Collaborative Research: SERPENT: Serpentinite, Extension, and Regional Porosity Experiment across the Nicaraguan Trench

Intellectual Merit

Water plays an important role in the volcanic processes occurring at convergent margins, as the release of water from the downgoing slab affects the rheology of the mantle, impacts seismicity, allows melting to occur more readily by lowering the solidus temperature, and alters the chemistry of arc-lavas. Yet, the amount of water entering the subduction system remains poorly constrained. One of the major uncertainties in terms of fluid inputs into the subduction factory, and a primary goal of the MARGINS program, concerns the extent of serpentinization of the oceanic upper mantle and the volumes of water that are being carried into the subduction system through this route. We propose a large-scale electromagnetic experiment along a 300 km profile off Nicaragua in a region that shows evidence for substantial fault related fluid circulation in the crust and possibly upper mantle, and high Ba/La ratios and water contents in adjacent onshore volcanics suggesting a strong slab fluid input into the arc-melting.

Our survey will combine controlled-source electromagnetics (CSEM) with broadband and long period magnetotellurics (MT) to provide a comprehensive picture of the conductivity structure from the seafloor to the upper mantle, representing the entire input into this part of the Central American subduction factory. Since conductivity is highly dependent on thermal structure, crack porosity and the presence of serpentinite, our proposed experiment will provide constrains on:

1. The fluid content and alteration state of the incoming plate.
2. The depth of active fluid circulation within the oceanic crust and mantle.
3. The variation of fluid circulation with distance from the trench, and hence with the degree of plate bending.
4. The porosity structure of the Nicaraguan margin prism.
5. The extent of dewatering of the subducting slab in the shallow portion of the mantle wedge.

These constraints will be strengthened through combined analysis with seismic data recently collected along the proposed EM profile.

Broader Impacts of Proposal

Dehydration of subducting slabs has been shown to impact seismicity, and so constraining water content and variability in subduction systems is important to our understanding of earthquake generation and potential hazard in these settings. Our proposal is collaborative with German colleagues who have already begun an MT campaign, deploying instruments along a profile across the Nicoya Peninsula and extending offshore, to the south of our proposed work area. This proposal will augment that study by deploying additional broadband and long period sites. As such, this second profile, which is in an area of markedly different seafloor morphology and arc volcanics to our primary survey area, will provide an important contrast to the area off Nicaragua in terms of mantle water content.

The proposed experiment will support the education of two Ph.D. students in marine EM methods, will promote the use of the Scripps marine EM instrument fleet for use in non-commercial geophysical experiments, will advance marine EM as a useful technique for studying continental margins, and will promote international collaboration. Data and modeling results will be submitted in a timely manner to the data management center, and will also be made available through our extensive web site at http://marineemlab.ucsd.edu.

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Collaborative Research: SERPENT: Serpentinite, Extension and Regional Porosity Experiment across the Nicaraguan Trench

Intellectual Merit

Introduction

Water plays an important role in the volcanic processes occurring at convergent margins (e.g., Bebout, 1996; Peacock, 1990, 1996; Davies and Stevenson, 1992), because the release of water from the downgoing slab affects the rheology of the mantle (Hirth and Kohlstedt, 1996), has an impact on seismicity (Kirby et al., 1996), allows melting to occur more readily by lowering the solidus temperature, and alters the chemistry of arc-lavas (e.g., Tatsumi and Eggins, 1995; Rupke et al., 2002). Yet, the amount of water entering the subduction system remains poorly constrained. One of the major uncertainties in terms of fluid inputs into the subduction factory concerns the extent of serpentinization of the oceanic upper mantle and the volumes of water that can be carried into the subduction system through this alteration mineral.

It has been suggested that pervasive faulting resulting from plate bending off Nicaragua allows fluids deep access through the crust and into the mantle (Figure 1; Ranero et al., 2003). These fluids should result in widespread serpentinization of mantle peridotite, where they remain bound until the down-going slab is warmed beyond the stability of serpentine minerals. Whether the mantle can actually be hydrated to such great depths remains uncertain, and even if it is, perhaps the alteration is only localized around deep faults. Other scenarios place the bulk of the fluid flux entering into the subduction system in sediments and other alteration minerals in the oceanic crust. If pervasive alteration of the mantle happens anywhere, the area off Nicaragua seems one of the best candidates for study.

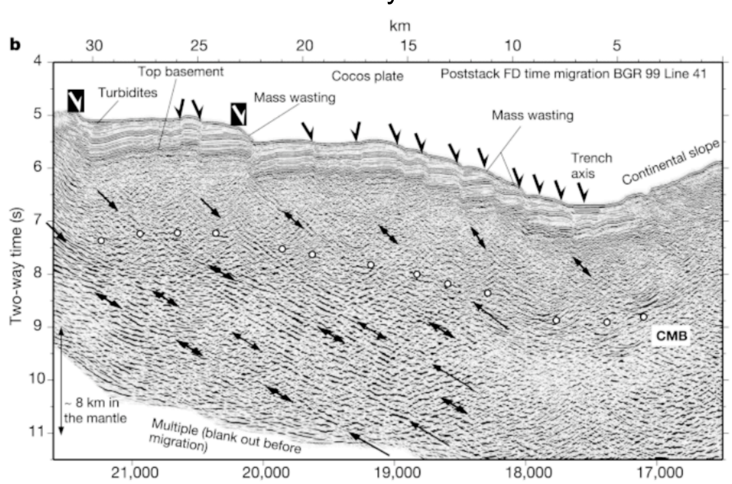

Figure 1: Seismic reflection image of deep faulting in the incoming plate at the subduction factory offshore Nicaragua. The ubiquitous bending related faults have been proposed to allow for widespread serpentinization of the shallow mantle. From Ranero et al., 2003.

We propose a large scale electromagnetic experiment of the subduction factory offshore Nicaragua and Costa Rica. This region has been extensively studied by other geophysical methods and was the focus of a recent major seismic experiment. Electromagnetic methods can be used to study the conductivity structure of oceanic crust and mantle. Since conductivity is highly dependent on thermal structure, crack porosity and the presence of serpentinite, electromagnetic methods can provide unique constraints on the fluid content and alteration state of the downgoing plate. Our survey will combine controlled-source electromagnetics (CSEM) with broadband and long period magnetotellurics (MT) to provide a comprehensive picture of the conductivity structure of the oceanic crust and upper mantle. This survey will fulfill a major scientific objective of the MARGINS program by providing quantitative information on one of the key forcing functions in arc volcanism: the distribution and volume of fluids carried down by subduction. These constraints can be strengthened through combined analysis with seismic reflection and refraction data already in hand, as well as other geologic indicators such as heat-flow and seafloor morphology.

