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On the importance of offshore data for magnetotelluric studies of ocean-continent subduction systems

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[1] The presence of water in the mantle wedge overlying a subduction zone is expected to significantly enhance electrical conductivity, raising it above that of the cold subducting slab, or surrounding regions of dehydrated mantle. This suggests that magnetotelluric (MT) transects across subduction systems, measuring regional electrical conductivity structure, might be able to indirectly trace the pathways of water migration into the mantle. For ocean-continent subduction, it is logistically simpler to collect MT transects on the continental side of the system. However, we show that such land data are relatively insensitive to details of the electrical connections between the ocean and mantle. In contrast, seafloor measurements on the landward and seaward side of the trench are very sensitive to these electrical connections, and are essential to understanding the electrical structure of the entire subduction system. In particular, the conductivity structure of the hydrated mantle wedge overlying the slab can only be studied using offshore MT data. We demonstrate this result using a model of an ocean-continent system, although our results can be generalised to other subduction geometries. *INDEX TERMS:* 3094 Marine Geology and Geophysics: Instruments and techniques; 8105 Tectonophysics: Continental margins and sedimentary basins

1. Introduction

[2] There is general agreement that water plays an important role in the volcanic processes occurring beneath convergent margins. Water is carried by downgoing hydrated sediments and oceanic crust into the mantle where it is released [*Bebout*, 1996; *Peacock*, 1990, 1996; *Davies and Stevenson*, 1992], affecting the rheology of the circulating mantle [*Hirth and Kohlstedt*, 1996] and the subsequent melting processes responsible for arc-volcanism [*Tatsumi and Eggins*, 1995]. Amphibole is the principal hydrous phase in the subducting slab, although other phases may also play a role in slab dehydration, depending on the P-T conditions on descent [*Anderson et al.*, 1976; *Fyfe et al.*, 1978; *Pawley and Holloway*, 1993]. The depths at which compositionally bound water is released from sediments are not well known, although evidence from fossil convergent plate margins indicate that in some subduction zones sediments are carried to depths of 30–70 km [*Ito et al.*, 1983], and there is abundant evidence from ^{10}Be concentrations in arc volcanics [*Tera et al.*, 1986; *Morris et al.*, 1990; *Plank and Langmuir*, 1993] that sediments carry compositionally bound water well into the mantle and participate in back-arc melting processes.

[3] Models of amphibole-derived water migration from the slab into the mantle wedge are given by *Davies and Stevenson* [1992] and *Davies and Bickle* [1991]. Once the wet solidus is crossed, melting occurs and the melt percolates upwards into the crust. The size of the water-rich region depends on the thermal structure of the mantle wedge (which is in turn dependent on slab dip, age, and the feed-back effect of melt on flow patterns [*Peacock*, 1996]), but is a feature that can be constrained by MT measurements. This flushing of volatiles provides a geochemical link between subducted material and both the magmatic processes occurring on the continent and components that are recycled back into the deep mantle. The amount of water carried into the system, the lateral pathways it takes, and the depths over which it is released into the mantle wedge are critical parameters which are poorly constrained by existing geophysical and geochemical data.

[4] It is now widely accepted that water has a substantial impact on mantle electrical conductivity at very low concentrations [*Karato*, 1990]. The presence of water in mantle materials may enhance conductivity in several ways and a discussion of these is given in *Hirth et al.* [2000] and *Lizarralde et al.* [1995]. The depth interval over which water is released from the slab, interacts with the mantle, and ultimately initiates melting will be a region which strongly influences MT measurements. Figure 1a shows a thermal model of a subduction zone [*Peacock and Wang*, 1999] used to generate three conductivity models. The first model (Figure 1b) assumes a dry composition in which conductivity depends on temperature alone and which is based on laboratory data [*Constable et al.*, 1992]. We have calculated the predicted impact of water on conductivity assuming an isotropic conductivity structure (Figure 1c) and an a-axis aligned structure (Figure 1d) with the conductivity along the a-axis shown. In both Figures 1c and 1d we have assumed that olivine is saturated in water following the relationship given by *Lizarralde et al.* [1995] based on laboratory data of *Bai and Kohlstedt* [1992]. We also assume that water is released through amphibole breakdown occurring at around 60km depth [*Pawley and Holloway*, 1993]. Clearly, in this model, there is a large conductivity contrast between the cold descending slab and the overlying mantle wedge. This contrast is enhanced if water is introduced into the mantle.

