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The Australian Continent: a Numerical Model of its Electrical Conductivity Structure, and Electromagnetic Response

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Abstract

Electromagnetic induction, commonly associated in exploration geophysics with applied source fields, takes place on continental and global scales. At these scales it is driven by natural magnetic fluctuations which arise external to the Earth. These magnetic fluctuations, and the secondary signals which they induce within the Earth, are measured at permanent magnetic observatories, "roving" temporary magnetic observatories, and at magnetotelluric field sites. Such observed data contain information on the electrical conductivity structure of the Earth, and are a major source of geophysical information. The global induction process is of such a magnitude that it could not be generated using applied source fields.

An electrical conductivity model of the Australian continent with its surrounding oceans has been constructed numerically, for the purpose of examining its response to natural magnetic fluctuations. This paper first presents the continental response plotted as Parkinson arrows, for period 1 hour. Parkinson arrows summarize the behaviour of the three components of the Earth's fluctuating magnetic field, and for the model show particularly the coast effect. The coast effect arises most strongly at the continental edge, and penetrates far into the continent. There are also secondary effects within the continent, which arise due to electrical conductivity changes associated with geological boundaries. The present exercise models continental geological structures in a regional sense; their improved definition on a local scale, both in the field and by modelling, is an important and major exercise for the future.

The response of the continental model has also been computed in terms of magnetotelluric impedance values, which take into account the electric fields occurring at the Earth's surface. Such impedance values are presented for six particular sites, using a Mohr circle method to display their characteristics. Generally the magnetotelluric data complement the pattern shown by the Parkinson arrows. They also give extra information on the regional distortion which may be expected for data observed on the Australian continent. The character of the Mohr circles indicates that the magnetotelluric "skew" caused regionally is small at the period of 1 hour, and that generally the computed impedances are two-dimensional (2D) in character. Such a predominantly 2D pattern for regional magnetotelluric impedances gives optimism for the interpretation of observed magnetotelluric data. Observed data for higher frequencies may be expected to be more affected by local distortion and more 3D in character; however knowledge that regional effects are 2D allows the use of decomposition techniques which are based upon local 3D effects perturbing a regional 2D pattern.

Key words: Australia, electrical conductivity, electromagnetic induction, magnetotelluric

Introduction

One of the main strengths of geophysics is its ability to bring a variety of methods to bear on a particular geological problem. These methods are commonly based on quite distinct and different phenomena of physics. Together, the strength of a combination of such methods is often much greater than their sum, taken individually.

Well-established examples of such geophysical methods are those of gravity and magnetics. There are now, for Australia, continental compilations of the gravity and magnetic fields. These compilations form a data base which is essential for exploration practice.

The characteristic of electrical conductivity of rock materials is another important geophysical parameter, which forms the basis of the electrical resistivity and electromagnetic induction methods. Generally in exploration practice electromagnetic induction operates with applied source fields; however the phenomenon also takes place with natural source fields, and its characteristics across a large continent like Australia are beginning to be synthesized into maps of continental response. It may be expected that in the future, maps of electromagnetic induction response will be as fundamental to geophsyics as maps of continental gravity and magnetics.

Natural electromagnetic induction on a continental scale depends not only on the electrical conductivity of continental rock material. It depends also on the electrical conductivity of seawater, and on the depths of oceans. The computation of the electromagnetic response of a continent set in its oceans is a task involving a 3D problem in electromagnetic induction. The wide importance of such induction problems has drawn attention to them in recent years, and a number of computer codes have been developed for their solution. The code used in this paper is that developed at the University of Victoria, Canada (Weaver, 1982; McKirdy *et al.*, 1985; Agarwal and Weaver, 1989). Its application to the Australian continent as a whole is an extension of its earlier application, by Heinson (1991), to eastern Australia and the Tasman Sea.