Our survey is collaborative with German colleagues who have already begun a MT campaign, deploying instruments along a profile across the Nicoya Peninsula and extending offshore, to the south of our main proposed work area (see Figure 7). This Nicoya profile will allow us to understand the along strike variations in structure, and may provide insights on why the geochemical signature of arc volcanism varies along strike. Onshore MT data adjacent to our profile offshore Nicaragua has been collected by a Swedish group (Elming and Rasmussen, 1997) and is proposed to be augmented by Spanish colleagues. Together, the combination of offshore and onshore MT data will permit a complete view of conductivity structure across the Nicaraguan subduction factory.

It is relevant to note that many of the important targets in the subduction system require offshore data in order for MT to reasonably constrain them (Evans et al., 2000). Furthermore, the progression of crack permeability in the crust with proximity to the trench can only be imaged through the use of the offshore techniques described in this proposal. The depth extent of the targets we propose to image requires a combination of CSEM and MT data covering a wide range of frequencies.

Background: The Central American Subduction System

The Central American subduction system has been well studied. In addition to being a MARGINS focus site for the Subduction Factory Experiment, it has also been the focus of extensive work by German scientists. Offshore, high resolution bathymetric mapping, seismic reflection profiling, an onshore-offshore seismic reflection/refraction experiment and onshore-offshore MT have been done in various parts of the system (Christeson et al., 1999; McIntosh and Sen, 2000; Ranero et al., 2000; 2003; Von Huene et al., 2000; H. Brasse –pers comm.). The volcanics have been extensively studied and reveal systematic trends in composition along the strike of the arc (Carr et al., 2003; Rupke et al., 2002).

One of the significant variations along strike is the boundary between the subduction of crust generated at the East Pacific Rise, and that generated by the Cocos Nazca spreading center. Off Nicaragua, the seafloor has a series of trench parallel faults that are interpreted to be caused by plate bending (Figure 1, Ranero et al., 2003). In contrast, the crust within the Cocos-Nazca plate off Costa-Rica appears largely unfaulted, but also contains an abundance of seamounts.

Heat flow through seafloor created at the EPR, i.e. off Nicaragua, is approximately ~70% lower relative to conductive lithospheric cooling models, but heat flow through adjacent, similarly-aged lithosphere generated at the Cocos-Nazca Spreading Center is more or less consistent with these models (Grevemeyer et al., 2005; Fisher et al., 2003; Stein, 2003; Hutnak et al., 2005). It has been argued that the low heat flux in EPR crust is the result of relatively shallow excess fluid flow (Fisher et al., 2003), within the uppermost few hundred meters of seafloor. However, when heat flow is examined as a function of distance from the trench, along with the density of normal faults (Figure 2) there is a clear correlation between the two, strongly suggesting enhanced hydrothermal exchange as a result of the plate bending (Grevemeyer et al., 2005). The deep faulting seen in seismic reflection profiles suggests that deep fluid penetration may be possible (Figure 1, Ranero et al., 2003).

Nicaraguan volcanics appear to be removed from the geochemical influence of the Galapagos hotspot track or the subduction of seamounts (Hoernle et al., 2008). Mafic magmas within this part of the arc also show evidence for high water contents (Roggensack et al., 1997) , and high Ba/La ratios in Nicaragua are indicative of a strong slab component in the melts, in contrast to those in Costa-Rica (Rupke et al., 2002). Seismic data suggest very low velocities in a region at the top of the downgoing slab. The measured velocities suggest water contents in the oceanic crust that are 2-3 times higher than is inferred in other subduction zones where similar data exist (Abers et al., 2003). Thus, both geochemical and seismic data suggest that areas of low heat flux, and presumably high hydrothermal circulation, are areas of high water inputs into the subduction zone. Grevemeyer et al., (2005) argue that "*It is reasonable to assume that the larger water flux is caused by serpentinization of the upper mantle, facilitated by bending-related faults cutting into the upper mantle*".

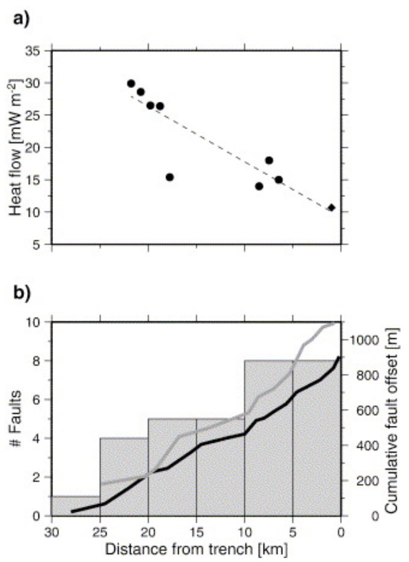

Figure 2. a) Heat flow data plotted as a distance from the Nicaraguan trench showing a steady decrease as the density of normal faults (b) increases. This is interpreted to reflect enhanced hydrothermal circulation as a result of plate bending at the trench, and may result in more widespread alteration of the upper mantle (From Grevemeyer et al., 2005).

Existing MT data from this region include a recent onshore-offshore transect across the Nicoya peninsula, essentially along the boundary between EPR generated crust and Cocos-Nazca generated crust (Brasse et al. in prep). The survey runs from the Nicoya shoreline, across the volcanic arc and into the San Carlos Basin (see Figure 7). Key features that have been imaged include several mantle conductors that may be associated with melting. A conductor seen at shallow depths beneath the coastline may represent shallow dewatering of the slab, but is not well constrained by the existing data. Our proposal to add instruments, particularly broadband MT receivers, to the offshore extension of this transect will aid in imaging this important feature. Adjacent to our main proposed survey line offshore Nicaragua is an onshore MT survey of 12 stations, which revealed a lower crustal conductive zone that was interpreted to be a melt layer beneath the arc volcanoes (Elming and Rasmussen, 1997).

Seismic constraints: The upper-mantle seismic velocity measured at one location beneath the outer rise and trench offshore Nicaragua is ~7.7 km/s (Ivandic et al., 2008; Grevemeyer, et al., 2007), suggesting that the mantle here has been affected by cracking and serpentinization. While seismic velocity measurements can easily distinguish pure peridotite from pure serpentinite [V_P ~8.1 km/s, Poisson's ratio ~0.25 versus ~4.8 km/s, Poisson's ratio ~0.34 (Christensen, 1996)], separating the effect of cracks from that of modest serpentinization is difficult based on seismic velocity alone. If the effect of cracks is ignored, as if for cracks that have been fully sealed with serpentinite, then an upper mantle velocity of 7.7 km/s suggests ~14% serpentinization (Ivandic et al., 2008; Carlson and Miller, 2003). However, a reduction of velocity from 8.1 to 7.7 km/s can also be explained by as little as 1% water-filled porosity in cracks.

