Estimating Upper Mantle Hydration from *In Situ* Electrical Conductivity

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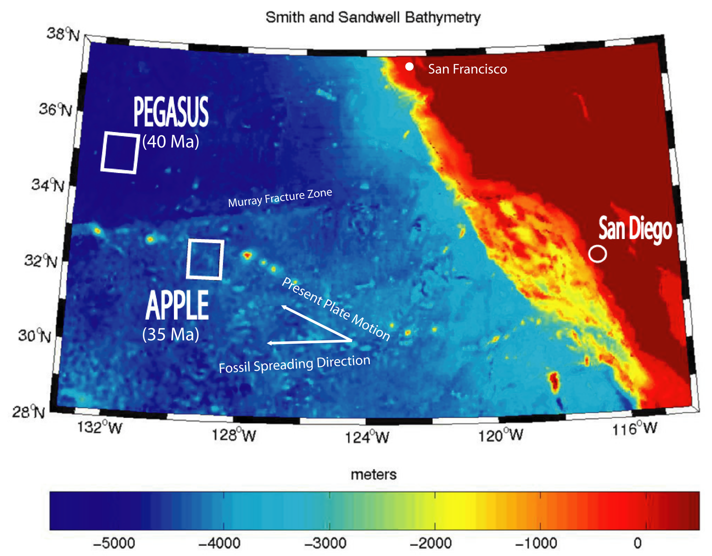
ABSTRACT

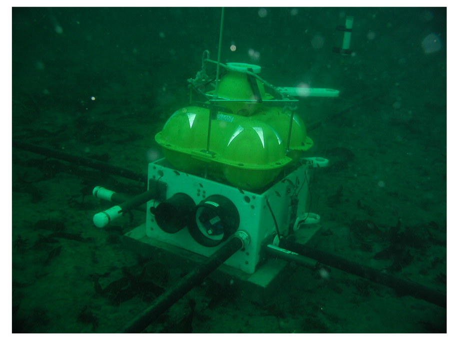
The electrical conductivity of 35-40 Ma Pacific plate has been measured *in situ*; one robust result is the presence of bulk anisotropy in the lithospheric upper mantle. We interpret this anisotropy to be a result of hydrothermal circulation into the upper mantle along spreading-ridge-parallel normal faults: the associated zones of serpentinized peridotite provide the pathways of enhanced electrical conductivity required by the data. Our modeling bounds the range of possible anisotropic ratios, which are then used to estimate the amount of water required to serpentinize the requisite amounts of peridotite.

These data sets, however, do not indicate anisotropy in the bulk conductivity of the crust, nor of the aesthenosperic mantle. This second point is significant, as recent measurements of sub-continental aesthenospheric conductivity have been interpreted to indicate anisotropy, with the conductive direction aligned with present plate motion.

LOCATION

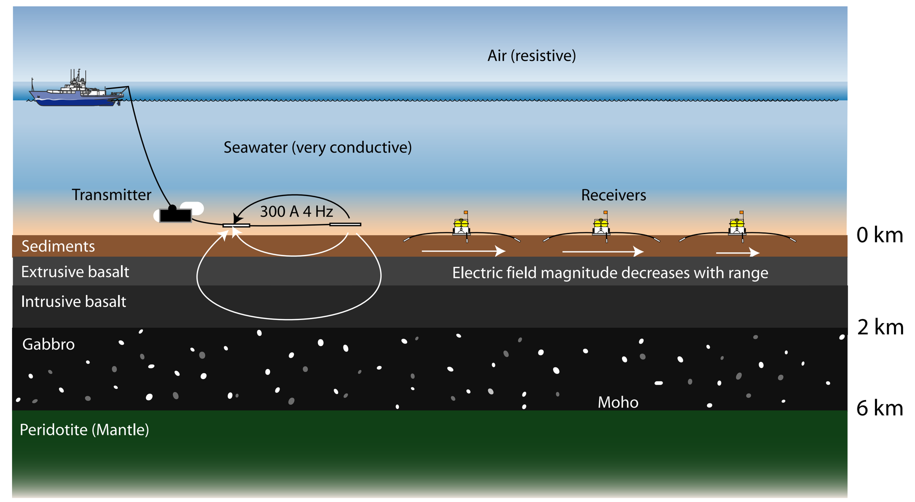


The Anisotropy and Physics of the Pacific Plate Experiment (APPLE) survey site was approximately 1000 km west of San Diego. APPLE was motivated by hints of anisotropy in the CSEM data collected at the PEGASUS survey site. The present plate motion is relative to a fixed Hawaiian Hotspot reference frame, and the fossil spreading direction, normal to the magnetic anomaly isochrons, is almost exactly East-West at the APPLE survey site. The water depth at APPLE is ~4400 m

