GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L02310, doi:10.1029/2008GL036397, 2009

Deep electrical resistivity structure of northwestern Costa Rica

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Received 22 October 2008; revised 18 December 2008; accepted 23 December 2008; published 30 January 2009.

[1] First long-period magnetotelluric investigations were conducted in early 2008 in northwestern Costa Rica, along a profile that extends from the coast of the Pacific Ocean, traverses the volcanic arc and ends currently at the Nicaraguan border. The aim of this study is to gain insight into the electrical resistivity structure and thus fluid distribution at the continental margin where the Cocos plate subducts beneath the Caribbean plate. Preliminary two-dimensional models map the only moderately resistive mafic/ultramafic complexes of the Nicoya Peninsula (resistivity of a few hundred Ωm), the conductive forearc and the backarc basins (several Ωm). Beneath the backarc basin the data image a poor conductor in the basement with a clear termination in the south, which may tentatively be interpreted as the Santa Elena Suture. The volcanic arc shows no pronounced anomaly at depth, but a moderate conductor underlies the backarc with a possible connection to the upper mantle. A conductor at deep-crustal levels in the forearc may reflect fluid release from the downgoing slab. **Citation:** Brasse, H., G. Kapinos, L. Mütschard, G. E. Alvarado, T. Worzewski, and M. Jegen (2009), Deep electrical resistivity structure of northwestern Costa Rica, *Geophys. Res. Lett.*, *36*, L02310, doi:10.1029/2008GL036397.

1. Introduction

[2] In the Central American subduction zone, the Cocos Plate subducts slightly obliquely in a northeastern direction beneath the Caribbean Plate with a convergence rate of $\sim$8.5 cm/a [*DeMets*, 2001]. Depth of the Middle America Trench (MAT) gradually decreases from offshore Nicaragua ($z > 5000$ m) to less than 2000 m in southern Costa Rica, where the Cocos Ridge is subducted. Similarly, the subduction angle decreases from near vertical beneath Nicaragua to sub-horizontal beneath S Costa Rica [*Protti et al.*, 1995; *Husen et al.*, 2003], implying a significant diversity in the geothermal regime [*Peacock et al.*, 2005]. The varying slab dip is seen as a result of differences in the strength of the mantle wedge beneath Nicaragua and Costa Rica [*Rychert et al.*, 2008]. The position of active arc volcanoes above the downgoing slab changes abruptly near the border between the two countries: While volcanoes in the Cordillera de Guanacaste of NW Costa Rica are located roughly above the 100 km depth contour line, Nicaraguan volcanoes sit above a much deeper segment (>150 km) of the Cocos plate [*Syracuse et al.*, 2008]. A significant variation of lava chemistry is observed, with larger fluid and sediment signature beneath Nicaragua than beneath Costa Rica [*Carr et al.*, 2003; *Rüpke et al.*, 2002]. Additionally, crustal thickness beneath the Costa Rican arc is significantly larger ($\sim$38 km) than beneath the Nicaraguan depression ($\sim$25 km) [*MacKenzie et al.*, 2008].

[3] The Pacific margin of Central America has in the recent past been studied intensively, particularly with seismological (on- and offshore) and geochemical methods; it is a key location of the NSF Margins Program and also addressed by a number of projects funded by the German Science Foundation. We present here the first results of a complimentary project which aims to investigate the electrical resistivity distribution at the margin by employing long-period ($T = 10-10000$ s) magnetotelluric and geomagnetic deep sounding (MTS and GDS). Data along a first profile comprising 18 sites with a spacing of $\sim$10 km were collected in February/March 2008. It extends from the Pacific coast near Sámara, crosses the volcanic arc at Tenorio volcano and ends in the backarc near the Nicaraguan border at Los Chiles (see Figure 1), and coincides with the line of an active seismic experiment [e.g., *Sallarès et al.*, 2001] and the TUCAN seismological study [e.g., *MacKenzie et al.*, 2008].

