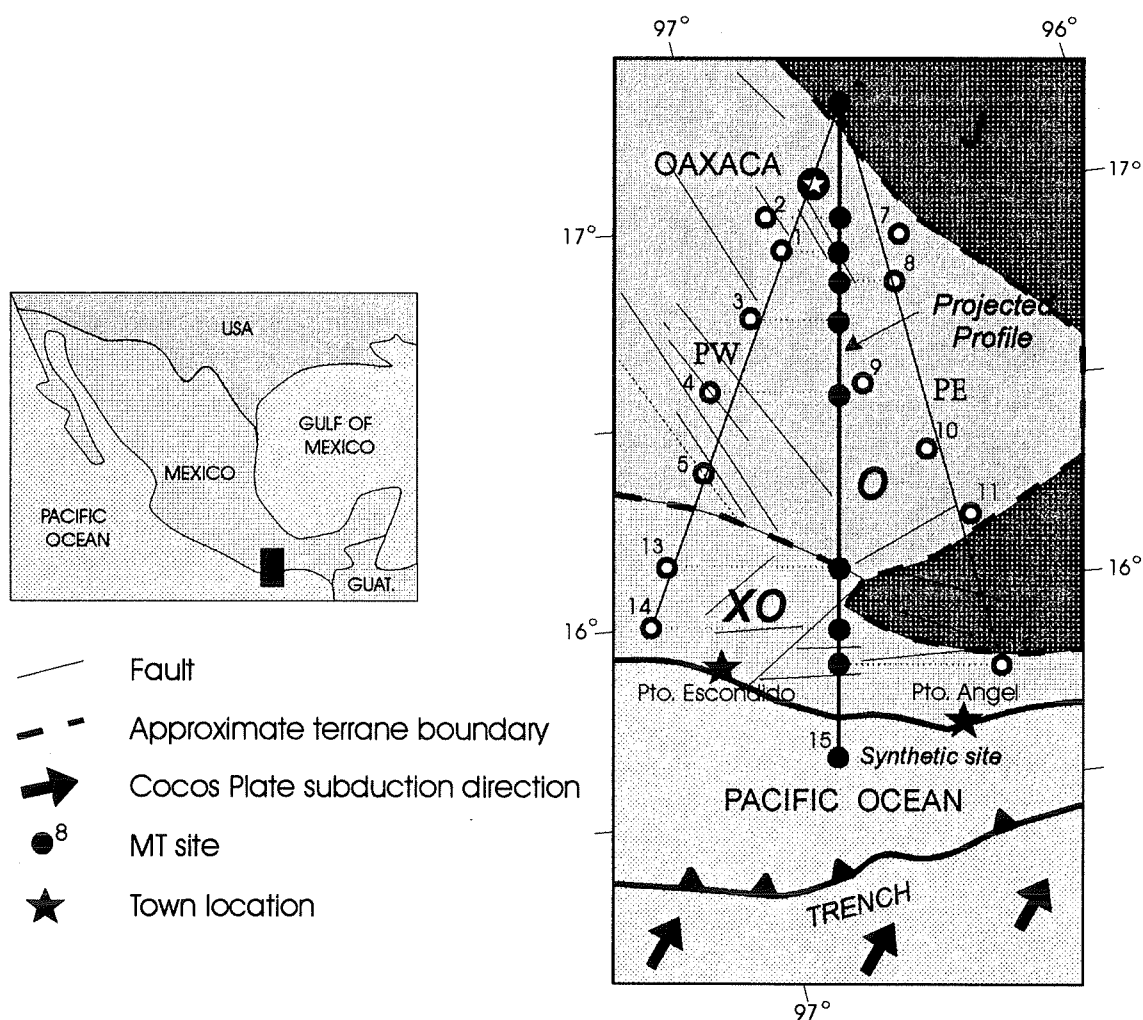


Fig. 18.- Location map of the magnetotelluric soundings showing the selected ones projected perpendicularly onto a central profile. A synthetic sounding (15) in the sea was included in an attempt to constrain the resistivity values.

conductivity. In the particular case of a 2-D conductivity anomaly it is expected that the induction arrows are perpendicular to the axis of the two dimensional structure (e.g. Schmucker, 1970). Figure 17 shows the tipper free of galvanic effects obtained

from the subtraction of the measured and predicted tipper (see Section 3.2) for all MT soundings at periods 100, 250 and 500 seconds. At 100 s, all soundings but 4, 5, 13 and 14 appear to be responding to some conductive structure apparently trending NW-SE. The rest of the soundings clearly respond to a different structure. At 250 and 500 seconds nearly all soundings along PW are pointing roughly to the same direction and almost perpendicular to the strike of the conductivity structure $\theta_{yx} = \theta + \frac{\pi}{2}$ along the axis of the major MT impedance, i.e. the subduction axis. Although the orientation of the induction vectors for the selected sites (Table 3) is not fully consistent with the orientation of the regional conductor (particularly sounding 6) the results obtained at $T = 250$ and 500 s support the idea that the major inductive feature at these periods is the subducting plate. Those located closer to the sea (particularly sites 12 and 14) are clearly influenced by it. The sparsity of useful soundings along the eastern profile prompted us to built a single MT profile that included both the PE and PW remaining stations. This was done by projecting perpendicularly the sites of both profiles onto a line that bisected them at the location of Site 6 (Fig. 18). In the following section the Rapid Relaxation Inverse (RRI) algorithm of Smith and Booker (1991) for the 2-D inversion of the data will be outlined and the results obtained from its application to the projected line are discussed.

4.3) Smith and Booker 2-D RR inversion

TE and TM modes

The physical laws that govern the interaction of the electric and magnetic

fields for an isotropic earth are given by Maxwell equations

$$\nabla \times \bar{H} = \sigma \bar{E} \quad (50)$$

$$\nabla \times \bar{E} = i\omega\mu_o\bar{H} \quad (51)$$

where $\bar{E}$ and $\bar{H}$ are the electric and magnetic fields respectively, σ the conductivity, μ_o the permeability of free space and $H = H_o e^{-i\omega t}$. The solution of these equations for a great diversity of EM problems can be found in many text books and papers, particularly among the MT community publications. In particular, the 2-D case is a well studied problem for which a great deal of information can be found (e.g. Ward and Hohmann, 1987). Thus, we only briefly discuss some important aspects of the 2-D inversion method developed by Smith and Booker (1991) used to interpret our field data.

In a 2-D earth, equations (49) and (50) split into two different modes, whether the electric field is parallel or perpendicular to the strike of the structure. The former case is known as the transverse electric mode (TE) while the later is the transverse magnetic (TM) mode. According to the tectonic distribution of the studied area and the way the data were collected, we have chosen the TE mode being oriented along the y-axis, which is the direction of the main current flow and is normally parallel to the coast. In this case (TE mode) equations (49) and (50) can be written as

$$\nabla^2 E_y = -i\omega\mu_o\sigma E_y \quad (52)$$

and

$$\frac{\partial E_y}{\partial z} = i\omega\mu_o H_x. \quad (53)$$

Because the electric field is polarized in the Y-Z plane then there are only two components of $\vec{E}$ that do not vanish. In this case equation (51) takes the form

$$\frac{1}{E_y} \frac{\partial^2 E_y}{\partial z^2} + \left[\frac{1}{E_y} \frac{\partial^2 E_y}{\partial x^2} \right] + i\omega\mu_o\sigma = 0 \quad (54)$$

where the term in brackets represent the lateral variations of the electric field which is equal to zero for a 1-D earth.

In the same reference frame, the equations equivalent to (51) and (52) for the TM excitation mode, i.e. when the currents are perpendicular to the axis of the conductivity structure are given by

$$\frac{1}{\sigma} \frac{\partial H_y}{\partial z} = E_x \quad (55)$$

and

$$\nabla \left(\frac{1}{\sigma} \right) \nabla H_y + \left(\frac{1}{\sigma} \right) \nabla^2 H_y = -i\omega\mu_o H_y \quad (56)$$

Here, it is the magnetic field which is polarized along the Y-Z plane, therefore the changes are limited to this plane and equation (55) can be rewritten in terms of H_y alone as

$$\frac{1}{H_y} \frac{\partial \rho}{\partial z} \frac{\partial H_y}{\partial z} + \left[\frac{1}{H_y} \frac{\partial \rho}{\partial x} \frac{\partial H_y}{\partial x} \right] + i\omega\mu_o = 0 \quad (57)$$

where $\rho = 1/\sigma$. Again, the term in brackets represents the lateral gradients of the magnetic field which indicate the two dimensional character of the induction.

Smith and Booker (1991) solve the 2-D inverse problem with some approximation in the evaluation of the lateral gradients of equations (53) and (56). They assume that the vertical field gradients are always larger than the horizontal ones and therefore, these could be approximated by their value at the surface. In other words

$$\left[\frac{1}{E_y} \frac{\partial^2 E_y}{\partial x^2} \right] \approx \frac{1}{E_{y_o}} \frac{\partial^2 E_{y_o}}{\partial x^2} \quad (58)$$

for the TE mode, and

$$\left[\frac{1}{H_y} \frac{\partial \rho}{\partial x} \frac{\partial H_y}{\partial x} \right] \approx \frac{\rho_o}{H_{y_o}} \frac{\partial^2 H_{y_o}}{\partial x^2} \quad (59)$$

for the TM mode. Using these approximations in equations (53) and (56) respectively Smith and Booker have shown after some manipulation, that the residuals between the measured field data at a given frequency and predicted data are given by

$$\delta d_{yx} = \int_0^\infty \frac{2\sigma_o(z) E_{y_o}^2(x_i, z)}{E_{y_o}(x_i, 0) H_{x_o}(x_i, z)} \delta(\ln \sigma) dz \quad (60)$$

for the TE mode, and

$$\delta d_{xy} = - \int_0^\infty \frac{2\sigma_o(z) E_{x_o}^2(x_i, z)}{E_{x_o}(x_i, 0) H_{y_o}(x_i, z)} \delta(\ln \sigma) dz \quad (61)$$

for the TM mode. These are called ‘pseudo-Frechet’ kernels because they differ from the 1-D Frechet kernels in that the fields used to compute the derivatives must satisfy the 2-D equations (53) and (56) with $\sigma = \sigma_o(x, z)$.

The vertical integration in equations (59) and (60) is done at each site x_i between the surface ($z=0$) and a point which is deep enough for the electric field to have decayed to zero. Starting with an initial guess for the conductivity structure $\sigma = \sigma_o(x, z)$ equations (51) and (52) are solved for $E_o(x, z)$ and $H_o(x, z)$ which are in turn used to estimate the data residuals (59) and (60). These can be inverted individually or separately for a conductivity perturbation beneath each site, then $\sigma_o(x_i, z)$ is updated and interpolated between sites to produce a new starting model. Next, equations (51) and (52) are solved again for new estimates of the 2-D fields, and the process is repeated until the data residuals reach a predetermined tolerance. The procedure of holding a part of the problem fixed (the updated fields in this case) while operating on another (the inversion of the residuals) is known as a relaxation technique (e.g. Press et al., 1988). This is where Smith and Booker’s rapid relaxation inversion method (RRI) takes its name from.

The method has the advantage that it is extremely fast, and therefore a large number of essays can be done to observe the effect of modifying the input matrix (discussed in the next paragraphs). However, the assumption that the 2-D lateral conductivity gradients can be represented by their value at the surface may be a crude approximation in some cases. As we will see later in this chapter, this seems to be the case in sites close the sea where a good fit is difficult to achieve.

Inversion of the projected profile

Our first attempts towards finding the adequate 2-D model that closely represents the subducting Cocos Plate in this part of the trench consisted of a simultaneous inversion (of TE and TM modes, or TEM) of the projected profile after soundings were rotated to the regional strike ($\theta = 8^\circ$ was used) as well as separated inversions of the TE and TM modes. In order to constrain the resistivity values, an additional sounding (a synthetic one that we will call sounding 15) located in the sea was included in the inversion process as the seaward extreme of the projected profile (see Fig. 18). Its resistivities and phases were estimated from a 1-D forward calculation using a model structure constructed from the available bathymetry (Shiple and Moore, 1985), the lithology from the near-by DSDP drilling (leg 66, SB26; OMDP, 1985) and accepted ocean crustal models from ophiolitic sections (Meissner, 1986). The site was located about 30 km away from site 14. According to the available information, at the chosen position its structure roughly consisted of a top layer of sea water ($\rho_1=0.3$ ohm-m, $h_1=3.5$ km) overlying a layer of saturated sediments ($\rho_2=50$ ohm-m, $h_2=1$ km) on top of a gabbroic oceanic crust ($\rho_3=1000$ ohm-m, $h_3=10$ km). A lower oceanic crust ($\rho_4=100$ ohm-m, $h_4=10$ km) was also included as it was the underlying upper mantle (a bottom half space of $\rho_5=5000$ ohm-m).

The inversion was done mainly on the phases (see Section 3.5). Large weights were given to the phases at all soundings and frequencies (except at isolated 'erratic points') with high weights for the resistivities only at soundings 3, 2 and 15. Soundings 2 and 3 are located in the Valley of Oaxaca and are regarded as unaffected or little affected by static shift. Together with the synthetic site 15, these were meant to

provide adequate values of the surface resistivity to constrain the solution. It turned out however, that good results are obtained only for the TE mode but not so for TM where the static shift was not fixed and large phase residuals were observed (up to 5 times larger than for TE). These results suggest that the sharp lateral conductivity contrast along the coast line can be adequately handled when the electric field is parallel to the strike (TE mode) but it seems that the discontinuous character of the electric field across strike (TM mode) does not allow to approximate the later gradients by their value at the surface when the conductivity contrast is large, which introduces and propagates large errors.

The inversion of the TE and TM modes separately for the projected profile without sounding 15 provided the better results (*i.e.* lower residuals) and yielded similar resistivity structures for the two polarization modes (see Appendix C). Figure 19 shows these results as well as the calculated phases. Both polarization modes show basically the same structure, however, the resistivities from the TM results are in general higher than those obtained from the TE inversion. The resistivity sections show major discrepancies close to the sea, at sites 12 and 14, where the TM mode sees a shallower conductor than the one observed in the TE section. It appears that currents across strike would gather near the surface due to the strong conductor nearby (the sea) obscuring local conductors at least one order of magnitude more resistive than the conductivity of sea water. The TE results on the other hand, seem to be unaffected by the relative closeness of the sea due to the continuity of the electric field at the boundary of a sharp conductivity contrast. Thus, we assume that the results of the TE mode are more accurate in this part of the profile. The upper part of the conductor, which is clearly dipping landwards, yields similar depths for

the rest of the profile except at sounding 6 where it is not well defined by the TM results. This was expected due to the change in regional electrical azimuth at this location. Also in figure 19 are shown the calculated phase and residuals for both TE (19a) and TM (19b) polarization modes. Generally speaking, residuals (*i.e.* the difference between the measured data at each frequency and that predicted by $\sigma_o(x, y)$ normalized by the observed error) are between 1 to 1.5 times the standard deviation of the observed data.

Smith and Booker's inversion algorithm is designed to find 2-D models with minimum structure. The specific form of the functional $Q(y_i)$ for measuring structure is the norm of a scaled Laplacian of the model $\mathbf{m}$ given by

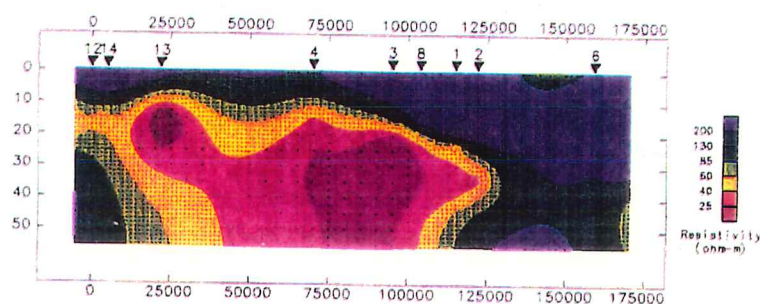
$$Q(y_i) = \int (z + z_o)^3 \left[\frac{\partial^2 m}{\partial z^2} + g(z) \frac{\partial^2 m}{\partial y^2} \right]^2 dz \quad (62)$$

where the factor $(z + z_o)^3$ arises from taking derivatives and integrating with respect to log depth. The $g(z)$ factor allows to trade-off between penalizing horizontal and vertical structures. Since the measured data are in error, the functional to be minimized is

$$W_i = Q_i + \beta_i e_i^2 \quad (63)$$

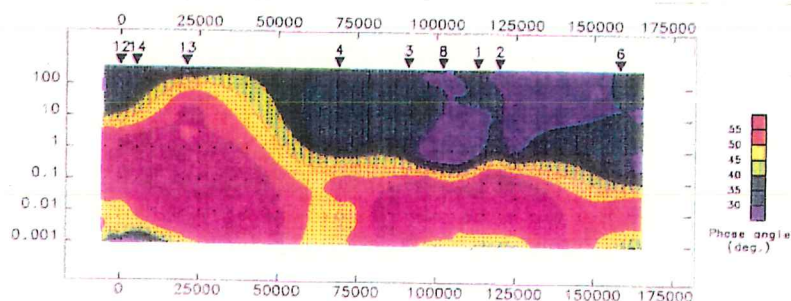
where Q_i is the discrete approximation of equation (61), and β_i is a trade-off parameter between model structure and misfit. The variances of the measurement errors are used to scale the data and pseudo-Frechet derivatives so that the squared misfit Σe_i^2 is the standard χ^2 statistics. Since the actual inverse problem is nonlinear, it is necessary

Depth (km)

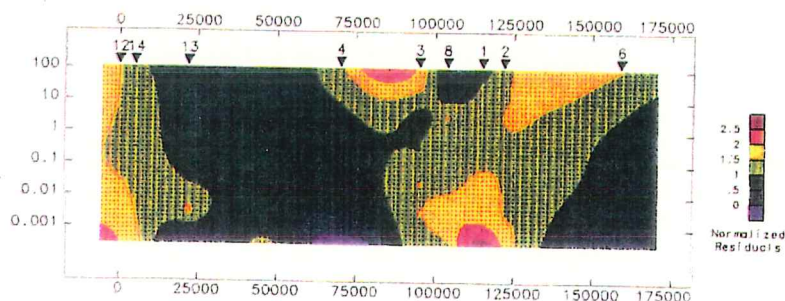


Resistivity structure

Frequency (Hz)



Observed phase



Normalized residuals

Fig. 19a.- Resistivity structure (top) for the TE polarization mode obtained from the 2-D inversion of the selected soundings (see Fig. 18) with the exception of the synthetic sounding 15, which introduced large errors. Also shown in this figure are the observed phase (middle) and normalized residuals (bottom). The residuals are normalized to the observed phase standard deviation at each frequency.

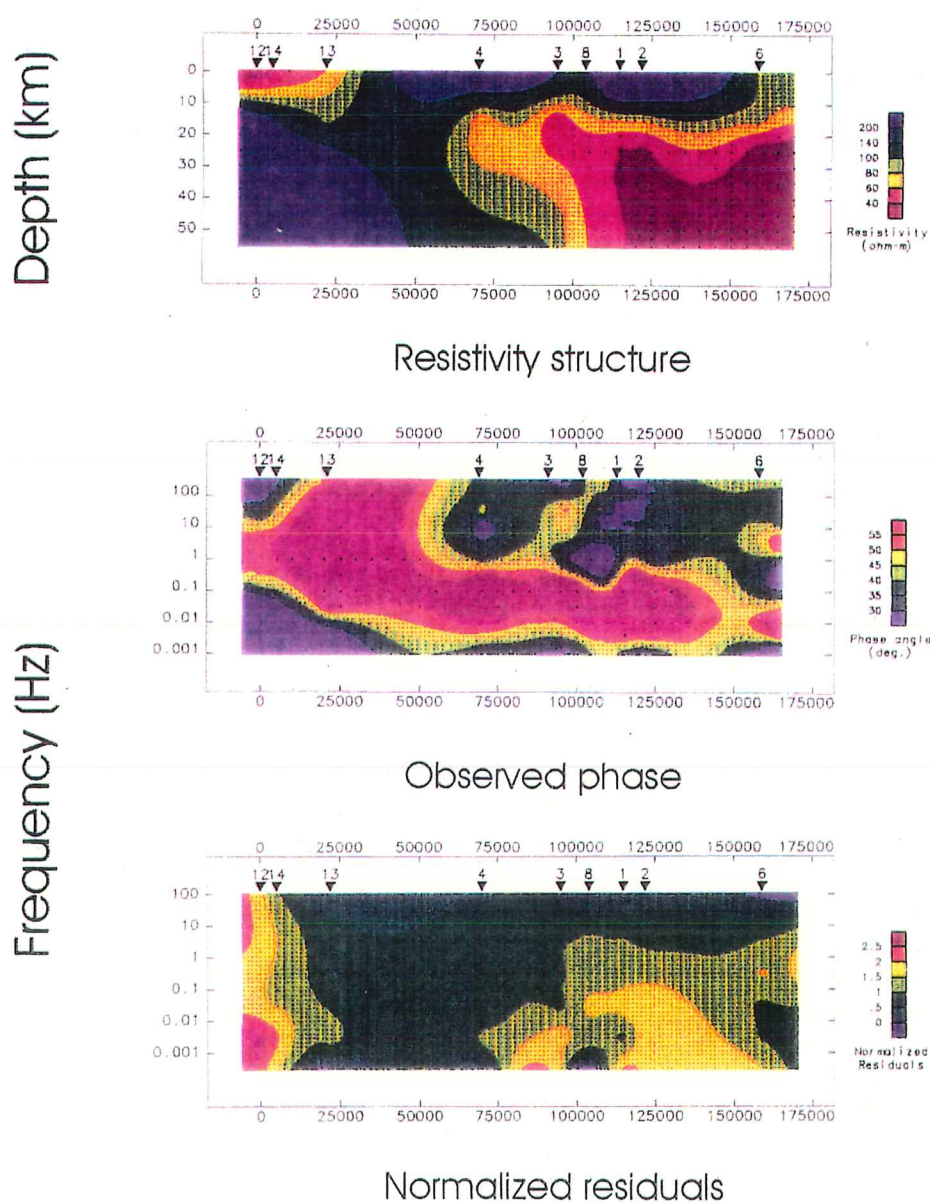


Fig. 19b.- Resistivity structure (top) of the TM polarization mode obtained from the 2-D inversion of the selected soundings (see Fig. 18) with the exception of the synthetic sounding 15, which was excluded because it introduced large errors. Also shown in this figure are the observed phase (middle) and normalized residuals (bottom). The residuals are normalized to

to reduce e^2_i to its ultimate goal in a series of steps, small enough that the linearization of equations (59) and (60) remains valid. The measure of acceptability used by Smith and Booker's inversion algorithm is given by

$$W_G = \sum_{i=1}^{n_{sites}} \frac{W_i}{\beta_i + \beta_{median}} \quad (64)$$

This scales the single site objective functions so that the coefficient multiplying the squared misfit e^2_i is of order 1, and W_G avoids being dominated by soundings with very large or very small β_i . Since β_i and β_{median} change with iteration, the value of W_G for a candidate model is compared to its value for the last accepted model calculated using the β_i variables and β_{median} from the current iteration. This makes the functional measuring acceptability identical for both models (Smith and Booker, 1991). To control the step size Smith and Booker introduce the factor ν_i by which the misfit e_o^2 for sounding i is to be reduced. In practice, the step size is such that the misfit is never reduced by more than 50% in a single step, and by never allowing ν_i to be less than $(e^2_{min}/e^2_o)^\epsilon$, where e^2_{min} is the smallest misfit that can be achieved by the linear inversion. ν_i is adjusted according to the success of the previous iterations.

Additional inversions of the TE and TM modes separately were performed using only the six soundings justifiably 2-D with $\theta \approx 8^\circ$ (12, 14, 3, 8, 1 and 2). Site 6 was excluded for reasons exposed in a previous sections, while sites 4 and 13 show high η values up to about 200 seconds. Figure 20 shows the results obtained for the resistivity distribution as well as the residuals and calculated phase for these sites. It can be seen that the conductivity structure for both TE and TM modes agree reasonably well in the most central sites. The depths to the center of the

conductor, taken as the depth to the minimum resistivity within the deeper anomaly, compare reasonably well sounding by sounding for the two modes. The discrepancy of calculated depths at station 3 is the largest between the two modes at about 8 km however, the larger residuals are observed precisely at a wide period band for the TM mode. At sounding 2 there is a difference of approximately 5 km, whereas at sites 8 and 1 this difference is practically non-existent. The discrepancy in the coastal soundings are still present. In the following section we will discuss the importance of these and the previous results from the full projected profile in terms of the stability of the calculated model.

4.4) Investigation of parameter stability

A stability test of the model obtained from the 2-D inversion was performed to determine its response to variations of depth and resistivity of the dipping conductor. The simplest way to do this is to alter the model by changing one of these parameters at a time and equally at all the site locations to observe the phase and resistivity response to these changes by means of a forward calculation of the fields. If variations in these parameters produce significant changes in the electromagnetic responses calculated at the surface, we can be sure that the parameters are resolved by the data. In reality, the data never resolve *all* the parameters of the model produced by inversion. Because of the goal of our model is to constrain some of the subduction parameters (dip, depth to the top of conductor, source of conductivity), it is the resolution of these parameters that we will particularly check.

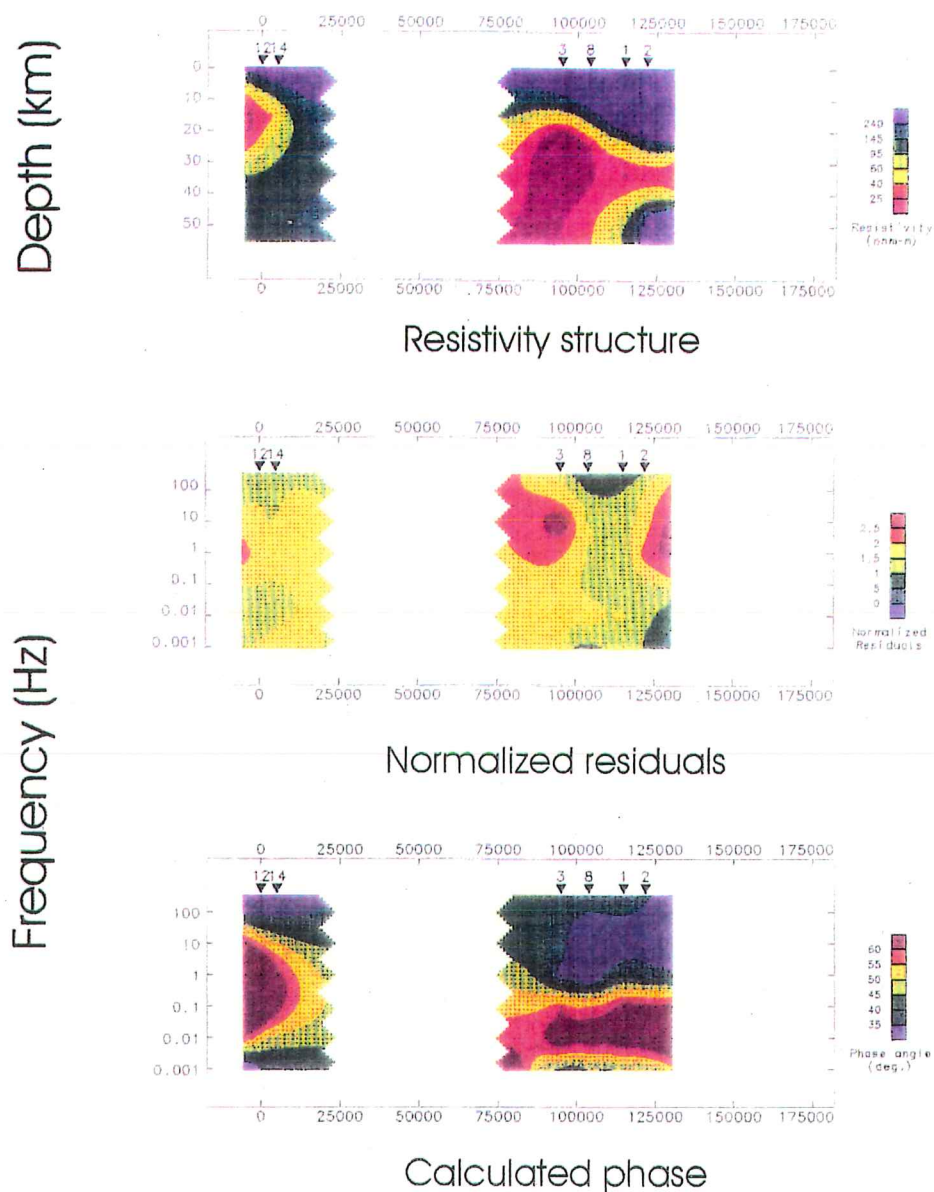
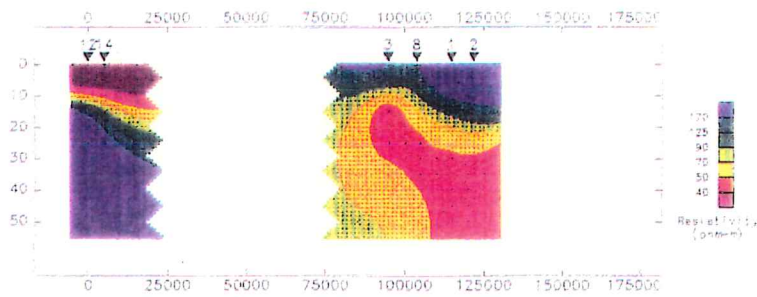


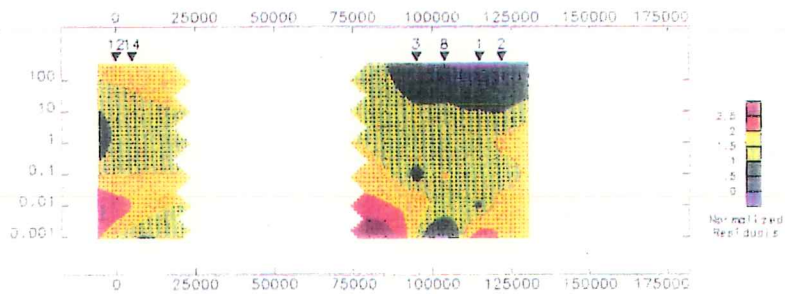
Fig. 20a.- Resistivity structure (top) for the TE polarization mode obtained from the inversion of soundings 12, 14, 3, 8, 1, and 2 only. Note that only the top of the conductor is well constrained (see text). Also shown in this figure are the normalized residuals (middle) and the calculated phase (bottom).

Depth (km)

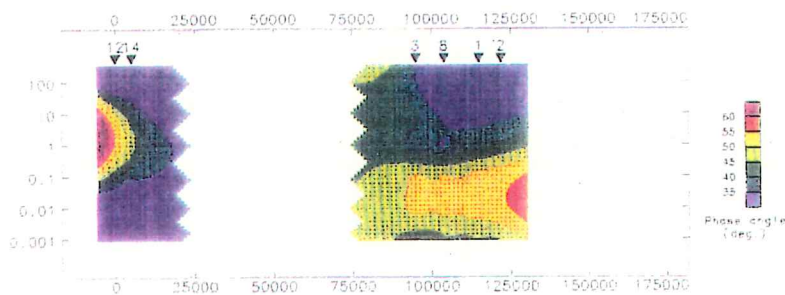


Resistivity structure

Frequency (Hz)



Normalized residuals



Calculated phase

Fig. 20b.- Resistivity structure (top) for the TM polarization mode obtained from the inversion of soundings 12, 14, 3, 8, 1, and 2 only. Note that only the top of the conductor is well constrained (see text). Also shown in this figure are the normalized residuals (middle) and the calculated phase (bottom). The enhanced conductivity zone is shown here shallower than for the TE mode.

From the eigenanalysis carried out in Section 4.1 we already know that the depth to the conductor is reasonably well determined. Figure 21 shows the schematic model used for the stability test performed using Wannamaker (1986) 2-D forward algorithm under GEOTOOLS (1991). The depth to its top and its resistivity were varied from 5 to 40 km and from 5 to 50 ohm-m respectively. The phase and resistivity responses were calculated at representative locations which roughly cover the different tectonic provinces across the survey line: at site 14 in the coastal area; at site 1 in the Valley of Oaxaca; at site 6 in the Sierra de Juarez located in the opposite extreme of the projected profile. The TE and TM phase responses to depth and resistivity variations for these soundings are displayed in figures 22 (sounding 1), 23 (sounding 6), and 24 (sounding 14). For simplicity, only the curves corresponding to a change in depth of ± 5 km and extreme values of resistivity (5 and 50 ohm-m) are included in the plots (see Appendix D for more). A variation in depth to the conductor of ± 5 km was found to be a reasonable depth margin to test the resolution of the MT method, since the discrepancies between the TE and TM models are of this order.

When the conductor is located 5 km shallower than actually is (filled circles) the TE and TM phase response at the location of sounding 1 (Fig. 22) will differ considerably for periods in the range between 0.01 and 1 seconds with the TM mode showing a larger variation. For periods longer than 1 second, the difference is of the order of a few degrees (max $\sim 5^\circ$ at around 100 seconds) larger than the error bars for this period range at most soundings. A conductor 5 km deeper however, does not produce noticeable changes except for a few degrees in the short periods for the TM

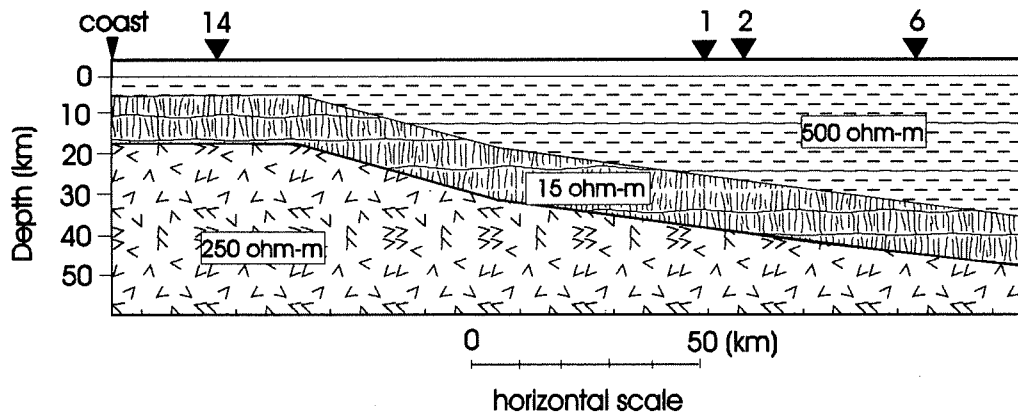


Fig. 21.- Schematic 2-D model of the conductor used in the stability test. Phase and resistivity response were calculated for several test sites (14, 1,2 and 6) for variations in depth to the conductor and conductivity.

mode. If the depth is fixed and the resistivity of the conductor is reduced from 15 to 5 ohm-m, a phase increase of up to 15° is produced in the range between 1 to 1000 seconds. Conversely, when the resistivity is increased to 50 ohm-m a phase reduction occurs in the same period interval for both TE and TM modes. In the short periods (< 1 s) neither an increase nor decrease in ρ_{cc} will affect the phase.

Sounding 6 (Fig. 23) has essentially the same behavior that sounding 1 in the short periods (0.01 to 1 s) for a shallower conductor; it also reduces the phase in the TE mode and increases it in the TM mode. Also, there is a period interval (1 to 10 s) in which a noticeable phase difference occurs for a conductor 5 km deeper, although this difference is obviously smaller because of the depth of the conductor is greater than for Site 1. In contrast, an increase or decrease in resistivity is observable for periods larger than 10 seconds. Depth and resistivity changes in the conductor

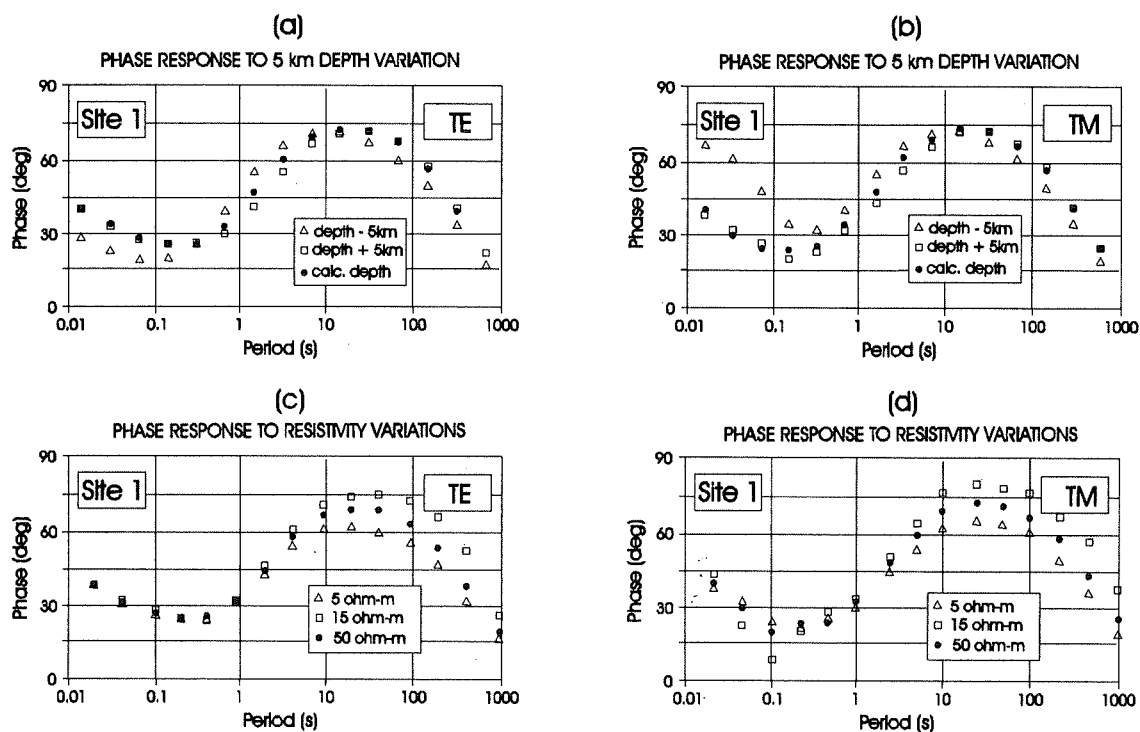


Fig. 22.- Model response to changes in depth at sounding 1: a) ϕ_{TE} , b) ϕ_{TM} for change of depth and, c) ϕ_{TE} , d) ϕ_{TM} for change of resistivity. When the conductor is placed 5 km shallower, the TE and TM phase responses differ considerably for periods in the range between 0.01 and 1 s with the TM mode showing a larger variation. For periods longer than 1 s their response is essentially the same, the larger difference being 5° at around 100 s. A 5 km deeper conductor however, does not produce noticeable changes except for a few degrees in the short periods for the TM mode.

obviously have a greater effect on the sites located in the coastal area because the conductor is closer to the surface.

Sounding 14 (Fig. 24) illustrates this. For a conductor 5 km shallower the phase response (TE and TM) is that of a homogeneous half space up to 10 seconds when it starts to drop below 45° . A deeper conductor also suggests relatively large phase changes within all the period band. Variations of resistivity on the other hand, modify the phase response considerably only at intermediate periods (1 to 100 s).

