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Electromagnetic investigation of the Eyre Peninsula conductivity anomaly

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ABSTRACT

Seafloor and land magnetotelluric (MT) data were collected in the SWAGGIE (Southern Waters of Australia Geoelectric and Geomagnetic Induction Experiment) project in April-May 1998, from 30 seafloor and 23 land sites. The principal objective of the experiment was to delineate the strike and depth of a zone of high electrical conductivity, known as the Eyre Peninsula Anomaly (EPA) in South Australia. Three linear arrays of marine magnetotelluric instruments were deployed across the continental shelf and slope to locate the offshore extension of the EPA on the continental margin, and to image the continental-oceanic lithosphere-asthenosphere transition. A land array of magnetometers was deployed at the same time to better resolve the EPA in the southern Eyre Peninsula. Robust remote-reference processing of time-series magnetic and electric data gives good MT and geomagnetic depth sounding responses in the bandwidth of 10^1 to 10^5 s, corresponding to skin-depths of mid-crustal (10 km) to mantle transition (400 km) range. Initial processing of marine and land data clearly indicates that the EPA is continuous to the edge of the continental shelf, with a conductance greater than 15 000 S confined to a narrow, near-vertical zone. At sites distant from the EPA, one-dimensional MT inversions fit the data well and provide a background conductivity structure for two and three-dimensional forward and inverse modelling of the EPA.

INTRODUCTION

The Eyre Peninsula Anomaly (EPA) is one of the most prominent crustal conductive anomalies in South Australia and bisects the southern part of the peninsula as shown in Figure 1 (White and Milligan, 1984; Kusi et al., 1998).

The western part of the Eyre Peninsula consists of rocks of the Sleaford Complex. These consist of Archaean to Palaeo Proterozoic granites and granitic gneisses, intruded and altered during the Sleaford Orogeny (2,500–2,300 Ma). The central part of the study area is covered by Hutchison Group metasediments, and to the east is a limited exposure of the Lincoln Complex granite intrusives (1,700 and 1,580 Ma). Hutchison Group sediments are estimated to be 1,500 to 2,000 Ma (Rutland et al., 1981), and are characterised by strong multiple phases of deformation and metamorphism during the Kimban Orogeny. A mylonite zone extents along the east coast of the Eyre Peninsula, parallel to the EPA, separating the Hutchison metasediments and the Lincoln Complex (Drexel et al., 1993). Offshore to the south of Eyre Peninsula lies the Duntroon Basin, which is one of a sequence of

