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Electrical Conductivity Anomalies in the Australian Lithosphere: Effects on Magnetic Gradiometer Surveys

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Abstract

The use of recording magnetometers to observe natural magnetic fluctuations across different parts of Australia is delineating areas where the fluctuations are anomalous. These areas are termed 'conductivity anomalies', as the fluctuation patterns must be due to regions in the lithosphere of high electrical conductivity, where the naturally induced electric currents are concentrated. The main causes of such enhanced lithospheric conductivity are thought to be (i) water, with impurities (especially salt), and perhaps with well-connected paths of conduction due to fracturing of rock; (ii) highly conducting minerals such as graphite, and (iii) heat (which may cause partial melting at the lithosphere base).

The fluctuating magnetic fields near a conductivity anomaly may cause difficulty for the data-reduction of a high-resolution aeromagnetic survey which is carried out during magnetic activity. Making gradiometer survey measurements avoids such effects, to the extent that the magnetic fluctuations are spatially uniform.

This paper examines the maximum spatial magnetic gradients likely to be associated with a strong (and shallow) continental conductivity anomaly, and determines values in the range 1 to 10 nTkm^{-1}. Such gradients in the static magnetic field are typical of a sedimentary basin, but are much less than those which occur where the magnetic relief is strong. While the magnetic fluctuation fields of conductivity anomalies should be kept in mind during magnetic surveying, gradiometer measurements should generally be effective in minimizing their influence.

Key words: electrical conductivity, conductivity anomalies, magnetic surveys

Introduction

This paper refers to the magnetic field measured at the Earth's surface. It is important to recognize the following two parts to this magnetic field (Parkinson 1983):

(i) The 'steady' or main magnetic field of the Earth, which originates in the Earth's core. This part is perturbed by the magnetized layer at the surface of the Earth to give the magnetic anomaly patterns of magnetic surveying. (Though termed 'steady', the main field changes over tens of years to exhibit the magnetic secular variation; over geological time-scales, in the past, the main field has reversed.)

(ii) The fluctuating or transient magnetic field of the Earth, which changes over time-scales of seconds, minutes, hours and days. This part arises from electric currents flowing outside the Earth (through the ionosphere), inside the Earth (especially through good electrical conductors), and in the oceans.

These two parts of the magnetic field at Earth's surface are quite distinct in physical cause: the former associated with rock magnetization, the latter with rock electrical conductivity. Their different physical causes typically give them different scale-lengths of horizontal variation (a point which is critical to the present paper).

Both phenomena are topical in geophysics at present: the former because of advances in high-resolution aeromagnetic surveying and data presentation, and the recognized value of the resulting maps to geological exploration; the latter because determining the electrical conductivity structure of continents, by mapping their magnetic fluctuation response, is analogous to the earlier geophysical challenges of mapping continental gravity and magnetic fields.

Though thus distinct in physics, the two phenomena do however overlap, because a moving survey vehicle, intent on measuring variations of the steady field with space, will also measure variations of the field with time. The data reduction procedures of magnetic surveying reduce such effects, but their complete elimination has become increasingly important with the development of modern high-resolution techniques in both survey design and instrumentation.

A major reduction of the fluctuating field problem is offered by magnetic gradiometer measurements, which will be unaffected by fluctuations which are spatially uniform. To check on the likely effectiveness of such gradiometer measurements, this paper therefore examines the spatial uniformity of the magnetic fields associated with a typical strong conductivity anomaly, chosen as a likely 'strongest case'.

A point needed for reference is that a 'total-field' magnetometer (as used in aeromagnetic surveying) will be affected only by that component of the fluctuating field which is in the direction of the steady total field. Thus if, in Figure 1, a field change ΔT perturbs the ambient field F, the total-field instrument will measure a change ΔF given by