[4] Further relevant geological structures which are traversed by the MT line (and which are expected to have a response on the transfer functions) are the mafic/ultramafic rocks (ophiolites) of the Nicoya Peninsula [*Hauff et al.*, 2000; *Hoernle and Hauff*, 2007] and the sedimentary basins in the fore- and backarc, i.e., the Tempisque and San Carlos Basins. Here a few drillings – mainly carried out for hydrocarbon exploration – provide some constraints on the structure of these basins [*Barboza et al.*, 1997; *Pizarro*, 1993]. In the backarc the profile crosses the so-called "Santa Elena Suture", extending from the peridotite outcrops of Santa Elena Peninsula in an easterly direction where it may connect with the Hess Escarpment as a major bathymetric step in the Caribbean plate and limit of the Caribbean Large Igneous Province. The Santa Elena Suture is believed by some authors to mark the boundary between allochthonous Chortis and Chorotega blocks. Note, however, that this interpretation is contended (see discussions by *Gazel et al.* [2006] and *Mann et al.* [2007]). The Chortis block is apparently a continental fragment, while the Chorotega block is probably a continuation of the Caribbean LIP.

2. Data Characteristics

[5] Data processing was carried out by employing the well-known, robust remote-reference scheme of *Egbert* [1997], which yielded mostly high-quality estimates of impedance (ratio between horizontal electric and magnetic field) and tipper (ratio of horizontal to vertical magnetic field) in the period range 10–10000 s (see auxiliary

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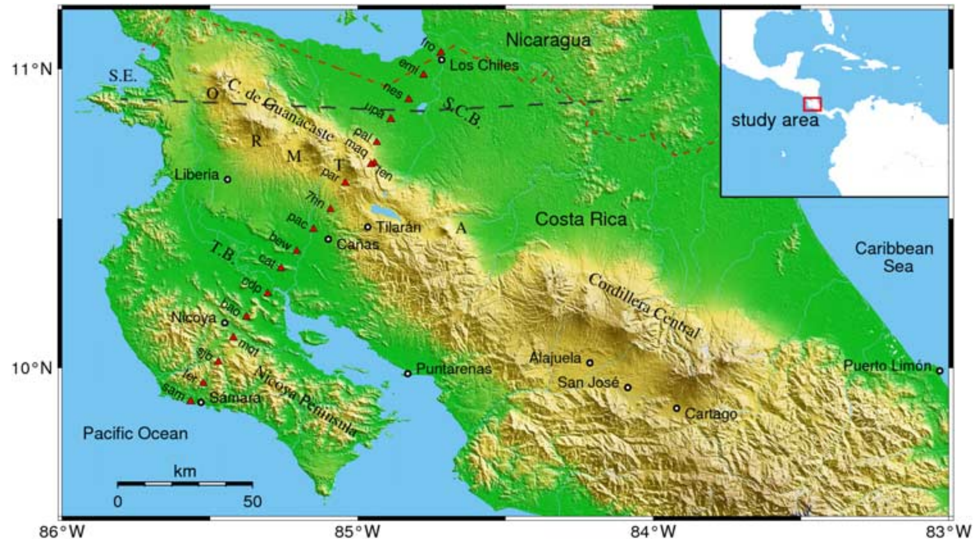

Figure 1. SRTM map of northwestern Costa Rica with location of MT sites (triangles). O, R, M, T, A denote Orosi, Rincón de la Vieja, Miravalles, Tenorio and Arenal volcanoes, respectively; S.E. is Santa Elena Peninsula, T.B. Tempisque Basin and S.C.B. San Carlos Basin. Dashed line is the proposed limit between Chortis and Chorotega blocks, extracted from *Sallarès et al.* [2001].

