

Magnetotelluric Studies across the Tasman Geosyncline, Australia

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Summary

Four magnetotelluric soundings have been made across the Tasman Geosyncline, a major tectonic feature of south-east Australia. The sites of the soundings lie in a line traversing the syncline approximately 150 km apart. Reliable data were procured for each site covering the period range from 10^3 to 10^4 s and following the usual methods of magnetotelluric interpretation, information on electrical conductivity is obtained at upper mantle depths. The conclusion is drawn that at these depths, the conductivity is higher, by an order of magnitude, beneath the geosyncline than to the west of it. This result is interpreted as indicating higher temperatures which are due to, or perhaps cause, the tectonic activity which has characterized the geosyncline, and which is still evident in seismicity studies of the present day. A heat flow contrast to the west of the geosyncline is predicted.

Introduction

Relatively few magnetotelluric experiments have been carried out in Australia, although simultaneous magnetic and telluric observations were first made on the continent as early as 1922. These measurements, which are reported by Gish (1923) and Gish & Rooney (1928), took place at the Watheroo Observatory, constructed by the Carnegie Institute of Washington in Western Australia. In the following decade the measurement of telluric currents was also commenced at the Mt Stromlo Observatory in the Australian Capital Territory, as a means of monitoring magnetic storm activity. Otherwise, the magnetotelluric work recorded in Australia is of quite recent origin. Lewis & Green (1965) reported an experiment in Tasmania, and Everett & Hyndman (1967a) published results for soundings on the West Australian pre-Cambrian shield. Some measurements in southern Queensland have been made by officers of the Bureau of Mineral Resources, and in addition the method has been tested by petroleum exploration companies, searching for evidence of structure in sedimentary basins.

This paper is concerned with four soundings carried out by the authors during 1969 and 1970 across the major geological structure of Eastern Australia, the Tasman Geosyncline. Each site was occupied for at least four weeks, longer than has so far been usual in magnetotelluric studies, to ensure that a sufficient number of active events were recorded. A proton-precession magnetometer measured the three orthogonal components of the magnetic field and the two horizontal components of the electric field were recorded by a digital voltmeter. The method of measuring and

digitally recording the data restricted the frequency range observed to periods of one minute and longer. However, the automatic operation of the equipment enabled long periods of data to be analysed, yielding information to frequencies less than 0.0001 Hz. The exercise has therefore been one in deep sounding, looking for electrical conductivity structure in the upper mantle, especially to see if any is associated with the Tasman Geosyncline. Although the magnetotelluric method utilizes the horizontal components only of the geomagnetic field, the vertical component of the time variations was also recorded. These records are currently being examined by another worker, and will be reported separately.

In this paper, the usual notation is adopted of H and D for the north and east magnetic components respectively. The letters A and B are introduced for the telluric north and east components, and the authors suggest that these might also be well adopted by other workers in the subject, as a uniform and simple notation. Thus $H-B$ magnetotelluric results are those obtained by combining north magnetic data with east telluric data.

Geological setting

The Tasman Geosyncline is a wide linear structure, on the eastern side of the Australian continent. It holds the Australian Alps and the Main Dividing Range, and so supports the major topographic features of Australia. Its situation is marked in Fig. 1. At the position of the magnetotelluric traverse, the geosyncline is approximately 250 km in width. Thus the station at Moruya is on one side, Spring Valley is near the crest of the structure, Wagga Wagga just past the western edge and Griffith is well beyond the western boundary.

