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Large-scale Electrical Conductivity Structure of Australia from Magnetometer Arrays

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ABSTRACT

A range of sets of electromagnetic observational data (geomagnetic depth sounding and magnetotelluric sounding) now exist for the Australian continent. These data show regions of the continent where the conductivity structure is approximately one-dimensional on a gross scale, relative to zones, called 'conductivity anomalies', where induced electric current flows preferentially.

Progress is being made in the development of a numerical method which inverts such observational data automatically, to give an image of the conductivity distribution of the whole continent, set in its surrounding seas. The thin-sheet algorithms developed by Weaver and Weidelt and colleagues are employed, and conductance values are found for grid units in a sheet representation of the continent which extends from the surface down to depth 10 km. The grid units are typically 100 km in horizontal dimension. The model is solved by numerical inverse methods.

This paper presents results obtained from inverting data in the form of Parkinson or Induction arrows, at a single period, for sites spread widely across Australia. The major continental conductivity anomalies are given quantitative expression in the model resulting from the inversion.

Keywords: Australia, electrical conductivity, geomagnetism, magnetometer arrays, thin-sheet modelling, geophysical inversion

INTRODUCTION

Following the thin-sheet modelling of electromagnetic induction in the Tasman Sea by Heinson (1991), and Heinson and Lilley (1993), the first numerical thin-sheet model for the Australian continent and its surrounding oceans was constructed by Lilley and Corkery (1993), and Corkery and Lilley (1993; 1994). That model was based on the gross surface geology as mapped, together with typical electrical conductance values for crystalline terranes, sedimentary basins, seawater and ocean crust. The modelling area was divided into a 30 x 30 grid, with a grid spacing of 180 km. A comparison of induction arrows for period 1 hour, both as observed and as calculated from the thin-sheet model, indicated that the model adequately explained the electromagnetic induction coast-effect along the Australian coastline, at that period. However, strong conductivity anomalies observed within the continent were not adequately accounted for by the thin-sheet model. Corkery and Lilley (1994) pointed out that the model is initial, with scope in future for grids of finer spacing, and for refinement in the geological information on which the model is based.

The present paper presents results of more advanced modelling. The thin-sheet model is refined, with the grid density now increased to 60 x 60. For the initial or 'base' model the conductance values for the cells within the continent are re-calculated, based on a basement-relief map of Australia recently released (in 1996) by the Australian Geological Survey Organisation (AGSO). A numerical inversion method is developed, which inverts the observed data automatically. An image is obtained of the electrical conductivity structures which are sensed by the observed data.

The present paper seeks to increase the understanding of natural electric and magnetic fields in Australia, and of the large-scale electrical conductivity structure of the continent. It is in the environment of these natural electric and magnetic fields, and of this conductivity structure, that all electric, magnetic and electromagnetic methods of exploration geophysics take place.

GEOMAGNETIC INDUCTION DATA AND CONDUCTIVITY ANOMALIES

Stationary magnetometers which record three components of the time-fluctuating magnetic field have been used in Australia since the pioneering work of Parkinson (1959). The method is known as geomagnetic depth-sounding, or GDS, and is an electromagnetic method of geophysics using natural source-fields. Through the work by Gough et al. (1974), the Australian National University (ANU) EM group, the Flinders University EM group, the University of Tasmania EM group and AGSO (formerly BMR), data are now held for about 460 magnetometer sites in Australia. Over the whole range of sites the response in the vertical magnetic component to magnetic storms shows wide variability, and characterises the presence of lateral conductivity contrasts both within the continent, and at its ocean boundaries. Figure 1, drawn using the GMT software of Wessel and Smith (1991), shows the distribution of magnetometer sites and the major geological features of Australia, together with regional conductivity anomalies shown by the magnetometer Parkinson-arrow pattern.

The first regional conductivity anomaly in Australia, the Flinders Anomaly, was found in the Adelaide Geosyncline of South Australia by the Gough et al. (1972; 1974) magnetometer array study, for which a magnetotelluric interpretation was contributed by Lilley and Tammemagi (1972). Subsequent work was carried out by White and Polatajko (1985), and Chamalaun (1985; 1986). A recent detailed GDS study by Paul (1994) revealed a conductivity anomaly in the middle and lower crust, following the main arcuate trend of the Houghton Anticline in the Adelaide Geosyncline. In a recent magnetotelluric study, Wang and Chamalaun (1995) interpreted the Flinders Anomaly to be a structure with resistivity of 1 Ωm above 20 km, and 100 Ωm deeper.

