DEEP SAN ANDREAS FAULT BOUNDARY STRUCTURE FROM MARINE MAGNETOTELLURICS

A proposal submitted to UC Shipfunds for New Horizon and Sproul shiptime

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SUMMARY

Knowledge of the distribution and volume of fluids in the tectonic structures associated with the San Andreas fault system is important for understanding the physical properties that govern the fault zone behavior. Electromagnetic methods provide the tools of choice for remote detection of conductive pore fluids. We had proposed to NSF a 50 site, 180 km long combined marine magnetotelluric (MT) and controlled-source electromagnetic (CSEM) sounding experiment on the continental margin west of the San Andreas Fault Observatory at Depth (SAFOD) in collaboration and coordination with a land MT survey being carried out by Oliver Ritter and colleagues of GeoForschungsZentrum (GFZ, Potsdam, Germany). Although well reviewed, the proposal was not funded, yet the land MT work is being carried out right now. Scripps posdoc Kerry Key and students Brent Wheelock and David Myer recently joined the Potsdam group to help collect land data. Although the NSF proposal failed, access to U.C. ship time would present us with an excellent opportunity for Scripps to contribute critical marine geophysical data to an international project being carried out 'in our own back yard'. Our proposed study would

- Extend existing and ongoing land MT surveys by the Potsdam group into an amphibious transect of 300 km total length, spanning the deep ocean to the Great Valley. This will be the largest amphibious MT survey to date and will provide a comprehensive electrical image of (i) the oceanic lithosphere and mantle, (ii) the continental shelf sediments and accretionary complex, (iii) the subducted and under-plated oceanic crust and mantle, and (iv) the onshore crust and mantle of the San Andreas fault zone. The vast coverage provided by the combined data set will allow us to decipher the source and distribution of fluids in the plate boundary and the role fluids may have played as this system evolved from subduction to strike slip motion during the past 20 Ma.

- Detect any high conductivity zones associated with detachment faulting and ductile flow along the boundary between under-plated oceanic crust and the overlying and deformed continental shelf. If detachment faulting occurs along serpentinized oceanic crust, there should be a detectable conductivity anomaly. This will help constrain models for the source of deep fluids beneath the San Andreas fault zone, as well as kinematic models for crustal shortening deformation west of the plate boundary.

- Detect the depth and lateral extent of conductivity anomalies, if they exist, associated with the Hosgri and Santa Lucia Bank fault zones on the continental shelf. Seismicity suggests that these faults are active and electrical conductivity images from the seafloor to the upper mantle will allow us to determine the relationship between faulting, seismicity, and crustal fluids in the offshore region.

The marine EM group at Scripps considers this opportunity so important that we will contribute accumulated discretionary funds to support this project, paying for technical support, deployment supplies, and so on. Although the entire cost of ship time is beyond our means, if needs be we could share the cost of this too. Data collected would provide Brent Wheelock, who recently passed his departmental exam, with material for his Ph.D. studies. Our track record is good in this regard; 3.5 days on station at Hydrate Ridge provided Karen Weitemeyer with all her thesis data, and a 4-day cruise off Hawaii gave David Myer enough data for a good Ph.D. To the extent possible on the New Horizon and Sproul, we would provide an opportunity for other Scripps students to see marine geophysics in action – the short duration would make this a good proposition for students who could not commit to a lengthy cruise.

SCIENTIFIC MOTIVATION

Several magnetotelluric (MT) studies of the San Andreas fault (SAF) in south-central California have identified an electrically conductive fault zone in the upper crust, attributed to fluids in the fault damage zone which in turn may be responsible for inhibiting seismicity in the upper 4 km. Starting in 2005, a research group led by Oliver Ritter of GeoForschungsZentrum (GFZ), Potsdam, Germany began acquiring long period and broadband MT data as part of the Deep Root project. The 50 by 50 km square of MT sites near Parkfield (the black square in Figure 1A) was designed to reveal the deep crustal roots of the San Andreas fault which were beyond the reach of the earlier MT surveys. Inversion of a profile of the Deep Root MT data (Figure 1B) shows a zone of high conductivity that extends to at least 25 km depth beneath the SAF. Underneath conductive near-surface sediments lies resistive Salinian granite in the west and the less resistive Franciscan accretionary complex to the east, with a conductive sub-vertical zone separating these formations beneath the SAF. The shallow fault zone conductor and deeper lower crustal conductor are connected by a slightly less conductive region across mid-crustal levels that coincides with the seismogenic zone. It has been suggested that the deeper conductor may be related to fluids in the lower crust and may represent a migration pathway for crustal fluids, since the conductivities imply a high level of interconnected pore fluids. Fluid-flow in the lower crust and upper mantle might also be responsible for the recently observed non-volcanic tremors near Cholame, approximately 40 km south of Parkfield.

