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THE EFFECT OF THE SOUTH-EAST COAST OF AUSTRALIA ON TRANSIENT MAGNETIC VARIATIONS

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Transient magnetic activity, recorded at five stations near the coast of south-east Australia, is analysed to determine the correlation between the vertical and horizontal variation fields. A first order estimate of the "coast effect" is thus obtained. A plot of the strength of this effect against the distance of the observatory inland is compared with results from other coastlines. Consistent with the known geology of the area, the curve for south-east Australia lies between that for a young, tectonically active province, and that for an old, stable field. The results are fitted to a model of a simple step occurring in the upper surface of a perfectly conducting medium. This can be interpreted in terms of a high electrical conductivity region at a depth of some 230 km below the surface of the continent, rising to some 30 km below the surface of the ocean.

1. Introduction

Between August 1969 and July 1970, the Australian National University occupied a series of five sites with a temporary magnetic observatory, recording time variations of the earth's magnetic field. The sites form a traverse going inland from the coast of south-east Australia, and may be referred to in fig. 2 below. Most of the data is in the form of activity recorded at a single field station, though for some events contemporaneous recording is also held for a base station near Canberra. The instruments used were biassed proton-precession magnetometers, as described by Everett and Hyndman [1].

Results for two stations near the Australian south-east coast were given by Everett and Hyndman [2]. The results of this paper enlarge on the earlier work and give a preliminary determination of a coast-effect profile, to a distance inland of some 450 km.

The term "coast effect" describes a phenomenon which is observed in magnetic field disturbances at coastal stations. The variation in the vertical component tends to be linearly related to the variation in the horizontal component that points towards the nearest deep ocean [3]. The higher electrical conductivity of sea-water cannot alone entirely account for the effect, at periods of order one hour or greater. It is thought to be evidence of a possible fundamental conductivity contrast between ocean basins and continents, (see Rikitake [4] for a review). The strength of the effect has been found to differ from coast to coast [2, 5], and it may be possible to classify the tectonic state of coastal regions by a coast-effect parameter. Hence the interest, in this paper, of measuring the coast effect of south-east Australia.

The traverse described covers the Southern Highlands fold belt of the Tasman Geosyncline. The main tectonic activity in this region took place during the Palaeozoic, with uplift and some vulcanism occurring subsequently in the Tertiary [6].

2. Analysis of the data

Each station was occupied continuously for from four to eight weeks, and from the data thus obtained, stretches of storm disturbance that lasted for a day or longer have been chosen for analysis. For each stretch of activity, the vertical component Z has been examined to see to what extent it can be regarded as resulting from the two horizontal components H and D acting as source signals. That is, a fit to the empirical relationship

$$Z = AH + BD \tag{1}$$

is sought, where each parameter is a function of frequency.

Posed in this manner, the problem of relating Z to H and D is the standard one of determining the characteristics of a two-input linear system, where A and B are frequency response functions. Because the horizontal components of a magnetic storm will in general show some polarization, the inputs H and D must be free to share a certain degree of coherence. This requires consideration of the theory for partial coherence in a two-input system, and the following outline of it follows Bendat and Piersol ([7], p. 112).

Denote an auto-power spectral density function (for H) by S_{HH}, and a cross-power spectral density function (between H and Z) by S_{HZ}. Then, expressing the ordinary coherence (between H and D) by γ^2_{HD},

$$\gamma^2_{HD} = \frac{|S_{HD}|^2}{S_{HH}S_{DD}} \tag{2}$$

the expressions for A and B as functions of frequency are

$$A = \frac{S_{HZ}\left[1 - \dfrac{S_{HD}\,S_{DZ}}{S_{DD}\,S_{HZ}}\right]}{S_{HH}\,[1 - \gamma^2_{HD}]} \tag{3}$$

$$B = \frac{S_{DZ}\left[1 - \dfrac{S_{DH}\,S_{HZ}}{S_{HH}\,S_{DZ}}\right]}{S_{DD}\,[1 - \gamma^2_{HD}]} \tag{4}$$

for $\gamma^2_{HD} \neq 1$: that is, H and D cannot be perfectly correlated.