[5] Given that the wedge of mantle beneath the overriding plate and above the subducting slab will be a conductive feature, it is tempting to suggest that MT measurements made on the overriding plate (or on land for an ocean-continent collision) would be sufficient to constrain key subduction structures. In fact, the full impact of an electrical connection between the seafloor and mantle on MT data, and hence the ability of an MT experiment to constrain critical dehydration and melting processes, is only realized if offshore data are collected on the subducting plate, on the seaward side of the trench. One approach to demonstrating this would be to use the models shown in Figure 1 as the basis for a numerical study, although these models are open to criticism on the basis of the rheological and compositional assumptions implicit to them. Instead, we have based our study on a model derived from field MT measurements made across the Andean subduction system [*Echternacht et al.*, 1997], which has the advantage of using a more realistic resistivity structure as a starting point. We

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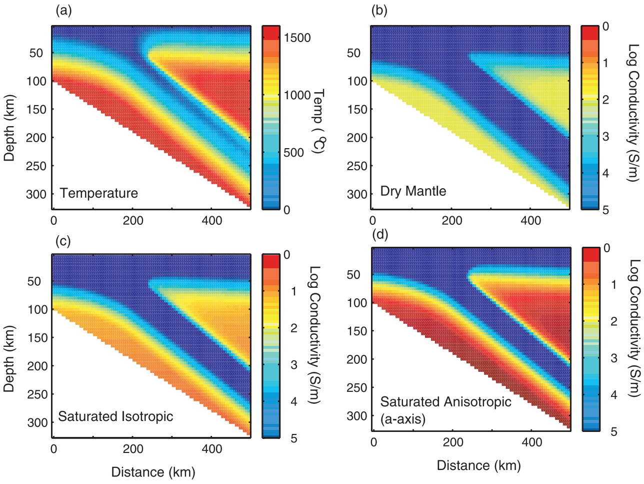

Figure 1. Numerical calculations of subduction zone conductivity structure for (a) a thermal structure based on a model of *Peacock and Wang* [1999]. (b) conductivity of a dry mantle composition shows the thermal signature of the mantle wedge contrasted against the cool slab. (c) isotropic and (d) anisotropic water saturated compositions.

have adjusted resistivities within the subducting slab and wedge (which are not constrained by the data of *Echternacht et al.* [1997]) to demonstrate through synthetic forward modeling the expected impact of wedge hydration on MT responses. Our model is based on Andean structure, but is not meant to be a further analysis of Andean data; our results can be generalised to other subduction geometries.

2. Model Study: The Andean System

[6] The Andean region near 21°S has been a particular international focus in the past decade and a half, with extensive MT and magnetovariation surveys completed [*Schwarz and Kruger*, 1997; *Echternacht et al.*, 1997]. These studies identify a zone of extraordinarily high conductivity that extends from the Precordillera to east of the Altiplano. The conductance (integrated conductivity) of much of this zone is so high that it implies massive amounts of partial melt (20% in the entire lower crust below 20 km) if it is due entirely to silicate melt. However, to date measurements have not been made on the ocean side of the subduction zone. Lack of such data means that there are few constraints available on the electrical structure of the downgoing slab or on the important processes occurring in the mantle wedge above it. To demonstrate this fact, we have generated a numerical model of the Andean system based on the results of *Echternacht et al.* [1997]. We have examined differences in forward responses resulting from perturbations to parts of the downgoing slab and overlying mantle wedge. The parts of the model perturbed are referred to as units (a) through (f) and are labelled and described in Figure 2. Below, we refer to the TE and TM mode decomposition of MT responses valid over a 2D medium (see *Wannamaker et al.* [1989a] for a complete discussion).

