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Electrical conductivity profiles and implications for the absence or presence of partial melting beneath central and southeast Australia

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A previous paper presented measurements by Australian magnetometer arrays of Earth response to the magnetic daily-variation source field, and interpreted these data by simple representative models of one-dimensional structure found by "forward model-fitting". This paper now supplements the earlier interpretation by seeking to clarify the ranges of acceptable models which fit the data; that is, to demonstrate the extent of the non-uniqueness of the interpretation. Searches for models which fit the data have been carried out on both a systematic and a random basis, with similar results.

The major conclusion of the earlier paper is confirmed; that there is a substantial difference in conductivity structure between central and southeast Australia. Beneath central Australia, the structure is consistent with a traditional continental geotherm and published laboratory measurements on the temperature dependence of the electrical conductivity of recognized upper-mantle crystalline olivine materials. Beneath southeast Australia, a higher conductivity by an order of magnitude in the depth range 200–300 km is most directly interpreted in terms of a small degree (perhaps 5%) of basalt melt.

Such a partial-melt zone under southeast Australia is consistent with previous natural electromagnetic measurements for the area; has earlier and independently been indicated by a variety of seismic studies; and correlates with proposed thermal models which involve crustal intrusion from some sub-lithospheric magma source.

1. Introduction

An earlier paper (Lilley et al., 1981, hereafter referred to as Paper 1; see also Woods, 1979) described methods of observation and data reduction followed to obtain values for Schmucker's electromagnetic response parameter c for two different blocks of the Australian continent, on the basis of magnetometer array observations. Paper 1 reported that the two different blocks of the Australian continent appeared to have substantially different electromagnetic responses, and presented electrical conductivity profiles for the two regions which demonstrated this difference. The final figure (fig. 5) of Paper 1, summarizing both the c-values and the models fitted to them, is now reproduced as Fig. 1 of the present paper.

The purpose of the present paper is to explore the ambiguity of the models shown in Fig. 1; that is, to determine ranges of models which are comparably acceptable, and then to interpret these models for information on conditions at depth within the Earth, using published data on the electrical conductivity and temperature relationships for possible upper-mantle materials. An interpretation is reached of a partial-melt zone present beneath southeast Australia, but absent beneath central Australia. This interpretation is examined for consistency with other geophysical evidence (electromagnetic, seismic, and geothermal) for the region.

In the first part of this paper, concerning model-fitting, a model is termed "accepted" by a data set if the computed response curve for the model passes through the appropriate *c*-value bars shown in Fig. 1. This definition causes the discrimination between accepted and rejected models to be perhaps arbitrarily sharp, in view of the fact

