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The Electrical Conductivity of the Lithosphere and Asthenosphere beneath the Coastline of Southern California

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Abstract

From November 1992 to March 1993, a ring-core fluxgate magnetometer was deployed on the ocean floor in 3850 m of sea-water, approximately 200 km from the coastline of southern California. Simultaneous magnetic field data were collected at a site next to the coastline, and data were also made available by the United States Geological Survey from the Tucson and Fresno Magnetic Observatories. Two of the main aims of the experiment were to measure the geomagnetic coast effect from the Californian margin and to probe the conductivity structure of the lithosphere and asthenosphere beneath.

Geomagnetic depth sounding and vertical gradient sounding estimates show a strong two-dimensional geomagnetic coast effect. Finite-element modelling suggests that the continental lithosphere has a resistivity-thickness product of the order of $3 \times 10^7\ \Omega m^2$, which is two orders of magnitude less than the measured resistivity-thickness product of the oceanic lithosphere off California. Below the lithosphere, the modelled electrical conductivity rises at a depth of 60 km, which may mark the boundary with the asthenosphere and the seismic low-velocity zone.

Key words: electrical conductivity, two-dimensional modelling, lithosphere, asthenosphere, California

Introduction

Many leading geophysical research institutes are located on the western seaboard of North America, so it is not surprising that the margin of southern California is one of the most extensively examined geological structures in the world. Apart