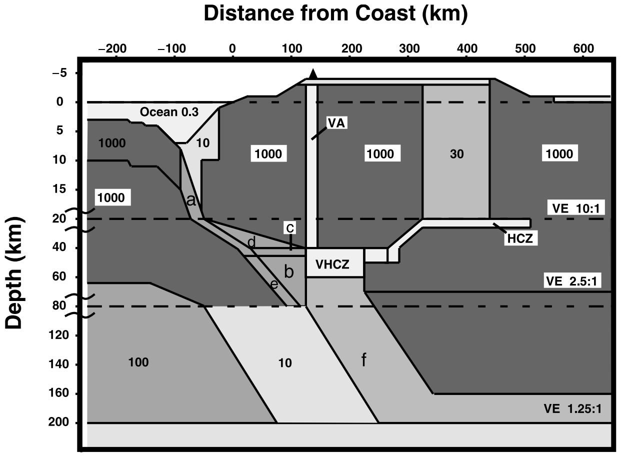

Figure 2. Cartoon of the resistivity structure used in the model study. The resistivities of the main parts of the model are as labelled. The VHCZ and HCZ have resistivities of 1 Ωm and the VA has a resistivity of 10 Ωm. The upper (0–40 km depth) and lower (40–80 km depth) Nazca plate are units (a) and (e), the mantle wedge is defined by units (b)–(d), and the asthenospheric corner flow region is (f). The resistivities of these elements (a–f) were varied as described in the text. The model continues for 2000 km on the western side.

[7] We first of all consider the effects on the MT response of a conductive subducting slab that provides an electrical connection from seafloor to mantle. Such electrical connections have previously been observed in the Cascadia subduction system [*Wannamaker et al.*, 1989a, b; *Kurtz et al.*, 1990]. Figure 3 shows the phase difference between Models A and B for the TE and TM modes as a function of distance from the coast at two periods. Model A is a background, where units (a)–(e) have the same resistivity (1000 Ωm) as the surrounding regions. Model B contains a more conductive subducted Nazca plate (unit (a) has a resistivity of 50 Ωm) which is comparable to Cascadia [*Wannamaker et al.*, 1989b]. From Figure 3, one can conclude that 1) the presence of a conductive seafloor connecting the ocean to the mantle has a dramatic effect on both modes, 2) the anomalies are much larger offshore compared to onshore, and 3) the TE anomaly dies out rapidly with period while the TM anomaly is more persistent. These anomalies are 2–20 times the standard error of typical phase measurements. Similar anomalies are seen in the TM apparent resistivity but with low (order 1 Ωm) magnitude, while the TE apparent resistivity is not a useful discriminant.

[8] We next consider smaller perturbations of the mantle wedge conductivity to demonstrate sensitivity to variations in the distri-

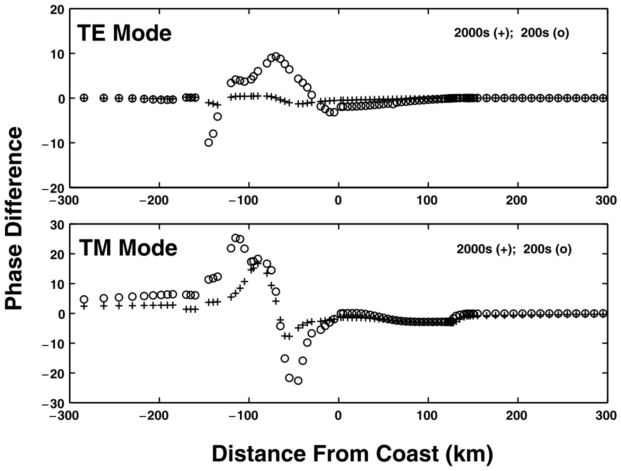

Figure 3. The phase difference between Model A (background model with resistive subducted slab and mantle wedge) and Model B (140 S conductance upper Nazca plate to 40 km; region (a) in Figure 2) as a function of distance, with 0 denoting the coastline. The + symbols are at 200 s period and the open circles are at 2000 s period. The difference between the two models is largest between the coast and the seaward side of the trench, and amounts to 2–20 times a conservative phase uncertainty of 3°.

