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Deep Schlumberger sounding and the crustal resistivity structure of central Australia

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Summary. Three 200 km Schlumberger resistivity soundings have been conducted over the central Australian shield, using telephone lines to obtain the large electrode spacings. These represent the first crustal scale controlled source electrical study to be carried out in this continent. A computer controlled data acquisition system was used which allowed precise measurements to be made with only modest emission currents (0.1–0.5 A).

The three soundings, centred on the towns of Renner Springs, Wauchope and Aileron, showed the southern part of the study area (the Arunta Block) to be an order of magnitude more resistive than the more northerly section (the Tennant Creek Block). This difference correlates with the higher heat flow of the Tennant Creek Block. A lowering of apparent resistivity at large electrode spacings for one sounding (Wauchope) is taken to indicate the presence of a low resistivity layer in the middle crust, at a depth less than 20 km. However, the effect of the highly conductive overburden characteristic of inland Australia, combined with the large transverse resistance of the crust, prevented the other two soundings from detecting such a layer. Without support from these two soundings, it is impossible to be sure that the lowered resistivity at Wauchope is not caused merely by lateral variations in near-surface resistivity.

The data also show that crustal resistivities are much lower than the expected values for dry rock, whether or not a low resistivity layer is included in the model. This implies a widespread occurrence of free water in the crust, with greater amounts occurring at depth if the low resistivity zone exists.

1 Introduction

The purpose of this paper is to report the first crustal scale sounding experiment using a controlled source in Australia. Three Schlumberger electrical soundings were performed over the central Australian shield using telephone lines to obtain current electrode spacings of

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about 200 km. Previously, electrical experiments in this country have employed natural source field methods such as magnetometer arrays (Everett & Hyndman 1967a; Bennett & Lilley 1974; Gough, McElhinny & Lilley 1974; Lilley 1976; White & Polatajko 1978; White & Hopgood 1979; Woods & Lilley 1979, 1980; Lilley, Woods & Sloane 1981a, b) and magnetotelluric sounding (Everett & Hyndman 1967b; Tammemagi & Lilley 1971, 1973; Vozoff *et al.* 1975; Vozoff & Cull 1981).

DC deep resistivity studies have been carried out by others in Europe and the USSR (Schlumberger & Schlumberger 1932; Migaux, Astier & Revol 1960; Antonov & Izyumov 1969; Blohm & Flathe 1970), southern Africa (van Zijl, Hugo & de Bellocq 1970; Blohm, Worzyk & Scriba 1977; van Zijl & Joubert 1975), and North America (Cantwell & Orange 1965; Cantwell *et al.* 1965; Keller 1968; Samson 1969; Keller & Furgerson 1977). A few controlled source studies have used em sounding techniques rather than DC electrical sounding (Sternberg 1979; Duncan *et al.* 1980; Connerney, Nekut & Kuckes 1980). These experiments were all situated on the Canadian Shield.

Controlled source methods tend to complement natural source methods, by providing shallower depths of investigation and being (in the DC limit) more sensitive to resistive structures. The availability of the telephone lines, the lack of cultural noise and gentle topography of inland Australia provided excellent conditions for a controlled source experiment.

2 Equipment and techniques

The Schlumberger sounding method is a well established geophysical technique, and will only be described briefly here (for a fuller description see, for example, Keller & Frischknecht 1966). Four electrodes, designated A, M, N and B, are emplaced in the ground in a colinear, symmetric array. The outer two electrodes (A and B) are used to pass a DC electric current, I, through the Earth. The M and N electrodes are placed relatively close together at the centre of the array and used to measure a potential difference, ΔV, resulting from the current flow. An apparent resistivity is given by

$$\rho_a = \frac{\pi(AB-MN)^2}{4I} \cdot \frac{\Delta V}{MN}.$$

The spacing of the current electrodes, AB, is systematically increased in an exponential manner to allow progressively deeper penetration of the electric current. Thus ρ_a is obtained as a function of AB, and plotted on log-log scales to give the usual representation of the resistivity sounding curve.

For current electrode spacings of up to 20 km, it was most practical to lay cable on the ground in a conventional manner. To obtain spacings greater than this, it is more convenient to use lines already installed for telephone or power services. For this study the overland telephone line between Alice Springs and Katherine in the Northern Territory of Australia was kindly made available by Telecom Australia. However, the telephone line could only be taken out of commission for a short time because of the inconvenience to local telephone subscribers.

Measurements of ΔV were made with the computer controlled equipment described by Constable (1983, 1984), which allowed maximum use to be made of the telephone lines in the time available for experimentation. In this system a desktop computer controls a programmable, 140 V/1.5 A power supply, enabling sinusoidal currents of arbitrarily low frequency to be generated. Emission currents of as low as 0.01 Hz are necessary to maintain a predominantly DC current flow for the larger electrode spacings. The use of sinusoidal signals, rather than the more easily generated square waves normally used, avoids the skin effect transients associated with abrupt switching. In deep soundings these transients may be very large relative to the DC signal and last for 30 s or more (van Zijl & Joubert 1975). The relatively low power used ensured that the telephone line did not become hazardous to the public.

Each current electrode normally consisted of between one and six interconnected aluminium stakes (1 m long, 2.5 cm diameter), driven into the ground several metres apart and watered with salt solution. Because of the large scale of the experiment it was often possible to use cattle grids, borehole casings, steel telephone poles and even town water supplies as current electrodes and still maintain a point source approximation. Each current electrode had an impedance of about 50–100 Ω. The telephone line resistance was slightly over $1\,\Omega\,km^{-1}$, so the total AB circuit impedance was between 100 and 500 Ω, allowing a source current of 250 mA to 1 A (peak) to be used.