The basis of the electromagnetic response is a numerical model. The model is of the electrical conductivity of the Australian continent, compiled on a regional scale. The

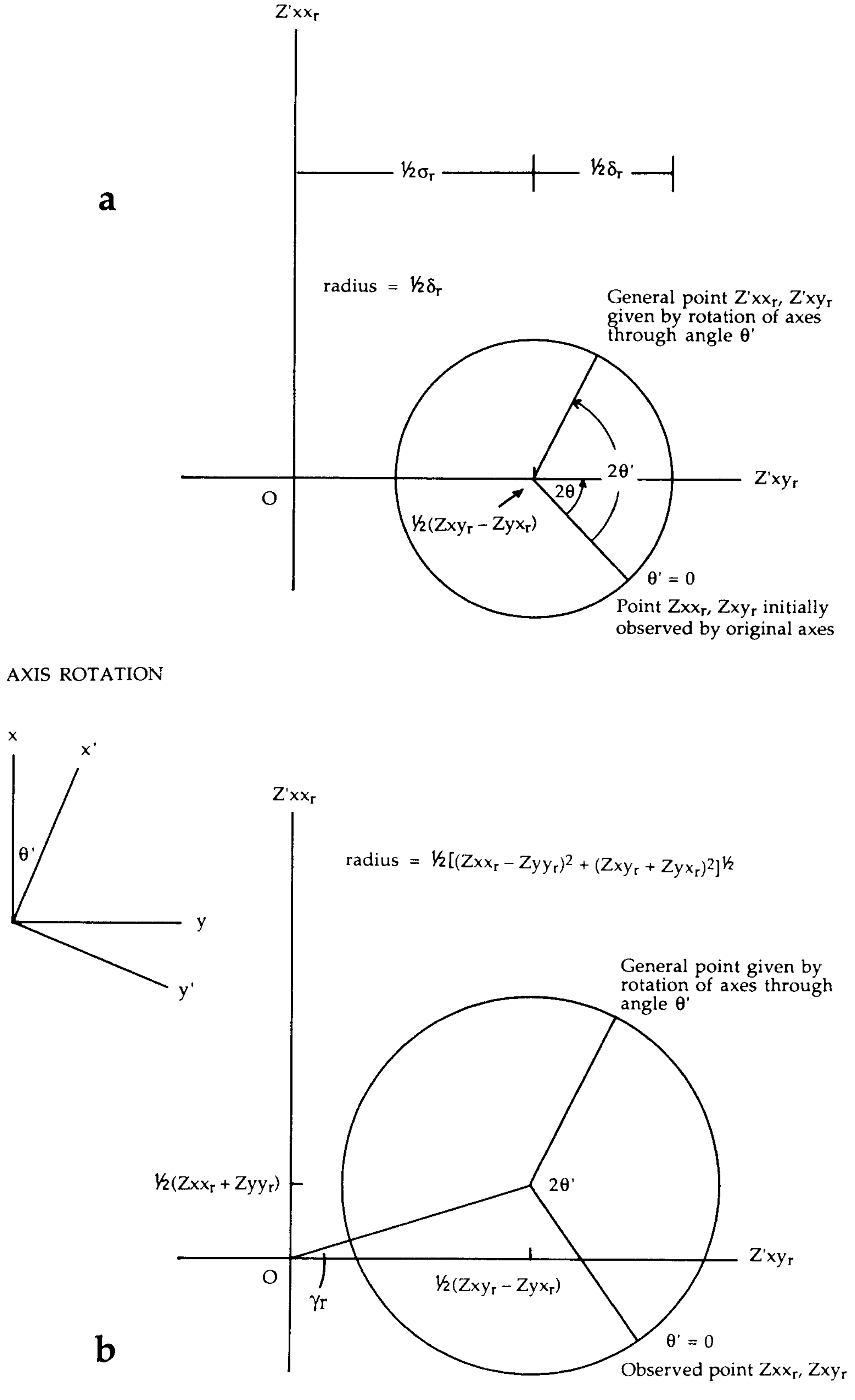

FIGURE 1
Diagram showing the method of representing magnetotelluric tensor information by Mohr circles. The circles trace the values taken by the elements of a magnetotelluric impedance tensor, as the measuring axes of the magnetic and electric field variations (which are used to estimate the tensor) are rotated through angle θ'.
a., Circle for a 2D structure (centre is on the horizontal axis).
b., Circle for a 3D structure (centre is off the horizontal axis).
For a 1D structure, the circle in Fig. 1a reduces to its central point.

