Broadband marine MT exploration of the East Pacific Rise at 9°50′N

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[1] We present the first use at a mid-ocean ridge of a recently developed broadband marine magnetotelluric (MT) instrument. The extended high frequency performance of the instrument allows resolution of electrical resistivity structure at shallower depths than traditional marine MT sensors. Our two-dimensional inversion model from data collected at four MT sites on the East Pacific Rise (EPR) at 9°50′N demonstrates the viability of the method to image electrical resistivity structure in both the crust and shallow mantle. While our pilot experiment falls far short of the coverage needed to provide rigorous constraints on structure, a low resistivity zone in the crustal portion of the inversion model agrees well with seismic tomography and seafloor compliance results. Resistivities beneath the ridge imply a crustal partial melt fraction of 1–20%. A total melt volume of about 0.75 km^3 per kilometer of ridge implies an average melt residence time of about 1000 years. *INDEX TERMS:* 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 3035 Marine Geology and Geophysics: Midocean ridge processes; 3094 Marine Geology and Geophysics: Instruments and techniques. **Citation:** Key, K., and S. Constable, Broadband marine MT exploration of the East Pacific Rise at 9°50′N, *Geophys. Res. Lett.*, *29*(22), 2054, doi:10.1029/2002GL016035, 2002.

1. Introduction

[2] The majority of Earth's crust is formed at mid-ocean ridges and so the mechanisms that generate, transport and emplace melt are important from a global tectonic perspective. Despite the vast number of previous ridge studies, many questions about the extent and distribution of melt in the crust and shallow mantle persist. Additionally, new questions have arisen about the role of hydrothermal circulation in the removal of heat from the crust and in determining the distribution of partial melt [*Dunn et al.*, 2000]. While the seismic techniques that have dominated ridge research are well suited to identifying structural boundaries, they have a more difficult time quantifying physical properties; other complementary methods of ridge exploration are needed. One good example is the seafloor compliance method [*Crawford et al.*, 1999; *Crawford and Webb*, 2002] which is sensitive to the shear velocity of both the crust and shallow mantle.

[3] Here we present results from another technique-the broadband marine magnetotelluric (MT) method-which is sensitive to the bulk electrical resistivity in both the crust and mantle. Oceanic lithosphere is typically very resistive. However, the inclusion of even a small amount of connected melt or sea water at spreading ridges can greatly decrease the bulk resistivity, making ridge structures a suitable target for electrical methods. Although MT studies of ridges are far from new [e.g., *Heinson et al.*, 1993], our experiment used instrumentation equipped with broadband sensors capable of measuring shorter period seafloor electric and magnetic fields than before, enabling resolution of structure at crustal depths. Previous ridge MT experiments [*Heinson et al.*, 1993; *Evans et al.*, 1999] were relatively insensitive to crustal resistivity, and thus focused on mapping mantle structure. An experiment that measured broadband magnetic fields at two sites on the Juan de Fuca ridge is presented by *Jegen and Edwards* [1998], but did not include measurement of broadband electric fields. The traditional technique to image crustal resistivity at ridges has been the controlled-source electromagnetic method [*Evans et al.*, 1991; *MacGregor et al.*, 1998, 2001].

[4] In February 2000, broadband marine MT instruments were deployed on the East Pacific Rise (EPR) near 9°50′N as part of a magnetometric resistivity (MMR) experiment designed to study the electrical resistivity of the shallow crust in the vicinity of the ridge [*Evans et al.*, 2002]. The MT instruments contained magnetometers suitable for recording the MMR transmissions, but also electric field dipoles, allowing us to carry out the first test of the instrument at a mid-ocean ridge. The instrument was developed for routine use for petroleum exploration on the continental shelves [*Constable et al.*, 1998], and uses AC coupled sensors designed to measure the small seafloor electric and magnetic field variations in the period range of 0.1 to 10,000 seconds. However, for this experiment the shortest measurable period is limited by attenuation in the conductive ocean and is about 18 seconds. Figure 1 shows the locations of the MT sites occupied near the ridge axis.

2. Sensitivity to Ridge Structures

[5] The resolving power of MT is heavily dependent on the frequency band of measurements, the subsurface resistivity structure, and also the density and lateral extent of measurement sites. In Figure 2 we present a simplistic two-dimensional (2D) model study illustrating the magnitude, lateral extent and bandwidth of the MT response generated by three possible ridge resistivity structures, shown in the left column. In the right column we plot the ratio of the MT response from a 1D oceanic resistivity profile (from the model sides), and the response of the full 2D models that included the conductive (10 ohm-m) inhomogeneities that represent regions of partial melt.