The potential difference across MN was measured using a digital voltmeter, which was also interfaced to the desktop computer. The computer control allowed the use of synchronous stacking, drift removal (using the algorithm of McFadden & Constable 1983) and Fourier analysis to obtain signal to noise improvement ratios of nearly 1000. This is necessary because signals as small as $10^{-8}\,V\,m^{-1}$ must be measured for the larger electrode spacings. Telluric noise amplitudes at the lower frequencies used (approximately 0.01 Hz) were about $10^{-6}\,V\,m^{-1}$. Non-polarizable copper/copper sulphate electrodes were used to measure potentials, and were emplaced at the bottom of 0.5 m holes to minimize temperature fluctuations.

AB electrode spacings up to 20 km were obtained by laying insulated copper wire on to the ground, which was recovered after the experiment using a motorized cable reeling machine. Because of the exponential increase in AB, about 80 per cent of the measurements could be collected in this way without taking the telephone lines out of commission. Measurements for $AB = 20–200$ km could be made using the telephone lines, which could be accomplished in about 24 hr.

The route the telephone line takes prevented an ideal Schlumberger geometry from being used. However, noting that an equatorial bipole-dipole array produces the same sounding curve as a Schlumberger array (over a 1-D earth), the data could be corrected to produce Schlumberger apparent resistivities.

3 Regional geology

A tectonic sketch map of the experimental area is shown in Fig. 1. The electrical soundings were restricted to that section of the telephone line which crosses the exposed preCambrian shield. The shield is bounded by deep sedimentary basins to the east, south and west. The shield area was chosen to avoid the screening effects of the conductive rocks of the basins. To the north the shield and basin rocks are overlain by a thin (< 150 m) cover of Cretaceous sediment. A sounding was attempted on this cover at Daly Waters, but was terminated at $AB = 20$ km because the surface had a conductance (conductivity-thickness product) greater than 20 S, making it unlikely that information about the deeper structure could be obtained through the screening effect of these layers.

The southernmost electrical sounding ('Aileron') was situated on the Arunta Block, an Archaean to Lower Proterozoic metamorphic complex of gneiss, schist, amphibolite, granulite and granite. The two northern soundings ('Wauchope' and 'Renner Springs') were conducted on the Tennant Creek Block, which is composed of Proterozoic sediments, mainly sandstone, siltstone and shale. These sediments have lost much of their primary

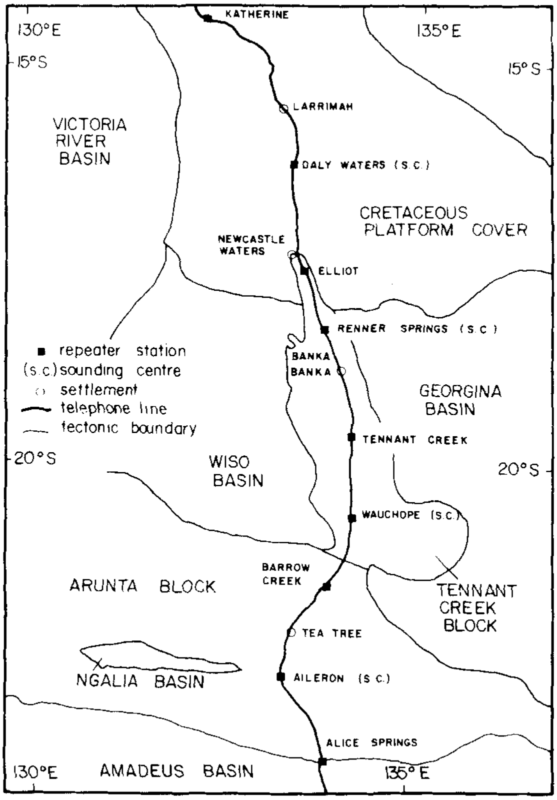

Figure 1. Map showing major tectonic units, telephone line and deep electrical sounding centres (Aileron, Wauchope and Renner Springs). The sounding at Daly Waters was limited to 20 km electrode spacings.

porosity as a consequence of their great age ($\sim 2 \times 10^9$ yr), and so are much more resistive that the younger, surrounding sedimentary basins.

It is unfortunate for this work that the geology of the shield is very heterogeneous, as attempts to interpret resistivity as a function of depth are made difficult if resistivity also varies laterally. Furthermore, sounding centres had to be located at telephone repeater stations to avoid cutting the lines, and so little choice was possible in the selection of sounding sites. However, the opportunity to use the telephone lines and the lack of controlled source data from Australia made it worth pursuing the experiment in spite of these difficulties.

3.1 LATERAL VARIATIONS IN RESISTIVITY

It is conventional to interpret resistivity data in terms of horizontal layers of isotropic resistivity. Thus a model consisting of n layers would be parameterized by a set of layer resistivities, $\rho_1, \rho_2, \ldots \rho_n$, and thicknesses, $t_1, t_2 \ldots t_{n-1}$. The nth layer is the deepest and extends to an infinite depth (i.e. a half-space). The calculation of theoretical apparent resistivity curves for such a model is easily performed by the linear filter method of Ghosh (1971), using the filter coefficients of Guptasarma (1982) for greater accuracy (for further details of the linear filter method, see the monograph by Koefoed 1979). Such a 1-D model produces a resistivity sounding curve which is relatively smooth.

