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# The Electrical Conductivity Structure of the Oceanic Lithosphere Beneath the Tasman Sea

**G. S. Heinson and F. E. M. Lilley**
*Research School of Earth Sciences*
*The Australian National University,*
*GPO Box 4, Canberra*
*ACT 2601, Australia*

## Abstract

Seafloor magnetotelluric observations of natural fluctuations of the Earth's magnetic and electric fields provide information about the electrical structure of the suboceanic lithosphere and upper mantle. However, such measurements may be distorted by three-dimensional induction effects in the overlying ocean, associated with the geomagnetic coast-effect and changes in bathymetry.

In the present paper electromagnetic three-dimensional modelling is applied to the Tasman Sea. A thin-sheet algorithm is used, and calculated magnetotelluric parameters are compared to observations made during the Tasman Project of Seafloor Magnetotelluric Exploration (TPSME). The model calculations suggest that, away from coastlines, three-dimensional induction in the ocean distorts the electromagnetic signature of the sub-oceanic lithosphere and upper mantle in a frequency-dependent but smooth manner. The model calculations thus permit the observed TPSME responses to be corrected for distortion, to give improved estimates of the electromagnetic response of the solid-Earth underlying the observation sites. Inversion of such (corrected) response estimates for one-dimensional electric structure reveals that the structures beneath 55 and 70 Ma seafloor sites are very similar. Furthermore, constraints imposed by the thin-sheet modelling indicate that to replicate the TPSME observations, a poorly conductive (less than $10^{-3}$ S/m) upper lithosphere is required. This result implies that electric currents which are induced and 'trapped' in the ocean may contaminate magnetotelluric observations far inland.

Key words: electromagnetic induction, thin-sheet modelling, Tasman Sea

## Introduction

The processes of electromagnetic induction, due to fluctuations of Earth's magnetic field, provide information about the electrical structure of the crust and upper mantle. Such information may then be used to constrain complementary geophysical information such as geothermal temperature, presence of volatiles, and partial melt fraction. While continental observations have an established history, observations on the seafloor are at a pioneering stage (Filloux, 1987) and are complicated by the highly conductive salt-water of the ocean.

Electromagnetic induction in the Tasman Sea has been studied by Filloux *et al.* (1985), Ferguson (1988), Bindoff (1988), Lilley *et al.* (1989), Kellett (1989) and White *et al.* (1990). Ferguson *et al.* (1990) show that three-dimensional (3D) induction effects influence the distribution of electric current, which is channelled around the resistive continental regions of southeast Australia and New Zealand, and deflected away from the Lord Howe Rise. The present paper extends the analysis reported in Heinson and Lilley (1989), to examine how 3D induction in the Tasman Sea may distort the one-dimensional (1D) electromagnetic signature of the underlying structure. A simple analytical technique is presented in which distortion due to induction in the ocean is removed, and the (corrected) estimates are inverted for 1D electrical structure. In addition, observed 3D induction effects are found to be dependent upon underlying structure, and a constraint is deduced on the average electrical structure of the lithosphere beneath the Tasman Sea.

## Thin-sheet Modelling

Electromagnetic experiments are often carried out in environments where a highly conductive layer, varying in lateral conductance, masks the electromagnetic response of the underlying structure which is the target of study. On land, the layer may be a salt crust, weathered layer or water-saturated horizon. In the oceans, seafloor MT observations are influenced by the highly conducting salt-water, and lateral changes in the ocean conductance over large distance scales (including both seafloor topography and coastlines) may have a profound effect in distorting the electromagnetic signature of the underlying crust and upper mantle.

Thin-sheet electromagnetic modelling is ideally suited to examining the effect of a surface layer with laterally varying properties. Such models have been applied to both electromagnetic exploration (Smith and West, 1987) and large-scale solid-Earth problems (McKirdy *et al.*, 1985). For the present problem, and as described by Heinson and Lilley (1989), application has been made of the theory and computer algorithm developed by the group led by J.T. Weaver at the University of Victoria, B.C., Canada (McKirdy *et al.*, 1985).