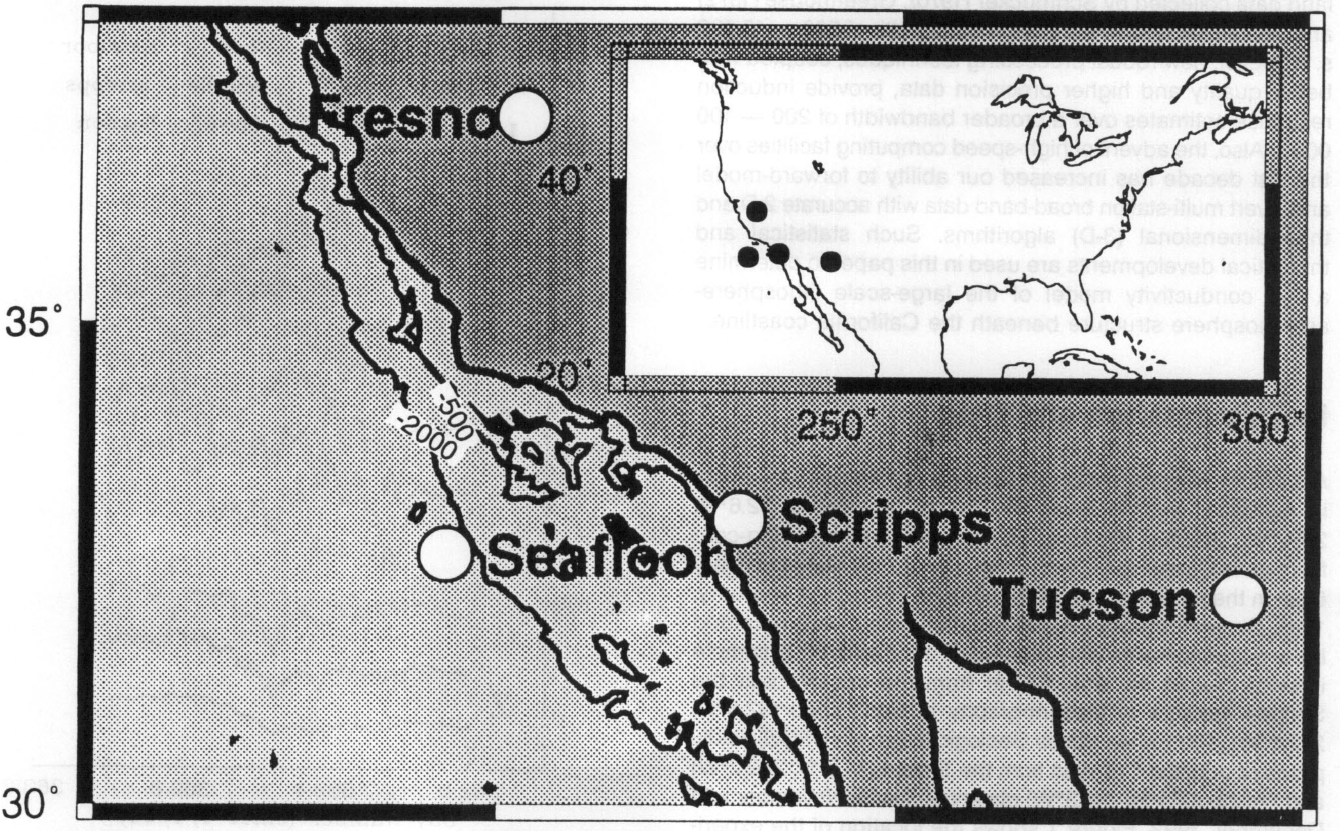

FIGURE 1
Location map of the magnetometer deployments on the seafloor and at the Scripps Institution, San Diego; also shown are the Fresno and Tucson Magnetic Observatories and the 500m and 2000m isobaths.

from its proximity, part of the enduring appeal to geophysicists is the active nature of the plate boundary, which is marked by the San Andreas fault line parallel to the coast. The dynamics of the fault is related to the presence of saline fluids in the brittle-ductile zone of the crust and decoupling of the rigid plates in the asthenosphere at some depth in the mantle. As the electrical conductivity of the crust and mantle is largely dependent upon the presence of melt and saline fluids in a considerably less conductive matrix, electromagnetic (EM) induction studies have been used extensively in this region.

Schmucker (1970), Greenhouse (1972) and White (1973a,b) first used geomagnetic depth sounding (GDS) methods on land and offshore to develop one-dimensional (1-D) and two-dimensional (2-D) geoelectric sections across the margin of California. They showed that observed induction responses were compatible with a model of an infinitely conductive asthenosphere at a depth of 160 km beneath an insulating lithosphere. More recently, Mackie *et al.* (1988) used a single land magnetotelluric (MT) station to determine the conductivity structure of the Pacific plate beneath the seafloor, which was less conductive than had previously been determined. Other terrestrial induction studies of the crust and mantle in southern California include those by Swift (1967) and Park *et al.* (1992). Offshore, Filloux (1977, 1980) deployed MT instrumentation approximately 700 km from the Californian coastline.

This paper describes an extension to these previous studies with a new set of seafloor magnetic field data. Induction response estimates are consistent with previous seafloor and land data collected by Schmucker (1970), Greenhouse (1972) and White (1973a,b) in the period-bandwidth of 500 — 15 000 s. However, new robust processing techniques, coupled with better quality and higher precision data, provide induction response estimates over a broader bandwidth of 200 — 100 000 s. Also, the advent of high-speed computing facilities over the last decade has increased our ability to forward-model and invert multi-station broad-band data with accurate 2-D and three-dimensional (3-D) algorithms. Such statistical and theoretical developments are used in this paper to determine a 2-D conductivity model of the large-scale lithosphere-asthenosphere structure beneath the California coastline.

Instrumentation and Data

A seafloor magnetometer, developed at Flinders University in Australia, was deployed in 3850 m of water at 32.6°N, 239.4°W, 200 km offshore. The three-component ring-core fluxgate magnetometer, with resolution 0.1 nT, sampled every 60 s on the seafloor from 20 November, 1992 to 24 February, 1993. Simultaneously coastal magnetic data were recorded by a magnetometer with resolution 1 nT and 60 s sample interval, buried on land 100 m from the ocean, near the Scripps Institute of Oceanography in San Diego (32.5°N, 242.8°W), The United States Geological Survey (USGS) kindly provided addition 1 nT-data from the Tucson (32.2°N, 249.2°W) and Fresno (37.1°N, 240.3°W) observatories for November and December, 1992. Figure 1 shows the location of the experiment, with the 500 and 2000 m bathymetric contours.