The real geology often cannot be adequately described by 1-D models and this is particularly true if lateral variations in resistivity occur near the surface. It is usually not possible to interpret these variations using 2-D or 3-D models because of the limited amount of data in a sounding curve. Distortions of electrical sounding data as a result of such lateral variations in resistivity are often termed electrode effects because they are associated with repositioning the electrodes. Unlike the random noise associated with individual measurements of ΔV, such distortions are deterministic and may imitate the smoothly varying sounding curves due to layered structure. Fortunately, the inability to fit resistivity curves (for layered models) to the sounding data may often be used to distinguish electrode effects from layered structure. Also, features in the surface geology which are likely to produce lateral changes in resistivity may be associated with components of the sounding data suspected of being electrode effects. In this regard it can be useful to note that electrode effects are biased negative (Keller & Furgerson 1977; Constable 1983), tending to lower values of apparent resistivity more than increasing them.

Schlumberger sounding was chosen for this work because it is known to be less sensitive to electrode effects than dipole-dipole or Wenner sounding, since in a Schlumberger array the potential electrodes remain fixed. Movement of the *AB* electrodes across changes in resistivity may, however, still distort a Schlumberger curve.

The sounding results of the three experiments are shown in Figs 2, 4 and 6. Those data known to be affected by electrode effects are shown as hollow symbols. These data cannot be fitted by layered earth models, have been correlated with features in the surface geology, and have not been included in the interpretation described below.

The lowering of resistivity or roll-over at the end of the Wauchope curve could also be caused by electrode effects, but this is considered unlikely. The current electrode spacings are 135 and 191 km for the last two data and so presumably it would require a very large inhomogeneity to distort the sounding curve on that scale. There is no evidence from the surface geology for such a feature, except the sedimentary basins to the east and west of the Tennant Creek Block. Applying the calculations of Mundry & Worzyk (1979) shows that even if the basins were infinitely conductive, they would result in a lowering of apparent

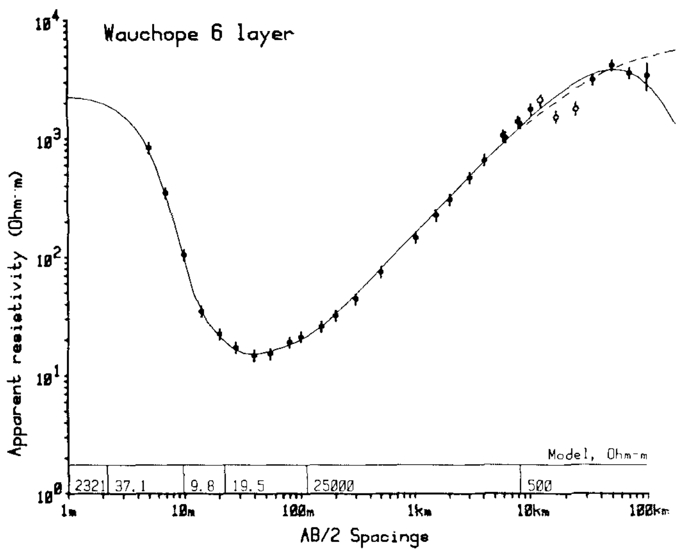

Figure 2. Wauchope sounding data and least squares model. Minimum standard errors are ±10 per cent. See text for details.

resistivity far smaller than the Wauchope roll-over. Also, if the basins were affecting the soundings, one would expect to see an even larger lowering of resistivity in the Renner Springs data, which is not observed. Unfortunately, without further experimentation, it is impossible to be certain that an inhomogeneity is not responsible for the Wauchope roll-over.

4 Interpretation methods

By using an interactive trial and error method, forward modelling (using the linear filter method) may be used to determine quickly how many layers are needed to fit the data, as well as approximate values for the layer parameters.

Further improvement in fitting the data is possible using the linearized inversion scheme of Marquardt (1963), which minimizes the sum of the squares of the residuals. The application of Marquardt inversion to resistivity data is discussed by Inman (1975) and Constable (1983). Using the model obtained by trial and error fitting as the starting point for the linearized inversion helps to prevent a local rather than global minimum of the sum of squares being found. The inversion routine described by Constable (1983) gives a least squares model, the linear errors of the model parameters, the system (or residual) variance and a linear correlation matrix for the model parameters. Additional information is obtained by performing the eigenanalysis (singular value decomposition) described by Inman, Ryu & Ward (1973) and Glenn & Ward (1976).

Both the inversion and eigenanalysis are performed using the logarithms of the model parameters and apparent resistivities. This stabilizes the inversion, both for the great range in resistivities and parameters and for small values of model parameters, and avoids negative model parameters. The use of a computerized data collection system results in measuring errors which are usually less than 1 per cent. However, the major contribution to total noise in the resistivity data comes from electrode effects, which are rarely less than 5 per cent. In order to furnish the inversion routines with a better estimate of total noise, the standard errors in ρ_a have been set equal to at least 10 per cent, which experience suggests is a reasonable value. The validity of such an estimate may be assessed from examination of the residual variance in the models.

5 Results

The Wauchope data are shown in Fig. 2. The vertical bars are ± 1 standard error (± 10 per cent as described above). The least squares model from the Marquardt inversion of the data is given at the bottom of the figure and the solid line is the calculated resistivity curve for this model. The model parameters and linear statistics are given in Table 1, and the eigenvalues and eigenvectors are shown in Fig. 3.