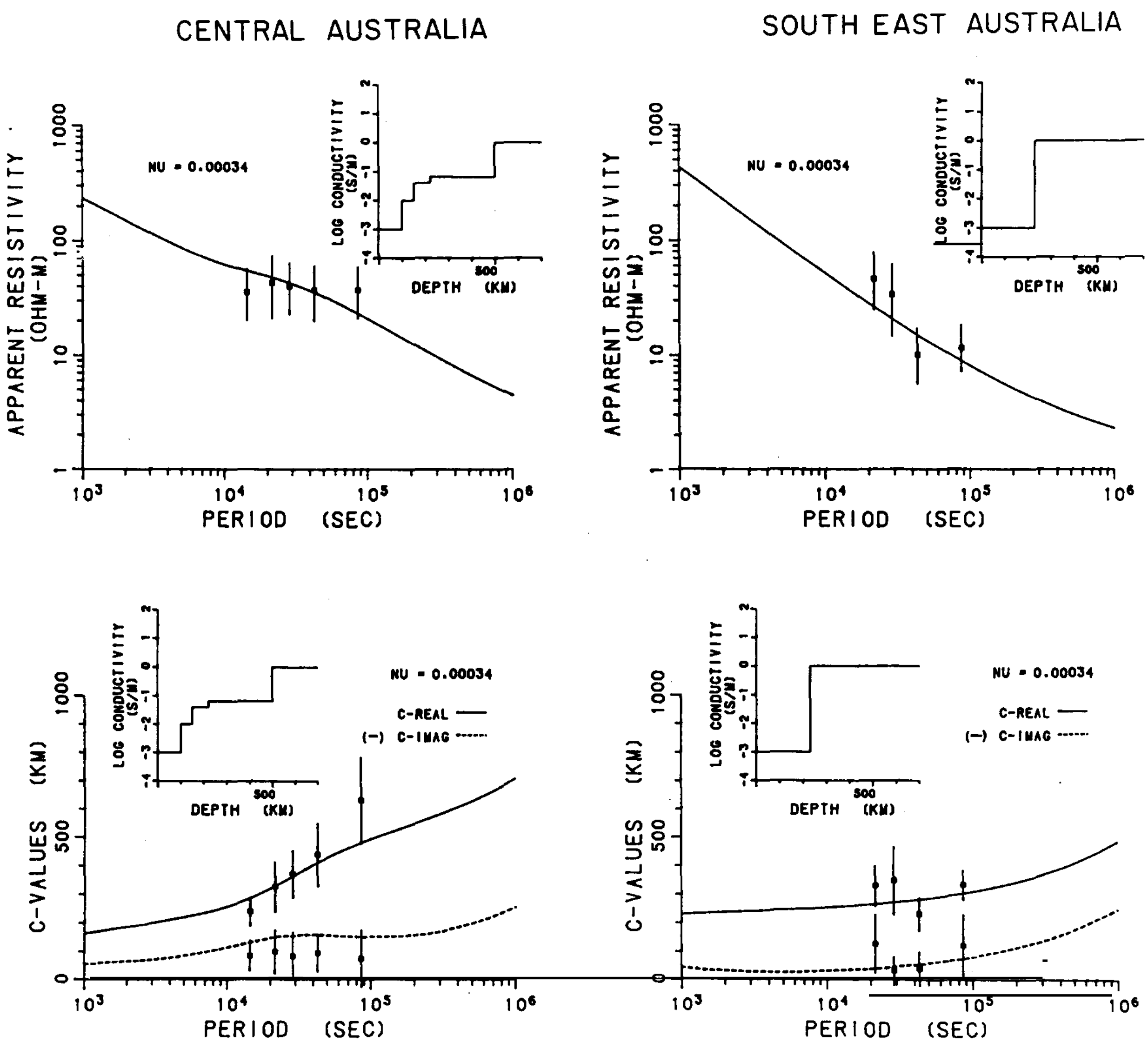

Fig. 1. Summary of electromagnetic response parameters for central and southeast Australia, from Paper 1. The apparent resistivity data bars (shown above) have been calculated from the real and imaginary *c*-value bars (shown below). Two conductivity models are shown, the responses of which fit the observed data. The first task of the present paper is to explore the variety of other models which also satisfy the data.

that the errors associated with the data bars in Fig. 1 are not well-understood (as explained in Paper 1): however, all model-fitting procedures require an "accepted/rejected" decision to be made somewhere, and the use of the data bars in Fig. 1 for this purpose is clear and straightforward. In this paper the unit of $S\text{-}m^{-1}$ is used throughout for electrical conductivity. In places the unit is left understood and conductivity is quoted simply as a number only: e.g. 10^{-2} (meaning 10^{-2} $S\text{-}m^{-1}$).

2. Electrical conductivity profiles for central Australia

The five-layer model shown fitting the central Australia data in Fig. 1 formed the starting point for a systematic search through some 250000 models, the details of which are listed in Table I. While the steps taken in the various parameters are necessarily quite coarse, in order to contain and keep practicable the total number of models to be tested, the models accepted, shown in Fig. 2, nevertheless define regions of possible and prohibited electrical conductivity quite clearly.

In three places accepted models lie along the search bounds, and in these regions the limits of acceptable conductivity (if any) have not been further explored. The physical significance of two of these regions is easily understood in terms of the depths at which the daily variation data in question may be expected to have poor resolution: at depths shallower than 200 km, where models with very low conductivity (even of the limit $\sigma \rightarrow 0$) might fit the data, and deeper than 500 km, where the penetration of the data has effectively ceased and so very high conductivity (even of the limit $\sigma \rightarrow \infty$) might fit the data. The third place where some models lie along a search bound is at the bottom of a step down to $\sigma = 10^{-2}$ which follows a shallower rise to order $\sigma = 10^{-1}$ at 200 km. Thus a poor conductor is underlying a good conductor in these models, and the low-conductivity limit of the poor conductor has not been fully explored.