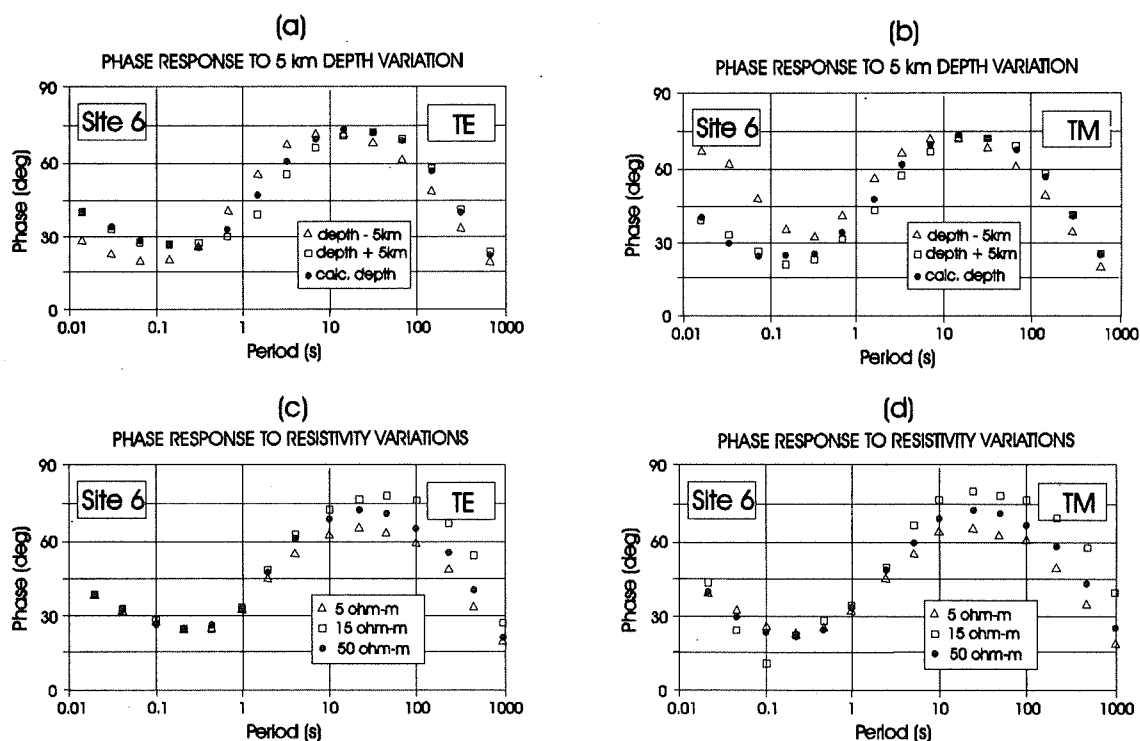


Fig. 23.- Model response to changes in depth and resistivity for sounding 6. a) ϕ_{TE} , b) ϕ_{TM} for change of depth and c) ϕ_{TE} , d) ϕ_{TM} for change in conductivity. It has essentially the same behavior that sounding 1 in the short periods (0.01 to 1 s) for a shallower conductor; it also reduces the phase in the TE mode and increases it in the TM mode. Also, there is a period interval in which a noticeable phase difference occurs for a 5 km deeper conductor, although this difference is obviously smaller because the overall depth to the conductor is greater than for sounding 1. In contrast, an increase or decrease in resistivity is observable for periods larger than 10 s even if the conductor is deeper.

Due to the dipping nature of the conductor, the resolution of its depth and the corresponding error margin depend substantially on the observation point at the surface as well as on the error associated with the inverted parameter. Thus, at the location of sounding 14, a 5 km variation in depth to the conductor produces appreciable changes in both the phase and the resistivity response. Clearly, the error margin in the depth determination is narrow in this area. However, it can be seen

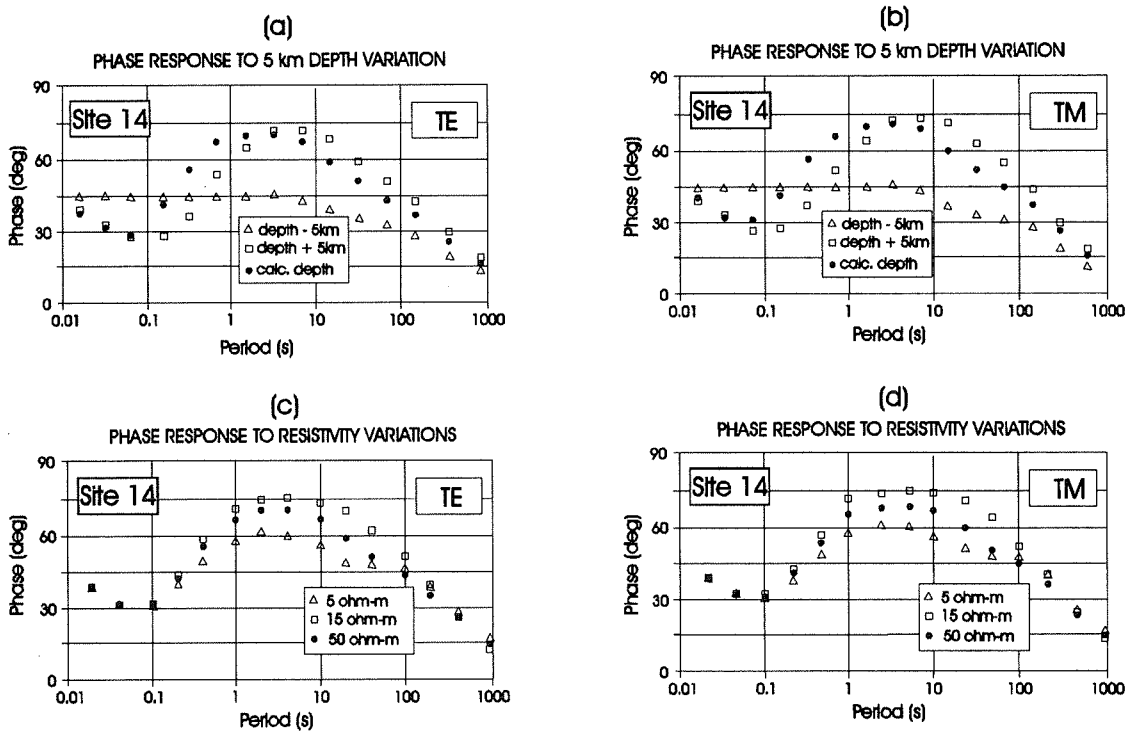


Fig. 24.- Model response to changes in depth and resistivity at sounding 14. a) ϕ_{TE} , b) ϕ_{TM} , for change of depth and c) ϕ_{TE} , d) ϕ_{TM} for change of resistivity. For a 5 km shallower conductor the phase response (TE and TM) is that of a homogeneous half space up to 10 s when it starts to drop below 45° . A deeper conductor also suggests relatively large phase changes within all the period band. A 5 km variation in depth to the conductor produces appreciable changes in both the phase and the resistivity. Variations of resistivity response, on the other hand, modify the phase response considerably only at intermediate periods (1 to 100 s).

that at the location of sounding 6 (the most inland station which we did not use in our final inversion) we are in the limit of resolution as the phase perturbation occurs in a limited period band and is small ($< 3 - 4^\circ$). Thus, only in the case of accurate data could we resolve the depth to the conductor.

If the measured data have a smaller error in the phase than the observed phase difference between the perturbed and original models, then we presume that the actual depth to the conductor is determined more accurately than the magnitude

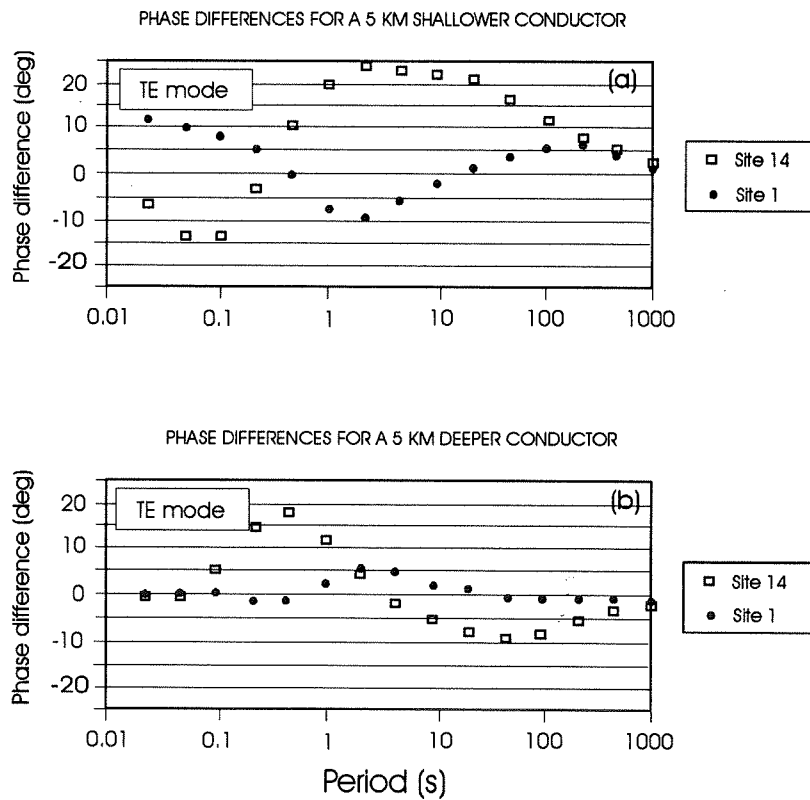


Fig. 25.- Phase differences between the original model and a 5 km shallower (a) and deeper conductor for the TE mode. A shallow conductor perturbs considerably the phase, whereas if the conductor is deeper the phase differences are appreciable mainly at the coastal sounding. As the phase error (2°) is smaller than the change introduced (5° from 1 to 10 s) by the change in depth at sounding 1, then we assume that the accuracy to which it is possible to determine the depth to the conductor in this location is smaller than 5 km, probably less than half of this.

of the depth variation used, in this case being better than 5 km. As observed in Chapter 2, the measured phases generally have small related errors (less than 2°) except occasionally at the longest periods. Hence, in this particular case the result means that the conductor at site 6, but also at site 1, is not likely to be found shallower than 5 km of the calculated depth, nor probably 5 km deeper. Except for a short period interval (e.g. 1 to 10 s for the TE mode), a conductor 5 km deeper

at site 1 is not appreciable in the phases, whereas if it were 5 km shallower it would be observable almost in the entire period band (Fig 22). Thus, the conductor is not shallower than the calculated depth at this location (~ 25 km) but it could be at least 5 km deeper. Figures 25a and b show the phase differences between the original model and a 5 km shallower and deeper conductor respectively for the TE mode. A shallow conductor perturbs considerably the phase at the three test sites, whereas if the conductor is deeper the phase differences are large mainly at the coastal site. However, the phase error ($\sim 2^\circ$) is smaller than the $\Delta\phi$ introduced ($\sim 5^\circ$ from 1 to 10 s) by the change in depth at sounding 1, then the accuracy to which it is possible to resolve the depth to the conductor in this location is $\delta h \leq 5$ km. At the location of sounding 14 the accuracy is much better.

Although the depth to the conductor is a well constrained parameter at site 14, it is also true that it is here that the models in the two polarization modes have the larger discrepancies. However, by the arguments given in the previous section related to the discontinuity of the electric field across strike, we regard the TE mode results to represent the earth structure in the area. The geological interpretation will therefore be based on this polarization mode. In the following section, we discuss results from the forward calculation of the vertical component of the magnetic field.

4.5) Constraints from the vertical field

The vertical magnetic field component H_z can be used to test the similarities between the observations and the model used for the error estimations in the previous

section. As observed before, near conductors, the relation between the vertical magnetic field and the horizontal magnetic field components H_x and H_y at any frequency is given by equation (6)

$$H_z = T_x H_x + T_y H_y, \quad (65)$$

where T_x and T_y are complex because they may include phase shifting. The vertical component H_z is an anomalous field associated with lateral conductivity gradients in the Earth, whereas H_x and H_y are dominated by the regional field. T_x and T_y are given by

$$T_x = A_r + iA_i \quad (66)$$

$$T_y = B_r + iB_i.$$

and it is usual to plot the real and imaginary components (A_r, B_r) and (A_i, B_i) separately. These define an induction vector or tipper in the horizontal plane which correspond to the in-phase (p) and quadrature (q) components respectively.

Both, the in-phase and quadrature components of the tipper without the galvanic component, *i.e.* the tipper responding exclusively to inductive effects, are plotted in Fig. 17 for selected periods within the induction band. We have noted previously that the in-phase tipper component is roughly perpendicular to the strike of the regional structure. The discrepancies are attributable to 3-D induction effects

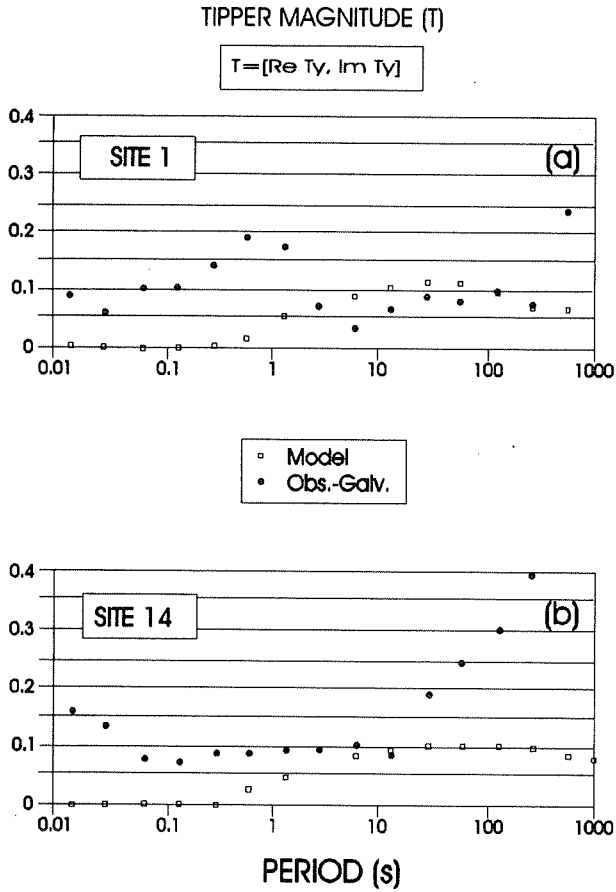


Fig. 26.- Inductive (i.e. observed minus galvanic) tipper magnitude as well as the model tipper magnitude plotted for soundings 1 (a) and 14 (b). See text for full explanation.

which are not removed with the tipper separation technique of Zhang et al. To further verify the validity of our schematic 2-D model we will compare the tipper magnitudes (observed versus calculated). For a 2-D situation with the strike along the Y axis (as it is the case here) the T_y component of Equation (6) vanishes and

$$H_z = T_x H_x. \quad (67)$$

In this case the in-phase tipper magnitude is simply given by A_r . The magnitude of the tipper is rarely as great as 1, with 0.1 to 0.5 being the common

range according to Vozoff (1989). In figure 26 the observed tipper magnitude T_p corrected for galvanic contribution (i.e. the inductive T_p) as well as the model tipper T_m (computed using GEOTOOLS) for Site 1 are plotted. T_p and T_m are of a similarly small magnitude (less than 0.2) in the period interval between about 10 to 1000 seconds, which agrees well with the regional conductor's induction band. At sounding 14 however, T_p and T_m differ for periods larger than 10 seconds. T_p increases rapidly after 10 seconds by effect of the induction of the near-by ocean which was not included in the forward model.

CHAPTER 5

STRUCTURE OF THE SUBDUCTION ZONE IN SOUTHERN OAXACA

5.1) Geometry of subduction according to MT data

Despite the presence of distorted soundings where static shift may not be adequately removed, the measured phases show a well defined elongated conductor for both polarization modes, which is equally observed in the eastern (PE) and western (PW) surveyed profiles. Some observed discontinuities in the phase, which are attributed mainly to near surface induction effects, have little or no relation to the deeper 2-D conductor that we associate with the subducting oceanic crust. Thus, it was necessary to exclude those soundings that are strongly influenced by local induction (and therefore present 3-D characteristics) from a modeling procedure aimed at determining the correct depth and dipping angle of a 2-D conductor. In order to eliminate the distorted soundings, selection criteria were established and applied to exclude soundings with scattered regional strike, large regional skew and scattered tippers (Sections 3.3 and 4.2). The exclusion of 3-D soundings supported a meaningful 2-D inversion that was performed mainly on the phases (maximum weight = 1). Fisher et al. (1992) among others, have demonstrated the stability of the phase with regard to the effects

of the static shift and its continuity at the surface of any conducting structure. However, to constrain the resistivity structure, the resistivity of several soundings which showed an undistorted 1-D behavior at high frequencies was included and given full weight in the inversion process. This resulted in a robust estimation of the geometry of the conductor, although the number of stations included in the interpretation was reduced to 6 from 14. Because the depth estimations between the full projected profile which included 9 soundings (see Fig. 19) were not significantly different from those calculated using only 6 of the projected soundings (see Fig. 20), we opted for plotting the former results (minus sounding 6) to have a more general perspective of the conductor structure.

Figure 27 shows the simplified geometry of the conductor for the TE and TM modes interpreted using the 8 sites mentioned above. The heavy line in this figure is simply the interpolated depth to the center of the conductor calculated at each sounding from the Smith and Booker inversion of the TE mode. The dashed line corresponds to the inversion of the TM mode. It is generally accepted (e.g. Meissner, 1986; Cox and Hart, 1986; Turcotte and Schubert, 1982) that the thickness of the oceanic crust is between 5 and 8 km. If we assume the extreme case, i.e. we presume that the conductive part of the subducting oceanic plate is 8 km thick, thus the top and bottom 'boundaries' lie 4 km above and below the minimum conductivity respectively. However, the artificial 'thickness' will not affect the interpretation. The depth to the center of conductor from the TE mode is found to vary from 8 km at sounding 12 to about 25 km at site 2, the most inland sounding located some 140 km away from the coast. The minimum resistivity observed below the location of soundings 13, 4, 3, 8, 1, and 2 vary from 2 to 15 ohm-m, whereas the coastal stations

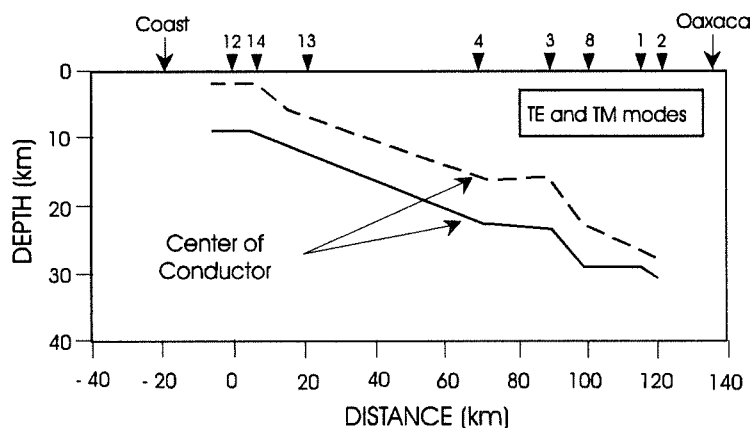


Fig. 27.- Interpreted depth to the center of the conductor for the TE (continuous line) and TM (dashed line) modes using the projected survey line selected in Section 4.2) without site 6.

12 and 14 present larger values; 25 and 50 ohm-m respectively. The estimated dipping angle of the conductor between soundings 12 and 2 is found to be $\alpha = 12^\circ$ which we assume corresponds to the subducting angle in this zone. The minimum resistivities observed in the TM mode of the interpreted structure are more homogeneous along the profile and generally higher than for the TE mode except at the extremes of the profile (25 to 40 ohm-m between soundings 13 and 2; 10 to 20 ohm-m for the soundings at the NE and SW end of the profile). Other major difference between the two polarization modes is that depths to the center of the conductor are shallower for the TM mode than those obtained for the TE polarization mode. Regardless of depth and conductivity differences, the general trend of both polarization modes is similar; the dipping angle between sites 12 and 2 is 12° . The 'jump' observed in depth to the conductor between soundings 3 and 8 is present in both modes of polarization and may be a consequence of the projection of soundings 3 and 8 from different profiles

onto the central line. In the remaining of this chapter we discuss the results of the magnetotelluric survey based on the TE mode and compare them with other available geophysical data.

5.2) Evidence of subduction from earthquake data

The subduction of oceanic plates under active continental margins has long been recognized, but the amount of evidence regarding this phenomenon is still limited. A great deal of information has been added to our knowledge through the analysis of earthquake data produced by the seismic activity in these zones.

A review of the general properties of subduction zones has been given by Uyeda (1982). Specific correlations of related parameters have been attempted; for example Ruff and Kanamori (1983) attempt to explain the variation in earthquake size in relation to the plate age and rate of subduction in specific areas of the globe. Using historical data (Gutenberg and Richter, 1954) they observed that the largest earthquakes occur in zones with young lithosphere and fast convergence rates and that zones with old lithosphere and slower rates are relatively aseismic for large earthquakes. Other results relate more to the rupture process. For instance earthquake size is directly related to the asperity distribution on the fault plane; the zones with larger earthquakes are supposed to have very large asperity regions while the zones with smaller earthquakes have small scattered asperities. Based on the estimation of fault extent from aftershocks, Ruff and Kanamori (1983) conclude that subduction zones are apparently seismically uncoupled below a depth of 40 km, and go further

to propose the basalt to eclogite phase change in the subducting slab as the cause of uncoupling.

Other interesting facts regarding the properties of the subduction zones have been reported. An example of this, which is relevant to the Middle American Trench (MAT) and particularly to the Oaxaca's subduction area, is the volcanic gaps associated with the consumption of aseismic oceanic ridges under the continental lithosphere (Nur and Ben-Avraham, 1983). It is assumed that the buoyancy of these ridges breaks the continuity of the subducted plate and therefore creates spatial and temporal volcanic gaps. Furthermore, if the ridges are consumed obliquely, as is the case for the Tehuantepec Ridge (Fig. 1), then the gap is expected to migrate with time.

A geotechnical study based mostly on the properties of sediments recovered by the Deep Sea Drilling Project (DSDP) within the convergence zone on the western continental margin of Mexico by Shepard and Bryant (1983) provides extensive information on the specific characteristics of subduction in this area. The authors observed that sediment consolidation ranges from very unconsolidated to highly overconsolidated. Very unconsolidated sediments can be caused by 1) high sedimentation rates; 2) low sediment permeability relative to the length of the drainage path; 3) laterally applied stress; and 4) induced pore water pressures resulting from the subduction of pelagic sediments with high water content. On the other hand, causes mentioned for overconsolidation of sediments are 1) tectonically induced pressures; 2) removal of overburden by mass movement processes; 3) low sediment accumulation rate; and 4) age. An important property found for all the trench zones studied (seven in total)

is that the porosity of subducting sediments generally exceeds 30 %, which Shepard and Bryant assume is the minimum that can be acquired during subduction. Their results suggest that there are two end members in the general geotechnical property model for convergent margin sediments. These are the clastic dominated margins, which are often characterized by a deformed thick trench sedimentary sequence (e.g. Vancouver continental margin), and the pelagic-dominated margins which are characterized by a thin clastic sediment sequence overlying pelagic sediments on a rapidly converging oceanic plate. An important difference among these end members is that in the later, well developed faults and graben-horst structures are observed clearly on the subducting plate. The Washington continental margin and the Japan trench zone are examples of the clastic and pelagic convergence models respectively.

The Middle America Trench along southwestern Mexico appears to be an intermediate case. The sedimentary sequence drilled off shore the coast of Oaxaca (DSDP leg 66) represents a transition from pelagic environment at the base to an environment influenced by continental margin sedimentary processes at the top as the ocean plate moves closer to the margin. The sediments are reported to maintain high water contents and high porosities over periods of times probably larger than 10 m.y. under significant accumulation of overburden. However, porosity may be reduced by the effect of increasing pressure landwards; most of the water carried by the sediments would be driven upwards through the faulted upper sediments before travelling long distances under the continental plate. Still, there is the possibility that an important amount of mineralized water, dragged with the sedimentary cover of the downgoing oceanic crust, remains trapped below the continental crust as it moves continent-wards. Trapped fluids have been reported as the cause of the conductivity observed

in Vancouver Island subduction zone (Kurtz et al., 1986) at depths ranging between 10 and 15 km from the surface. Initially this conductor was thought to correspond directly to the top of the subducting Juan de Fuca Plate. However, seismic reflection studies carried out subsequently (Green et al., 1986, 1987) seem to indicate that the conductor, which correlates well with a 'bright' or highly reflective zone, corresponds in fact to fluids trapped above the subducting oceanic plate. This recent result has led researchers to think that upward migration of fluids in subducting regimes could be a common phenomena. It is assumed that a thermochemical mechanism exists to seal and then trap the fluids at a characteristic depth below the surface (e.g. Hyndman, 1988, Hyndman and Shearer, 1989), for example, at approximately 400 °C where silicates precipitate and plug all the pores. Although this model may be valid in many cases, we argue that in certain instances this is not observed. This will be discussed later in this chapter.

Plate segmentation along the MAT

Seismicity data have revealed the existence of seismic gaps along the Mexican subduction zone, which are thought to be associated either to the consumption of the Tehuantepec Ridge, or to nonuniform seismic slip rates of plate consumption (Kelleher and McCann, 1977; McNally and Minster, 1981). It is not clear whether the aseismicity observed in the trench portions of the subduction zone where the Tehuantepec ridge intersects the continent (Fig. 1) is due to the aseismicity of the ridge to large earthquakes or to anomalously large repeat times leading to no documented seismic events in these regions (Singh et al., 1981). Although the origin of the ridges has not been precisely established, it is well known that these are low density

regions compared with their surroundings, that they are aseismic and low velocity zones. Therefore, it seems reasonable to argue that the lack of volcanism along the portion of the trench north of the intersection of the Tehuantepec Ridge with the North American Plate as well as the shallow dipping angle of the subducting Cocos Plate are influenced by the bouyancy and obliqueness of the subducting ridge.

Nishenko and Singh (1987) suggested that the seismic gaps observed in the region are likely a consequence of the obliqueness of subduction and differential plate velocities along the Middle American Trench. McNelly and Minster (1981) estimated seismic slip rates along the MAT using seismic moments of large earthquakes, and found that slip is an inherently spacially non-uniform function, which suggests non-uniform physical conditions along the trench. Singh et al. (1981) and Nishenko and Singh (1987) analysed the epicenters of recent shallow interplate large earthquakes ($M_s \geq 7.0$) combined with a catalog from the nineteenth century as well as relocated epicenters from the early part of this century to outline seismic gaps and recurrence periods in the subduction zone between Jalisco (20° N, 105.5° W) and Tehuantepec (15° N, 94.5° W). Based on a comparison of rupture zones determined from intensity compiled isoseismal maps (Figueroa, 1970; Singh et al., 1984) and aftershock locations, they defined periodicity in several regions along the subduction zone, by grouping events of $M_s \geq 7.5$ into separate source zones. The segmentation observed in their study was delineated by the rupture zones of the most recent earthquakes occurring in each of the defined areas. They argue that the earthquake sources in Oaxaca are simple (i.e. long-period body waveforms that can be modeled as point sources) while sources in Michoacan, Colima and Jalisco are complex (i.e. long-period waveforms, modeling require multiple point sources). The contrast between simple

and complex ruptures is connected to the amount of heterogeneity on the fault surface and the degree of interaction between adjacent asperities. It is suggested that simple events reflect a relatively homogeneous distribution of asperities in the fault surface, such that the failure of one does not trigger rupture in adjacent asperities. However, while this behavior is observed at long period body waveforms, it does not indicate a similar behavior at shorter periods (Tijama, 1984). Based on the pattern of earthquake occurrence, Singh et al. (1984) and Nishenko and Singh (1987) note that the plate interface in Oaxaca appears to be divided into at least 3 large segments which cyclically rupture their entire dimension (Fig. 1). These segments or source zones are:

- Zone 1: Eastern Oaxaca (95.2° to 96.4°)
- Zone 2: Central Oaxaca (96.4° to 97.3°)
- Zone 3: Western Oaxaca (97.3° to 97.7°)

Note that all MT soundings were done within the Central Oaxaca segment (Zone 2). Therefore, the anomalous tipper observed at soundings located in the central part of the eastern profile (PE) must not be related to the assumed segmentation of the plate but to other conductors, possibly related to the contact of the Xolapa and Oaxaca terranes (see figs. 4 and 18).

Chael and Stewart (1982) analysed several large earthquakes ($M_s \geq 7.0$) and also found that body waves of the Oaxaca events (three in total) indicate simple faulting processes and estimated focal depths of 15 to 20 km in the Central Oaxaca

segment. They calculated the lateral extent of faulting, which defined segments that agree well with the source zones determined by Nishenko and Singh (1987), and estimated the strike of the eastern and central Oaxaca segments as being close to zero.

Subducting plate model from seismicity data

Several models based on seismicity of the subducting Cocos plate have been proposed in the past few years for the region. Based on the aftershocks recorded by the Red Sismica Mexicana de Apertura Continental (RESMAC) of the October 1980 earthquake in the Mixteca highlands, Lomnitz (1982) proposed a structural model for the subduction zone. A prominent amplitude and low-frequency content seismic wave was present at all the stations arriving 15 to 20 seconds after the initial *P* signal. Lomnitz suggested that this was due to the presence of a refractor (acting as a waveguide) located below the subducting oceanic crust. He argued that when the focus of the earthquake is within or close to the waveguide, much of the seismic energy can be trapped and later refracted upwards as *P* or as *S* waves. He estimated the focus of the Mixteca earthquake to lie at a depth of 70 km, or near the bottom of the subducted oceanic crust which has a velocity estimated at ~ 6.8 km/s, assuming that the waveguide has exactly the structural position and velocity expected for the subducting Cocos Plate. The proposed model shows the oceanic crust dipping at an angle of 17° which levels off inland. It is supported by the fact that under the Gulf of Mexico coastal plain of Veracruz (east of the Mixtec epicentre of 1980) focal depths are typically in the range of 80-100 km suggesting that the Benioff zone in that area is gently dipping east-west.

Valdés et al. (1982) analysed the aftershocks of the Petatlán, Guerrero earthquake of March, 1979 ($M_s = 7.6$) recorded for a period of 26 days after the main event, and found that these fall almost entirely within a zone 20 to 25 km thick dipping 15° in a $N20^\circ E$ direction perpendicular to the trench. Their result supports the idea of a gently dipping subducting plate. However, their stations were all located within 40 km off the coast making it impossible to observe a possible levelling off of the plate further inland. Nava et al. (1985) proposed two alternative structural models featuring a dipping oceanic plate in the subduction zone based on the relocation of 77 aftershocks of the 1980 Huajuapán, Oaxaca earthquake ($M_s = 7.0$) recorded by the RESMAC. The aftershocks generated signals that were identified previously by Lomnitz (1982) as trapped seismic waves travelling along the lower continental crust-top of the subducting layer, and/or along the bottom of the subducting slab-upper mantle interphases. Assuming that the rupture zone occurred completely through the subducted crust, and not beyond, they defined the top of the subducted plate by means of a plane joining the bottom of the trench as given by the bathymetry with the upper end of the rupture. The position of the bottom of the oceanic crust was defined also by means of another plane parallel to the first one, through the bottom of the rupture. In this way they calculated a thickness for the seismogenic zone of about 24 km which is in agreement with that obtained by Valdés et al. (1982), and a dipping angle of 13° , also in agreement with other estimations (e.g. Zuñiga and Valdés, 1980; McNally, 1981). More recently, Suarez et al. (1990) used a teleseismic array north of Acapulco which recorded during a period of three months, as well as recent earthquake data from a permanent network. Their hypocentral distributions also revealed a plate slab dipping at a shallow angle beneath the North American

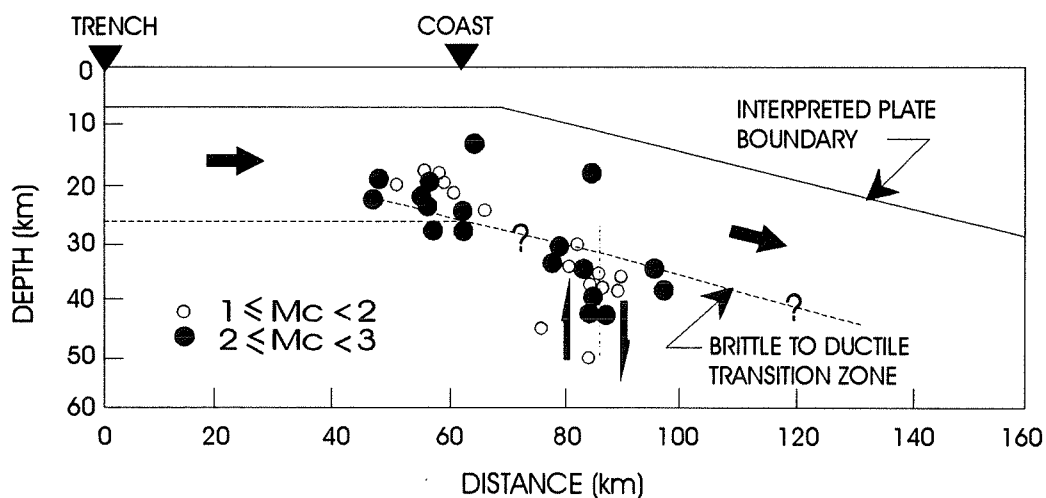


Fig. 28.- Cross section of seismicity (modified after Suarez et al., 1990; section 'D'). There is a lack of thrust-type earthquake along the interpreted top of the subducting plate. Earthquake activity is generally observed deeper and can be associated to the brittle to ductile transition zone known as the Benioff-Wadati zone. The absence of shallow seismic activity can be explained in terms of 'stable slip' which may be possible in the presence of a fluid phase on top of the subducting plate.

plate and steepening progressively to about 12° . The maximum depth of strong seismogenic plate contact is 25 km (Fig. 28); at 30 km the plate bends following a quasi-horizontal trajectory underplating the North American plate for at least 150 km. The rupture areas of interplate events in this region are consistently shallower than 20 km. Compared with the plate geometry of central Perú and Argentina (Barazangi, 1979; von Huene and Lallemand, 1990) where the Nazca plate subducts also subhorizontally, the lithospheric thickness of the overriding plate in central Mexico is found to be 45 km in average, whereas in South America the horizontal seismic zone lies at an average depth of 100 km. This thin lithosphere in southern Mexico is similar to an oceanic plate and is probably best explained in terms of the accretion of the allochthonous terranes (oceanic in nature) onto the continent since the Paleozoic

(Ortega-Gutierrez, 1981; Campa and Coney, 1983). It has also been suggested that it could be originally continental and later thinned by an extensional phase of deformation when dykes were intruded (Ortega-Gutierrez, 1981). Most important of all, it seems however, that the apparently buoyant subducted oceanic crust follows the lower topography of the thin lithosphere in this region.

5.3) Seismic Refraction and gravity results

Recent discussions of seismic reflexion data support the interpretation that a zone of high reflectivity observed at middle to lower crustal levels corresponds to a conductive zone with high content of trapped mineralized fluids (e.g. *Ádám*, 1987, Jones, 1987, Hyndman, 1988). The correlation of both, highly reflective and anomalously highly conductive layer has been observed in subduction areas as well as in stable continental crust (e.g. Jones, 1992). While in the case of stable continental crust there are discrepancies on what is the origin of such reflectors, it is widely accepted that in subducting regimes the sharp reflecting interface can be directly associated with a zone of high water content. This can be due either to the dewatering of the subducting oceanic crust with water trapped at some upper level or with the top of the subducting plate itself. Whether it corresponds to one or the other case will depend on several factors. Among these are the quantity of sediments on top of the oceanic crust and its effective porosity, its age and convergence rate, its temperature, etc. More on the properties affecting the subduction process have already been mentioned in Chapter 1.

Refraction studies have not been used systematically with MT data because the correlation with the observed conductor is less direct. Also, the interpretation is prone to ambiguity when the velocity gradient is negative as would be expected if the lithospheric sequence contains a porous rock unit filled with fluids. However, in the absence of seismic reflection data, the results of two seismic refraction studies were analyzed here in conjunction with the electrical model obtained from the MT interpretation. This combination, as we shall see, turned out to be very useful.

Seismic velocity and resistivity structure

Several refraction studies in Mexico have been reported (Steinhart and Meyer, 1961; Hales et al., 1970; Couch and Woodcock, 1981; Valdés et al., 1986; Nava et al., 1988; Suarez et al., 1992), however most are out of the range of the area of study. Only two of them can be used to correlate with the electrical model discussed at the beginning of this chapter.