compilation used here is that of Corkery (1992), which is discussed also in Corkery and Lilley (1994). In the present paper the basic results of the electromagnetic response of the model are described, and then analysed for their significance to magnetotelluric data recorded on the Australian continent. Particular attention is paid to the question of distortion of magnetotelluric data. A novel method to display and analyse the data is employed: that of Mohr circle analysis.

Parkinson Arrows and Mohr Circles

Parkinson arrows are a well-established method for mapping geomagnetic induction information (see for example Parkinson, 1959; Lilley and Arora, 1982; Parkinson, 1983). Denoting the components of the local fluctuating magnetic field at a particular frequency by X (horizontal north), Y (horizontal east) and V (vertically downwards), then it is commonly observed at a particular site that the following linear relationship holds:

$$V = A X + B Y$$

where A and B are constants (and so functions of geology only). The quantities X, Y, V, A and B, are all complex, with real and quadrature parts. (Often Z is used for the vertical component but V is used here, to avoid confusion with the Z used for the magnetotelluric impedance tensor, introduced below).

A Parkinson arrow is then constructed by plotting, on a map of the site, an arrow with component A to the south and B to the west. Electromagnetic induction in the Earth acts in such a way that such arrows generally point to the high conductivity side of any nearby geological electrical conductivity contrast. The arrows presented in the figures below have been constructed in this manner, using the model results.

Representation of magnetotelluric data by Mohr circles is, by contrast, a new technique. The magnetotelluric method determines, for an observing site, an impedance tensor **Z** which relates horizontal fluctuations in the magnetic field **H** to horizontal fluctuations in the electric field **E** according to

$$\mathbf{E} = \mathbf{Z}\mathbf{H}$$

Here **E** and **H** both have two components (north and east) denoted by subscripts x and y, thus tensor **Z** has elements Zxx, Zxy, Zyx and Zyy (see, for example, Vozoff, 1972). In addition, further subscripts r and q may indicate real and quadrature parts (respectively) of a quantity.

It is central in magnetotelluric practice to know how the elements of **Z** depend on the alignment of the measuring axes, and how they will vary with measuring axis rotation. It is therefore useful that the consequences of axis rotation can be displayed using Mohr circles (the name comes from the Mohr circle of mechanical stress and strain), with one circle for the real part of the impedance tensor and another circle for the quadrature part of the impedance tensor. The derivation of such rotational properties for Mohr circles, in the magnetotelluric case, is given by Lilley (1976a, 1993). Figure 1 shows an actual format for drawing such circles.

The Numercial Model of Australian Continental Conductivity

The numerical model set up for the electrical conductivity structure of the Australian continent is "thin-sheet" in an electromagnetic sense. Here the term thin-sheet means that, in the model, the surface layer of rock material (and sea-water, in ocean regions) is thin in terms of the electromagnetic skin depth of the rocks of the lower crust. In the present case, a surface layer of thickness 10 km adequately meets this "thin-sheet" criterion. In terms of horizontal dimensions, the present model covers an area for Australia and its surrounding oceans of some 5400 km by 5400 km. This area is divided into a grid of 30 units by 30 units, with each unit 180 km by 180 km in size. (The grid is marked on Figs 2 and 3 below).

Electrical conductance values are determined by integrating the electrical conductivity of the crustal rocks from the surface down to depth 10 km (the bottom of the thin sheet). The work of compiling such a thin-sheet model formed part of the honours research project of Corkery (1992), and is based on maps of the regional geology of Australia. Conductivity values of 0.0002, 0.1, 0.001 and 3.2 S/m were taken for Precambrian crust, sedimentary basins, oceanic crust and sea-water, respectively, and a value of 0.01 S/m was taken for crust underlying the top layer. More details are given in Corkery and Lilley (1994).