The Tasman Sea region is divided into three grids, consisting of 30 x 30 nodes at grid-node spacing 100, 150 and 200 km,

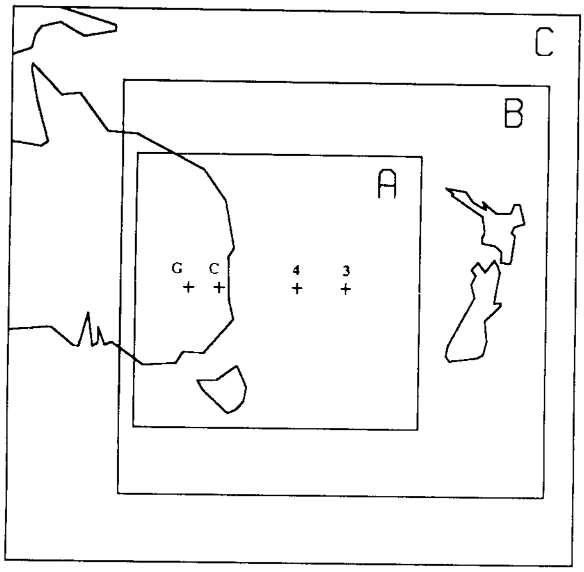


FIGURE 1
**Three grid areas A, B, and C, covering successively larger regions of the Tasman Sea for thin-sheet calculations of successively lower frequency. The sites marked G, C, 4 and 3 are those of Griffith, Canberra, TP4 and TP3 respectively.**

as shown in Figure 1. The three grids are used to examine different ranges of inducing frequency, which overlap so that the accuracy of numerical calculations can be assessed (see Table 1). Numerical approximations are satisfied if a sheet of thickness 10 km is taken; conductance values are calculated at each grid-node as the sum of the conductances for depth of ocean and thickness of oceanic crust, the parameters for which are listed in Table 2. The 1D layered electrical structure taken to underly the thin-sheet model is a simple adaptation from the inversions, by Ferguson *et al.* (1990), of the TPSME response at site TP3 (Figure 1).

TABLE 1
**Frequency ranges used in calculations for the three different thin-sheet grids.**

| Grid | Grid Node Separation (km) | Frequency Range (cycles per hour) |
|---|---|---|
| A | 100 | 5.263 - 0.481 |
| B | 150 | 2.079 - 0.104 |
| C | 200 | 0.481 - 0.031 |

TABLE 2
**Conductivity and depth parameters used in the construction of the thin-sheet models. The dashed line corresponds to the bottom of the thin sheet.**

| | Conductivity (S/m) | Depth (km) |
|---|---|---|
| Seawater | 3.3 | variable |
| Oceanic crust | 0.001 | variable |
| Continental crust | 0.01 | 10 |
| ----------------------------- | -------------------------- | ------------------ |
| Suboceanic lithosphere | 0.001 | 200 |
| High-conductivity layer | 0.1 | 250 |
| Upper mantle | 0.03 | 400 |
| Deep conductor layer | 1.0 | ∞ |

## Three-dimensional Distortion

Figure 2 presents MT parameters from the thin-sheet calculations, for 25 inducing frequencies, at two land-based and two seafloor locations (Figure 1). The parameters have been rotated (Swift, 1967) so that the apparent resistivities are oriented parallel (E-pol) and perpendicular (B-pol) to the principal direction of strike, which in this case is approximately the coastline of southeast Australia. The solid lines in the figure show the (analytically calculated) 1D electromagnetic response of the structure (given in Table 2) which underlies the thin sheet. Without the effects of the thin sheet, the points would all lie on their appropriate lines.