Although additional layers have been included to improve the fit, the upper layers of the model corresponds to a simple soil profile of three zones. A dry, resistive overburden (layer 1) is underlain by damp, conductive overburden (layers 2, 3 and 4). This surface cover is underlain by unweathered bedrock (layer 5), which is resistive because of its lower porosity. Below the bedrock layer is a zone of higher conductivity (layer 6).

It is well known that for a resistive layer between two conductive layers, the Schlumberger method is sensitive only to the resistivity–thickness product, or transverse resistance, T, of the resistive layer. This is demonstrated in this case by the high linear correlation between t_5 and ρ_5 (Table 1) and also by the third eigenparameter (Fig. 3) which is $(\log \rho_5) + (\log t_5) = \log(\rho_5 t_5) \pm 2.8$ per cent. That ρ_5 and t_5 do not otherwise appear in any but the unresolved

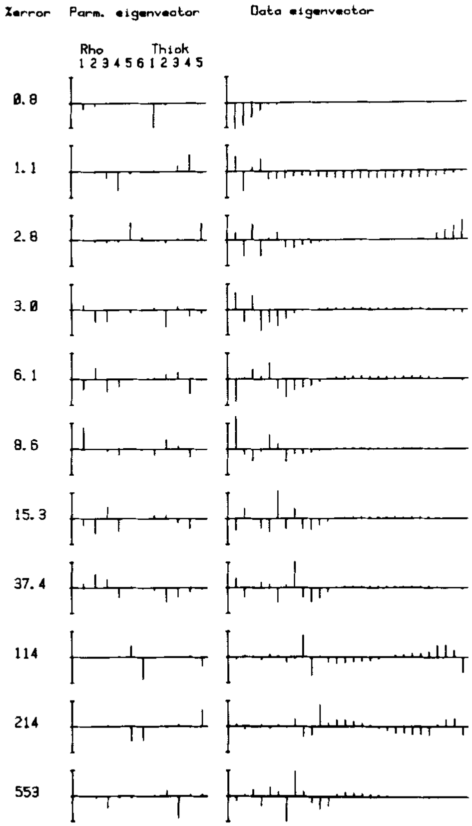

Figure 3. Eigenanalysis of the six layer model fitted to the Wauchope data. Parameter eigenvectors are linear combinations of the logarithms of physical parameters (layer resistivities and thickness). The errors are the reciprocals of the associated eigenvalues, and give the linear standard error in the (logarithmic) eigenparameters. The data eigenvectors reflect which physical data are contributing to each eigenparameter. ($AB/2$ increasing from left to right.)

eigenparameters (those with an error > 100 per cent) shows they cannot be separated. The effect of this high correlation on the inversion is to allow t_5 and ρ_5 to get very large and very small (or vice versa) as long as the product, T, stays the same. This has been avoided by holding ρ_5 fixed at 25 000 Ωm. For Wauchope, T is $2.1 \times 10^8\ \Omega\mathrm{m}^2 \pm 6$ per cent. The error in the estimation of the physical parameters ρ_5 and t_5 cannot be obtained from the linear inversion statistics, because they may vary over far too great a range for the linear approximations to be valid. Resorting to trial and error forward modelling shows that while ρ_5 may be lowered to about $10^4\ \Omega\mathrm{m}$ before a misfit to the data occurs, it may also be made arbitrarily large. The thickness t_5 is constrained to be less than 20 km.

The resistivity of the deep conductor, ρ_6, is an unresolved parameter, having a large linear error and appearing only in the unresolved eigenparameters. It has been held fixed at 500 Ωm for the inversions, and trial and error modelling may be used again to show that $\rho_6 < 1000\ \Omega\mathrm{m}$.

Applying a similar model to the Renner Springs sounding yields the results of Figs 4 and 5 and Table 2. The inclusion of the fourth layer is not justified by the Renner Springs data alone. However, if this layer is included on the basis of the Wauchope model, a stable

Table 1. Least squares model and linear statistics for the Wauchope data. Parameter values are in Ωm ($\rho_1 \ldots$) or m ($t_1 \ldots$). Column *A* gives the standard (linear) errors of the parameters, and column *B* gives the errors when the parameters marked '*' are held fixed. The correlation matrix shows linear correlations between parameters. Chi squared is the sum of the squares of residuals (weighted by data variance), and the system (or residual) variance is chi squared divided by the number of degrees of freedom of the problem.

Parameter value		A (+ – per cent)	B (+ – per cent)	Correlation matrix ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	t_1	t_2	t_3	t_4	t_5
ρ_1	2320	25	18	1.0										
ρ_2	37.1	99	45	0.77	1.0									
ρ_3	9.76	480	102	0.63	0.92	1.0								
ρ_4	19.5	64	31	0.39	0.66	0.84	1.0							
ρ_5	25 000	254	*	0.09	0.14	0.18	0.31	1.0						
ρ_6	500	447	*	0.02	0.03	0.05	0.08	0.42	1.0					
t_1	2.22	11	7	−0.95	−0.91	−0.77	−0.50	−0.11	−0.03	1.0				
t_2	7.65	221	64	−0.69	−0.97	−0.99	−0.78	−0.17	−0.04	0.82	1.0			
t_3	12.7	906	209	0.61	0.90	1.0	0.88	0.20	0.05	−0.74	−0.98	1.0		
t_4	90.9	52	20	−0.64	−0.89	−0.94	−0.64	0.01	0.00	0.76	0.94	−0.92	1.0	
t_5	8250	283	10	−0.08	−0.13	−0.18	−0.29	−0.99	−0.56	0.10	0.16	−0.19	−0.01	1.0

System variance = 0.792 (= 0.709 if parms marked * held fixed).
Chi squared = 13.47.