A number of seismic lines were shot earlier this year (2008) across the trench and along the lower plate offshore Costa Rica and Nicaragua as part of the MARGINS-funded TICO-CAVA active-source seismic project (P.I.s: W.S. Holbrook, D. Lizarralde, H. van Avendonk, P. Kelemen). One goal of this project is to estimate the degree of serpentinization within the upper mantle of the subducting plate and it's along-trench variability. The seismic lines that target upper-mantle serpentinization are indicated in Figure 3 and include two seismic lines along the outer rise that will constrain the along-trench variation in upper mantle seismic velocity, both along the rough "Cocos Ridge" portion of the plate and the smoother plate offshore Nicoya Peninsula and Nicaragua; two trench perpendicular profiles offshore central Costa Rica and Nicaragua; and a star/circle seismic shoot designed to measure azimuthal seismic anisotropy offshore Nicaragua.

The trench-perpendicular seismic line offshore Nicaragua coincides with the EM transect of this proposal. This seismic line, along with the multiple intersecting seismic lines and shots along arcs at 75- and 55-km radii, will provide us with our most complete measurement to date of upper-mantle seismic velocity structure, including seismic anisotropy, at a bending plate as it enters the subduction zone. Our hope is that measured seismic anisotropy will enable us to better distinguish between the effects of cracking and serpentinization. The joint constraints provided by this seismic dataset and the proposed EM dataset are likely to provide a definitive test to the hypothesis of substantial upper-mantle serpentinization near the outer rise as well as tight constraints on volume estimates of bound water.

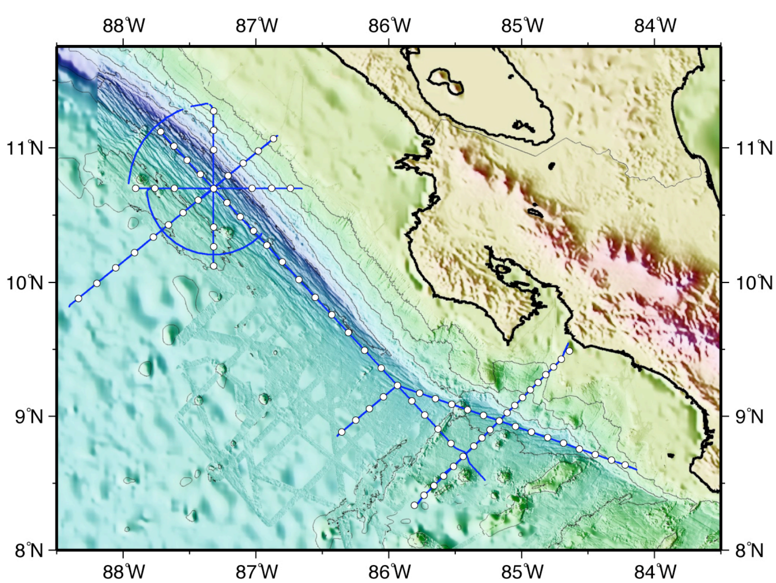

Figure 3. Seismic lines (blue) and OBS positions (dots) of the 2008 seismic experiment targeting upper mantle serpentinization of the subducting plate.

Background: Marine Electromagnetic Methods

Electrical conductivity can be remotely estimated using both passive and active source methods. EM techniques have been used by academics for marine exploration for decades and have recently been incorporated as a standard tool for hydrocarbon exploration on the continental shelves (e.g., Constable and Srnka, 2007). With recent industry interest and support, improvements in instrumentation and interpretation techniques are now facilitating large 2D and 3D array experiments (e.g., Constable et al., 1998; Key et al., 2005; Key et al., 2006; Mackie et al., 2007; Commer and Newman, 2008).

Magnetotellurics (MT) is a passive method that uses naturally occurring variations in Earth's electric and magnetic fields to provide a frequency dependent measure of the subsurface electrical conductivity. Long period MT instruments (200-100,000 s) have been used in the deep ocean for decades, but it is only through the development of broadband marine MT instrumentation that the shorter period signals (1-100 s) needed to image continental shelf structure and the mid-lower oceanic crust have been obtainable (e.g., Constable et al., 1998; Key and Constable, 2002; Key et al., 2006). Long period MT studies have been used to provide valuable insights on upper mantle melting and hydration at mid-ocean ridges (Baba et al., 2006, Evans et al., 2005) and in oceanic-oceanic subduction zones (see prior support section). The only previous NSF funded continental margin subduction zone MT experiment was conducted nearly two decades ago offshore Oregon (Wannamaker et al., 1989). While this experiment provided unique insights on subduction structure, the marine array was limited to only a handful of available long period MT receivers. The current availability of 50 broadband receivers from Scripps, 10 long period receivers from WHOI, and 10 long period systems from Germany provides a significantly improved capability for marine studies of subduction structures.

Controlled-source EM (CSEM) is an active-source electromagnetic technique that employs a deep-towed horizontal electric dipole to generate electric and magnetic fields at much higher frequencies than are measurable in the natural source MT spectrum. CSEM fields are recorded by the broadband MT sensors (while also recording MT data) and are sensitive to conductivity at crustal depths. This technique has been widely used in the deep ocean to study mid-ocean ridge magmatic and hydrothermal systems (Evans et al., 1991, 1994; MacGregor et al., 1998, 2000, 2001). The technique has also been recently used at 9N on the EPR (Key and Constable, 2005; see prior support section) and at Hydrate Ridge, offshore Oregon (Weitemeyer et al., 2006). While previous academic experiments relied on a transmitter system operated by Cambridge University in the UK (now at Southampton), Scripps has used industrial sponsorship to develop two CSEM transmitter systems with large dipole moments (500A on a 200m antenna) capable of deep towing at depths of up to 6 km.

Long-wire EM sensors (LEMs) use antennae 10-100 times longer than conventional EM/MT sensors and are thus able to record CSEM data to larger source-receiver offsets, providing greater depth sensitivity. Previous LEM experiments have measured CSEM transmissions to 90 km range in order to constrain oceanic lithosphere conductivity and upper mantle anisotropy (Constable and Cox, 1996; Behrens, 2005). The Scripps broadband receivers are easily converted into LEMs. Since LEMs require a significant amount of ship-time to deep-tow the long antennas to the seafloor, their use in experiments is usually limited to only a few systems.

Scientific Objectives:

1) Quantify the volume of water input to the subduction factory through pore fluids and serpentinization by mapping the electrical conductivity of the incoming oceanic lithosphere.

2) Constrain the depths of active fluid circulation within the oceanic crust and upper mantle.

3) Employ a combined analysis of EM and seismic data off Nicaragua to more tightly constrain the physical state of the upper mantle, in particular the degree of serpentinization of the mantle.

4) Estimate changes in fluid circulation with distance from the trench and, hence, with degree of plate bending.

5) Constrain porosity, fluid content and fluid origin in the forearc by mapping forearc conductivity structure.

6) Compare conductivity profiles measured along our proposed MT transect in concert with a separately proposed land profile with a similar onshore-offshore profile off the Nicoya Peninsula. Use this comparison to look for first order differences in structure along trench that may relate to differences in the fluid input and output arc volcanism.