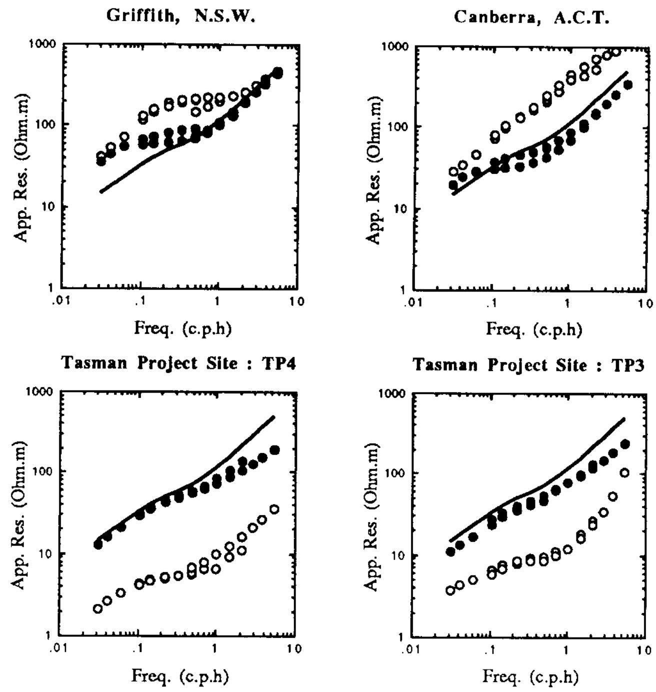


FIGURE 2
**Thin-sheet MT calculations for grid nodes corresponding to Griffith (NSW) and Canberra (ACT) and two seafloor sites TP4 and TP3. The MT calculations are rotated to orientations parallel (E-pol, solid circles) and perpendicular (B-pol, open circles) to the principal direction of strike, which is approximately the coastline. The solid line represents the analytically calculated 1D response of the underlying structure; i.e. the ideal response in the absence of any thin-sheet effects.**

On land, for the grid location at Griffith, the MT calculations deviate from the ideal 1D response for frequencies less than one cycle per hour, whilst at Canberra there is an appreciable anisotropy at all frequencies. (Similar anisotropy in MT field estimates at Griffith were observed by Tammemagi and Lilley, 1971.) In the present thin-sheet modelling exercise the continental section is assumed laterally isotropic, so the modelled anisotropy for these land sites results from induction in the oceans. As seen in Figure 2, the 3D response (with varying frequency) of the thin-sheet model is generally a smooth transformation of the 1D response, and is clearly frequency dependent.

The calculations of seafloor apparent resistivity for sites TP4 and TP3 indicate that the induction effects in the ocean cause gross anisotropy between the E-pol and B-pol modes. The E-pol calculations are marginally reduced relative to the 1D response of the model, indicating that the electric current flow is relatively unimpeded for the polarisation parallel to the coastline. However, the coastline is not strictly 2D, and the Lord Howe Rise trends obliquely to it; as a consequence there is a small attenuation of the electric field in this orientation. (At TP4 the electric field is also channelled by the proximity of the Gascoigne Seamount, 50 km to the north.) By contrast, the B-pol MT calculations are very much reduced relative to the 1D response of the model, and the degree of attenuation decreases away from the coast (consistent with the results of Ranganayaki and Madden, 1980). This attenuation is, in general, frequency independent (except at the highest frequencies, where the model calculations approach an isotropic response which is less than the 1D response of the underlying structure).

The modelled anisotropy between the E-pol and B-pol apparent resistivities at sites TP4 and TP3 is approximately 10, whereas the TPSME observations show values of order 20 (Ferguson *et al.*, 1990). Thin-sheet modelling suggests that such anisotropy for the Tasman Sea depends strongly on the conductivity of suboceanic lithosphere, and that, for this parameter, a value of less than $10^{-3}$ S/m is required.

## Removal of Three-dimensional Induction Effects

A simple matrix method is used to examine 3D induction due to the ocean. The calculated impedance tensors for the thin-sheet ($\mathbf{Z}^{TS}$) and for the underlying 1D structure ($\mathbf{Z}^{1D}$) are linked by the transformation

$$\mathbf{Z}^{TS} = \mathbf{D}\mathbf{Z}^{1D} \qquad (1)$$

where D is the distortion matrix, and is determined from the results of the thin-sheet modelling (which give $\mathbf{Z}^{TS}$) and from the analytic determination of $\mathbf{Z}^{1D}$, described above. The inverse of the distortion matrix is then applied to the observed TPSME impedance tensors, to remove the 3D induction effects due to the Tasman Sea as modelled. Figure 3 illustrates the original (Ferguson *et al.*, 1990) and corrected (as just described) MT estimates of apparent resistivity and phase for sites TP4 and TP3. For many estimates corrected for distortion there are several values for a particular frequency, corresponding to the values obtained from numerical grids of different spacing. The range in these values results from the numerical approximations involved in the thin-sheet modelling, and is typically less than 10%, which is within the resolution of most seafloor MT estimates. The largest distortion occurs at the highest frequencies, and so the corrected MT estimates at these frequencies exhibit the greatest change, with a bias towards higher apparent resistivities. This effect is most clearly seen for site TP4, and may indicate that the attenuating effect of the Gascoigne Seamount has been removed.