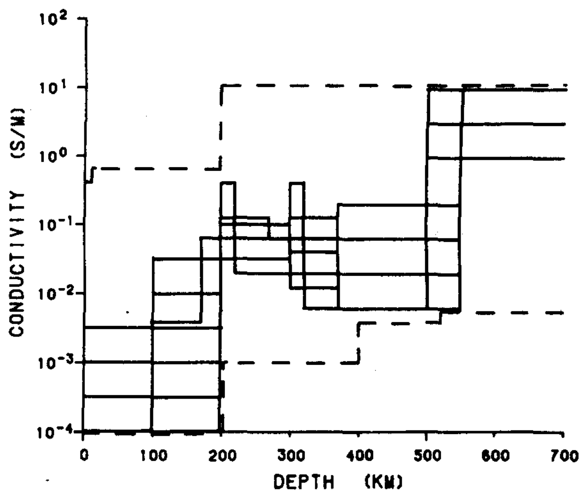

Fig. 2. Combined plot of models found by systematic searching to fit the central Australia c-values in Fig. 1. Out of 253125 models tested, 105 were accepted. The procedure of plotting the models together obscures the characteristics of any particular model, but indicates regions of possible and prohibited conductivity. The parameter space within which the systematic search was conducted is shown by the dashed lines on the diagram. Details of models searched are given in Table I.

TABLE I

Details of models tested by systematic search for acceptance by the central Australia data. Models of five layers were tested, searching the parameter space around the model shown for central Australia in Fig. 1. All possible 253125 combinations of the parameters shown were searched

Layer number	Thickness (km)	$\log_{10}$ electrical conductivity ($S\text{-}m^{-1}$)
1	0, 100, 200	-4 to -2 in steps of 0.5
2	0, 100, 200	-3 to -1 in steps of 0.5
3	20, 70, 120	-2.4 to -0.4 in steps of 0.5
4	180, 280, 380	-2.2 to -0.2 in steps of 0.5
5	∞	-1.0 to $+1.0$ in steps of 0.5

The third place described is probably the most serious of the three shown on Fig. 2, due to the general principle that restricting a model search in one part of parameter space may affect, in an unobvious manner, another part of the parameter space of the models accepted. However, for other geophysical reasons the electrical conductivity of the upper mantle is unlikely to be below 10^{-2} at depths greater than 300 km (Anderssen, 1970), and so this particular limitation of the model-fitting in Fig. 2 is not regarded as critical.

~~The models of Fig. 2 thus confirm the conclu-~~

sion stated in Paper 1, that a rise in conductivity of at least an order of magnitude takes place near 500 km depth; the models also demonstrate that a more shallow rise is required to take the conductivity to order $10^{-1.5}$ by depth 200 km.

The range of models which fit the central Australia data has also been explored using a Monte Carlo method arranged by Woods (1979). In this procedure models are generated at random within prescribed bounds, and their theoretical responses are computed and tested for acceptance by the data in question. As applied to the central Australia data from Paper 1, the Woods (1979) Monte Carlo routine generates a five-layer model in which the thicknesses and the conductivities of the layers are random within "a priori" bounds given by Anderssen (1970) but subject to the following restriction: generally the electrical conductivity of successively deeper layers must increase except that one layer of the deeper four is allowed to have a conductivity less than that of the layer above it.

Two accepted models, shown in Fig. 3 with their "a priori" bounds, were thus found for the central Australia data of Fig. 1. Both models are generally consistent with the areas of possible conductivity evident on Fig. 2. These two accepted models were found in a search of some 410000 models generated randomly; a low yield which confirms the point made upon the basis of "trial-and-error" fitting in Paper 1, that the *c*-value data bars for central Australia tightly constrain acceptable models. Widening the data bars to be fitted would undoubtedly produce many more accepted models, but this has not been done as consistency would then be lost with the accepted models of Fig. 2.

In Fig. 4 an envelope is drawn upon the basis of Figs. 2 and 3, defining regions of possible and prohibited electrical conductivity to be carried through for interpretation below in Fig. 8.