Figure 2 shows a large magnetic storm on 27 December 1992, recorded on the seafloor, at the coastline and at Tucson observatory, 500 km inland. Two prominent features of these data's are worth remarking on. Firstly, high-frequency (short period) signals in the horizontal fields, H and D, observed on land are almost absent on the seafloor. The ocean-layer effectively filters out such magnetic field fluctuations as the sea-water is highly electrically conducting in comparison with the crust and mantle beneath. Secondly, the anomalous vertical field, Z, is large at the coast and on the seafloor, but smaller at Tucson. Variations in the magnitude and phase of Z across the coastline (the 'geomagnetic coast effect') arise primarily from lateral changes in Earth's conductivity, between the resistive continents and the considerably more conductive sea-water. Less conspicuous differences between the data from the three sites are also present, such as phase changes between the coastline and seafloor data, and larger amplitude H and D fields at Tucson compared to Scripps.

Geomagnetic Depth Sounding

The GDS method relates the anomalous Z field to the 'normal' horizontal magnetic fields, H and D, by a transfer function in the frequency domain. For an approximately 2-D lateral conductivity contrast, anomalous Z fields occur from the TE mode of EM induction, where electric currents are induced to flow parallel to the coastline. Generally, GDS transfer functions are plotted as induction arrows by the method of Parkinson (1962), where the real, or in-phase arrow points

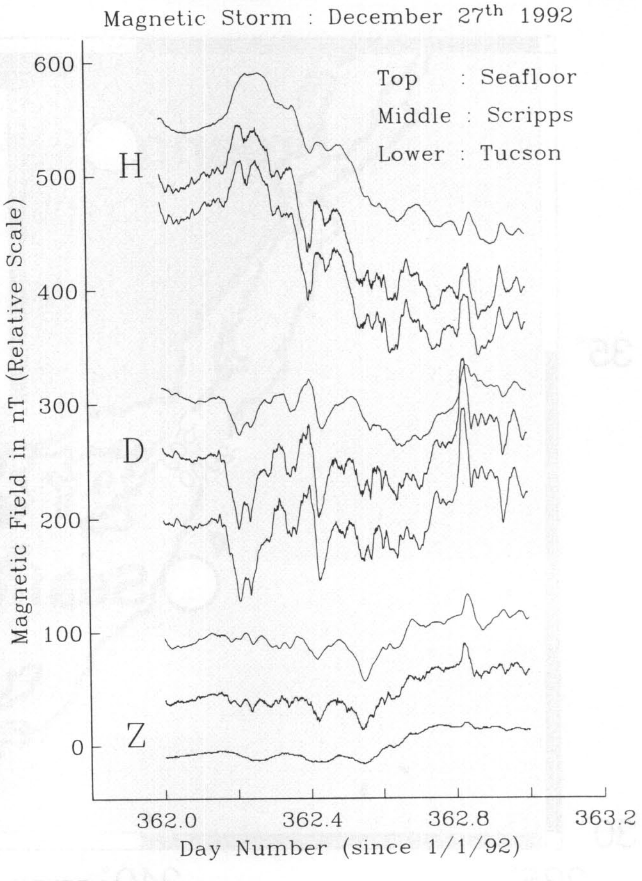

FIGURE 2
Magnetic field data from the seafloor, Scripps Institution and Tucson Magnetic Observatory during 27 December, 1992. The geomagnetic north (H), geomagnetic east (D) and vertical (Z) components are shown.

towards the good electrical conductor. The utility of this induction arrow approach is that it clearly maps the dominant lateral variations in conductivity.

One practical difficulty occurs in determining what constitutes the 'normal' horizontal fields, relatively free from non-uniform induction effects. Schmucker (1970) suggested that because the anomalous Z field variations are small at Tucson, the coast effect is minimal there and, therefore, H and D fields are close to being normal. This assumption is tested in later 2-D modelling in this paper. Figure 3 shows real induction arrows, calculated from the robust processing method of Egbert and Booker (1986), using 'normal' H and D fields from Tucson and the anomalous Z field at four sites for periods of 0.5 and 4 hours. The tendency of real arrows to point towards the deep ocean and away from the most resistive continental crust clearly illustrates the geomagnetic coast effect. Quadrature arrows, not shown here, exhibit more period-dependence in orientation and magnitude, and are probably more sensitive to local induction effects.