[6] The simplified crustal partial melt conductor included in model (a) is based on seismic tomography at the EPR 9°30′N [*Dunn et al.*, 2000] and seafloor compliance at 9–10°N [*Crawford and Webb*, 2002], which both suggest the crust contains a 4–5 km wide region of partial melt

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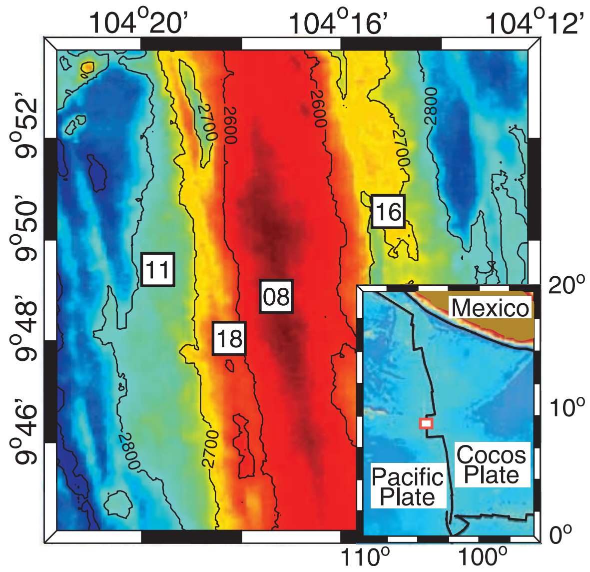

Figure 1. Bathymetry map of the experiment location. MT measurement sites are shown as numbered squares. Seafloor depths are in meters. The inset shows the location of the experiment (red box) and plate boundaries (black lines).

extending from about 1.5 km depth to near the base of the crust. The anomalous response indicates that the signal from this structure manifests itself at periods of 1–100 seconds, is up to about a factor of 10 different from the 1D response, and extends to distances just beyond the width of the structure. Model (b) is an extension of model (a), to which has been added a 20 km wide conductive zone in the shallow mantle that represents partial melt accumulating at the base of the crust [*Dunn et al.*, 2000]. The response of this model indicates that a shallow mantle partial melt region will affect data at periods of about 10–300 seconds. Model (c) includes a deeper and broader region of partial melt in the mantle that extends down to 60 km depth and is sensed by data up to about 8000 seconds period. Although the shortest period measured for this experiment is about 18 seconds, this model study suggests that our MT responses should contain a significant amount of information about crustal and upper mantle structure.

3. Data and Modeling

[7] The MT sites recorded data simultaneously during the experiment, which allowed us to form frequency dependent MT impedance estimates by using a robust multivariate approach [*Egbert*, 1997]. Our analysis yielded good MT impedances at periods of 18 to 6000 seconds period, suitable for detecting both crustal and upper mantle structure. Impedance strike and skew estimates [*Swift*, 1967] show that the impedances are predominantly 2D with low skew values, but also show a frequency dependence in the strike direction. Two main groupings exist in the strike estimates. At periods less than about 100 seconds, the strike directions are nearly aligned with the ridge strike of about −8° from geographic North; this is as expected given bathymetry and ridge structure. At periods greater than about 100 seconds, strike directions cluster around 20° from North. The change in strike direction for the long period data may be caused by a shift in structural strike at depth, the distortion of the long period MT fields by the geomagnetic coast effect, or possibly by anisotropic resistivity of mantle olivine. We mention these possible causes for completeness, but a thorough discussion is beyond the scope of this paper. For the purpose of 2D modeling, we have chosen to maximize the off diagonal impedance components by rotating the data at 100 seconds period and less to the ridge strike of −8° and to 20° for data at periods greater than 100 seconds. Figure 3 shows the MT apparent resistivity and phase for each site after rotation. The responses are fairly complicated and show a strong asymmetry between the TE (strike aligned electric field) and TM (strike aligned magnetic field) modes.

[8] As demonstrated for previous ridge MT surveys [e.g., *Heinson et al.*, 1993], much of the structure in MT response is due to the distortion of the incident MT fields by the rugged seafloor bathymetry. However, ridge bathymetry can be measured (if not already available in sufficient detail), is predominantly 2D on a regional scale (away from transforms and seamounts), and can be included as a priori information in MT modeling. We used a standard 2D MT inversion algorithm [*de Groot-Hedlin and Constable*, 1990] that incorporates a finite element forward modeling code [*Wannamaker et al.*, 1987] capable of using triangular elements to smoothly approximate the 2D seafloor bathymetry. This technique yields realistic MT responses to periods at least as short as 10 seconds.