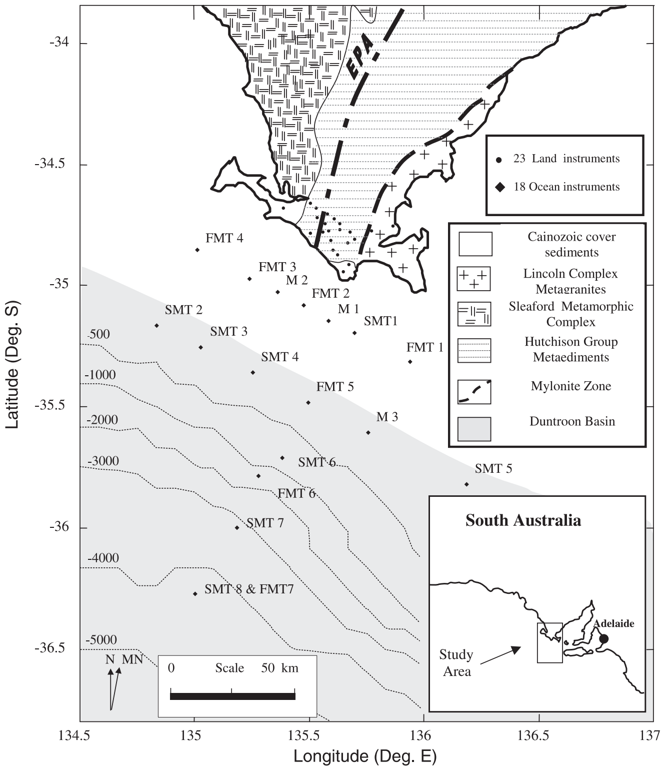

Fig. 1. Land and marine instrument location during the SWAGGIE experiment (positions of the high-frequency marine MT instruments are not shown). Inter-site spacing between land instrument was about 5 km, and for seafloor instruments 25 km. Also shown are the major geological regions of the Eyre Peninsula and the proposed position of the Eyre Peninsula Conductivity Anomaly (EPA) as determined by Kusi et al. (1998). Bathymetric contours are shown, with the 500 m contour representing the edge of the continental shelf.

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marginal sedimentary basins along Australia's southern coastline. Pre-rifting sedimentation in the Jurassic and Cretaceous was followed by post-rifting deposition resulting in sediment thicknesses of up to 11 km (Stagg et al., 1990; Hill, 1991).

The EPA was first identified from geomagnetic array studies in the early 1980s (White and Milligan, 1984). From 1984 to 1989, a series of ten geomagnetic depth sounding (GDS) arrays were deployed to study the spatial extent of the anomaly (White and Milligan, 1984; Milligan, 1989; Milligan et al., 1989). From two-dimensional profiles across the EPA, White and Milligan (1984) determined that the anomaly was caused by a major fracture or shear zone located within the top 10-15 km of the crust. The cause of the anomaly was unclear and White and Milligan (1984) considered three possible hypotheses, namely; (i) saline fluids in fractures connecting with the ocean, (ii) graphite in a shear zone, (iii) current channeling effects from induced currents in the ocean into the continent. However, land geomagnetic anomalies alone were not sufficient to differentiate the possible causes.

From December 1993 to March 1995 a further 60 recording magnetometers were deployed (Kusi, 1996). Instruments were deployed to fill gaps in the previous studies where instruments had failed, and also to extend the data northwards. Two-dimensional inversions of the GDS responses using Occam's inversion (Constable et al., 1987) showed that the conductance of EPA the lies between 3 000 and 10 000 S, and there is evidence of an increase in conductance from north to south and an indication of offshore extension.

Between April and May 1998 the SWAGGIE (Southern Waters of Australia Geoelectric and Geomagnetic Induction Experiment) project took place on land, and across the continental shelf and slope south of Eyre Peninsula. The experiment was jointly conducted by Flinders University of South Australia, Scripps Institution of Oceanography (USA), the Australian Geological Survey Organisation and the Australian National University. The principal objectives of SWAGGIE were to map the EPA across the continental shelf using GDS data; to determine the depth and width of the EPA using magnetotelluric techniques; and to define the continental margin structure across the Duntroon Basin. This paper reports initial results from the SWAGGIE experiment.

INSTRUMENTATION AND DATA

Twenty-three land-based magnetometers and twenty seafloor instruments were used in the SWAGGIE experiment (Figure 2). Land-based instruments were deployed across the southernmost part of the Eyre Peninsula with distances between them about 5 km. These instruments had a least–count of 1 nT and sampled every 10 s. The marine experiment utilised two high-frequency MT instruments that were deployed for two days at a time (Constable et al., 1998), fifteen low-frequency MT instruments deployed for the entire two-month experiment duration, and three low–frequency seafloor magnetometers.

The low-frequency instruments comprised a magnetometer with a sample rate of 10 s and a least-count of 0.1 nT, and an electrometer that sampled at either 1 s or 10 s, with a least count of 0.05 µV/m. Such instruments represent a combined resource developed at Flinders University and Scripps Institution of Oceanography, USA. The Australian National University also deployed three single magnetometers (0.1 nT resolution). These instruments were deployed in early April 1998, from the Oceanographic Research Vessel (ORV) Franklin as shown in Figure 2. The two high-frequency MT instruments, with magnetic field resolution of approximately 1 pT and electric field resolution of 0.05 µV/m, sampled at 25 Hz and have been specifically designed for sedimentary basin exploration (Constable et al., 1998;