About 100 km west of the MT survey area, but along a profile approximately parallel to the MT profiles, Valdés et al. (1986) obtained a model for the P-wave velocity structure using a two-dimensional ray-tracing propagation technique. Their initial model was constrained from results of other studies (Steinhart and Meyer, 1961; Couch and Woodcock, 1981; Ortega-Gutierrez, 1981). In addition to travel times, they used waveform amplitude data to constrain velocity gradients within layers as well as to resolve uncertainties in phase correlation. Although they recognize that the resolution and uniqueness of their 2-D forward models are difficult to quantify, a sensitivity analysis of the interpreted interfaces and gradients, allowed them to

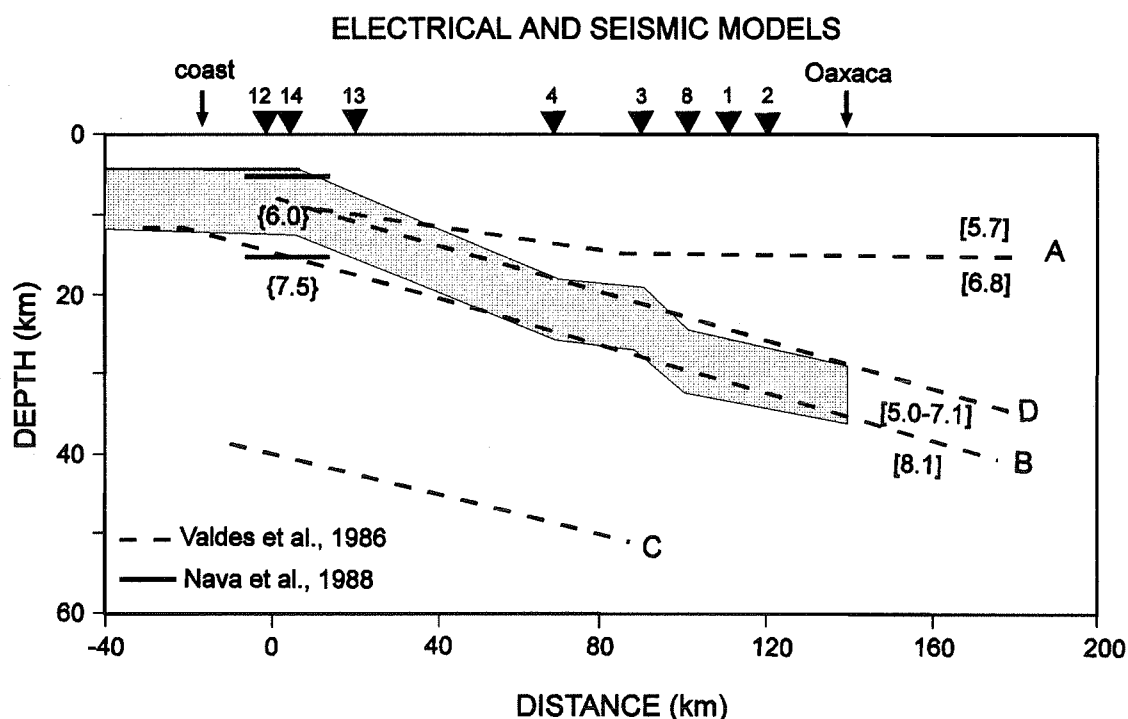


Fig. 29.- Correlation of the bottom of the conductor and the main seismic velocity interface (B) assuming a thickness of the conductive zone of 8 km. Since below this boundary the resistivity increases by one order of magnitude (from 10 to 100 ohm-m or more) and the seismic velocity changes from 7.1 to 8.1 km/s, we assume that this interface defines the top of a non-porous rock unit that could be associated to the denser (and more resistive) gabbroic layer of the oceanic crust. The top of the interpreted conductor on the other hand, roughly follows the upper boundary of the low velocity zone (interface D).

estimate a range of uncertainty of less than 4 km for the Moho. Figure 29 shows in continuous light grey lines their interpreted velocity structure. The interfaces with a velocity contrast greater than 1 km/s were plotted as these represent horizons that are likely better defined (capital letters *A*, *B* and *C*). Also included is their interpreted low velocity zone of variable density which increases landward from 2.7 to 3.2 gr/cm³. This variation was introduced in their model so as to fit both their gravity and seismic

data. The numbers in the square brackets represent the velocities (in km/s) of each layer. The conductivity structure outline in Section 5.1 is plotted in the same figure. Assuming a thickness of 8 km for the conductive zone one can correlate the bottom of the conductor with the seismic interface B. Since below this boundary the resistivity increases by one order of magnitude (from about 10 to 100 ohm-m or more) and the velocity changes from 7.1 to 8.1 km/s, we can assume that this interface defines the top of a non-porous rock unit that could be associated to the gabbroic layer 3A (Banerjee, 1984) of the oceanic crust. The top of the interpreted conductor on the other hand, roughly follows the upper boundary of the low velocity zone (line D).

A seismic refraction survey carried out along the Oaxacan Pacific coast by Nava et al. (1988) intersects the MT survey line at sounding 14. They interpreted the travel times using a direct ray tracing method for 2-D inhomogeneous media (Gebrande, 1976). The two layer velocity model they obtained is shown in Figure 29 (short thick lines) at the point it intersects the MT resistivity section. Again, only those layers with the higher contrast in velocity were plotted as we assume that the sharp contrast in velocity corresponds to a large change in the fluid content of the rock units, and consequently in the resistivity contrast. The numbers in brackets indicate the estimated velocity in km/s.

The crustal structure of Oaxaca reported by Valdés et al. (1986), and Nava et al. (1988) are remarkable in that their results match well the electrical model. Thus, they support electrical the model and together suggest that fluids remain within and at the top of the plate in this region for at least 150 km from the trench without a noticeable upward migration. Assuming a plate convergence rate of 7.0 cm/y (Cross

and Pilger, 1982) this is equivalent to saying that during about 20 million years after major expulsion at the accretionary prism, fluids remain bounded to the oceanic crust and to the sedimentary cover on top of it. After such a period it seems that upwards migration of conductive fluids may be significant; however, we need more data to test this hypothesis.

Gravity model and resistivity structure

Recently, Urrutia-Fucugauchi (1993) and Arzate et al. (1993) reported results of a gravity survey along the MT (western) profile, which extends from the Pacific Ocean to the Gulf of Mexico. A first analysis of the gravity anomaly without previous assumptions on the geometry and density contrast of the surface units was completed. Spectral analysis (Spector and Grant, 1970) was used to provide a statistical estimation to the top of the assemblages of bodies. Results for the profile in terms of the logarithmic plot of the smoothed amplitude spectrum as a function of wave number yield interfaces located at 15, 18, 28 and 44 km. Further analysis of the data was completed with an iterative algorithm that modifies the lower boundary geometry of a two layer model until a fit to the observed gravity anomaly was obtained. Several models with different density contrast and average depths to the interface were tested. A similar analysis with a polygonal model that allows the density to increase with depth from 2.6 to 3.3 gr/cm³ gave essentially the same results with high frequency fluctuations superimposed. Figure 30 shows the first 120 km of a gravity model (the gravity model towards the Gulf of Mexico is not included because it is out of the range of the MT study) with a density contrast of 0.7 gr/cm³ and an initial average depth of 30 km superimposed with the interpreted conductor. There

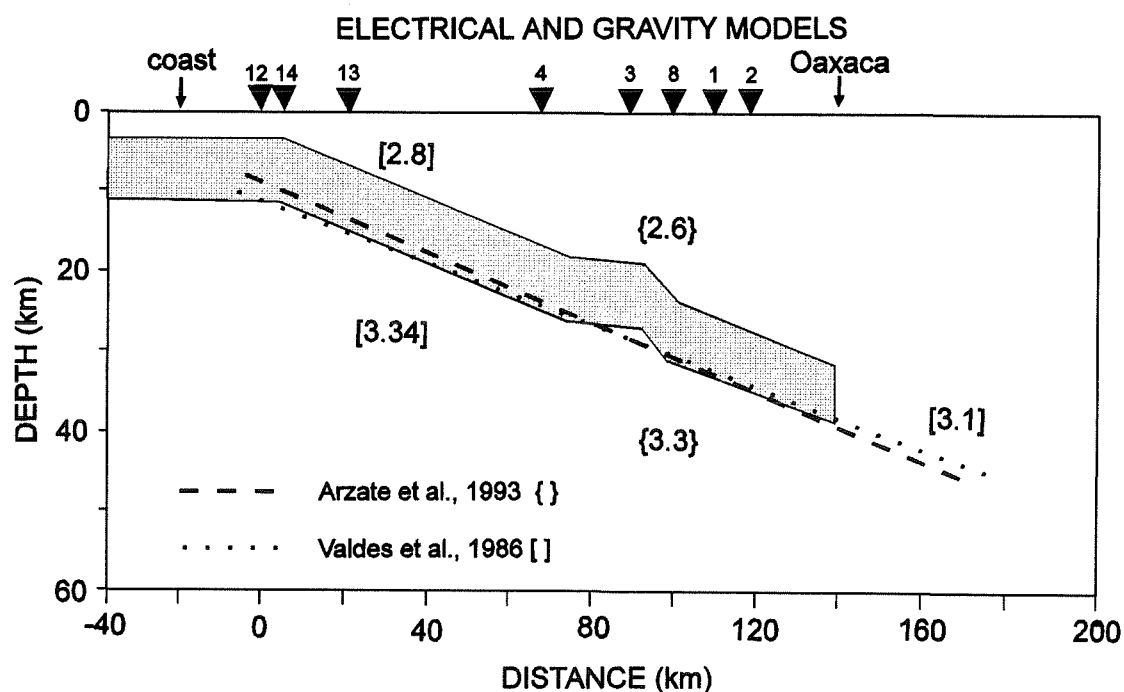


Fig. 30.- Interpreted conductor superimposed with existing gravity models. There is good correlation in depth and dip between the higher density interface and the bottom of the region of enhanced conductivity which can be explained by a porous media filled with conducting fluids laying on top of a denser fluid-free layer.

is good correlation in depth and dip between the higher density interface ($\alpha = 13^\circ$) and the bottom of the region of enhanced conductivity which can be explained by the presence of a more porous media filled with conducting fluids on top of a denser fluid-free layer at the density contrast horizon. However, the upper boundary of what we assume to be a porous layer cannot be resolved by the gravity data. This may be due to the inherent low resolution of gravity or to a gradual change in porosity.

Valdés et al. (1986) carried out a gravity survey along their refraction profile located some 100 to 150 km east of the PW magnetotelluric profile. A constant dipping

oceanic crust model (13°) fitted well their Bouguer anomaly profile only for about 200 km landwards from the trench. They assumed the misfit of the northeastern part of their profile to be due to a change in density of the subducting plate, citing previously observed changes beneath the Chilean Trench. They argue that higher densities in the descending lithosphere were needed to fit both the gravity anomaly and the refraction profile and can be explained in terms of phase changes from basalt to eclogite and from plagioclase peridotite to garnet peridotite (Grow and Bowin, 1975). Figure 30 shows the model high density interface. In square brackets is indicated the corresponding density in gr/cm^3 used to fit their data. The remarkable good correlation with the interpreted conductor and the gravity model reported by Arzate et al. (1993) further supports a porous subducting oceanic crust model whose conductivity is enhanced by the mineralized fluids it contains. In the following section, a correlation between the electrical model and a thermal model of this area is used in an attempt to constrain our interpretation on fluids location.

5.4) The electrical conductor and the 300-400°C isotherm

The thermal provinces identified in the work of Ziagos et al. (1985) based on heat flow measurements at 20 different locations along a profile parallel to the western profile PW, define the regional character of the thermal anomalies associated to the subduction of the Cocos Plate. The authors observed a low heat flow zone ($\leq 40 \text{ mW/m}^2$) close to the Pacific Ocean and assumed that it is a region parallel to the trench beginning south of the Trans Mexican Volcanic Belt (see Fig. 3) and which continues southwards at least up to the border with Guatemala (Fig. 31). Subsequent

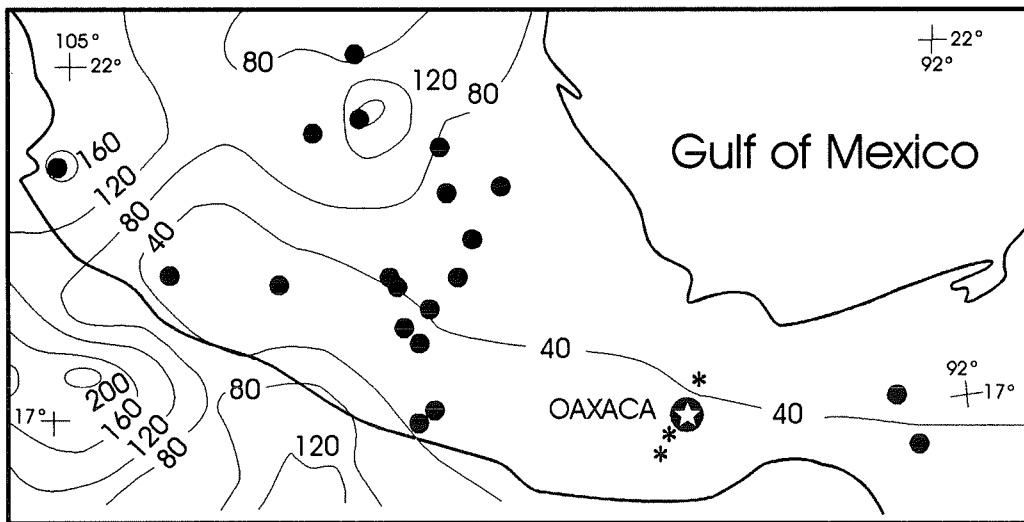


Fig. 31.- Low heat flow zone ($< 40 \text{ mW/m}^2$) parallel to the trench that begins south the trans-Mexican Volcanic Belt and seems to continue southward at least to the border with Guatemala. Filled circles are from Ziagos et al. (1985). Asterisks are from Urrutia-Fucugauchi (1991).

heat flow measurements in four wells located along the western MT profile (Urrutia-Fucugauchi, 1991) support the existence of this regional trend. This low heat flow zone appears to be a predominantly tectonic related thermal effect due to the subduction process, which suggests regional significance (Ziagos et al., 1985) and is probably the result of a relatively thin upper crust underlined by a shallow and cold subducting slab. The reported values are similar to those observed in the Basin and Range and the Peruvian trench ($q_0 = 40 \text{ mW/m}^2$) and favor the idea that similar conditions prevail in subduction regimes (or Trench-Arc-Back Arc systems).

There have been arguments suggesting that the enhanced conductivity observed in active continental margins is due to the presence of fluids trapped at some level in the crust above the subducting plate (see Chapter 1 and previous sections).

It is assumed that the fluids are mineralized, which allows an impermeable layer to be formed by silicate precipitation at temperatures ranging between 350 and 400 °C. Such a layer prevents the migration of fluids towards the surface and keeps them trapped for periods of time in the order of tens of millions of years (Hyndman, 1988; Hyndman and Shearer, 1989). Thus, if this hypothesis were to hold for Oaxaca's continental margin, the observed conductor should correlate with the isotherm of 350-400 °C computed for this region.

In order to test this argument, a first order time independent thermal model of the region was prepared based on the heat conduction theory. Assuming that the heat is transferred only in the vertical direction and that the earth is in equilibrium, the heat conduction equation that relates the temperature T as a function of depth z is given by (e.g. Turcotte and Shubert, 1982):

$$T_{(i+1)}(z) = T_i + \frac{q_i z}{k_i} - \frac{A_i z^2}{2k_i} \quad (68)$$

with

$$q_i(z) = q_{(i-1)} - zA_{(i-1)} \quad (69)$$

where q_i is the contribution of the i_{th} layer to the heat flow, A_i is the constant heat production in layer i , and k_i is the thermal conductivity for the i_{th} layer which depends on the rock type. This recursive relation was used to calculate a set of temperature profiles for different surface heat flows and heat production in the Oaxaca's subduction zone. The position of sounding 4, located in the Valley of Oaxaca, was chosen to compare the thermal and electrical models. Thus, from the MT results we assume

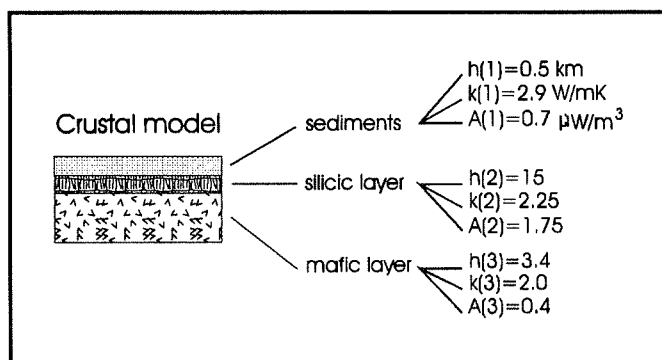


Fig. 32.- Parameters used in the calculation of the thermal model. The values shown here are averages of measured and/or assumed values. See text for more details.

that the lithosphere at sounding 4 is composed of three principal layers 0.5, 15 and 35 km thick respectively. At the top of the sequence lies a sedimentary layer of Paleozoic-Mesozoic age composed mainly of limestones. Its thermal conductivity was taken as $k_{sed} = 2.93 \pm 0.47$ W/mK which is the average value obtained from measured samples of this rock type in three wells at the location of soundings 6 and 2 as well as other samples some 20 km north of sounding 6. Underlying the sediments we assume a tonalitic (or silicic) basement, which is on top of a granulite facies (mafic) layer that extends down to lower crustal depths. Meissner (1986) considers this sequence as being common in Phanerozoic continental crusts based upon exposed ophiolitic complexes. The thermal conductivity of these two units is around 2.0 W/mK. However, a slightly larger value for the silicic layer would be more appropriate (Mareschal J.C., 1993). Thus, their thermal conductivity were taken as $k_{sil}=2.0$ W/mK and $k_{maf}=2.25$ W/mK respectively. Calculation done varying the values of these parameters up to 10 % showed no significant differences in the temperature profiles.

Other parameters needed to produce a thermal model of the zone are the

heat productions A_i of the three layers due to the presence of radioactive minerals. Roy et al. (1968) have found, for several thermal provinces in the U.S. using combined radioactivity and heat flow measurements, that local variability of heat flow is due to sources in the uppermost 10 km of the earth's crust and that the contribution from the lower crust and upper mantle is quite uniform over large regions. Thus, a commonly accepted value for the mafic layer that reflects the low heat production in this layer is $A_{maf}=0.4 \mu \text{ W/m}^3$, whereas for the silicic layer $A_{sil}=1.75 \mu \text{ W/m}^3$ represents an acceptable average. These values are based on typical abundances of radioactive elements in silicic and mafic igneous rocks respectively (Sass et al., 1971). A heat production calculation of $A_{sil}=1.77 \pm 0.9 \mu \text{ W/m}^3$ at 10 km of depth by Ziagos et al. (1985) for the nearby Acapulco trench zone supports this value for the silicic layer. For the relatively thin sedimentary layer ($\sim 0.5 \text{ km}$) composed mainly of limestones, a value of $A_{sed}=0.7 \mu \text{ W/m}^3$ was suggested (Mareschal J.C., 1993). The physical parameters used in the calculations of the thermal model are given in Figure 32.

A set of depth-temperature curves was obtained by varying the heat flow q_o at the surface from 30 to 60 mW/m² in steps of 10. The results are plotted in Figure 33. The temperature-depth profile corresponding to a heat flow of 40 mW/m² at the surface, which is considered an upper limit for this region, is shown in filled circles. As depth increases, the temperature tends to stabilize at around 400 °C for the bottom of the crust. At depths beyond 40 to 50 km it is expected that mantle heat sources play a dominant role that increases substantially the temperature or decreases it locally in subduction zones. However, no considerations have been made to model deeper phenomena, which would be feasible if values of k_{mantle} and A_{mantle}

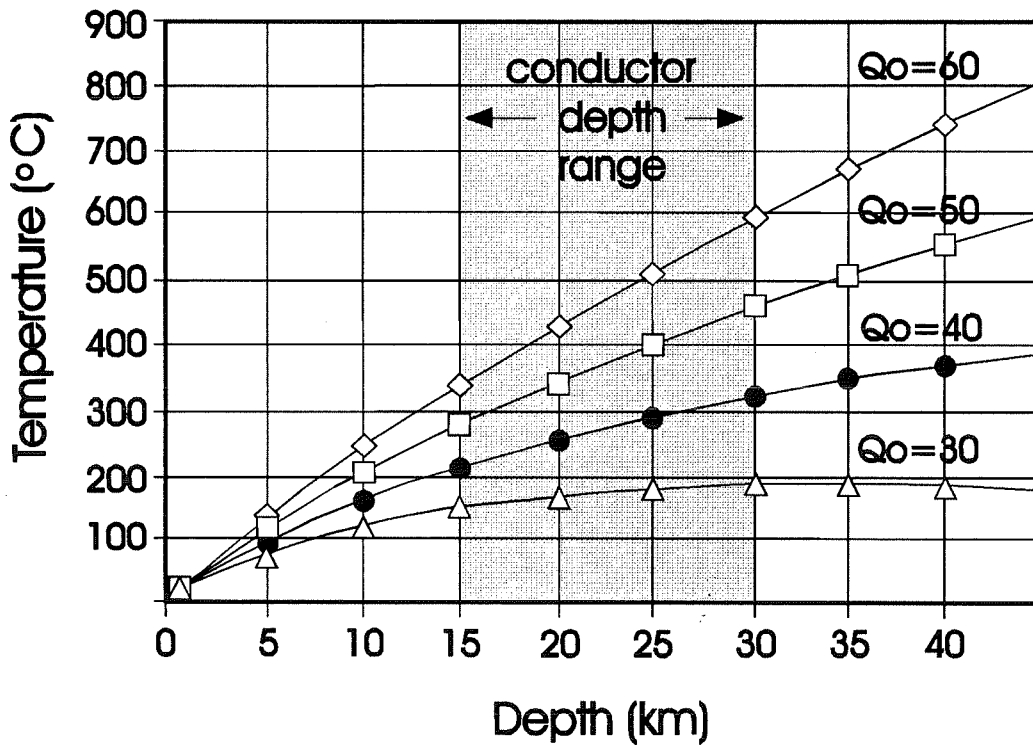


Fig. 33.- Set of time-independant depth-temperature curves obtained by varying the heat flow at the surface from 30 to 60 mW/m^2 in steps of 10. The temperature-depth profile corresponding to a heat flow of 40 mW/m^2 at the surface, which is regarded as the upper limit for this region, is shown in filled circles. The conductor depth range is shown in grey patten. It can be observed that higher heat flows would be needed to observe fluid precipitation (300-400 $^{\circ}\text{C}$) at the interpreted conductor depths.

where available.

Note that the curve corresponding to $q_o = 30 \text{ mW/m}^2$ has a negative slope at depths larger than 35 km. This is obviously not a realistic result which would indicate that the earth cools down with depth. This problem arises because the mantle has not been modeled. Therefore only the first 35 to 40 km are expected to be a good first approximation to the heat conduction processes taking place in this specific area. For the purposes of correlating the observed zone of enhanced conductivity with the

350 °C isotherm this depth interval is sufficient.

According to the results shown, the temperature-depth curve computed using a surface heat flow $q_o=40 \text{ mW/m}^2$ does not reach the isotherm of 350 °C in this depth interval. Instead, the depth extent of the conductor is bracketed by the 200 and 300 °C isotherms. Only if the surface heat flow is increased to 50 mW/m^2 or more does the 350-400 °C isotherm intersect with the electrical conductor. However, values larger than 40 mW/m^2 are not observed in the area of the MT survey. On the contrary, Ziagos et al. (1985) and Urrutia-Fucugauchi (1991) found that 40 mW/m^2 is an upper limit for the heat flow measurements for the thermal province parallel to the Middle American Trench. Thus, it should be expected that temperatures are generally lower than those computed using 40 mW/m^2 rather than larger.

Thus, our results suggest that the zone of enhanced electrical conductivity observed in the Oaxacan continental margin is not related to the 350-400 °C isotherm. Then, it must correspond to the top of the subducting plate. The fact that the observed conductor appears as a relatively compact unit just above a high seismic velocity interface and that an apparent low velocity zone correlates well in location with the electrical conductor (see Fig. 29) suggests that a fluid-filled low porosity zone exists just above a more compact region apparently related to the subduction. A possible mechanism that explains this observation involves the sealing of pores and fractures in the upper plate with eroded material produced by the frictional forces involved in the dynamic of subduction. Erosion along the underside of the upper plate has been found to be a common occurring phenomena in convergent margins (von Huene and Lallemand, 1990).

In the following (and last) chapter we discuss the similarities and differences between the Juan de Fuca subduction zone at Vancouver Island, the Nazca Plate subduction zone at the Chilean coast and the Cocos Plate at the Oaxacan margin.

CHAPTER 6

CONCLUSIONS

In the preceeding chapter, we have studied the relation between the electrical model and other geophysical models. The TE mode of the MT observations is known to give the best geometrical representation of the subducting plate (Booker, 1993) and to reproduce the enhanced conductivity zone correctly (Jones, 1992). The model is found to be consistent with both a low velocity layer from Valdés et al. (1986) refraction model as well as with a low density boundary obtained from gravity measurements (Arzate et al., 1993; Valdés et al. 1986). In the following sections we summarize the main results obtained from the interpretation of the MT model.

6.1) Fluid phase: on top or above the plate?

The correlation between the electrical model, obtained through a selection of undistorted 2-D MT soundings and a thermal model, based on heat flow measurements in the region, seems to rule out the possibility that the conductor represents fluids that would have migrated upwards and later trapped at some thermal level in the overriding crust. Our results indicate that fluids remain on top of the subducting slab for about 20 m.y. assuming a convergence rate of 7 cm/y, typical for this area. The subducting angle defined by MT ($\approx 12^\circ$) is similar to that defined from

earthquake and gravity studies ($\approx 13-14^\circ$) and considered representative of the area.

A possible mechanism that keep fluids on top of the lower plate is through the sealing of pores and fractures on the underside of the upper plate with desegregated material from abrasive erosion. Subduction erosion has been suggested to play a significant role in the thinning of the crust (von Huene and Lallemand, 1990) and may well be a major element in controlling fluids movement. Whether a thin continental crust is due to erosional processes or to the accumulation of accreted submarine terranes to the southern North American plate (Suarez et al., 1990) is irrelevant to the argument that fluids are kept within the subducting layer.

The lack of MT data northeast of Oaxaca city prevents the exact definition of how long fluids remain trapped on top of the lower plate beyond the Valley of Oaxaca. We expect that longer period (≥ 4000 s) MT work, along a complementary profile from the Valley of Oaxaca towards the Gulf of Mexico currently being interpreted (Mührs, 1994), will provide useful elements in this respect. The 1-D thermal model is regarded to be a good approximation to depths of up to 35 km which is within the range of the interpreted depths to the electrical conductor. The assumption that heat is transferred only in the vertical direction, although may not be completely accurate, it is expected to be a good first order approximation within the Central Oaxaca segment. However, it is clear that a more precise time dependent model that includes possible lateral temperature variations is desirable to constrain further the MT model. The construction of a time dependent 2-D thermal model though, requires a large amount of thermal and geological data not readily available in the studied area at this time.

A possible change to a steeper dipping angle of the plate below the Valley of Oaxaca would imply higher temperatures in the base of the continental crust which would create the conditions to trigger a fluid migration-silicate precipitation mechanism to trap fluids above the plate. However, seismicity studies (*e.g.* Lomnitz, 1982; Suarez et al., 1990) indicate that the plate follows a subhorizontal trajectory beyond the Oaxaca Valley, which in turn suggests that the subducting slab is likely to remain relatively cold under a thin continental crust, also explaining the lack of active volcanism parallel to the trench.

There is a lack of thrust-type earthquakes along what we regard as the subducting plate boundary; earthquake activity is generally observed deeper (Fig. 29) and is often associated to the brittle to ductile transition known as the Benioff-Wadati zone. The absence of shallow seismic activity can be explained in terms of 'stable slip' (*i.e.* smooth and continuous motion) along the contact between the continental crust and the downgoing oceanic slab (detachment fault), which may be possible in the presence of a fluid phase on top of the subducting plate. Seismic decoupling has been explained in terms of a basalt to eclogite phase change as subduction progresses (*e.g.* Ruff and Kanamori, 1983, Kanamori, 1986, Kirby and Hacker, 1993), a process which is unlikely to occur at the temperature-pressure conditions prevailing (*e.g.* Wyllie, 1982) on top of the subducted plate under a thin and cold continental crust.

6.2) Relation of MAT to other subduction zones

The Juan de Fuca (JdF) plate at Vancouver Island

The Juan de Fuca subduction zone is probably one of the more studied active margins in the world (e.g. EMSLAB group, 1988). As mentioned earlier, the observed conductive zone under Vancouver Island (Kurtz, 1986, 1990) coincident with a zone of enhanced reflectivity (Green et al., 1987), was originally thought to represent the boundary between the JdF plate and the overriding North American plate (Green et al., 1986). However, based on the analysis of teleseismic shear wave arrivals (Cassidy and Ellis, 1991, 1992) it is now suggested that the top of the subducting oceanic crust is some 10 km deeper. Instead, the conductive/reflective zone is assumed to represent a thermal/metamorphic boundary below which fluids are trapped (Jones, 1987).

Although there are similarities between the JdF and the Cocos plate subductions, such as the obliqueness and age of the convergence, there are differences that can help to explain the different geophysical results. These differences include the rate of convergence, which is about half for JdF than that estimated for the Cocos plate (e.g. Hyndman and Wang, 1993; Cross and Pilger, 1982). A slower convergence rate predicts a steeper subducting angle for the JdF plate (e.g. Cross and Pilger, 1982; Shemenda, 1993) which is in accordance with the observations (about 5° steeper for JdF plate). More important however is the fact that, unlike the subducting plate in the Oaxaca region which appears to become almost subhorizontal, the JdF plate continues to descend, carrying saturated sediments to zones of higher temperatures and pressures favorable for metamorphic reactions. The subduction of the relatively light Tehuantepec Ridge (Cross and Pilger, 1982) with the Cocos plate under the continental margin helps explain the buoyancy of the lithosphere and low subduction angle in this region. This is a major element absent in the JdF subduction zone.

The Nazca plate (Np) at southern Peru

The subduction of the Nazca plate along the Peruvian coast bears some resemblance with that of the Cocos plate, the more notorious of which is the presence of the aseismic Nazca ridge in the convergence zone. Similarly to what occurs in the Oaxacan continental margin, it is likely that this feature also causes the observed sub-horizontal trajectory of the Nazca plate under the South American continent (Suarez et al., 1990) after an original steep descent. However, a fundamental difference is that while the lithospheric thickness of the overriding plate in central Peru is about 90 km, in southern Mexico it is about half of this (*ibid*).

It is expected that subducted fluids within the Nazca plate will reach higher temperatures and pressures at a relatively shorter distance from the trench due to its steeper subducting angle ($\sim 25\text{-}30^\circ$). The steeper subducting angle combined with a fast convergence rate (11 cm/y according to von Huene and Lallemand, 1990) would promote massive dehydration that triggers the generation of magmas which eventually reach the surface (*e.g.* Peacock, 1990a). Under a 'high dipping angle-fast convergence rate' regime, fluids are subducted at mantle depths to produce metamorphic reactions and magma generation before fluids migration-precipitation can occur. Thus, it is expected that in this conditions, the MT responses would resolve deep possibly flat conductors. MT measurements in this region have been completed but date back to a time when electrical distortion was not removed from the data. Therefore, it is expected that these older models are highly dependent on static shift and no reliable comparison can be made with the results obtained over the Cocos plate.

6.3) Future Work

Several questions arise from the previous discussion. Among them is whether or not the alkaline volcanism in San Andrés de Tuxtla located at the edge of the Gulf of Mexico, between 350 to 400 km northeast of the Oaxacan trench zone, could be directly related to the subduction of the Cocos plate at Oaxaca's continental margin. This possibility is suggested by the apparent horizontal trajectory of the slab underplating southern Mexico which is likely to bend downwards and plunge rapidly reaching asthenospheric depths at some point bellow this active volcanic zone (Fig. 35). However, the mainly alkaline nature of the observed volcanism suggests a more complicated tectonic setting under the Gulf of Mexico coast (Stix, 1994); calc-alkaline magmas which are normally associated to subduction are totally absent in the Tuxtlas region. Additional geophysical and geological data are needed to construct a more realistic tectonic model.

This and other related features such as the segmentation of the Cocos plate and the role of the Tehuantepec Ridge during subduction will only be understood when enough geophysical research is completed in the zone. It would be necessary to launch a project that include enough heat flow measurements to construct a 2-D thermal model along a transect from Puerto Escondido, in the Pacific coast, to San Andrés de Tuxtla, in the Gulf of Mexico coast. Coincident MT data is already available from this and the work from a MT German team (Jödicke, 1993) which we expect to combine once their interpretation is concluded. A key question to consider will then be whether it is possible to image the progressively less conductive zone associated with the plate as subduction progresses northeasterly. It would also

be advantageous to expand the teleseismic network to the Isthmus of Tehuantepec region particularly in the surroundings of San Andrés de Tuxtla. Finally, it would be important to have access to PEMEX archives in the search of seismic and other geophysical data of the oil-rich coastal region of the gulf, which combined with the extended MT and thermal studies, would allow us to continue this work and to build a tectonic model with a broader base to explain the events associated to active convergence margins.

REFERENCES

ÁDÁM, Á., 1987, Are there two types of conductivity anomaly (CA) caused by fluids in the lower crust?, *Phys. planet. Inter.*, 45, 209-215

ARZATE J.A., MARESCHAL M., AND URRUTIA-FUCUGAUCHI J., 1993, A preliminary crustal model of the Oaxaca continental margin and subduction zone from magnetotelluric and gravity measurements, *Geof. Int.*, v.32, no.3, pp. 441-452

AUBOUIN J., BOURGOIS J., AND AZEMA J., 1985, Two types of active margins: convergent-compressional margins and convergent-extensional margins, *in* Formation of Active Ocean Margins by Nasu et al. (eds.), pp. 109-129

BAHR, K., 1992 *pers. comm.*

BAHR, K., 1991, Geological noise in magnetotelluric data: a classification of distortion types, *Phys. Earth Planet. Inter.*, 66, 24-38

BAHR, K., 1988, Interpretation of the magnetotelluric impedance tensor: regional induction and telluric distortion, *J. Geophys.*, 62, 119-127

BAHR, K., 1985, Magnetotellurische messung des elektrischen widerstandes der erdkruste und oberen mantels in gabielen mit locaten und regionalen leitfahigkeitsanomalien, Ph.D. Thesis, Gottingen

BALDIS J.M., FOURNIER H.G., GASCO J.C., GHIDELLA M., MAMANI M.J., POMPOSIELLO M.C., AND VACA A., 1985, Structures très diverses de la croûte et du manteau supérieur dans la maitié Nord de l'Argentine, avec découverte d'une zone géothermale, *C.R. Acad. Sc. Paris*, t. 301, Série II, no.17

BANERJEE S.K., 1984, The magnetic layer of the oceanic crust-How thick is it?, *Tectonophysics*, v.105, pp.15-27

BARAZANGI M. and Isacks B.L., 1979, Subduction of the Nazca plate beneath Purú: evidence from spacial distribution of earthquakes, *Geophys. J. R. Astron. Soc.*, v.57, pp. 537-555

BERDICHEVSKY M.N., AND DMITRIEV V.I., 1976, Basic principles of interpretation of magnetotelluric curves, in *Geoelectric and Geothermal Studies* by Adam A. (ed.), Akademini Kiado, 165-221

BÖHNEL H., ALVA-VALDIVIA L., GONZALES-HUESCA J., URRUTIA FUCU-GAUCHI J., MORAN-ZENTENO D.J., AND SCHAAF P., 1989, Paleomagnetic data and the accretion of the Guerrero terrane, southern Mexico continental margin, in *Deep structure and pasy kinematics of accreted terranes* by Hillhouse J.W. (ed.), Am. Geophys. U. Monograph 50, pp. 73-92

BOOKER R.B., 1993, IAGA conference, Buenos Aires, Argentina

BOSTIK F.X., Electromagnetic array profiling (EMAP), 1986, 56th Ann. Mtg. Soc. Expl. Geophys., Expanded Abstracts, pp. 60-61

BURBACH, G.V., FROHLICH, C., PENNINGTON, W.D., AND MATUMOTO, T., 1984, Seismicity and tectonics of the subducted Cocos Plate, J. Geophys. Res., 89, 7719-7735

CALVERT A.J. AND CLOWES R.M., 1990, Dee, high-amplitude reflections from a major shear zone above the subducting Juan de Fuca plate, *Geology*, v.18, pp. 1091-1094

CAMPA, M.F., AND CONEY, P.J., 1983; Tecnostratigraphic terrranes and mineral resource distribution in Mexico, *Can. J. Earth Sci.*, 20, 1040-1051

CARFANTAN, J.C., 1981, Paleogeography and tectonics of the Sierra de Juarez-Isthmus of Tehuantepec area and its relation with other terranes of southern Mexico and Central America, PhD. Thesis

CASSIDY, J.F. AND ELLIS, R.M., 1991, Shear wave constrains on a deep crustal reflective zone beneath Vancouver Island, J. Geophys. Res., 96, pp. 19843-19851

CHAKRIDI R., CHOUTEAU M., AND MARESCHAL M., 1992, A simple technique for analysing and partly removing galvanic distortion from the magnetotelluric impedance tensor: Application to Abitibi and Kapuskasing data (Canada), *Geophys. J. Int.*, 108, pp. 917-929

CHAE E.P. AND STEWART G.S., 1982, Recent large earthquakes along the Middle

American Trench and their implications for the subducting process, *J. Geophys. Res.*, v.87, pp. 329-338

CONEY P.J., 1989, Structural aspects of suspect terranes and accretionary tectonics in western North America, *J. Struct. Geol.*, v.11, no. 1, pp. 107-125

CONEY, P.J., 1989, Structural aspects of suspect terranes and accretionary tectonics in western North America, *J. Struc. Geol.*, 11, 102-125

CONEY P.J., JONES D.L., AND MONGER J.W.H., 1980, Cordilleran suspect terranes, *Nature*, v.88, pp. 229-233

COUCH R.W. AND BURBACH G.V., 1985, Cross section, Southern Mexico, Guatemala, and Costa Rica margin, in Ladd, J.W. and Buffler R.T. (eds.), *Middle America Trench off western Central America*, Atlas 7, Ocean Margin Drilling Program, Regional Atlas Series: Marine Science International, Woods Hole, MA, sheet 13.