Induction arrows in Fig. 3 vary in orientation between sites close to the coastline because the continental crust is heterogeneous and the coastline is not strictly a 2-D feature. To minimise the effect of such localised conductivity variations, a technique known as hypothetical event analysis (Bailey *et al.*, 1974) can be used to determine the anomalous Z field response at each site for a 1 nT horizontal field perpendicular to the coastline. This approach provides induction arrows that are always normal to the shelf-break and the deep ocean, and can be modelled with a 2-D algorithm.

Vertical Gradient Sounding

If sediments, crust and mantle below the ocean were infinitely resistive, then magnetic field fluctuations at the sea-surface would be completely attenuated on the seafloor. However, Fig. 2 shows that signals are clearly observed on the seafloor, and that the attenuation of H and D is period-dependent. The ratio of the horizontal fields, H and D, on the sea-surface to those on the seafloor can be related to Earth's conductivity structure below the seafloor using the vertical gradient sounding (VGS) method. In practice, it is difficult to procure sea-surface horizontal magnetic data, so a remote coastal measure of the horizontal fields is often substituted. Although this approximation presents some problems in interpretation (Ferguson *et al.*, 1990), this method gives an estimate of both the TE and TM modes of induction for the relatively 2-D coastline. In the TM mode, electric currents are induced to flow perpendicular to the coastline. The additional TM mode information is particularly useful, as it complements the TE mode GDS response estimates and provides an important constraint for modelling.

The VGS response estimates on the seafloor may be parameterised as period-dependent apparent resistivity and phase, as shown in Fig. 4. The TE and TM modes were calculated using Egbert and Booker's (1986) robust processing technique after rotating the H and D field components (Swift, 1967) to orientations parallel and perpendicular to the coastline. It can be shown that the VGS and MT methods produce nearly identical responses, with the exception of the TE mode apparent resistivity, which is smaller by a period-independent factor when calculated by the VGS method (Ferguson *et al.*, 1990). The peak in TE apparent resistivity at short periods and the almost uniform TM apparent resistivity at all periods are typical of measured MT responses close to a continental margin (Heinson and Lilley, 1993); there is a similar character to the phases. The TE phase reversal and the peaked nature of the TE apparent resistivity show that the seafloor horizontal field oriented perpendicular to the coast undergoes a change in phase and is close to zero magnitude at periods of 1000 — 1500 s.

A 2-D Conductivity Model of the Californian Margin

The GDS and VGS response estimates in Figs 3 and 4 shows a strong 2-D geomagnetic coast effect. Although the coastline of California is not particularly straight, the 2000 m bathymetric contour, which marks the middle of the continental slope, is relatively linear for thousands of kilometres (see Fig. 1) with a strike of approximately 25°W of geographic north. The continental shelf break, and continental slope provide the greatest contribution to the geomagnetic coast effect (e.g. DeLaurier *et al.*, 1983), and, on this basis, 2-D modelling was undertaken. A 2-D cross-section passing through the seafloor magnetometer site perpendicular to the 2000 m isobath was chosen, and a finite-element algorithm (Wannamaker *et al.*, 1987) was used.