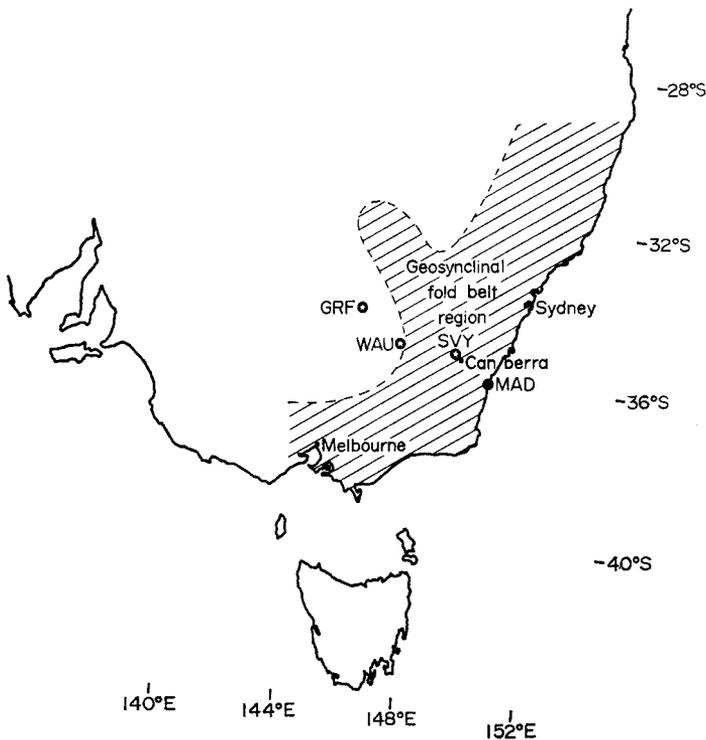


FIG. 1. Sketch map of south-east Australia, showing the four observing sites, and the position of the Southern Highlands Fold Belt of the Tasman Geosyncline.

The syncline consists of belts of rocks of Ordovician to mid-Devonian ages, folded and metamorphosed. A major unit is the granite batholith which forms Mt Kosciusko (2219 m), the highest point of the Australian continent. The geology of the region is described in more detail by Packham (1969), who uses the term 'Southern Highlands Fold Belt' to describe the part of the Tasman Geosyncline relevant to this paper. Little is known of the structure immediately to the west of this fold belt. Outcrops are poor, and other than the surface mapping of a sedimentary basin, little else has been found.

Evidence from seismic refraction studies (Doyle, Underwood & Polak 1966) indicates that the crustal rocks are approximately 40 km deep beneath the Canberra area, thinning to approximately 20 km beneath the coast. Seismicity studies of the region, as carried out by Doyle, Everingham & Sutton (1968) and J. R. Cleary (personal communication), indicate a rather clear western boundary for the present tectonically active belt. At the eastern side, near the coast, the situation is less clear. Some seismicity is evident even on the continental shelf. There is a heat flow difference between the measured values of $1.1-1.2 \mu \text{ cal cm}^{-2} \text{ s}^{-1}$ at Moruya on the coast, and $2.0-2.2 \mu \text{ cal cm}^{-2} \text{ s}^{-1}$ at Spring Valley and in the Snowy Mountains (Jaeger 1970). There are not yet any heat flow measurements off to the immediate west of the syncline, and these are to be awaited with interest.

Method

Field technique

During the period of September 1969–April 1970 four magnetotelluric stations were occupied in turn to form a traverse across the Tasman geosyncline in New South Wales, Australia. The recording sites are Moruya (MAD), Spring Valley (SVY), Wagga Wagga (WAU), Griffith (GRF) and are shown in Fig. 1. Six to eight weeks of recording at each location yielded sufficient magnetic activity for frequency analysis to be performed.

The geomagnetic field was measured by a modified proton precession magnetometer and the three orthogonal field components, *H*-magnetic north, *D*-magnetic east, *Z*-vertically down, were recorded to an accuracy of ± 1 gamma. Three lead electrodes were buried at a depth of 1 metre to form an L-shaped array aligned to magnetic co-ordinates, with each arm about 400 m in length. From this array the telluric potentials (*A*: north, *B*: east) were measured to an accuracy of ± 0.1 mV by a digital voltmeter. The magnetic and electric readings were recorded digitally on paper tape at 60-s intervals. The complete system has been described in an earlier paper (Everett & Hyndman 1967b).