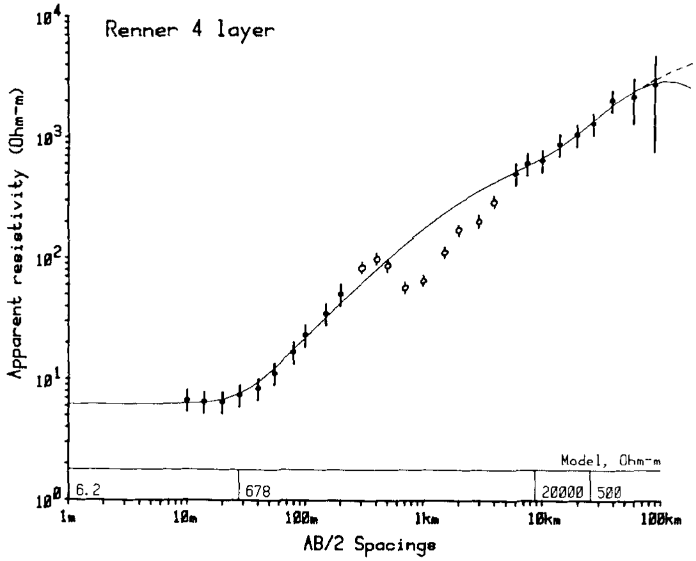

Figure 4. Renner Springs sounding data and least squares model. The minimum standard errors have been set to ± 20 per cent because of the large electrode effects and large measuring errors for $AB/2 > 10\,\text{km}$. See text for details.

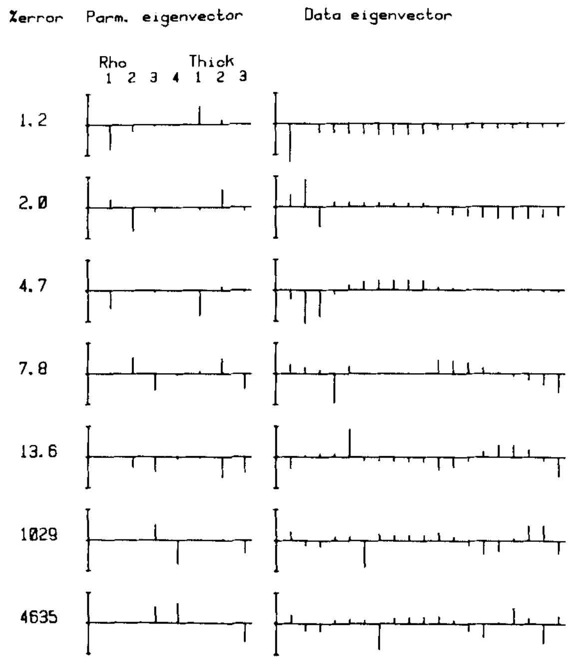

Figure 5. Eigenanalysis of the four layer model fitted to the Renner Springs data. See caption for Fig. 3.

solution is obtained which yields $T = 3.3 \times 10^8\,\Omega\text{m}^2 \pm 31$ per cent. This is similar to that of Wauchope ($2.1 \times 10^8\,\Omega\text{m}^2$), providing further evidence that the Wauchope roll-over is due to layered structure and not lateral variations in resistivity. Layer 2, of intermediate resistivity, is probably fitting residual noise. The small system variance (0.193 in Table 2) reflects this. A variance much less than one suggests that either the structure is truly 1-D (which is known

Table 2. Least squares and linear statistics for the Renner Springs data. See caption for Table 1.

Parameter value		A	B	Correlation matrix ρ_1	ρ_2	ρ_3	ρ_4	t_1	t_2	t_3
		(+ – per cent)								
ρ_1	6.19	6	5	1.0						
ρ_2	678	18	11	0.05	1.0					
ρ_3	20 000	5980	*	0.02	0.63	1.0				
ρ_4	500	9940	*	0.01	0.40	0.90	1.0			
t_1	27.1	8	7	0.86	0.18	0.07	0.04	1.0		
t_2	8560	197	19	0.02	0.73	0.99	0.83	0.09	1.0	
t_3	16 600	7030	65	−0.02	−0.61	−1.0	−0.92	−0.07	−0.98	1.0

System variance = 0.193 (= 0.165 if parms marked * held fixed).
Chi squared = 2.32.

not to apply at Renner Springs) or the model is fitting noise introduced by a non-1-D structure.

The Aileron data, like those of Renner Springs, do not on their own justify the inclusion of the conductive layer, yet produce a stable solution to the inverse modelling when it is included (Figs 6 and 7 and Table 3). The transverse resistance for this sounding is 10 times that of Wauchope and Renner Springs, or $3.0 \times 10^9\,\Omega m^2 \pm 22$ per cent. Thus the Arunta Block appears to be an order of magnitude more resistant than the Tennant Creek Block, implying an order of magnitude difference in resistivity, as long as the thickness of the resistant part of the crust does not differ appreciably between the two sites. In the Aileron model a system variance of 3.77 (Table 3), which is significantly greater than 1, reflects the inability to fit the Aileron data exactly using a 1-D model. It may be noted in Fig. 6 that the experimental sounding curve rises more steeply than 45° between 50 m and 5 km, which is impossible over a 1-D earth. Thus the assumed 10 per cent error is underestimating the effects of a non-1-D structure.