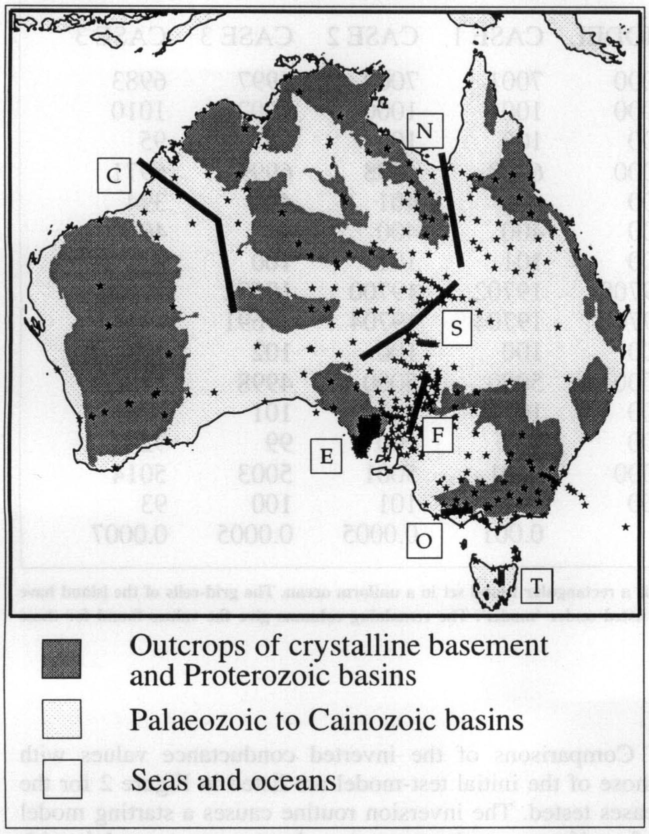


Figure 1. The position of magnetometer sites (marked by stars), major geological features of Australia, and the regional conductivity anomalies (marked by black lines) inferred from Parkinson arrows. C marks the Canning Basin Anomaly, E the Eyre Peninsula Anomaly, F the Flinders Anomaly, N the Carpentaria Anomaly, O the Otway Anomaly, S the Southwest Queensland Anomaly, and T the Tamar Anomaly.

The Eyre Peninsula Anomaly was first detected during studies of the coast effect of South Australia (eg, White and Polatajko, 1978). Southern Eyre Peninsula contains a shallow zone of anomalously high electrical conductivity with an effect so strong that it dominates the normal coast effect. White and Milligan (1985; 1986) investigated this anomaly by an array of 40 closely spaced magnetometers, typically 5 km apart. A north–south line of naturally-induced electric current flow, about 70 km long, was interpreted as a large fracture system, less than 15 km deep in the Gawler Block. Recently, R. Kusi of Flinders University has carried out detailed studies on the position and extent of the Eyre Penisula Anomaly.

In 1971 a magnetometer array indicated a pronounced anomaly near the southern coast of Victoria (Lilley and Bennett, 1972, 1973; Bennett and Lilley, 1973, 1974) which was further investigated by an array in 1973/1974 across the Bass Strait region. It was established that the centre of the anomaly was over the coast of Victoria near the Otway Ranges, and it was named the Otway Anomaly. Lilley (1976) concluded that the anomaly is a response to a region of partial melting associated with the volcanic province in southern Victoria, also noting that the region is one of seismic activity, which may cause increased electrical conductivity in fractured crustal rocks (Lilley, 1975).

Parkinson and Hermanto (1986) investigated indications of anomalous behaviour in northern Tasmania shown by the 1973/1974 Bass Strait array, and reported results from some 40 magnetometer sites. They observed a pronounced conductivity anomaly coincident with the Tamar lineament, called the Tamar Anomaly. The physical cause of the anomaly is not clear, but one possibility is an accumulation of highly conducting sedimentary rocks in a graben structure. The University of Tasmania group (W.D. Parkinson and students) has also observed over an extensive range of sites in central and southern Tasmania.