COUCH, R.W., AND WOODOCK, S., 1981, Gravity structure of the continental margins of southern Mexico and northwestern Guatemala, *J. Geophys. Res.*, 86, pp. 1829-1840

COX A. AND HART R.B., 1986, *Plate tectonics; How it works*, Blackwell Sci. Pub., Inc., p. 391

CROSS T.A. AND PILGER R.H., 1982, Controls of subduction geometry, location of magma arcs, and tectonics of arc and back-arc regions, *Geol. Soc. Am. Bull.*, v.93, pp. 545-562

DUBA A., HELKAMP S., MEURER W., NOVER G., AND WILL G., 1994, Evidence from borehole samples for the role of accessory minerals in lower-crustal conductivity, *Nature*, v.367

EDWARDS R.N., BAILEY R.C., AND GARLAND G.D., 1981, Conductivity anomalies: lower crust or asthenosphere?, *Phys. Earth Planet. Int.*, v.25, pp. 263-272

EMSLAB GROUP, the, 1988, *The EMSLAB Electromagnetic sounding experiment*, EOS, Trans. Am. Geophys., v.69,no.7,p.89

ENGEBRETSON D.C., COX A., AND GORDON R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin, *Geol. Soc. Am. Spec.*

Paper 206

FIGUEROA J., 1970, Catálogo de sismos ocurridos en la República Mexicana, Report no. 272, Instituto de Ingeniería, U.N.A.M., México

FISHER G., SZARKA L., ADAM A., AND WEAVER J.T., 1992, The magnetotelluric phase over 2-D structures, *Geophys. J. Int.*, v.108, pp 778-786

FISHER G., 1985, Some remarks on the behavior of the magnetotelluric phase, *Geophys. Prosp.*, v.33, pp. 716-722

GAMBLE T.D., GOUBAU W.N., AND CLARKE J., 1979, Magnetotellurics with a remote magnetic reference, *Geophysics*, v.44, pp.53-68

GEBRANDE H., 1976, A seismic ray tracing method for two-dimensional inhomogeneous media, in *Explosion seismology in central Europe: data and results*, Springer, Berlin

GREEN A.G., MILKEREIT B., MAYRAND L., SPENCER C., KURTZ R.D., AND CLOWES R.M., 1987, LITHOPROBE seismic reflection profiling across Vancouver Island, *Geophys. J. R. Astron. Soc.*, v.89, pp. 85-90

GREEN A.G., CLOWES R.M., YORATH C.J., SPENCER C., KANASEWICH E.R., BRANDON M.T., AND SHUTERLAND BROWN, A., 1986, Seismic reflection imaging of the subducting Juan de Fuca plate, *Nature*, v.319, pp. 210-213

GROOM R.W. AND BAILEY R.C., 1991, Analytical investigations of the effects of near-surface three-dimensional galvanic scatterers on MT tensor decompositions, *Geophysics*, v.56, no.4, pp. 496-518

GROOM, R.W. AND BAILEY, R.C., 1989, Decomposition of magnetotelluric impedance tensor in the presence of local three-dimensional galvanic distortion, *J. Geophys. Res.*, 94, 1913-1925

GROW J. A. AND BOWIN C.O., 1975, Evidence for high density crust and mantle beneath the Chile Trench due to descending lithosphere, *J. Geophys. Res.*, v.80, pp. 1449-1458

GUTENBERG B. AND RICHTER C.F., 1954, *Seismicity of the Earth*, Princeton Univ. Press, 2nd ed., pp. 310

HAACK, V. AND HUTTON, V.R.S., 1986, Electrical resistivity in continental lower crust, in *The Nature of the Lower Continental Crust*, Dawson, J.B., Cowell, D.A., Hall, J., and Wedepohl, K.H., (eds.), Geol. Soc. Spec. Pub., 24, 35-49

HALES A.L., HELSLEY C.E., AND NATION J.B., 1970, *P* travel time for an oceanic path, J. Geophys. Res., v.75, pp. 7362-7381

HILDE T.W.C., 1983, Sediment subduction versus accretion around the Pacific, Tectonophysics, v.99, pp. 381-397

HYNDMAN, R.D., 1988, Dipping seismic reflectors, electrically conductive zones and trapped water in the crust over a subducting plate, J. Geophys. Res., 93, pp. 13391-13405

HYNDMAN R.D. AND WANG K., 1993, Thermal constraints on the zone of major thrust earthquake failure: The Cascadian subduction zone, J. Geophys. Res., v.98, pp. 2039-2060

HYNDMAN R.D., YORATH C.J., CLOWES R.M., AND DAVIS E.E., 1990, The northern Cascadian subduction zone at Vancouver Island: seismic structure and tectonic history, Can. J. Earth Sci., v.27, pp. 313-329

HYNDMAN, R.D. AND KLEMPER, S.L., 1989, Lower crustal porosity from electrical measurements and inferences about composition from seismic velocities, Geophys. Res. Lett., 16, pp. 225-258

HYNDMAN, R.D. AND SHEARER, P.M., 1989, Water in lower continental crust: modelling magnetotelluric and seismic reflection results, Geophys. J. Int., 98, pp. 343-365

ILKISIK O.M. AND JONES A.G., 1984, Statistical evaluation of MT and AMT methods applied to a basalt-covered area in southeastern Anatolia, Turkey; Geophys. Prosp., v.32, pp. 706-724

JACKSON D.D., 1972, Interpretation of inaccurate, insufficient and inconsistent data, Geophys. J. R. Astron. Soc., v.28, pp. 97-107

JÖDICKE H., 1993, *pers. comm.*

JONES, A., 1992, Electrical conductivity of the continental lower crust, *in* Continental lower crust by Fountain et al. (eds.), Chap.3, pp.81-143

JONES, A., 1992, Electromagnetic images of modern and ancient subduction zones, *Tectonophysics*, accepted

JONES A., 1987, MT and reflection: an essential combination, *Geophys. J. R. astr. Soc.*, 87, pp. 7-18

JONES A., 1986, Parkinsons' pointers' potential perfidy!, *Geophys. J. R. Astron. Soc.*, v.87, pp. 1215-1224 Kanamori, 1986

KELLEHER J. AND MCCANN W., 1977, Bathimetric highs and the development of convergent plate boundaries, *in* Island arcs, deep sea trenches and back-arc basins, Talwani M. and Pitman W.C. (eds.), *Am. Geophys. Union*, v.1, pp. 115-122

KENT D.V. and Van der Voo R., 1990, Paleozoic paleogeography from paleomagnetism of the Atlantic-bordering continents, *in* Paleozoic biogeography and paleogeography, by McKerrow W. and Scotese C.R. (eds.), *Geol. Soc. (london)*, memoir 12, pp. 49-56

KEYS, R.G., 1986, An application of Marquardt's procedure to the seismic inversion problem, *Proc. IEEE*, 74, 476-478

KIRBY S. AND HACKER B., 1993, Sismicidad en las raices de los arcos volcánicos, *GEOS, Bol. Unión Geofis. Mex.*, v.13, no.2, pp.25-26

KURTZ, R.D., DELAURIER, J.M., AND GUPTA, J.C., 1990, The electrical conductivity distribution beneath Vancouver Island: A region of active plate subduction, *J. Geophys. Res.*, 95, 10929-10946

KURTZ R.D., DELAURIE J.M., AND GUPTA J.C., 1986A, A Magnetotelluric sounding across Vancouver Island sees the Subducting Juan de Fuca Plate, *Nature*, 312, p.596-599

LARSEN J.C., 1977, Removal of local surface conductivity effects from low frequency mantle response curves, *Acta Geodaet., Geophys. Montanist. Acad. Sci. Hung.*, v.12, pp.183-186

LAW L.K. AND RIDDIHOUGH R.P., 1971, A geographical relation between geomagnetic variation anomalies and tectonics, *Can J. Earth Sci.*, v.8, pp. 1094-1106

LOMNITZ C., 1982, Direct evidence of a subducted plate under southern Mexico, *Nature*, v.296, pp. 235-238

MARESCHAL J.C., 1993, *pers. comm.*

MARESCHAL M. AND CATELAND C., 1989, A linear inversion scheme applied to magnetotelluric observations from Charlevoix Crater, Quebec, *J. Geomag. Geoelectr.*, v.41, pp. 627-641

MARQUARDT, D.W., 1963, An algorithm for least-square estimation of non-linear parameters, *J. Soc. Indust. Appl. Math.*, v.11, pp. 431-441

MCNALLY K.C., 1981, Plate subduction and the prediction of earthquakes along the Middle America trench, *Earthquake Prediction*, *Am. Geophys. Union*, v.4, pp. 63-72

MCNALLY K.C. AND MINSTER J.B., 1981, Nonuniform seismic slip rates along the Middle America Trench, *J. Geophys. Res.*, v.86, pp. 4949-4959

MEISSNER R., 1986, The continental crust; A geophysical approach, *International Geophysics Series*, v.34, Academic Press, Inc.

MOLNAR, P. AND SYKES, L.R., 1969; Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity, *Geol. Soc. Am. Bull.*, 80, pp. 1639-1684

MOORE J.C. AND VROLIJK P., 1992, Fluids in accretionary prisms, *Rev. Geophys.*, v.30, pp. 113-135

MÜHRS, J. 1994, Ph.D. project, Institut für Geophysik, Münster, Germany

NAVA F., NUÑEZ-CORNÚ F., CÓRDOBA, MENA M., ANSORGE J., GONZÁLEZ J., RODRIGUEZ M., BANDA E., MUELLER S., UDIAS A., GARCIA-GARCIA M. AND CALDERÓN G. (Reporters), 1988, Structure of the Middle America trench in Oaxaca, Mexico, *Tectonophysics*, v.154, pp. 241-251

NAVA F., TOLEDO V., AND LOMNITZ C., 1985, Plate waves and the 1980 Huajuapán de León, Mexico, earthquake; *Tectonophysics*, v.112, pp. 463-492

NISHENKO S.P. AND SINGH S.K., 1987, Conditional probabilities for the recurrence of large and great interplate earthquakes along the Mexican subduction zone, *Bull. Seism. Soc. Am.*, v.77, no.6, pp. 2095-2114

NIXON, G.T., 1982, The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted ocean lithosphere, *Geol. Soc. Am. Bull.*, 93, pp. 514-523

NUR A. AND BEN-AVRAHAM Z., 1983, Volcanic gaps due to oblique consumption of aseismic ridges, *Tectonophysics*, v.99, pp. 355-362

OMDP, 1985, Cross section, Southern Mexico, Guatemala, and Costa Rica margin, in Ladd, J.W. and Buffler R.T. (eds.), *Middle America Trench off western Central America, Atlas 7, Ocean Margin Drilling Program, Regional Atlas Series: Marine Science International, Woods Hole, MA, sheet 13.*

ORTEGA-GUTIERREZ F., 1981, La evolución tectónica premisisipica del sur de México, *Revista del Inst. de Geol., U.N.A.M., México*

PEACOCK S.M., 1990a, Fluid processes in subduction zones, *Science*, v.248, pp. 329-337

PINDELL J.L., CANDE S.C., PITMAN W.C., BROWLEY D.B., DEWEY J.F., LABRECQUE J., AND HAXBY W., 1988, A plate-kinematic framework for models of Caribbean evolution, *Tectonophysics*, v.155, pp. 121-138

PRESS W.H., FLANNERY B.P., TEUKOLSKY S.A., AND VETTERLING W.T., 1988, *Numerical recipes; the art of scientific computing*, Cambridge Univ. Press

PROL-LEDEZMA, R.M., 1991, Terrestrial heat flow in Mexico, in Cermák, V., and Rybach, L. (eds.), *Exploration of the deep continental crust*, Springer-Verlag, Berlin, pp. 475-485

RATCHBACHER, L., RILLER, U., MESCHEDE, M., HERRMANN, U. AND FRISCH, W., 1991, Second look at suspect terranes in southern Mexico, *Geology*, 19, pp. 1233-1236

ROY R.F., BLACKWELL D.D., AND BIRCH F., 1968, Heat generation of plutonic rocks and continental heat provinces, *Earth Planet. Sci., Lett.*, v.5 pp. 1-12

RUFF L. AND KANAMORI H., 1983, Seismic coupling and uncoupling at subduction zones, *Tectonophysics*, v.99, pp. 99-117

RUIZ, J., PATCHETT, P.J. AND ORTEGA-GUTIERREZ, F., 1988, Proterozoic and Phanerozoic basement terranes of Mexico from *Nd* isotopic studies, *Geol. Soc. Am. Bull.*, 100, pp. 274-281

SASS J.H., LECHENBRUCH A.H., AND MUNROE R.J., 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat flow determination, *J. Geophys. Res.*, v.76, pp. 3391-3401

SCHMUCKER, U., 1970, Anomalies of Geomagnetic variation in the South-Western Uninated States, *Bull. Scripps Init. Ocean., Univ. of Calif., San Diego*, 13.

SCHMUCKER U., HARTMANN O., GIESECKE A.A., CASAVERDE M., AND FORBUSH S.E., 1964, Electrical conductivity anomaly in the Earth's crust in Perú, *Carn. Inst. Washington Yearbook*, v.63, pp. 354-362

SCHWARZ G., 1988, Electrical conductivity of the Earth's crust and upper mantle, Review paper given at IX Workshop on Electromagnetic Induction in the Earth and Moon, IAGA, Sochi, USSR

SCHWARZ G., HAAK V., MARTINEZ E., AND BANNISTER J., 1984, The electrical conductivity of the Andean crust in northern Chile and southern Bolivia as inferred from magnetotelluric measurements, *J. Geophys.*, v.55, pp. 169-178

SHEMENDA A.I., 1993, Subduction of the lithosphere and back arc dynamics: insights from physical modeling, *J. Geophys. Res.*, v.98, pp. 16167-16185

SHEPARD L.E. AND BRYANT W.R., 1983, Geotechnical properties of lower trench inner-slope sediments, *Tectonophysics*, v.99, pp. 279-312

SHIPLEY T.H. AND MOORE G.F., 1985, Sediment accretion and subduction in the Middle America Trench, *in* Formation of Active Ocean Margins, by Nasu et al. (eds.), pp. 179-191, Tokio

SINGH, S.K. AND MORTERA, F., 1991, Source time functions of large Mexican subduction earthquakes, morphology of the Benioff Zone, age of the plate, and their tectonic implication, *J. Geophys. Res.*, 96, pp. 21487-21502

SINGH S.K., RODRIGUEZ M., AND ESPINDOLA J.M., 1984, A catalog of shallow earthquakes of Mexico from 1900 to 1981, *Bull. Seism. Soc. Am.*, v.74, pp.267-279

SINGH S.K., ASTIZ L., AND HAVSKOV J., 1981, Seismic gaps and recurrence periods of large earthquakes along the Mexican subduction zone: a reexamination, *Bull. Seis. Soc. Am.*, v.71, no.3, pp. 827-843

SMITH, J.T. AND BOOKER, R.B., 1991, Rapid inversion of two- and three-dimensional magnetotelluric data, *J. Geophys. Res.*, 96, pp. 3905-3922

STERNBERG B.K., BULLER P.L., KISABETH J.L. AND MEHRETEAB E., 1982, Electrical methods for hydrocarbon exploration: II, Magnetotelluric (MT) method, *Proc. Southern Methodist Univ. Sympos.*

STERNBERG B. K., WASHBURNE J.C. AND PELLERIN L., 1988, Correction for the static shift in magnetotellurics using transient electromagnetic soundings, *Geophysics*, v.53, no.11, pp. 1459-1468

STEINHART J.S. AND MEYER R.P., 1961, Explosion studies of continental structure, Publication 622, Carnegie Inst. of Washington, p. 409

STIX J., 1994, *pers. comm.*

SUAREZ G., LIGORRIA J.P., AND PONCE L., 1992, Preliminar crustal structure of the coast of Guerrero, Mexico, using the minimum apparent velocity of refracted waves, *Geof. Internacional*, v.31, no.3, pp. 247-252

SUAREZ, G., MONFRET, T., WITTLINGER, G., AND DAVID, C., 1990, Geometry of subduction and depth of the seismogenic zone in the Guerrero gap, Mexico, *Nature*, 345, pp. 336-338

SWIFT, C.M., Jr., 1967, A Magnetotelluric investigation of an electrical conductivity anomaly in the Southwestern United States, Ph.D. thesis, Mass. Inst. of Technol., Cambridge.

TIJAMA F., 1984, Study of the source processes of the 1965, 1968, and 1978 Oaxaca earthquakes using short-period records, *J. Geophys. Res.*, v.89, pp. 1867-1873

TORRES-VERDIN C., 1985, Implications of the Born approximation for the MT problem in three-dimensional environments, M.Sc. thesis, Univ. of Texas, Austin

TURCOTTE D.L. AND SCHUBERT G., 1982, Geodynamics: Applications of continuum physics to geological problems, John Wiley & Sons, p. 450

URRUTIA-FUCUGAUCHI J., 1992, *pers. comm.*

URRUTIA-FUCUGAUCHI J., 1991, *unpublished thermal data*

UYEDA S., 1982, Subduction zones: an introduction to comparative subductology, Tectonophysics, v.81, pp. 133-159

VALDÉS C.M., MOONEY W.D., SINGH S.K., MEYER R.P., LOMNITZ, J.H., LUETGERT C.E., HELSLEY C.E., LEWIS B.T.R., AND MENA M., 1986, Crustal structure of Oaxaca, Mexico, from seismic refraction measurements, Bull. Seis. Soc. Am., v.76, no.2, pp. 547-563

VALDÉS C., MEYER R.P., ZUÑIGA R., HAVSON J. AND SINGH S.K., 1982, Analysis of the Petatlán aftershocks: numbers, energy release, and asperities, J. Geophys. Res., v.87, pp. 8519-8527

VON HUENE R., 1985, Some implications regarding tectonic mechanisms from the structural diversity along several modern convergent margins, in Formation of Active Ocean Margins, by Nasu et al. (eds.), pp. 179-191, Tokio

VON HUENE R. AND SCHOLL D.W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust; Rev. Geophys., v.29, pp. 279-316

VON HUENE R. AND LALLEMAND S., 1990, Tectonic erosion of convergent margins, Geol. Soc. Am. Bull., v.102, pp. 704-720

VOZOFF K., 1989, The magnetotelluric method, in Electromagnetic methods in applied geophysics, by Nabighian M.N. (ed.), Soc. Expl. Geophys.

WAFF H.S., RYGH J.T., LIVELYBROOKS D.W., AND CLINGMAN W.W., 1988, Results of a magnetotelluric traverse across western Oregon: crustal resistivity structure and the subduction of the Juan de Fuca plate, Earth Plan. Sci. Lett., v.87, pp. 313-324

WANNAMAKER P.E., HOHMANN G.W., AND SANFILIPO W.A., 1984a, Electromagnetic modeling of three-dimensional bodies in layered earths using integral

equations, *Geophysics*, v.49, pp. 60-74

WANNAMAKER P.E., HOHMANN G.W. AND WARD S.H., 1984b, Magnetotelluric response of three-dimensional bodies in layered earths, *Geophysics*, 49, pp. 1517-1533.

WANNAMAKER P.E., BOOKER J.R., JONES A.G., CHAVE A.D., FILLOUX J.H., WAFF H.S., AND LAW L.K., 1989, Resistivity cross section through the Juan de Fuca subduction system and its tectonic implications, *J. Geophys. Res.*, v.94, pp. 14127-14144

WANNAMAKER ET AL., 1989, Resistivity cross section through the Juan de Fuca subduction system and its tectonic implications, *J. Geophys. Res.*, 94, p. 14127-44

WANNAMAKER P.E., STODT J.A., AND RIJO L., 1986, Two-dimensional topographic responses in magnetotellurics modeled using finite elements, *Geophysics*, v.51, pp. 2131-2144

WARD S.H. AND HOHMANN G.W., 1987, Electromagnetic theory for geophysical applications, in *Electromagnetic methods in applied geophysics-theory*, Nabighian M.N. (ed.), v.1, S.E.G., pp. 131-311

WARNER B.N., BLOOMQUIS M.G., AND GRIFFITH P.B., 1983, Magnetotelluric interpretations based upon new processing and display techniques, 53rd Ann. Mtg. Soc. Expl. Geophys., Expanded Abstracts, pp. 151-154

WHITMAN J.M., HARRISON C.G.A., AND BRASS G.W., 1983, Tectonic evolution of the Pacific Ocean since 74 Ma, *Tectonophysics*, v.99, pp. 241-249

WIGGINS R.A., 1972, The general linear inverse problem: implication of surface waves and free oscillations for Earth structure, *Rev. Geophys. Space Phys.*, v.10, pp. 251-285

WYLLIE P.J., 1982, Subduction products according to experimental prediction, *Geol. Soc. Am. Bull.*, v.93, pp. 468-476

YAÑEZ, P., RUIZ, J., PATCHETT, J., ORTEGA-GUTIERREZ, F., AND GEHRELS G.E., 1991, Isotopic studies of the Acatlan complex, southern Mexico: Implication for Paleozoic North America tectonics, *Geol. Soc. Am. Bull.*, 103, pp. 817-828

ZHANG P., ROBERTS, R.G. AND PEDERSEN L.B., 1987, Magnetotelluric strike rules, *Geophysics*, 52, 267-278.

ZHANG P., PEDERSEN, L.B., MARESCHAL, M., AND CHOUTEAU, M., 1992, Channelling contribution to tipper vectors: a magnetic equivalent to electrical distortion, submitted

ZIAGOS J.P., BLACKWELL D.D., AND MOSSER F., 1985, *J. Geophys. Res.*, v.90, pp. 5410-5420

ZUÑIGA F. AND VALDEZ C., 1980, Analisis de las replicas del temblor de Petatlán del 14 de marzo de 1979, Tesis Profesional, Fac. Ing., U.N.A.M., México

APPENDIX A

TIPPER SEPARATION PARAMETERS AND 'C' FUNCTIONS

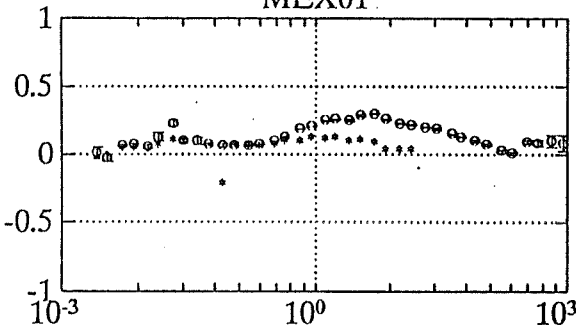
The following set of 14 figures show the measured (circles) and local or galvanic tipper elements (asterisks) for each one of the soundings used in this thesis. Each figure is composed of four plots each one of which represent the real (the two plots to the left) and imaginary (two plots to the right) parts of the measured and local tipper or (A, B) and (A_l, B_l) respectively. On top of the upper left plot it is indicated the sounding number. The parametrization of the tipper components defined by Eq. (14) was applied to obtain these figures that can be used to distinguish qualitatively the period band for which the local tipper is due predominantly to current channelling versus multidimensional induction.

The following 7 figures show the induction depth or Schmucker "C" function given by

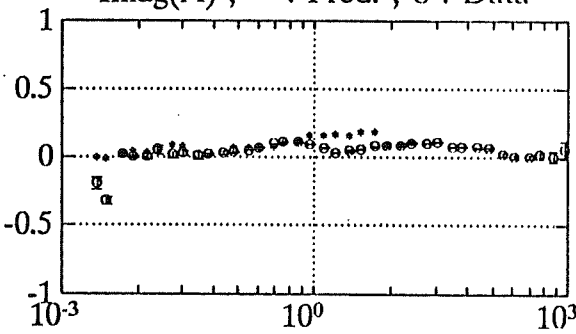
$$C = \frac{Z}{i\omega\mu}$$

It is calculated assuming a two layered earth, the bottom layer being less conductive than the top one. Also, it is assumed that there is no attenuation of the signal for the frequency range considered and that the depth of penetration in the lower layer is small compared with its wave length. Thus, the depths computed in this form can be used as an upper limit of the actual exploration depths.

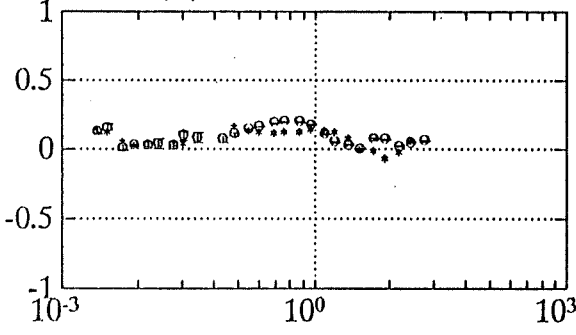
MEX01



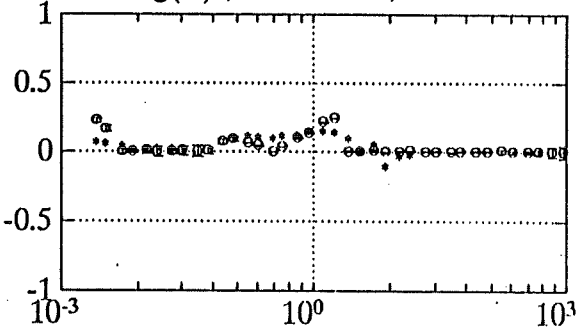
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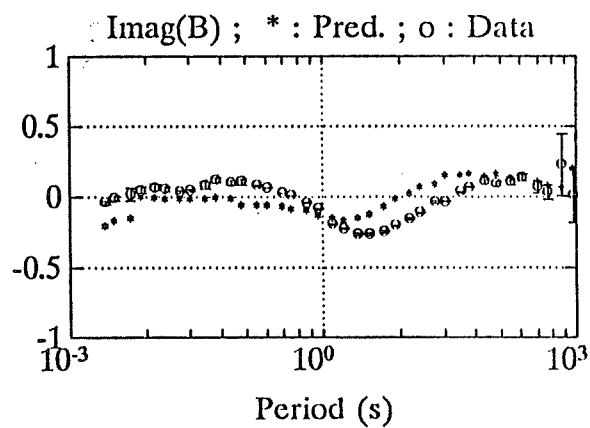
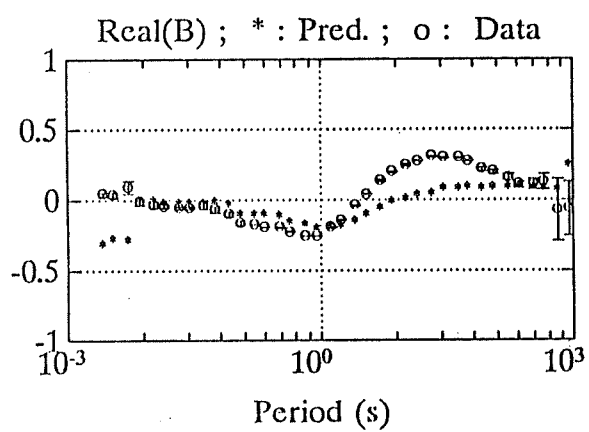
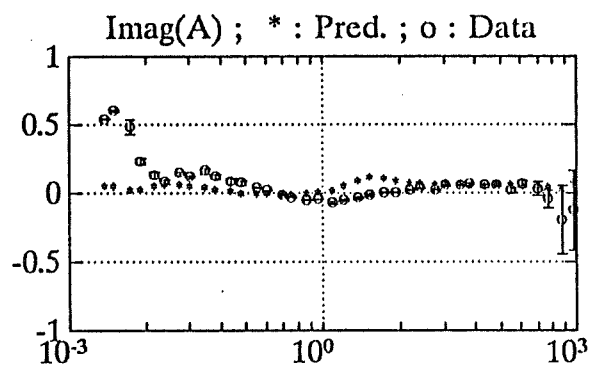
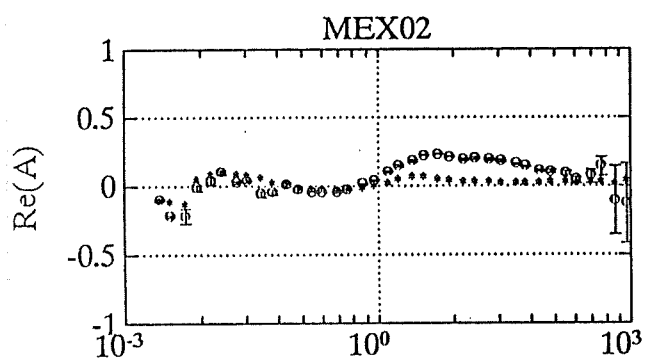


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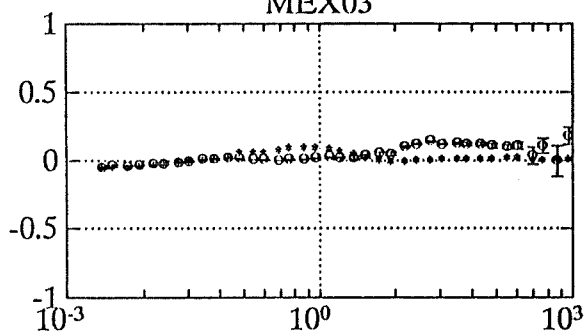


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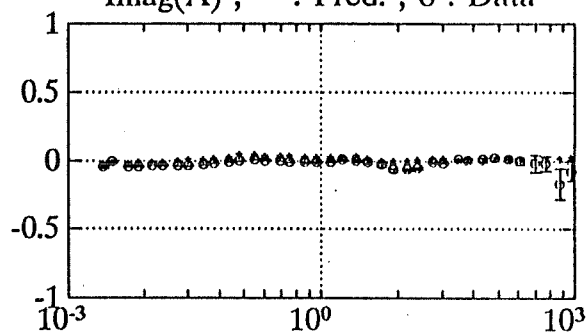
Period (s)



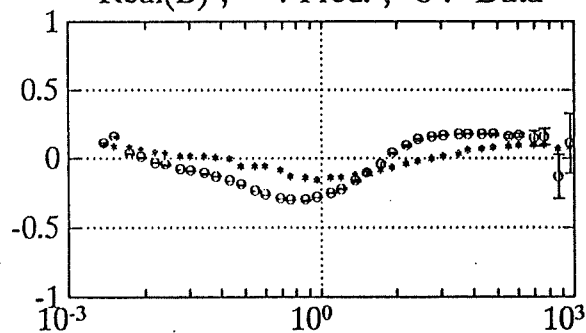
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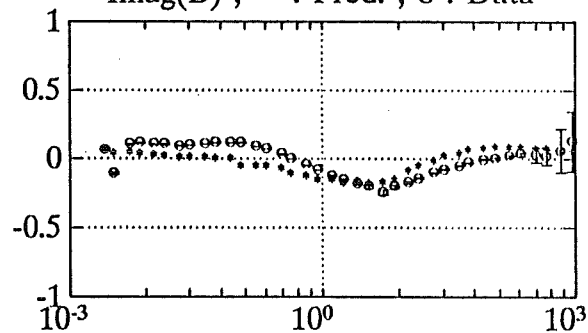


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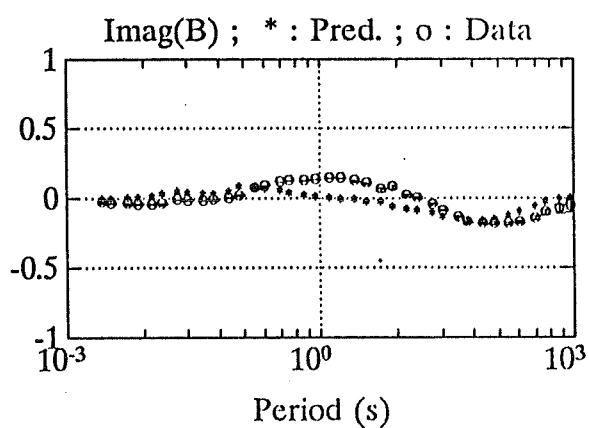
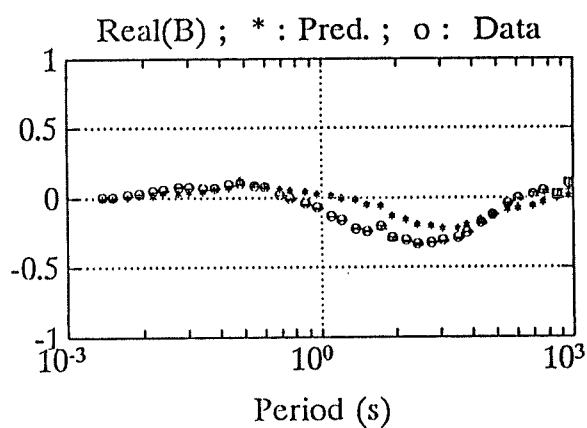
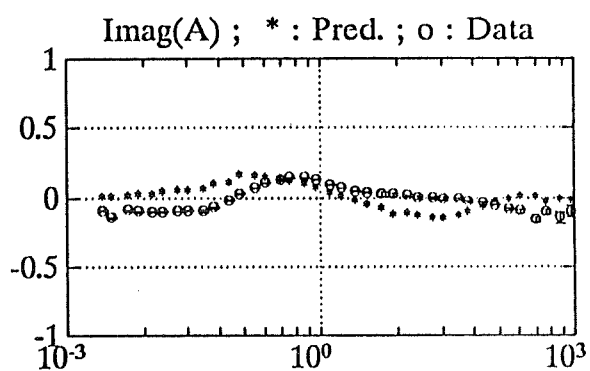
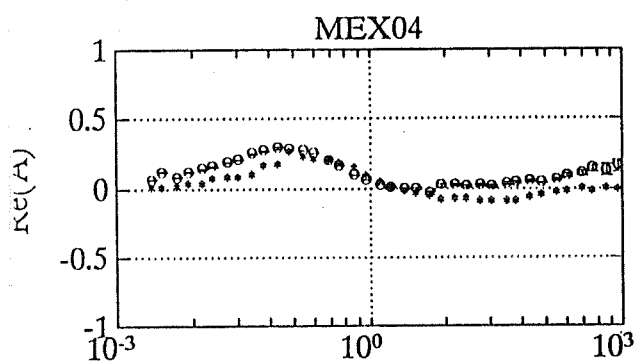


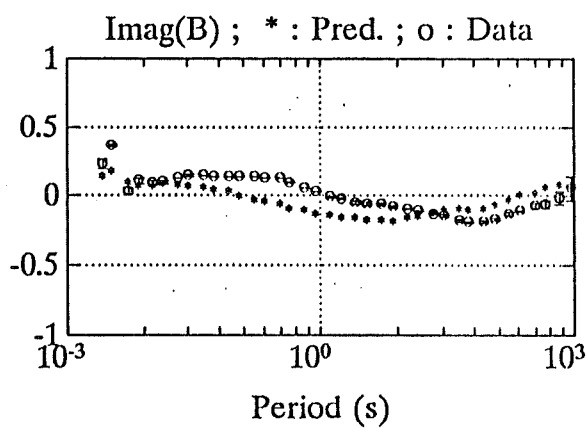
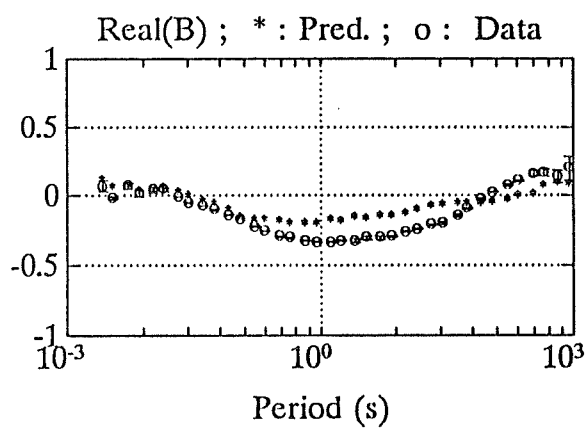
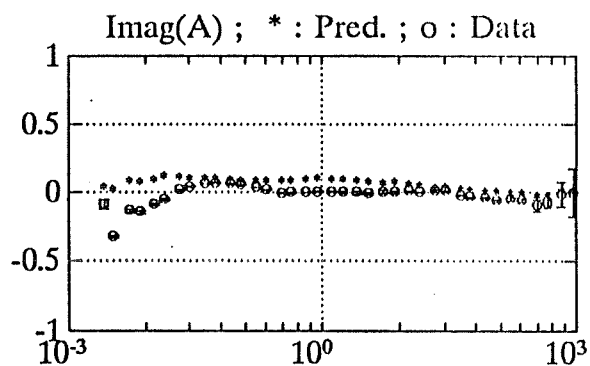
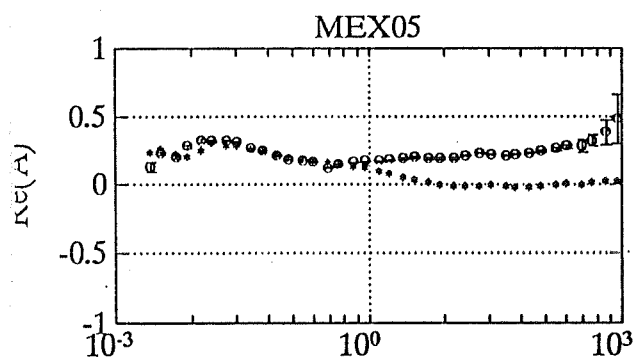
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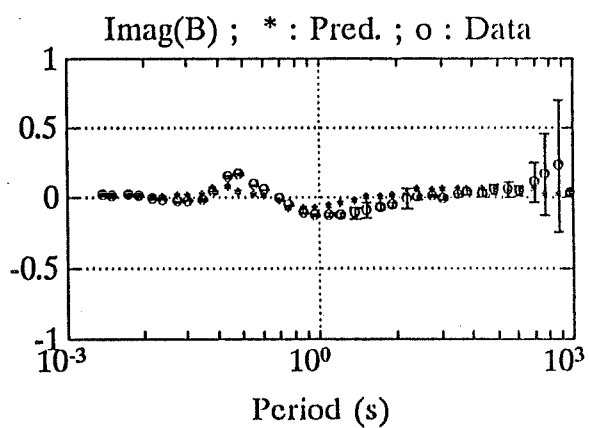
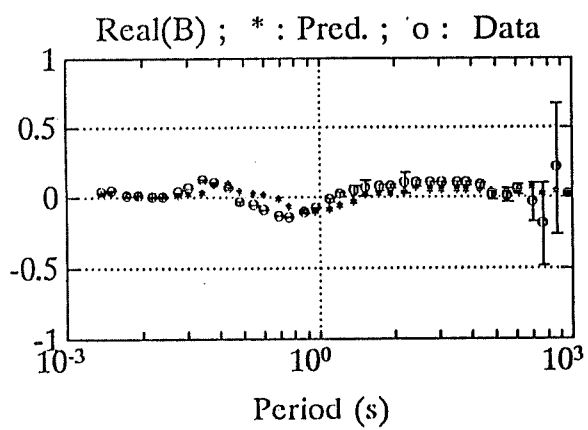
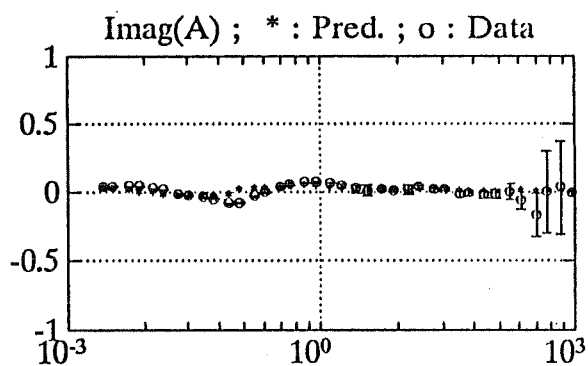
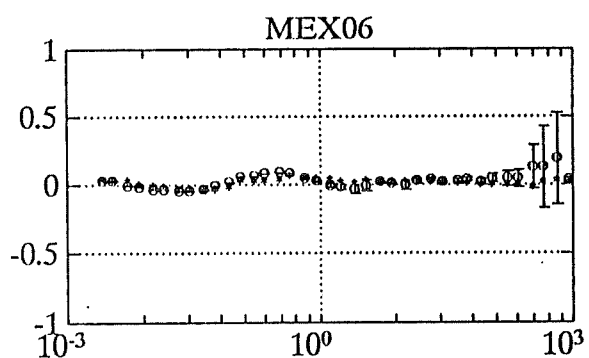
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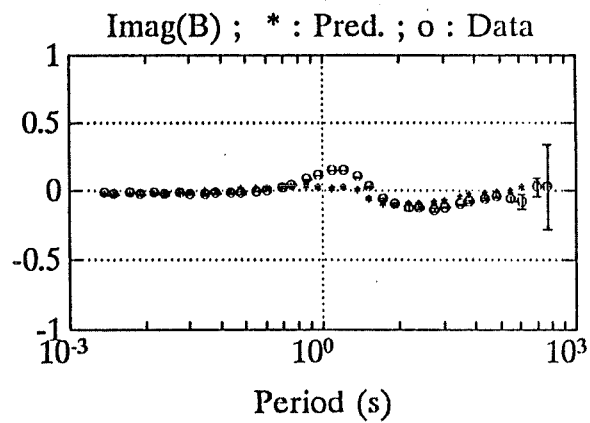
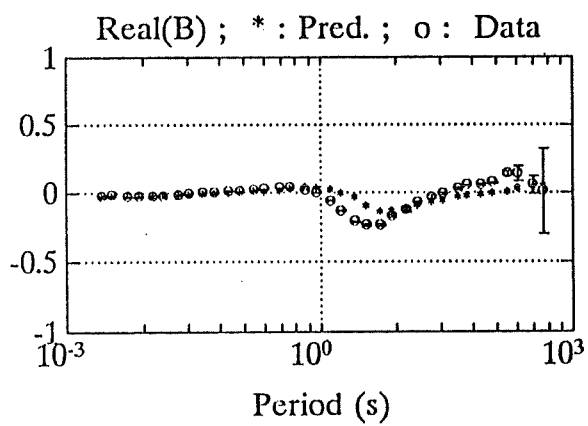
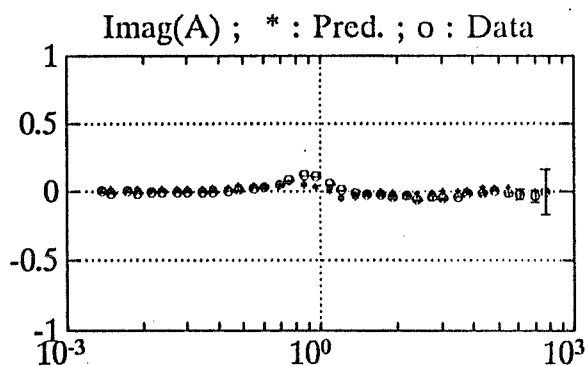
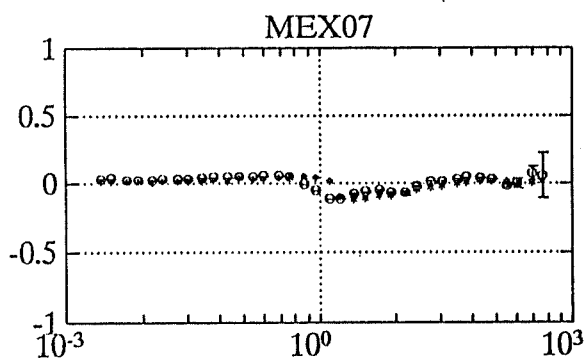