The Pattern of Continental Induction Response

The response of the conductance model, computed using the code of the Weaver group, is shown in Figs 2 and 3, in terms of real and quadrature Parkinson arrows respectively. The computed period of oscillation is one hour. A dominant feature of the response is the strong coast effect shown, consistent with the observatory results of Parkinson (1962) and Milligan (1988), and with a range of temporary magnetic observatory data (for example Lilley and Bennett, 1972; Lilley, 1976b; White and Polatajko, 1978; Ferguson, 1988; Kellett *et al.*, 1991; and Chamalaun and Barton, 1990).

Within the continent the induction pattern, thus computed, does not reproduce adequately the "conductivity anomalies" which have been observed using recording magnetometers in arrays of temporary magnetic observatories (for example Gough *et al.*, 1974; Woods and Lilley, 1980; Lilley, 1982; White and Milligan, 1984; Parkinson *et al.*, 1988; Chamalaun and Cunneen, 1990). Experiments in modifying such a continental model so that its response reproduces strong and more local conductivity anomalies is the subject of a separate paper (Corkery and Lilley, 1994), and the topic is not pursued further here. It is appropriate to note, however, that a more detailed investigation and interpretation of such conductivity anomalies is a major frontier in Australian geophysics.

Magnetotelluric distortion

In order to examine the patterns that the regional response shown in Figs 2 and 3 predicts for the distortion of magnetotelluric observations made within the continent, six sites were chosen for analysis as shown on Figs 2 and 3 by the letters A to F. The magnetotelluric Mohr circles for these sites are shown in Fig. 4, drawn according to the format of Fig. 1b. The results in Fig. 4 are now discussed.

Site A (grid co-ords 17,7)

This site shows very little traditional skew, as both circles are centred close to the horizontal axes. (For the real circle the traditional skew angle is 4°; that is, a line joining the circle centre to the origin makes an angle of 4° with the horizontal axis.) The two-dimensionality is itself quite weak, as the circles are of small radii: the anisotropy angles, (half the angles subtended by the circles at the axes origins), are 11° for the real, and 7° for the quadrature circles. The radial arms of the real and quadrature circles are closely parallel, which is an indicator of 2D (as opposted to 3D) form.

These radial arms, by their orientation, indicate that the north and east measuring axes of the calculation should be rotated to bearings 30° and 120° to align them with the effective 2D strike of the model at site A. This result is in reasonable accord with the directions of the Parkinson arrows in Figs 2 and 3, though not in exact agreement. The real and quadrature