material[1]). A crucial step for further investigation is the check if the transfer functions reflect a two-dimensional (2-D) subsurface or if three-dimensional (3-D) structures are required by the data. As can be seen from Figure 2 (top), the assumption of two-dimensionality is roughly but not completely fulfilled. Electrical strike directions – calculated from the impedances after *Smith* [1995] – for the entire profile are shown in Figure 2 (note the 90°-ambiguity inherent to impedances; the decision for the true strike may be based on geology or tipper information). Data are split into three period bands (short, intermediate and long) and show basically similar characteristics: The strike is between N45°W and N55°W with a slightly larger scatter at short periods (10–100 s). This scatter is not surprising, as the influence of near-surface anomalies is larger for short periods. Additionally, for near-coastal sites, the bending of the coastline (which is not parallel to the trench) becomes relevant. Summarizing, the impedance data suggest that a 2-D approach is suitable and the resulting strike is approximately perpendicular to the profile.

[6] This clear statement is obscured somewhat by the induction arrows or vectors, as shown in Figure 2 (bottom) for three periods. Induction arrows are calculated from the tipper; their real parts ($\overrightarrow{P}$) point towards or away from high conductivity zones (at least in simple environments), depending on convention. We use the latter here, and consequently at the coast arrows point away from the well-conducting ocean. This coast effect reaches a large magnitude of about 1.1 at site sam for periods between 1000 s and 2000 s, which is due to the proximity of the 4 km-deep trench off Nicoya, an effect which is enhanced by the relatively resistive ultramafic rocks of the peninsula. Interestingly the coast effect does not reach far inland; it is obviously compensated by the sediments of the Tempisque Basin and perhaps another, deeper anomaly. Near Tenorio volcano (site par) arrows do not point away from the edifice at short periods, but rather hint at a conductive zone farther to the west, i.e., Miravalles volcano (where a large geothermal reservoir is encountered). Even more evident is the deviation of arrows in the Tempisque Basin itself at longer periods. This may either be caused by still deeper sediments in the NW or could even be attributed to the deepening of the trench near northernmost Costa Rica and off Nicaragua.

[7] Thus induction vectors sense significant 3-D effects along the profile. One may argue that these arrows pointing perpendicularly to the profile in the center of the basin do not pose a problem for 2-D modeling; the projected arrows are almost zero and do not require a conductive structure directly beneath the line. Nevertheless, care must be taken when interpreting the following 2-D model.

3. Results of Preliminary 2-D Modeling

[8] Taking the strike angle analysis and the direction of most induction arrows into account, we rotated all data by −53°, i.e., basically assuming a strike perpendicular to profile direction. The common non-linear conjugate gradient algorithm of *Rodi and Mackie* [2001] was used, which implements a Tikhonov-type, regularized 2-D inversion scheme. The program allows for a multitude of settings with respect to regularization factor, weighting functions penalizing horizontal or vertical structure, and error floors, among others.

[9] A number of tests were carried out to check dependence on starting models and inversion parameters. For the model shown in Figure 3 crude bathymetry was included; seawater was given a fixed resistivity of 0.3 Ωm. Additionally, the oceanic lithosphere was set as a resistive feature with a resistivity of 1000 Ωm. Slight horizontal smoothing was applied, and the regularization parameter was set to a value of 10 after a trade-off analysis between misfit and model roughness. To reduce the influence of static shift

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036397.