(A)

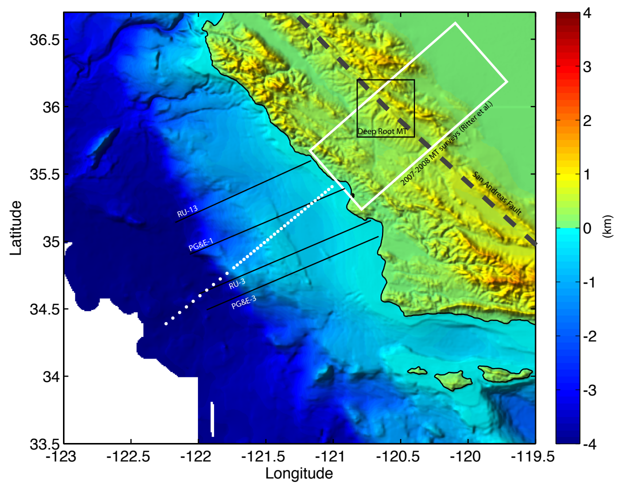


Figure 1A: Proposed experiment location. Marine MT receiver sites are shown as white dots. A CSEM tow will pass over the entire 180 km line of 40 receivers. Black lines show the location of past marine seismic lines. Black square shows location of existing land MT sites and white rectangle shows location of extensive land MT data being collected in 2007-2008 by GFZ Potsdam researchers. We have oriented the marine MT survey line to be perpendicular to the coastline and major topographic features of the continental slope.

(B)

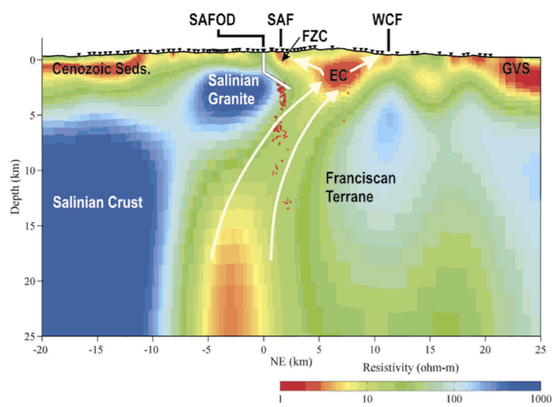
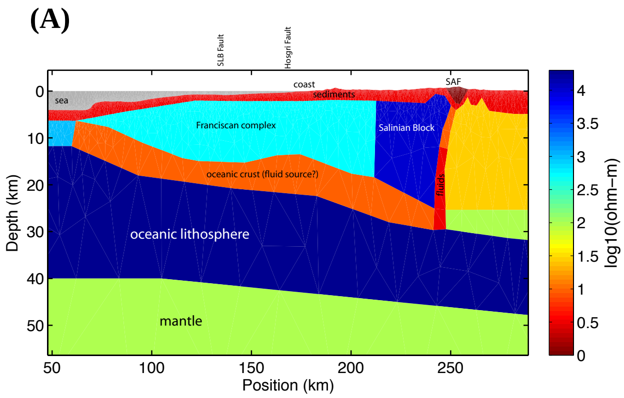


Figure 1B: Electrical conductivity model from the 50 km Deep Root profile, across the SAF near the SAFOD site. Superimposed on the model are the SAFOD main hole and seismicity (red dots). A broad zone of high conductivity northeast of the SAF is imaged below the Parkfield Grade (EC). This anomaly is sandwiched between two resistive formations: Salinian Granite adjacent to the southwest of the SAF and a resistive block (presumably within the Franciscan Terrane) in the northeast. The zone of high conductivity could represent a migration path for fluids originating from the lower crust and/or upper mantle.

Currently (2007–2008), extensive additional land MT data are being collected by the GFZ group, in an area shown by the white box in Figure 1A. The wider aperture and coverage to the south will facilitate imaging the lower crustal and upper mantle conductivity in the region of deep non-volcanic tremors near Cholame and help decipher the deep sources of fluids (or high conductivity) migrating through the SAF system near Parkfield. Since a key part of this work is to image deep structure, they will extend their MT lines to the coast, where the land arrays must obviously stop. The shiptime requested in this proposal will allow us (Scripps) to extend one of these lines across the continental shelf and onto the oceanic lithosphere, in collaboration with the GFZ group. Figure 1A shows the location of our proposed survey line.



