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THE ELECTRICAL CONDUCTIVITY STRUCTURE OF GEODYNAMIC PROCESSES

F.E.M. LILLEY

Research School of Earth Sciences, Australian National University, Canberra, A.C.T. (Australia)

ABSTRACT

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Geodynamic processes involving heating and especially melting should have distinctive electrical conductivity structures, as the electrical conductivity of rock is strongly dependent on temperature and may change by an order of magnitude upon incipient melting; electrical conductivity can also change with the fabric modification of a rock, as in the formation of serpentine.

Regional electrical conductivity can be studied by exploiting the common phenomenon of natural electromagnetic induction in the earth. Much of the physics of this process is still being analyzed and described, so that the method is not at the stage of being part of "orthodoxy". Both model and field examples show that rifts and trenches, the basic elements of geodynamics, should and do exhibit conductivity anomalies. While the anomaly of a particular model can be computed quite accurately, quantitative models for particular field data usually have poor resolution and are useful mainly to demonstrate the nature of any qualitative conductivity contrast present.

A number of major conductivity structures have so far been found in Australia, a continent free of active first-order rifts and trenches. The causes of these structures are undetermined at present, and are a subject for research in the future.

PREAMBLE ON THE EARLY OBSERVATION OF MAGNETIC FLUCTUATIONS IN TASMANIA

This paper will be concerned with the interpretation of fluctuations of the earth's magnetic field as recorded by geophysical observatories, both permanent and temporary. In this contribution to the Carey Symposium held in Hobart, it is appropriate to note that the first regular magnetic observatory in Australia operated in Hobart from 1840 to 1853. Built by 200 convicts under the patronage of the then governor Sir John Franklin, and named "Rossbank", the observatory itself and the publication of its observations are described in recent historical papers by Day (1966) and Green (1972). A painting of "Rossbank" by Thomas Bock is held by the Royal Society of Tasmania.

INTRODUCTION

The strategy of the subject of this paper has much in common with other geophysical researches, in that a process of physics occurring within the earth is examined to see what geological information it might yield. The particular process of physics in this instance is natural electromagnetic induction, which depends upon the electrical conductivity of the earth. Information on the electrical conductivity in the earth may thus be sought, though it should be noted from the outset that there is no "a priori" basis to expect this information to be given at all completely. The situation is more that certain conclusions may be possible if the electromagnetic induction can be assumed or shown to occur under certain conditions. These physical constraints are still being determined, but generally no reasonable assumption allows the problem to be solved completely, with the conductivity then known everywhere.

The basic physics of the process is that electric currents flow outside the solid earth in the ionosphere and magnetosphere, and that they change with time. They thus induce, by common electromagnetic induction, electric currents which flow in the earth, in the sea water, and preferentially where the rock is of greatest electrical conductivity. By using magnetic observatories to detect the fields of the secondary currents, the current paths may be mapped. Extra information, particularly concerning depth, may come from using the wide frequency band over which natural electromagnetic induction occurs. Figure 1 illustrates the phenomenon.

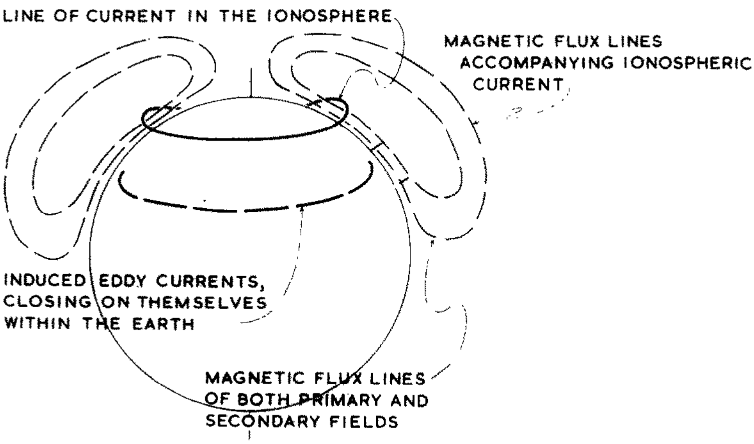

Fig. 1. Sketch of the process of natural electromagnetic induction in the earth. All the magnetic fields and electric currents shown vary with time.

The method is feasible because electrical conductivity varies over orders of magnitude in common earth materials. Some representative examples demonstrating this range are:

	Conductivity (S/m)	Resistivity (Ωm)
Igneous rock	10^{-4}	10^{4}
Sedimentary rock	10^{-2}	10^{2}
Molten basalt	10^{0}	10^{0}
Sea water	4	0.3

A fundamental ambiguity follows from the fact that electrical conductivity by no means uniquely determines geological composition, fabric or temperature. Even when the difficulties of physical interpretation are overcome and an electrical conductivity structure is arrived at, creative interpretation taking other geological information into account is still required to transform the physical model into a geological one.

