Geophys. J. Int. (1993) **114**, 717–723

In defence of a resistive oceanic upper mantle: reply to a Comment by Tarits, Chave and Schultz

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Accepted 1993 February 5. Received 1993 February 2; in original form 1993 January 4

1 INTRODUCTION

In a previous paper (Heinson & Constable 1992) we discussed the effect of coastlines on sea-floor magnetotelluric (MT) data collected deep within the ocean basins. In order to quantify the geomagnetic coast effect we developed a model for oceanic upper mantle electrical conductivity independent of previous sea-floor MT interpretations, based on sea-floor controlled-source electromagnetic (CSEM) soundings, laboratory studies of mantle materials, and global geomagnetic-sounding estimates for lower mantle conductivity. We demonstrated that the coast effect of our model was large, was not manifest as severe anisotropy in the MT response if the ocean basins were bounded by coastlines on three or more sides, and that a qualitative agreement existed between the MT response of our simple coastline model and published sea-floor MT data. The implication of the latter is that by including the effect of the coastlines additional mechanisms for enhanced upper mantle conductivity, such as volatiles, carbon, melt, hydrogen and other factors, may not be required by the MT data.

Tarits, Chave & Schultz (1993) question the validity of a large number of aspects of our work. Their principal conclusions are that (a) horizontal or vertical leakage paths between the ocean and other oceans or the mantle will substantially reduce the magnitude of the ocean-wide coast effect; (b) the principle of extrapolating laboratory electrical-conductivity measurements to mantle conditions is unreliable from uncertainties in the understanding of pressure, temperature and petrological states of the upper mantle; (c) published sea-floor MT data sets examined by us were of such vintage that any conclusions drawn were unreliable or incorrect; and (d) the conductivity profile compiled by Chave, Flosadottir & Cox (1990), based on 1-D interpretations of sea-floor MT and CSEM data that took no account of the coast effect, is consequently a more reliable estimator of mantle-conductivity structure than our model.

While all aspects of Tarits *et al.*'s comments were addressed to some extent in our original paper, we did not investigate all details fully either in the interests of conciseness, or because the impact on our conclusions was minimal. We will take this opportunity to delve further into some of these issues, but before considering the complications it will be useful to reiterate the motivation for our work. First, Oldenburg's (1981) and Oldenburg, Whittal & Parker's (1984) 1-D interpretations of three sea-floor MT data sets included a high-conductivity zone (HCZ) in the oceanic upper mantle that decreased in magnitude and deepened with increasing age. The existence of a HCZ has become a paradigm not only amongst the electromagnetic community but also with seismologists, petrologists and mineral physicists. Many entire papers are written on the subject, attempting to explain the disparities between laboratory measurements of olivine conductivity at upper mantle temperatures and the HCZ, correlating the HCZ with seismic low-velocity zones (LVZ), examining the temporal evolution of the HCZ, etc. The impact of Oldenburg's work has been so large that it seemed appropriate to re-examine the basis of the HCZ and question whether it is indeed required by the data. Note that no criticism of Oldenburg's work is implied by this; it is the way the work has been received, rather than the study itself, that concerned us.

Secondly, the existence of an oceanic upper mantle with resistivity-thickness product around $10^9\ \Omega\mathrm{m}^2$ is also part of the current conventional wisdom, and accepted by Tarits *et al.* While the impact of a resistive upper mantle on the sea-floor MT response has been noted before for 2-D coastlines, we wished to examine the effects of 3-D ocean basins. In particular, we were interested in the extent of anisotropy in the 3-D MT responses (i.e. disagreement between the two orthogonal components), because lack of anisotropy in MT response functions is normally taken to be a good indicator of 1-D structure, or at least quoted in support of 1-D interpretation.

We discussed the complications of leakage paths between ocean basins and through the mantle in our original paper, but will show below that Tarits *et al.*'s particular quantification of leakage effects do not invalidate our conclusions. In response to the other conclusions by Tarits *et al.* cited above, we urge readers with an interest in these matters to examine our original work. We make no claim that our 'model of electrical conductivity represents the real Earth', nor that the three MT data sets considered were necessarily of the best quality. Our intention was principally to establish a framework using state-of-the-art modelling and analytical techniques within which more specific problems could be addressed.