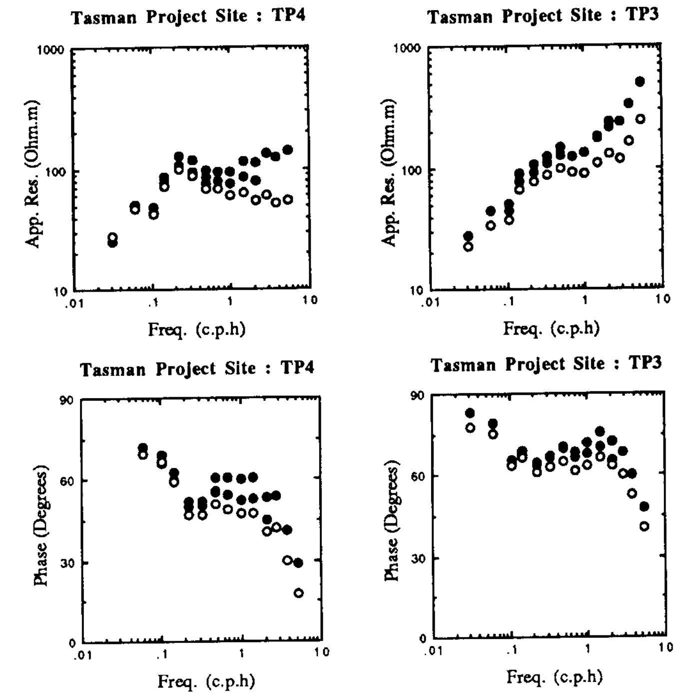


**FIGURE 3**
**MT estimates for TPSME sites TP4 and TP3 from Ferguson *et al.*, (1990) (open circles) and corrected MT estimates (solid circles), in which the distortion due to induction in the ocean is calculated and removed.**

## One-dimensional Inversions

Inversions of the original MT estimates (dashed line) and corrected MT estimates (solid line) for TP4 and TP3 are shown in Figure 4. A smooth modelling technique was applied (Constable *et al.*, 1987) in a manner described by Ferguson *et al.* (1990). The conductivity profile for TP4 from the corrected corrected estimates is considerably less conductive in the top 150 km, whereas deeper structure remains largely unchanged. The profile for site TP3 shows a more profound change: the high-conducting layer discussed in Ferguson *et al.* (1990), and the deeper rise in conductivity at ~400 km are modelled at a greater depth.

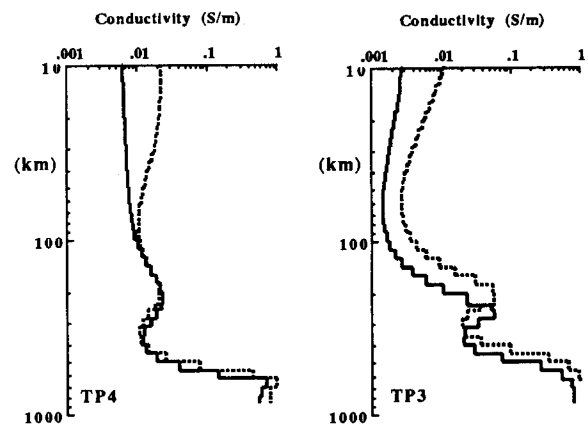


**FIGURE 4**
**Smooth 1D models of the electrical conductivity for sites TP4 and TP3 from the estimates of Ferguson *et al.* (1990) (dashed lines), and from the estimates corrected for distortion (solid lines).**

## Conclusion

Electromagnetic 3D induction in the ocean can be modelled using a thin-sheet algorithm in a useful and instructive manner. Numerical models of the Tasman Sea suggest that MT observations on the seafloor are strongly influenced by electric current channelling in the oceans; further, land MT observations are also distorted, particularly at low frequencies.

Calculations from the thin-sheet model suggest that 3D induction, away from sharp changes in conductivity, acts to smoothly transform the 1D response of an underlying layered structure. This characteristic infers that seafloor observations which are distorted by ocean induction effects may still yield valuable information about the conductivity structure beneath the observing sites. Thin-sheet modelling also places constraints on the average 1D electrical structure underlying the Tasman Sea, with a poorly conductive upper lithosphere, of conductivity less than $10^{-3}$ S/m, required to replicate the TPSME observations. With the observations then corrected for distortion, 1D electrical conductivity structures are found to be very similar for 55 and 70 Ma oceanic lithosphere.

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