Specific Hypotheses to be Tested:

(a) Hydrothermal cooling of crust and upper mantle in lithosphere entering the subduction zone off Nicaragua is extensive and results in widespread serpentinization. The converse hypothesis is that the bulk of the fluid flux entering into the subduction system is in sediments and alteration minerals in the oceanic crust.

(b) The observed decrease in heat-flow with proximity to the trench is caused by increased hydrothermal circulation and cooling. A corollary is that the degree of cracking within the oceanic crust increases with proximity to the trench.

(c) Seeps on the margin result from mineral dewatering processes at the plate boundary that migrate upward through the forearc sediment complex.

Imaging Crack Porosity, Serpentinite and Anisotropy with Marine EM

Hypotheses (a) and (b) involve pathways for seawater to enter the crust and mantle. Since seawater is several times more conductive than basalts and gabbros, the conductivity of the oceanic crust depends largely on the amount of seawater in cracks and pores. Thus, electromagnetic methods are a good candidate for mapping the lateral and depth extent of pores fluids. From ambient seafloor temperatures to around 350°C, the conductivity of seawater increases nearly linearly with temperature from 3 S/m to around 30 S/m (Nesbitt, 1993; Quist & Marshall, 1968), with little pressure dependence. As the temperature passes the critical point around 410°C (Bischoff & Rosenbauer, 1985), the conductivity rapidly drops, essentially to zero. If the active part of the circulation is sufficiently well mixed that fluids remain at temperatures below about 450°C, then the entire circulating region will have a strong and measurable effect on seafloor conductivity. If a thermal structure is assumed, then Archie's law and other binary mixing formulas can be used to infer bulk porosity from conductivity measurements. A 2D example of CSEM constraints on crustal porosity and thermal structure is presented in MacGregor et al. (1998).

If the deep cracks extend into the mantle, pore fluids will serpentinize mantle peridotite. Although hydrous minerals are not themselves conductive (consider mica), the electrical conductivity of serpentinite measured in the laboratory has been seen to be substantially higher (3-4 orders of magnitude) than serpentine-free peridotite, gabbro or basalt (Stesky and Brace, 1973), although there is a wide range of observed values in samples from other locations (Vagshal, 1969; Popp and Kern, 1993; Xie et al., 2002; Bruhn et al., 2004). It is likely that this variability relates to the presence, oxidation state and interconnectivity of highly conductive magnetite within the serpentinite host. The connectivity of magnetite will depend critically on the scale of the sample examined and may well vary dramatically from sample to sample on the laboratory scale. Conductivity is also likely to vary with the degree of serpentinization, as observed in magnetic properties (e.g., Oufi et al., 2002), and on the history of the rock; these and other parameters may also be a function of processes operating at different tectonic settings. Physical property measurements were made on serpentinite bearing core samples recovered during IODP drilling, close to the Kane OCC. Site 920 is situated on the western rift valley in a 2-km-wide belt of serpentinized peridotite (Cannat et al, 1995). Resistivity measurements on samples from Hole 920D show values from 10-100 Ohm-m range, with notably low values of 3-11 Ohm-m seen in the uppermost serpentinized harzburgite unit. Resistivity and seismic velocity values of core samples appear to co-vary, with low velocity corresponding to low resistivity. Thus, compared with peridotite resistivity of > 10,000 Ohm-m at Moho depths, it is likely that zones of mantle serpentinization will present a strong conductivity contrast and will be good targets for electromagnetic exploration.

In a seafloor with an oriented crack geometry, the electrical conductivity will be anisotropic (Yu et al., 1996). For a series of vertical cracks with a common strike direction, the most conductive direction will be either along strike or in the vertical. The conductivity across the cracks will be lowest. CSEM soundings with complete azimuthal transmission coverage can be used to determine, in a bulk sense, if the conductivity shows an anisotropic signature resulting from aligned cracks, whether those cracks are located in the crust and contain conductive pore fluids, or the cracks extend into the mantle and contain zones of conductive serpentinite (e.g., Everett and Constable, 1999).

Crack anisotropy has been studied with electromagnetic methods for the APPLE project on 35 Ma Pacific lithosphere (Behrens, 2005, Constable et al., in revision). This experiment used vector LEM sensors and a 30 km radius circular CSEM tow in order to measure the shape of the CSEM polarization ellipse, which is sensitive to the geometry of conductivity anisotropy (Everett and Constable, 1999; Behrens, 2005). If conductivity is isotropic, the polarization ellipse maximum is circular and there is no minimum component. For anisotropic conductivity, the polarization depends on the transmitter azimuth and a distinctive clover leaf pattern is seen in the polarization minimum. The APPLE data show this distinctive pattern (Figure 4) and are compatible with vertical cracks aligned parallel to the paleo-spreading center. Because numerical modeling constrains the anisotropy to mantle depths, the inference is that deep paleo-ridge parallel cracks have allowed fluid penetration and serpentinization of the shallow mantle. We expect to see an even larger anisotropic CSEM response at the Nicaraguan Trench due to the significant faulting.

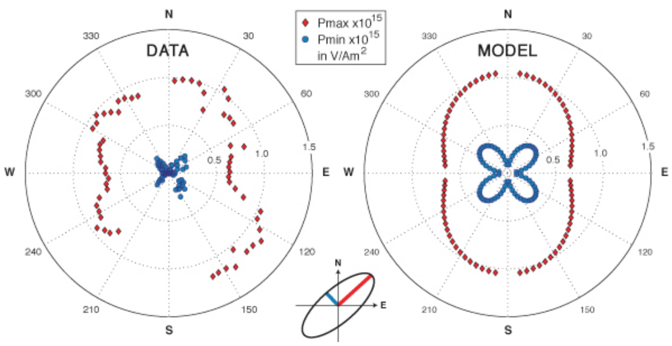

Figure 4. Previous evidence for mantle penetrating faults and serpentinization from the APPLE experiment. Magnitudes of the major (Pmax) and minor (Pmin) axes of the elliptically polarized electric field for CSEM data (left) and model response (right) as a function of receiver–transmitter bearing on a large circular tow. The model is a uni-axially anisotropic upper mantle with vertical sheets of increased electrical conductivity aligned N–S, parallel to the paleo-spreading center. The two resistivities in the anisotropic layer are 10,000 Ohm-m and 100,000 Ohm-m.