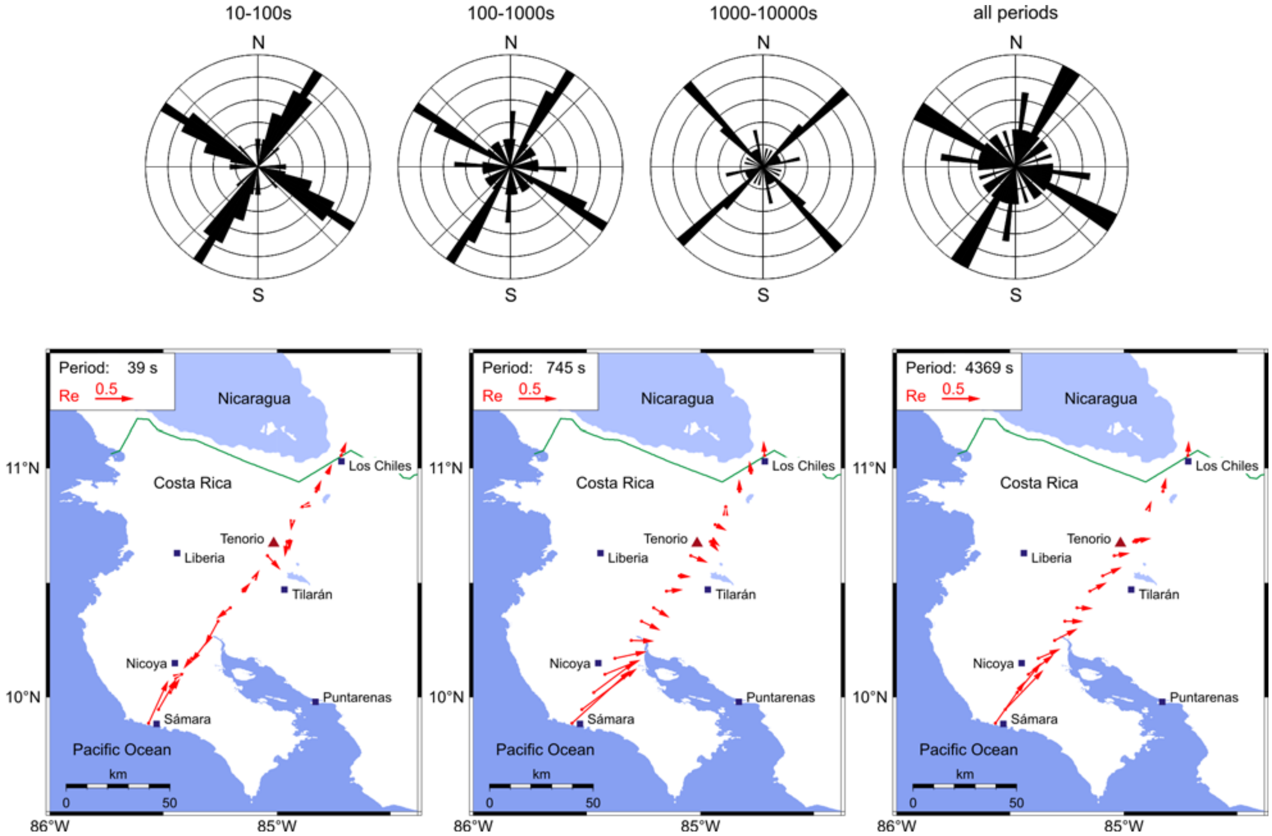

Figure 2. (top) Electrical strike directions determined from impedances for the entire profile for short, intermediate, and long period bands, and for the whole period range. (bottom) Induction arrows (real part) for short, intermediate and long periods (39 s, 745 s and 4369 s, respectively).

effects, error floors were set to higher values for apparent resistivities than for phases. All possible combinations of data sets were tested; the model of Figure 3 was obtained by joint inversion of tipper, TE (tangential-electric, electric field parallel to strike) and TM (tangential-magnetic, magnetic field parallel to strike) mode data. The resulting model yields an rms of 2.09, while the inversion of individual modes shows smaller values (better fits) of around 1.3 to 1.5. This is to be expected and may be regarded as a sign for inherent three-dimensionality. However, the most relevant features of the model in Figure 3 are recovered by all runs and a combination of TE, TM and tipper data. Data and model response are shown in the auxiliary material.