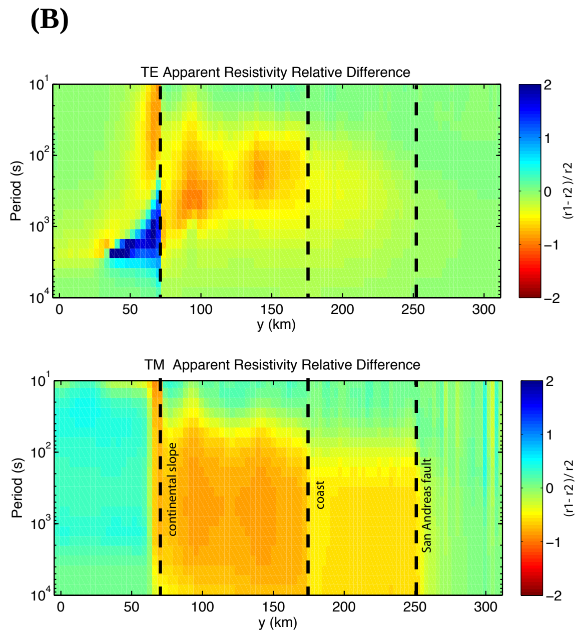


Figure 2A: Hypothetical conductivity model beneath the proposed MT transect. Near the San Andreas fault, the model is derived from the model shown in Figure 1B. Offshore structure is interpreted from seismic studies. Figure 2B: MT anomaly pseudosections computed between the model shown in (A) and a similar model without the conductive under-plated oceanic crust. Shaded colors indicate the $\log_{10}$ apparent resistivity ratio between the two models. A value of 1 (and -1) corresponds to an order of magnitude difference in the model responses. The position of major seafloor topographic boundaries and the San Andreas fault zone are shown as dashed vertical lines. The character of the MT anomalies changes markedly near both the coast and continental slope, showing strong coupling between currents flowing in the seawater and the deeper conductive under-plated oceanic crust. While the conductor resides between the continental slope and the San Andreas fault, the largest anomalies are observed for the offshore MT sites (positions $<$ 180 km).

As a feasibility study for the proposed experiment, we computed MT responses for models derived from the extensive regional marine seismic profiles, offshore/onshore common offset profiles, and existing land MT models. Figure 2A shows our hypothetical conductivity model. The resistive lithosphere on the deep ocean side of the model is constrained from recent controlled-source EM studies of the eastern Pacific plate by Scripps student Jim Behrens, underlain by resistivity predicted by a model of mantle olivine conductivity. Subduction occurred along this plate margin during the Oligocene to the Miocene (19 Ma), and seismic results show strong evidence that the continental shelf is under-plated by the subducted oceanic crust of the Monterey plate. Hence we have extended the oceanic crust and lithosphere in our model beneath the continental margin. MT responses were computed for two variants of the model shown in Figure 2A using our new adaptive finite element modeling code. In the first model, the subducted oceanic crust is relatively fluid free and has a high resistivity of 1000 Ωm. In the alternate model, the subducted oceanic crust has an abundance of conductive fluids or serpentinization, resulting a lower resistivity of 10 Ωm.

Comparison of the responses between the two models for offshore sites shows phase differences of up to 20 degrees, well above the 5-10% uncertainty for broadband marine MT data, and that the largest differences occur at 10-2000 s periods, well within our recording range. Figure 2B shows MT anomaly pseudosections computed between the model shown in Figure 2A and a similar model without the conductive under-plated oceanic crust. Shaded colors indicate the $\log_{10}$ apparent resistivity ratio between the two models. A value of 1 corresponds to an order of magnitude difference in the model responses. The character of the MT anomalies changes markedly near both the coast and continental slope, showing strong coupling between currents flowing in the seawater and the deeper conductive under-plated oceanic crust. While the conductor extends from the continental slope and onshore to the San Andreas fault, the largest anomalies are observed for the offshore MT sites (positions < 180 km), suggesting that marine MT will provide strong contraints on the existence and lateral extent of lower crustal conductive anomalies associated with the San Andreas fault zone. In the deep ocean at positions 30 to 70 km, there is a very large anomaly in the TE mode due to strong coupling between the currents flowing in the deep ocean and currents flowing beneath the continental shelf, showing that MT sites out in the deep ocean are strongly sensitive to structure beneath the continental shelf and will be a critical part of our MT survey.