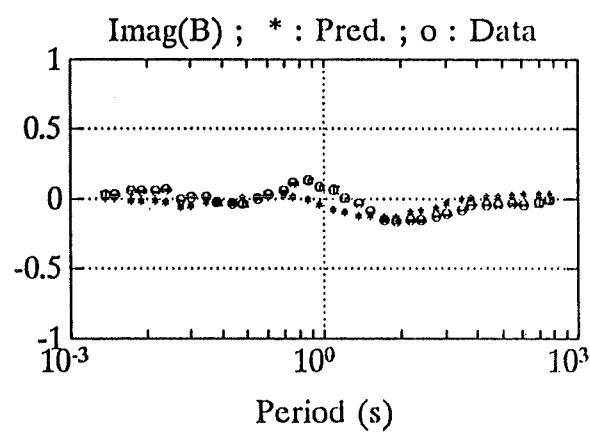
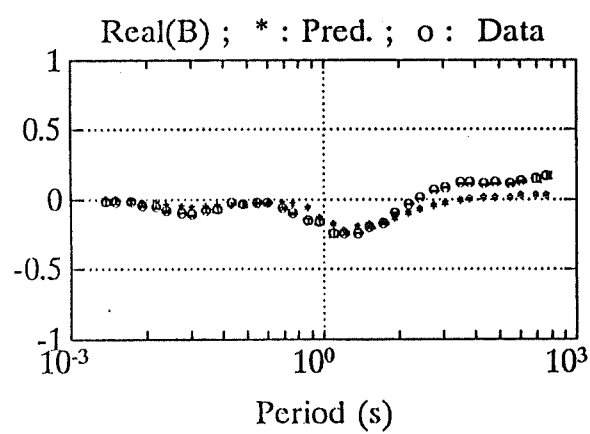
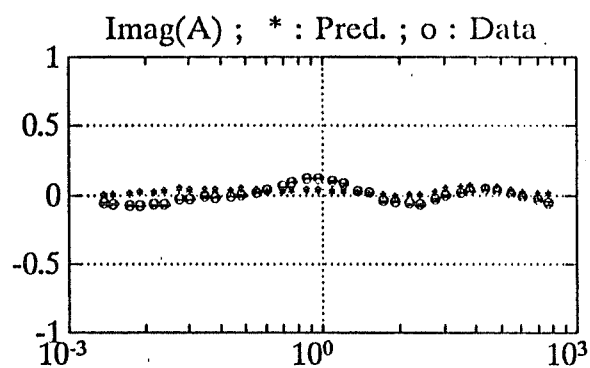
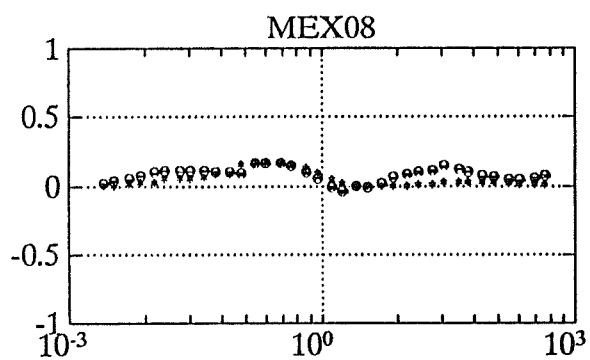
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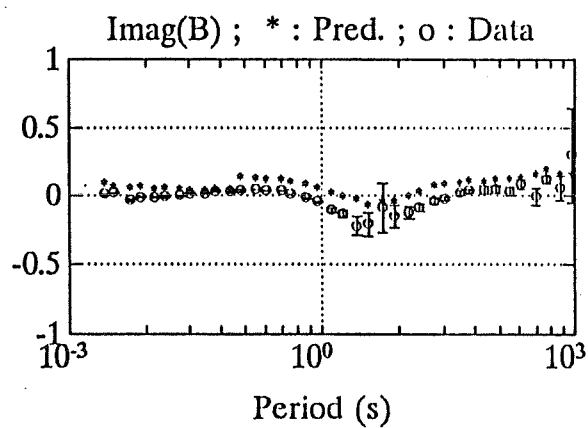
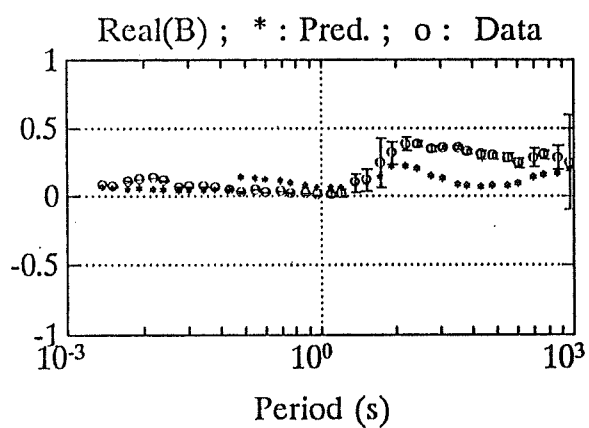
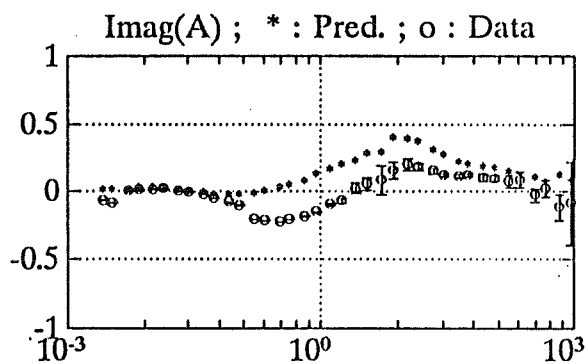
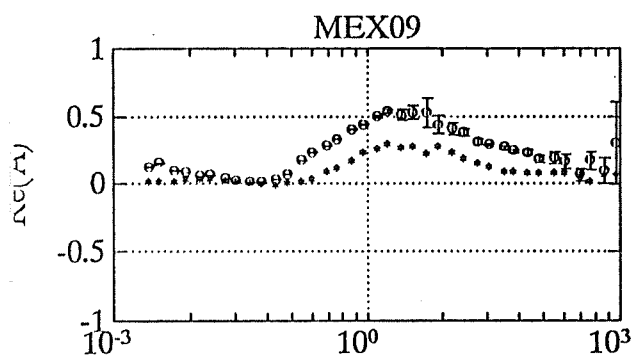


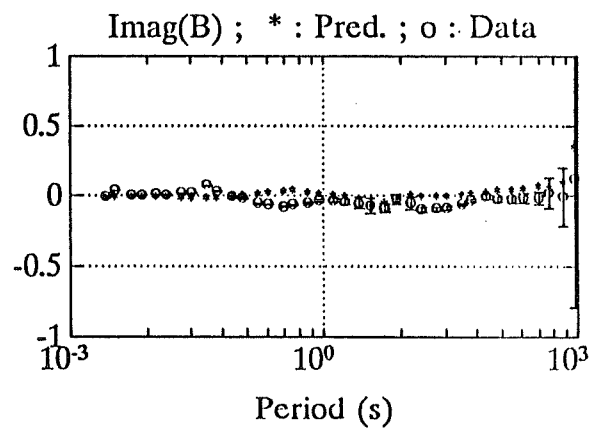
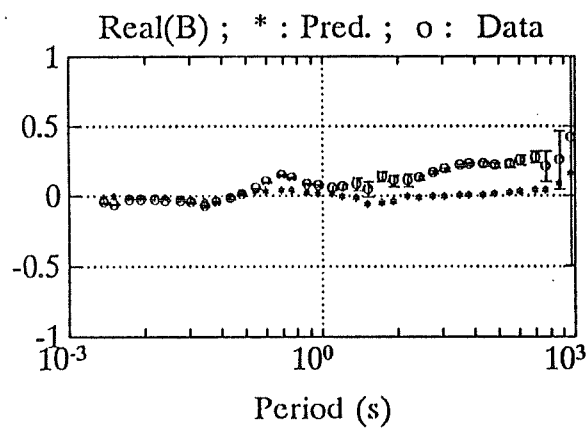
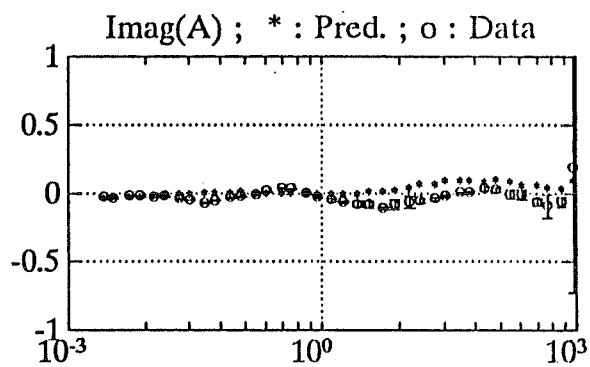
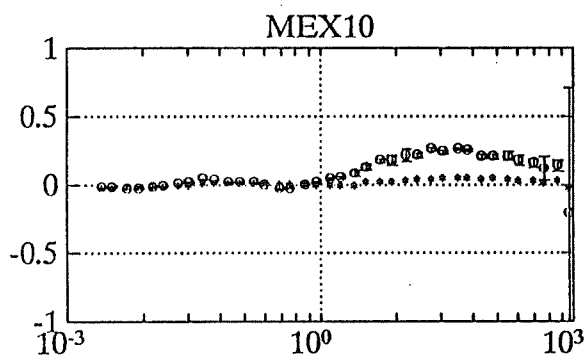




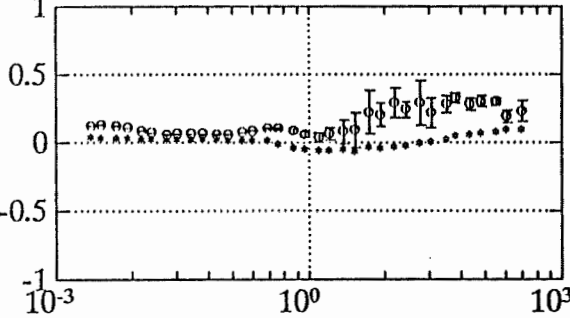




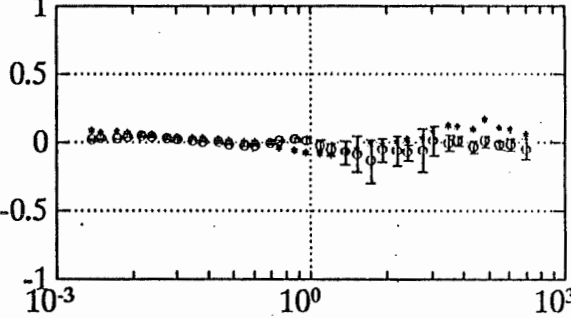




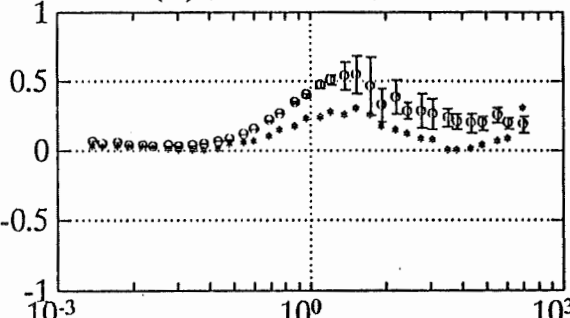
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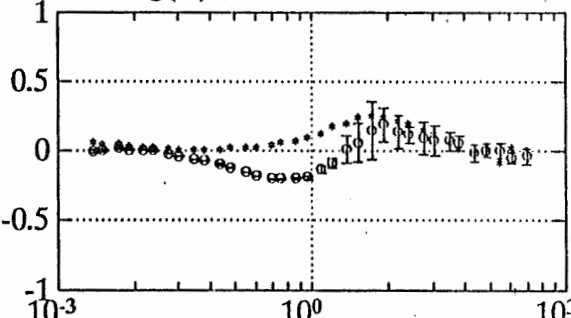
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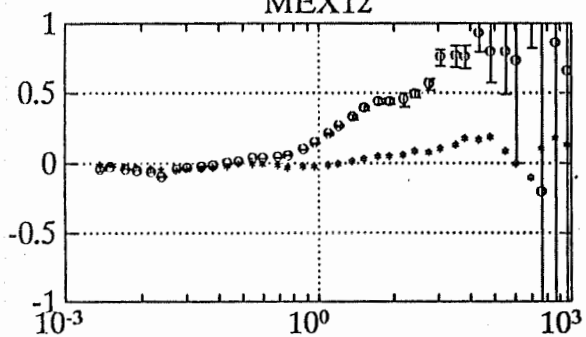
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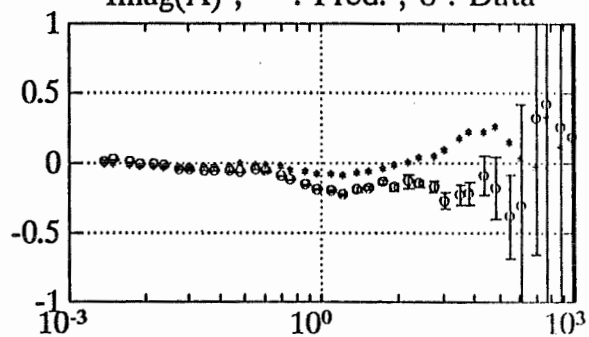
Period (s)

Period (s)

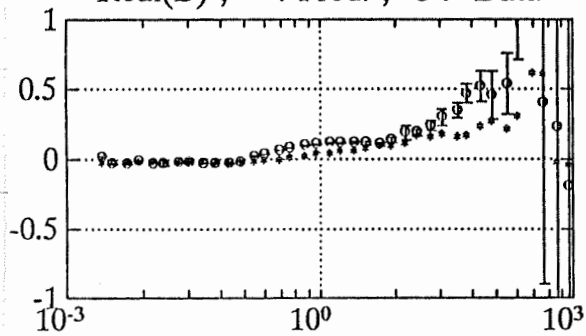
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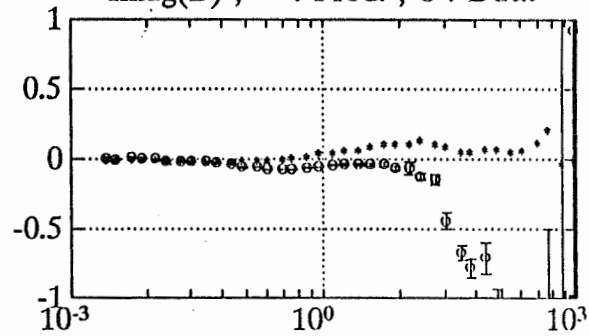


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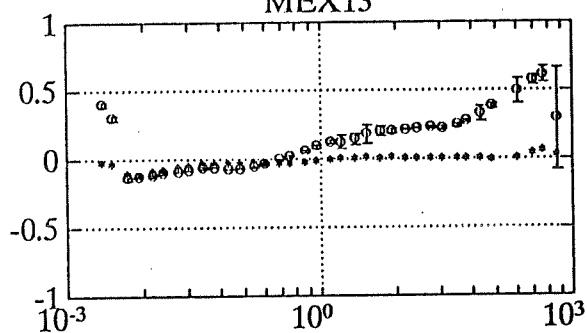
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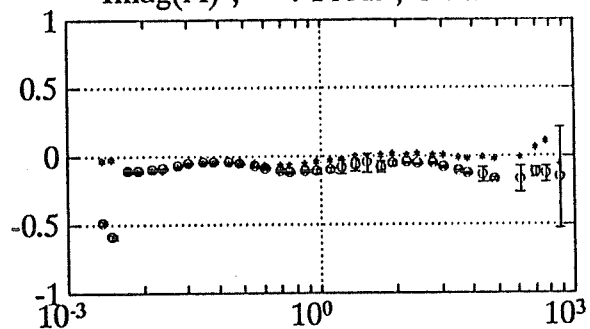


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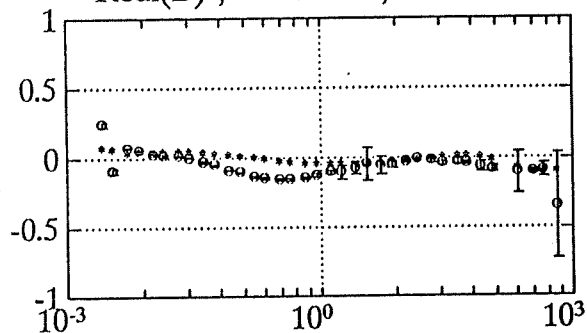
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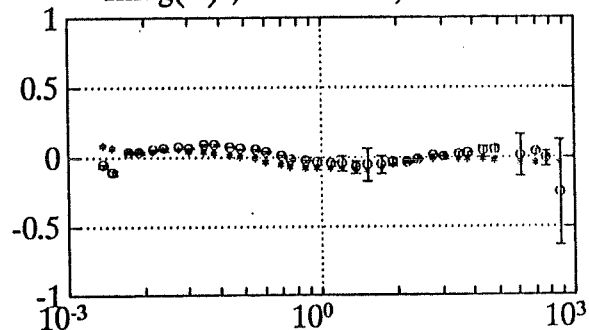


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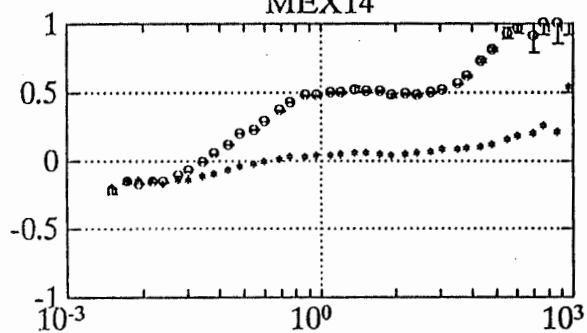
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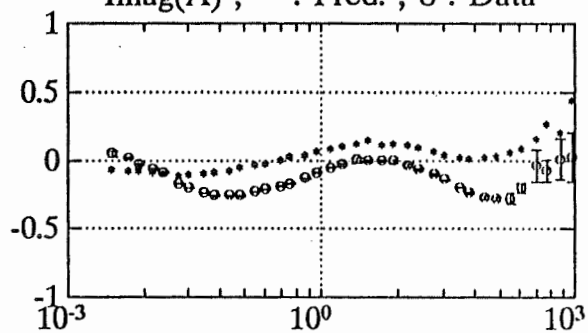


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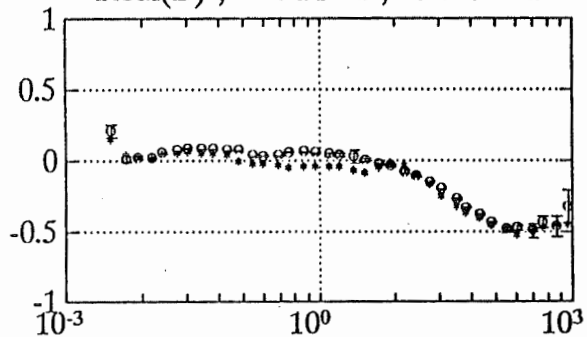
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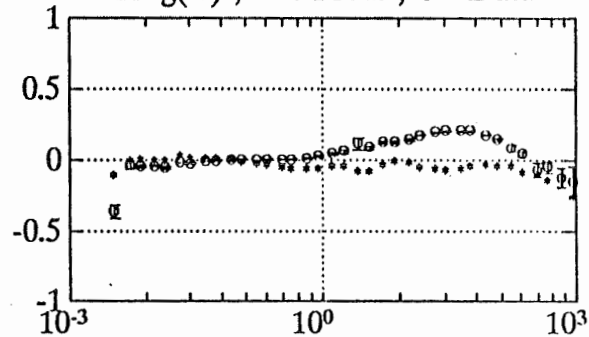


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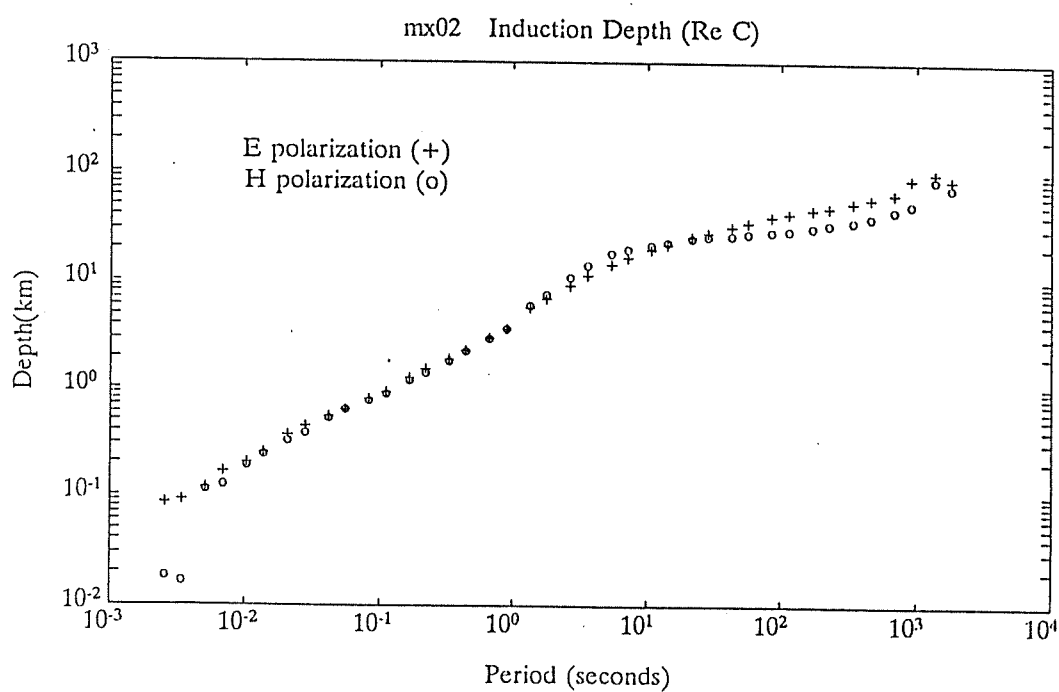
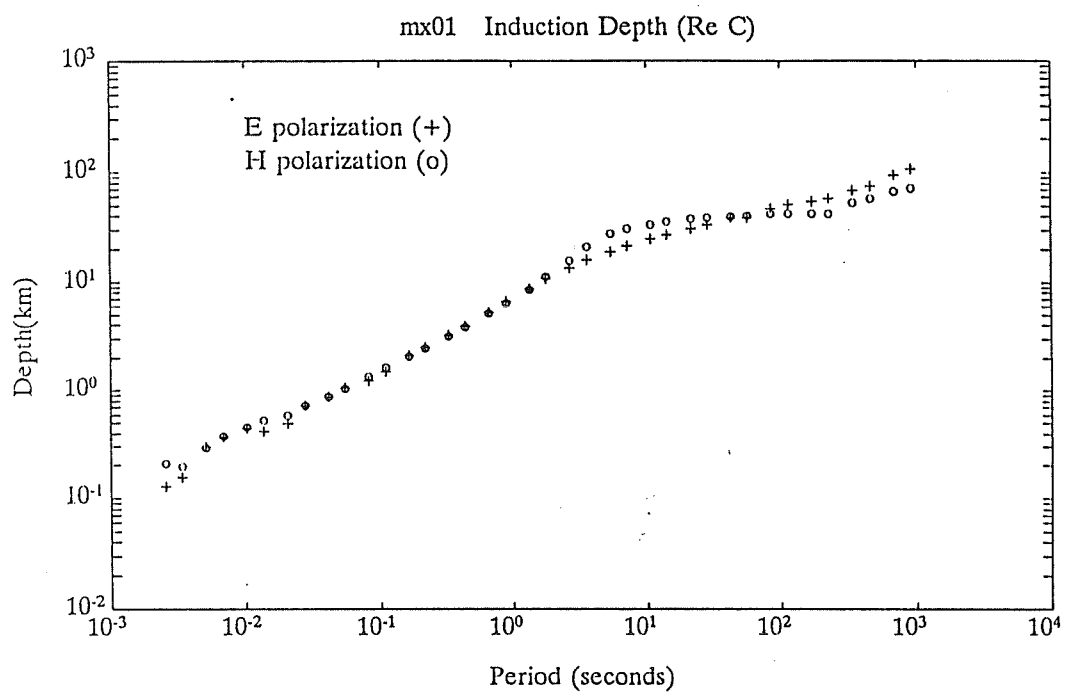


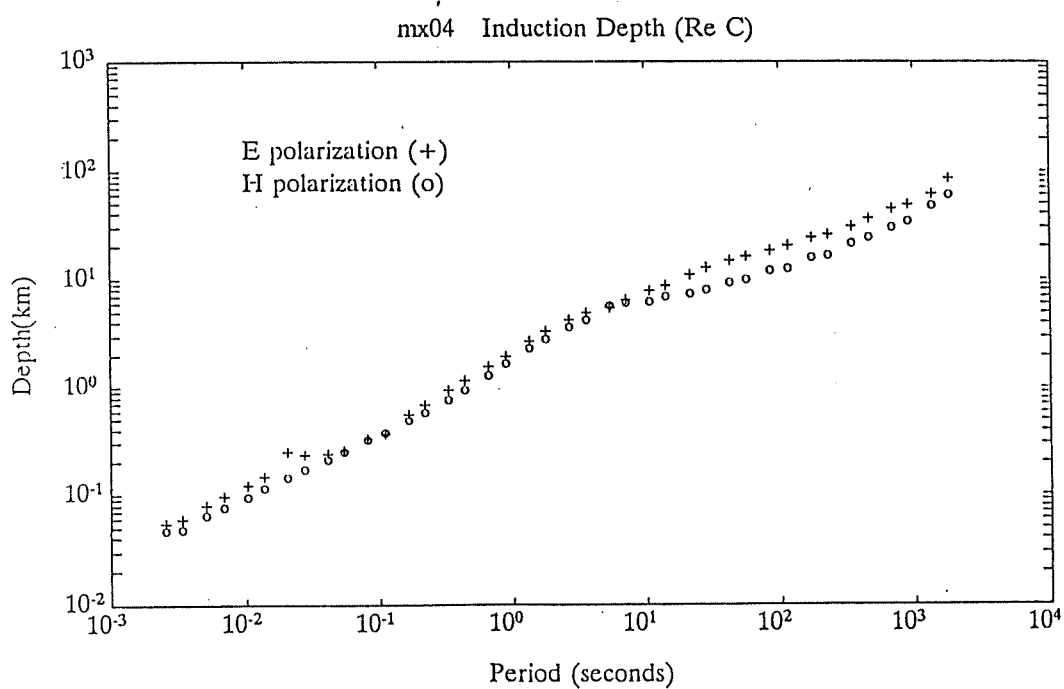
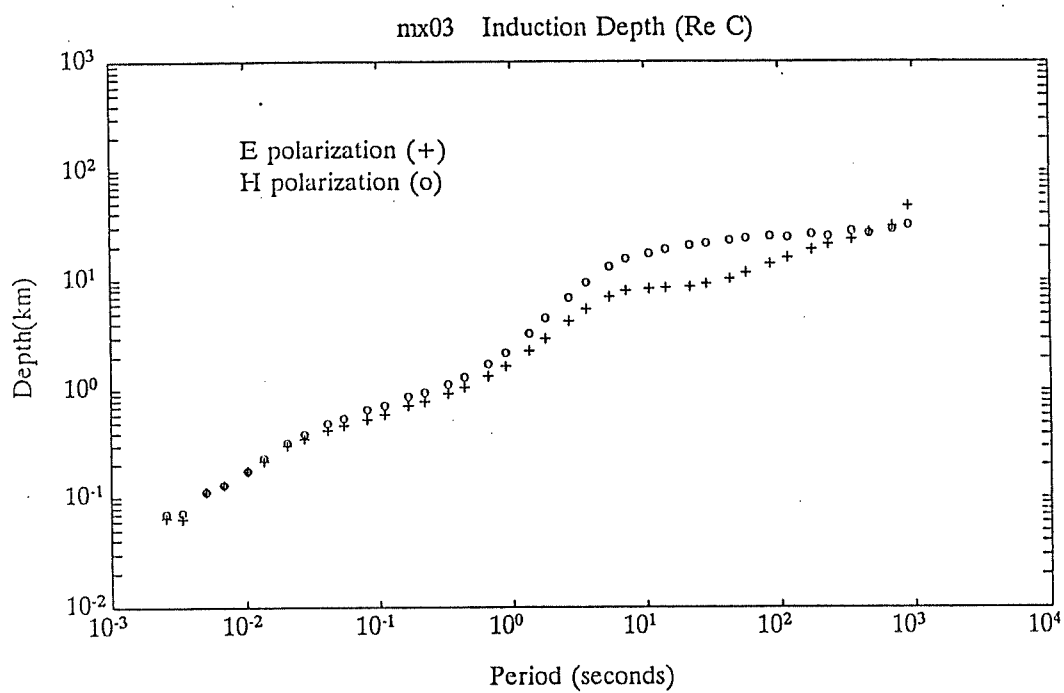
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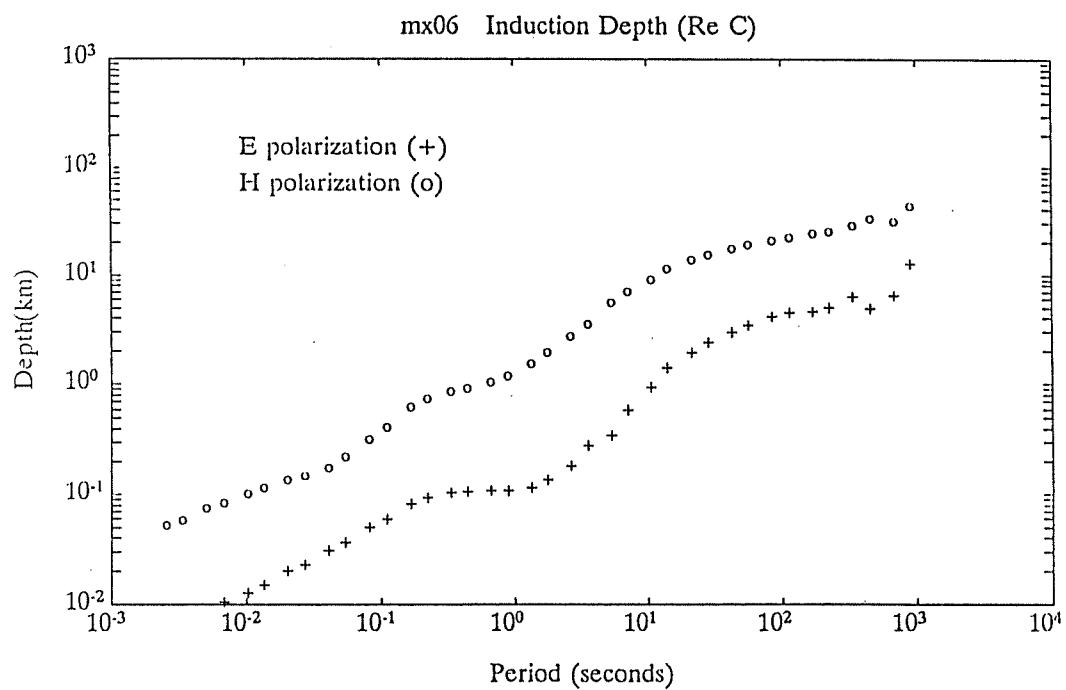
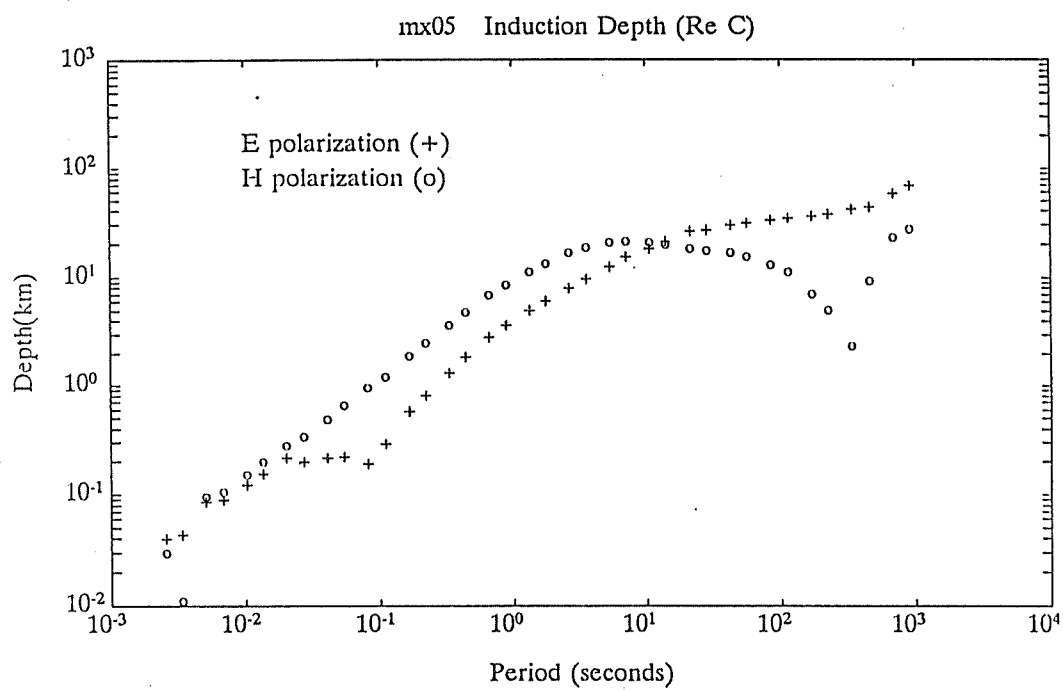
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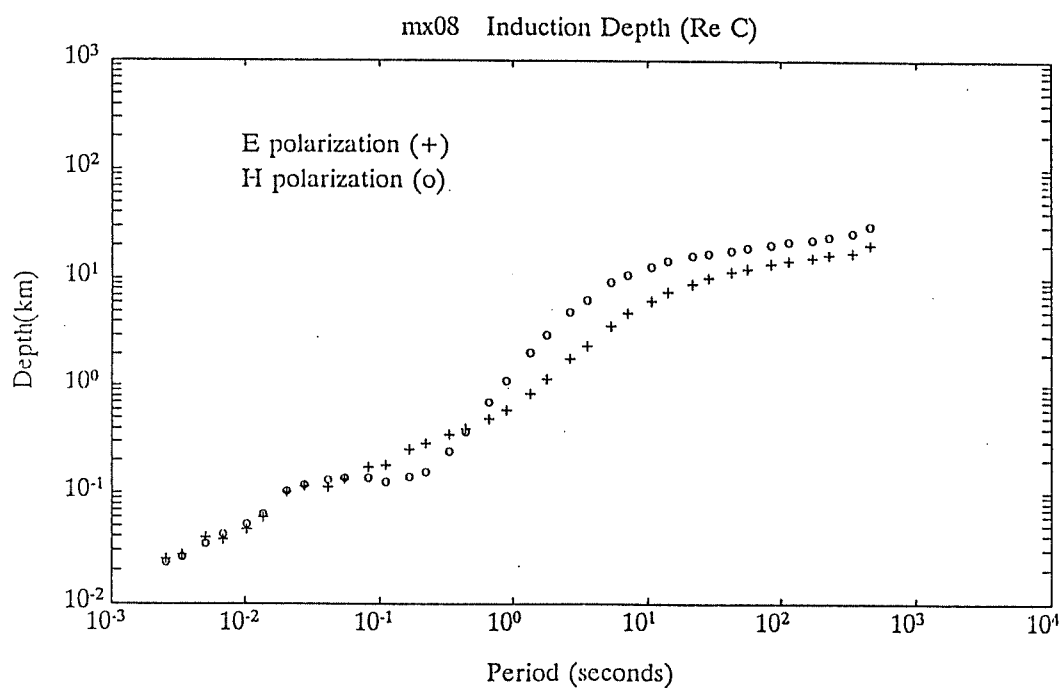
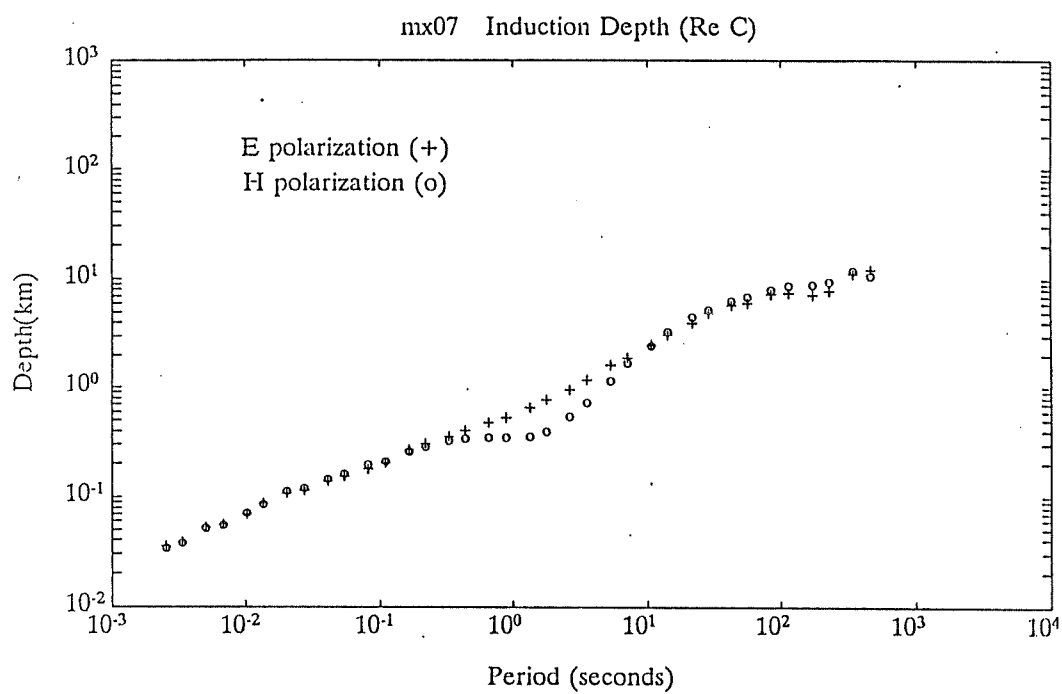