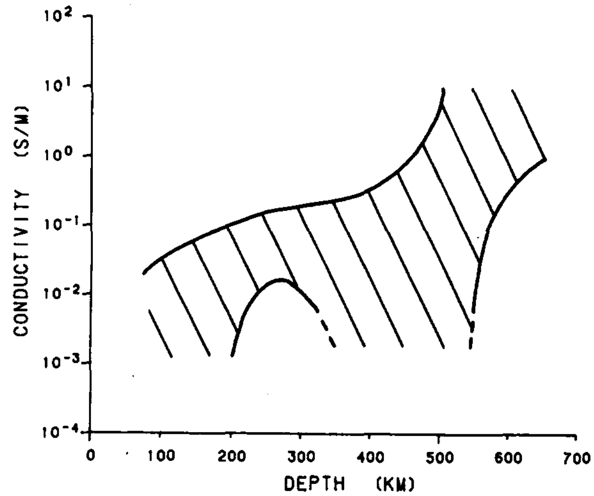

Fig. 4. Envelope drawn upon the basis of Figs. 2 and 3 defining regions of possible and prohibited electrical conductivity for central Australia, and carried through to Fig. 8 for interpretation.

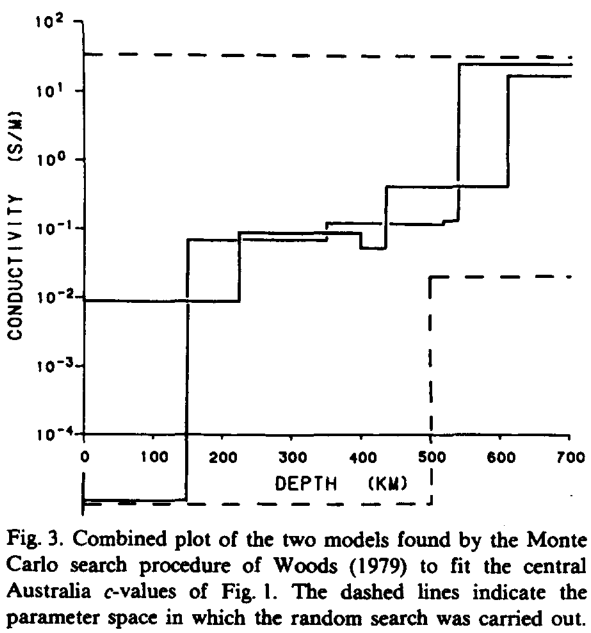

Fig. 3. Combined plot of the two models found by the Monte Carlo search procedure of Woods (1979) to fit the central Australia *c*-values of Fig. 1. The dashed lines indicate the parameter space in which the random search was carried out.

3. Electrical conductivity profiles for southeast Australia

A systematic search has also been carried out for models to fit the southeast Australia data. As the initial trial-and-error model fitting found, and Fig. 1 demonstrates, the southeast Australia data bars are less restrictive in the models they accept and a variety of simple models are accepted by

TABLE II

Details of models tested by systematic search for acceptance by the southeast Australia data. Models of three layers were tested, searching the parameter space around the model shown for southeast Australia in Fig. 1. All possible 32928 combinations of the parameters listed were searched

Layer number	Thickness (km)	$\log_{10}$ electrical conductivity ($S\text{-}m^{-1}$)
1	0 to 200 in steps of 40	− 4.0 to − 1.0 in steps of 0.5
2	0 to 600 in steps of 40	− 3.5 to − 0.5 in steps of 0.5
3	∞	− 1.0 to 2.0 in steps of 0.5

them. The systematic search has thus been carried out over a family of three-layer models, as specified in Table II.

The models accepted by this systematic search for the southeast Australia data are plotted together in Fig. 5. As in Fig. 2, the plotting of superimposed models obscures the detail of individual profiles; however, again as for Fig. 2, parameter spaces of possible and prohibited conductivity are clearly defined. A curve of maximum possible conductivity down to depth of order 300 km is evident, as is a minimum conductivity barrier which rises steeply to order $10^{-0.5}$ at depth 280 km. Deeper than this rise, below say 350 km, the conductivity is not resolved, because, physically, the natural magnetic variations upon which the observed data are based do not penetrate the models to such depths.

Models accepted by the systematic search and plotted in Fig. 5 encounter the low conductivity bounds of the search at shallow depths. The models also, at depths greater than 300 km, impinge upon the bounds for both high and low conductivities. However, the requirement of a rise in conductivity to $10^{-0.5}$ by depth 280 km is not thought to be affected by these bound restrictions.