The partial coherence of Z onto H, with the effect of D removed by least squares prediction from H and Z, is

$$\gamma^2_{HZ.D} = \frac{|S_{HZ\cdot D}|^2}{S_{HH.D}\,S_{ZZ.D}}\,, \tag{5}$$

where

$$S_{HZ.D} = S_{HZ}\left[1 - \frac{S_{HD}\,S_{DZ}}{S_{HH}\,S_{HZ}}\right], \tag{6}$$

$$S_{HH.D} = S_{HH}\,[1 - \gamma^2_{HD}]\,, \tag{7}$$

$$S_{ZZ.D} = S_{ZZ}\,[1 - \gamma^2_{DZ}]\,. \tag{8}$$

The partial coherence of Z onto D is expressed in a similar way.

The eqs. (3) and (4) are well known, being given, for example, in [2] and [5]. The application of the partial coherence estimate (eq. (5)) to magnetic variation studies does not, however, appear to have been made so widely. It is nevertheless very useful as an indicator of the quality of data: perfect data satisfying eq. (1) will give partial coherence estimates of unity for both Z onto H and Z onto D, even though H and D may have some correlation. However if H and D are correlated, the ordinary coherence estimates of Z onto H and Z onto D may be erroneous and misleading.

For each site, estimates of A and B have thus been computed, for the period range 15 min to 2 hr. The procedure for the computation of power spectra has been the standard one of using the Fast Fourier Transform technique. The digitization interval has been 1 min and generally 2048 points have been taken (about 34 hr). In the cases where the storm activity has not lasted for this length of time, zeros have been added. Up to 256 lags have been used, giving a frequency interval of 0.00392 c/min and 16 degrees of freedom.

The original digital recording of the data has enabled its direct machine reduction. However, two test exercises which have been carried out deserve mention. Both are intended to test for a possible trouble inherent in the design of biassed total-field instruments.

The principle of the magnetometers is such that they basically measure three orthogonal components of field, say L, M and N, where L is aligned close to the direction of total field, M is at right angles to it horizontally to the magnetic west, and N completes the right-handed system [1]. The components Z, H and D are then obtained from L, M and N by a simple rotation of axes,