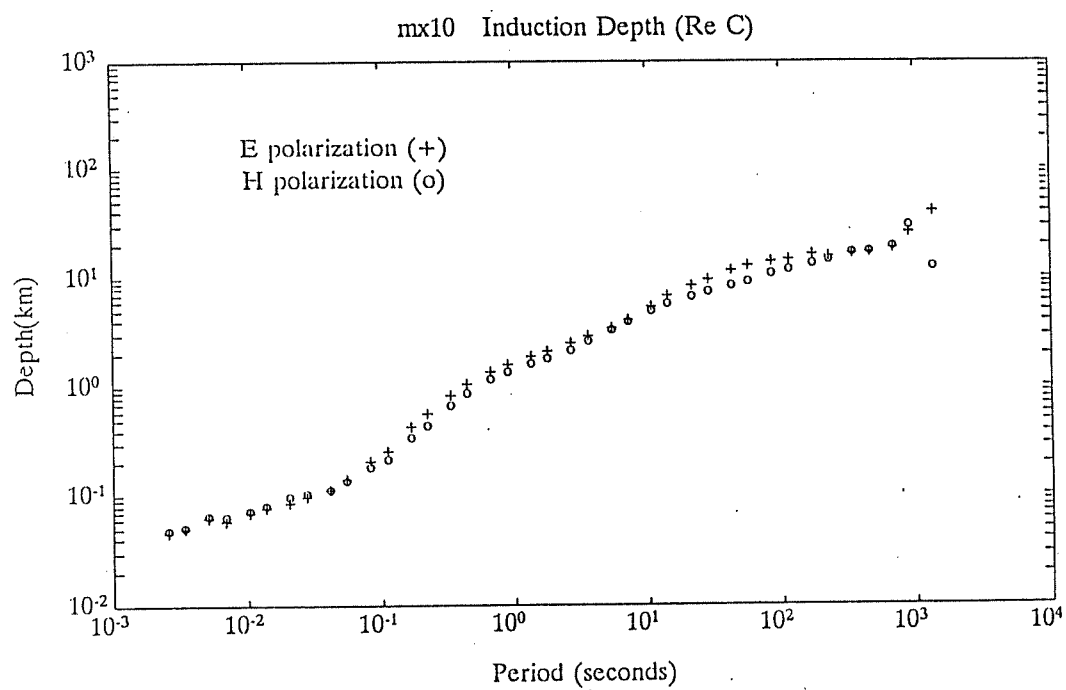
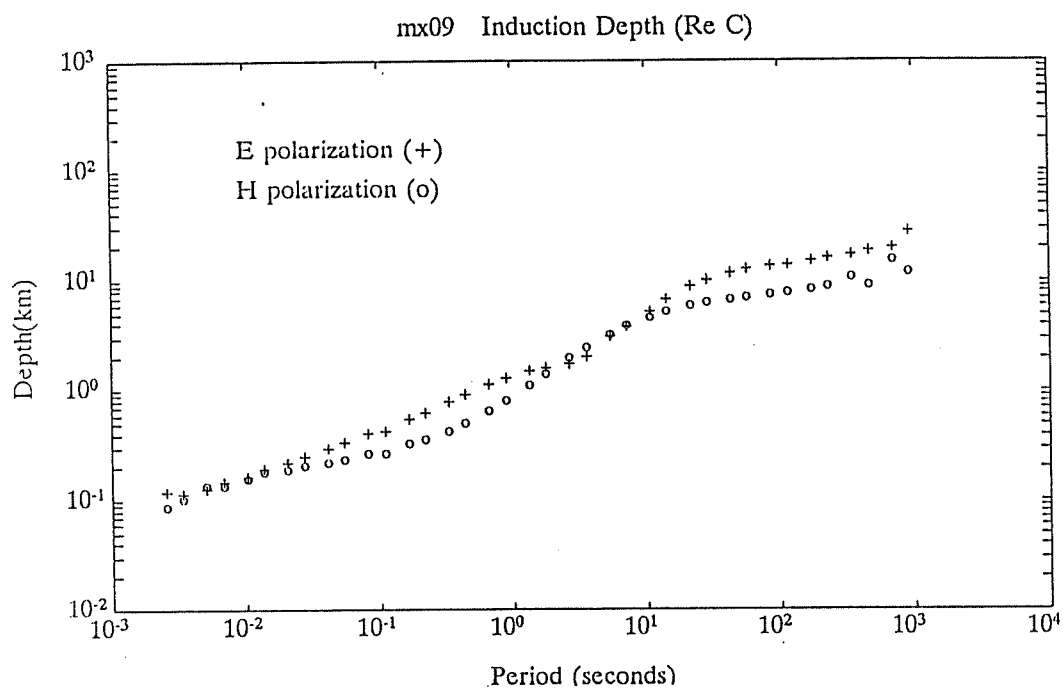
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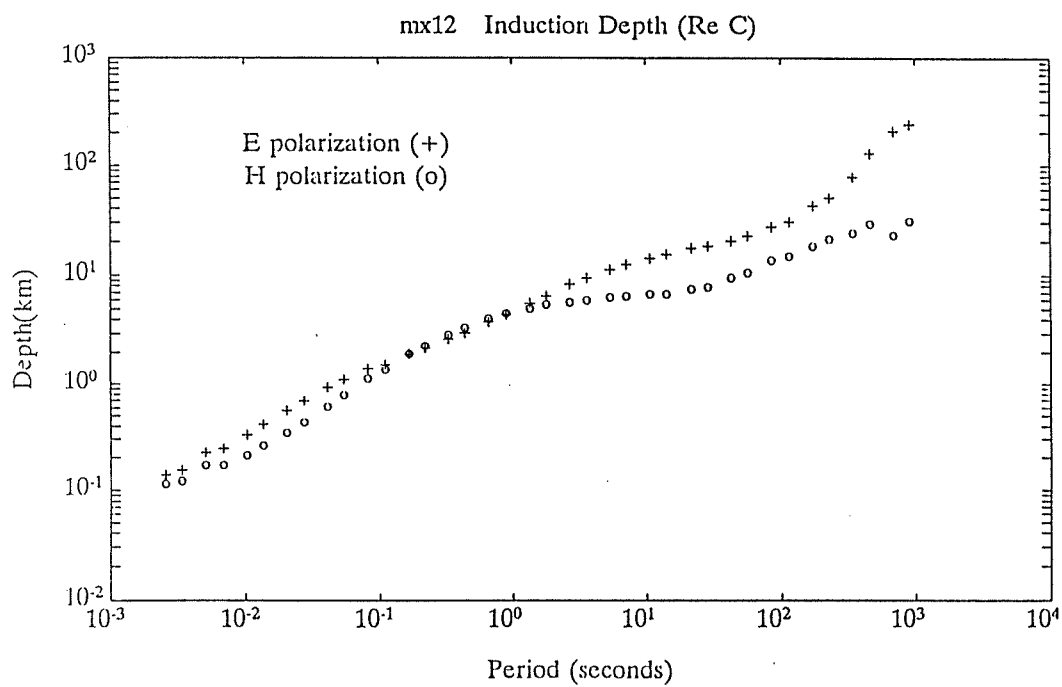
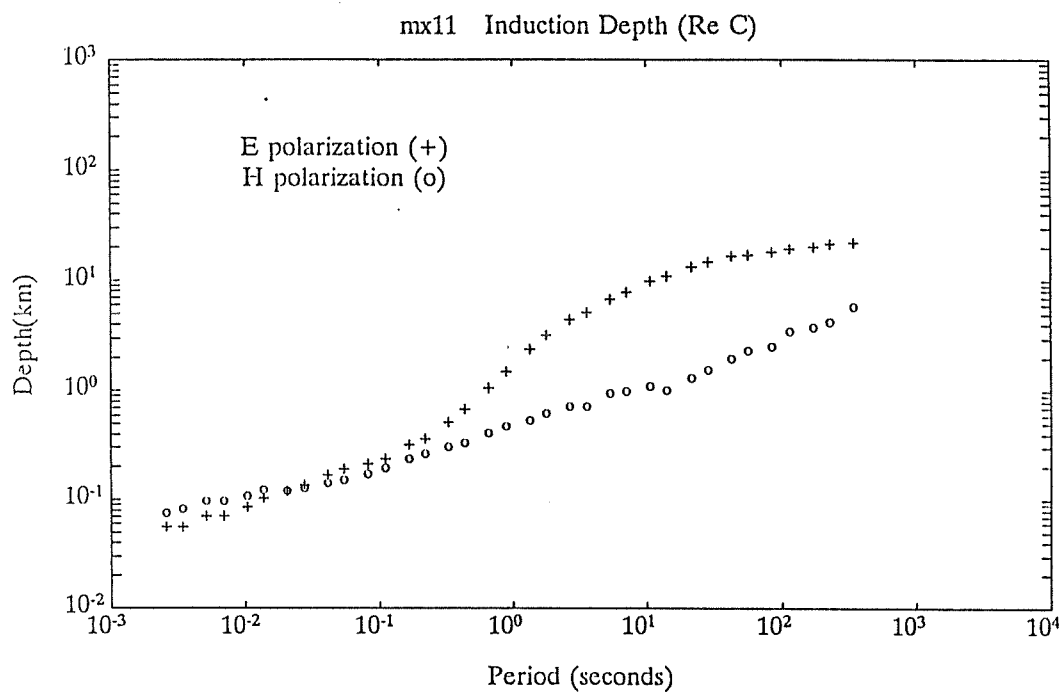


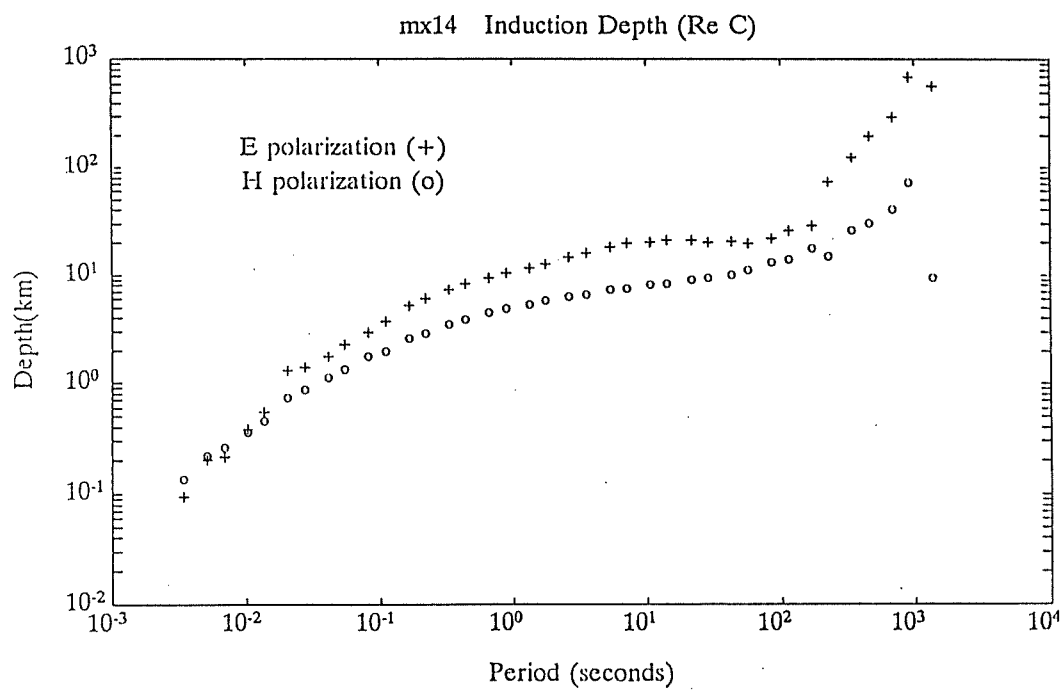
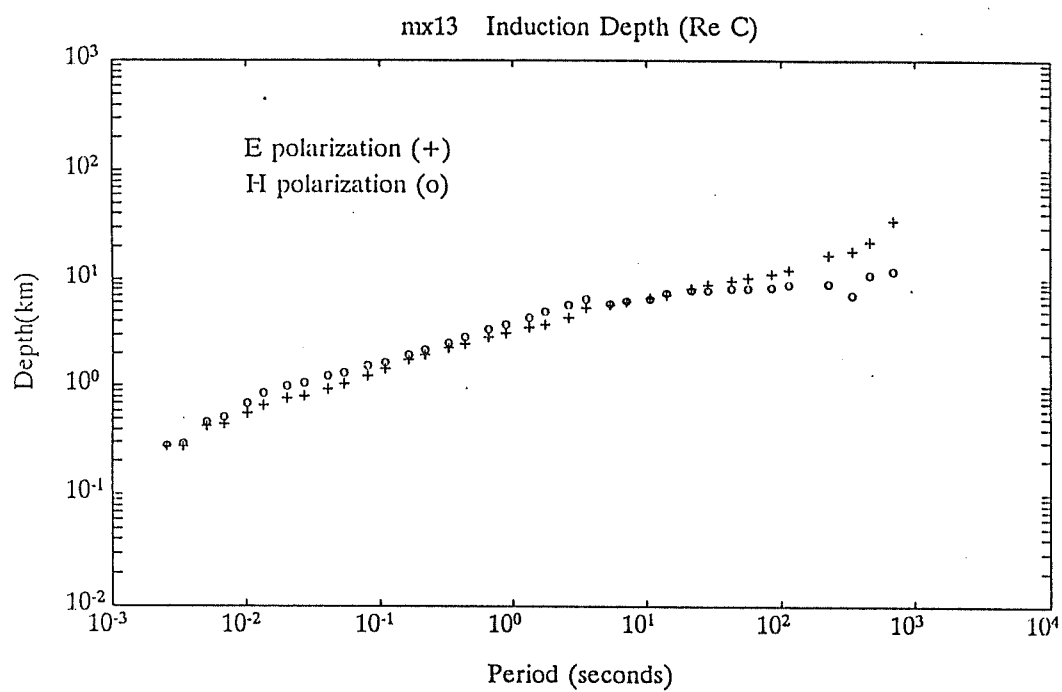












APPENDIX B

TABLES OF EIGENPARAMETERS

The following set of tables show the resolved model parameters (bold type) for each of the soundings used in this thesis. The parameters were obtained using single value decomposition (SVD) described in Section (4.1). The first column in the table indicates the logarithm of the original parameters $\mathbf{p}$ whereas the following columns contain the weight given to each dp_i to make up the corresponding eigenparameter dp'_i (eq. 43). Each column represents an eigenvector that relates the logarithm of the original parameters with the newly defined eigenparameters. The value we have taken as the threshold error to accept or reject the significance of a parameter is $1/L_{ii} = 1$; the parameters that had associated a fractional error $1/L_{ii} > 1$ were assumed to be unresolved by the MT method.

Resolved model parameters for Site Mex01

	Eigenvectors							Model parameters
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log ρ (1)	-0.725	0.307	-0.157	0.4	0.594	0.011	0.001	$\rho(1)=20.6$
log H (1)	0.469	-0.295	0.225	0.229	0.768	0.007	0.001	$H(1)=0.14$
log ρ (2)	0.502	0.66	-0.509	-0.174	0.148	0.007	0.001	$\rho(2)=95.7$
log H (2)	-0.047	-0.597	-0.799	-0.028	0.042	-0.026	-0.001	H(2)=7.1
log ρ (3)	-0.008	-0.162	0.162	-0.953	0.179	0.086	0.007	$\rho(3)=5.2$
log H (3)	0	-0.007	-0.03	0.08	-0.027	0.962	0.259	$H(3)=15.1$
log ρ (4)	0	0.001	0.007	-0.014	0.004	-0.258	0.966	$\rho(4)=24.7$
1 / λ	0.14	0.33	0.53	1	> 1	> 1	> 1	
Resolved param.	$\rho(1)/\rho(2)$	$(2)/H(2)$	$H(2)\rho(2)$	$\rho(3)$	---	---	---	

Resolved model parameters for Site Mex02

		Eigenvectors							Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log $\rho(1)$		-0.719	0.438	-0.116	0.528	-0.001	0	0	$\rho(1)=19.3$
log H(1)		0.519	-0.156	0.016	0.84	0.003	0	0	$H(1)=0.26$
log $\rho(2)$		-0.462	-0.844	0.244	0.124	0.009	0	0	$\rho(2)=88.5$
log H(2)		0.022	0.266	0.95	0.018	0.161	0	0	$H(2)=7.2$
log $\rho(3)$		0.002	0.035	0.157	0.006	-0.987	-0.001	0	$\rho(3)=8.7$
log H(3)		0	0	0	0	0.001	-0.991	0.135	$H(3)=84.6$
log $\rho(4)$		0	0	0	0	0	0.135	0.991	$\rho(4)=40.3$
1 / λ		0.002	0.012	0.021	0.043	0.106	> 1	> 1	
Resolved param.		H(1) $\sigma(1)$	$\rho(2)$	H(2)	H(1)	$\rho(3)$	--	--	

Resolved model parameters for Site Mex03

		Eigenvectors									Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$		-0.313	0.84	-0.123	0.066	-0.163	0.092	-0.279	0.248	-0.012	$\rho(1)=60$
log H(1)		0.052	-0.373	0.253	0.008	-0.14	0.195	-0.609	0.565	-0.03	$H(1)=0.2$
log $\rho(2)$		-0.071	0.068	0.07	-0.085	0.191	-0.053	0.136	-0.087	-0.002	$\rho(2)=360$
log H(2)		-0.305	0.107	0.584	-0.346	0.613	-0.028	0.009	0.079	-0.011	$H(2)=0.31$
log $\rho(3)$		-0.874	-0.328	-0.01	0.064	-0.305	0.006	0.046	-0.148	0.02	$\rho(3)=52$
log H(3)		0.187	0.161	0.615	-0.041	-0.446	0.111	-0.089	-0.36	0.083	$H(3)=1.4$
log $\rho(4)$		-0.019	-0.063	-0.431	-0.536	0.168	0.147	-0.249	-0.005	0.073	$\rho(4)=133$
log H(4)		0.048	0.016	-0.038	-0.729	-0.376	-0.063	-0.037	-0.168	-0.012	$H(4)=2.8$
log $\rho(5)$		0.019	0.019	0.091	-0.207	-0.281	-0.149	0.601	0.64	-0.113	$\rho(5)=35$
log H(5)		0.001	0.001	0.012	0.018	-0.032	-0.886	-0.256	0.052	0.37	$H(5)=4.4$
log $\rho(6)$		0	0	0.002	0	-0.008	-0.325	-0.181	-0.114	-0.914	$\rho(6)=7.2$
1 / λ		0.0081	0.0197	0.0413	0.101	0.2703	0.2703	0.3125	0.4	0.7692	
Resolved param.		$\rho(3)$	$\rho(1)$	$H(2)H(3)$	$H(4)\rho(4)$	$H(2)$	$H(5)$	$\rho(5)/H(1)$	$H(1)$	$\rho(6)$	

Resolved model parameters for Site Mex04

		Eigenvectors							Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log $\rho(1)$		-0.715	0.519	-0.091	-0.459	-0.007	0	0	$\rho(1)=23.4$
log H(1)		0.496	-0.083	-0.023	-0.863	-0.048	0.002	0	H(1)=0.28
log $\rho(2)$		-0.49	-0.822	0.199	-0.205	-0.043	0.002	0	$\rho(2)=98.9$
log H(2)		0.045	0.211	0.973	-0.025	0.075	-0.002	0	H(2)=5.5
log $\rho(3)$		0.006	0.052	0.066	0.052	-0.995	0.032	-0.006	$\rho(3)=11.7$
log H(3)		0	0	0	0	-0.012	-0.551	-0.834	$H(3)=21.4$
log $\rho(4)$		0	0	-0.001	0	0.03	0.834	-0.551	$\rho(4)=19.2$
1 / λ		0.004	0.018	0.035	0.05	0.2	> 1	> 1	
Resolved param.		$\rho(1)$	$\rho(2)$	H(2)	H(1)	$\rho(3)$	--	--	

Resolved model parameters for Site Mex05

	Eigenvectors							Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log $\rho(1)$	-0.663	0.042	-0.413	0.084	-0.204	-0.582	-0.003	$\rho(1)=17.0$
log H(1)	0.607	-0.06	0.167	0.019	-0.141	-0.761	-0.008	$H(1)=0.14$
log $\rho(2)$	-0.435	-0.248	0.828	-0.114	0.14	-0.175	-0.006	$\rho(2)=255$
log H(2)	0.043	-0.96	-0.213	0.105	-0.112	0.087	0.006	$H(2)=4.5$
log $\rho(3)$	0.02	-0.106	-0.265	-0.505	0.791	-0.192	-0.029	$\rho(3)=27$
log H(3)	0.001	0.019	0.017	0.838	0.529	-0.076	0.104	$H(3)=4.9$
log $\rho(4)$	0	0.001	0.003	0.104	0.033	0.007	-0.994	$\rho(4)=1.6$
$1/\lambda$	0.005	0.018	0.058	0.107	0.148	0.225	> 1	
Resolved param.	$H(1)\sigma(1)$	H(2)	$\rho(2)$	H(3)	$\rho(3)$	H(1)	--	

Resolved model parameters for Site Mex06

	Eigenvectors									Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$	-0.114	0.075	-0.699	0.041	-0.004	0.001	-0.164	0.682	0	$\rho(1)=1$
log H(1)	0.112	-0.074	0.687	-0.04	0.004	0	-0.167	0.693	0	$H(1)=0.001$
log $\rho(2)$	-0.984	-0.088	0.149	-0.03	0.002	0	0	0	0	$\rho(2)=25$
log H(2)	-0.071	0.99	0.12	0.037	0.002	0	0.001	0	-0.002	$H(2)=2.6$
log $\rho(3)$	0	-0.002	0	-0.001	0	-0.001	0.204	0.049	-0.978	$\rho(3)=2500$
log H(3)	0.018	0.045	-0.057	-0.988	0.135	-0.025	0.01	0.003	0.003	$H(3)=9.7$
log $\rho(4)$	0.001	0.006	-0.002	-0.106	-0.684	0.197	-0.66	-0.159	-0.146	$\rho(4)=1$
log H(4)	0	-0.005	0.001	0.087	0.667	-0.174	-0.684	-0.164	-0.151	$H(4)=0.4$
log $\rho(5)$	0	0.001	0	-0.011	-0.264	-0.964	-0.012	-0.002	-0.002	$\rho(5)=22$
$1/\lambda$	0.012	0.033	0.073	0.134	0.474	> 1	> 1	> 1	> 1	
Resolved param.	$\rho(2)$	H(2)	$H(1)\sigma(1)$	H(3)	$H(4)\sigma(4)$	--	--	--	--	

Resolved model parameters for Site Mex07

		Eigenvectors							Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log $\rho(1)$		-1	0.009	-0.005	0.001	0	0	0	$\rho(1)=15$
log H(1)		-0.009	-1	0.006	-0.009	0.005	0.002	0.002	H(1)=2.2
log $\rho(2)$		0	0.005	-0.004	-0.006	0.842	0.378	0.384	$\rho(2)=3300$
log H(2)		0.005	-0.005	-0.984	-0.1	0.067	-0.13	-0.031	H(2)=6.2
log $\rho(3)$		0	0	-0.004	-0.004	0.245	0.367	-0.898	$\rho(3)=254$
log H(3)		0.001	-0.002	-0.149	-0.009	-0.476	0.84	0.214	H(3)=0.93
log $\rho(4)$		0.001	-0.01	-0.1	0.995	0.008	-0.002	-0.002	$\rho(4)=4$
$1/\lambda$		0.0051	0.0165	0.0847	0.625	> 1	> 1	> 1	
Resolved param.		$\rho(1)$	H(1)	H(2)	$\rho(4)$	--	--	--	

Resolved model parameters for Site Mex08

	Eigenvectors							Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log $\rho(1)$	-0.753	0.592	-0.178	0.228	-0.001	0	0	$\rho(1)=3$
log H(1)	0.651	0.607	-0.228	0.396	-0.002	0.001	0	H(1)=0.17
log $\rho(2)$	-0.101	-0.488	-0.091	0.862	-0.003	0.006	0.001	$\rho(2)=79$
log H(2)	0.006	0.207	0.942	0.217	0.152	-0.003	-0.006	H(2)=7.1
log $\rho(3)$	0.001	0.031	0.144	0.029	-0.971	0.177	0.055	$\rho(3)=4$
log H(3)	0	0.003	0.022	0.01	-0.173	-0.984	0.034	H(3)=12.8
log $\rho(4)$	0	0	-0.003	-0.001	0.061	0.023	0.998	$\rho(4)=23$
$1/\lambda$	0.003	0.027	0.033	0.04	0.24	0.735	> 1	
Resolved param.	H(1) $\sigma(1)$	H(1) $\rho(1)$	H(2)	$\rho(2)$	$\rho(3)$	H(3)	--	

Resolved model parameters for Site Mex09

	Eigenvectors									Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$	-0.175	0.934	-0.156	-0.011	-0.242	-0.003	-0.119	0.001	0	$\rho(1)=71$
log H(1)	-0.145	0.289	0.418	0.03	0.768	0.009	0.361	-0.003	0	H(1)=0.21
log $\rho(2)$	-0.83	-0.175	0.273	0.028	-0.029	-0.008	-0.451	0.005	0	$\rho(2)=19$
log H(2)	0.463	0.1	0.19	-0.031	0.322	-0.022	-0.797	0.011	0	H(2)=0.41
log $\rho(3)$	-0.212	-0.065	-0.811	-0.198	0.49	-0.024	-0.119	0.005	0	$\rho(3)=65$
log H(3)	0.003	0.004	0.18	-0.952	-0.085	-0.227	0.054	0.019	-0.005	H(3)=6.0
log $\rho(4)$	0	0	0.024	-0.225	0.008	0.968	-0.015	0.099	0.031	$\rho(4)=6$
log H(4)	0	0	0.003	-0.042	0.001	0.09	-0.014	-0.993	0.054	H(4)=16.1
log $\rho(5)$	0	0	0	0.004	0	-0.036	0.002	0.051	0.998	$\rho(5)=67$
1 / λ	0.011	0.024	0.068	0.085	0.128	0.385	0.54	0.746	> 1	
Resolved param.	$\rho(2)$	$\rho(1)$	$\rho(3)$	H(3)	H(1)	$\rho(4)$	H(2)	H(4)	--	

Resolved model parameters for Site Mex10

	Eigenvectors									Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$	-0.755	0.09	-0.641	0.082	0.004	0.058	0	0	0	$\rho(1)=10.5$
log H(1)	0.608	-0.091	-0.666	0.25	0.02	0.342	-0.001	0	0	$H(1)=0.19$
log $\rho(2)$	-0.225	-0.188	0.346	0.219	0.048	0.863	-0.004	0	0	$\rho(2)=105.2$
log H(2)	-0.094	-0.923	-0.013	0.246	-0.014	-0.282	0.003	0	0	H(2)=1.6
log $\rho(3)$	0.019	-0.312	-0.161	-0.907	0.019	0.231	-0.007	0	0	$\rho(3)=15.4$
log H(3)	0	-0.004	-0.003	-0.006	-0.991	0.057	0.12	0	0	H(3)=8.3
log $\rho(4)$	0	0	0	0.006	-0.12	0	-0.993	0	0	$\rho(4)=1.6$
log H(4)	0	0	0	0	0	0	0	-1	0	$H(4)=58.4$
log $\rho(5)$	0	0	0	0	0	0	0	0	-1	$\rho(5)=27.4$
1 / λ	0.005	0.025	0.047	0.086	0.135	0.178	> 1	> 1	> 1	
Resolved param.	H(1) $\sigma(1)$	H(2)	H(1) $\rho(1)$	$\rho(3)$	H(3)	$\rho(2)$	--	--	--	

Resolved model parameters for Site Mex11

		Eigenvectors							Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	
log P(1)		-0.048	0.106	-0.165	0.027	0.039	-0.01	-0.978	$\rho(1)=247$
log H(1)		-0.226	0.599	-0.723	0.11	0.114	-0.003	0.205	H(1)=0.06
log P(2)		-0.944	0.048	0.316	-0.053	-0.061	0.002	-0.006	$\rho(2)=37$
log H(2)		0.229	0.762	0.482	-0.107	-0.35	0.025	-0.026	H(2)=0.7
log P(3)		-0.054	-0.216	-0.316	-0.05	-0.0918	0.077	-0.006	$\rho(3)=137$
log H(3)		-0.003	0.004	0.137	0.966	-0.084	0.202	-0.001	H(3)=7.1
log P(4)		0	0.001	0.02	0.192	-0.1	-0.976	0.008	$\rho(4)=3$
1 / λ		0.002	0.005	0.013	0.017	0.031	0.15	> 1	
Resolved param.		$\rho(2)$	H(2)	H(1)	H(3)	$\rho(3)$	$\rho(4)$	--	

Resolved model parameters for Site Mex12

	Eigenvectors									Mod. par.
	dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$	-0.436	0.453	-0.667	0.055	-0.29	0.1	-0.198	0.155	0.003	$\rho(1)=130$
log H(1)	0.256	-0.295	0.15	0.018	-0.465	0.197	-0.581	0.481	0.009	$H(1)=0.3$
log $\rho(2)$	-0.717	0.092	0.539	-0.038	0.255	-0.047	-0.244	0.242	0.006	$\rho(2)=452$
log H(2)	-0.447	-0.509	0.037	-0.135	-0.546	0.171	0.284	-0.337	-0.009	$H(2)=2.8$
log $\rho(3)$	-0.167	-0.66	-0.472	0.101	0.43	-0.243	-0.098	0.224	0.011	$\rho(3)=158$
log H(3)	0.05	0.001	-0.124	-0.956	0.17	0.153	-0.129	-0.005	-0.004	$H(3)=4.6$
log $\rho(4)$	0.016	0.072	0.051	-0.232	-0.341	-0.786	0.277	0.354	0.043	$\rho(4)=50$
log H(4)	0	0	0	0.003	0.078	0.465	0.606	0.614	0.183	$H(4)=11.4$
log $\rho(5)$	0	0	0	0.003	-0.006	-0.049	-0.115	-0.141	0.982	$\rho(5)=411$
1 / λ	0.012	0.033	0.073	0.135	0.476	2.38	> 1	> 1	> 1	
Resolved param.	$\rho(2)$	$H(2)\rho(3)$	$\rho(2)/\rho(1)$	H(3)	H(2)	$\rho(4)$	--	--	--	

Resolved model parameters for Site Mex13

		Eigenvectors									Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$		-0.316	0.897	-0.286	0.114	-0.002	0.023	-0.003	0	0	$\rho(1)=746$
log H(1)		-0.733	-0.079	0.322	-0.583	-0.012	-0.108	0.015	-0.002	0	$H(1)=1.2$
log $\rho(2)$		-0.591	-0.346	-0.151	0.653	0.062	0.277	-0.041	0.003	0.001	$\rho(2)=172$
log H(2)		-0.104	-0.235	-0.715	-0.126	-0.341	-0.514	0.127	-0.013	-0.003	$H(2)=2$
log $\rho(3)$		-0.011	-0.026	-0.081	-0.016	0.024	-0.073	-0.004	0.003	0.01	$\rho(3)=82$
log H(3)		0	-0.001	-0.004	-0.003	-0.034	0.009	0.009	-0.002	0.004	$H(3)=0.14$
log $\rho(4)$		0.043	-0.106	-0.504	-0.452	0.203	0.687	-0.126	0.001	0.002	$\rho(4)=73$
log H(4)		0.02	0.041	0.141	-0.003	-0.867	0.405	0.232	-0.049	-0.003	$H(4)=3.1$
log $\rho(5)$		0	0.004	0.018	0.004	-0.288	-0.073	-0.954	0.026	0.021	$\rho(5)=10$
log H(5)		0	0	-0.001	-0.004	-0.04	0.014	0.041	0.994	0.097	$H(5)=14.8$
log $\rho(6)$		0	0	0	0	0.006	-0.001	0.017	-0.097	0.995	$\rho(6)=83$
$1/\lambda$		0.0694	0.146	0.2941	0.4762	0.9091	> 1	> 1	> 1	> 1	
Resolved param		$H(1)\rho(2)$	$\rho(1)$	$H(2)$	$\rho(2)/H(1)$	$H(4)$	--	--	--	--	

Resolved model parameters for Site Mex14

		Eigenvectors									Mod. par.
		dp'(1)	dp'(2)	dp'(3)	dp'(4)	dp'(5)	dp'(6)	dp'(7)	dp'(8)	dp'(9)	
log $\rho(1)$		-0.231	0.585	-0.189	0.091	-0.184	0.082	-0.164	-0.005	-0.702	$\rho(1)=18$
log H(1)		0.225	-0.581	0.187	-0.09	0.18	-0.078	0.154	0.004	-0.712	$H(1)=0.01$
log $\rho(2)$		-0.295	0.328	0.107	-0.214	0.549	-0.284	0.605	0.018	-0.005	$\rho(2)=2200$
log H(2)		0.774	-0.314	0.076	-0.173	0.235	0.095	-0.45	-0.02	0.004	$H(2)=2.6$
log $\rho(3)$		-0.453	-0.232	0.088	0.23	-0.63	-0.024	0.531	0.03	-0.001	$\rho(3)=429$
log H(3)		-0.066	-0.242	-0.876	0.307	0.217	-0.135	0.102	-0.006	-0.001	$H(3)=3.3$
log $\rho(4)$		0.037	-0.045	-0.37	-0.86	-0.272	0.169	0.129	0.036	0	$\rho(4)=120$
log H(4)		0	-0.001	0	0.148	0.241	0.897	0.249	0.231	0	$H(4)=13.8$
log $\rho(5)$		0	0.001	0.003	-0.007	-0.033	-0.212	-0.101	0.971	0	$\rho(5)=570$
$1/\lambda$		0.0049	0.014	0.0272	0.0654	0.1042	0.1754	0.2703	0.8333	> 1	
Resolved param.		H(2)	$H(1)\sigma(1)$	H(3)	$\rho(4)$	$\rho(2)/\rho(3)$	H(4)	$\rho(2)$	$\rho(5)$	--	

APPENDIX C

RESULTS FROM INVERSION OF PROJECTED PROFILE

In the following pages are the results of the 2-D inversion of the projected profile for the TE and TM polarization modes performed separately. The column headers from pages 178 to 185 are: the sounding location (the reference point is sounding 12), the calculated depth in meters, the calculated E-polarization phase angle, its associated error, the calculated B-polarization phase angle and its associated error respectively. The column headers from pages 186 to 193 are: the sounding location, the calculated depth, the logarithm of the calculated E-polarization resistivity, and the logarithm of the calculated B-polarization resistivity. The phase and resistivity was computed at 37 different frequencies.