A MID-OCEAN RIDGE AS AN EXAMPLE OF A MODEL CALCULATION

Calculating the geophysical response of a particular model structure is now commonly known as solving a "forward problem". Figure 2 shows such a problem in electromagnetics solved for a particular ocean ridge model. The electromagnetic response of the structure is strong, easily resolvable with modern instruments, and representative of anomalies found over recognized rift valleys; for example in Kenya (Banks and Ottey, 1974) and the Gulf of California (White, 1973). Carey's (1970) rift model would have a similar electromagnetic response.

Figure 2 is in fact for a mid-ocean ridge and includes the effect of ocean water, and a possibility for the future lies in setting up lines of ocean-bottom observatories across recognized mid-ocean rift systems.

INTERPRETATION OF OBSERVED DATA: THE "INVERSE PROBLEM"

The model in Fig. 2 is specified quite precisely; in the interpretation of actual observed data, however, such precision (though often shown) may be quite misleading: actual structures cannot be determined with such resolution. The very difficult problem of inverting real data is currently receiving much attention. The present status of the subject is that, with some computing effort, simple models may be constructued which at best fit the data satisfactorily. While each such simple model will be specified precisely, little is generally known about its resolution: that is, the extent to which other similar (or dissimilar) models would also fit the data. In the absence of such resolution information, the main use of particular quantitative models lies in demonstrating the kind of qualitative structure which may be said to definitely exist.

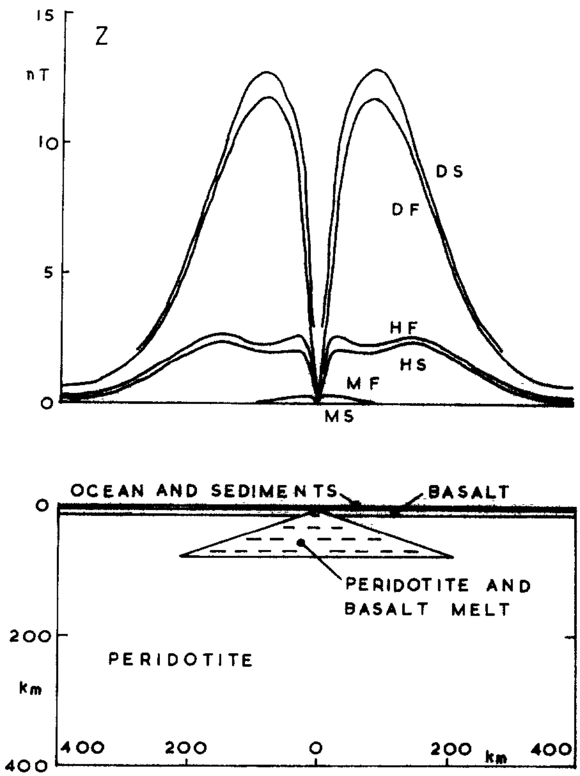

Fig. 2. Electrical conductivity model for a mid-ocean ridge and its electromagnetic response, from Duba and Lilley (1972). *Z* is the amplitude of the vertical component of magnetic field fluctuation due to the ridge structure. *D*, *H* and *M* stand for fluctuations of period 1 day, 1 h and 5 min, respectively. *F* and *S* stand for measurements at the sea floor and sea surface, respectively. The inducing field is horizontal across the ridge and of amplitude 50 nT.

An example of the interpretation of observed data is that of the coast effect, first demonstrated by Parkinson (1959). Figure 3a shows Parkinson's arrows for Australia, which indicate a conductivity contrast at or near the coastline, with the better conductor on the ocean side. The seawater makes a major contribution to this effect, but may not be sufficient to account for it completely. To interpret data recorded in southeastern Australia at the long periods of the daily variation, Bennett and Lilley (1974) found it necessary to postulate also a substantial body of good conductor beneath the sea floor. This interpretation model for the Tasman Sea is shown in Fig. 3b.