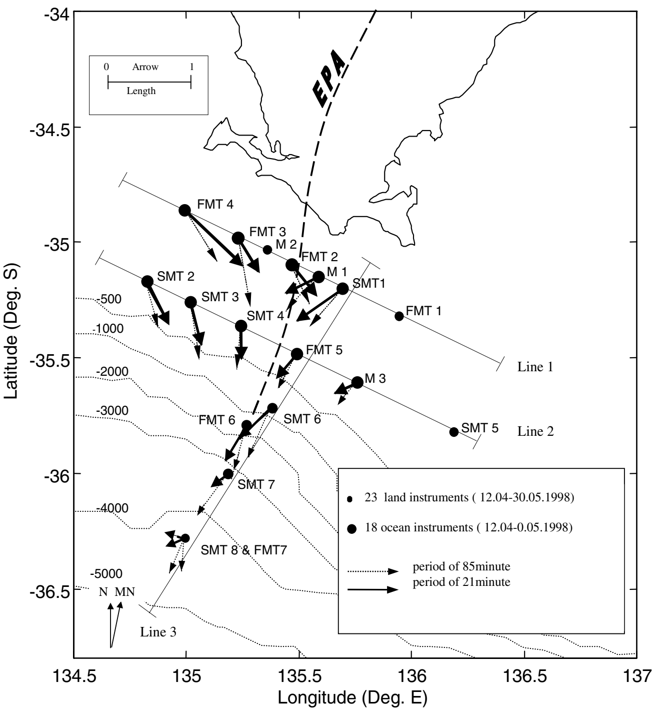

Fig. 2. Real GDS induction arrows at marine MT instrument sites at periods of 21 and 85 minutes. Magnetic data were not obtained at sites FMT1 (lost), and at SMT5 and M2, hence no arrows are plotted. The marine MT sites were grouped into three profiles (Lines 1-3). GDS induction arrows point towards zones of high electrical conductance, from which the inferred offshore extent of the EPA is indicated.

Hoversten et al., 1998). During the two-week cruise these high-frequency instruments were deployed in twelve locations, although sites on the continental shelf were dominated by oceanographic noise. Processing of these high-frequency MT sites is currently in progress, and will be added to the low-frequency MT data to increase the frequency bandwidth and improve interpretation of the uppermost crust.

Seafloor MT instruments were deployed in three linear profiles (Figure 2). Table 1 summarises seafloor instrument location and performance. The first set of instruments was on the inner continental shelf in water 95-100 m deep (Line 1). This set included five low-frequency MT instruments (FMT1-4, SMT1), and two single magnetometers (M2 and M1). A second profile (Line 2) occupied the outer-shelf zone in water depths of 120 to130 m. There were five low-frequency (SMT2-5, FMT5) MT instruments sites, and 1 single magnetometer (M3) site. The third line (Line 3) crossed the continental slope in depths of 500 to 5,000 m. All low-frequency instruments were successfully retrieved at the end of May 1998 from the ORV Franklin, with the exception of one MT instrument at site FMT1.

The three lines were designed to investigate different aspects of the southern margin's conductivity structure. The inner and outer shelf lines were located approximately perpendicular to the strike of the postulated marine extent of the EPA. An instrument spacing of about 25 km was required to span the possible extent of the anomaly. The inner shelf line sites were on a thin layer of marine sediments, while the outer line was above the Duntroon Basin, as shown in Figure 1. The line across the continental slope provided information about the continent-ocean transition.

Magnetometer and electrometer data were corrected for tilt and clock drift, and a few jumps and spikes were removed. The amplitude of magnetic field variations decreases with increasing ocean depth. High-frequency magnetic field variations are strongly attenuated from inner shelf sites (100 m) to deep-ocean sites (4,580 m) due to the shielding effect of the highly conducting salt water.

GEOMAGNETIC DEPTH SOUNDINGS

Geomagnetic depth sounding was used to map the position and strike of lateral variations in electrical conductivity within the Earth. Parkinson (1962) introduced a graphical method for presenting three-component magnetic field observations as induction arrows (also known as Parkinson arrows). These arrows describe the linear relationship between the components of the vertical and horizontal variation fields. By displaying induction arrows on a map it is easy to identify the orientation and qualitative intensity of the conductivity anomaly.