INTERPRETED PHASE (deg.) AND ERROR FOR PROJECTED PROFILE

SITE LOC.	DEPTH(m)	PHA-TE	ERR-TE	PHA-TM	ERR-TM
(SITE 12)					
0.000000	0.000000	31.71000	2.120000	18.69000	1.460000
0.000000	200.0000	31.49000	1.930000	21.53000	1.600000
0.000000	400.0000	32.02000	2.450000	23.36000	1.700000
0.000000	620.0000	33.65000	1.430000	25.84000	1.960000
0.000000	862.0000	35.34000	1.670000	27.67000	2.220000
0.000000	1128.000	38.27000	1.750000	30.50000	2.470000
0.000000	1421.000	40.60000	1.780000	32.76000	2.470000
0.000000	1743.000	44.08000	1.810000	36.29000	2.290000
0.000000	2097.000	46.60000	1.840000	38.95000	2.260000
0.000000	2487.000	50.06000	1.890000	42.71000	2.250000
0.000000	2916.000	52.40000	1.930000	45.25000	1.080000
0.000000	3388.000	55.47000	2.020000	48.39000	1.820000
0.000000	3906.000	57.53000	2.040000	50.20000	1.890000
0.000000	4477.000	60.39000	2.100000	51.98000	1.950000
0.000000	5105.000	62.43000	2.140000	52.64000	1.980000
0.000000	5795.000	65.22000	2.300000	52.65000	2.020000
0.000000	6555.000	67.02000	2.530000	52.04000	2.030000
0.000000	7390.000	69.11000	0.7200000	50.39000	2.030000
0.000000	8309.000	70.20000	0.5000000	48.79000	2.050000
0.000000	9320.000	71.12000	1.520000	46.09000	2.830000
0.000000	10432.00	71.33000	1.650000	43.96000	0.8000000
0.000000	11655.00	71.00000	1.710000	40.72000	1.360000
0.000000	13000.00	70.33000	1.740000	38.27000	1.460000
0.000000	14481.00	68.78000	1.760000	34.71000	1.310000
0.000000	16109.00	67.30000	0.6600000	32.23000	1.160000
0.000000	17900.00	64.82000	0.4700000	29.02000	1.020000
0.000000	19869.00	62.99000	2.050000	27.10000	0.1600000
0.000000	22036.00	60.59000	2.420000	25.06000	5.700000
0.000000	24420.00	59.05000	2.820000	24.14000	3.850000
0.000000	27042.00	56.82000	0.7800000	23.53000	2.920000
0.000000	29926.00	54.92000	0.5500000	23.56000	2.520000
0.000000	33099.00	51.55000	1.470000	24.11000	2.490000
0.000000	36589.00	48.76000	1.570000	24.80000	2.340000
0.000000	40428.00	44.56000	1.570000	26.09000	2.340000
0.000000	44650.00	41.70000	1.550000	27.16000	2.540000
0.000000	49295.00	38.19000	1.510000	28.83000	2.660000
0.000000	54405.00	36.37000	1.450000	30.03000	2.360000

(SITE 14)

5000.000	0.000000	31.53000	0.9400000	17.81000	0.0000000
5000.000	200.0000	31.33000	1.140000	20.63000	2.260000
5000.000	400.0000	31.90000	0.7300000	22.47000	1.940000
5000.000	620.0000	33.64000	1.460000	24.98000	1.450000
5000.000	862.0000	35.41000	0.0000000	26.84000	0.0000000
5000.000	1128.000	38.46000	0.4100000	29.75000	0.8300000
5000.000	1421.000	40.91000	1.600000	32.08000	0.8700000
5000.000	1743.000	44.59000	1.380000	35.70000	1.140000
5000.000	2097.000	47.29000	1.070000	38.43000	1.320000
5000.000	2487.000	51.06000	0.5900000	42.29000	1.430000
5000.000	2916.000	53.65000	1.040000	44.89000	1.970000
5000.000	3388.000	57.06000	0.4300000	48.11000	1.620000
5000.000	3906.000	59.31000	0.3200000	49.96000	1.470000
5000.000	4477.000	62.29000	0.5000000	51.80000	1.190000
5000.000	5105.000	64.28000	0.9600000	52.49000	1.080000
5000.000	5795.000	66.88000	0.8400000	52.54000	0.9200000
5000.000	6555.000	68.50000	1.170000	51.95000	0.4600000
5000.000	7390.000	70.34000	0.8400000	50.34000	0.6800000
5000.000	8309.000	71.27000	0.9000000	48.76000	0.8400000
5000.000	9320.000	72.02000	1.050000	46.10000	1.070000
5000.000	10432.00	72.14000	0.5900000	43.99000	2.420000
5000.000	11655.00	71.74000	1.330000	40.79000	0.3200000
5000.000	13000.00	71.05000	1.850000	38.36000	2.120000
5000.000	14481.00	69.49000	1.800000	34.83000	2.190000
5000.000	16109.00	68.00000	1.770000	32.35000	2.040000
5000.000	17900.00	65.53000	1.860000	29.13000	2.040000
5000.000	19869.00	63.70000	1.890000	27.21000	2.010000
5000.000	22036.00	61.29000	1.960000	25.16000	2.030000
5000.000	24420.00	59.72000	1.930000	24.22000	2.030000
5000.000	27042.00	57.37000	1.950000	23.60000	2.050000
5000.000	29926.00	55.32000	1.940000	23.62000	2.040000
5000.000	33099.00	51.69000	1.900000	24.16000	2.110000
5000.000	36589.00	48.71000	0.0000000	24.84000	2.150000
5000.000	40428.00	44.27000	0.0000000	26.13000	2.070000
5000.000	44650.00	41.30000	3.120000	27.19000	2.170000
5000.000	49295.00	37.71000	2.000000	28.85000	0.7400000
5000.000	54405.00	35.87000	2.790000	30.05000	1.430000

(SITE 13)

22000.00	0.000000	39.62000	0.0000000	47.94000	0.0000000
22000.00	200.0000	43.10000	0.0000000	50.97000	0.9900000
22000.00	400.0000	45.97000	0.2300000	52.43000	0.0000000
22000.00	620.0000	50.11000	1.250000	53.52000	0.4800000

..	22000.00	862.0000	52.85000	0.6500000	53.72000	0.0000000
	22000.00	1128.000	56.12000	0.6700000	53.48000	1.710000
	22000.00	1421.000	57.92000	1.960000	53.18000	0.0000000
	22000.00	1743.000	59.66000	0.8700000	52.95000	0.0799998
	22000.00	2097.000	60.33000	0.0500001	53.11000	1.240000
	22000.00	2487.000	60.57000	0.9200000	53.89000	0.6700000
	22000.00	2916.000	60.36000	0.6200000	54.76000	0.8100000
	22000.00	3388.000	59.81000	1.310000	56.23000	1.340000
	22000.00	3906.000	59.49000	0.0200000	57.25000	0.4300000
	22000.00	4477.000	59.49000	0.6400000	58.45000	0.0900004
	22000.00	5105.000	59.98000	0.6900000	59.05000	0.2700000
	22000.00	5795.000	61.43000	0.3200000	59.55000	0.6100000
	22000.00	6555.000	62.92000	0.3300000	59.68000	0.3100000
	22000.00	7390.000	65.42000	0.8400000	59.61000	0.4100000
	22000.00	8309.000	67.27000	0.2100000	59.39000	0.1600000
	22000.00	9320.000	69.72000	0.0000000	58.81000	0.2100000
	22000.00	10432.00	71.24000	0.0000000	58.17000	0.1800000
	22000.00	11655.00	72.95000	0.0700000	56.85000	0.1200000
	22000.00	13000.00	73.83000	1.410000	55.55000	0.7800000
	22000.00	14481.00	74.58000	0.8900000	53.06000	1.460000
	22000.00	16109.00	74.75000	1.380000	50.77000	1.420000
	22000.00	17900.00	74.50000	1.490000	46.87000	1.390000
	22000.00	19869.00	73.93000	1.580000	43.81000	1.390000
	22000.00	22036.00	72.41000	1.730000	39.55000	1.290000
	22000.00	24420.00	70.51000	1.830000	36.84000	1.130000
	22000.00	27042.00	66.09000	1.970000	33.79000	0.6400000
	22000.00	29926.00	61.52000	2.050000	32.23000	0.1200000
	22000.00	33099.00	53.59000	2.080000	30.89000	4.820000
	22000.00	36589.00	47.69000	2.080000	30.47000	0.8500000
	22000.00	40428.00	40.08000	1.900000	30.49000	0.8700000
	22000.00	44650.00	35.72000	0.0000000	30.84000	0.3600000
	22000.00	49295.00	31.17000	0.0000000	31.68000	0.1500000
	22000.00	54405.00	29.14000	0.0000000	32.42000	0.1200000

(SITE 4)

	70000.00	0.000000	36.08000	0.2000000	31.18000	0.0000000
	70000.00	200.0000	37.94000	1.290000	35.22000	1.940000
	70000.00	400.0000	37.69000	1.570000	37.24000	0.5900000
	70000.00	620.0000	36.35000	0.9600000	38.66000	1.320000
	70000.00	862.0000	35.49000	0.0099998	38.68000	0.2000000
	70000.00	1128.000	34.94000	2.040000	37.57000	0.0000000
	70000.00	1421.000	34.92000	1.360000	36.28000	0.0000000
	70000.00	1743.000	34.97000	1.050000	34.31000	0.8000000
	70000.00	2097.000	34.86000	0.9300000	33.09000	2.120000
	70000.00	2487.000	34.48000	0.2900000	31.88000	2.100000

70000.00	2916.000	34.13000	0.8700000	31.42000	0.0000000
70000.00	3388.000	33.65000	0.7800000	31.30000	0.5200000
70000.00	3906.000	33.45000	0.7800000	31.58000	0.1400000
70000.00	4477.000	33.63000	0.1300000	32.55000	1.140000
70000.00	5105.000	34.26000	0.1000000	33.71000	0.3300000
70000.00	5795.000	36.06000	0.6300000	36.09000	1.190000
70000.00	6555.000	38.00000	0.3500000	38.30000	1.420000
70000.00	7390.000	41.49000	1.010000	41.99000	0.1600000
70000.00	8309.000	44.30000	1.030000	44.83000	0.8200000
70000.00	9320.000	48.34000	0.1100000	48.78000	1.050000
70000.00	10432.00	51.01000	0.1600000	51.33000	0.7500000
70000.00	11655.00	54.26000	1.260000	54.25000	0.2800000
70000.00	13000.00	56.12000	0.3800000	55.72000	0.0000000
70000.00	14481.00	58.20000	0.4700000	56.84000	0.0000000
70000.00	16109.00	59.39000	0.1900000	56.92000	0.0000000
70000.00	17900.00	60.82000	0.0000000	56.07000	0.0000000
70000.00	19869.00	61.74000	2.560000	54.85000	0.6400000
70000.00	22036.00	62.92000	2.420000	52.41000	1.220000
70000.00	24420.00	63.67000	2.250000	50.33000	1.370000
70000.00	27042.00	64.41000	0.0000000	47.23000	1.420000
70000.00	29926.00	64.33000	0.0000000	45.11000	1.350000
70000.00	33099.00	62.54000	0.0000000	42.49000	1.330000
70000.00	36589.00	59.72000	0.0000000	41.00000	1.150000
70000.00	40428.00	53.87000	0.0000000	39.45000	1.020000
70000.00	44650.00	49.19000	0.0000000	38.74000	0.2100000
70000.00	49295.00	43.06000	0.0000000	38.22000	0.5400000
70000.00	54405.00	39.75000	0.0000000	38.14000	0.9900000

(SITE 3)

95000.00	0.000000	38.32000	1.810000	28.36000	0.0700000
95000.00	200.0000	37.48000	1.870000	32.12000	0.0000000
95000.00	400.0000	36.59000	1.940000	34.43000	1.100000
95000.00	620.0000	36.12000	2.170000	37.25000	1.160000
95000.00	862.0000	36.69000	2.670000	39.01000	0.9600000
95000.00	1128.000	38.62000	0.9700000	41.16000	0.0000000
95000.00	1421.000	40.34000	0.5500000	42.44000	1.680000
95000.00	1743.000	42.28000	0.0299999	43.77000	1.740000
95000.00	2097.000	42.80000	0.7000000	44.27000	0.1200000
95000.00	2487.000	41.93000	0.0500001	44.11000	0.5400000
95000.00	2916.000	40.24000	1.750000	43.27000	1.170000
95000.00	3388.000	36.80000	0.1800000	41.07000	1.560000
95000.00	3906.000	34.03000	0.2200000	39.03000	0.6500000
95000.00	4477.000	30.39000	0.1600000	36.10000	0.0000000
95000.00	5105.000	28.46000	0.4500000	34.48000	0.6600000
95000.00	5795.000	27.30000	0.3400000	33.43000	1.170000

95000.00	6555.000	27.90000	1.500000	33.78000	1.210000
95000.00	7390.000	30.95000	1.460000	35.87000	1.230000
95000.00	8309.000	34.56000	1.470000	38.33000	0.9900000
95000.00	9320.000	41.11000	1.500000	42.67000	0.9200000
95000.00	10432.00	46.25000	0.7900000	45.98000	1.800000
95000.00	11655.00	53.38000	1.880000	50.38000	0.0000000
95000.00	13000.00	57.93000	1.780000	53.04000	0.0000000
95000.00	14481.00	63.24000	1.750000	55.88000	0.0000000
95000.00	16109.00	66.17000	1.680000	57.19000	0.0000000
95000.00	17900.00	69.17000	1.600000	58.08000	1.360000
95000.00	19869.00	70.56000	1.590000	58.07000	2.140000
95000.00	22036.00	71.60000	1.540000	57.24000	1.890000
95000.00	24420.00	71.75000	1.550000	56.15000	1.900000
95000.00	27042.00	71.12000	1.550000	54.09000	1.960000
95000.00	29926.00	69.90000	1.540000	52.41000	2.020000
95000.00	33099.00	66.75000	1.520000	49.96000	2.130000
95000.00	36589.00	63.45000	1.490000	48.31000	2.140000
95000.00	40428.00	57.53000	1.430000	46.25000	2.060000
95000.00	44650.00	52.94000	1.370000	45.07000	2.040000
95000.00	49295.00	46.68000	1.400000	43.77000	0.0000000
95000.00	54405.00	43.03000	1.270000	43.14000	2.150000

(SITE 8)

104000.0	0.000000	25.11000	0.0000000	8.410000	0.0000000
104000.0	200.0000	31.81000	0.0000000	11.94000	0.0000000
104000.0	400.0000	35.65000	0.0000000	14.95000	0.0000000
104000.0	620.0000	38.60000	0.0000000	19.61000	0.0000000
104000.0	862.0000	38.65000	0.0000000	22.95000	0.0000000
104000.0	1128.000	36.13000	0.4600000	27.33000	0.0000000
104000.0	1421.000	33.04000	1.260000	30.01000	2.890000
104000.0	1743.000	27.83000	1.170000	33.00000	1.270000
104000.0	2097.000	24.05000	1.920000	34.47000	1.420000
104000.0	2487.000	19.21000	1.780000	35.45000	1.580000
104000.0	2916.000	16.33000	1.450000	35.26000	1.570000
104000.0	3388.000	13.30000	1.920000	33.78000	1.080000
104000.0	3906.000	12.03000	1.840000	32.14000	0.5700000
104000.0	4477.000	11.67000	1.790000	29.80000	0.3700000
104000.0	5105.000	12.47000	1.710000	28.70000	0.5900000
104000.0	5795.000	15.07000	0.9900000	28.59000	1.340000
104000.0	6555.000	17.89000	0.9000000	29.66000	1.610000
104000.0	7390.000	23.20000	1.970000	32.70000	1.780000
104000.0	8309.000	27.89000	1.760000	35.69000	1.830000
104000.0	9320.000	35.54000	0.2900000	40.59000	1.880000
104000.0	10432.00	41.36000	0.4500000	44.17000	1.890000
104000.0	11655.00	49.46000	0.0599999	48.85000	1.890000

104000.0	13000.00	54.72000	0.6700000	51.66000	1.940000
104000.0	14481.00	60.98000	1.700000	54.67000	1.930000
104000.0	16109.00	64.49000	1.690000	56.11000	2.020000
104000.0	17900.00	68.09000	1.680000	57.20000	2.750000
104000.0	19869.00	69.71000	1.680000	57.36000	0.5400000
104000.0	22036.00	70.77000	1.710000	56.82000	1.410000
104000.0	24420.00	70.81000	1.760000	55.96000	1.470000
104000.0	27042.00	70.06000	1.880000	54.24000	1.510000
104000.0	29926.00	68.90000	1.990000	52.78000	1.500000
104000.0	33099.00	66.19000	2.110000	50.58000	1.410000
104000.0	36589.00	63.41000	2.600000	49.05000	1.150000
104000.0	40428.00	58.39000	2.850000	47.11000	0.6600000
104000.0	44650.00	54.38000	3.510000	45.94000	0.4200000
104000.0	49295.00	48.67000	0.0000000	44.63000	0.1300000
104000.0	54405.00	45.18000	0.0000000	43.97000	0.0500001

(SITE 1)

115000.0	0.000000	37.36000	2.500000	28.59000	1.360000
115000.0	200.0000	36.23000	1.180000	29.72000	2.280000
115000.0	400.0000	35.91000	0.0000000	30.12000	0.0000000
115000.0	620.0000	35.93000	0.7800000	30.29000	0.0000000
115000.0	862.0000	35.97000	1.030000	30.22000	0.0000000
115000.0	1128.000	35.60000	1.440000	30.02000	0.0000000
115000.0	1421.000	34.94000	0.8000000	29.91000	0.0000000
115000.0	1743.000	33.65000	0.7200000	29.90000	0.7000000
115000.0	2097.000	32.71000	1.010000	30.06000	1.390000
115000.0	2487.000	31.68000	0.1100000	30.58000	1.190000
115000.0	2916.000	31.30000	0.5100000	31.15000	0.4300000
115000.0	3388.000	31.31000	1.940000	32.17000	1.420000
115000.0	3906.000	31.68000	2.170000	33.00000	1.300000
115000.0	4477.000	32.69000	1.420000	34.26000	1.100000
115000.0	5105.000	33.77000	0.2300000	35.21000	0.4900000
115000.0	5795.000	35.94000	0.6200000	36.67000	1.110000
115000.0	6555.000	38.13000	0.6500000	37.90000	1.410000
115000.0	7390.000	42.35000	2.030000	40.04000	1.580000
115000.0	8309.000	46.10000	1.930000	41.91000	1.630000
115000.0	9320.000	52.02000	2.060000	44.98000	1.690000
115000.0	10432.00	56.25000	0.9500000	47.31000	1.730000
115000.0	11655.00	61.74000	1.460000	50.47000	1.800000
115000.0	13000.00	65.06000	1.720000	52.45000	1.830000
115000.0	14481.00	68.75000	1.920000	54.67000	2.030000
115000.0	16109.00	70.62000	1.960000	55.81000	2.290000
115000.0	17900.00	72.18000	2.040000	56.79000	1.950000
115000.0	19869.00	72.50000	1.970000	57.05000	0.0000000
115000.0	22036.00	71.97000	2.000000	56.85000	0.0000000

115000.0	24420.00	71.09000	1.900000	56.31000	0.0000000
115000.0	27042.00	69.46000	1.720000	55.05000	0.6200000
115000.0	29926.00	68.08000	1.430000	53.88000	2.130000
115000.0	33099.00	65.61000	1.460000	52.01000	0.0200004
115000.0	36589.00	63.34000	2.350000	50.65000	1.200000
115000.0	40428.00	59.28000	3.580000	48.81000	1.620000
115000.0	44650.00	55.95000	3.480000	47.65000	1.720000
115000.0	49295.00	50.98000	0.9800000	46.27000	1.770000
115000.0	54405.00	47.77000	1.860000	45.52000	1.790000

(SITE 2)

122000.0	0.000000	37.40000	0.0000000	26.31000	0.0000000
122000.0	200.0000	35.28000	2.040000	28.33000	1.040000
122000.0	400.0000	33.95000	2.160000	29.42000	1.660000
122000.0	620.0000	32.70000	2.060000	30.60000	1.140000
122000.0	862.0000	32.24000	1.700000	31.24000	0.0200000
122000.0	1128.000	32.07000	1.360000	31.92000	0.0000000
122000.0	1421.000	32.24000	1.380000	32.23000	0.0000000
122000.0	1743.000	32.87000	1.610000	32.43000	1.340000
122000.0	2097.000	33.41000	1.830000	32.42000	1.010000
122000.0	2487.000	33.73000	1.920000	32.29000	0.3400000
122000.0	2916.000	33.27000	1.800000	32.24000	1.360000
122000.0	3388.000	31.82000	1.530000	32.42000	1.010000
122000.0	3906.000	30.79000	1.220000	32.83000	0.1200000
122000.0	4477.000	30.18000	1.440000	33.86000	1.690000
122000.0	5105.000	30.54000	1.700000	34.87000	1.780000
122000.0	5795.000	32.21000	2.050000	36.63000	1.810000
122000.0	6555.000	34.27000	2.070000	38.07000	0.0000000
122000.0	7390.000	38.50000	1.140000	40.39000	0.5400000
122000.0	8309.000	42.35000	0.4600000	42.25000	1.140000
122000.0	9320.000	48.52000	1.430000	45.09000	1.960000
122000.0	10432.00	53.02000	0.2200000	47.16000	1.980000
122000.0	11655.00	58.98000	1.030000	49.93000	2.120000
122000.0	13000.00	62.65000	1.440000	51.69000	2.030000
122000.0	14481.00	66.76000	1.580000	53.77000	2.300000
122000.0	16109.00	68.86000	1.640000	54.97000	2.320000
122000.0	17900.00	70.59000	2.200000	56.27000	2.340000
122000.0	19869.00	70.95000	2.020000	56.90000	2.400000
122000.0	22036.00	70.40000	2.010000	57.31000	2.240000
122000.0	24420.00	69.51000	1.890000	57.24000	2.380000
122000.0	27042.00	67.93000	1.700000	56.59000	2.550000
122000.0	29926.00	66.68000	1.460000	55.80000	2.570000
122000.0	33099.00	64.59000	0.5100000	54.32000	0.5200000
122000.0	36589.00	62.70000	0.6600000	53.12000	1.360000
122000.0	40428.00	59.28000	2.860000	51.38000	1.590000

122000.0	44650.00	56.39000	2.920000	50.21000	1.640000
122000.0	49295.00	51.95000	0.6900000	48.70000	1.680000
122000.0	54405.00	48.97000	0.4100000	47.82000	1.710000

(SITE 6)

159000.0	0.000000	41.02000	1.640000	10.70000	0.0000000
159000.0	200.0000	42.09000	0.7700000	14.98000	0.0000000
159000.0	400.0000	41.79000	1.200000	18.46000	0.0000000
159000.0	620.0000	39.88000	0.2200000	23.54000	0.0000000
159000.0	862.0000	37.68000	1.400000	27.01000	0.0000000
159000.0	1128.000	34.14000	1.710000	31.51000	2.470000
159000.0	1421.000	31.95000	1.870000	34.39000	0.1200000
159000.0	1743.000	30.17000	0.2900000	38.05000	0.8700000
159000.0	2097.000	30.14000	0.9400000	40.47000	1.310000
159000.0	2487.000	31.97000	0.8400000	43.67000	1.480000
159000.0	2916.000	34.36000	0.8500000	45.72000	1.370000
159000.0	3388.000	38.19000	1.460000	47.98000	0.9800000
159000.0	3906.000	40.22000	1.540000	48.71000	0.3300000
159000.0	4477.000	40.71000	1.150000	47.82000	1.630000
159000.0	5105.000	39.10000	0.0000000	45.58000	2.130000
159000.0	5795.000	34.91000	0.7200000	40.51000	1.350000
159000.0	6555.000	31.72000	0.4600000	36.26000	1.550000
159000.0	7390.000	28.74000	0.5600000	30.78000	1.600000
159000.0	8309.000	28.27000	0.8400000	27.94000	1.570000
159000.0	9320.000	29.99000	0.1700000	25.88000	1.500000
159000.0	10432.00	32.64000	0.2500000	25.78000	0.7200000
159000.0	11655.00	37.76000	0.0099998	27.29000	0.0000000
159000.0	13000.00	41.93000	0.3800000	29.33000	1.420000
159000.0	14481.00	47.79000	1.160000	33.23000	1.500000
159000.0	16109.00	51.56000	1.570000	36.48000	1.190000
159000.0	17900.00	55.90	1.600000	41.29000	0.0200000
159000.0	19869.00	58.15000	1.130000	44.58000	0.4900000
159000.0	22036.00	60.15000	0.2400000	48.63000	0.7200000
159000.0	24420.00	60.86000	1.400000	50.89000	0.1600000
159000.0	27042.00	61.16000	0.5800000	53.06000	0.9500000
159000.0	29926.00	61.05000	0.3200000	53.90000	1.000000
159000.0	33099.00	60.51000	1.110000	54.26000	0.5100000
159000.0	36589.00	59.81000	2.320000	54.06000	1.930000
159000.0	40428.00	58.29000	1.730000	53.34000	1.790000
159000.0	44650.00	56.81000	0.0000000	52.65000	1.750000
159000.0	49295.00	54.22000	0.0000000	51.55000	1.740000
159000.0	54405.00	52.27000	0.0000000	50.78000	0.0000000

INTERPRETED RESISTIVITY (log ohm-m) FOR PROJECTED PROFILE

SITE LOC.	DEPTH(m)	RHO-TE	RHO-TM
(SITE 12)			
0.000000	0.000000	1.826000	1.981000
0.000000	200.0000	1.826000	1.981000
0.000000	400.0000	1.790000	1.786000
0.000000	620.0000	2.353000	1.553000
0.000000	862.0000	2.813000	1.348000
0.000000	1128.000	3.075000	1.210000
0.000000	1421.000	3.197000	1.144000
0.000000	1743.000	3.227000	1.142000
0.000000	2097.000	3.195000	1.191000
0.000000	2487.000	3.118000	1.273000
0.000000	2916.000	3.003000	1.372000
0.000000	3388.000	2.852000	1.475000
0.000000	3906.000	2.666000	1.575000
0.000000	4477.000	2.446000	1.669000
0.000000	5105.000	2.199000	1.756000
0.000000	5795.000	1.943000	1.834000
0.000000	6555.000	1.709000	1.906000
0.000000	7390.000	1.529000	1.972000
0.000000	8309.000	1.426000	2.035000
0.000000	9320.000	1.395000	2.094000
0.000000	10432.00	1.416000	2.151000
0.000000	11655.00	1.464000	2.207000
0.000000	13000.00	1.522000	2.262000
0.000000	14481.00	1.579000	2.318000
0.000000	16109.00	1.631000	2.372000
0.000000	17900.00	1.679000	2.427000
0.000000	19869.00	1.724000	2.481000
0.000000	22036.00	1.766000	2.533000
0.000000	24420.00	1.806000	2.583000
0.000000	27042.00	1.846000	2.630000
0.000000	29926.00	1.885000	2.674000
0.000000	33099.00	1.921000	2.713000
0.000000	36589.00	1.953000	2.747000
0.000000	40428.00	1.980000	2.773000
0.000000	44650.00	2.000000	2.792000
0.000000	49295.00	2.010000	2.802000
0.000000	54405.00	2.010000	2.802000

(SITE 14)

5000.000	0.000000	2.447000	1.378000
5000.000	200.0000	2.447000	1.378000
5000.000	400.0000	2.897000	1.998000
5000.000	620.0000	3.203000	1.738000
5000.000	862.0000	3.357000	1.394000
5000.000	1128.000	3.420000	1.154000
5000.000	1421.000	3.417000	1.049000
5000.000	1743.000	3.367000	1.060000
5000.000	2097.000	3.283000	1.144000
5000.000	2487.000	3.174000	1.260000
5000.000	2916.000	3.042000	1.384000
5000.000	3388.000	2.884000	1.503000
5000.000	3906.000	2.686000	1.611000
5000.000	4477.000	2.441000	1.707000
5000.000	5105.000	2.148000	1.791000
5000.000	5795.000	1.830000	1.864000
5000.000	6555.000	1.535000	1.929000
5000.000	7390.000	1.331000	1.988000
5000.000	8309.000	1.256000	2.043000
5000.000	9320.000	1.286000	2.096000
5000.000	10432.00	1.364000	2.147000
5000.000	11655.00	1.451000	2.197000
5000.000	13000.00	1.527000	2.248000
5000.000	14481.00	1.590000	2.300000
5000.000	16109.00	1.642000	2.352000
5000.000	17900.00	1.687000	2.405000
5000.000	19869.00	1.728000	2.457000
5000.000	22036.00	1.768000	2.509000
5000.000	24420.00	1.807000	2.559000
5000.000	27042.00	1.847000	2.606000
5000.000	29926.00	1.885000	2.650000
5000.000	33099.00	1.922000	2.689000
5000.000	36589.00	1.955000	2.723000
5000.000	40428.00	1.983000	2.750000
5000.000	44650.00	2.002000	2.769000
5000.000	49295.00	2.013000	2.779000
5000.000	54405.00	2.013000	2.779000

(SITE 13)

22000.00	0.000000	2.788000	2.369000
22000.00	200.0000	2.788000	2.369000
22000.00	400.0000	3.279000	1.969000
22000.00	620.0000	3.300000	2.083000

22000.00	862.0000	3.059000	2.199000
22000.00	1128.000	2.744000	2.196000
22000.00	1421.000	2.455000	2.079000
22000.00	1743.000	2.266000	1.891000
22000.00	2097.000	2.167000	1.703000
22000.00	2487.000	2.115000	1.577000
22000.00	2916.000	2.098000	1.526000
22000.00	3388.000	2.101000	1.517000
22000.00	3906.000	2.090000	1.514000
22000.00	4477.000	2.025000	1.505000
22000.00	5105.000	1.872000	1.493000
22000.00	5795.000	1.620000	1.487000
22000.00	6555.000	1.282000	1.496000
22000.00	7390.000	0.9050000	1.522000
22000.00	8309.000	0.5610000	1.562000
22000.00	9320.000	0.3150000	1.615000
22000.00	10432.00	0.2010000	1.677000
22000.00	11655.00	0.2090000	1.746000
22000.00	13000.00	0.3090000	1.821000
22000.00	14481.00	0.4640000	1.899000
22000.00	16109.00	0.6440000	1.980000
22000.00	17900.00	0.8240000	2.060000
22000.00	19869.00	0.9910000	2.138000
22000.00	22036.00	1.138000	2.213000
22000.00	24420.00	1.265000	2.283000
22000.00	27042.00	1.372000	2.348000
22000.00	29926.00	1.463000	2.407000
22000.00	33099.00	1.540000	2.459000
22000.00	36589.00	1.603000	2.504000
22000.00	40428.00	1.654000	2.539000
22000.00	44650.00	1.691000	2.562000
22000.00	49295.00	1.712000	2.574000
22000.00	54405.00	1.712000	2.574000

(SITE 4)

70000.00	0.000000	1.554000	1.845000
70000.00	200.0000	1.554000	1.845000
70000.00	400.0000	2.760000	1.756000
70000.00	620.0000	2.235000	2.106000
70000.00	862.0000	1.742000	2.349000
70000.00	1128.000	1.997000	2.479000
70000.00	1421.000	2.239000	2.533000
70000.00	1743.000	2.325000	2.542000
70000.00	2097.000	2.304000	2.527000
70000.00	2487.000	2.254000	2.504000

70000.00	2916.000	2.230000	2.486000
70000.00	3388.000	2.241000	2.478000
70000.00	3906.000	2.262000	2.479000
70000.00	4477.000	2.256000	2.482000
70000.00	5105.000	2.197000	2.475000
70000.00	5795.000	2.076000	2.447000
70000.00	6555.000	1.905000	2.386000
70000.00	7390.000	1.719000	2.285000
70000.00	8309.000	1.561000	2.149000
70000.00	9320.000	1.457000	1.989000
70000.00	10432.00	1.402000	1.831000
70000.00	11655.00	1.373000	1.702000
70000.00	13000.00	1.354000	1.619000
70000.00	14481.00	1.335000	1.583000
70000.00	16109.00	1.308000	1.583000
70000.00	17900.00	1.271000	1.605000
70000.00	19869.00	1.226000	1.638000
70000.00	22036.00	1.182000	1.679000
70000.00	24420.00	1.147000	1.724000
70000.00	27042.00	1.129000	1.773000
70000.00	29926.00	1.131000	1.822000
70000.00	33099.00	1.154000	1.870000
70000.00	36589.00	1.193000	1.915000
70000.00	40428.00	1.237000	1.953000
70000.00	44650.00	1.277000	1.983000
70000.00	49295.00	1.300000	2.000000
70000.00	54405.00	1.300000	2.000000

(SITE 3)

95000.00	0.000000	1.778000	1.833000
95000.00	200.0000	1.778000	1.833000
95000.00	400.0000	2.709000	1.885000
95000.00	620.0000	2.337000	1.786000
95000.00	862.0000	1.749000	1.747000
95000.00	1128.000	1.779000	1.794000
95000.00	1421.000	2.067000	1.893000
95000.00	1743.000	2.330000	2.017000
95000.00	2097.000	2.514000	2.150000
95000.00	2487.000	2.632000	2.279000
95000.00	2916.000	2.710000	2.390000
95000.00	3388.000	2.765000	2.476000
95000.00	3906.000	2.809000	2.529000
95000.00	4477.000	2.845000	2.544000
95000.00	5105.000	2.874000	2.517000
95000.00	5795.000	2.893000	2.447000

95000.00	6555.000	2.898000	2.332000
95000.00	7390.000	2.886000	2.179000
95000.00	8309.000	2.851000	1.998000
95000.00	9320.000	2.785000	1.810000
95000.00	10432.00	2.673000	1.642000
95000.00	11655.00	2.498000	1.515000
95000.00	13000.00	2.240000	1.442000
95000.00	14481.00	1.884000	1.422000
95000.00	16109.00	1.437000	1.442000
95000.00	17900.00	0.9540000	1.486000
95000.00	19869.00	0.5570000	1.542000
95000.00	22036.00	0.3470000	1.602000
95000.00	24420.00	0.3170000	1.661000
95000.00	27042.00	0.4070000	1.716000
95000.00	29926.00	0.5600000	1.767000
95000.00	33099.00	0.7360000	1.812000
95000.00	36589.00	0.9050000	1.850000
95000.00	40428.00	1.050000	1.879000
95000.00	44650.00	1.161000	1.894000
95000.00	49295.00	1.222000	1.901000
95000.00	54405.00	1.222000	1.901000

(SITE 8)

104000.0	0.000000	1.211000	1.023000
104000.0	200.0000	1.211000	1.023000
104000.0	400.0000	2.127000	1.114000
104000.0	620.0000	2.439000	1.270000
104000.0	862.0000	2.512000	1.499000
104000.0	1128.000	2.612000	1.727000
104000.0	1421.000	2.751000	1.930000
104000.0	1743.000	2.890000	2.103000
104000.0	2097.000	3.005000	2.247000
104000.0	2487.000	3.091000	2.362000
104000.0	2916.000	3.150000	2.450000
104000.0	3388.000	3.190000	2.511000
104000.0	3906.000	3.216000	2.546000
104000.0	4477.000	3.233000	2.553000
104000.0	5105.000	3.241000	2.534000
104000.0	5795.000	3.241000	2.489000
104000.0	6555.000	3.230000	2.419000
104000.0	7390.000	3.204000	2.328000
104000.0	8309.000	3.155000	2.223000
104000.0	9320.000	3.078000	2.109000
104000.0	10432.00	2.965000	1.997000
104000.0	11655.00	2.807000	1.895000

104000.0	13000.00	2.601000	1.807000
104000.0	14481.00	2.348000	1.737000
104000.0	16109.00	2.061000	1.684000
104000.0	17900.00	1.766000	1.647000
104000.0	19869.00	1.496000	1.623000
104000.0	22036.00	1.285000	1.610000
104000.0	24420.00	1.152000	1.608000
104000.0	27042.00	1.103000	1.615000
104000.0	29926.00	1.129000	1.630000
104000.0	33099.00	1.207000	1.650000
104000.0	36589.00	1.307000	1.672000
104000.0	40428.00	1.404000	1.692000
104000.0	44650.00	1.474000	1.708000
104000.0	49295.00	1.512000	1.717000
104000.0	54405.00	1.512000	1.717000

(SITE 1)

115000.0	0.000000	2.109000	2.115000
115000.0	200.0000	2.109000	2.115000
115000.0	400.0000	2.784000	2.369000
115000.0	620.0000	2.673000	2.537000
115000.0	862.0000	2.431000	2.631000
115000.0	1128.000	2.433000	2.704000
115000.0	1421.000	2.617000	2.759000
115000.0	1743.000	2.819000	2.799000
115000.0	2097.000	2.967000	2.824000
115000.0	2487.000	3.054000	2.836000
115000.0	2916.000	3.094000	2.834000
115000.0	3388.000	3.110000	2.820000
115000.0	3906.000	3.122000	2.791000
115000.0	4477.000	3.142000	2.750000
115000.0	5105.000	3.177000	2.696000
115000.0	5795.000	3.225000	2.630000
115000.0	6555.000	3.280000	2.553000
115000.0	7390.000	3.333000	2.465000
115000.0	8309.000	3.375000	2.366000
115000.0	9320.000	3.395000	2.259000
115000.0	10432.00	3.384000	2.145000
115000.0	11655.00	3.333000	2.027000
115000.0	13000.00	3.229000	1.911000
115000.0	14481.00	3.062000	1.799000
115000.0	16109.00	2.819000	1.699000
115000.0	17900.00	2.489000	1.613000
115000.0	19869.00	2.074000	1.545000
115000.0	22036.00	1.608000	1.497000

115000.0	24420.00	1.198000	1.469000
115000.0	27042.00	0.9930000	1.459000
115000.0	29926.00	1.030000	1.463000
115000.0	33099.00	1.218000	1.478000
115000.0	36589.00	1.448000	1.498000
115000.0	40428.00	1.651000	1.518000
115000.0	44650.00	1.787000	1.536000
115000.0	49295.00	1.856000	1.546000
115000.0	54405.00	1.856000	1.546000

(SITE 2)

122000.0	0.000000	1.999000	1.957000
122000.0	200.0000	1.999000	1.957000
122000.0	400.0000	2.797000	2.238000
122000.0	620.0000	2.766000	2.338000
122000.0	862.0000	2.570000	2.373000
122000.0	1128.000	2.514000	2.409000
122000.0	1421.000	2.583000	2.457000
122000.0	1743.000	2.666000	2.513000
122000.0	2097.000	2.704000	2.570000
122000.0	2487.000	2.693000	2.622000
122000.0	2916.000	2.664000	2.664000
122000.0	3388.000	2.661000	2.693000
122000.0	3906.000	2.710000	2.706000
122000.0	4477.000	2.816000	2.704000
122000.0	5105.000	2.961000	2.684000
122000.0	5795.000	3.122000	2.646000
122000.0	6555.000	3.280000	2.591000
122000.0	7390.000	3.420000	2.517000
122000.0	8309.000	3.534000	2.426000
122000.0	9320.000	3.616000	2.318000
122000.0	10432.00	3.662000	2.197000
122000.0	11655.00	3.666000	2.065000
122000.0	13000.00	3.621000	1.929000
122000.0	14481.00	3.515000	1.795000
122000.0	16109.00	3.334000	1.670000
122000.0	17900.00	3.058000	1.562000
122000.0	19869.00	2.666000	1.475000
122000.0	22036.00	2.146000	1.414000
122000.0	24420.00	1.541000	1.378000
122000.0	27042.00	1.031000	1.365000
122000.0	29926.00	0.9330000	1.371000
122000.0	33099.00	1.182000	1.390000
122000.0	36589.00	1.522000	1.416000
122000.0	40428.00	1.813000	1.441000

122000.0	44650.00	1.994000	1.464000
122000.0	49295.00	2.080000	1.477000
122000.0	54405.00	2.080000	1.477000

(SITE 6)

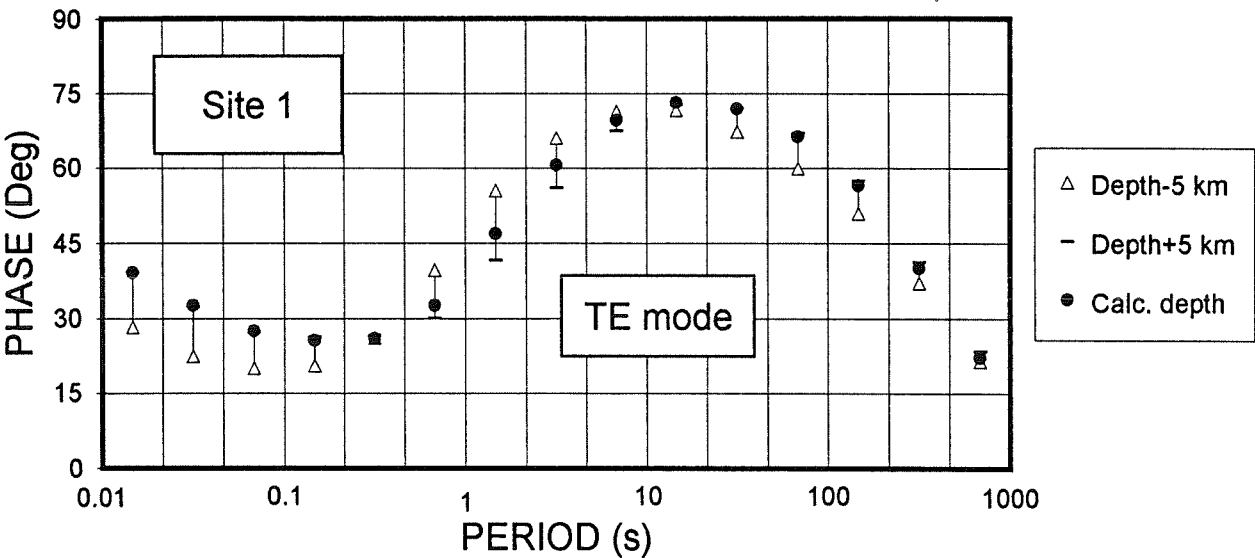
159000.0	0.000000	1.808000	1.133000
159000.0	200.0000	1.808000	1.133000
159000.0	400.0000	1.980000	1.096000
159000.0	620.0000	2.318000	0.8280000
159000.0	862.0000	2.562000	0.8350000
159000.0	1128.000	2.751000	1.083000
159000.0	1421.000	2.835000	1.415000
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159000.0	2487.000	2.230000	2.215000
159000.0	2916.000	1.934000	2.379000
159000.0	3388.000	1.855000	2.501000
159000.0	3906.000	2.037000	2.585000
159000.0	4477.000	2.345000	2.637000
159000.0	5105.000	2.669000	2.660000
159000.0	5795.000	2.960000	2.657000
159000.0	6555.000	3.199000	2.628000
159000.0	7390.000	3.386000	2.577000
159000.0	8309.000	3.523000	2.504000
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159000.0	11655.00	3.651000	2.174000
159000.0	13000.00	3.601000	2.038000
159000.0	14481.00	3.500000	1.896000
159000.0	16109.00	3.350000	1.754000
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159000.0	22036.00	2.651000	1.410000
159000.0	24420.00	2.404000	1.346000
159000.0	27042.00	2.212000	1.312000
159000.0	29926.00	2.105000	1.307000
159000.0	33099.00	2.067000	1.323000
159000.0	36589.00	2.060000	1.351000
159000.0	40428.00	2.055000	1.383000
159000.0	44650.00	2.043000	1.410000
159000.0	49295.00	2.033000	1.425000
159000.0	54405.00	2.033000	1.425000

APPENDIX D

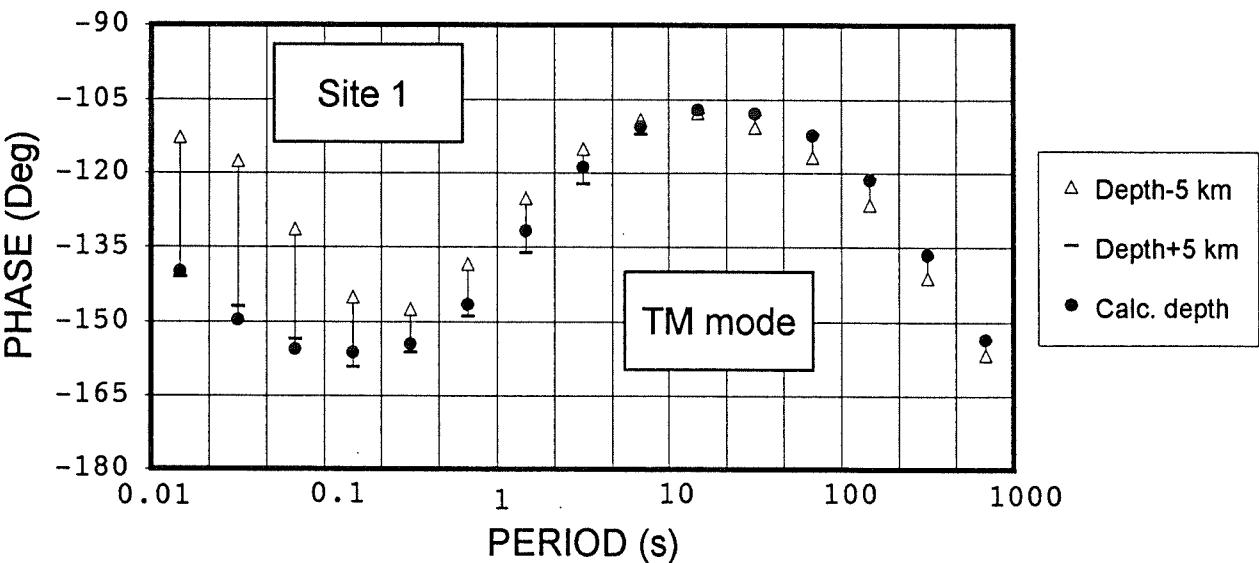
PLOTS FROM THE STABILITY TEST

Additional plots from the 2-D forward modelling for the stability test carried out in Section (4.4). The first three pages contain results for the test soundings 1, 6, and 14 due to 5 km variations in depth of the model conductor for the E and B polarization modes. The following three pages show the phase response to resistivity variations of the model conductor for the same soundings and polarization modes, whereas the last three pages show the resistivity response to 5 km depth variations of the model conductor.