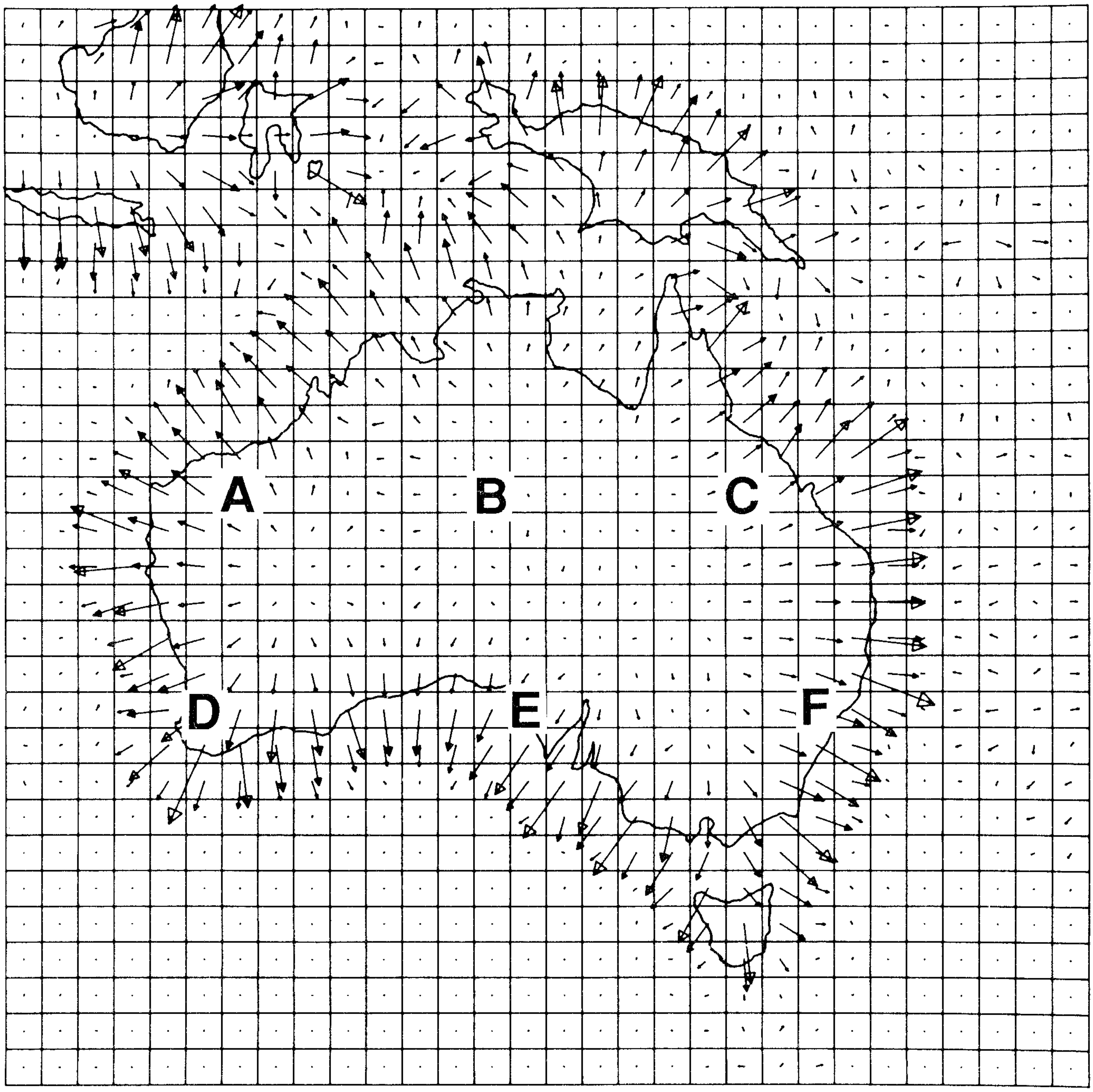

FIGURE 2
Parkinson arrows for a period of 1 hour, real part, computed for a numerical model of the continental geology of Australia. The sites marked A to F are referred to in the text. Arrow scale is given by one grid-width being equivalent to an arrow length of 0.3. The model covers an area of 5400 km by 5400 km. Each unit square is 180 km by 180 km.

Parkinson arrows themselves are not parallel at site A, indicating departure from simple 2D induction.

Site B (grid co-ords 17,14)

Site B, in the middle of the continent, is seen to have an ideal 1D response in the quadrature component, as the quadrature circle has reduced almost to a single point. There is a slight 2D response in the real component (the circle, of small radius, has an anisotropy angle of 11°). The radial arm of the real circle, which in Fig. 4B lies along the horizontal axis, indicates that the bearings for the measuring axes to be along (and across) effective geological strike are 0° or 90°.

Site C (grid co-ords 17,21)

The behaviour of the response at this site is similar to that at site A, though with an increased anisotropy. (For the real circle the anisotrophy angle is 16°, and for the quadrature circle it is 10°). There is little 3D skew effect (for the real circle the traditional skew angle is 5°), and the radial arms of the real and quadrature circles are again closely parallel.