2 VERTICAL AND HORIZONTAL LEAKAGE

In our original paper we noted that vertical and/or horizontal electrical-current leakage paths, not included in our simple models, would diminish the coast effect. We believe that leakage paths do exist in Earth, as outlined in our original paper, and indeed a small amount of leakage would shift our ρ_a response to a better fit with the field data (Heinson & Constable 1992; Fig. 14). However, we argued that even allowing for leakage paths, the coast effect would still be significant and could not be ignored when interpreting deep-ocean MT data. Tarits *et al.* have provided a valuable extension to this qualitative observation by modelling two specific cases of horizontal and vertical connections.

While our models, with no horizontal or vertical electrical connections, are extreme, we present the case that Tarits *et al.*'s models represent an opposing extreme. Their five ocean channels through the continental crust of their ocean-basin model amount to 1000 km of 5 km depth ocean connection (equivalent to an extra conductance of 1000 S around the entire 16500 km coastline), which cannot be found in the North Pacific. Continental rocks are, with little exception, at least an order of magnitude more resistive than seawater, and even major conductivity anomalies, such as suture zones and large sedimentary basins, have conductances of only a few thousand Siemen at most (e.g. Gough 1989). The continental lower crust has conductance of between a few tens and a few thousands of Siemen (e.g. Schwartz 1990), so even in the extreme of a ubiquitous lower-crustal conductive layer of 1000 S (a 10 km thick layer of conductivity $0.1\ \mathrm{S\ m^{-1}}$), the effect is only the same as the horizontal leakage model of Tarits *et al.*

The plausibility of their vertical conduction path, a 50 km thickness of $5 \times 10^{-3}\ \mathrm{S\ m^{-1}}$ extending to 400 km depth, is more difficult to assess. Subducted water, and melt, are commonly invoked to explain why subduction zones should be conductive. Indeed, two of the most important EM studies above subduction zones by Kurtz, De Laurier & Gupta (1986, 1990) and Wannamaker *et al.* (1989b) show a region of high-electrical conductance at, and above, the subducted plate margin of the Juan de Fuca Plate, but to a maximum depth of only 40 km. Such high conducting regions were considered to be ascending saline pore fluids subducted with sediments, trapped in the continental lower crust by an impermeable middle crust. However, free water is not a particularly stable phase under mantle conditions, and there is little geological evidence for a high conducting path beneath the limit of free water. Pure water is expelled by depths of <40 km (Peacock 1991) and the bulk of subducted water almost certainly makes the descent as hydrous metamorphic minerals (Gill 1981), which are not electrically conductive (Olhoeft 1981). During subduction the various hydrous minerals pass the limits of their stability fields and any water liberated by dehydration will either be incorporated into other hydrous phases, or lower the mantle solidus to initiate melting. Melt is gravitationally unstable and very mobile under mantle conditions, rising as isolated bodies rather than as a continuous stream (Scott & Stevenson 1986). Gill (1981) estimates the depth of melting from the distribution of andesitic volcanism as between 125 to 250 km, depending upon the Benioff angle and the rate of subduction, with only one or two exceptions.

While the effect of this dynamic metamorphic geology on electrical conductivity is difficult to estimate, $5 \times 10^{-3}\ \mathrm{S\ m^{-1}}$ is probably too conductive. The ocean crust itself, before subduction, only attains this conductivity in the upper 1–2 km (Becker *et al.* 1982). In particular, there is little geological evidence for significant and stable electrical connection between the lowest depth of stable pore fluids (<40 km), and the maximum depth for stability of phlogopite (≈125 km). We note that the 2-D models of both Kurtz *et al.* (1986, 1990) and Wannamaker *et al.* (1989b) have conductive regions terminating at depths of about 40 km, underlain by the resistive parts of the upper mantle and in no direct electrical connection to the deep mantle (necessary to mitigate the coast effect).