Data analysis

The magnetotelluric data was decoded from the paper tape using a CDC 3600 computer at the Commonwealth Scientific and Industrial Research Organization, Canberra. Analogue CALCOMP plots were formed and three sets of activity were chosen to be analysed for each site. The criterion of their choice was 'power' content and thus at least one magnetic storm was included at each location. The data of interest were transferred onto punched cards and the remainder of the data analysis was performed with an IBM 360/50 computer at the Australian National University. Standard power spectral formulae were employed to give auto and crosspower spectral density estimates for the electric and magnetic field components. Statistical smoothing was carried out using the Parzen window (Richards 1967) and computational efficiency achieved using fast Fourier Transform techniques (Gentleman & Sande 1966). No prewhitening was used and the maximum lag was taken as equal to or less than one tenth of the data length. As the digitizing interval was 60 s and the data length generally a day or more, this resulted in an approximate period bandwidth of 10^2 to 10^4 s.

Apparent resistivity versus period curves were calculated using the autopower spectral estimates of the magnetic and orthogonal electric fields, from the standard magnetotelluric equation (Cagniard 1953),

$$\rho_a(T) = 0.2 T \left| \frac{A(T)}{D(T)} \right|^2 = 0.2 T \left| \frac{P_{AA}(T)}{P_{DD}(T)} \right| \quad (1)$$

where ρ_a denotes the apparent resistivity in Ohm-metres, T the period in seconds and P_{AA} , P_{DD} the telluric north and magnetic east autopowers respectively. Similarly another apparent resistivity curve was calculated for each site from the H and B data. Calculations of the crosspower, P_{AD} , between orthogonal electric and magnetic fields yielded the coherence parameter,

$$\text{coh}_{AD}(T) = \frac{|P_{AD}(T)|}{\sqrt{[P_{AA}(T) P_{DD}(T)]}} \quad (2)$$

The phase, ϕ , between the electric and magnetic fields was also calculated, using

$$\tan \phi_{AD}(T) = \frac{\text{Imaginary} [P_{AD}(T)]}{\text{Real} [P_{AD}(T)]} \quad (3)$$

To test the basic auto and crosspower spectral computer programs, two artificial time series were generated to simulate an ideal electric and magnetic field, impinging on a uniform half space of resistivity 1000 Ohm m. The synthetic magnetic time series consisted of two chains of sine waves superimposed, one of 3000-s period and amplitude 20 gammas, the other of 300-s period and amplitude 20 gammas. The synthetic electric field also consisted of sine waves of 300 and 3000-s periods but the amplitudes were calculated to give an apparent resistivity of 1000 Ohm m from equation (1). To test the phase (equation (3)) the 3000 period component of the electric field was made to lead the 3000 period component of the magnetic field by 0.4 rad (22.9 deg) and likewise the 300 period component was 0.3 rad (17.2 deg) advanced. The results of analysing the artificial time series by the machine programs developed are shown in Fig. 2. It is evident that the autopower, coherence and phase are reliably estimated when the signal holds appreciable energy, that is, at periods of

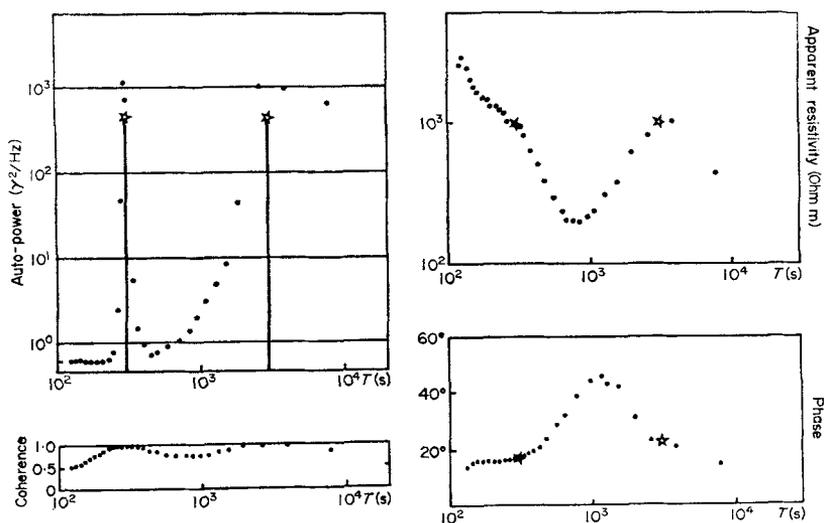


FIG. 2. Results of testing computer programs with synthetic data.