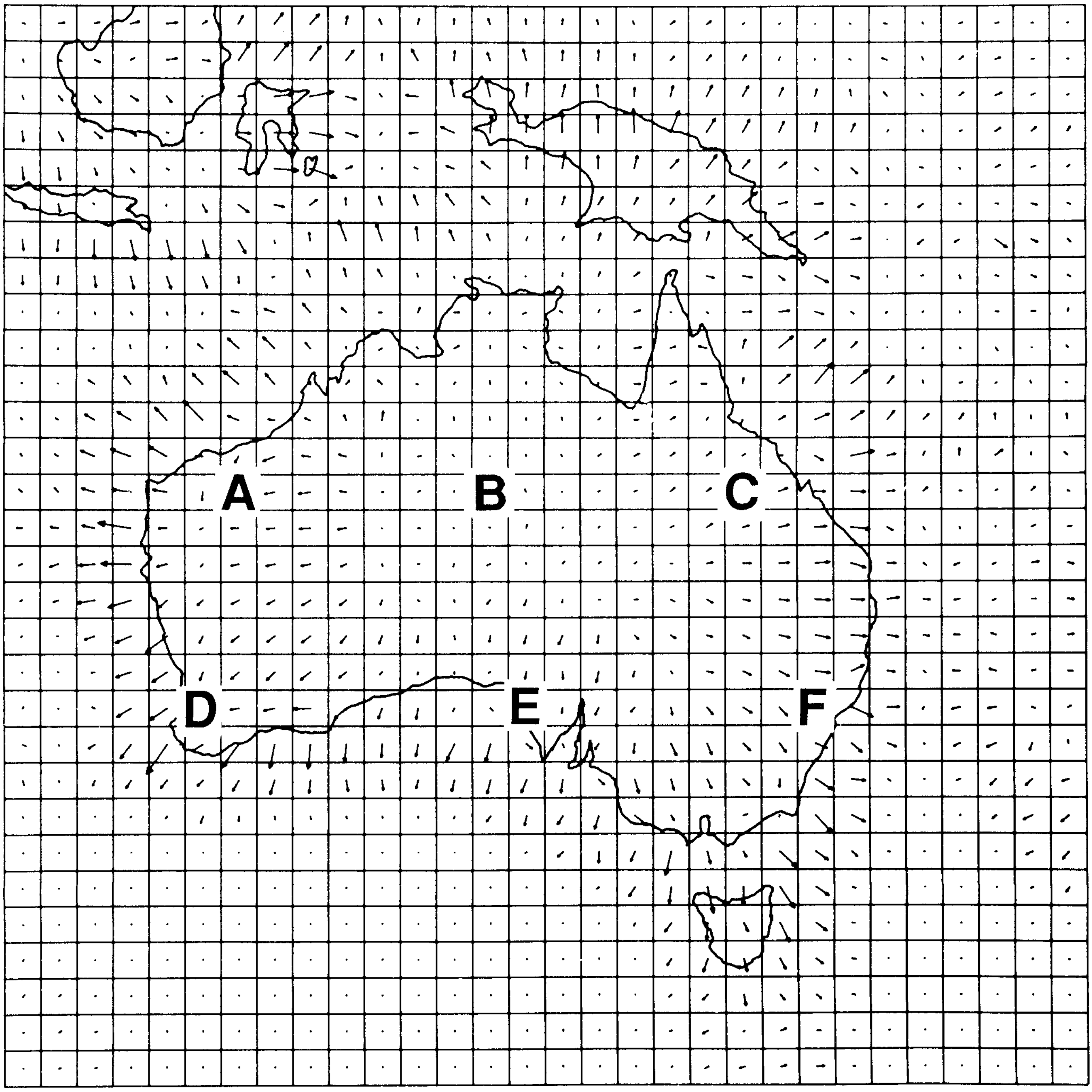

FIGURE 3
Parkinson arrows for a period of 1 hour, quadrature component, computed for a numerical model of the continental geology of Australia. The sites marked A to F are referred to in the text. Arrow scale is given by one grid-width being equivalent to an arrow length of 0.3. The model covers an area of 5400 km by 5400 km. Each unit square is 180 km by 180 km.

The orientations of the radial arms indicate that measuring axes bearing 36° and 126° will lie along and across effective geologic strike. These bearings are consistent with the directions of the Parkinson arrows at site C, but not in exact agreement.