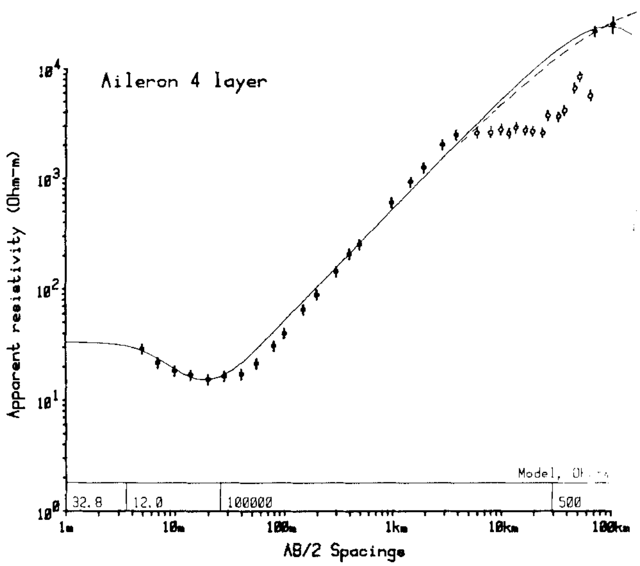

Figure 6. Aileron sounding data and least squares model. Minimum standard errors are ±10 per cent. See text for details.

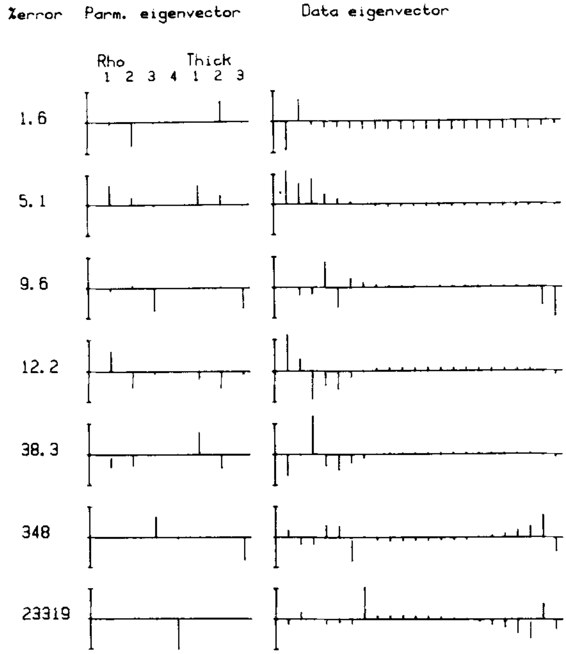

Figure 7. Eigenanalysis of the four layer model fitted to the Aileron data. See caption for Fig. 3.

Table 3. Least squares and linear statistics for the Aileron data. See caption for Table 1.

Parameter value		A	B	Correlation matrix						
		(+ – per cent)		ρ_1	ρ_2	ρ_3	ρ_4	t_1	t_2	t_3
ρ_1	32.8	40	36	1.0						
ρ_2	12.0	35	31	0.62	1.0					
ρ_3	100 000	1020	*	0.07	0.16	1.0				
ρ_4	500	5681	*	0.05	0.12	0.80	1.0			
t_1	3.57	65	58	−0.88	−0.85	−0.11	−0.08	1.0		
t_2	22.4	42	37	0.66	0.98	0.25	0.19	−0.87	1.0	
t_3	29 700	1780	43	−0.06	−0.15	−0.97	−0.92	0.10	−0.24	1.0

System variance = 3.77 (= 3.33 if parms marked * held fixed).
Chi squared = 56.54.

The total conductance of the layers above the resistive layer at Renner Springs is about three times greater than at Wauchope. This increased screening effect would prevent a deeper conductive layer from influencing the sounding curve at Renner Springs until the greatest electrode spacing is reached. The increased transverse resistance of the crust at Aileron would similarly prevent the roll-over from developing in the $AB = 200$ km sounding.

The possibility that the Wauchope roll-over is merely noise must be considered. The broken lines in Figs 2, 4 and 6 show the result of inverting the data without the inclusion of the deep conductor. These models give the resistivity of the Tennant Creek Block crust as 5700 Ωm ± 14 per cent (Wauchope) and 5900 Ωm ± 51 per cent (Renner Springs) and the Arunta Block crust as 45 000 Ωm ± 37 per cent. An order of magnitude difference in the resistivity of the two provinces is still shown. If the transverse resistance of the crust is calculated using an assumed crustal thickness of 40 km, results very close to those when the conductive layer was included are obtained.

6 Comparison with other studies

Conductive zones in stable crust have been previously observed in North America (Keller 1963; Keller, Anderson & Pritchard 1966; Samson 1969; Mitchell & Landisman 1971; Cochrane & Hyndman 1974; Chaipayungpun & Landisman 1977; Lienert & Bennett 1977; Sternberg & Clay 1977; Lienert 1979; Connerney *et al.* 1980; Duncan *et al.* 1980), the USSR (Antonov & Izyumov 1969; and see also a compilation of MT experiments in Keller 1971), southern Africa (van Zijl 1969, 1977; van Zijl & Joubert 1975; Blohm *et al.* 1977) and Europe (Migaux *et al.* 1960; Jones & Hutton 1979; Jones 1982).

The studies of van Zijl also employed the Schlumberger method for deep crustal sounding, in southern Africa. The lower surface conductance of his sounding locations (0.3–0.5 S) compared with the present study (2.6 S) allowed a much clearer observation of a mid-crustal conductor using similar electrode separations to those used here.