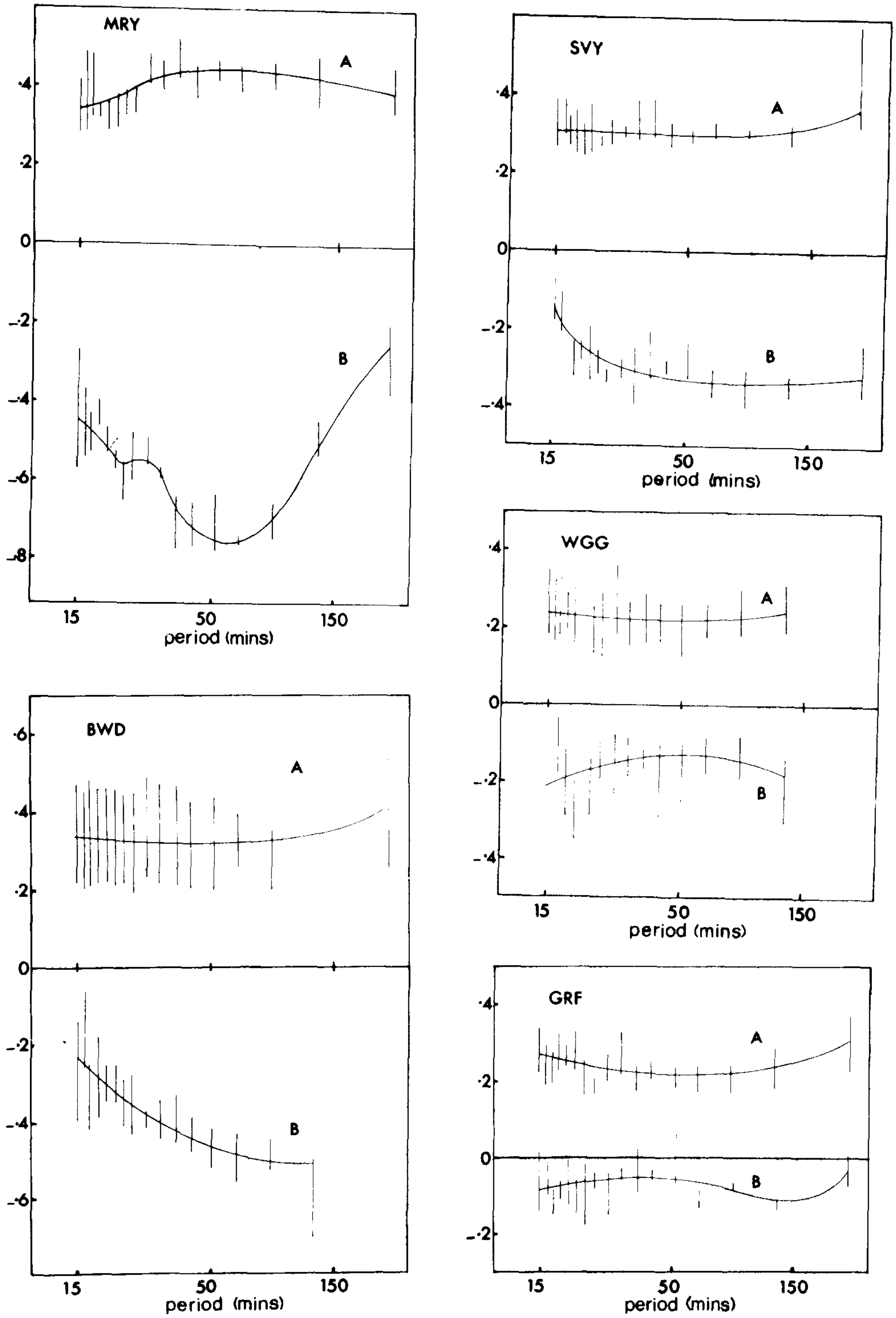

Fig. 1. Real frequency response estimates for the five sites occupied. A is the magnetic north value, and B the magnetic east value

$$H = L \cos I + N \sin I$$

$$D = -M$$

$$Z = L \sin I - N \cos I$$

where I is the inclination of the earth's field. These equations are given to emphasize the point that if a spurious signal occurs on L or N, it will in fact be transferred to both Z and H with very good coherence. This will confuse the use of a high partial coherence estimate as an indication of good quality data.

The two tests which have been carried out to check for this effect are as follows. Firstly, test time series for a particular station have been constructed taking alternate readings of the original time series for the horizontal and vertical fields; thus, if the original time series were H_i, D_i and Z_i, (with $i = 1, 2, 3$ ...), the test series H_{2i} and D_{2i} have been used with Z_{2i-1}, and vice versa. Secondly, vertical field data from one station have been taken with contemporaneous horizontal field data from an adjacent station. This second exercise is a test not only of noise correlation, but also of the effect of spatial variation in the horizontal fields. The results of both tests lie generally within the error limits of the results obtained using the original time series.

3. Results

Plots of the real parts of the A and B response functions are presented in fig. 1. Partial coherence values were determined for every A and B estimate made, and in drawing the curves in fig. 1 bias has