Imaging Fluids in the Margin with Marine EM:

The margin offshore Nicaragua and Costa Rica is thought to be dominated by subduction erosion, as indicated by slope subsidence and tectonic extension. Evidence for rapid dewatering of the margin wedge, regional fluid flow and the presence of mud mounds (Talukder et al., 2007, 2008) suggest a large component of fluid output occurs on the accretionary margin. Furthermore, over 100 methane seeps were discovered to occur in a margin parallel band centered about 30 km landward from the trench (Sahling et al., 2008). The widespread presence of a bottom simulation reflector (BSR) in seismic data suggests the presence of free gas and methane hydrate. Recent seismic studies suggest these fluids may originate in the subducting plate, and arise through a network of faults and fractures due to fluid overpressure (Talukder et al., 2007, 2008). Both marine CSEM and MT can provide conductivity constraints on porosity, fluids, methane hydrate and free gas in an accretionary margin setting. Figure 5 shows new results from the CSEM survey of Hydrate Ridge on the accretionary margin offshore Oregon (Weitemeyer et al., 2006). Free gas and hydrate are much more resistive than the surrounding porous sediments are well imaged by CSEM data. From models such as this, quantitative estimates of the bulk hydrate content, pore water content and depth extents can be made.

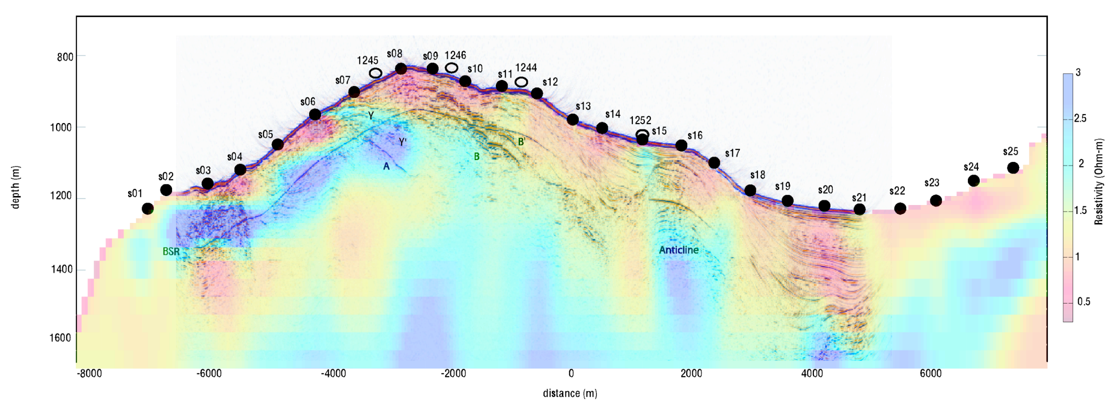

Figure 5. Seismic and CSEM conductivity data from Hydrate Ridge, offshore Oregon (image from Scripps student Karen Weitemeyer's pending Ph.D. thesis). This 2D inversion model was obtained by inverting 25 sites of CSEM data using a proprietary 2D CSEM inversion from WesternGeco, Schlumberger. Shallow resistive (blue) regions correlate with the location of the BSR and indicate the presence of methane hydrate and free gas.

Marine MT data can provide constraints on deeper conductivity. Figure 6 shows a 2D conductivity model obtained from a pilot broadband MT survey on the accretionary margin offshore northeastern Japan. Although the data coverage is sparse, the inversion model illustrates that the MT data are sensitive to significant conductivity variations in both the accretionary prism, the subducting plate and the underlying mantle.

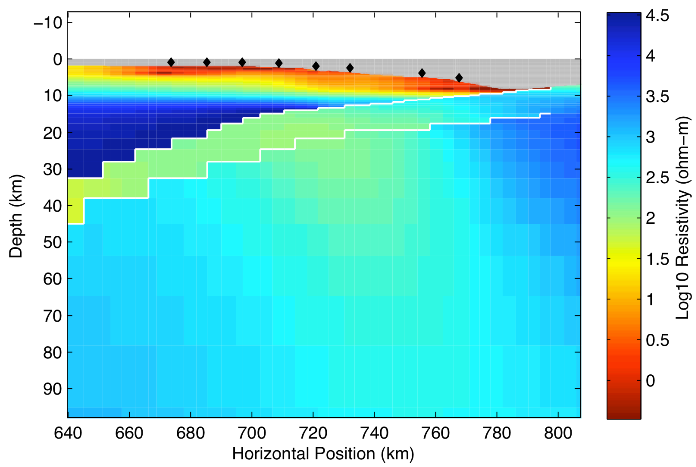

Figure 6. Example of broadband MT on an accretionary prism. Occam2DMT inversion model obtained from broadband MT data collected in a pilot experiment offshore northern Japan. Resistivity jumps were allowed at the top and base of the seismically imaged slab (white lines). Despite the limited number of MT sites (black diamonds), the data are sensitive to low resistivity sediments (red), a resistive mantle wedge (dark blue) and a conductive subducting slab. This work in progress was funded by JAMSTEC, Japan.

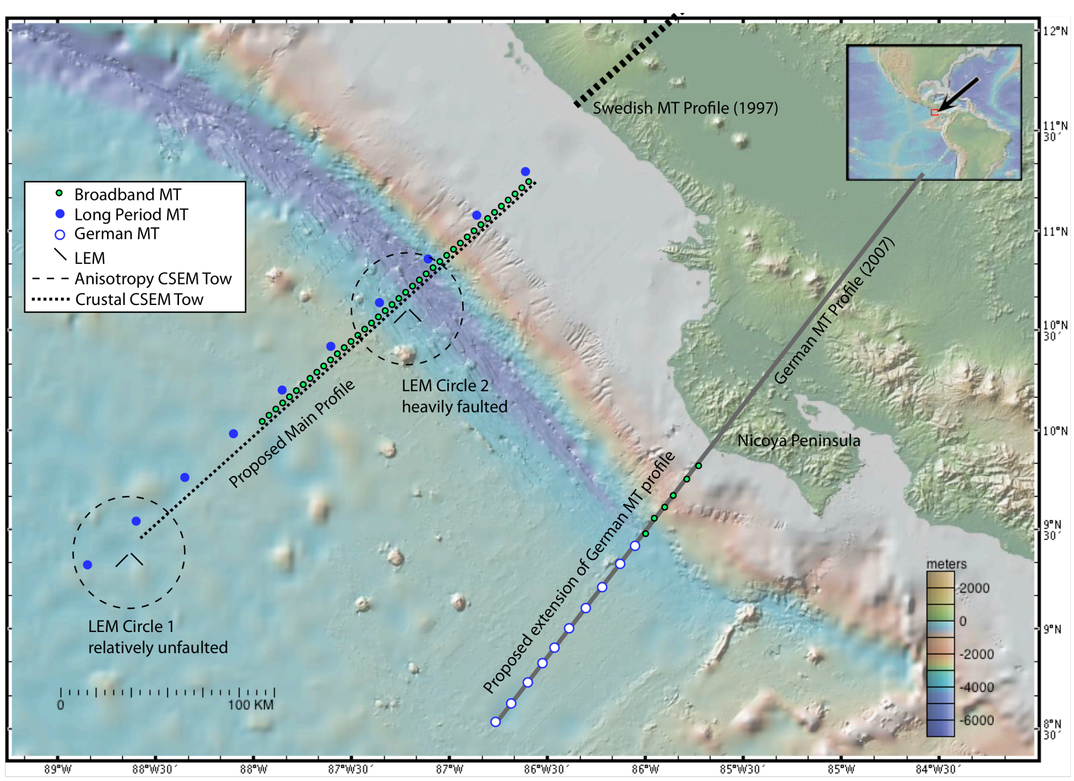

Figure 7: Experiment Map. Bathymetry base map created using GeoMapApp.