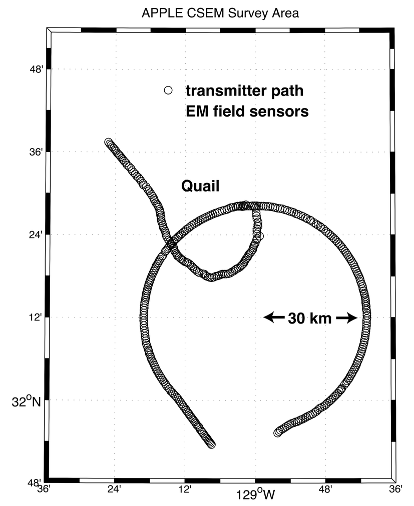


Scripps Institution of Oceanography
Seafloor Electromagnetic Field Sensor

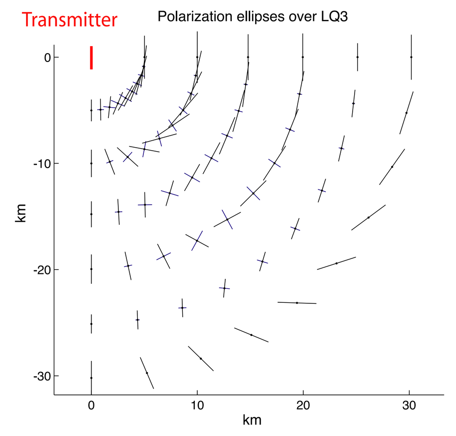
CSEM METHOD



In the APPLE Controlled-Source Electromagnetic Sounding (CSEM) experiment, electromagnetic energy was transmitted at 4 Hz from a horizontal dipole deeptowed along the seafloor. The fields diffuse through the seafloor and are measured by an array of autonomous receivers. Shown here is typical cross-section of oceanic lithosphere. At the APPLE survey site, sediment thickness is ~50 m.



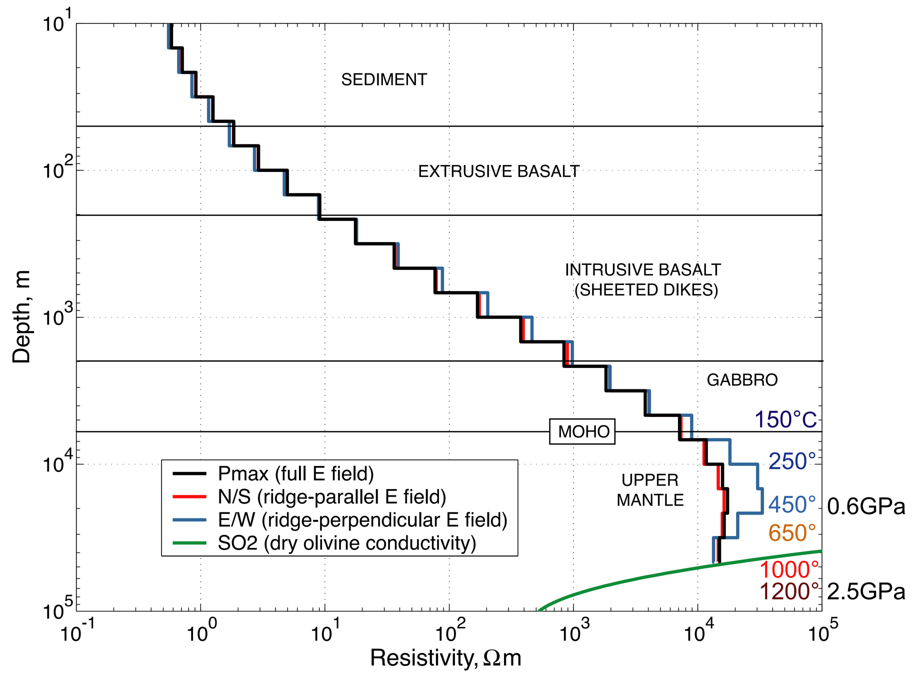
The transmitter was deeptowed around a 30 km radius circle, with receivers positioned at the center and around the perimeter. A 15 km radius semicircle was towed around instrument Quail, and the maximum source-receiver separation of 70 km was acquired at the end of the long radial tow. The short-offset data constrain crustal resistivity structure, and the long-offset data add sensitivity to the upper mantle.