300 and 3000 s. However, away from these limited bandwidth areas the coherence does not go to zero, although it does decrease, and what appear to be valid phase and apparent resistivity values are recorded. A very important criterion then in choosing valid magnetotelluric data is not only that coherence be high but also that power be present at the frequencies in question. This factor will be seen to severely restrict the useable bandwidth of the analytical data presented in the next section.

Results

At each site three separate magnetic events or periods of activity were chosen for frequency analysis. The times of these events are listed in Table 1 with the geographic co-ordinates and code names of the stations. A typical event (event 1 for Moruya) is shown in Fig. 3. The three events were analysed for each site, and one event was selected as representative, and used for interpretation. The representative events were chosen on the basis of power content and high coherence and are indicated in Table 1 by asterisks.

The apparent resistivity, magnetic and electric autpowers, and coherence, were calculated as functions of period and are given in Figs 4 and 5. Figs 4(a) and 5(a) show that below periods of approximately 900 s the coherence drops from about 0.8 to below 0.5; in this range the autpowers of the field components are also very small, as well as very scattered. Thus, on the basis of testing carried out on the synthesized time series, it was decided that any data below the period of 900 s had too low a power content to be considered reliable. For interpretation, only the data to the right of the dashed vertical line in Fig. 4(a) were considered.

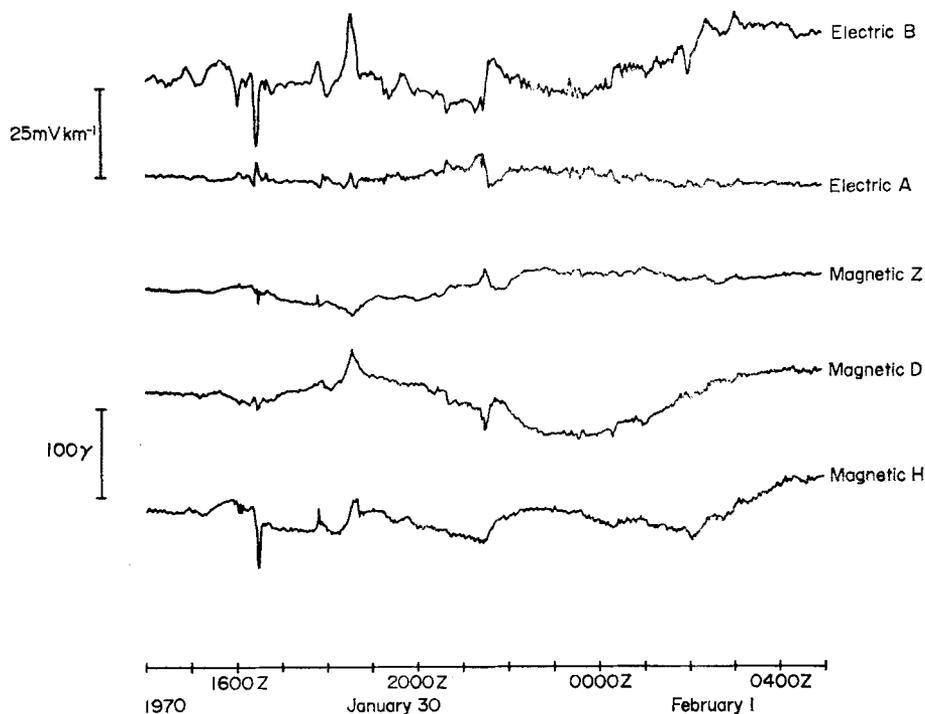


FIG. 3. An example of the data recorded at the coastal station Moruya (1970 January 30).