The Experiment

The proposed experiment consists of a spectrum of EM techniques and is designed to provide overlapping coverage of electrical conductivity from the shallow crust to upper mantle depths. Our main objective is to map electrical conductivity along a 2D profile located offshore Nicaragua, coincident with recent seismic reflection/refraction data. 40 broadband and 10 long period MT instruments will be deployed over the 300 km long profile. The CSEM transmitter will be deep-towed along this profile and the broadband MT receivers will record the higher frequency CSEM transmissions in addition to the MT data, as done on previous experiments. Two deep crustal/shallow mantle CSEM anisotropy surveys will be conducted on un-faulted and faulted regions. For each of these, the CSEM transmitter will be towed in a 30 km radius around a vector pair of highly sensitive long-wire EM sensors (LEMs), as was done previously to constrain shallow mantle anisotropy on the APPLE project (Behrens, 2005). 10 additional long period MT sites will be collected along the marine portion of the German MT profile using long period MT instruments belonging to our German colleague Marion Jegen. These latter stations will augment an existing 10 marine MT stations already completed with German funding. We will also deploy 6 additional broadband MT sites on the accretionary margin of the German profile since they will provide a view of the mantle wedge at shallow depths and will constrain slab dewatering—especially when coupled with the existing German broadband land MT data.

The combination of broadband MT, long period MT and CSEM data will allow this experiment to meet the objectives listed earlier. The 300 km long profile of broadband and long period MT will provide a unique image of the conductivity of the upper mantle. MT sites extending 100 km onto the forearc will constrain the conductivity of the slab as it is subducted, as well as providing constraints on the depth and extent of any slab dehydration. CSEM and MT data collected on the accretionary prism will allow characterization of the fluid content of the prism. CSEM data collected along the deep ocean profile will map crustal conductivity variations along the path of subduction to examine changes in porosity associated with flexural faulting. Long-offset CSEM data will constrain the degree of conductivity anisotropy within the lithospheric mantle, which can be related to the degree of deep fluid filled cracks. Detailed CSEM anisotropy tows set up to identify the magnitude and depth extent of crustal and mantle cracking anisotropy will be carried out at two distances from the trench. Together these can be used to estimate the degree of serpentinization and, importantly, its variation towards the trench. In addition, MT and CSEM responses along the profile will highlight any transitions in conductivity arising from a progression of cracking.

While the majority of the MT data will be collected by broadband instruments, the long period data will be vital for constraining the deeper mantle conductivity structure, and will provide a background context for considering any shallow mantle conductivity variations imaged with the broadband data. The long-period data will also be important as a tie in to understanding the regional structure (i.e. when combined with land data) and are also expected to have sensitivity on their own (particularly in the TM mode) to connections between the downgoing slab and the mantle wedge, providing insights into the dehydration and melting processes of the subduction system. The modeling shown in Evans et al. (2002) demonstrates that periods up to 10000s are required to fully capture the details of connections between the ocean and mantle wedge that, in turn, depend of where water is released from the slab and where melting occurs.

Deployment of several broadband instruments off Nicoya will aid in resolving a conductor seen in inversions of land data that is suggestive of a shallow dewatering process, but which is poorly resolved by the existing data set. The 10 long period instruments to be deployed here are in addition to 10 sites already recovered, so the density of stations along this profile will be about ½ that along our proposed main line. Together, the long period and broadband MT data will provide a very complementary data set for integration with existing and proposed land MT data.

Cruise Plan

The proposed experiment consists of a main cruise on a R/V Revelle or Melville class ship to deploy all the sensors and to deep-tow the CSEM transmitter, and a second cruise approximately 6 months later to recover the long period MT sensors. Since only 20 instruments will be recovered on the second cruise, a much smaller vessel such as the R/V New Horizon could be used. The duration of each cruise and tasks to be performed are given in the tables below. We have requested 2 contingency days for the main cruise and have also budgeted for two extra LEM anchor/antenna systems. If all goes as planned (or we are ahead of schedule), we will use the extra days to collect additional CSEM deep-tows and will deploy two additional LEMs.

Main Cruise

Task	**Days**
Transit to German Profile off Nicoya Peninsula	0.5
Deploy 6 Scripps Broadband MT	1
Transit to main survey line	0.5
Deploy 40 Scripps Broadband MT	4
Deploy 10 WHOI Long Period MT	2
Deploy 2 LEMs at Circle 1	1
Deploy 2 LEMs at Circle 2	1
Deeptow Circle 1	2
Deep Tow CSEM on 300 km profile	5
Deeptow Circle 2	2
Recover 40 Scripps MT and 4 LEMs	5
Transit to German MT line off Nicoya	0.5
Deploy 10 German MT	2
Recovery 6 Scripps MT	1
Transit to Puntarenas	0.5
Contingency/Weather Days	2
Total	**30**

Long Period MT Recovery Cruise

Task	**Days**
Transit to main survey line, 500 km	1
Recovery 10 long period MT	4
Transit to German MT line off Nicoya	0.5
Recovery 10 German MT	4
Transit to Puntarenas	0.5
Contingency/Weather Days	1
Total	**11**

Equipment

CSEM, LEM and broadband MT data will be recorded using Scripps' fleet of 50 EM receivers, which were developed almost entirely under industrial sponsorship. These receivers were used on several recent experiments and are described in Constable et al. (1998). Based on results from the 2004 EPR 9N experiment, a recording duration of 2 weeks will provide good MT response estimates at 20-5000 s period for the deep ocean MT sites and about 1-5000 s period on the shallower margin prism (see Figure 8 for relevant examples of broadband MT responses). Receiver orientations will be measured using an external electronic compass/tilt sensor which has replaced our less reliable internal compass. The 10 WHOI long period MT instruments were built for the MELT experiment (Evans et al. 1999; Baba et al., 2006) and use suspended magnet sensors which are extremely low-power and stable to long periods. The 10 German MT sensors were built by Marion Jegen's research team at GEOMAR and have been deployed several times to date.