In the process of investigation, GDS data were analysed in both time- and frequency-domains. In this paper, seafloor GDS induction arrows were calculated for each instrument, using a remote reference robust analysis technique (Chave and Thompson, 1987). To reduce bias from correlated noise, a remote reference was used. The remote reference fields were usually taken from the nearest magnetometer. As is standard practice (Lilley and Arora, 1982), the real part of the complex transfer functions between the vertical magnetic field and orthogonal horizontal magnetic field components is reversed in sign so that plotted arrows point towards the regions of high electrical conductance (depth integrated conductivity).

The vertical variational fields are significant at all sites, and when processed to GDS induction arrows tend to point towards the EPA. These real (in-phase) arrows are plotted in Figure 2 at two representative periods of 21 min and 85 min. As noted from previous land studies (Kusi et al., 1998) there is a consistent rotation towards the EPA at shorter periods. Outer shelf arrows are smaller, presumably due to the effect of conductive sediments. Quadrature (out-of-phase) arrows (not shown) are generally smaller than the real arrows at most periods, but also point almost directly towards the conductive zone.

MAGNETOTELLURIC RESPONSES

Magnetotelluric response estimates have been generated at most of the seafloor instrument sites using the remote-reference

Site Code	Name of Instrument	Depth (m)	Latitude (Deg. S)	Longitude (Deg. E)	List count	Sample	Fields	Instrument type and Institution
FMT 4	"Ernie"	95	34º 51.913´	134º 59.833´	0.1nT 0.05µV/m	10	E, B	Flinders University (MT)
FMT 3	"Jonah"	100	35º 58.898´	135º 13.686´	0.1nT 0.05µV/m	10	E, B	Flinders University (MT)
M 2	"Check"	95	35º 2.240´	135º 20.890´	0.1nT	60	No Data	SOMEX (Mag.)
FMT 2	"Fuzzy"	95	35º 5.640´	135º 27.720´	0.1nT 0.05µV/m	10	B, (No electric)	Flinders University (MT)
M 1	"Twosome"	60	35º 9.026´	135º 34.820´	0.1nT	60	B	SOMEX (Mag.)
SMT 1	"Trevor"	98	35º 12.369´	135º 41.201´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
FMT 1	"Alf"	100	35º 19.433´	135º 55.544´	0.1nT 0.05µV/m	10	Lost	Flinders University (MT)
SMT 2	"Kermit"	117	35º 9.009´	134º 47.271´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
SMT 3	"Ulysses"	131	35º 15.905´	135º 0.953´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
SMT 4	"Noddy"	122	35º 22.852´	135º 14.859´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
FMT 5	"Igor"	126	35º 29.624´	135º 28.869´	0.1nT 0.05µV/m	10	E, B	Flinders University (MT)
M 3	"Tertius"	130	35º 36.422´	135º 42.630´	0.1nT	60	B	SOMEX (Mag.)
SMT 5	"Quail"	122	35º 50.021´	136º 10.376´	0.1nT 0.05µV/m	10	E, (No magnetic)	Scripps Institution (MT)
SMT 6	"Opus"	512	35º 43.272´	135º 22.000´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
FMT 6	"Charlie"	2000	35º 47.733´	135º 15.952´	0.1nT 0.05µV/m	10	E, B	Flinders University (MT)
SMT 7	"Rhonda"	3050	36º 0.600´	135º 10.433´	0.1nT 0.05µV/m	10	E, B	Scripps Institution (MT)
SMT 8	"Lolita"	4580	36º 17.146´	134º 59.434´	0.1nT 0.05µV/m	10	B, (No electric)	Scripps Institution (MT)
FMT 7	"Horace"	4580	36º 17.144´	134º 59.425´	0.1nT 0.05µV/m	10	B, (No electric)	Flinders University (MT)

Table. 1. Summary of seafloor instruments location and performances during SWAGGIE experiment. E – Electric data, B- Magnetic data.