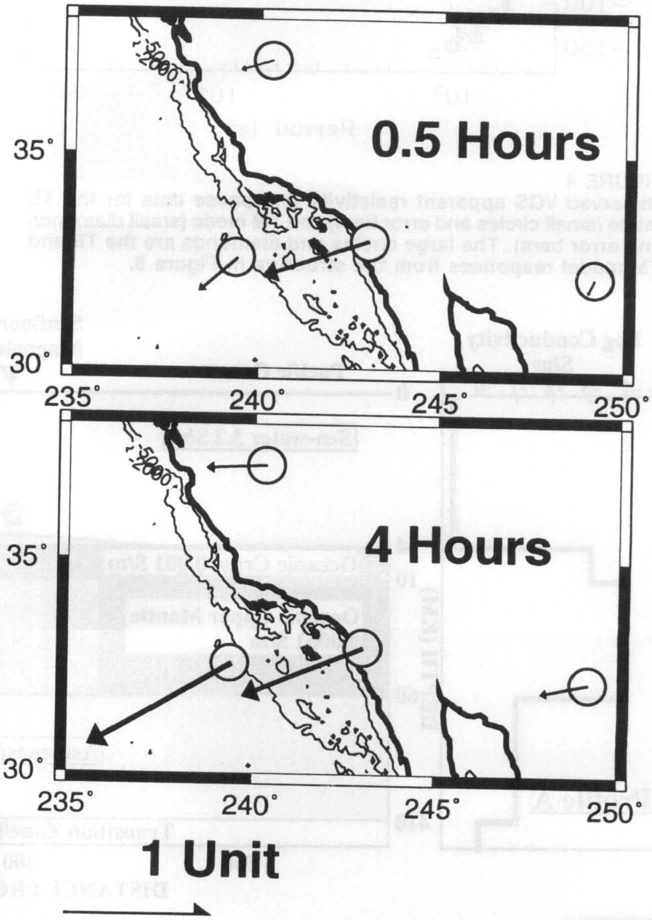

FIGURE 3
Real induction arrows, using the anomalous vertical field at each site, and the 'normal' horizontal fields at Tucson, for two periods.

Figure 5 shows the best-fitting 2-D conductivity model from a preliminary forward-model search. The model was developed to minimise the misfits with both the GDS and VGS data simultaneously, so that both TE and TM modes of induction were used. The induction problem is, of course, non-unique, so an infinite number of possible structures are compatible with the data. To restrict the non-uniqueness, a number of *a priori* constraints on the conductivity structure were made. Beneath the ocean floor, the modelled conductivity of the oceanic lithosphere was based on down-hole resistivity measurements (Becker *et al.*, 1982), controlled-source EM soundings (Cox *et al.*, 1986) and MT measurements (Mackie *et al.*, 1988). Below the transition zone at a depth of 410 km, the conductivity was assumed to rise to ∼1 Sm^{-1} (Banks, 1969). On the continental side, a range of conductivity structures were tested, with only the deep conductivity fixed below 410 km.

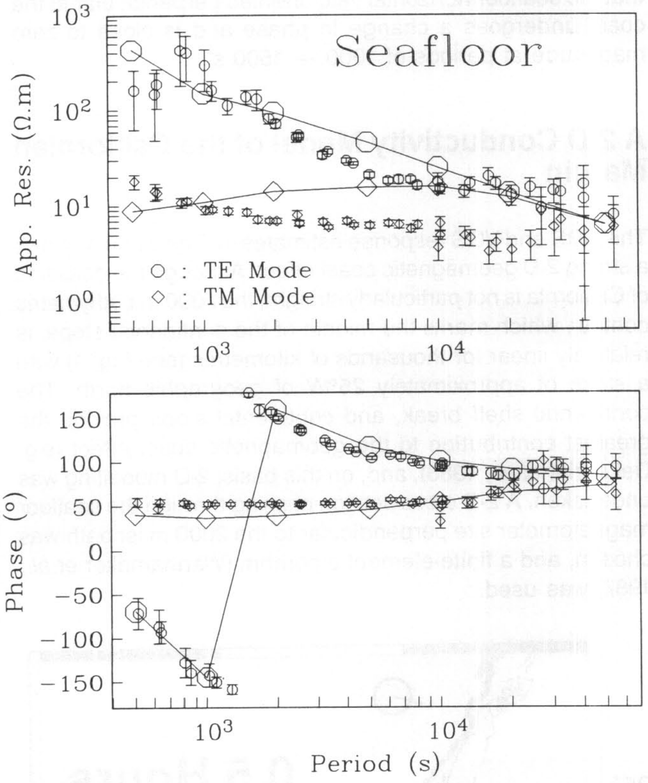

FIGURE 4
Observed VGS apparent resistivity and phase data for the TE mode (small circles and error bars) and TM mode (small diamonds and error bars). The large circles and diamonds are the TE and TM model responses from the structure in Figure 5.