[9] An inversion fitting the data to an RMS misfit of 1.0 is shown in Figure 4. Both TE and TM modes of data were

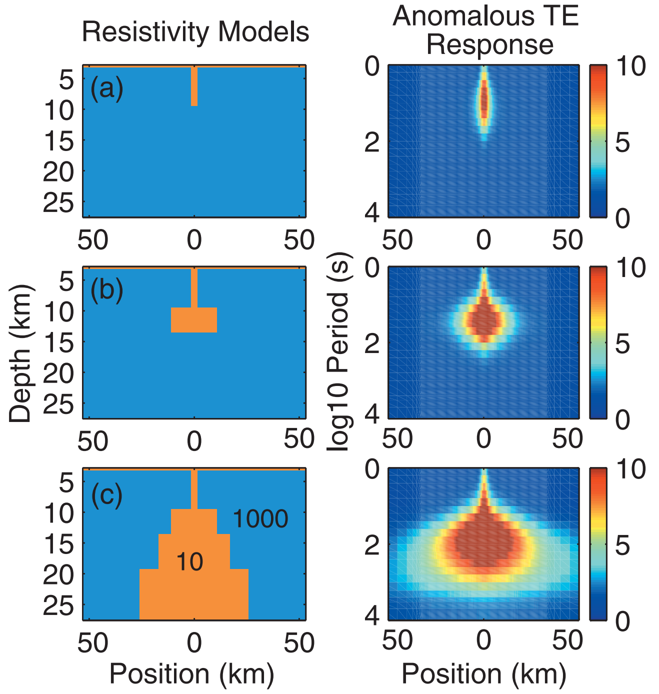

Figure 2. Simplistic 2D forward model study of the response generated by possible ridge resistivity structures. The left column shows the 2D resistivity forward models, and the right column shows the anomalous TE mode response generated for each model. See text for a description of the structures included in each model.

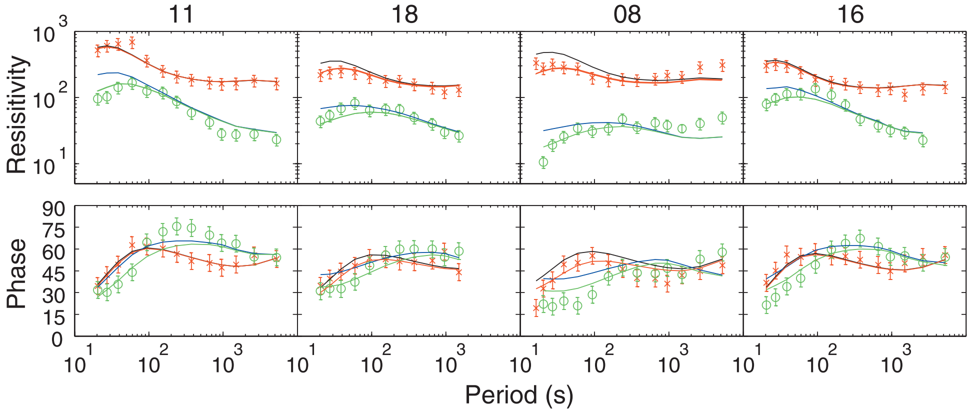

Figure 3. MT data and model responses. Apparent resistivity units are ohm-m and the phases are degrees. TE and TM mode data are shown as green and red symbols, respectively. Inversion model responses from Figure 4 are shown as green and red lines. Blue and black lines show the TE and TM mode responses for the same model, but with the mid-crustal conductive zone resistivities set to a floor of 100 ohm-m.

inverted, with a minimum error floor of 20%. The forward response of the model is shown along with the data in Figure 3. Although the model was parameterized to estimate 2D resistivity structure as deep as 300 km, and features a highly conductive zone (about 1–10 ohm-m) at depths of 60–120 km beneath the ridge, the limited aperture of MT sites (4 sites all within 5 km of the ridge) does not constrain the position or extent of deep structure extending outside the width of the array. Therefore, we have chosen to focus our analysis on the crustal and shallow mantle portion of the model. Inversion using only the data at periods less than 200 seconds yields a model with similar crustal and shallow mantle structures to Figure 4.

4. Discussion and Conclusions

[10] The inverted model shows a significant amount of structure in both the crust and shallow mantle. The left and right sides of the model show a predominantly 1D layered structure with resistivities of about 10–100 ohm-m to depths of about 1 km beneath the seafloor, increasing rapidly to about 10,000 ohm-m at greater depths. While this structure is outside the array of sites and is not well constrained, it does agree with controlled-source electromagnetic soundings on 40 Ma normal oceanic lithosphere in the north-east Pacific [*Constable and Cox*, 1996], and suggests that the transition from low resistivities dominated by the magmatic system at the ridge axis to the dry and cold resistive lithosphere away from the axis starts occurring within a distance of about 6–10 km.

[11] Our shallow (<1km) resistivities are generally consistent with controlled-source soundings at the EPR near 13°N [*Evans et al.*, 1991], where a steep resistivity gradient was shown to exist as resistivity increases from about 1 ohm-m to 100 ohm-m in the first kilometer, both at the ridge axis and on 100,000 year old crust (about 5 km off axis). MMR results [*Evans et al.*, 2002] agree with our off-axis resistivities, but are more conductive on-axis. The on-axis disagreement is probably due to a lack of shallow resolution and the relatively wide MT site spacing.