processing codes of Chave and Thompson (1987). Horizontal magnetic and electric fields are combined with remote-reference magnetic field data to form MT responses in the bandwidth 10^{-1} to 10^{-5} Hz (10–10,000 s). At sites where only electric or magnetic fields were recorded, MT responses have been generated using the missing field components from the closest site. For example, magnetic data at site FMT2 were combined with electric field data at either SMT1 or FMT3 to generate MT responses. Processing of low-frequency MT data is almost complete, with high-quality responses at most sites. High-frequency MT estimates from the Scripps Institution instruments are currently being processed sssssssss(K. Key, pers. Comm., 1999).

Modeling and inversion of the data has just commenced and only preliminary one–dimensional models have been obtained. Figure 3 shows MT responses at site SMT3 on the outer continental shelf (as shown in Figure 2) for the component of the electric field in the geomagnetic east-west orientation and the magnetic field in the geomagnetic north-south orientation. Data are shown as apparent resistivity and phase values with error bars of one standard deviation. Even at this early stage, there are a few interesting points to note. Firstly, apparent resistivities range from very low values (1 ohm-m) at the highest frequencies (shortest periods) to an almost constant value of 30 ohm-m at low frequencies. Similarly, phases increase from very low values (0-10º) to almost half–space values (40-50º). Such variations in the MT response indicate that the near surface has very low resistivity, and this increases with depth to an almost constant value. The MT responses at site SMT3, which is some distance from the EPA, are primarily sensitive to horizontal structure, and do not show strong anisotropy, suggesting that the structure here is relatively one-dimensional. We note that the GDS responses, which indicate vertical changes in conductivity, are much more sensitive to the EPA.

Figure 3 also shows a preliminary one-dimensional inversion using Occam's inversion (Constable et al., 1987). Calculated values are shown as the continuous lines on the apparent resistivity and phase plots. The one–dimensional model can be broadly split in to three parts. In the top 10 km the resistivity starts at a value approximately equivalent to that of seawater, increasing with depth as a result of sediment compaction in the Duntroon Basin. Beneath this is resistive lithosphere followed by a 30 ohm-m asthenosphere below 80 km. This structure is similar to the two-dimensional resistivity model for South Australia determined by White and Heinson (1994). The top layer has a conductance of approximately 3,000 S which is representative of high-porosity sediments in the Duntroon Basin. The fit to the observations is good given the proximity to the deep ocean and the high-conductance EPA.

Two and three-dimensional modelling is in progress. This modelling aims to include the changes in bathymetry, shape of the coastline, varying conductivity of sediments such as in the Duntroon Basin, and the postulated extent of the EPA. We have previously noted that the existence of the EPA is not as explicit in the MT responses as in the GDS responses, indicating that the EPA is relatively narrow and probably quite vertical. MT responses have little sensitivity to vertical structure unless it is connected to low-resistivity regions in the mantle, and it appears from the initial inversions that the crust and mantle are effectively insulators, preventing vertical current flow from the ocean into the mantle. The Duntroon Basin contains up to 11 km of higher porosity sediment that precludes significant galvanic distortion effects. Thus, sites on the outer continental shelf will be relatively straightforward to model. There are much stronger three-dimensional induction effects present in the MT responses along the inner shelf, as high-resistivity crystalline basement is much closer to the surface.

DISCUSSION AND CONCLUSION

As result of the GDS observations it appears that the EPA is continuous to the edge of the continental shelf. The magnitude of the vertical field response due to the EPA is greater than that due to induction within the 5 km-deep ocean, suggesting that the EPA has to have a conductance of at least 15,000 S. From the analysis presented in Figure 2, the axis of EPA lies between sites FMT2 and M1 across the inner shelf zone, and between sites SMT4 and FMT5 on the outer shelf zone. The symmetrical response of the GDS induction arrows indicates that the EPA is in a thin near-vertical zone.