Site D (grid co-ords 11,6)

Site D has intentionally been chosen to be adjacent to the coast, at a place where the coastline departs from simple linearity. Thus some 3D effects in the computed response may be expected. In fact, because the circles in Fig. 4D have their centres very close to the horizontal axes, the traditional magnetotelluric skew (which is a measure of how far the circle centres are off axis) is effectively zero for site D. The circles for site D indicate anisotropy, as would be expected: the anistropy angles are 25° for the real circle, and 19° for the quadrature circle.

Also, for site D, the radial arms are not parallel, which is another measure of departure from true two-dimensionality. This latter phenomenon shows that the real impedance is sensing a geological structure of different strike than the quadrature impedance; the magnetotelluric response is thus showing the influence of the "corner" in the coast-line.

Site E (grid co-ords 11,15)

Site E is again close to a complicated coastline. The effects of the conductivity structure are shown in the Mohr circles by an increased anisotropy, evident in the greater radii of the circles. The anisotropy angles are 29° for real, and 15° for quadrature. In the site E circles there is also (as for site D) the indicator of three-dimensionality in that the radial arms depart from being parallel.

However again like site D, the traditional magnetotelluric skew for site E is weak, as the circles are centred close to the horizontal axes. (For the real circle for site E the traditional skew angle is 6°.)

Site F (grid co-ords 11,23)