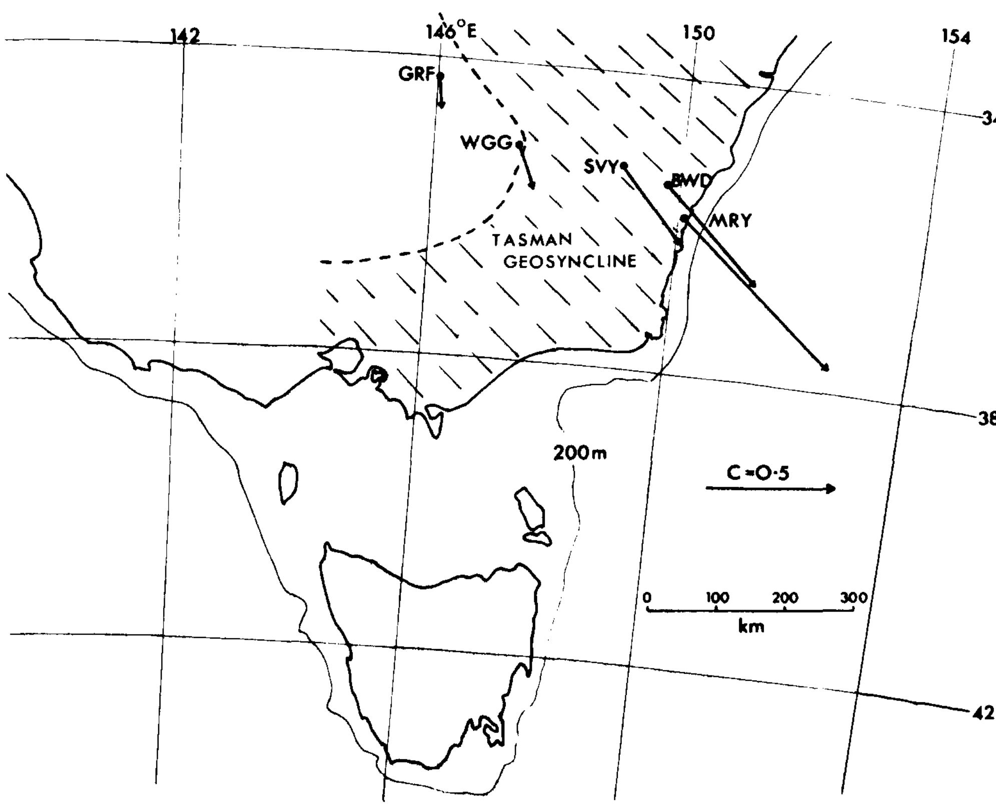

Fig. 2. Map of the observing sites and the response vector for one hour obtained at each one. The codes are MRY: Moruya, BWD: Braidwood, SVY: Spring Valley, WGG: Wagga Wagga, and GRF: Griffith.

been given to the points of higher partial coherence. Where several estimates of a value have been made, the error bar marks the standard deviation about the mean point. Where only a single estimate is held, (the case of BWD where only one good event occurred during the observing period), the error bar marks the standard deviation arising from a computation according to eq. (3) or (4). The standard error of the spectral density estimates used in these computations has been taken as $(m/N)^{1/2}$, where m is the maximum number of correlation lag values taken, and N is the number of points in the data series [7]. The imaginary parts of A and B, which were also computed, are too small to show any systematic pattern above their error level, and are not presented here.

From the values of real A and B at period one hour, taken from fig. 1, directional vectors were computed. These are plotted in fig. 2, with signs reversed so that they are equivalent to Parkinson vectors, though they have been obtained by a different method. In fig. 3 the amplitude of the vector resolved perpendicular to the 200 m depth line of the Australian east coast, c, is plotted against distance from this depth line, together with curves from [2] and [5] for some other coasts.

4. Interpretation

4.1. *The tendency of the vectors to point south*

It is striking that fig. 1 shows each station to have a real A value of about 0.2. This effect could have the following possible causes: (i) There may be a region of high conductivity beneath the Australian Alps to the south. (ii) It may be caused by the distant oceans to the south and south-west of the traverse. (iii) There may be a systematic Z–H correlation in the primary or 'normal' source fields, (though, in mid-latitudes, this is generally assumed to be small).

At present no distinction can be made between these possibilities.

4.2. *The coast effect*

If the effect at a coastline is indeed related to its geologic history, then the response shown by the values plotted in fig. 3 is consistent with the major tectonic activity of the area having taken place during the Palaeozoic [6]. Such a coast effect is most likely caused, as previous workers have concluded, by a conductivity contrast at the continent–ocean boundary. Taking a spherically symmetric global model, there is evidence of an increase of electrical conductivity of several orders of magnitude taking place at a depth of about 400 km [8]. As a preliminary interpretation, therefore, the data have been fitted to a step rise in the upper surface of the very good conductor, the step occurring beneath the edge of the continental shelf. Schmucker's [9] calculations for a step have been used (though it is appropriate to note that in his 1964 paper Schmucker did not strongly support such a step as a model for the ocean–continent boundary). For reasons of mathematical simplicity,

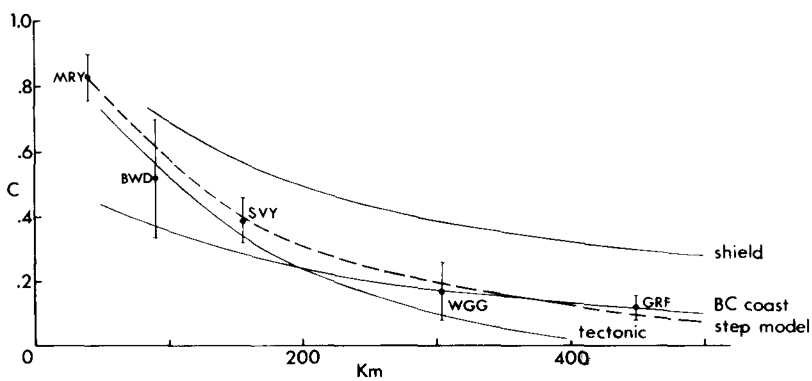

Fig. 3. The coast effect response values, C, for a period of one hour with curve computed from model. Also typical curves for some other coastlines (after [2] and [5]).

the conductivity contrast of several orders of magnitude is modelled by the extreme approximation, of zero conductivity overlying perfect conductivity. This may be justified to a degree by considering the scale of the model in terms of skin depths, calculated using more realistic conductivity values.