Robust remote-reference processing of time-series magnetic and electric data gives good MT responses in the period of 10^1 to 10^5 s, corresponding to skin-depths of mid-crustal (10 km) to mantle transition zone (400 km). Initial one-dimensional modelling indicates that estimates of the thickness of the Duntroon Basin, and the broad-scale lithosphere-asthenosphere structure will be obtained, providing a background for further two- and three-dimensional forward and inverse models of the EPA. The cause of the EPA is unknown, but any models of it must take into account the continuity of the EPA from the edge of the continental margin several hundred kilometres north. Popular candidates for linear high conductance zones within the crust are hot saline fluids or graphite.

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REFERENCES

Chave, A.D. and Thompson, D.J., 1987, Some comments on the magnetotelluric response function estimation: J. Geophys. Res., 94, 14215-14225.

Constable, S., Orange A., Hoversten G.M., and Morrison H.F., 1998, Marine magnetotellurics for petroleum exploration Part 1. A seafloor instrument system: Geophysics, 63, 816-825.

Constable, S.C., Parker R.L., and Constable C.G., 1987, Occam's Inversion: a practical algorithm for generating smooth models from EM sounding data: Geophysics, 52, 289-300

Drexel, J.F., Preiss, W.V. and Parker, A.J., 1993, The Geology of South Australia Vol 1, The Precambrian. South Australia Geological Survey, Bulletin 54.

Hill, A.J., 1991, Revisions to the Cretaceous stratigraphic nomenclature of the Bight and Duntroon Basins, South Australia: South Australia Geological Survey, Quarterly Geological Notes, 120.

Hoversten, G.M., Morrison H.F. and Constable S., 1998, Marine magnetotellurics for petroleum exploration Part 2. Numerical analysis of subsalt resolution: Geophysics, 63, 826-840.

Kusi, R., 1996, Electromagnetic induction studies in the Eyre Peninsula, South Australia: Ph.D thesis, Flinders University of South Australia.

Kusi R., White, A., Heinson, G.S. and Milligan, P.R., 1998, Electromagnetic induction studies in the Eyre Peninsula, South Australia: Geophys. J. Internat. 132, 687-700.

Lilley, F.E.M. and Arora, B.R., 1982, The sign convention for quadrature Parkinson Arrows in geomagnetic induction studies: Rev. Geophys. Space Phys., 20, 513-518.

Milligan, P.R., White A. and Chamalaun, F.H., 1989, Extension of the Eyre Peninsula conductivity anomaly: Expl. Geophys., 20, 187-190.

Milligan,P.R., 1989, Geomagnetic variations in South Australia: The Eyre Peninsula Anomaly: Ph.D thesis. Flinders University of South Australia.

Parkinson, W.D., 1962, The influence of continents and oceans on geomagnetic variations: Geophys. J. Roy. Astr. Soc., 6, 441-449.

Rutland, R.W.R., Parker, A.J., Pitt, G.M., Preiss, W.V. and Murrell, B., 1981, The Precambrian of South Australia: in Hunter, D.R., Eds., Precambrian of the Southern Hemisphere, Developments in Precambrian Geology Series, 2, 309-360.

Stagg, H.M.V., Cockshell, C.D., Willcox, J.B., Hill, A.J., Needham, D.V.C., Thomas, B., O'Brien, G.W. and Hough, L.P., 1990, Basins of the Great Australian Bight region: geology and petroleum potential: Bureau of Mineral Resources, Continental margins Program Folio 5.

White, A. and Heinson, G.S., 1994, Two-dimensional electrical conductivity structure across the southern coastline of Australia: J. Geomag. Geoelectr., 46, 1067-1081.

White, A. and Milligan, P.R., 1984, A crustal conductor on the Eyre Peninsula, South Australia: Nature, 310, 219-222.