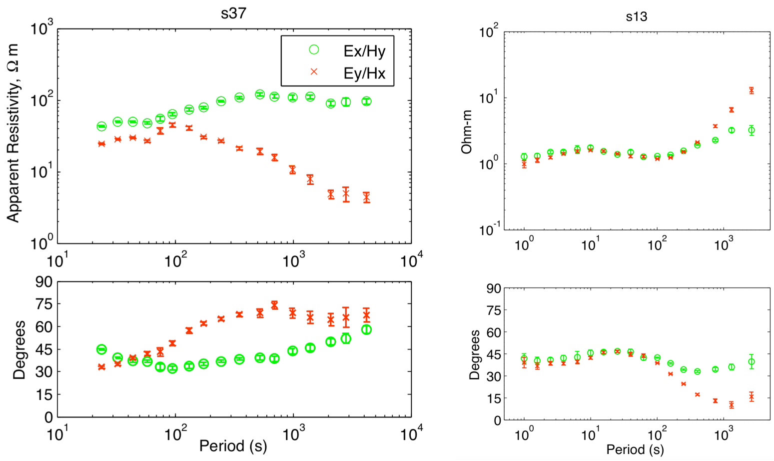

Figure 8. Example broadband MT responses obtained at 9°30'N on the East Pacific Rise using 2 weeks recording (left, Key et al., 2005) and at Gemini Prospect on the continental shelf, northern Gulf of Mexico using 2 days recording (right, Key et al., 2006).

For the CSEM data, we will use the Scripps Undersea EM Source Instrument (SUESI), which is a deep-towed transmitter capable of a 100 kAm dipole moment. SUESI transmits a programmable waveform that can be tailored to generate energy in the 0.01-100 Hz band. For this experiment SUESI will transmit a custom waveform with fundamental frequencies of 0.1, 1 and 10 Hz. Phase is controlled through GPS clock synchronization. The capability of recording multiple frequency transmissions with stable phase control on both electric and magnetic sensors is a significant improvement over the older generation of CSEM experiments from the 1990's, which relied on a single transmission frequency of poor phase stability with only electric field data recordings. SUESI is equipped with additional sensors including a depth gauge, altimeter, real time current monitoring, seawater conductivity meter, and an onboard digital acoustic system for accurate positioning and navigation. Recent experiments using SEUSI include the EPR at 9N (Key et al., 2005), Hydrate Ridge (Weitemeyer et al., 2006), Loihi Seamount (Myer et al., 2006), Catalina Crater (Wheelock et al., 2007) and the San Diego Trough (Constable, Key and Lewis, in revision). As a backup, we will bring along a second complete SUESI transmitter and power supply system.

Data Workup Plan

MT data. Time series analysis and processing of the MT data will follow standard robust and controlled leverage approaches (Egbert, 1997; Chave and Thomson, 2004). Tools for array processing of large marine data sets have been developed through Scripps' involvement with industry and are based upon the Egbert (1997) multi-station approach. This algorithm is unique since in addition to computing robustly estimated MT responses, it procedures diagnostics for quantifying whether the data are compatible with a plane-wave MT source field. Several algorithms for modeling and inverting marine MT data exist (deGroot-Hedlin and Constable, 1992; Rodi and Mackie, 2001; Commer and Newman, 2008). The primary MT analysis will use the open source Occam2DMT inversion (deGroot-Hedlin and Constable, 1992) that is freely available at http://marineemlab.ucsd.edu/Projects/Occam/2DMT. Anisotropic effects will be estimated using an inversion code that solves for conductivity in three orthogonal directions, based upon a generalization of the code of Rodi and Mackie (2001). This algorithm was generated as part of the MELT MT analysis and was used to show evidence for electrical anisotropy and infer hydration of the oceanic upper-mantle off-axis at the southern East Pacific Rise (Evans et al., 2005). As part of the Marianas MT experiment the 2D inversion code DASOCC (Siripunvaraporn and Egbert, 2000; 2007), has been modified for marine use, and a 3D inversion code (Siripunvaraporn et al., 2005) is being similarly modified. We expect the data to exhibit significant distortions from the large regional seafloor topography. Two methods that have been used successfully for addressing topography effects include direct modeling using finite elements (Wannamaker et al., 1987; Key and Weiss, 2006; Constable, Key and Lewis, in revision) and an indirect method that iteratively removes the topographic distortion from the data, thus reducing the complexity of the numerical modeling grid (Baba and Chave, 2005). Both methods have their relative merits and we expect to utilize them both in analyzing the MT responses for this experiment.

CSEM data. CSEM amplitude and phase versus source-receiver offset data for all electric and magnetic field components will be analyzed using several methods. 1D forward and inversion modeling (Flossadottir and Constable, 1996) will be carried out as a first cut examination. Seafloor bathymetry effects will be included in 2.5D forward modeling by using an adaptive finite modeling code (Li and Key, 2007; Li and Constable, 2007). 1D anisotropic modeling can be performed using the algorithms presented in Xiong (1989) and Everett and Constable (1999). However, data near the trench will require 2D anisotropic modeling that incorporates bathymetry trends. Under industrial sponsorship, the Scripps group is developing a 2.5D CSEM inversion code that will include anisotropy and which uses the adaptive finite modeling method presented in Li and Key (2007). We expect this to be available in advance of the 2010 CSEM cruise leg.

Joint Seismic and EM Interpretation.

A key aspect of the proposed work is the joint interpretation of electrical conductivity measured by this experiment and seismic velocity measured by the recently completed TICO-CAVA experiment. Such joint interpretations are surprisingly rare but hold great promise. The two physical properties are expected to respond differently to cracking through the crust and serpentinization of the upper mantle. Joint inversion and interpretation of seismic and EM methods is an area of active research. In some cases it is instructive merely to overlay a reflection profile with an EM model (e.g., see Figure 5, as wells other examples presented in Key and Constable, 2002; Key et al., 2006), or to use boundaries inferred from reflection profiles in EM inversions. Marion Jegen, our colleague in this project, has students working on joint EM and seismic inversion techniques with these approaches in mind. In this project we will investigate the combination of conductivity and seismic velocity as a means of more tightly discriminating the degree of serpentinization of the mantle along with the degree of cracking present. This will require not only estimates of the two physical properties, but also estimates of the degree of seismic and electrical anisotropies of the lower crust and upper mantle. The first step in this approach will be to explore parameter space by calculating expected conductivities and velocities for a range of fluid volume fractions and crack networks and also for varying degrees of serpentinization. One means of doing this would be to use the effective medium approach for EM and seismic velocities developed by Greer (2001) and discussed in Sinha and Evans (2004). This joint effective medium modeling assumes that the pores consist of spheroidal inclusions with random orientations, so that pore distribution can be represented in terms of two parameters: porosity and pore aspect ratio. In contrast to previous studies, this approach uses identical probability arguments to explicitly account for the degree of interconnection of the pore spaces, in both the seismic and the electrical modeling. By making appropriate assumptions about the physical properties of both seawater and the rock matrix, it is possible to find a combination of porosity and pore aspect ratio that simultaneously fits both the observed P-wave velocity and electrical resistivity. We will investigate extensions to this approach that may be needed for the conditions in a serpentinized upper-mantle.