The Monte Carlo search procedure has also

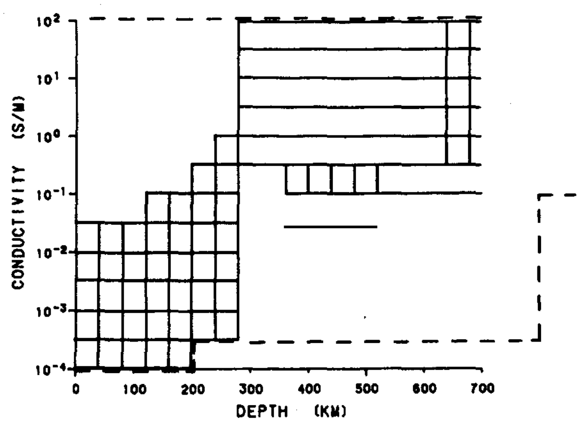

Fig. 5. Combined plot of models found by systematic searching to fit the southeast Australia c-values in Fig. 1. Out of 32928 models tested, 234 were accepted. Details of the models searched are given in Table II. The parameter space within which the systematic search was conducted is shown by the dashed lines on the diagram. Note that the lowest level of conductivity accepted at depths below 350 km is controlled by the lower bound of conductivity (of 10^{-1} $S\text{-}m^{-1}$) allowed in a third layer.

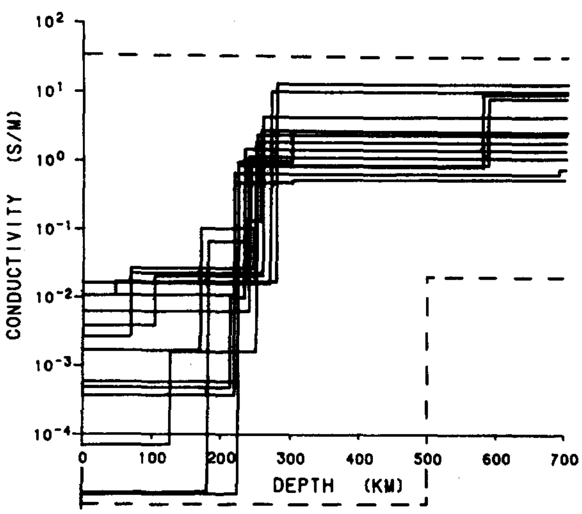

Fig. 6. Combined plot of 15 of the 140 three-layer models found by the Monte Carlo search procedure of Woods (1979) to fit the southeast Australia c-values in Fig. 1. The dashed lines indicate the parameter space in which the random search was carried out.

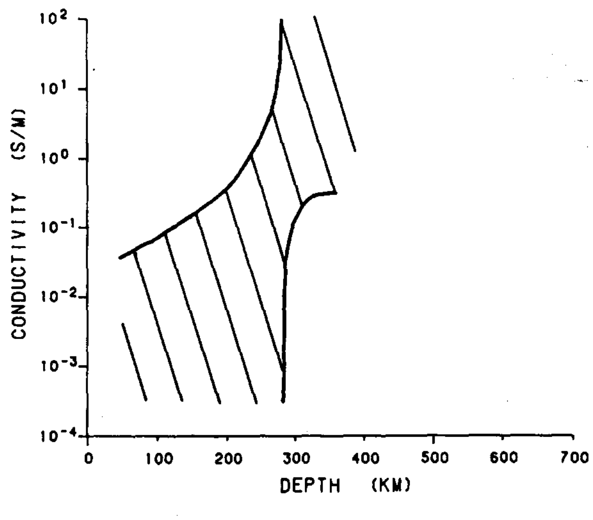

Fig. 7. Envelope drawn upon the basis of Figs. 5 and 6 defining regions of possible and prohibited conductivity for southeast Australia, and carried through to Fig. 9 (below) for interpretation. Note that for southeast Australia, the conductivity is considered to be not resolved for depths in excess of 350 km.

been applied to the southeast Australia data, this time testing models generated to have three layers. Some 140 models have been accepted out of some 25000 tested, and 15 of these are shown in Fig. 6. All 140 random models accepted agree well with the results in Fig. 5, especially concerning the characteristics of the possible and prohibited regions of electrical conductivity parameter space. The greater return of accepted models by the random search for the southeast Australia data demonstrates again the less restrictive nature of the southeast Australia data bars in Fig. 1.

Figure 7 shows an envelope for the regions of possible and prohibited electrical conductivity taken from Figs. 5 and 6 (and the other accepted random models not shown on Fig. 6) and now carried through to Fig. 9 for interpretation.