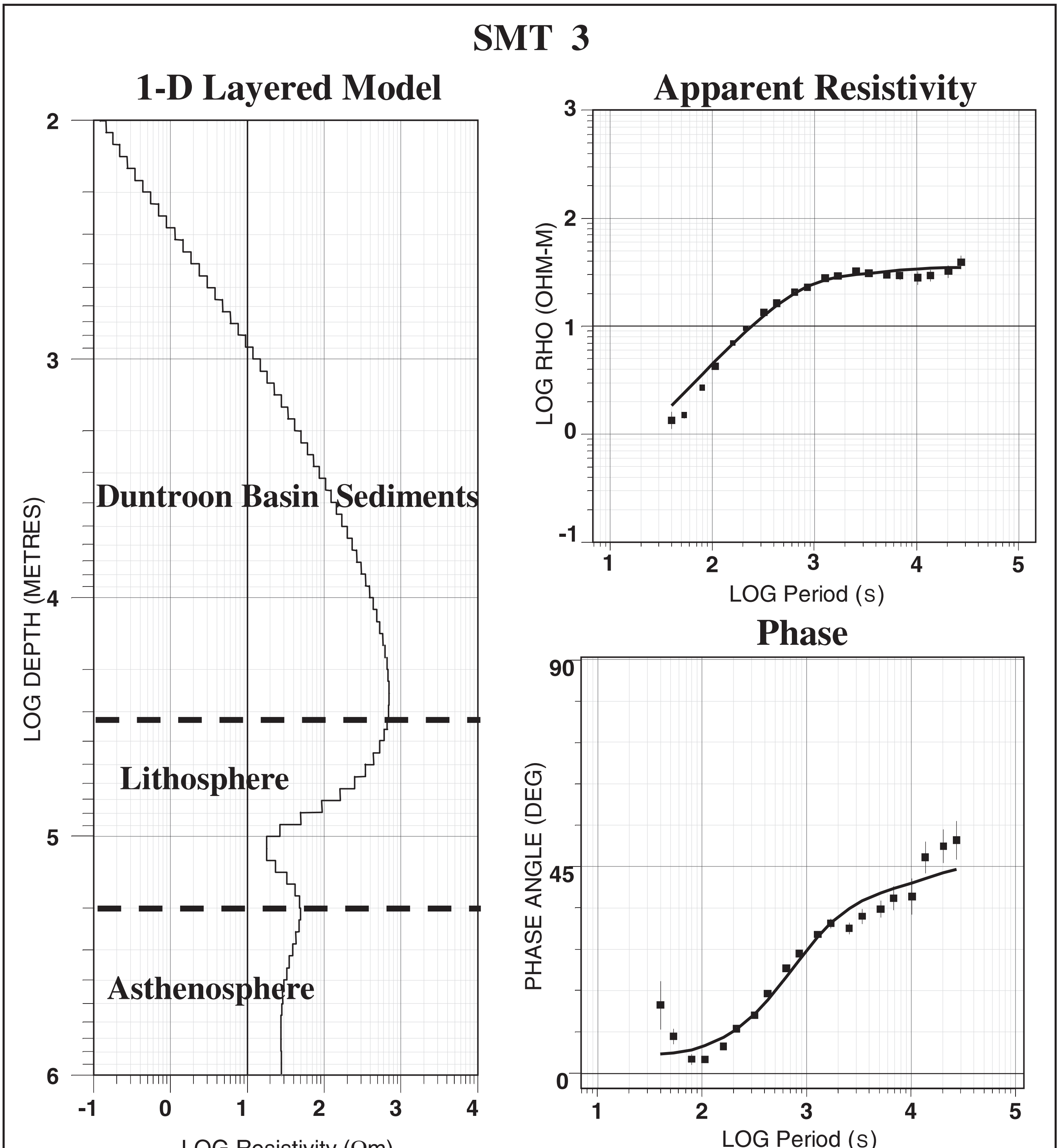

Fig. 3. Apparent resistivity and phase at outer-shelf site SMT3 (see Figure 1 for location) for the electric field approximately parallel to the edge of the continental shelf, and the perpendicular component of magnetic field. The observed data are represented by squares with errors bars of one standard deviation. A one-dimensional Occam's inversion of the data is also shown (solid lines on the apparent resistivity and phase plots). The resistivity profile is divided into three sections, namely; the Duntroon Basin Sediments (0-11 km); continental lithosphere depth (11 - 80 km), and asthenosphere below 80 km.