Three separate conductivity anomalies define what Chamalaun and Barton (1993) refered to as the Australian intercratonic zone. The first one is the Southwest Queensland Anomaly (mapped by 1976 and 1977 array studies, Woods and Lilley, 1979; 1980). This anomaly was modelled by Woods and Lilley (1980) as a current flowing in surface sedimentary rocks along the western edge of the Great Australian Basin. The second conductivity anomaly is the Canning Basin Anomaly, which was mapped by the 1985 magnetometer array of Chamalaun and Cuneen (1990). This anomaly is interpreted as essentially a line current, and appears to be associated with the Jurgurra and Barbwire Terraces of the Fenton Fault system in the Canning Basin. Interpreting data from the Australia Wide Array of Geomagnetic Stations (AWAGS) experiment, Chamalaun and Barton (1990; 1993), suggested that those two conductivity anomalies may be electrically connected, to form a major continent-wide interatonic conductivity zone extending northwards into the Gulf of Carpentaria. In 1995, a magnetometer array of 42 sites was conducted in northern Queensland by ANU and Flinders University in collaboration, to clarify the indication in western Queensland concerning conductive structures. Preliminary results of this array study confirmed the existence and location of a major conductivity anomaly, which may link to the earlier discovered Southwest Queensland Anomaly. Here it is referred to as the Carpentaria Anomaly.

THIN-SHEET FORWARD MODELLING

There are two well-known and much-used algorithms to find, by numerical methods, the patterns of electromagnetic induction in non-uniform surface sheets which may be considered 'thin' electromagnetically. One algorithm was developed by Vasseur and Weidelt (1977), and the other by Dawson and Weaver (1979), Weaver (1982) and McKirdy et al. (1985). The Vasseur and Weidelt (1977) algorithm requires that the anomalous domain in the sheet should occur entirely within a uniform surrounding region. The thin sheet is underlain by either a one-dimensional layered substratum, or by a half-space. The Dawson and Weaver (1979) algorithm allows a two-dimensional structure in the surface sheet to extend to infinity, and was further developed by McKirdy et al. (1985), and Weaver (1994).

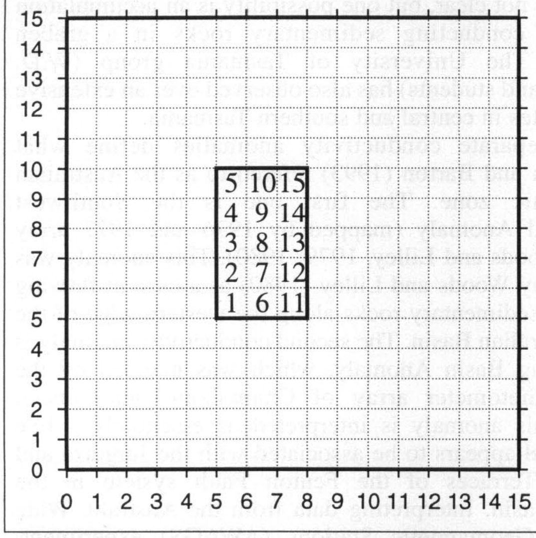
In the present study, code provided by P. Weidelt (pers. comm., 1996) is used for thin-sheet modelling in the inversion routine, taking advantage of its lesser computation time and memory storage. The code provided by J.T. Weaver (pers. comm., 1989) is used to calculate the response of the final model, so that no false structures are needed to be introduced along the edge of the modelling area.

The term 'conductance' is used in this paper in the sense of the electrical conductivity of a material (in S/m) multiplied by its vertical thickness (in m). For a thin-sheet model, conductance may be thought of as electrical conductivity integrated vertically through the thickness of the material which the sheet represents.