4. Laboratory data for the variation of electrical conductivity with temperature

The conductivity envelopes of Figs. 4 and 7 reflect changing conditions of temperature, pressure, chemical composition, and phase with depth in the Earth. For example, the rise in conductivity from order 10^{-1} to 10^{0} shown in Fig. 4 for central Australia at depth of order 500 km has been evident for some years from global studies of natural electromagnetic induction, and has been interpreted (e.g., by Banks, 1969) as accompanying phase changes in olivine which occur in the transition zone of the mantle as a result of temperature and pressure increasing with depth (Liu, 1979).

To extract further information from the conductivity profiles it is necessary to refer to the conductivity – temperature behaviour of appropriate upper-mantle mineral materials. Recently, many papers have been published on this subject, such as those by Mao and Bell (1977), Chelidze (1978), Gupta and Sharma (1978), Rai and Manghnani (1978), Schulien et al. (1978), Vanyan and Slutskiy (1978), Hermance (1979), Tozer (1979), Will et al. (1979), and others referred to elsewhere in this section. The range in possible electrical conductivity values for upper-mantle material at a given temperature is wide; for the sake of a basis for proceeding with interpretation, this paper will follow the practice of Shankland and Waff (1977) and Drury (1978) in adopting the laboratory results of Duba et al. (1974) and Schock et al. (1977) for olivine.

A particular temperature dependence for the electrical conductivity of olivine can then be combined with data for a particular geotherm to produce a model electrical conductivity profile with depth. This is the procedure followed by Drury (1978), whose predicted conductivity profile will now be compared with the model range of Figs. 4 and 7.

4.1. The central Australia results and a predicted continental conductivity profile

Figure 8 shows the range of possible conductivity models from Fig. 4 for central Australia. Superimposed is the curve of Drury (1978), as predicted from the characteristic continental geotherm of Ringwood (1969) and the olivine conductivity results of Duba et al. (1974). The curve lies within the possible conductivity range and thus demonstrates that three sets of data are here self-

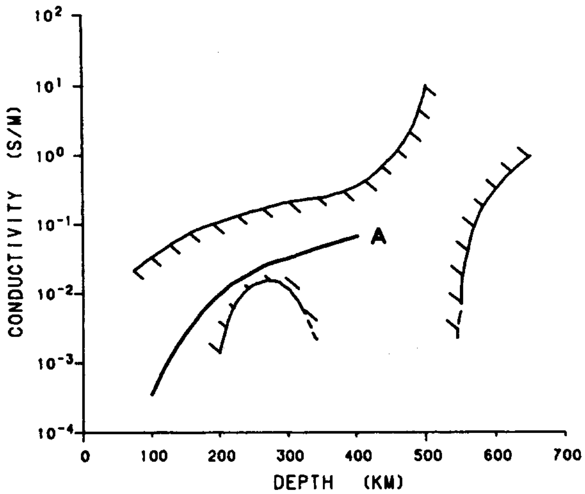

Fig. 8. Envelope defining possible conductivity space for central Australia as taken from Fig. 4, and the conductivity profile (A) predicted for such a continental region by Drury (1978). The increase in conductivity evident for central Australia at depths of order 500 km is traditionally attributed to phase changes in olivine in the mantle transition zone.

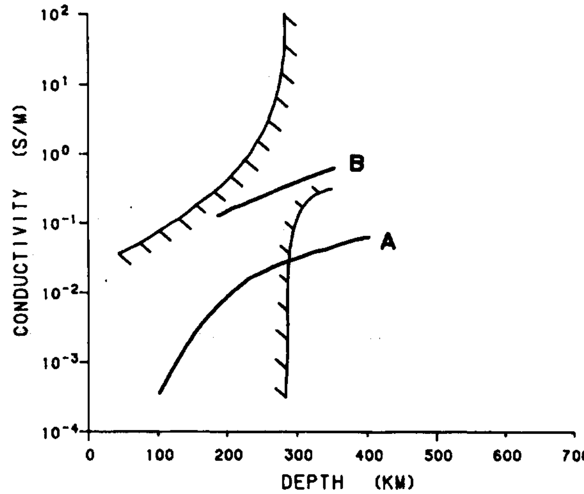

Fig. 9. Envelope defining possible conductivity space for southeast Australia as taken from Fig. 7, and some conductivity profiles. A: As predicted by Drury (1978) and shown in Fig. 8. B: Computed using Shankland and Waff's (1977) partial melt data as explained in section 4.2 of the text. That curve B lies within the envelope, whereas curve A does not, indicates the likelihood of a partial melt zone as an explanation for the high electrical conductivity interpreted for southeast Australia.

consistent:
(i) The *c*-values as determined in Fig. 1.
(ii) The Duba et al. (1974) data taken as representing mantle conductivity.
(iii) The Ringwood (1969) geotherm for central Australia.