[12] The mid-crustal conductive zone, which extends to about 3 km on both sides of the ridge axis at depths of about 1.5 to 6 km below the seafloor, has resistivities of about 1–100 ohm-m and coincides with a low *P* wave velocity region detected at 9°30′N using seismic tomography [*Dunn et al.*, 2000] and a low shear velocity region detected at 9°48′N using seafloor compliance [*Crawford and Webb*, 2002]. To demonstrate that the MT responses are sensitive to this feature, we have computed the response of the inversion model with the mid-crustal conductive zone resistivities set to a floor of 100 ohm-m. The RMS misfit increases to 1.4 and the response, shown as blue and black lines in Figure 3, is significantly different at all sites for periods less than about 100 seconds, especially for the TE

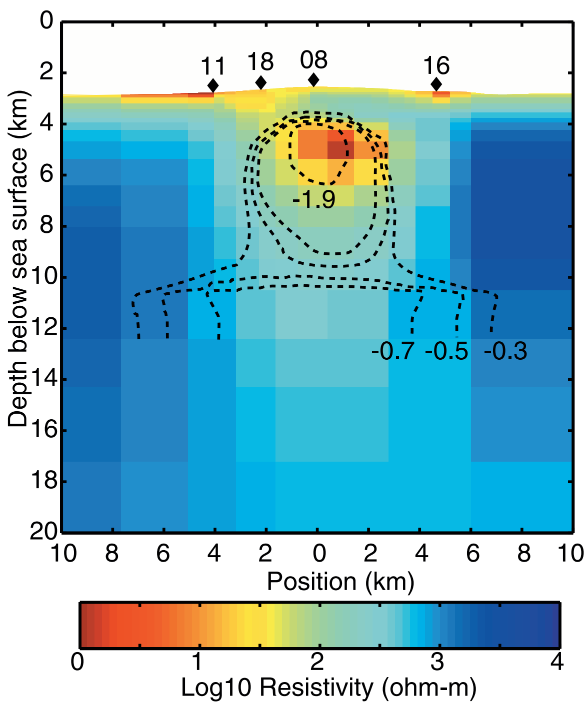

Figure 4. Inversion model fitting the data to an RMS misfit of 1.0. MT sites are shown as black diamonds. Seismic velocity perturbation contours for ΔV_p = −1.9, −0.7, −0.5 and −0.3 km/s from *Dunn et al.* [2000] are shown for comparison.

mode. The difference in misfit suggests that the conductive region is required by our data. For comparison, in Figure 4 we have included four seismic velocity perturbation contours from the tomography experiment, which show a relatively narrow low velocity region in the crust with the largest velocity perturbations residing at depths of about 1.5 to 3 km beneath the seafloor, in agreement with the lowest resistivities shown in our model. Assuming this region contains well connected partial melt in a thin film geometry, we can use standard mixing laws [*Schmeling*, 1986] to estimate about 1–20% partial melt, in agreement with both the compliance and tomography results. A 100 m thick melt lens that caps the partial melt region [e.g., *Kent et al.*, 1993] is too thin to be resolved by the MT data, but does contribute to the overall low bulk resistivity in this region. While the tomography and compliance results indicate that melt accumulates in a broader region at the base of the crust (below about 6–7 km beneath the seafloor), the resistivity model shows a zone of lower resistivities-about 100–500 ohm-m and 10 km wide-that extends from the crust to the shallow mantle with no significant change in width. However, the limited number of sites and small aperture of our experiment do not allow sufficient lateral resolution to distinguish between such features at these depths.

[13] To explain the change in width of the low velocity region, both the tomography and compliance experiments suggest that deep hydrothermal circulation in the crust acts to convectively cool the flanks of the crustal partial melt region. Such deep hydrothermal circulation would dominate the bulk resistivity of the crustal rocks and result in resistivities much lower than 1000–10,000 ohm-m on the flanks of the partial melt region. If this is indeed occurring, then our model suggests it is limited to the region about 3–6 km either side of the ridge axis, although the details of the transition zone shown in our model may well be influenced by the smoothness constraints in the inversion.

[14] While the structural similarity of our inversion with that obtained using seismic tomography is exceptional, especially considering the small number of sites in the MT experiment, our results are obviously limited by the lateral coverage. However, the ability to estimate the electrical resistivity and partial melt fraction allows us to estimate about 0.75 km^3 of crustal melt per kilometer of ridge. Using the ridge spreading rate of 110 km per My and assuming the 7 km thick crust is formed by a steady state solidification of crustal melt, we can predict an average melt residence time of about 1000 years.

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