From an examination of the world-wide studies quoted above, the transverse resistance, T, of the crust is well constrained between 1.1 and $8.4 \times 10^8\,\Omega\mathrm{m}^2$. The present results of 2.1 and $3.3 \times 10^8\,\Omega\mathrm{m}^2$ for the Tennant Creek Block fall well within this range. The value of $3.0 \times 10^9\,\Omega\mathrm{m}^2$ for Aileron is outside this range, but this value is very poorly determined. The depth to the conductive zone has been variously estimated as between 5 and 40 km, but it is more commonly quoted as being between 15 and 25 km. There is some evidence that the depth to the top of such zones varies over relatively short distances (e.g. van Zijl & Joubert 1975; Jones & Hutton 1979). The maximum depth of 20 km to the conductive zone from the present study is consistent with these other results.

The present study gives no estimate of the thickness of the conductive zone. In contrast to the well-defined transverse resistivity of the upper crust, the conductance of the conductive layer has been variously reported as being between 30 and 2000 S.

7 Discussion

A strong heat-flow gradient exists between the Arunta Block and the Tennant Creek Block, as shown by the compilation of Cull (1982). The heat flow at Aileron is about $67\,\mathrm{mW\,m^{-2}}$, whereas the average for the Tennant Creek Block is about 92, with a peak value of about $117\,\mathrm{mW\,m^{-2}}$. Combining the geotherms for central Australia from Sass & Lachenbruch (1979) with these heat-flow values, three possible temperature–depth profiles are obtained, shown in Fig. 8(a). Using the dry granite/granodiorite resistivity–temperature relations of Kariya & Shankland (1983):

$$\log \rho = (4.32 \pm 0.46)\,(1000/t) - (0.39 \pm 0.48)$$

where t is absolute temperature, the resistivity–depth curves of Fig. 8(b) are obtained. It may be seen that the surface heat-flow accounts for the inferred order of magnitude difference in resistivity between the Arunta and Tennant Creek Blocks.

The dry rock resistivities above 40 km are too large to be consistent with the electrical sounding results, whether a uniform crust of resistivity $5700-45\,000\,\Omega\mathrm{m}$ is used or a conductive layer (the shaded region of Fig. 8a) is included to interpret the data. It is evident that the dry rock conductivities must be enhanced throughout the entire thickness of the crust. A compositional change from acidic to basic would lower the curves of Fig. 8(a) only by an order of magnitude (Kariya & Shankland 1983), and so may be eliminated as a cause of the lowered resistivity. The temperature–depth curves do not cross the dry granodiorite

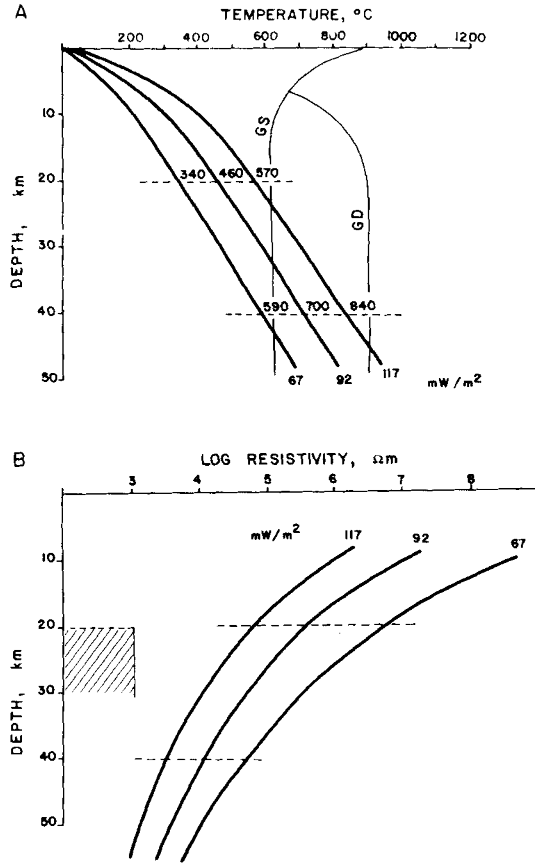

Figure 8. (a) Geotherms for central Australia given three values of least flow: 67 mW m^{-2} (Arunta complex), 92 mW m^{-2} (Tennant Creek Block average) and 117 mW m^{-2} (Tennant Creek Block peak). GS is the water saturated granodiorite solidus and GD is the dry granodiorite solidus. Temperature at depths of 20 and 40 km are given for the three geotherms (after Sass & Lachenbruch 1979). (b) Resistivity versus depth for dry granite/granodiorite derived from the geotherms in (a). The shaded area indicates the possible low resistivity region observed by the present study (the top boundary may be made shallower than 20 km).

solidus, and so partial melting of dry rock may also be excluded. However, if the crust were water saturated (as is discussed below), then the high heat-flow of the Tennant Creek Block suggests that partial melting might indeed occur.

Olhoeft (1981) shows that a few per cent by weight of water lowers the resistivity of dry granite by 9 orders of magnitude at surface temperatures and by 3 orders of magnitude near the melting point (about 1000°C). It is almost certain that water in cracks and fissures lowers the resistivity of igneous rocks at the surface of the Earth to their observed values of 10^3–10^6 Ωm. However, it is thought that lithostatic pressure at depths of 2–5 km closes these cracks which then anneal with time (Feves, Simmons & Siegfried 1977), allowing the rock resistivities to approach their dry values (10^6–10^9 Ωm). The transverse resistance for 10 km of such a crust would be 10^{10}–10^{13} Ωm^2, which is much higher than is observed in this or other studies. It thus seems that a small amount of water is present throughout the upper crust, probably on the order of 0.1 per cent. It is possible that this is due to the maintenance of porosity by tectonic stresses.