While the models presented by Tarits *et al.* are extreme, they are nevertheless useful in setting bounds on the behaviour of MT responses. Fig. 1(a) shows a comparison of the MT responses from our open-ocean-basin model with no leakage paths, and from Tarits *et al.*'s calculations which include a large number of horizontal leakage channels. The figure also presents the 1-D response to the underlying mantle, and it can be seen that while the inclusion of horizontal leakage paths reduces the amount of distortion, neither model is close to the 1-D response. Our conclusion is that even with a large amount of horizontal leakage, the mid-ocean MT response is badly distorted by the coast effect. This conclusion is complicated by the differences in the MT response calculated for the same ocean-basin model in our original paper and by Tarits *et al.* We have not been able to establish why this is so; it is possibly associated with the different boundary conditions used in the two algorithms which require different model configurations, or from the extreme conductivity contrasts between the oceans and underlying structure resulting in numerical round-off problems. We note that the thin-sheet conditions are satisfied at a period of 1000 s using the McKirdy, Weaver & Dawson (1985) algorithm. The 'droop' in the short-period phase response cited by Tarits *et al.* is not evident in our responses, which have been checked against analytical solutions.

In Fig. 1(b) we plot the corresponding responses for the 2-D case with the vertical leakage path as proposed by Tarits *et al.* We have recomputed our 2-D response using a finite element algorithm (Wannamaker *et al.* 1987) for consistency. Once again, we see that while the leakage path decreases the coast effect, the response is still far from the 1-D response. Tarits *et al.*'s comment strongly implies that the coast effect can safely be ignored; we see that this is not the case even with the extremes of leakage they suggest. Tarits *et al.* clearly state that the existing MT conductivity profiles embodied in Chave *et al.*'s (1990) paper provide a more reliable estimate of mantle conductivity than our model, as they are based on field observations rather than laboratory data. It is therefore reasonable to consider the effect of the coastline and vertical leakage on this more conductive profile. In Fig. 1(c) we plot responses for the 2-D ocean basin using Chave *et al.*'s (1990) model of mantle conductivity. The sea-floor responses are far from 1-D even