Table 1

Site	Mnemonic	Geographic co-ordinates	Event 1	Event 2	Event 3
Moruya	MAD	35°55' S 150°10' E	1970 Jan. 30 Feb. 1 0500Z* 0500Z*	1970 Feb. 2 Feb. 4 0330Z	1970 Feb. 4 Feb. 6 0100Z
Spring Valley	SVY	35°16' S 149°05' E	1969 Oct. 10 Oct. 10 2300Z	1969 Oct. 24 Oct. 25 0600Z	1969 Nov. 8 Nov. 12 0500Z*
Wagga Wagga	WAU	35°09' S 147° 24' E	1970 Feb. 18 Feb. 19 1000Z	1970 Feb. 24 Feb. 25 1200Z	1970 Feb. 28 Mar. 2 1800Z*
Griffith	GRF	34°19' S 146°03' E	1970 Mar. 31 Apr. 1 0500Z	1970 Apr. 18 Apr. 19 1800Z	1970 Apr. 20 Apr. 22 1500Z*

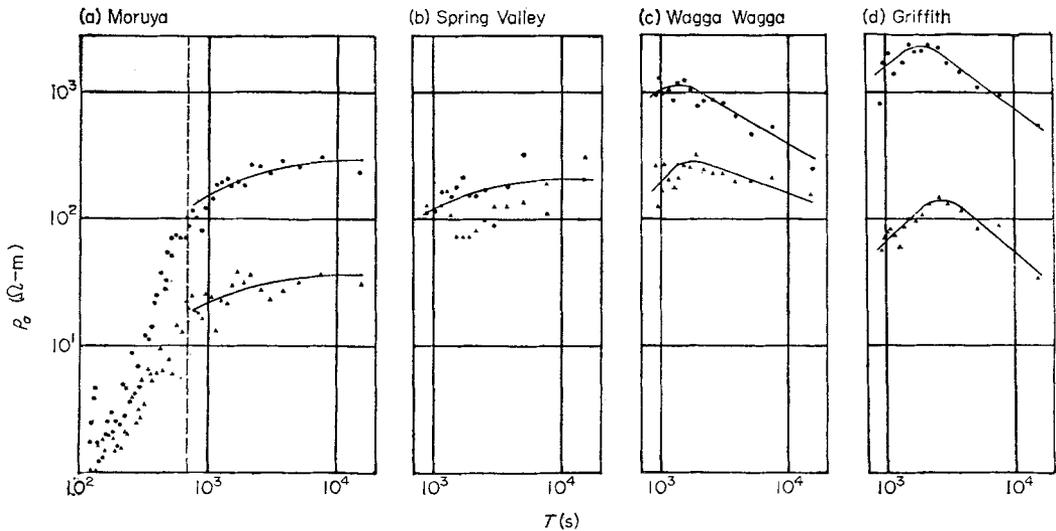


FIG. 4. Apparent resistivity data for four sites. ● *H-B* data; ▲ *D-A* data. Solid lines indicate typical acceptable master curves.

The apparent resistivity and attendant autopower and coherence curves for Spring Valley, Wagga Wagga and Griffith show that, as for Moruya, the data of periods below about 900 s were unreliable; these data have been omitted from the figures. The coherences for Spring Valley are low but the apparent resistivity data for that station are confirmed by the analysis of the other two events.

The phase difference between the electric and magnetic fields was also calculated and plotted as a function of period. The results are generally too scattered for quantitative interpretation; an example is given in Fig. 6. There is, however, some qualitative correlation of phase with apparent resistivity at those sites which exhibit anisotropy. The correlation is that greater phase difference accompanies higher apparent resistivity.

Physical interpretation

The set of apparent resistivity data obtained for each station was interpreted by fitting it with members of the portfolio of master curves published by Srivastava (1967). The determination of the best fitting master curve was achieved solely by visual comparison with the field curves. The assumption was made that the impinging electromagnetic disturbances were plane waves, a reasonable simplification for Australian data taken in geomagnetic mid-latitudes (Madden & Nelson 1964). As good experimental data are available over a period bandwidth of little more than one decade, it would be meaningless to fit elaborate conductivity models. However, some conclusions can be drawn for resistivities at depths in the lower crust and upper mantle. The four stations are now dealt with in turn, taken from east to west.