Figure 6 shows the hypothetical event induction arrows for an inducing field perpendicular to the 2000 m bathymetry contour; positive values indicate arrows pointing towards the deep ocean, negative values indicate arrows pointing inland. Superimposed on the observed data are the model responses at seven periods. The agreement is generally quite good, with the exception of the quadrature arrows at the Scripps Institution site, and for all magnetometers at periods 20 000 to 40 000 s. The discrepancy at Scripps is most probably due to a relatively shallow continental platform that was not included in the 2-D model transect, but possibly also due to crustal conductivity heterogeneities inland. At the longest periods, the sudden increase in the real induction arrow magnitude at all of the sites is not reproduced by the model. Such observed variations do not relate to solid-Earth conductivity structures; the decrease in this effect inland suggests that oceanically-induced EM signals at the M_2 tidal period and their harmonics are responsible (Bindoff *et al.*, 1988). The VGS observed data and model responses are shown in Fig. 4. There is particularly good agreement for the TE mode, but model TM apparent resistivities are too large at long periods.

The structure in Fig. 5 is poorly constrained from just four sets of data, particularly as the TM mode induction can only be determined for the seafloor site. Wannamaker *et al.* (1984) have shown that the TM mode is very important in constraining 2-D structure. However, some features of this

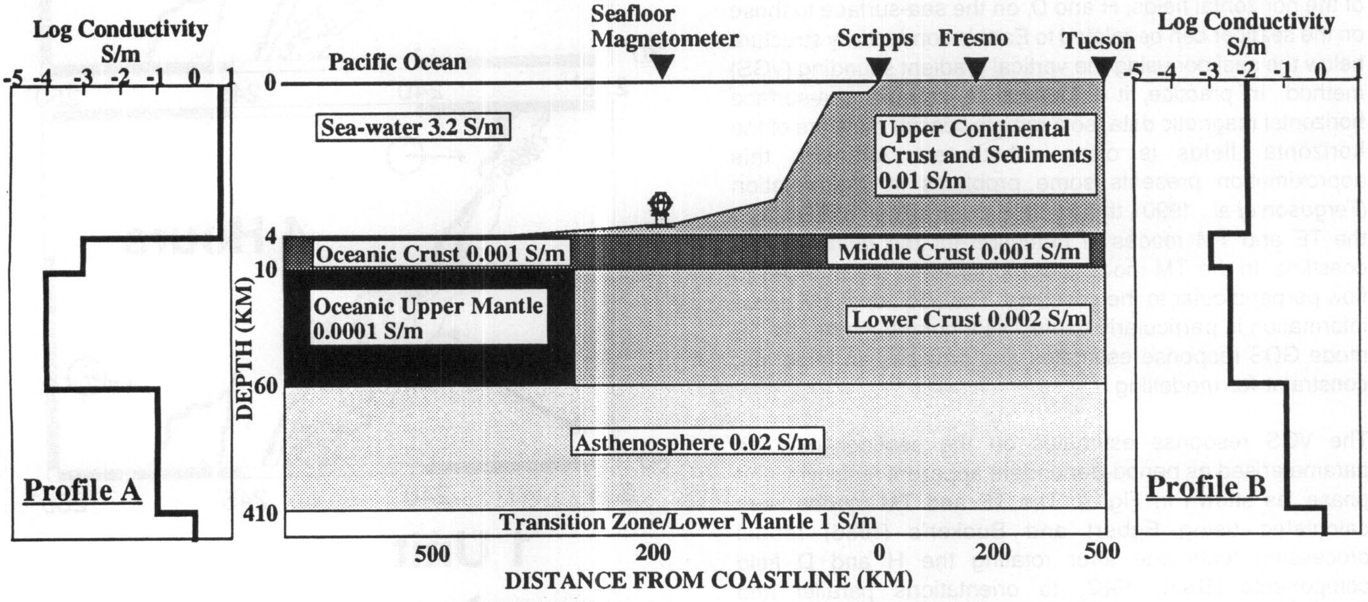

FIGURE 5
The final 2-D finite-element conductivity model across the margin of southern California, based on *a priori* constraints and forward modelling to minimise the misfit with the observed data. One-dimensional section, A and B, show the conductivity structure beneath the oceans and continents, respectively.

model are relatively robust. To illustrate this, the responses from three different conductivity models were calculated. The first conductivity model is that shown in Fig. 5; the other two have laterally uniform conductivity structures by extending either the resistive oceanic side of the model (Profile A) or the more conductive continental side of the model (Profile B) across the whole 2-D section. These three structures produce almost no variation in the GDS or VGS TE responses, but have a significant effect on the VGS TM response. Figure 7 suggests that any conductivity contrast between oceanic and continental lithosphere in Fig. 5 is poorly constrained, but the continental lithosphere must be reasonably conductive in order to channel electric currents from the ocean. This is shown by the extremely poor model fit when a resistive lithosphere is extended under the continent.