[10] The crust beneath Nicoya Peninsula (structure A) is resistive (several hundred Ωm), but not as much as could be expected from its geological setting with predominantly

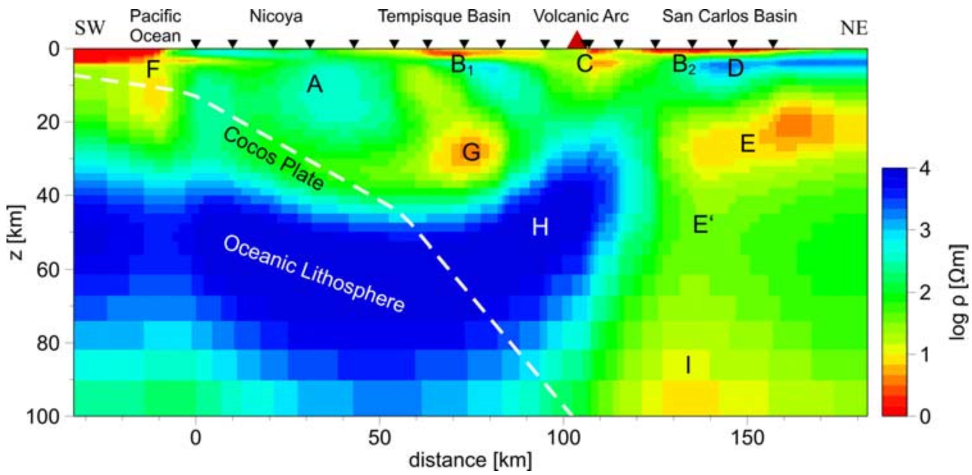

Figure 3. Two-dimensional resistivity model from joint inversion of tipper, TE and TM mode data. Location of Cocos plate boundary is taken from *Sallarès et al.* [2001]. Data fit and sensitivity issues as well as estimates on fluid content are treated in the auxiliary material. For further explanation see text.

mafic and ultramafic rocks, which should display resistivities in the order of 1000 Ωm and more. This may hint at a certain fluid input from the downgoing slab (see discussion later). The fore- and backarc basins (B_1 and B_2) are well resolved; thickness of conductive sediments corresponds to results of drillings in the vicinity of the MT line. In the Tonjibe borehole (San Carlos Basin) ultramafic rocks – similar to those outcropping in Santa Elena Peninsula – constitute the basement at a depth of ~2 km [*Pizarro*, 1993]. In the Tempisque Basin well-conducting sediments seem to reach slightly larger depths, perhaps with a maximum off-profile to the NW, as indicated by induction arrows.

[11] The northeastern part of the section shows a poor conductor which rather abruptly terminates in the region of Caño Negro (D). This location agrees well with the proposed trace of the Santa Elena Suture [cf. *Sallarès et al.*, 2001], and may be regarded as the southern terminus of the Chortis block. Note, however, that *MacKenzie et al.* [2008] place this boundary slightly further to the north in Nicaragua. Interestingly the mid- and lower crust in northern Costa Rica is underlain by a good conductor (E). It may have a connection (conductive path) to the upper mantle, slightly NE of the volcanic chain and thus already in the backarc (E′). An upper crustal conductor is visible just NW of Tenorio volcano beneath sites *ten* and *maq* (C). This may indicate a shallow magma deposit, but the lack of sites at the volcano edifice (where topographic gradients and dense rain forest limit accessibility) does not permit a more definite statement. In contrast, no enhanced conductivity is modeled at lower crustal or upper mantle depth beneath the volcanic arc as was proposed by *Elming and Rasmussen* [1997] from the inversion of MT data in Nicaragua. Note, however, that Tenorio volcano is considered as dormant, unlike the highly active volcanoes in the Nicaraguan depression. This may be the consequence of the absence of a large magma deposit at depth.

[12] Near-coastal conductive feature F in Figure 3 poses a more severe problem for interpretation. It may be an inversion artifact (like the over-estimation of seafloor depth) as it is located seaward from and thus outside the profile (coastal site sam also has the worst fit; see auxiliary material). It may on the other hand signify a substantial fluid release from the slab and input into the crust, as was suggested for Central America from seismological observations due to bending-related faulting of the Cocos plate at the MAT [*Ranero et al.*, 2003]. Note that such a conductive feature seaward from the coastline appears in models of other subduction zones, too, for instance in South Chile [*Brasse et al.*, 2009] and Cascadia [*Soyer and Unsworth*, 2006]. Without an offshore prolongation of the profile and ocean-bottom stations near the coast the resolution problems are difficult to overcome. Sea-bottom MT stations were deployed by IFM-Geomar (Kiel); these data are still under evaluation.