INVERSION SCHEME

A non-linear geophysical inversion can be implemented by linearisation and an iterative procedure. The problem can be mathematically represented in the following form:

$$J(m)=\frac{1}{2}\left[g(m)-d\right]^T C_{dd}\left[g(m)-d\right]+\frac{1}{2}\left[m-m_p\right]^T C_{mm}\left[m-m_p\right] \quad (1)$$



CELL	MODEL	CASE 1	CASE 2	CASE 3	CASE 3*
1	7000	7001	7002	6997	6983
2	1000	1001	1000	1002	1010
3	100	100	101	99	95
4	7000	6998	6998	6999	6971
5	400	400	401	400	394
6	400	400	400	401	408
7	100	101	101	100	91
8	19700	19702	19700	19582	19488
9	19700	19704	19704	19691	19719
10	100	100	100	102	109
11	5000	5000	5000	4998	4986
12	100	101	101	101	108
13	100	100	100	99	92
14	5000	5001	5001	5003	5014
15	100	101	101	100	93
Misfit		0.001	0.0005	0.0005	0.0007

Figure 2. Synthetic test-model for the inversion procedure, and results. Left: The model is a rectangular island set in a uniform ocean. The grid-cells of the island have identifying numbers. Right: The grid-cell conductance values for the island model are listed under 'model'. The remaining columns give the values found for these conductances in the tests of the inversion procedure after 8 iterations.

where $J(m)$ denotes the object function to be minimised; g denotes the 'forward modelling' operator; m denotes a 'model vector', and comprises the parameters which specify a model; d denotes an 'observed data vector', and is comprised of observed parameters; m_p denotes an 'a priori' model, to be improved upon if possible; and C_{dd} and C_{mm} denote data covariance matrices for the model and the data, respectively.

There are many procedures for obtaining a solution to this minimisation problem. In the Levenberg-Marquardt approach, the model parameter m at kth iteration is determined by the following steps. (1) Calculate $g(m_k)$, the response of the current model, and its misfit $e = \sum|g(m_k) - d|$. (2) Compute the gradient of the object function ∇J. (3) Approximate the Hessian matrix $H_k = [\nabla J][\nabla J]^T$. (4) Solve the linear equation $\delta m(H_k + \beta I) = -\nabla J$, where βI is a damping factor. (5) Update the model parameters: $m_{k+1} = m_k + 1$. (6) Test the misfit; stop, or return to step (1).

A set of synthetic 'observed data', to test the efficiency and accuracy of the inversion routine, was generated using a thin-sheet forward code. The thin sheet for this test model consists of a non-uniform island as an anomalous domain, comprising 15 unknown cell conductances, as shown in Figure 2. The island is surrounded by a uniform ocean, of conductance 10 000 S. The underlying half-space is assumed to have a conductivity of 0.005 S/m down to depth 30 km, and 0.1 S/m below 30 km. The following three cases of synthetic data distribution were tested, as input for the inversion.

Case 1. 'Observed data' (both real and quadrature values) are held for each cell in the whole modelling area. The number of 'observation sites' is greater than the number of parameters inverted.

Case 2. 'Observed data' are held for each cell in the anomalous domain. The number of 'observation sites' equals the number of parameters inverted.

Case 3. 'Observed data' are held for the cells of the anomalous domain, except for cells 1, 3, 5, 7, 9, and 13, which are 'missing data'. The number of 'observation sites' is less than the number of parameters inverted. For Case 3*, only the real parts of the magnetic transfer functions are used in the inversion.

Comparisons of the inverted conductance values with those of the initial test-model are listed in Figure 2 for the cases tested. The inversion routine causes a starting model of uniform conductance to change to a model with conductance values very close to the original model (less than 0.1% misfit). The efficiency and accuracy of this inversion routine gives confidence that it is suitable for practical use with field data.

THIN-SHEET MODEL FOR AUSTRALIA

The modelling area covers 6000 km x 6000 km. This area is divided into a grid of 100 km x 100 km mesh points, yielding a total of 3600 cells. To construct a thin-sheet model, the lateral conductivity variations for the area are confined to a surface layer of thickness 10 km. This layer then becomes, mathematically, a 'thin-sheet' of variable electrical conductance. Following Corkery and Lilley (1994), conductance values have been calculated for all 3600 cells. A map of the resulting conductance distribution is shown in Figure 3.

A thin-sheet model which is geologically reasonable has thus been constructed for the Australian continent and surrounding oceans. This model is taken as the 'base model' (Figure 3). The layer to 150 km represents a cold and resistive lithosphere. The middle layer then extends to 650 km, with a conductivity of 0.01 S/m (a conductive asthenosphere and upper mantle). The lowest layer is a half-space, with conductivity of 1.0 S/m (lower mantle).