Moruya

Moruya is on the coast so the ocean may be expected to produce strong anisotropy in the results. This is indeed so and this can be seen visually in the variograms of Fig. 3, as well as in the apparent resistivity curves of Fig. 4(a). The *H-B* data give higher resistivities than the *D-A* data. This anisotropy is in accordance with the results of Swift (1967) for electromagnetic behaviour near a simple two dimensional conductivity contrast, if the north-south trending coastline structure is taken to be

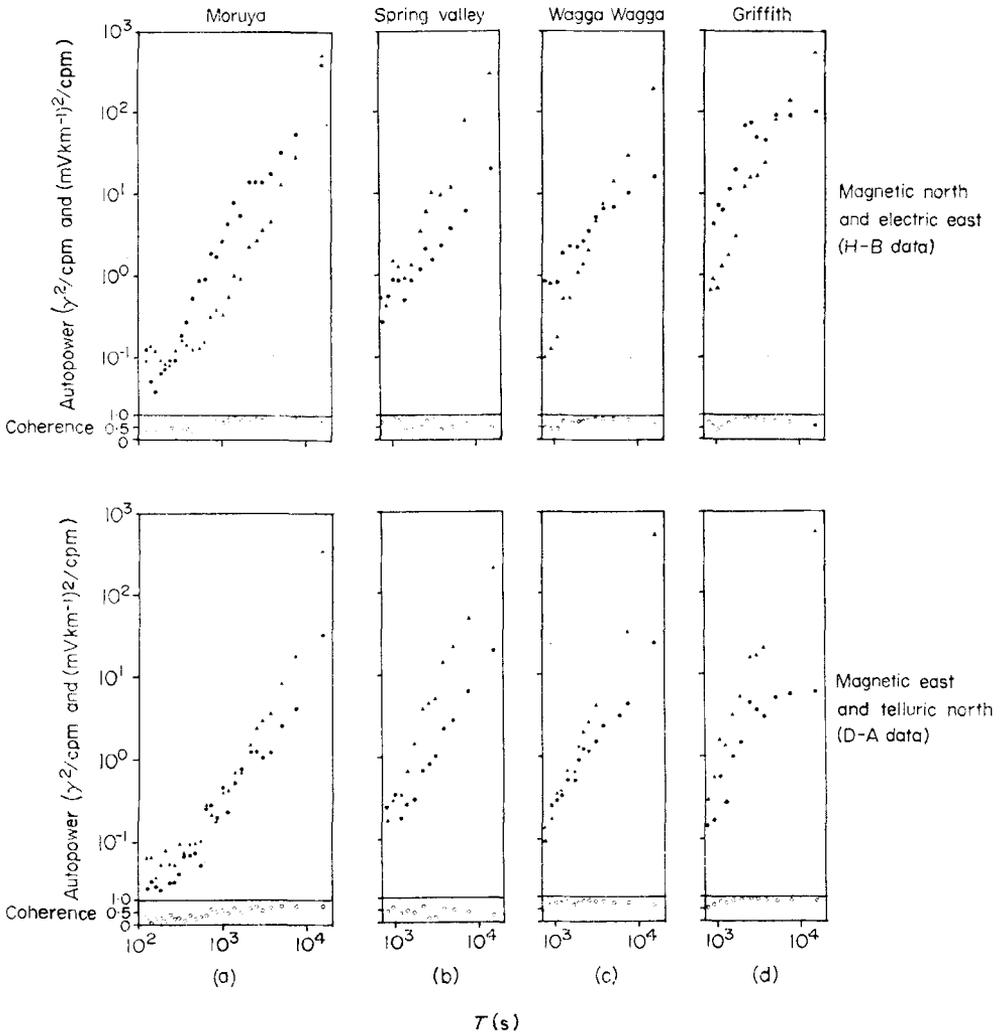


FIG. 5. Results of autopower and coherence analysis for four sites. \blacktriangle autopower of magnetic component; \bullet autopower of telluric component; \circ coherence estimate.