This is not to claim, of course, that all sets of data are precisely correct, and indeed considerable variation in many of the parameters is possible which would still give the sort of agreement evident between the observed and predicted profiles in Fig. 8. However, for the purposes of the present paper, it is sufficient to note that the observations for central Australia are adequately accounted for by a traditional continental geotherm in a mantle with the electrical conductivity of crystalline olivine.

4.2. The southeast Australia results and a zone of partial melt

Figure 9 shows the range of possible conductivity from Fig. 7 for southeast Australia, with Drury's (1978) curve for a predicted continental conductivity profile superimposed again as in Fig. 8. The predicted profile lies clearly below the interpreted real conductivity which is required to rise to order $10^{-0.5}$ or higher by depth of order 300 km.

One reasonable petrologic model to consider in accounting for electrical conductivities as high as those indicated for southeast Australia in Fig. 9 is that of a partial melt. Shankland and Waff (1977) summarize evidence for basalt melts having conductivities in the range $10^{0.5}-10^{1.5}$, and examine in some detail the conditions under which partial melts of mantle materials may be expected to have conductivities in the range $10^{-1} \rightarrow 10^{0}$. Clearly a zone of basalt melt of such conductivity under southeast Australia, extending down from a depth of 150 km, would satisfy the observations as interpreted.

The Shankland and Waff (1977) data are for partial melts at pressures between 0 and 30 kbar, and do not cover the 200 and 300 km depths at which the zone of high conductivity is evidently required in Fig. 9. The effect of pressure on the conductivity of a partial melt is uncertain, but possibly weak. If, as an approximation, the 30 kbar data are considered also to hold at greater pressures, then the data may be combined with a geotherm to produce a conductivity profile for a partial melt. For example, Fig. 9 also shows the conductivity profile obtained by combining the data of Shankland and Waff (1977, fig. 7, melt fraction 0.05) with a geotherm taken midway between the ocean and shield geotherms of Clark and Ringwood (1964). This latter conductivity profile then lies within the envelope of Fig. 9, so that a partial melt zone (of modest melt fraction 5%) accounts for the southeast Australia observations of Fig. 1.

5. Discussion and correlation with other geophysical evidence

The central Australia data are interpreted by a traditional geotherm in upper-mantle olivine, as has been discussed. The predicted curve in Fig. 8 lies near the lower side of the envelope, and higher conductivites such as might result from a small degree of partial melting are permitted by the data, though none are required by it. This much is consistent with a shield geotherm lying below a mantle solidus, as for example in Ringwood (1975, p. 215, fig. 6-4).

The southeast Australia data, however, are not satisfied by the conductivity profile predicted by a traditional geotherm in regular crystalline upper-mantle material. Higher conductivities are required, possibly given most simply by postulating the presence of a partial-melt zone of basalt. A small melt fraction (of say 5%) gives the correct order of magnitude for the electrical conductivity. The zone of melting indicated, say from 200 to 300 km depth, is, however, deeper than the 75 to 150 km depth range where an oceanic geotherm might intersect the solidus of a pyrolite mantle with 0.1% water content (Ringwood, 1975, p. 215) and so cause an oceanic partial-melt layer. There may be here, then, some evidence for different depths to partial-melt layers beneath oceans and young continental blocks such as that of southeast Australia.

It is now relevant to consider the results of other geophysical studies of the areas in question.

5.1. Previous electromagnetic studies

A significant point about the present work is that it uses the long-period data provided by the magnetic daily variation to probe deep into the Earth. Most previous electromagnetic studies in Australia have concentrated more on shorter-period magnetic fluctuations, resolving structure at shallower depths in the Earth, say in the upper 100 or 200 km. The envelopes of the accepted models in Figs. 4 and 7 are wide at these shallower depths, and so quite comfortably accommodate the conductivity profiles of previous magnetotelluric studies such as those of Everett and Hyndman (1967a,b), Tammemagi and Lilley (1971, 1973; see also Lilley and Tammemagi, 1972), and Vozoff et al. (1975). The last paper reported results from a magnetotelluric traverse running north from the area where the southeast Australia data of Fig. 1 were observed, and should be particularly noted for its determination of a consistent rise in conductivity to order 10^{-1} at depths of order 100 km, interpreted by the authors as possibly representing the base there of the tectonic plate.