The thin-sheet model (Figure 3) is period-dependent. For geomagnetic variations of period 1 hour, the skin depth of seawater is about 16 km, which is three times the average depth of ocean. The skin depth of the layer immediately beneath the sheet is 955 km, which is 95 times greater than sheet thickness (10 km), and 9 times greater than the cell spacing (100 km). The required conditions of Weaver (1982) are thus met, as are two more required for practical calculations: the length of modelling area (6000 km) is several skin depths of the first layer (955 km); and sharp conductivity boundaries in the model, unless perpendicular to the grid edges, are at least one skin depth (955 km) away from the grid edges.

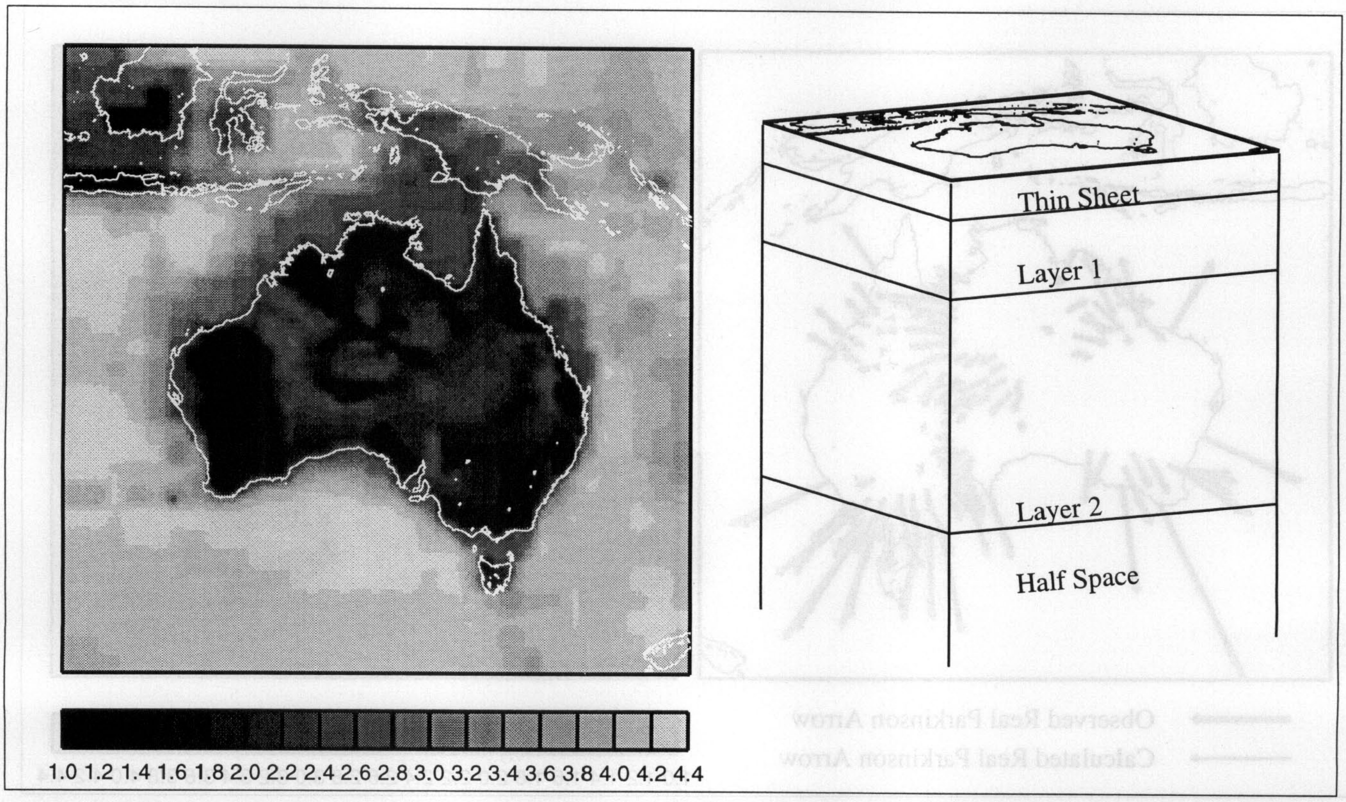


Figure 3. The thin-sheet 'base' model of Australia set in its surrounding oceans, based on known geology and ocean bathymetry. The model comprises a 60 x 60 grid, with a grid spacing of 100 km. The map displays different values of the thin-sheet conductance in different shades of grey. The scale for the different shades of conductance gives the logarithm of conductance (in siemens) to the base ten.