The horizontal electric field is elliptically polarized. The magnitude of the major axis, the eccentricity, and the orientation are functions of both the dipole geometry and the subsurface electrical conductivity.

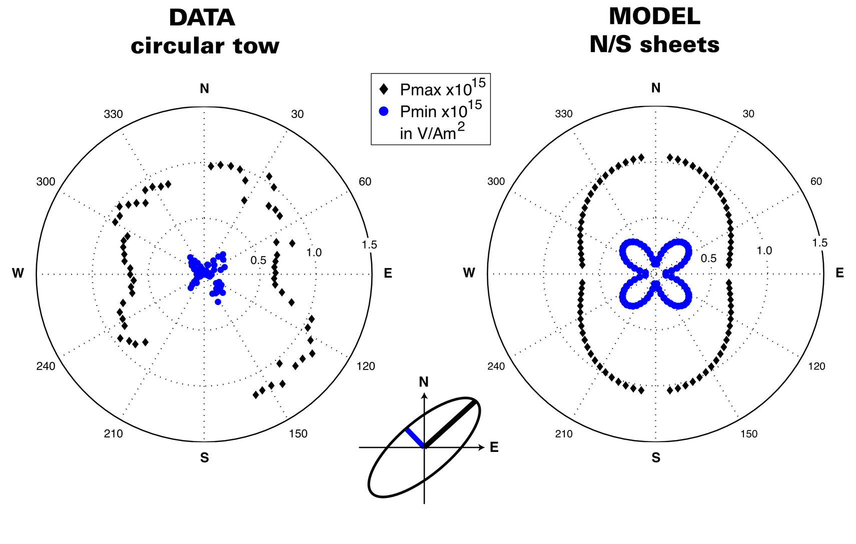
This plot represents one quadrant of the dipole field over an isotropic 1-D model. Ellipse scale varies between radii.

LITHOSPHERIC ANISOTROPY: MANTLE SERPENTINIZATION?



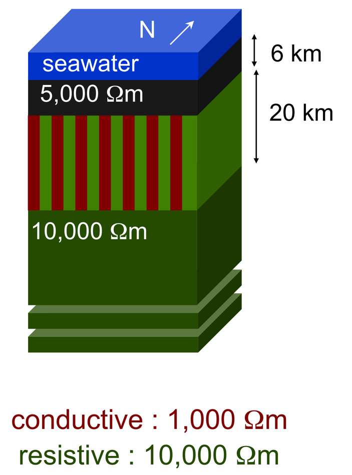
Smooth inversion of both Pmax and single-component data: a subset of the data were selected which have a varied mix of transmitter-receiver geometries and offsets (for sensitivity to the entire lithospheric section), while the transmitter and receiver locations were restricted to the northwest quadrant of the survey area to minimize heterogeneity. The data lose sensitivity around 30 km below the seafloor.

The data require anisotropy in the upper mantle of at least a factor of 3, which could be caused by **ridge-parallel normal faulting and subsequent localized serpentinization of upper mantle peridotites**. Serpentinization tends to lower the resistivity of peridotites. Measured lithospheric resistivities are less than that of pure, dry olivine.



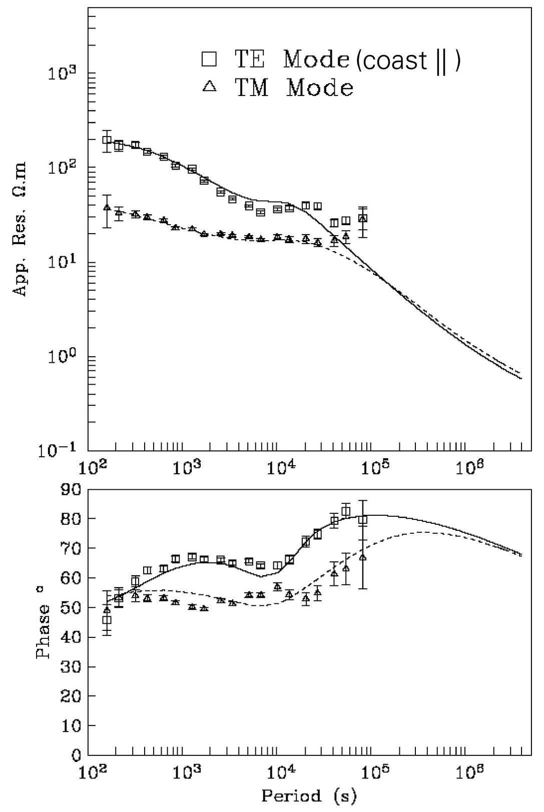
Data are magnitudes of the axes of the horizontal electric field polarization ellipse measured at the center of the array during the 30 km radius circular tow. The model is equivalent to paleo-ridge-parallel aligned vertical sheets of increased conductivity in the upper mantle.