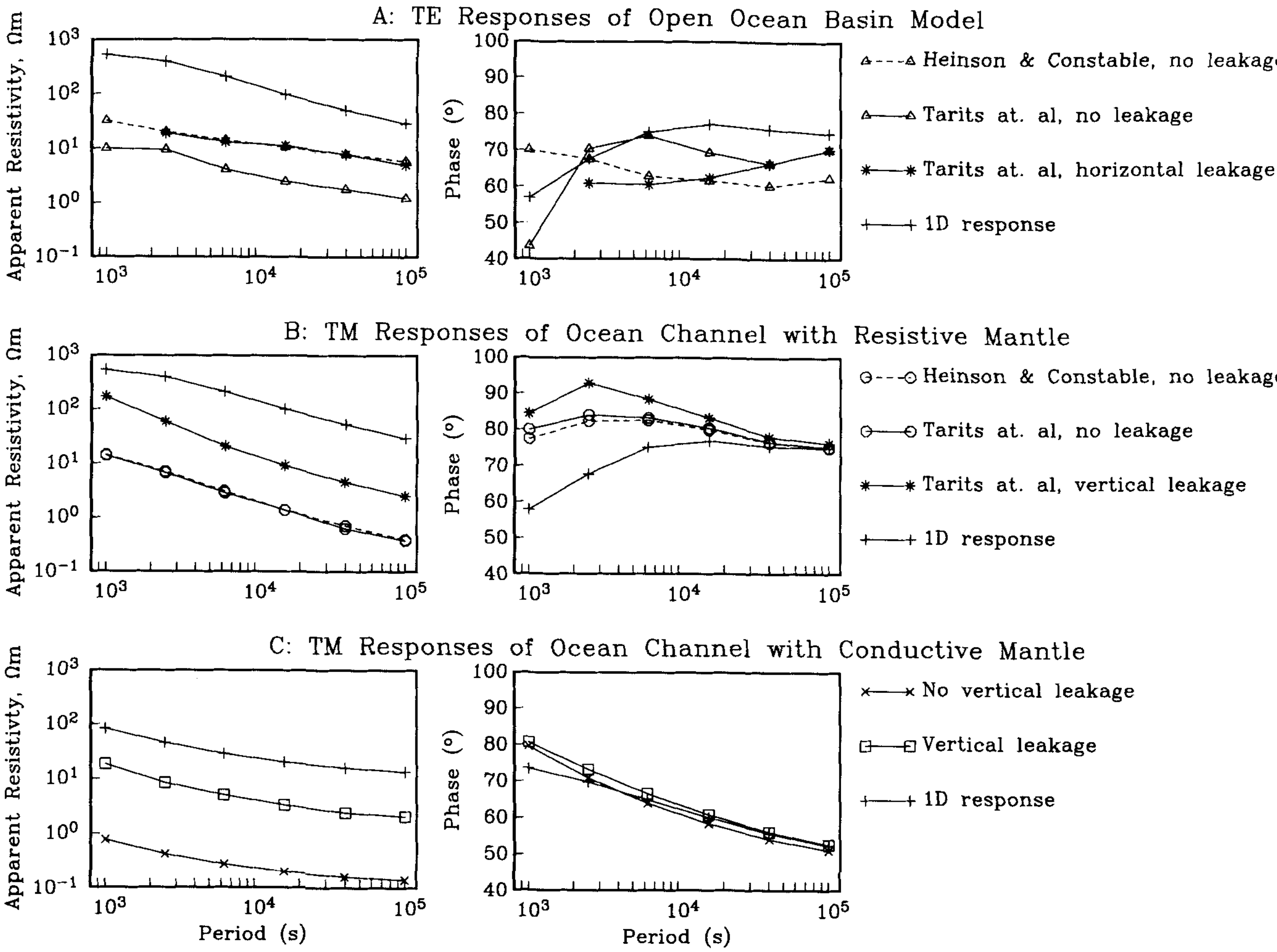

Figure 1. Sea-floor MT responses calculated at a node towards the centre of 3-D and 2-D ocean basin models, 2283 km from the east coastline.

A: north–south polarization ('TE') of electric field in the Open Ocean Basin Model II, an ocean surrounded by land to the north, west and east (Heinson & Constable 1992, Fig. 11). Calculations by Heinson & Constable (1992) are from the thin-sheet algorithm of McKirdy *et al.* (1985), while Tarits *et al.* (1993) use the thin-sheet algorithm of Vasseur & Weidelt (1977).

B: east–west (TM) polarization of electric field in the Ocean Channel Model III, comprising an ocean bounded to the west and east (Heinson & Constable 1992, Fig. 11). Data attributed to Heinson & Constable are recalculated using the finite-element algorithm of Wannamaker *et al.* (1987), while Tarits *et al.* (1993) use a finite difference algorithm.

C: similar to B but using the oceanic mantle conductivity model proposed by Chave *et al.* (1990) for the underlying 1-D structure. This model was not considered by either Heinson & Constable (1992) or Tarits *et al.* (1993).

with the vertical leakage paths, and we conclude that 1-D interpretation would fail despite a highly conductive mid-mantle and extreme leakage paths.

The difficulty of applying 1-D interpretational methods to deep ocean MT sounding has long been acknowledged, and we meant no criticism of the previous published 1-D models. Our intention was merely to stimulate an improvement in analysis techniques and to challenge the notion that 1-D or even 2-D interpretations will necessarily provide the correct mantle conductivities. The thin-sheet method is extremely well suited to characterizing 3-D induction due to irregularly shaped ocean basins, as the coastlines and bathymetry are some of the most accurately known geophysical data available. We believe that the inclusion of such data in deep ocean MT interpretation will significantly improve our understanding of oceanic-mantle conductivity.

3 ELECTRICAL CONDUCTIVITY ENHANCEMENT IN THE MANTLE

We will take this opportunity to 'thoroughly discuss the various candidate mechanisms which could affect the conductivity of mantle silicates' as suggested by Tarits *et al.* Our contention was never that conductivities higher than that of dry olivine do not exist in the mantle, but rather that they need not exist to satisfy the MT data, as had been previously supposed. However, the contaminants necessary to make mantle conductivity compatible with early MT interpretation are all limited in their ability to make significant changes in mantle conductivity.

Melt: to enhance electrical conductivity, melt must be connected, but mantle melt is gravitationally unstable in very small concentrations ($\ll$1 per cent) if it is connected (McKenzie 1989) and migrates upwards, probably as isolated plumes, with an efficiency of the second or third power of porosity (Scott & Stevenson 1986). It is likely that significant amounts of melt only exist in dynamic environments such as mid-ocean ridges where there is continuous replenishment. Even in such dynamical systems, melt fractions are likely to be small: McKenzie (1985) estimates only about 2 per cent asthenospheric melt exists beneath the ridge. Our model of pyrolite mantle melt is most probably extreme with >1 per cent melt, but removing this melt from the model would, of course, only make the mantle less conductive and the distorted MT responses further from the 1-D response.