$$\Delta F = \Delta T \cos A$$

where $\Delta T = (\Delta H^2 + \Delta Z^2)^{1/2}$

and A is the angle between ΔT and F, or, more directly

$$\Delta F = \Delta Z \sin I + \Delta H \cos I \tag{1}$$

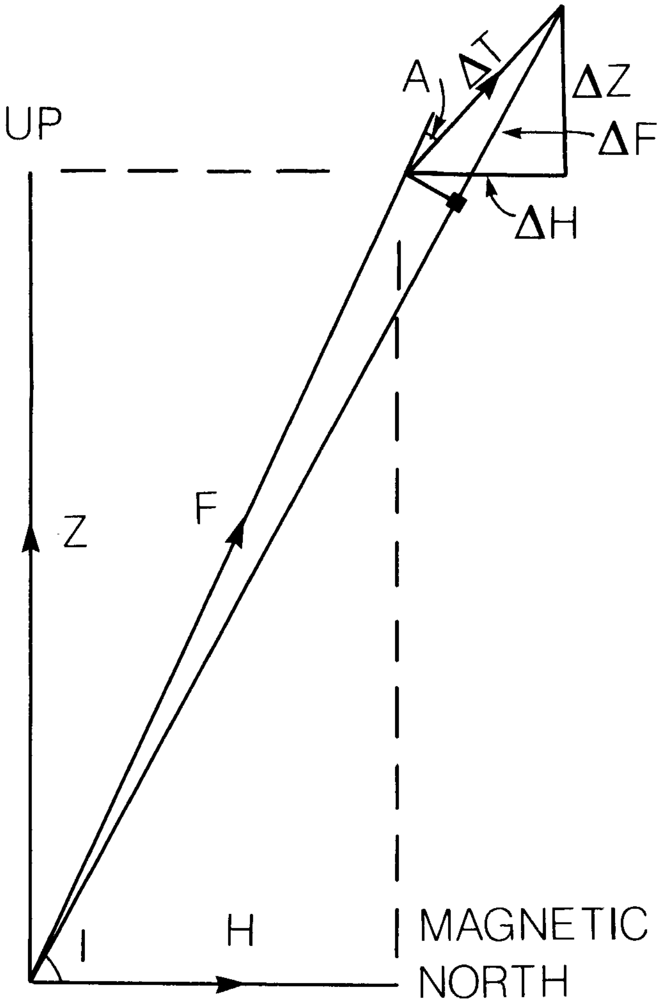

FIGURE 1
The effect of superimposing a magnetic fluctuation ΔT (of horizontal and vertical components ΔH and ΔZ) upon a steady magnetic field F (of components H and Z). The total field increases not by ΔT but by ΔF. The changes (assumed small) are exaggerated in the figure for clarity. Note that a similar small change in declination, a swing of the field horizontally to the east or west, does not affect the magnitude of F.

Electrical Conductivity Anomalies in the Australian Lithosphere

By observing naturally occurring magnetic fluctuations, with instruments which are essentially magnetic observatories set up at temporary sites, an electromagnetic survey of a continent like Australia can be made using natural source fields. Because such a temporary magnetic observatory at a site should record for a time of at least days and preferably weeks, coverage of a large continent is slower than, for example, a gravity survey. However, a major advance for Australia occurred recently with the AWAGS project (Chamalaun and Barton, 1989, 1990) which observed at a network of sites across the whole continent. Such studies are demonstrating considerable character in electrical conductivity structure, as demonstrated by the different examples of the Eyre Peninsula anomaly in South Australia (White and Milligan, 1984, 1986), and the Tamar anomaly in Tasmania (Parkinson and Hermanto, 1986; Parkinson *et al.,* 1988). A third recent example is the Canning Basin anomaly reported by Chamalaun and Whellams (1990).

Effect of Conductivity Anomalies upon Magnetic Gradiometers

The effect referred to in the introduction (that changes of the magnetic field with time will contribute error to the data of a moving survey vehicle) can be greatly reduced by making the survey measurements with a magnetic gradiometer. Then, changes of the magnetic field with time which are spatially uniform will have no effect upon the gradiometer records. However the fluctuating magnetic field of a conductivity anomaly will in fact have some (non-zero) gradient in space, and this matter is now addressed.

Figure 2 shows a simple model for a conductivity anomaly: that of a line of electric current buried in the Earth. The magnetic fields at the Earth's surface of such a line current are shown in the figure; these are the anomalous components due to the conductivity anomaly, and they will vary with time as the supporting current grows and decays. The figure is based on direct-current theory, for slow changes with time, though the line current is itself induced by changing electric currents outside the Earth. Due to the spatial uniformity of the ionosphere at mid-latitudes like Australia, the external source fields are taken to be uniform for the present exercise.