Apart from the results of the present paper, magnetometer arrays in Australia have generally aimed at investigating areas of departure from horizontally-layered geology, and so have not commonly produced profiles of regional conductivity with depth. Bennett and Lilley (1973) report a "normal conductivity profile" from Bennett (1972) for southeast Australia, predicted from earlier laboratory and geotherm data rather like Drury's (1978) profile shown in Figs. 8 and 9 above. Bennett and Lilley (1973) use the normal profile as a background against which to model conductivity anomalies. The profile would have to be elevated at 300 km to pass through the envelope of Fig. 9 above; an adjustment which would, however, not be expected to markedly affect the conclusions of that paper regarding conductivity anomaly models. In particular, the electrical conductivity model advanced by Bennett and Lilley (1973) to account for the "coast effect" in magnetic variations at diurnal periods is completely consistent with a partial-melt zone which steps deeper crossing from the Tasman Sea to beneath southeast Australia.

5.2. *Evidence from seismology*

Independent evidence of a low-velocity zone existing beneath east but not central Australia has come from three separate projects in seismology. A zone of low seismic velocity may be most directly explained by a zone of partial melt. The three seismological projects are:

(i) The observations of P arrival times from the Cannikin explosion of 1971 (Cleary et al., 1972). The explosion originated on Amchitka Island and the relative arrival times of direct seismic P waves were late, by times of up to 1 s, across southeast Australia. Travel-time delays of such magnitude probably require a zone of low primary seismic velocity to account for them, in addition to a possible general reduction in the velocity profile due to an elevated geotherm beneath southeast Australia.

(ii) Surface wave studies of Goncz and Cleary (1976) indicated a zone of low seismic shear-velocity beneath east but not central Australia. Goncz and Cleary centred a low-velocity zone of thickness about 70 km at a depth of about 150 km. Subsequent work for east Australia by Mills and Fitch (1976) suggested that such a zone should be entirely below depth 140 km, a conclusion supported by the results of the present paper.

(iii) A long-range seismic profile in southeastern Australia by Muirhead et al. (1977) was interpreted to show a zone of low seismic primary velocity in the depth range 155–190 km. For central Australia, recent seismic travel-time studies by Hales et al. (1980) indicate no significant low velocity zone above 200 km depth, though the interpretation of these authors does allow the possible existence of a low velocity zone below 200 km depth.

5.3. *Heat flow*

The thermal state of the Australian crust has been reviewed recently by Sass and Lachenbruch (1979), who develop a family of geotherms down to depth 40 km upon the basis of measurements of surface heat-flow and crustal radioactivity. Sass and Lachenbruch take into account much of the geophysical evidence mentioned in sections 5.1 and 5.2 above, and interpret the high heat flows of southeast Australia as being due to widespread crustal intrusion. The intruding magma would come from a deeper source such as the partial-melt zone of the present interpretation.

6. Conclusions

The present paper, like Paper 1 before it, rests on what is as yet a relatively new technique in the study of geomagnetic fluctuations: the application of spatial gradient measurements to determine "c-values", in this case using the magnetic daily-variation source field. As explained in Paper 1, the limitations and the errors of the method are not yet fully understood. However, from the basic c-values for central and southeast Australia there are differences evident between the two continental blocks which strongly suggest, ambiguities in interpretation notwithstanding, a partial melt zone under southeast Australia relative to a crystalline upper-mantle beneath central Australia. In current terminology, southeast Australia may have a well-developed asthenosphere, central Australia less so.

As a case history, these results may have important implications for the study of Earth electrical conductivity, as they are a further example of departures from radial symmetry in the Earth at depths shallower than 500 km. Further, the results demonstrate the use of the spatial gradient method, applied to different geologic blocks, to resolve such gross horizontal conductivity contrasts as may exist. A suitable source-field is of course required, such as the quiet magnetic daily-variation in mid-latitudes.

It may also not be redundant to remark again that partial-melt zones stand out as particularly strong targets for the application of electromagnetic methods in geophysics.

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