Tectonic Interpretation and Conclusion

The 2-D model in Fig. 5 suggests that the conductivity of the continental lithosphere must be of the order of 0.002 Sm^{-1} to model the TM mode data. The resistivity-thickness product of the continental lithosphere is approximately 3×10^7 $\Omega\mathrm{m}^2$, which is two orders of magnitude less than that proposed for the oceanic lithosphere off California (Mackie *et al.,* 1988). Evidence for a conductive continental lithosphere beneath southern California is also found from terrestrial MT studies (Park *et al.,* 1992), from which high conductivities were found over a depth range of 10 to 90 km. Park *et al.* (1992) suggest that such high conductivities result from the presence of fluids in the brittle-ductile zone of the lower crust.

A more conductive asthenosphere, of the order of 0.02 Sm^{-1} is required at a depth of 60 km beneath both the continent and ocean to model the TE mode data. The rise in conductivity probably results from a rise in temperature within the Earth, and may mark the boundary between the lithosphere and asthenosphere.

The experiment was designed with the twin objectives of testing new instrumentation and methods in a tectonically active area, and to measure the geomagnetic coast effect of southern California. The experiment successfully procured over 100 days of high-quality three-component magnetic field data on the seafloor, and, simultaneously, data were collected on land. We have shown in this paper how a simple 2-D conductivity model may be constrained even with relatively few data, and have discussed the limitations of the approach.