The field components due to the line current are therefore the contribution of the conductivity anomaly to the total-field pattern, and add on as shown in Figure 1. For regions of high magnetic inclination (and most of Australia has a magnetic inclination numerically greater than 50°), equation (1) shows that signals in the vertical-field component ΔZ will make the dominant contribution to the observed total-field anomaly ΔF.

To return to the line current of Figure 2, the vertical field shown varies with horizontal distance x (measured from the line-current position) as

$$V(x) = k\,x\,(x^2+p^2)^{-1}$$

where $k = \tfrac{1}{2}\,\mu_0\, I\, \pi^{-1}$

μ_0 is the permeability of free space ($4\pi 10^{-7}$ mks units), I is the strength of the line current in ampere, and p is the depth of burial (in metre) as shown.

Also, when the line current model is superimposed upon the Earth's steady field, V(x) becomes ΔZ.

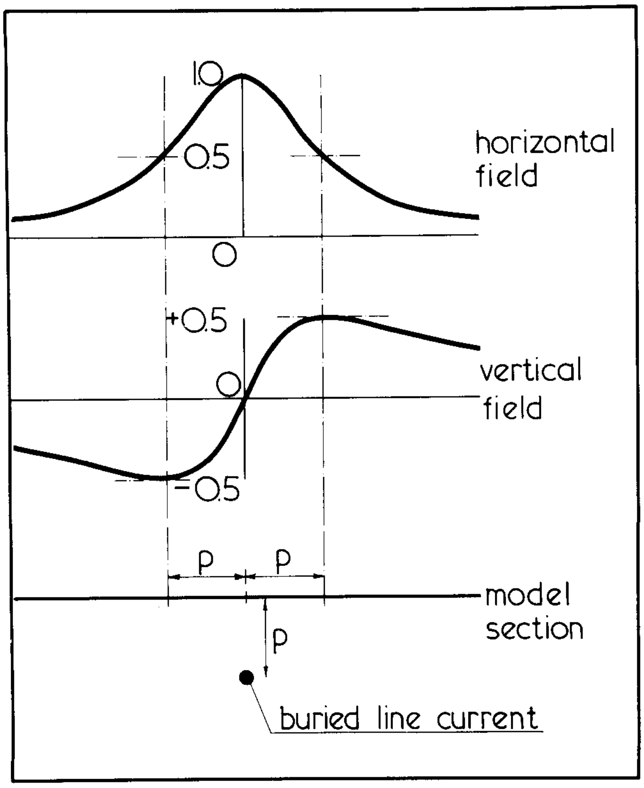

FIGURE 2
Profiles of horizontal and vertical magnetic field across a buried line current, which is long in the direction perpendicular to the diagram. Field strengths are scaled in units of $\mu_0 I/(2\pi p)$ mks, where I is the strength of the line current and p its depth of burial. Thus a current at depth 10 km of strength 5000 A gives a peak-to-peak vertical field anomaly of 100 nT.

The horizontal gradient of V(x) is given by

$$\frac{dV(x)}{dx} = \frac{k}{p^2}\,\frac{(1-x^2/p^2)}{(1+x^2/p^2)^2}$$

with maximum value, k/p^2, above the line current. The peak-to-peak range of V(x) is k/p, so that the maximum horizontal gradient is in fact this peak range divided by the depth of burial.

In a strong case, the peak-to-peak range of the fluctuating field above a conductivity anomaly could be say 10 to 100 nT. Thus, for a depth of burial of say 10 km, the horizontal gradient is in the range 1 to 10 nTkm^{-1}, with 10 nTkm^{-1} as a maximum figure.

As an actual example, the data of Figure 3 for the Eyre Peninsula conductivity anomaly of White and Milligan (1984), at the peak of the magnetic storm event, show a difference of some 100 nT in the vertical component between stations CB and OT, which are 16 km apart. Hence a horizontal gradient is present in the vertical magnetic field of order 6 nTkm^{-1} averaged between stations CB and OT (very possibly, between these two stations, there are places where the gradient is locally steeper). The example from Tasmania in Parkinson and Hermanto (1986) would give a comparable result.