two dimensional with the continental side more resistive. By comparison with the master curves, it was found that the data were most suitably fitted by simple two-layer models. Although a large number of varied models were acceptable, certain limits could be deduced. The resistivity of the underlying half-space is fixed, although the resistivity and depth of the first layer may vary; and although the first layer depth is variable, it cannot exceed a certain maximum. Models were found for each of the two different apparent resistivity curves, yielding two differing conductivity models for this one site. This discrepancy or anisotropy has long been a dilemma of magnetotelluric interpretation, and different authors have dealt with it in various ways, some rather arbitrarily. In this instance, as the north-south coastline is thought to provide an approximate two-dimensional conductivity contrast, a simple average is taken of the two models obtained from the anisotropic data. The final model thus consists of an upper layer of maximum thickness 10 km and resistivity equal to or less than 50 Ohm m, which is underlain by an infinite half-space of resistivity approximately 225 Ohm m. This structure is shown in Fig. 7(d).

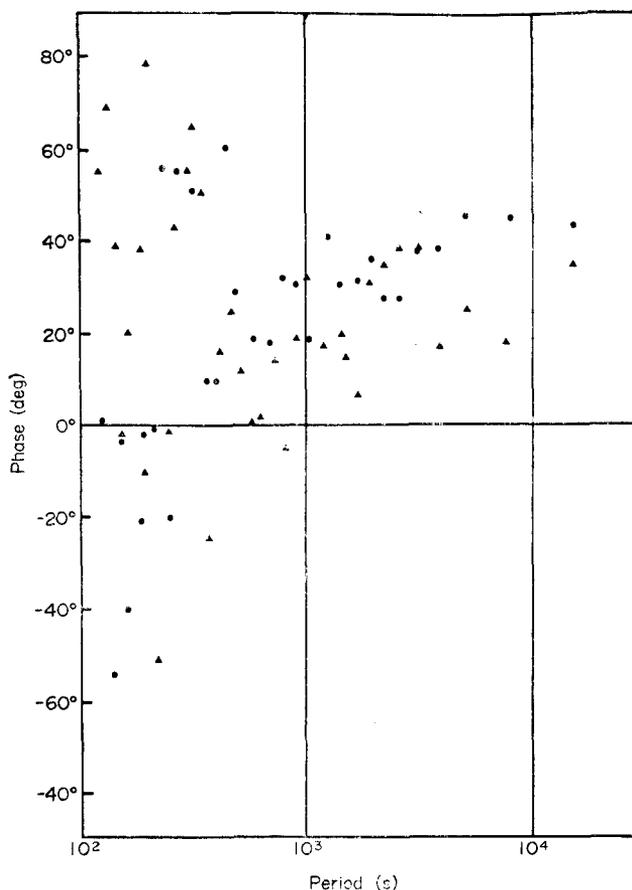


FIG. 6. An example of phase data (from Moruya). ● *H-B*, ▲ *D-A*.

Spring Valley

The data for Spring Valley are more easily interpreted as they show little or no anisotropy. Again two-layer models are most suitable for fitting the field curves and although a range of electrical conductivity structures are possible, the bottom layer resistivity is fixed and the top layer thickness and resistivity cannot exceed certain maxima. As no anisotropy is present, one conductivity model is consistent with both apparent resistivity curves, and this is shown in Fig. 7(c). The model consists of a top layer of maximum thickness 20 km and maximum resistivity 45 Ohm m underlain by an infinite half-space of resistivity approximately 225 Ohm m.

Wagga Wagga

The apparent resistivity curves of Fig. 4 for this station exhibit strong anisotropy; they also show that the conductivity layering below this site is more complicated than at Moruya or Spring Valley. Indeed the simplest models that could be fitted from the master curves were three layer ones, indicating a conductive-resistive-conductive structure.

Again a large number of models could be fitted to the data; however, the depth to the bottom conductive half-space remained fixed. The top two layers could be varied both in depth and resistivity but the top layer always remained thin and conductive relative to the second. Representative models were chosen for each of the different apparent resistivity curves. As for Moruya their average was taken to