Site F is close to a coastline which is simple and linear, and

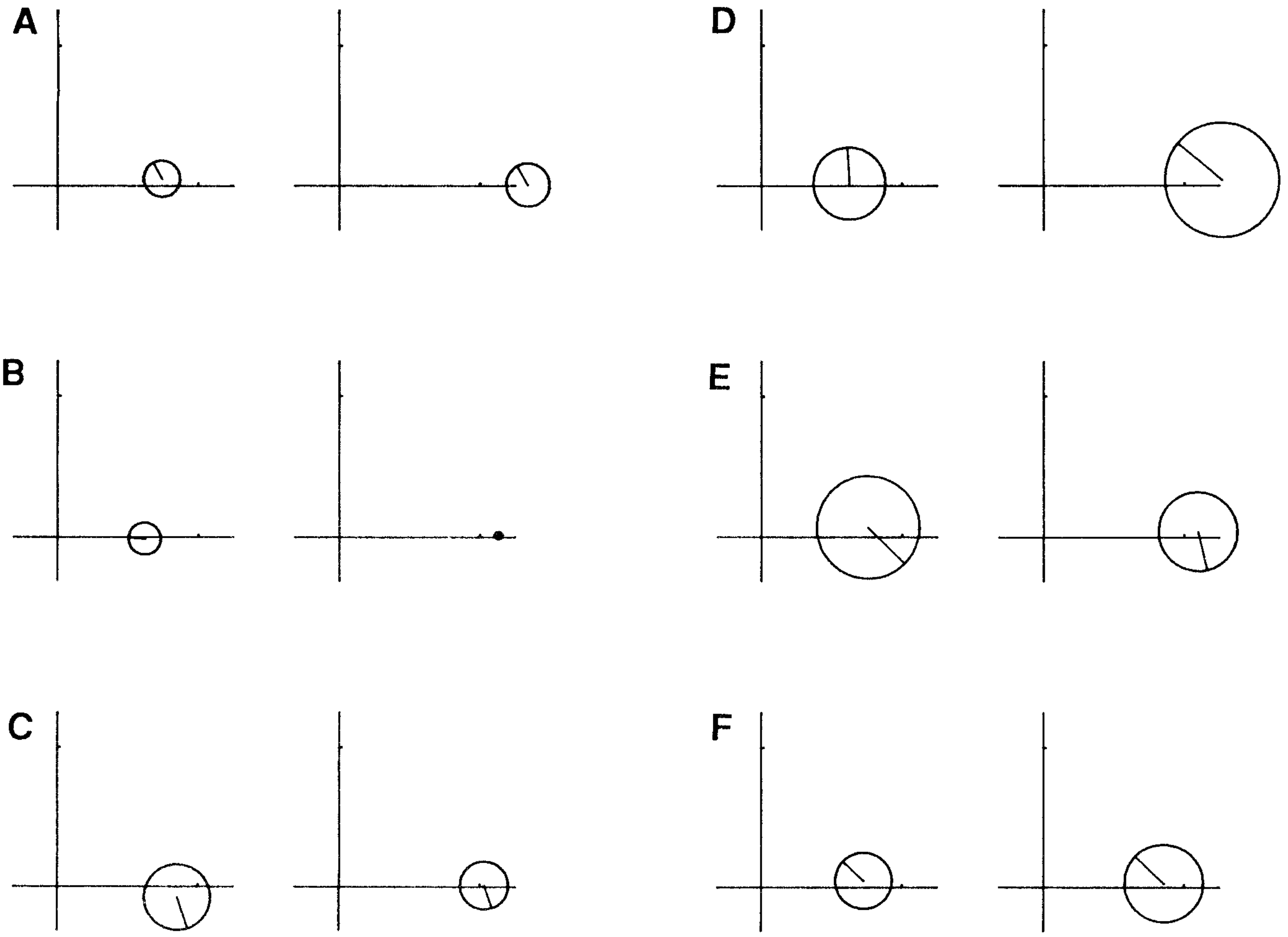

FIGURE 4
Mohr circle representations of the magnetotelluric impedance tensors, for the six sites marked on Figs 2 and 3. For each site a pair of circles is plotted, with the real circle to the left, and the quadrature circle to the right. Each circle is plotted according to the format of Fig. 1b (for the quadrature circles, quadrature values of the impedance tensŏr elements are used). The radial arms go to the points determined by the computation, which is for measuring axes aligned north and east. Scale is given by the origins of the real and quadrature axes being apart a distance of 0.57 MT impedance units, for each pair of circles. Also, there are marks on the axes at 0.286 (approx 0.3) impedance units from the origin. The unit is the practical one of mV/km/nT.

the circles show behaviour very much like sites A and C. The anisotropy angles are 16° for the real circle, and 19° for the quadrature circle. The orientations of the circle radial arms (which are parallel) indicate that measuring axes at bearings 22° and 112° will lie along and across effective geologic strike. These values agree well with the directions for strike indicated by the Parkinson arrows (19° for real and 27° for quadrature, respectively).

The traditional skew angles for the circles are less than 5°. Thus as might be expected from its proximity to a long and straight coastline, site F is nearly an ideal 2D site.

Conclusions

This paper examines in detail one aspect of calculating the electromagnetic response of a whole continent surrounded by sea. The period for the calculation is one hour, at which the continental geology may be effectively modelled as a thin sheet. The Parkinson arrows for the continent show primarily the coast effect due to the electrical conductivity contrast between the deep oceans and the continental rock material, with additional effects due to electrical conductivity structure within the continent.

Magnetotelluric impedance tensors for a suite of representative sites, plotted as Mohr circles, show responses which are basically 2D in character, and low in their traditional magnetotelluric skew values. There are departures from 2D evident in the non-parallel nature of the circle radial arms, but the consistency of 2D-style circles, centred on or close to the horizontal axes, is maintained.

The regional 2D nature of the computed magnetotelluric responses may have an important consequence for the interpretation of field data. Methods have recently been developed for the decomposition of 3D magnetotelluric data into the local 3D perturbation of a regional 2D response (Bahr, 1988; Groom and Bailey, 1989; Bahr, 1991; Jones and Groom, 1993); such a regional 2D response is then more amenable to inversion and interpretation. The evidence of the circles in Fig. 4 is that at period 1 hour the response of Australian data may be 2D on a regional scale, and thus bearings of effective geologic strike may be determined at that period.

Such geologic strike directions may then form a basis for de-distorting (by tensor decomposition) the impedances measured at higher frequencies. This process may be useful for high frequency data which are more affected by local geologic structure, and show more 3D character in their impedance tensors.

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