IMAGE OF CONDUCTIVITY STRUCTURE FOR AUSTRALIA

The data used in the inversion are the real parts of the transfer functions at 1 hour period. The data are selected from a larger data base, so that each cell is occupied by at most one data site. The starting model for the inversion is the base model.

The inversion procedure then ran to completion at iteration 10, at that point the change in the misfit, from the previous iteration, being less than 0.2. The model from the output of iteration 10, and its response at the sites of the selected data upon which the inversion is based, are shown in Figure 4. It is evident that the model fits the observed data inland very well, while some differences exist between model and observations along the coast. These differences may reflect a smoothing of anomalous field components by the 100 km grid, reducing the computed amplitude of the vertical field; or that the coast effect is not computed for as sharp a conductivity contrast as actually occurs.

The cause of any differences between the base and inverted models is that the base model is a representation of known 'surface' geology, while the inverted model is showing information on the orientation, location and lateral extent of conductive structures which are revealed by the geophysical data. In Figure 4 the conductance values of the inland enhanced structures, shown by the inversion, are at least ten times the normal value for conductive sedimentary rocks (compare Figure 2), so there are significant differences between the base model and the inverted model. The features of the inverted conductance map are now compared with the conductivity anomalies shown in Figure 1.

Starting in southeastern Australia, there is an enhanced structure in the region of the Otway Basin, to the west of the Lachlan Fold Belt. Thus the Otway Anomaly is expressed in the inverted model.

In South Australia, the Flinders Anomaly is also expressed as a major conductive structure. This structure was considered to be possibly linked with the Southwest Queensland Anomaly (Woods and Lilley 1980). However, there may be a break between these two structures (Figure 4), consistent with the conclusion of Paul (1994). The expression of the Flinders Anomaly in the inverted model in Figure 4 shows that the thin-sheet model, although it cannot give a section with depth of a conductive structure, nevertheless has the ability to image deep structures when long-period data are inverted (1 hour in this study).

Along the Australian 'intercratonic arc', three enhanced conductance regions, revealed from the inversion, correspond to the Canning Basin Anomaly, the Southwest Queensland Anomaly, and the Carpentaria Anomaly. Because of the sparse GDS coverage of western Australia, at this stage it is difficult to say if the Canning Basin Anomaly is linked to the Southwest Queensland Anomaly. The Southwest Queensland Anomaly seems clearly to join the Carpentaria anomaly from the arrow pattern, though the inverted model shows a minor break between the southwestern and the northwestern Queensland conductive structures.

An enhanced conductive region found near the southwestern Australian coast is another major feature of Figure 4. Corkery (1992) showed that for a model consisting of seawater of variable depth and an electrically uniform crust, induction arrows at the coast sites should be nearly perpendicular to the coast (his ocean model). However, the observed induction arrows for southwestern Australia by Everett and Hyndman (1967) differ from the distinctive pattern for an electrically-uniform continental crust. If the arrows can be treated as vectors (Weaver and Agarwal, 1991), they can be resolved into parts perpendicular and parallel to the coast. The inland arrows of Everett and