Water: at subduction zones, hydrous minerals, such as phlogopites, amphiboles, hornblendes, serpentines and talcs are likely to take up free water at depths up to 125 km, subject to the availability of the necessary elements to complete the metamorphic minerals; Peacock (1991) reasons that below 40 km water is carried into the mantle by subduction zones solely as hydrous phases. Recent research suggests that water might also be stored in silicates as point defects; mantle concentrations of up to 0.1 per cent are inferred for olivine (Bai & Kohlstedt 1992), and pyroxene in xenoliths is observed to contain about an order of magnitude more water than olivine (Bell & Rossman 1992). Dehydration reactions along the descending slab may generate free water if the mantle moves out of the stability field of a hydrous mineral, but free water will either ascend to the stability field of phlogopite or amphiboles, enter silicates, or produce and enter a melt which will migrate as described above. We also note that water generated by dehydration reactions is not necessarily rich in dissolved ions and is therefore not necessarily as conductive as crustal brines and seawater.

Hydrogen: the presence of hydrogen ions as point defects in olivine may enhance mantle conductivity (Karato 1990) and was discussed in our original paper. However, Karato's calculation considered only the crystallographic direction with highest hydrogen diffusivity. If the two orders of magnitude in crystal anisotropy for hydrogen diffusion (Mackwell & Kohlstedt 1990) is taken into account then conductivity predicted from the hydrogen model drops by an order of magnitude (Constable 1993). To explain the traditional MT profiles this way 1 per cent, rather than 0.1 per cent, hydrogen is required. This is an order of magnitude larger than Ringwood's (1975) estimate of mantle water, and also assumes that water does not preferentially enter hydrous phases or pyroxene.

Carbon: graphitic carbon has been suggested as a means of enhancing the conductivity of crustal rocks (Duba & Shankland 1982) and indeed connected networks of graphite have been observed in lower-crustal black shale as Tarits *et al.* note. However, the evidence is weaker for carbon as a mantle conductor. Carbon is undoubtedly present throughout the mantle, possibly as graphite but also in equilibrium with water and oxygen as the non-conductive volatiles CO and CO_2 and carbonate phases through a complex system of buffering reactions (Blundy, Brodholt & Wood 1991). The diamond stability field (Kennedy & Kennedy 1976) applies a lower limit to carbon as conducting graphite at 150–160 km, which is not inconsistent with Oldenburg's (1981) models of a HCZ. However, carbon conductivity has a very low thermal-activation energy (Duba & Shankland 1982), so that graphitic carbon conductivity is essentially the same at lithospheric temperatures (150–1280 °C) as at asthenospheric temperatures (1280–1400 °C). An unknown mechanism is therefore required to remove the influence of graphitic carbon at shallower depths, which is necessary to accommodate the highly resistive uppermost mantle of Cox *et al.* (1986).

Straining: it has been suggested that deformation associated with plate motion is responsible for seismic attenuation in the LVZ (Minster & Anderson 1981). Because crystal defects are responsible for electrical conduction, and straining increases the number of dislocations in olivine, it was thought that a stain-induced seismic LVZ would also be an electrical HCZ. However, in a careful set of experiments, Hirsch & Wang (1986) and Hirsch (1989) showed that deformation of olivine did not increase its conductivity significantly.

Grain boundaries: the presence of grain boundaries and grain boundary impurities has long been thought a mechanism for about an order of magnitude increase in the conductivity of the mantle over that of single-crystal olivine. However, Constable & Duba (1990) found that at mantle temperatures the conductivity of a dunite was slightly less than that of single-crystal olivine (Duba, Heard & Schock 1974), despite grain boundaries in the dunite. Roberts & Tyburczy (1991) used measurements made over a broad range of frequencies to separate the effect of grain boundaries from grain interior conduction in both synthetic and natural olivine polycrystals. They showed that grain boundary conduction acted in series with grain interior conduction and was evident only at the lowest frequencies used (less than 100–1000 Hz). We note that because the magnitudes of grain boundary and grain interior resistances are approximately the same, at the low frequencies (long periods) used in MT sounding the effect of grain boundaries is to roughly halve the conductivity of the mantle over single-crystal and high-frequency laboratory studies. The effect of pressure on grain boundaries is unknown and may be much larger than on olivine, which has shown to be minor (Duba *et al.* 1974).