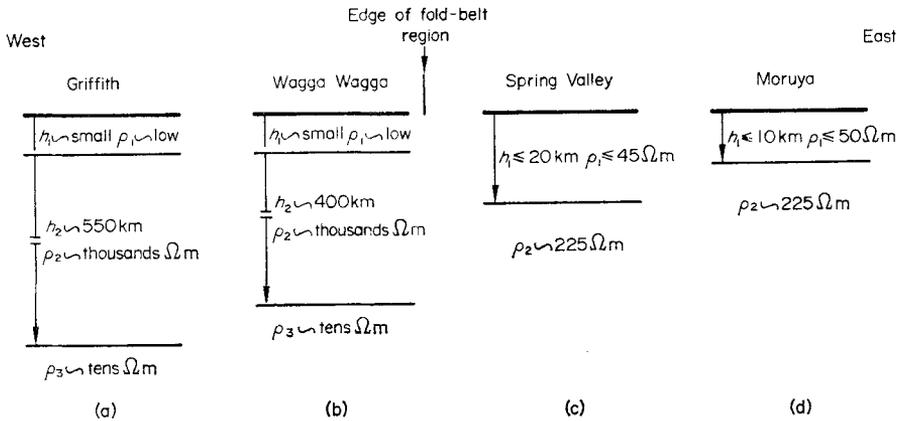


FIG. 7. The conductivity structure models interpreted from the apparent resistivity data.

be the most reasonable interpretation and this is shown in Fig. 7(b). The model consists of a thin, conductive surface layer; this is underlain by a thick, resistive layer approximately 400 km deep and of the order of thousands of Ohm-metres in resistivity; finally a conductive medium of approximately 10's of Ohm-metres is reached.

Griffith

As at Wagga Wagga, this station is troubled with anisotropy. Both the raw data and the analytic results for all the events analysed, indicated an enhanced east-west telluric signal. The apparent resistivity curves were very similar in shape to those of Wagga Wagga and were likewise fitted to three layer models. A conductive-resistive-conductive model resulted with the depth to the bottom half-space fixed but the top two layers fairly variable. The average of the two anisotropic models was taken and is shown in Fig. 7(a). The conductive-resistive-conductive layering is very similar to the one chosen for Wagga except the depth to the bottom conductive half-space is slightly greater at 550 km.

Conclusion

Geological interpretation

The ambiguities inherent in the interpretation of magnetotelluric data are well known, especially when the apparent resistivity curves exhibit anisotropy and cover only a limited range of frequency. For this reason there would be no justification for interpreting fine detail from the results of this paper. There is, however, one basic and important fact clearly evident in the apparent resistivity curves for the four stations, which is accordingly reflected in the proposed conductivity models. This is that the electrical conductivity at depths in the range 100–300 km is an order of magnitude greater under the stations Moruya and Spring Valley than it is under the stations Wagga and Griffith. This corresponds to the electrical conductivity being higher under the Tasman Geosyncline Fold Belt than it is under the area to the west of it. A reasonable interpretation of this fact is that the electrical conductivity contrast is caused by a temperature difference, especially in view of the excellent correlation between electrical conductivity and heat flow found in Colorado and Utah by Reitzel *et al.* (1970). Taking the electrical conductivity to temperature relationships as discussed by Tozer (1970), a contrast in conductivity of an order of magnitude at a depth of order 200 km would indicate a temperature contrast of order 200°. That is,

the upper mantle material under the geosyncline fold belt should be hotter by several hundred degrees than the material at the same depth to the west. The enhanced tectonic activity of the geosyncline region has already been noted, and this fact may correlate well with an upper mantle material of enhanced temperature. There is unlikely to be any significance in the fact that the Moruya and Spring Valley data do not show a third deep layer of high conductivity. This is probably due to the stronger 'screening' effect of the more conductive second layer which underlies them.

The heat flow over the central part of the geosyncline has been given as slightly greater than $2\mu\text{ cal cm}^{-2}\text{ s}^{-1}$. On the basis of this and other isolated heat flow measurements, the simple picture has arisen that the heat flow over the whole of south-eastern Australia is high. However, there are no heat flow determinations in the area to the west of the geosyncline for some hundreds of kilometres, and those at Broken Hill are themselves in another tectonic region, the Adelaide Geosyncline. It is quite possible that between these two geosynclines the heat flow may be lower. The indication of this magnetotelluric study is that it should be, if the surface heat flow is related to the temperatures at upper mantle depths.

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