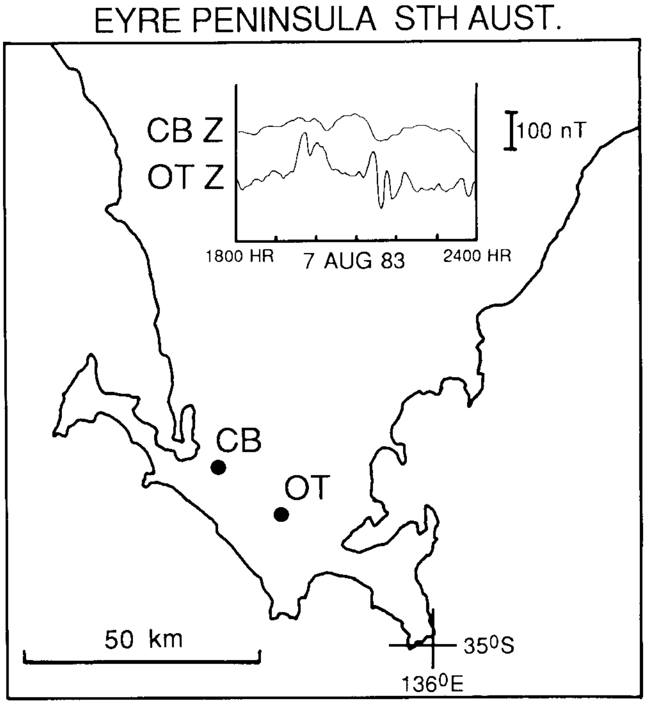

FIGURE 3
Data from White and Milligan (1984) for the Eyre Peninsula, South Australia, showing the contrast in vertical field fluctuations at two stations CB and OT. The two stations lie on either side of a major electrical conductivity anomaly.

Actual aeromagnetic maps show gradients or order 500 nTkm^{-1} to be common in areas of strong magnetic relief (for example where volcanic rocks outcrop at the surface), ranging down to order 1 nTkm^{-1} for a very flat and featureless field, as over a sedimentary basin. It may be expected then that the effect of a conductivity anomaly, at its strongest, will be unimportant in the former case, but perhaps not negligible in the latter.

To some extent the seriousness or otherwise of a conductivity anomaly error will depend upon the purposes to which the survey gradient data are to be put. If the purpose is to define regions of strong magnetic relief by identifying the characteristic of strong horizontal derivative, then the gradiometer data will be effective in removing fluctuation effects. If however the purpose is to recover the total-field profile by integration (a procedure which would certainly require care), then a weak conductivity anomaly gradient, of order 1 nTkm^{-1}, would be important if integrated over a distance of order 100 km.

The cases examined in this paper have been set up as 'strongest cases' (or 'worst cases') from the point of view of magnetometer survey error. During undisturbed magnetic periods, even above such conductivity anomalies, gradiometer surveys will be relatively error-free. For at such times the varying background field will be the quiet daily variation (Milligan, 1986), and due to its longer period and deeper penetration in the Earth, the daily variation does not exhibit conductivity anomalies as spatially sharp as those discussed above.

Conclusion

For gradiometer magnetic surveys, as for regular total-field magnetometer surveys, it is valuable to know the major electrical conductivity anomalies of a continent. Away from them, magnetic surveying should be able to proceed even during disturbed times; in their vicinity it may clearly be circumspect to operate only during magnetic quiet periods.

For the fluctuating field of a conductivity anomaly to give a spurious magnetic gradient comparable to that of a magnetically anomalous area, very particular circumstances would need to apply. The conductivity anomaly would need to be shallow in source (of maximum depth several km) and strong, and the survey instrument would need to cross it during strongly active magnetic conditions. To the extent that these circumstances are unlikely to occur together, gradient measurements are confirmed as generally an effective guard against the effects of conductivity anomalies.

The gradiometer is effective in such cases because of its basic property of filtering out a signal of long horizontal wavelength (and conductivity anomalies have magnetic fields of this kind), relative to the short horizontal wavelength of the magnetic anomalies of crustal rocks. Thus it is basically an inequality of two horizontal scale-lengths which renders the 'filtering' by gradiometer effect. The gradiometer is not therefore such a good discriminant above rock magnetic anomalies of long spatial wavelength, such as those typically found over sedimentary basins. Also any spatial integration of observed gradiometer data must clearly be carried out with care.

In high-resolution aeromagnetic surveying, the effects of induction are subtle rather than dramatic: where gradiometers are used, even the strongest effects of induction are slight. However the way to ensure they do not introduce serious error is to remain on guard for them.

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