Olivine genesis: Constable, Shankland & Duba (1992) noted that olivines that had been metamorphically regrown from serpentine and talc were about 0.6 orders of magnitude less conductive than mantle xenolith olivines, whose conductivities cluster tightly with a variation of less than a factor of 2 at 1200 °C. The reason for this difference, which represents the largest variability between experiments in which the oxygen fugacity (f_{O_2}) is controlled, is currently unknown. Duba & Constable (1993) suggest it might be associated with different levels of pyroxene buffering in the experiments on the two types of olivines.

Iron content and oxygen fugacity: the iron content of olivine and f_{O_2} both affect olivine conductivity, but both these variables are fairly well constrained for the mantle. The Fe/(Fe + Mg) ratio of mantle olivines is almost always close to 0.09 and the f_{O_2} of the mantle lies between the iron-wustite and quartz-fayalite-magnetite buffers (Blundy *et al.* 1991). A 10 per cent uncertainty in the Fe/(Fe + Mg) ratio of olivine corresponds to about 0.1 order of magnitude in olivine conductivity (Constable & Duba 1990; Hirsch, Shankland & Duba 1993) while the variation between the two oxygen buffers has about a 0.2 order of magnitude effect (but larger in metamorphic olivines).

In summary, all actual measurements of mantle olivine conductivity made at controlled f_{O_2} are reproducible and cluster very well. This includes recent measurements by Duba & Constable (1993) on a lherzolite which correspond more closely to the upper mantle environment than any previous study. The largest documented effect which undermines the reliability of the SO2 model is the halving of conductivity at low frequencies (long periods) due to grain boundaries, but since the grain interior lherzolite conductivities are about 50 per cent higher than SO2, we conclude that SO2 is representative of current measurements plus or minus about 0.2 order of magnitude. All other factors which have been hypothesized to affect mantle conductivity are speculative or based on indirect observations, and all have counter-arguments against them. So, while our main conclusion (that the coast effect will propagate into the centres of ocean basins) does not depend on the accuracy of the SO2 model, the SO2 model is likely to prove reliable.

4 RELIABILITY OF MARINE MT RESPONSES

We agree with Tarits *et al.* that, by virtue of their vintage, data tabulated by Oldenburg (1981) are not necessarily the best estimates of the true sea-floor MT response. New robust processing techniques and the use of a remote reference have significantly improved sea-floor MT response estimation. We clearly stated in our original paper these limitations, but also gave reasons for choosing Oldenburg's (1981) tabulated data. The reader is reminded that Oldenburg's 1-D interpretations of these data are widely accepted in the geophysical community as providing the best estimates of mantle conductivity (e.g. Chave *et al.* 1990). Furthermore, with the exception of EMSLAB (Wannamaker *et al.* 1989a) and the Tasman Project (Ferguson, Lilley & Filloux 1990), which were both relatively near the coast, very few more recent data sets have been published.

It was our appreciation of the unreliability of the error estimates for these data that led to the statistical treatment we presented. Oldenburg, and many workers after him, tested the magnitude of the χ-squared misfit of the D^+ response. However, the D^+ response is a least-squares fit and so is independent of scaling of the errors; an 'acceptable' χ-squared misfit can be obtained simply by making the error bars large enough. We, like Oldenburg, decided that on this test alone the responses were not incompatible with the 1-D hypothesis. However, serial correlation in the residuals is not affected by error scaling; doubling or halving the error bars would not have changed the result of the runs test we used, which is why we proposed that such a test was important when using D^+ to examine the 1-D hypothesis. A frequency-dependent scaling of errors would affect the D^+ model and response slightly, but probably not to the extent that the gross patterns in the residuals would change greatly.