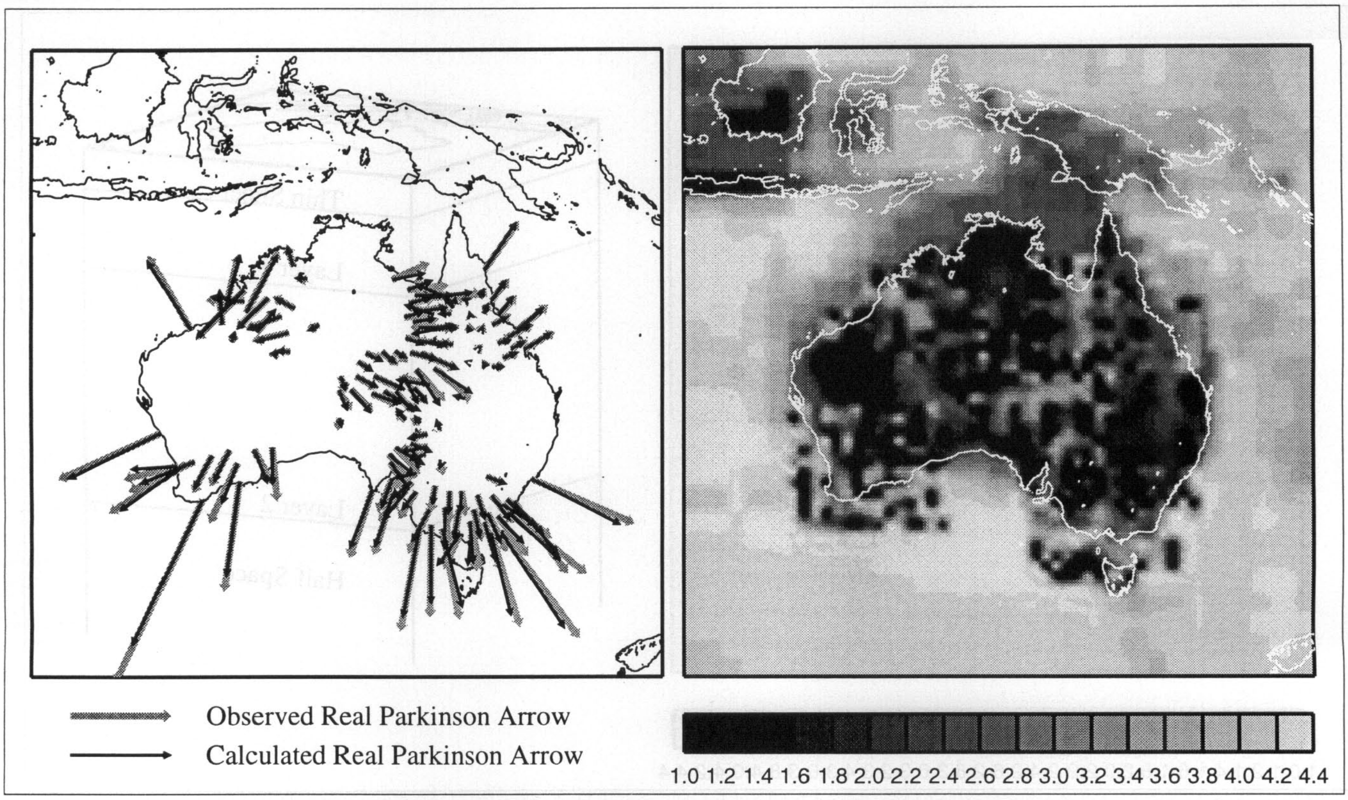


Figure 4. The model resulting from the inversion procedure. Left: Comparison of induction arrows, observed and calculated. Right: The inverted model after 10 iterations. The scale for the conductance in siemens is logarithmic as in Figure 3.

Hyndman (1967) then indicate a conductivity structure west of their observing sites, and the inverted conductance map shows the existence of inland conductive structures at the south end of the Yilgarn Block. The conductance of the structures in the inverted model (Figure 4) is nearly fifty times background. More work is needed to substantiate the presence of such conductivity structures.

Isolated high conductance spots in the inversion model (Figure 4) should be treated with caution. Most are located in areas where data are few (Western Australia and the Northern Territory). Most of the isolated high conductance cells are not well-controlled by observed data. This matter is important for further investigation, and work in progress involves inversions with model smoothness constraints to test the extent to which such high conductance spots are required.

CONCLUSION

The thin-sheet method allows complex three-dimensional electromagnetic induction effects to be studied in a relatively straightforward manner. An inverted model has been obtained for the Australian continent, which displays the position and orientation of highly conductive structures sensed by GDS observed data. In addition to evidence for its success inland, there are indications that the inversion technique is able to image the existence of highly conductive structures in coastal areas, where it is difficult for other interpretation techniques to do so (eg, induction arrows) because of the dominating conductivity contrast between land and ocean in a coastal area.

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