LOGISTICS

Our proposed 180 km marine MT profile, extending from the deep ocean onto the continental shelf, is shown in Figure 1A. Forty broadband MT sites will be collected at a site spacing of 3.6 km on the shelf and 7.2 km in the deep ocean. This high density of MT sites will allow for good lateral and depth constraints on conductivity structure from a few kilometers deep to well into the upper mantle. We will augment the MT data set with a single line of deep-towed, multi-frequency, controlled-source electromagnetic (CSEM) transmissions using the Scripps Undersea EM Source Instrument (SUESI). A single CSEM tow over all 40 receivers at 3 km/hr (1.5 kts) will only add an additional 2.5 days to our proposed experiment (plus 6 hours each to deploy and recover the transmitter). While MT is preferentially sensitive to conductors, CSEM is preferentially sensitive to resistors and so the two data sets will offer complementary constraints on structures in the upper few kilometers. Additionally, resistivity derived from the CSEM data can be used for modeling and correcting for subtle topographic distortions in the MT data. This experiment will be a significant advancement over previous marine EM studies and will be the first large scale use of combined broadband CSEM and MT data for imaging the tectonic structure of a continental margin. Four nearly coast perpendicular seismic profiles surround the survey region and will be used to form an integrated interpretation of seismic and EM data. The EM profile crosses both the Santa Lucia Bank fault on the continental shelf, and the Hosgri fault closer to shore. The MT and CSEM data will allow us to determine whether these faults, like the San Andreas, also contain fault zone conductors.

Table 1. Deployment and Recovery Cruise Schedules

Deployment Cruise, NH	Days	Recovery Cruise, Sproul	Days
Transit to site from San Diego	1.5	Transit to site from San Diego	1.5
Deploy 40 EM receivers	3	Recover 40 EM receivers	4
Deeptow SUESI	3	Transit to San Diego	1.5
Transit to San Diego	1.5		
Port day	1		
Total NH time	10	Total Sproul time	7

Our original proposal was for two legs on a R/V New Horizon class ship using all 50 SIO EM receivers and carrying out CSEM operations on the recovery cruise. However, by cutting back the number of receivers to 40 we can squeeze all the instruments and the transmitter on the New Horizon for the first leg, and then could carry out a recovery cruise on the Sproul, reducing the total cost of the project. Table 1 summarizes the time required for each cruise leg. Transit to the deployment area at 121.5°W, 35°N from San Diego will require about 1.5 days time. During the first leg, we will deploy 40 EM receivers at an average rate of about 1-2 hours per instrument (3 days estimated) and tow SUESI (3 days). We will then transit back to San Diego and leave the EM receivers to record MT data undisturbed for 7-14 additional days. On the recovery cruise we will release instruments (10 minutes each), have an average rise time of 100 minutes (20 m/min in 2000 m water), and a transit time between stations of 20 minutes, to give an average recovery rate of 130 minutes per instrument, for a total recovery time of about 4 days. This is conservative – if the next instrument along the line is within acoustic range, we may be able to halve this time and return early.

We have no particular constraints on the timing of the cruise. It would be nice to avoid the worst of the winter weather, since we will be operating outside the effect of Point Conception.

JUSTIFICATION FOR USE OF SIO SHIP FUNDS

The chances of getting this project funded through the NSF are minimal. We do not believe this is based on the merits of the project, which reviewed quite well, but what might be most charitably called programmatic issues with the panel. It is a sad reflection on the current state of US science funding that a German group is studying seismic hazard in California.

We consider this project so important that we will contribute accumulated discretionary funds to support the field work, paying for technical support, deployment supplies, and so on. Although the entire cost of ship time is beyond our means, if needs be we could share the cost of this too. Obviously, this shiptime request is a derivative of the NSF proposal, written by Kerry Key (postdoc) and Steven Constable (PI). However, after the proposal was submitted Brent Wheelock (student), who recently passed his departmental exam, took an interest in this project. Brent spent several weeks in the field this month with the GFZ group, helping to collect the land MT data. The ship time we are requesting would provide Brent with an absolutely first class data set for his Ph.D. studies. Importantly, this would be a data set he helped collect, and not something handed down to him, as is so often the case with big marine projects. Our track record for opportunistically providing students with data is very good; 3.5 days on station at Hydrate Ridge provided Karen Weitemeyer with all her thesis data, and a 4-day cruise off Hawaii gave David Myer enough data for a good Ph.D.

To the extent possible on the New Horizon and Sproul, we would provide an opportunity for other Scripps students to see marine geophysics in action – the short duration would make this a good proposition for students who could not commit to a lengthy cruise (we did this on a New Horizon cruise last year for an SIO231 class). It is also likely that once we mobilize the New Horizon with our CSEM transmitter, we will attract some extra support for add-on tests funded by our industry sponsors.