We concur with Tarits *et al.* that new processing techniques may not only reduce the magnitude of the errors, but also change the magnitudes of the MT estimates themselves. Ferguson *et al* (1990) show that the use of a remote reference has a significant effect on the magnitude of apparent resistivity estimates at periods shorter than 1000 s, but at longer periods the use of remote reference is less important as signal-to-noise levels increase. The use of such techniques affects the ability of 1-D or 2-D models to fit MT responses of period-bandwidths 100–10 000 s (such as the EMSLAB data), and serial correlation in model residuals may be different. But, the three MT data sets tabulated by Oldenburg (1981) and examined in our original paper are at periods >1000 s (with the exception of one data point at site JDF), so the lack of remote reference is probably less significant for these response estimates.

The vertical gradient sounding (VGS) technique involves a 1-D transformation of horizontal magnetic fields through the ocean, but this does not imply that the VGS response will necessarily be 1-D, as Tarits *et al.* imply. For example, the JDF data used in our original paper and tabulated by Oldenburg (1981) are themselves derived from anisotropic VGS response estimates (Law & Greenhouse 1981), which are clearly not 1-D. At periods >1000 s the ocean acts as a thin sheet, with negligible thickness compared to the skin depth in the underlying crust and mantle. In this limiting case the VGS technique reduces to Price's (1949) thin-sheet equation, in which the equivalence of the VGS and sea-floor MT responses is implicit.

5 CONCLUSIONS

The details of the arguments outlined above are clearly complicated and open to further interpretation and research. However, we would like to stress that our main original conclusions stand, almost regardless of which combination of factors affecting the coast effect are chosen. That is:

(a) the coast effect propagates well into the the centre of the ocean basins and produces MT responses which are always distorted but not necessarily anisotropic. That is, the components parallel (TE) and perpendicular (TM) to the nearest coastline are similar in the 3-D case but are far from the 1-D response. In the 2-D case they will not agree, and the TE response is more faithful to the underlying 1-D mantle; however, the coast effect is so large that few, if any, parts of the world exhibit a purely 2-D geometry. Our modelling suggests that the effect of coastlines on 1-D interpretations of deep-ocean MT soundings is always to make the resulting conductivity profiles too conductive. Vertical and horizontal leakage between the ocean basins and the mantle will reduce the coast effect, but 1-D interpretations are still likely to fail. The influence of the coastlines is primarily associated with the presence of a resistive upper mantle layer, and the inclusion of more conductive asthenosphere does not change this conclusion.

(b) While a mantle high-conductivity zone (HCZ) at the base of the lithosphere might well exist, it is not strictly required by the data sets analysed by Oldenburg (1981). Acceptance of a mantle HCZ has previously required the assumption of enhancement of electrical conductivity over that of dry, subsolidus olivine. Current understanding of the petrology and pressure-temperature state of the upper mantle places quite strong limitations on possible mechanisms for such enhanced conductivity. We have re-examined these above in some detail, and conclude that it is difficult to conceive of any geologically feasible factor that may enhance mantle conductivity to the levels required by 1-D interpretation of MT response functions.

(c) By including coastlines around ocean basins in simple configurations, we show similar trends in model MT responses to those observed on the sea-floor. Our intention was not to model the three data sets exactly, as is obvious from the simple basin shapes chosen, but to illustrate how one might approach more specific problems of sea-floor MT interpretation. Better quality data and accurate modelling of the ocean basins may lead to a much better understanding of mantle conductivity, and the possible existence or otherwise of a HCZ.

(d) Finally, we would like to conclude by stating that, in our opinion, Oldenburg's work was the best of its kind when carried out. However, 3-D rather than 1-D, modelling is now the state of the art and we would like to encourage its use in an environment in which it is clearly appropriate. Similarly, we cast no aspersions on the practice of marine MT sounding, but believe that because the coastlines and bathymetry are extremely well known, *a priori*, the use of thin-sheet methods may significantly improve interpretation for mantle conductivity, particularly in tectonically active areas such as subduction zones and spreading ridges where bathymetry and coastlines are complicated.

6 ACKNOWLEDGMENTS

The authors wish to thank A. Duba for continued discussion on mantle conductivity and J. Ryan for helpful advice on fluids in subduction zones. The figure in this paper was produced with PLOTXY, kindly supplied by R. L. Parker. The authors were funded by the National Science Foundation under grant OCE9101783; GSH wishes also to thank the Australian Research Council for support.

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