Relevance to MARGINS Program

Quantifying the fluxes of fluids into subduction factory is a primary goal of the subduction factory component of the MARGINS program, and the Central American system is a focus site for that effort. We have chosen our line to be coincident with the primary Nicaraguan profile in the recent seismic refraction experiment (Holbrook and Lizarralde et al. P.I.s). Furthermore, we have chosen Nicaragua because it appears to offer the highest likelihood of showing extensive mantle alteration as a result of plate bending leading to faulting and hydrothermal circulation. As an ocean-continent system, the proposed profile complements that carried out by one of the P.I.s in collaboration with Japanese scientists across the Marianas system (see results of prior support).

Broader Impacts of Proposal

The proposed experiment will promote the use of the Scripps marine EM instrument fleet for use in non-commercial geophysical experiments and will advance marine EM as a useful technique for studying continental margins. Data and modeling results will be submitted in a timely manner to the data management center, as done for Constable and Key's EPR 9 N MT experiment. A project webpage for disseminating project information, the cruise report, photographs and results to the public and other researchers will be maintained at the extensive Scripps Marine EM Lab website (http://marineemlab.ucsd.edu), as also done for previous projects.

International collaboration. This experiment is a stand-alone component of a larger international effort. German colleagues have already completed land MT in Costa-Rica and have deployed 10 MT stations offshore. Spanish colleagues are proposing a land MT profile in Nicaragua. Our effort will augment the existing German line (and Marion Jegen from GEOMAR will participate and provide instruments for this survey) and will link up as closely as logistically possible with the Nicaraguan land MT profile. The offshore MT data will greatly improve the ability of the land profiles to image key features of the subduction system, beyond those highlighted as specific targets of our survey (e.g., Evans et al., 2000).

Education. The proposal will support two Ph.D. students, one at Scripps and the other at WHOI. The student at Scripps will focus on the MT analysis, while the student at WHOI will work on the CSEM data. Both students will work with PIs at both institutions and we propose exchange visits to enhance training. In the latter stages of the project, the students will benefit from co-PI Dan Lizarralde, who will assist in assimilating seismic models into our analysis.

Results of Prior NSF Support:

R. Evans: *US and Japanese Collaborative Research: A Magnetotelluric (MT) Transect Across the Mariana Subduction Factory* Project No: OCE0405641 $1,170,110; (06/01/2004-05/31/2009) Funded an extensive MT profile across the central Mariana area to image the electrical structure of the Mariana subduction, fore-arc, arc, back-arc system. The transect will address issues of hydration in the mantle wedge from the subducted slab, the property and distribution of subsequent melting, and patterns of flow in the mantle wedge. Instruments were deployed at 33 ocean bottom electro-magnetometers (OBEMs), 7 sets of ocean bottom magnetometers (OBMs) and ocean bottom electrometers (OBEs) were deployed at 40 sites in December of 2005. 28 OBEMs, 7 OBMs, and 6 OBEs were recovered in September of 2006, and 2 further instruments were recovered in November of 2007. The full length of the transect is about 700km. Site spacing in the fore-arc and Pacific Ocean basin are several tens of kilometers, but in the vicinity of the back-arc spreading center is only a few km. The recorded data at 33 full MT sites have been combined with 6 from previous studies (Filloux, 1983; Goto et al., 2003; Baba et al., 2005; Seama et al., 2007) and are currently under analysis and forms the focus of a PhD dissertation by Tetsuo Matsuno. Matsuno has accepted a post-doctoral fellowship at WHOI (funded by WHOI) which he will commence this coming December. Initial results have been presented at international meetings and at a MARGINS meeting in Hawaii last November. Initial features in the models, obtained from 2D inversion using a version of DASOCC (Siripunvaraporn and Egbert, 2000) modified for the seafloor, include: (1) a high resistivity region beneath the fore-arc and the trench extending to a depth of about 300km, (2) a low resistivity region beneath the back-arc spreading center which extends to a depth of 100km and connects to a deeper low resistivity region, (3) a low resistivity region beneath the volcanic arc extending to a depth of 50km, (4) a low resistivity region beneath the serpentine diapirs in the fore-arc extending to a depth of 30km. The area in the fore-arc is particularly relevant to this proposal. Although data density and bandwidth is not as extensive as we propose, the low resistivity rocks suggest a serpentinized mantle, and high fluid contents in well-connected crack networks beneath the serpentine diapirs.

D. Lizarralde, G.Axen, A.Harding, W.S. Holbrook, G.Kent, P.Umhoefer: *Collaborative Research: Seismic and Geologic Study of Gulf of California Rifting and Magmatism,* OCE0111983; $504,921 (4/1/2001 to 3/31/2003). This project was aimed at defining the crustal-scale style of extension across multiple rift segments in the Gulf of California, assessing variations in extensional style along the length of the gulf, and interpreting these variations in terms of key parameters such as temperture, gross pre-rift crustal structure, extention rate, etc. MCS and OBS seismic data were acquired across three spreading segments in the southern Gulf of California. We found surprisingly large variation in rifting style and magmatism between these from wide rifting with minor syn-rift magmatism to narrow rifting in magmatically robust segments. These differences encompass much of the variation observed across nearly all other non-end-member continental margins. We explain this variation by invoking mantle depletion to account for wide, magma-poor rifting and mantle fertility and possibly the influence of sediments to account for robust rift and post-rift magmatism. These factors may vary laterally over small distances in regions that have transitioned from convergence to extension, as is the case for the Gulf of California and many other rifts.

Lizarralde, D., G. J. Axen, H. E. Brown, J. Fletcher, A. González-F., A. J. Harding, W. S. Holbrook, G. M. Kent, P. Paramo, F. Sutherland, and P. J. Umhoefer, Variation in styles of rifting in the Gulf of California, *Nature, 448,* doi:10.1038/nature06035, 466-469, 2007.

Páramo, P., W. S. Holbrook, H. E. Brown, D. Lizarralde, J. Fletcher, P. Umhoefer, G. Kent, A. Harding, A. Gonzalez, and G. Axen, Seismic structure of the southern Gulf of California from Los Cabos block to the East Pacific Rise, *J. Geophys. Res., 113*, B03307, doi:10.1029/2007JB005113, 2008.

S. Constable: *Collaborative Research: The APPLE •Anisotropy and Physics of the Pacific Lithosphere Experiment*; OCE0002381; $372,005 (2/15/2001 to 1/31/2004)
This project used combined controlled source EM and magnetotelluric soundings to resolve the strike directions and depth extents of electrical anisotropy from the near-surface through the crust and upper mantle of 35 Ma oceanic lithosphere. The CSEM data unambiguously show a ridge parallel anisotropy frozen into the lithospheric mantle, which we interpret in terms of serpentinization of mantle-penetrating normal faults. This project was the focus of James Behrens' PhD thesis and a manuscript is being revised for resubmission. Additional information can be found at http://marineemlab.ucsd.edu/Projects/APPLE/.

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