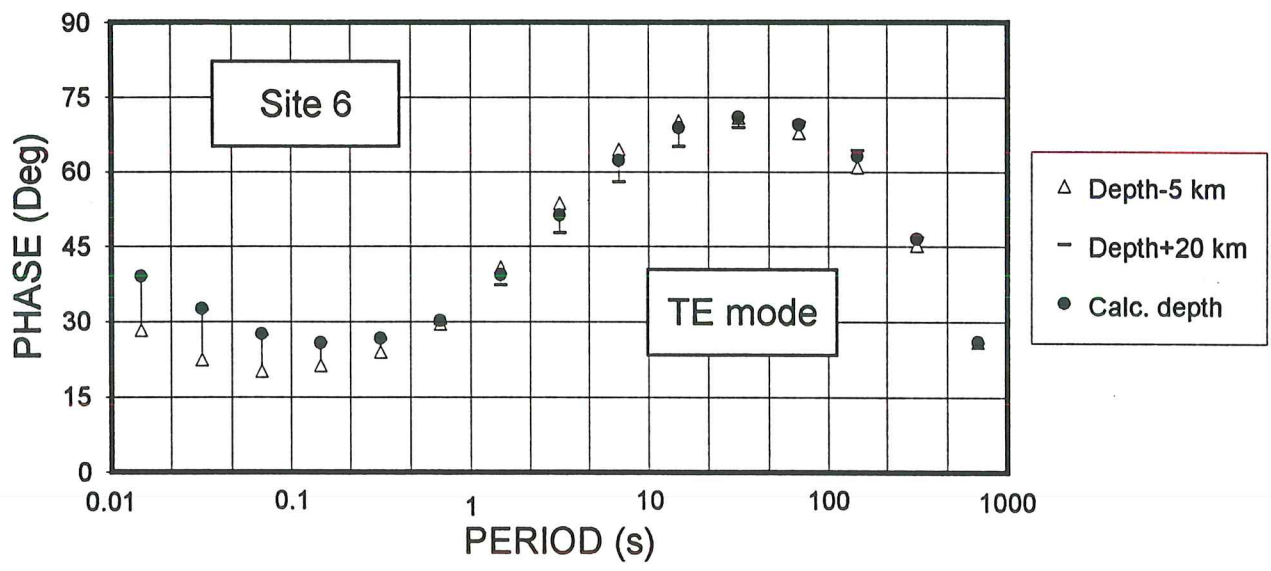
PHASE RESPONSE TO 5 KM DEPTH VARIATION



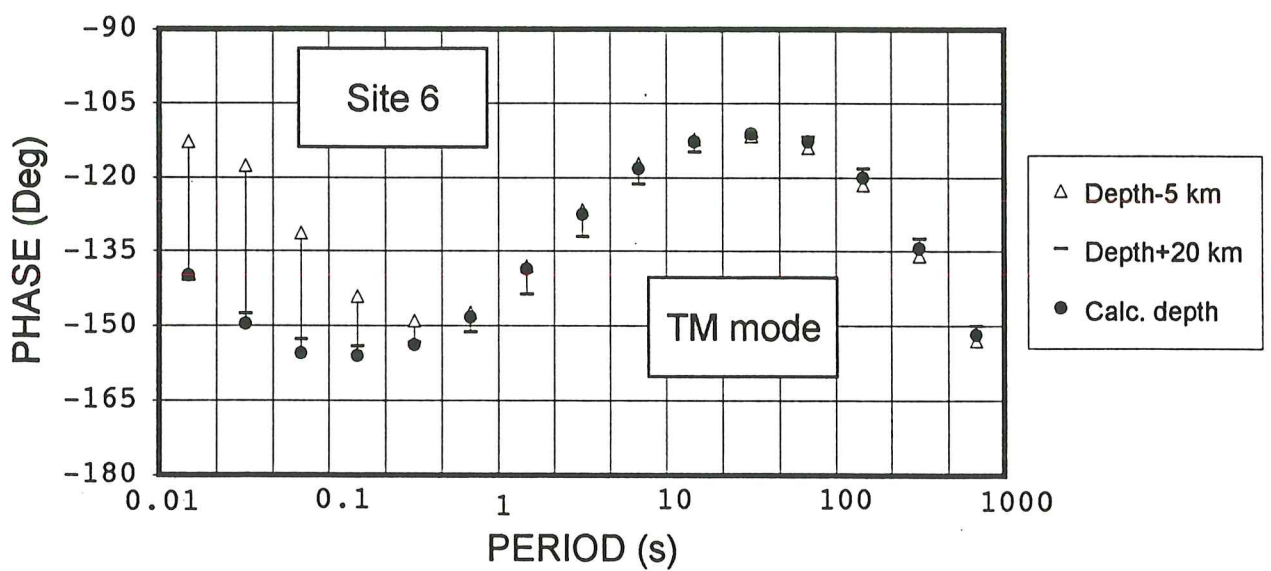
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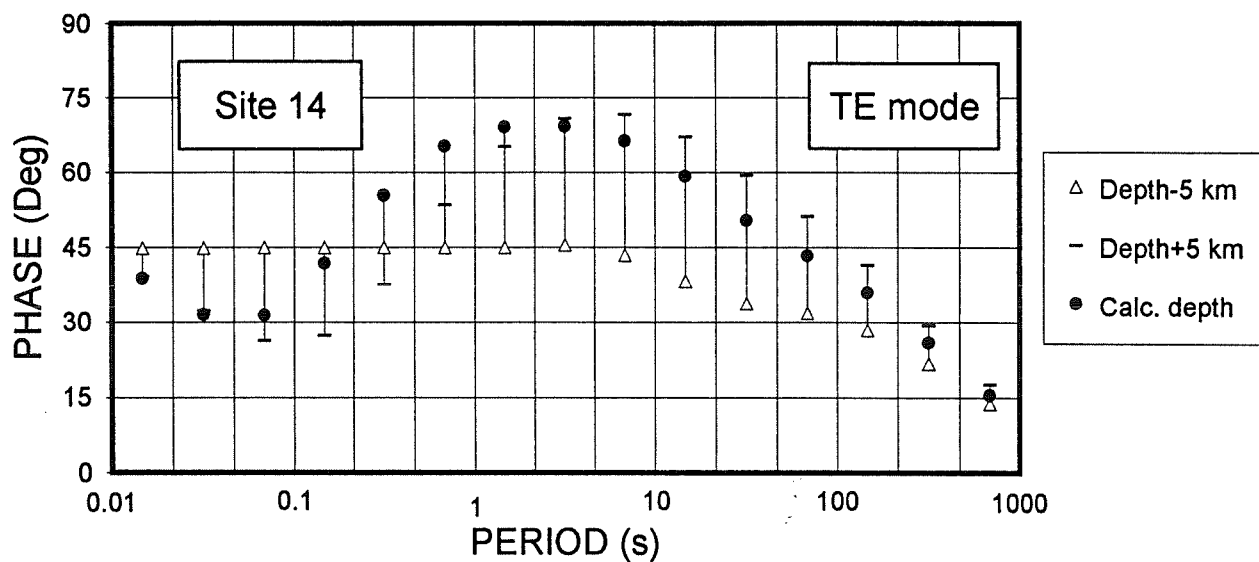
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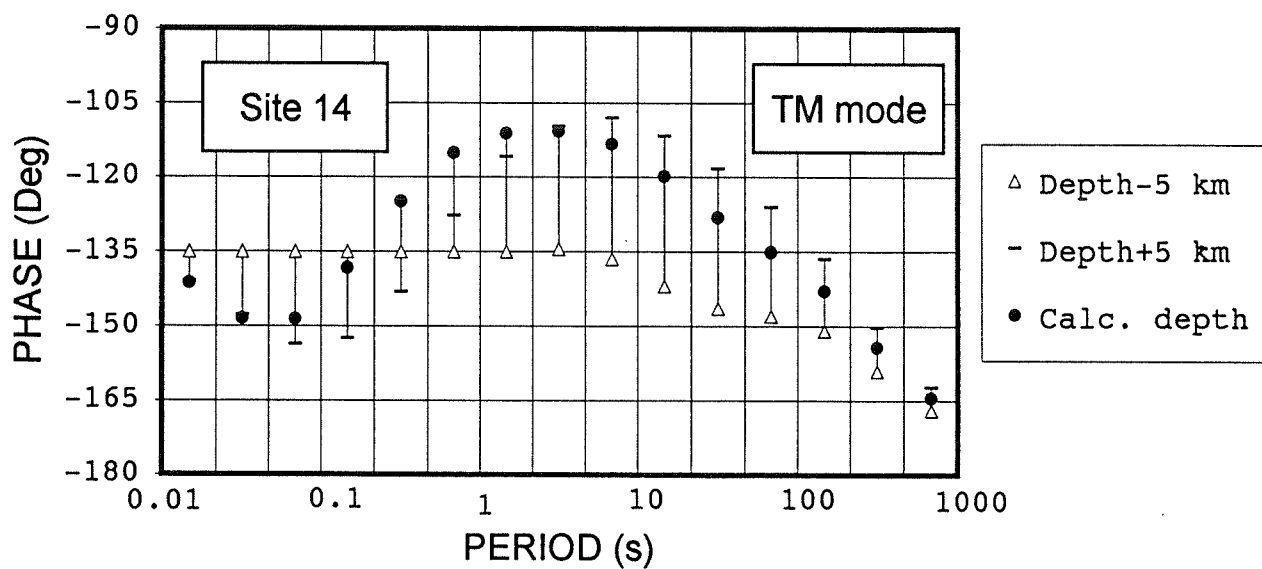
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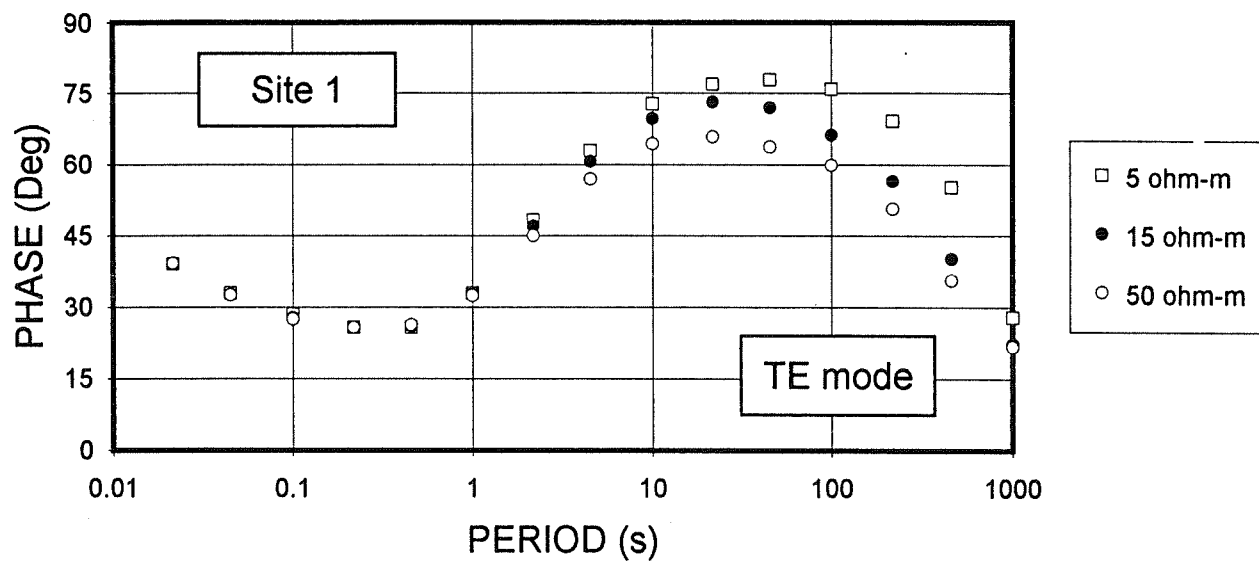
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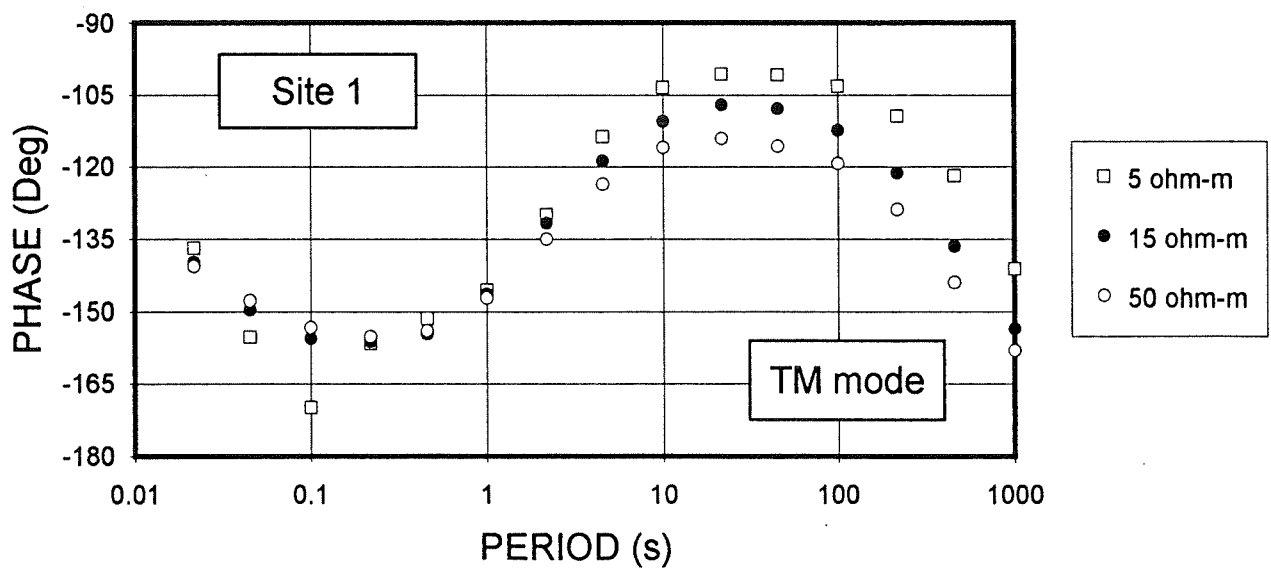
PHASE RESPONSE TO 5KM DEPTH VARIATION



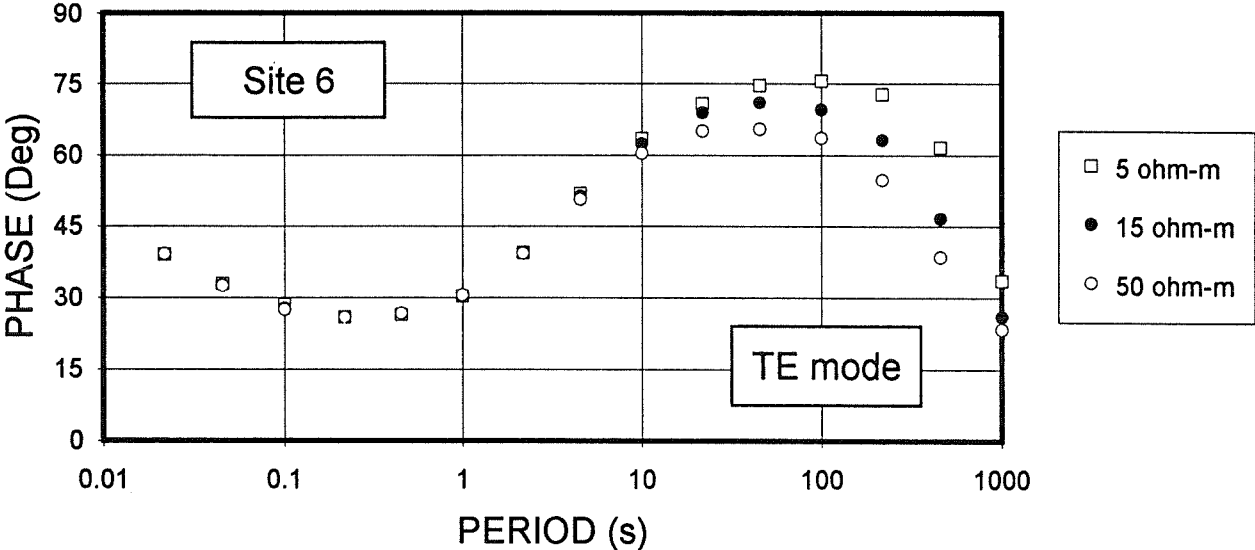
PHASE RESPONSE TO RESISTIVITY VARIATIONS



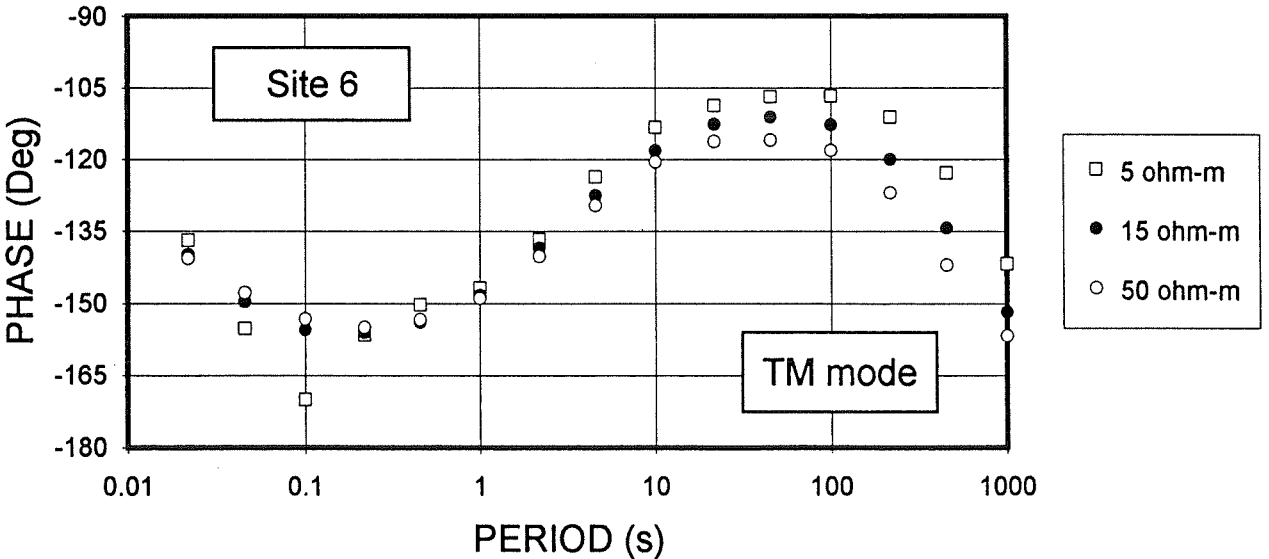
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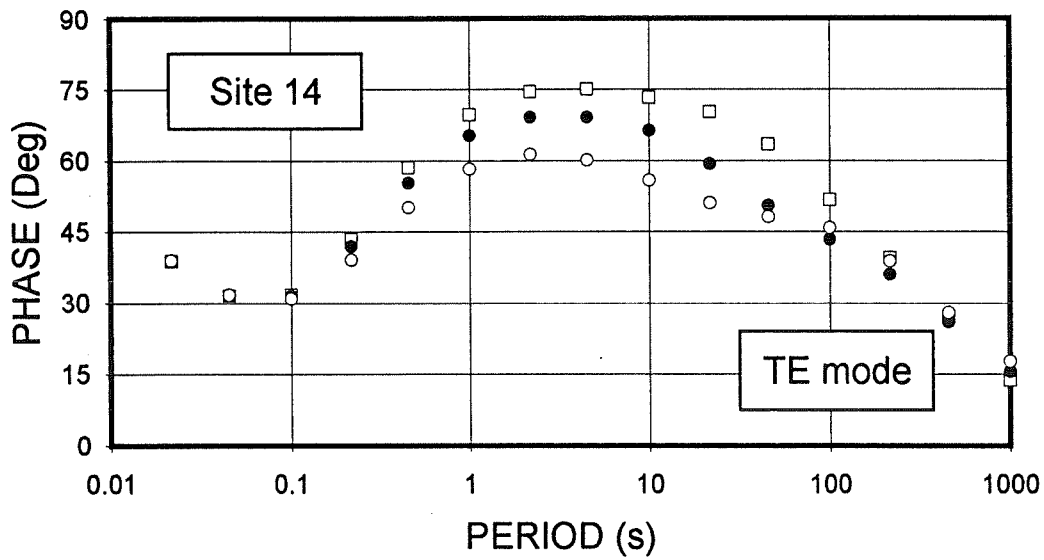
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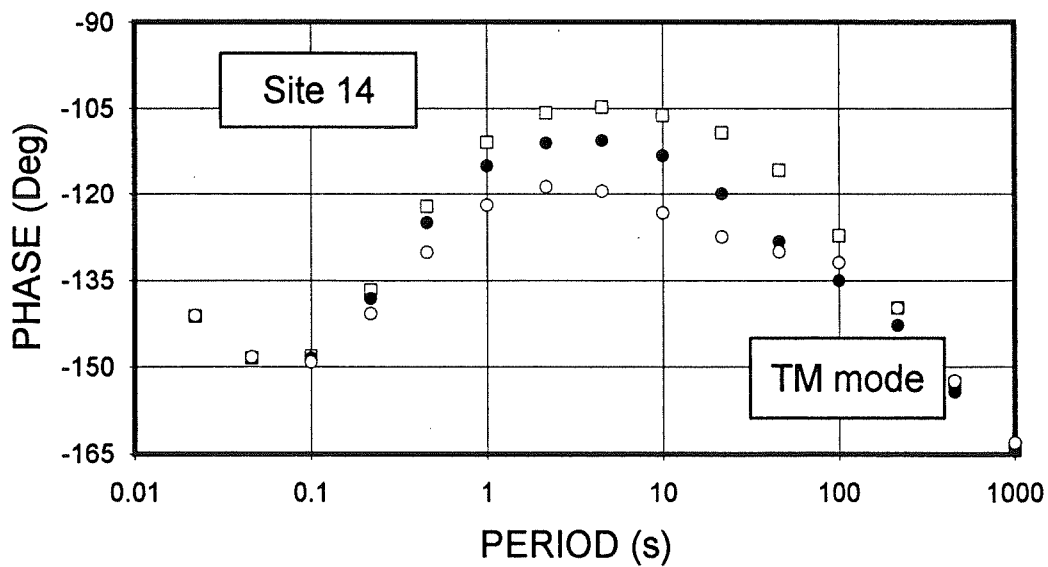
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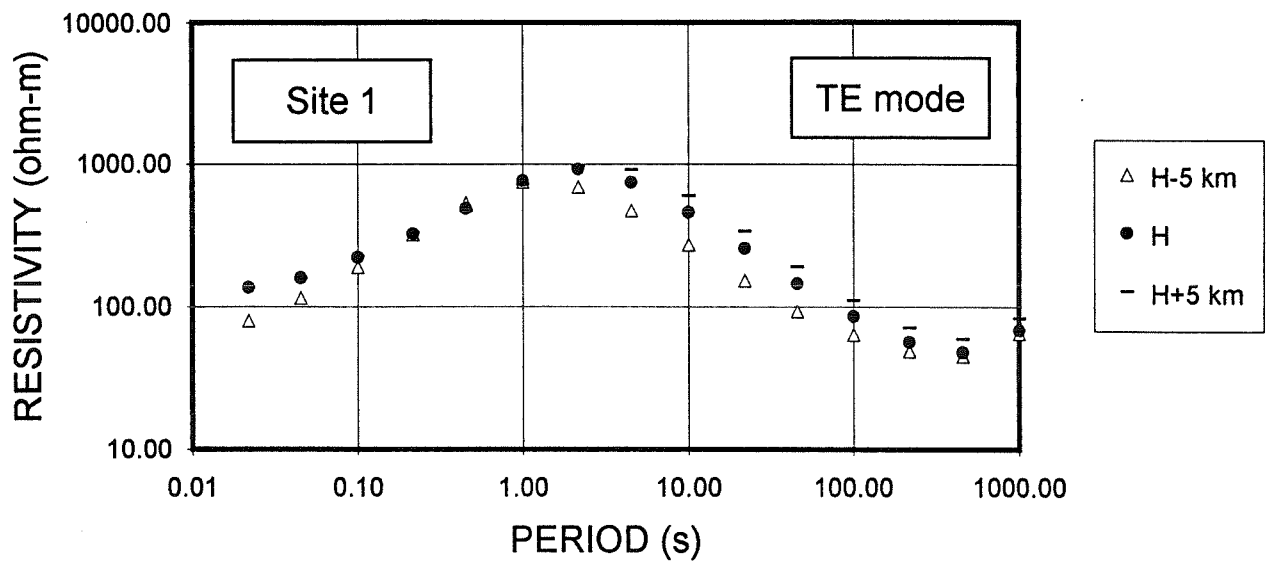
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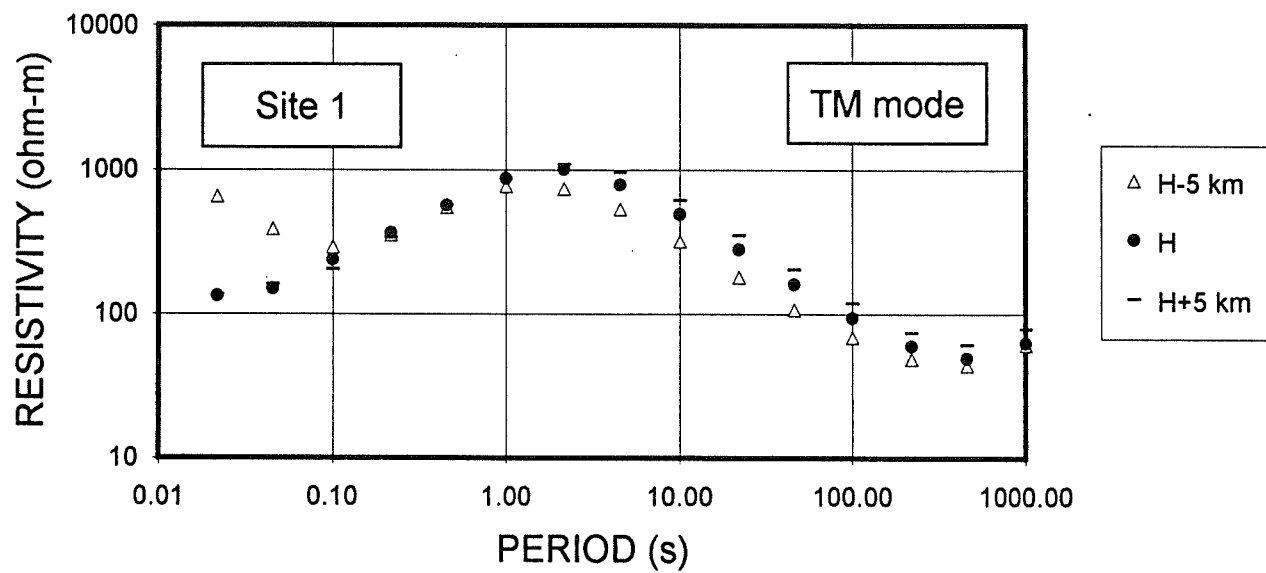
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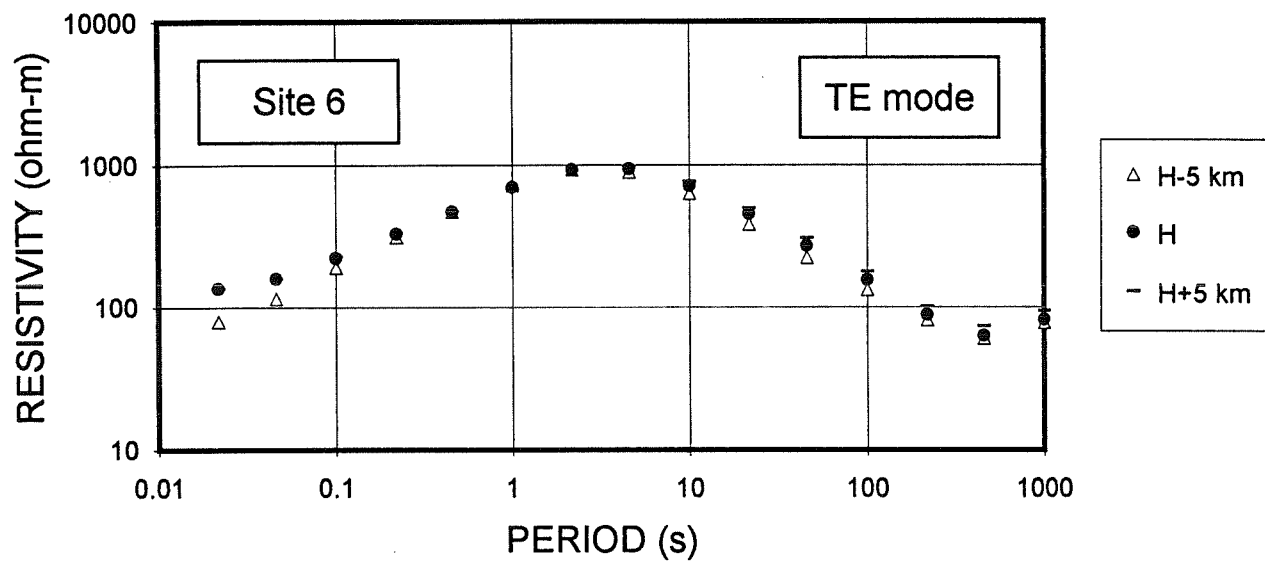
RESISTIVITY RESPONSE TO DEPTH VARIATIONS



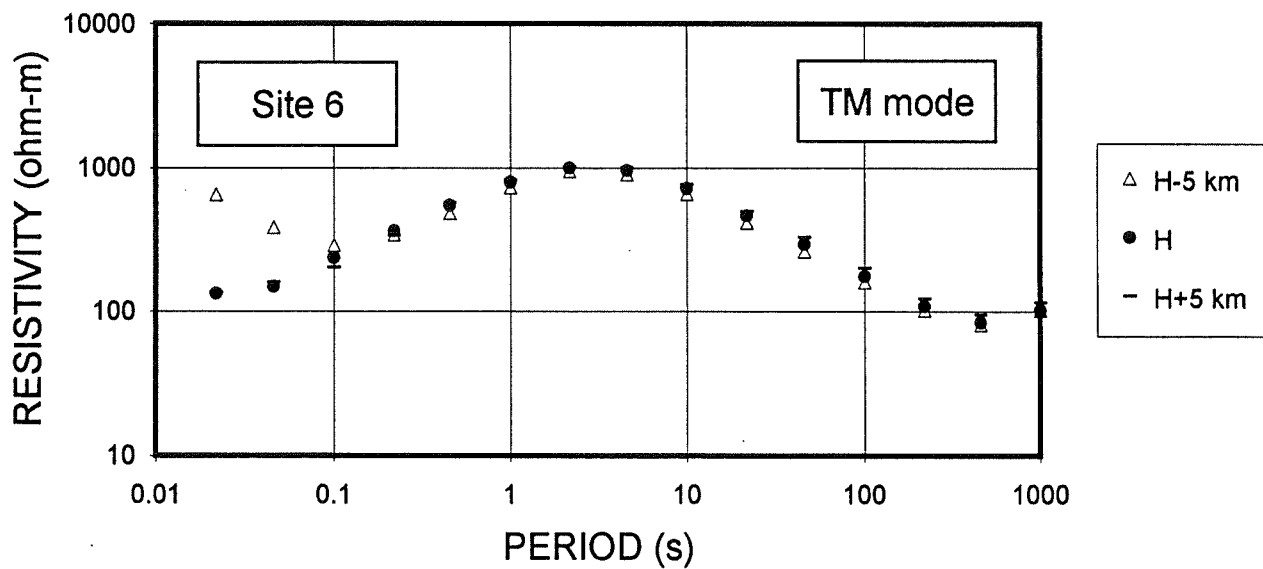
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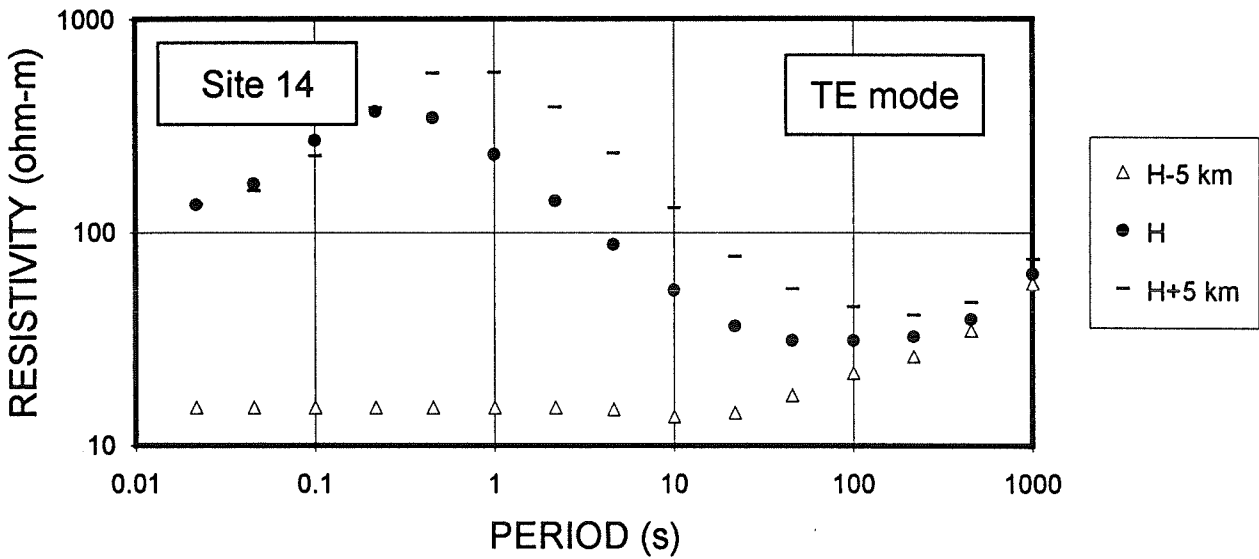
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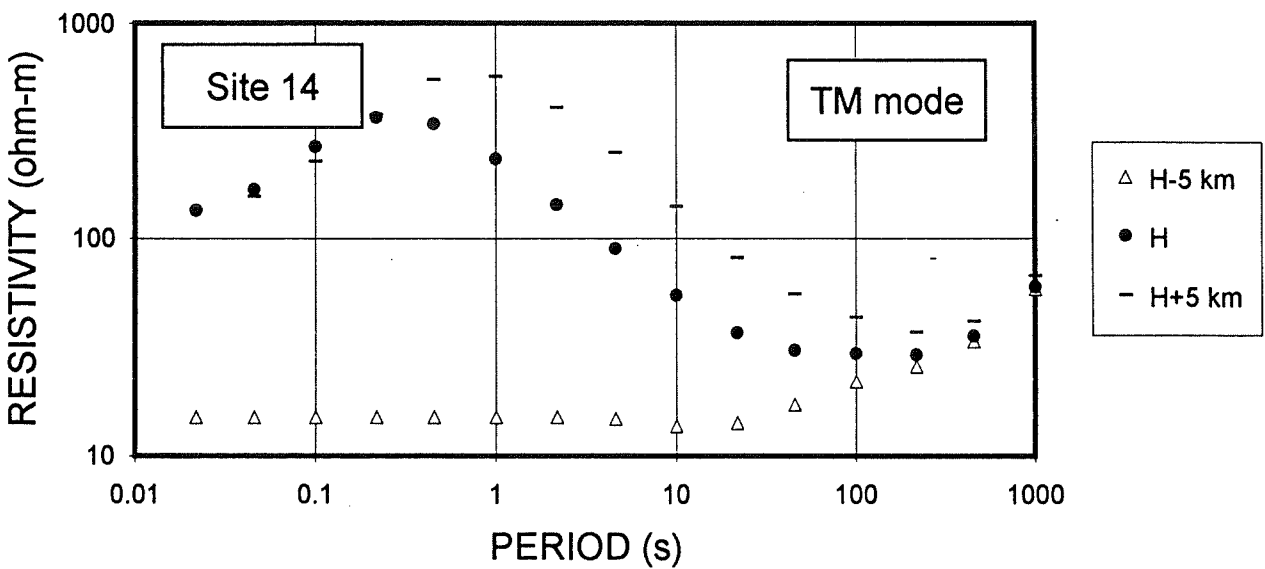
RESISTIVITY RESPONSE TO DEPTH VARIATIONS



RESISTIVITY RESPONSE TO DEPTH VARIATIONS



RESISTIVITY RESPONSE TO DEPTH VARIATIONS



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