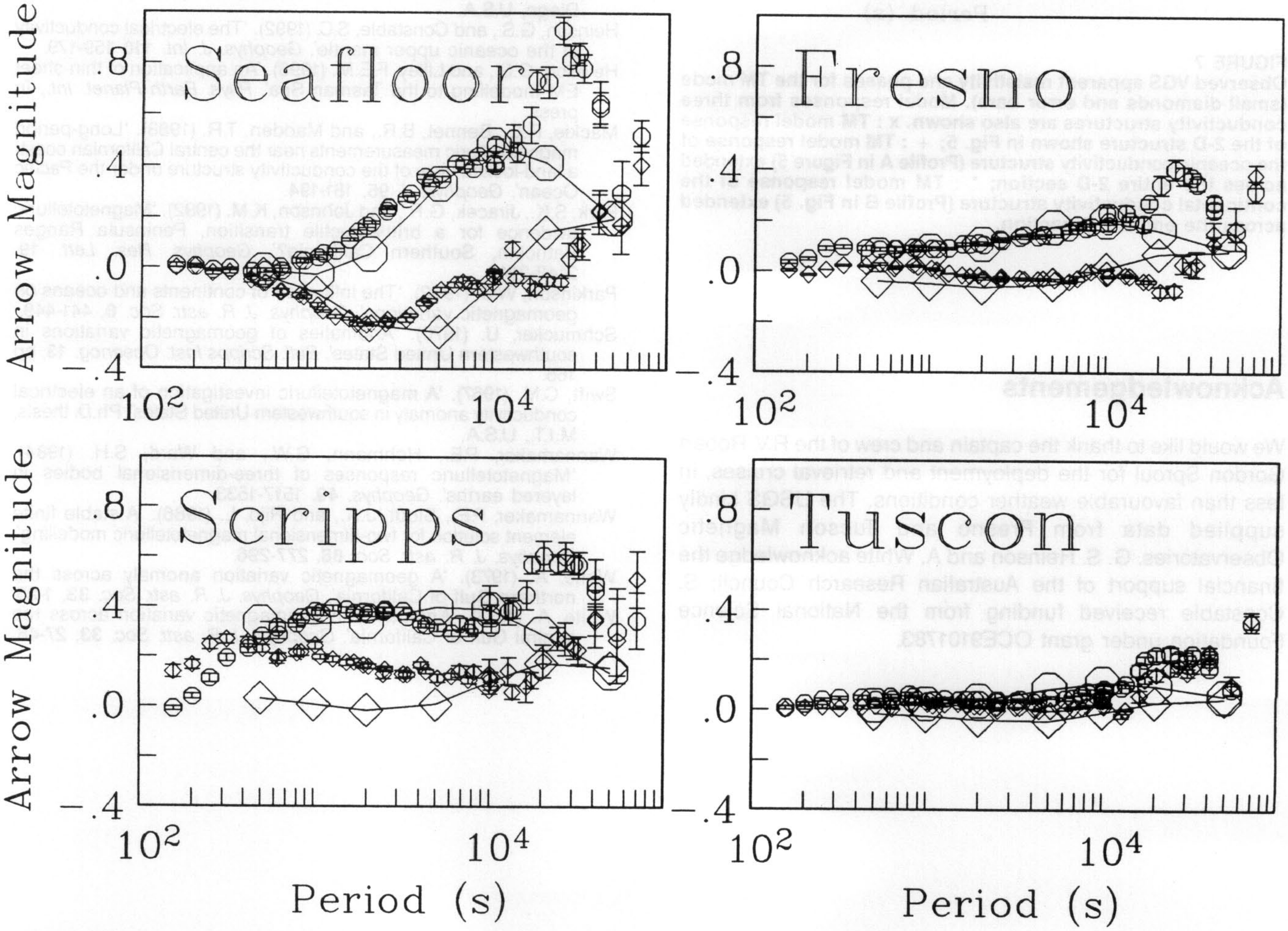

FIGURE 6
Hypothetical event analysis induction arrows for a inducing magnetic field perpendicular to the 2000 m bathymetrical contour. Real arrows are shown by the small circles, with error bars, and quadrature arrows by the small diamonds and error bars. A positive value has the arrow pointing towards the ocean; negative values are for arrows pointing inland. The large circles and diamonds are real and quadrature model responses from the structure in Fig. 5.

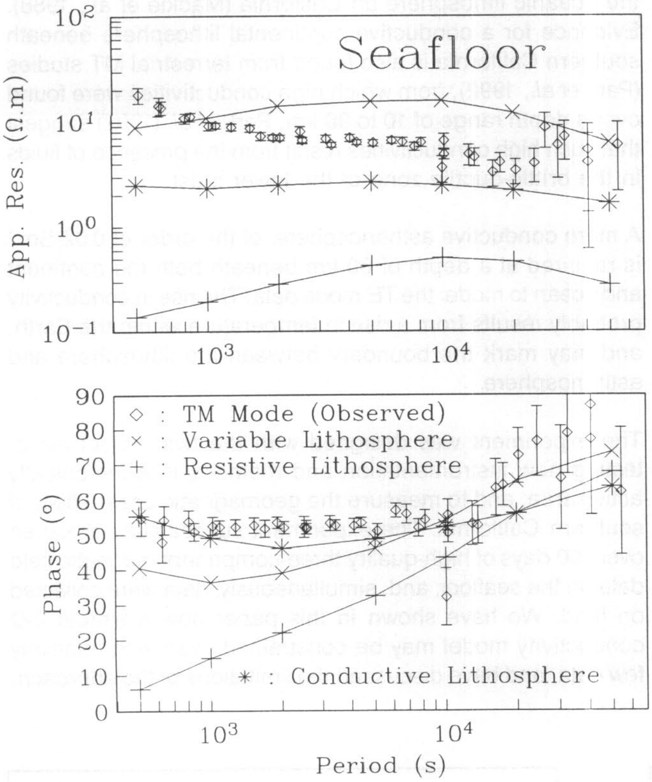

FIGURE 7
Observed VGS apparent resistivity and phases for the TM mode (small diamonds and error bars). Model responses from three conductivity structures are also shown. x : TM model response of the 2-D structure shown in Fig. 5; + : TM model response of the oceanic conductivity structure (Profile A in Figure 5) extended across the entire 2-D section; * : TM model response of the continental conductivity structure (Profile B in Fig. 5) extended across the entire 2-D section.

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