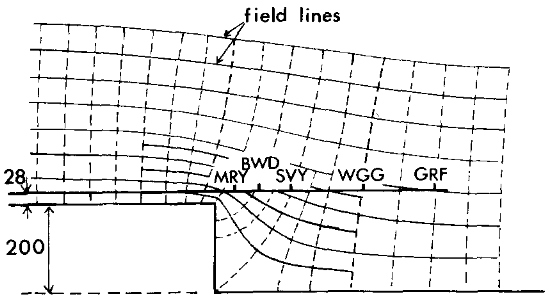

Fig. 4. The interpretation of the traverse results in terms of a step in the upper surface of a perfectly conducting material. The errors for the dimensions shown are 200 ± 30 km and 28 ± 6 km. Model and field lines after Schmucker [9].

Fig. 4 shows Schmucker's horizontal fields conforming to a step function, and the fit of the present traverse to the model. The fit has been located initially using the MRY and SVY data: two loci were drawn in on the diagram, tracing the points with response values appropriate to MRY and SVY respectively. The position of best fit for the traverse was then found from the fact that the ratio of the two distances, continental edge to MRY, and MRY to SVY, was known to be 1 : 2.88. For the present data this procedure gives quite a precise fit, which then provides the appropriate absolute scale for the model, and hence the absolute dimensions of the step. These dimensions are marked in fig. 4. The major errors in the determination arise from errors in the determination of the response functions. The theoretical curve for the whole traverse can be drawn, and this is the curve given passing through the data points in fig. 3. The result rests on the assumption that horizontal source fields induce the coast effect, and, also, it has been obtained using data of period one hour. Although the response of a perfectly conducting model should not be frequency dependent, the data of fig. 3 clearly are so. This partly demonstrates the limitations of using a perfectly conducting model, and in fact if data of shorter period had been used the step model fitted would have been at a slightly greater depth.

The depths obtained to the surface of the very good conductor, 28 km for the ocean and 230 km for the continent, are within the range of the results of other workers. The oceanic level is in remarkable agreement with the depth of 30 km to a high conductivity region given by Cox, Filloux and Larsen [10]. The continental value of 230 km is more than that of 100 km assumed by Everett and Hyndman [2], but it is in good agreement with the depth of 170 km found in western North America in recent work by Porath et al. [11]. The magnetotelluric work by Tammemagi and Lilley [12] across the same traverse in south-east Australia did not detect a third highly conducting layer beneath the geosyncline region, but examination of the resistivity curves given in [12] shows that such a good conductor could occur beneath the geosyncline up to a minimum depth of 120 km.

Of further interest is the postulate of Tammemagi and Lilley that a change in basement occurs between SVY and WGG. This change is evidently equivalent to another step or slope in the top of the conductor, from depth 230 km (found in this paper) beneath SVY to depth 400 km (given in [12]) beneath WGG. The resolution of the WGG and GRF values in fig. 3 is not, however, sufficient to show them rising systematically above the curve for the model with a single step at the continent-ocean boundary. A similar step, from depth 200 km to 400 km, between SVY and WGG, would in fact cause a much weaker effect than the shallower coastal step, and it would be unresolvable with the data of this paper in the presence of the coast effect.

Finally, some skin depth values. For a period of one hour the skin depth in sea water (of conductivity 4 mho m^{-1} [13]) is about 14 km, so the variations should easily penetrate the deep ocean (of typical depth 4 km). For crustal rocks of conductivity 0.002 mho m^{-1} or less, the skin depth is 600 km, so that the magnetic variations should penetrate in to meet a highly conducting surface which is at 230 km. Within the highly conducting layer itself, if a more realistic estimate of 0.2 mho m^{-1} is taken for the conductivity, the skin depth is 60 km. This distance is smaller than the dimensions of the step model, but not as small as would be necessary for complete confidence in the applicability of the perfectly conducting model used.

5. Conclusions

The results presented in this paper are essentially 'first order', because no allowance has been made for the possible normal part of the vertical variation fields, and the assumption of a step in the surface of a perfectly conducting half-space can only be regarded as a first approximation. Nevertheless the coast effect is strong enough to be well detected and interpreted by these methods, and a definite result has been obtained.

Observations have recently been carried out with an array of twenty-five magnetic variometers over an area covering that described here. When the array data is ultimately reduced the coast effect should be known with more precision, and a more accurate interpretation of it should be possible.

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