In the absence of anisotropy, Pmin would be essentially zero and Pmax would vary only due to heterogeneities.

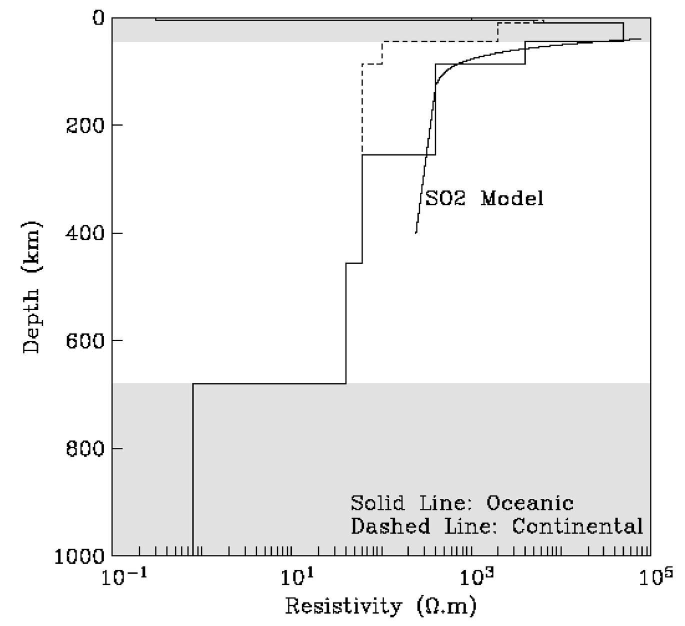


AESTHENOSPHERIC CONDUCTIVITY: DRY, ISOTROPIC OLIVINE

Marine Magnetotelluric (MT) data were also collected. Fluctuations in the earth's magnetic field induce subterranean electrical currents; thus, measurements of the transfer function between orthogonal electric and magnetic fields at the surface are sensitive to mantle conductivity. Lower frequencies are sensitive to deeper structure. High frequency energy is absorbed by the seawater, motivating the use of CSEM to determine shallow structure.



A 2-D, isotropic aesthenosphere model fits the MT data exceedingly well. On the ocean side, the top 30 km were set to the CSEM Pmax inversion result, with dry laboratory olivine conductivity (SO2) below. The sub-continental aesthenosphere must be ~ 10 times more conductive to fit the data.



The conductivity estimate for the mantle below the 660 km discontinuity is based on studies of global magnetic field observatory data.

CONCLUSIONS

CRUST:

Electrical Resistivity increases exponentially with depth, due to decreasing porosity and fluid permeability. No significant bulk anisotropy has been detected.

LITHOSPHERIC UPPER MANTLE:

There is evidence for bulk anisotropy from independent parts of the CSEM data set, using independent forward modeling algorithms.

The preferred model has

(a) an isotropic crust

(b) an anisotropic layer beginning at the base of the crust, and extending 20 km into the upper mantle

(c) vertical sheets within this anisotropic layer, parallel to the paleo-spreading ridge, that are ~10 times more conductive.

These sheets could be the result of hydrothermal circulation into the upper mantle via ridge-parallel normal faults: laboratory measurements show that serpentinization often increases the conductivity of peridotites.

The maximum temperatures of serpentine stability and brittle fracture in oceanic mantle are both ~500°C. The top of the anisotropic model layer cools through 500°C at 3-4 Ma, while 26 km deep mantle won't do so until ~35 Ma, which is the approximate age of the lithosphere studied in this experiment.

Less than 10% serpentinization (by volume) is required to match the data.

An inversion scheme is being developed to further constrain this model.

AESTHENOSPHERE:

MT fields, penetrating into the aesthenosphere, can be modeled by combining the CSEM inversion result with laboratory measured, high-temperature dry olivine conductivity (SO2) at depth.

Thus, conductivity-enhancing volatiles are not required to be present to account for sub-oceanic mantle conductivity. They have been invoked in the past to explain anomalously high sub-continental mantle conductivity estimates.

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