Water in larger quantities (0.5–2 per cent) may be responsible for producing a low resistivity layer in the crust. The concept of a wet lower crust was first proposed by Hyndman & Hyndman (1968). These authors suggested that water would be present under immature crust, but would be eliminated during metamorphism and tectonism, leaving a stable continental shield with a dry lower crust. This is in contrast to many of the studies cited above which, like the present one, were conducted in shield areas. It may be that some shield areas have retained water over long periods of geological time.

Serpentine has also been proposed as a lower crustal conductor (van Zijl 1977), based on studies such as by Zablocki (1964) and also Stesky & Brace (1973), who observed a 3 to 4 orders of magnitude lower resitivity in serpentinized rocks. However, not all the samples of Stesky & Brace (1973) had such lowered resistivity, and the authors speculated that the texture of the associated oxide minerals (magnetite, titanomagnetite, chromite) was important. This view has recently been supported by Parkhomenko (1982).

Magnetite has a resistivity of about $10^{-4}\,\Omega$m (Keller 1966), but it normally forms euhedral crystals which would not significantly enhance conductivity. However, during the serpentinization of olivine and pyroxene, iron is not accommodated in the lattice of serpentine and is excluded as magnetite as well as native iron, awaruite (Ni_3Fe) and wairauite (CoFe). This magnetite tends to form continuous aggregates of very fine grains around the pre-alteration grain boundaries, in a manner which could be expected to decrease the resistivity greatly. This hypothesis is substantiated by a study of Brace & Orange (1968), who observed a serpentinized gabbro having an anomalously low resistivity (about 6 Ωm). Non-serpentinized gabbros of similar oxide content had more normal resistivities of 10^3–$10^5\,\Omega$m. Because magnetite has such a low resistivity, it would require only about 0.1 per cent or less dispersed through the rock to increase conductivity appreciably.

Although hydrated minerals are common in the lower crust, they are not necessarily more conductive than non-hydrated ones; Olhoeft (1981) showed that dry hornblende (an amphibole) has a similar resistivity to dry granite throughout the crustal temperature range. However, such minerals, including serpentine, do decompose at high temperature to produce free water. Mitchell & Landisman (1971) proposed that if a crustal temperature–pressure curve crossed the equilibrtium boundary for such a decomposition, then a wet zone would appear in the crust. This mechanism would produce a conductive zone at a well defined pressure and temperature, fairly independently of crustal homogeneity. The difficulty with this theory is that the equilibrium temperatures (500–1000°C at surface pressures) are probably too high to occur in the crust.

Thus, unless the magnetite hypothesis is considered a tenable one, it is probable that the central Australian crust contains significant quantities of free water, whether meteoric, connate or derived from the dehydration of minerals. Partial melting is not likely to occur at crustal depths in this region without the presence of free water to depress the melting temperature.

8 Conclusions

In this study the use of the Schlumberger method for studying deep resistivity structure in Australian has met with limited success. The two major obstacles to the method are high surface conductance and lateral variations in resistivity. The use of the sophisticated signal processing system developed for this work (Constable 1983, 1984) in no way helps to overcome these two problems, although it does allow measurements to be made at large electrode spacings quickly and precisely.

Dipole-dipole or other resistivity sounding arrays offer no improvement on the Schlumberger method, in many respects they would be worse. Given more time and resources, additional measurements could be made to help resolve the geological noise problem (e.g. crossed soundings or the movement of one current electrode at a time). All resistivity methods would be plagued by the high surface conductance, which could only be overcome by extending the sounding curve yet further.

It appears that $AB = 200$ km represents the practical limit for resistivity studies (unless, like Blohm *et al.* 1977, one has a power station to provide the emission current). Extending the experiment to the entire length of available telephone line ($AB = 700$ km) would require several days' stacking per measurement using a 100 kW power supply to obtain only half a decade more data. Further deep crustal electrical studies in Australia should either combine Schlumberger sounding with high-frequency MT sounding, as suggested by Vozoff & Jupp (1975), or use a controlled source em method. Electromagnetic energy will propagate readily through the resistive portion of the crust, making it easier to detect any drop in resistivity below. Geological noise will always be a problem, but may be partially overcome by taking redundant measurements at different receiver positions or by detecting the magnetic rather than electric fields. The magnetic field response to an em experiment is less sensitive to small, near-surface inhomogeneities.

Notwithstanding the above comments, this work has provided valuable data. Firstly, it has been shown that the Arunta Block is an order of magnitude more resistant than the Tennant Creek Block. A difference in resistivity at the surface may be explained in terms of differing geology. For the deeper portion of the crust, which is likely to be more homogeneous because of the dominant effect of pressure and temperature, the higher heat flow of the Tennant Creek Block fully explains a difference in resistivity.

Secondly, this study shows that at least a small amount of water probably exists throughout the crust. Resistivities measured at all three sites are lower than estimated dry rock values for depths above 40 km.

Thirdly, it appears that there exists a large lowering of resistivity in the upper or middle crust. Unfortunately, the evidence for this conductive layer cannot be distinguished from geological noise with complete certainty. However, the large scale of the experiment and the lack of evidence in the surface geology for a structure capable of distorting the data suggest that the experiment is truly measuring resistivity variation with depth. If such a conductive zone exists, then it would indicate larger quantities of water, say 0.5–1 per cent, at depth in the crust. Alternatively, mechanisms such as partial melting or serpentinization could account for the lowered resistivity.

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