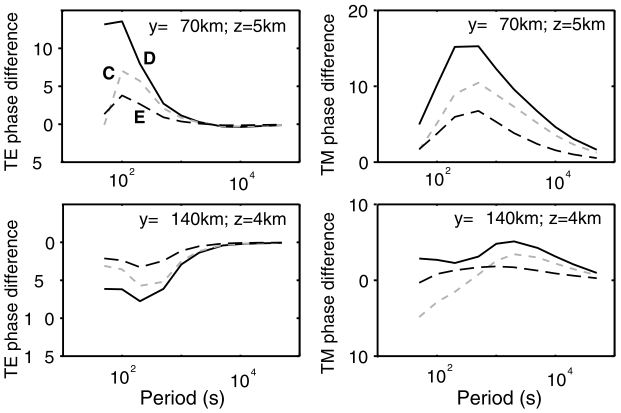

Figure 4. The phase difference between three models (C, D, and E) and Model B, as a function of period at 70 km and 140 km offshore (straddling the trench). The solid line is for all of the mantle wedge units (b–d) hydrated and conductive (Model D); the dark dashed line is for a conductive (50 Ωm) lower Nazca plate (unit e: Model E); and the light dashed line is for a resistive mantle wedge capped by a 10 Ωm conductor (unit c: Model C) connecting the ocean to the VHCZ. The differences between these three models are larger than a conservative value for the uncertainty to which phase can be measured.

bution of water as it leaves the slab. Figure 4 shows the TE and TM phase responses for three additional model changes differenced against that from Model B for clarity. The differences with Model A are even larger but tend to obscure the intermodel variations. Model C considers the effect of a 10 Ωm (500 S conductance) short (unit c) between the subducted seafloor unit and the VHCZ with the remaining mantle wedge units held at 1000 Ωm, simulating the effect of a water-rich layer trapped below a metamorphic boundary at 40 km depth. Model D considers a conductive (100 Ωm) mantle wedge in units (b), (c) and (d) simulating strong connection of the ocean through the upper subducted plate to the mantle wedge to the deeper asthenospheric corner (f in Figure 2.). Model E contains a resistive (1000 Ωm) mantle wedge but a slab conductor of 50 Ωm (or 140 S conductor) at (e) connecting the upper subducted Nazca plate (a) nearly but not directly to the Andean asthenosphere (f). In all cases, the TE anomaly is gone at a distance of 200 km offshore and is largely confined to periods below 1000 s. The TM anomaly generally persists to periods of over 10000 s and decays much more slowly offshore. In all cases, the difference between the anomalies is much larger than the uncertainty in a single phase measurement and is dominantly seen offshore rather than on land. This is also true for the TM mode apparent resistivity (not shown).

[9] In addition to the features directly associated with the subducted slab, models were run to test the effect of varying the conductance in the VHCZ, HCZ, and VA at offshore points. The TM mode data west of the coast are almost unaffected by either a reduction in the VHCZ conductance by a factor of 10 or the absence of the VA. This means that along-strike variations in these structures will not compromise structural interpretations based on offshore data. The offshore TE mode data are unaffected by the presence of the VA, but will provide constraints on the VHCZ conductance. Finally, changes in the resistivity of the asthenospheric corner below the VHCZ (unit f in Figure 2) has no effect on the TE mode, but does measurably affect the TM mode phase on the offshore side.

[10] To understand why offshore data are required to image subduction related structures beneath the continent, one needs to appreciate the physical basis for the coupling of the offshore and onshore data. Electromagnetic induction fields are globally determined, and it is not unusual for structures many kilometers offline to influence measurements at a point. An extreme example of sideways influence occurs with data near coastlines, especially when the oceanic and continental structures are strongly connected electrically, as appears to be the case at subduction zones [*Wannamaker et al.*, 1989b; *Kurtz et al.*, 1990]. This is because electric currents flowing near the coast mostly originate in and beneath the oceans, and unless sufficient information in this source region is available, the constraints may be too few to elucidate the structure.

3. Conclusions

[11] Our modeling study raises two key points. The first is that MT techniques, unlike any other geophysical method, can provide a means of studying mantle hydration processes associated with subduction. This is true for both ocean-continent and ocean-ocean subduction systems and arises because the conductivity of olivine is dramatically altered by the presence of dissolved hydrogen.

[12] The second point is that MT data should be collected on both sides of the subducting slab (i.e. including offshore data for an ocean-continent collision, or both oceanic and back-arc for an oceanic system). The model studies shown here, for an ocean-continent collision, indicate that only the offshore MT data are sensitive to the geometry and magnitude of electrical connections between the ocean and mantle through the deeper parts of a subduction zone, all of which are beneath the continent. These connections, between ocean and mantle, are diagnostic of the pathways by which fluid reaches the sub-continental mantle and their conductance is diagnostic of the amount of water present. This result is a surprising piece of physics and highlights the often non-intuitive nature of MT for which data can be sensitive to structure far removed laterally from the point of measurement.

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