[13] Note that the top of the slab (set resistive in the starting model) is changed to medium-resistive during the inversion process. The model in Figure 3 is compatible with fluid release from the oceanic crust, serpentinization of the forearc mantle, and perhaps dehydration further into the Caribbean plate (G). A serpentinized forearc mantle wedge beneath Nicoya has already been proposed by *DeShon and Schwartz* [2004] from seismological studies. Serpentinite itself is probably only a moderate conductor [*Bruhn et al.*, 2004]. Thus structure G cannot be explained by serpentinite alone; a free, interconnected fluid phase is necessary to explain the low resistivities in the order of 5–10 Ωm. This result concerning a fluid-rich forearc is in general agreement with seismological findings [*Husen et al.*, 2003].

[14] At depths between 40 and 90 km the plate interface and the Caribbean plate upper mantle have a similar high resistivity of several thousand Ωm (H in Figure 3), comparable with the oceanic lithosphere and implying dry conditions throughout. Any occurrence of free fluids/melts is restricted to greater depth, as can be deduced from the low resistivities in the asthenospheric wedge (I). Note that a postulated rise of fluids/melts from the asthenospheric wedge towards the volcanic arc (from I via E′ to E and perhaps C) cannot be vertical or direct – H is a robust structure in the inversion process. It is generally compatible with a forearc mantle sliver found by *Walther et al.* [2000] further NW beneath Nicaragua and a zone of high velocities above the slab as inferred by *Syracuse et al.* [2008] from data of the recent TUCAN seismological experiment in Costa Rica and Nicaragua.

4. Conclusion

[15] Long-period magnetotelluric investigations resulted in the first deep resistivity image at the Costa Rica margin. Its principal features and implications are a) the depth and low resistivity of the fore- and backarc basins, b) the apparent termination of the Chortis block at the Santa Elena Suture in northernmost Costa Rica, c) a highly conductive backarc mid-crust and upper mantle, d) the image of fluid release from the downgoing slab in the forearc, and e) a very resistive forearc mantle adjacent to the subducted plate. The resistivity image of fluid release from the downgoing slab is generally consistent with seismological observations. We assume hydrous fluids as a cause for the modeled resistivities in the forearc regions, as the temperature in the slab is probably too low to allow for partial melting. Partial melts may, however, occur in the asthenospheric wedge of the overriding plate and explain the high conductivities in the backarc.

[16] The obtained resistivity cross-section should be seen as a first order approximation. More field data are necessary to constrain 3-D effects – their collection and an additional, comparative profile in Nicaragua are included in the project and planned in the near future. Incorporating the sea-bottom MT data into the models will further contribute to the question of fluid content in the downgoing plate.

[17] **Acknowledgments.** We thank the geophysics field group of the Instituto Costarricense de Electricidad (ICE) as well as Anja Schäfer, Vanessa Rojas and Patrick Durán for their help in setting up the field equipment, Maureen Bonilla for managing import/export and the staff at OSIVAM Seismological and Volcanological Observatory (Chiripa/Tilarán) for their support and hospitality. We are particularly grateful to Waldo Taylor for logistical support. We thank H. van Avendonk and an anonymous reviewer for their constructive comments. Two of the field devices were supplied by the Geophysical Instrument Pool Potsdam (GIPP). The project is funded by German Science Foundation (DFG) with grant BR1351/7-1 to H. Brasse. This manuscript is contribution number 168 of the Sonderforschungsbereich 574 "Volatiles and Fluids in Subduction Zones" at Kiel University.

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