REVERSED COAST EFFECT IN SOUTH AMERICA

The coast effect is observed widely throughout the world, but there are some notable perturbations to it in tectonic areas. A particularly strong

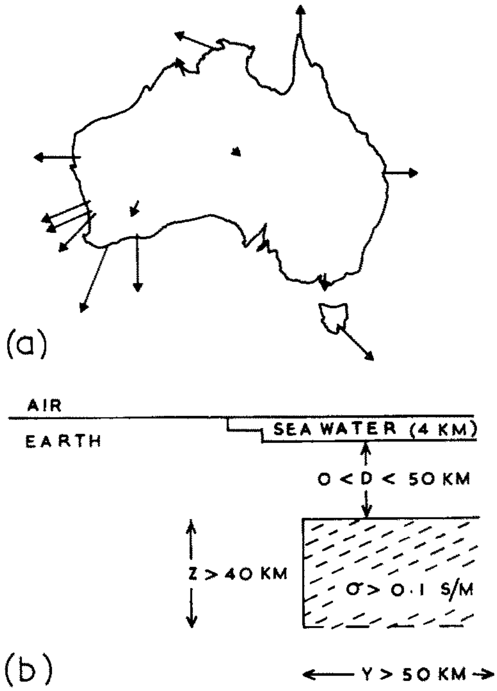

Fig. 3a. Parkinson's arrows for Australia showing the coast effect, (from Parkinson, 1964). b. Electrical conductivity model for the southeast Australia coast and the Tasman Sea (from Bennett and Lilley 1974), showing the region of high conductivity interpreted on the basis of daily variation observations to exist beneath the sea floor.

example, where the coast effect is even reversed, occurs in southern Peru. Figure 4 shows the line of the conductivity anomaly mapped to lie beneath the Andes, of such major proportions that its effect on a coastal station outweighs the effect of the ocean structure on the other side of the station.

An interpretation model for the anomaly from Schmucker (1973) is also shown in Fig. 4. Although apparently simple, it is the result of much advanced mathematical computation. However, its resolution would be such that its exact shape and conductivity values cannot be taken literally, but rather signify the qualitative and fundamental fact that a very substantial body of good conductor lies under the Andes. Considering the volcanic history of the region, this body clearly may be a melt zone.

WORK IN AUSTRALIA

Following the pioneering work of Parkinson, there have been a number of different projects intended to study the electrical conductivity of the Australian continent, using natural electromagnetic induction. Four array studies (see Fig. 5) have specifically sought electrical conductivity structure in

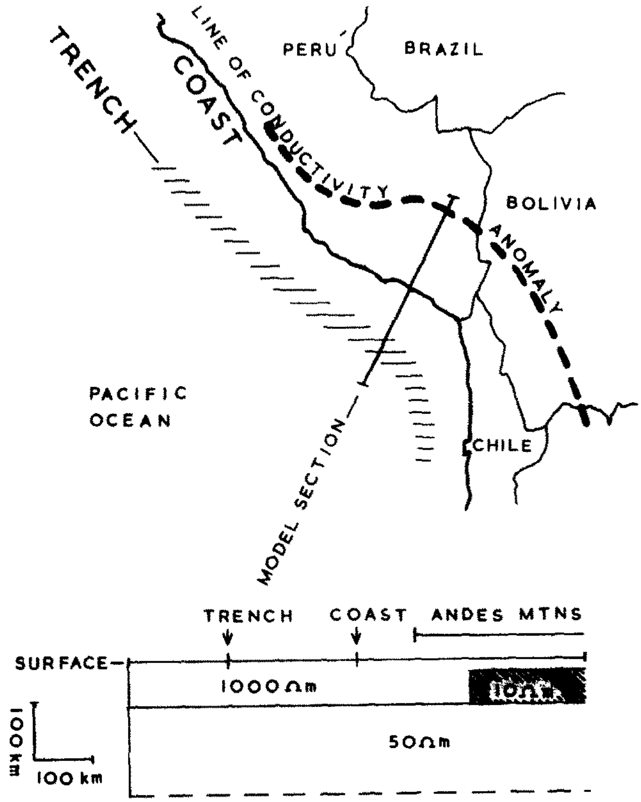

Fig. 4. Map of the Pacific coast of South America, showing the line of the Andean conductivity anomaly. Drawn beneath is the interpretation model for the structure, showing the body of good conductor interpreted to exist under the mountain range, after Schmucker (1973). Resistivity rather than conductivity values are given: the latter are the reciprocal of the former.

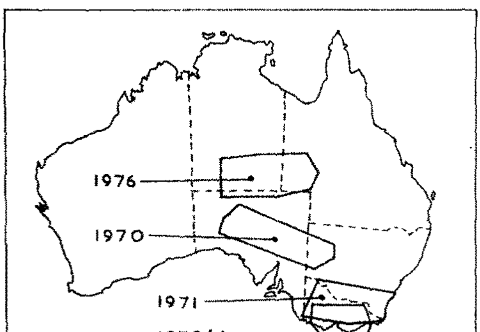

Fig. 5. Map of Australian magnetic variometer array operations.

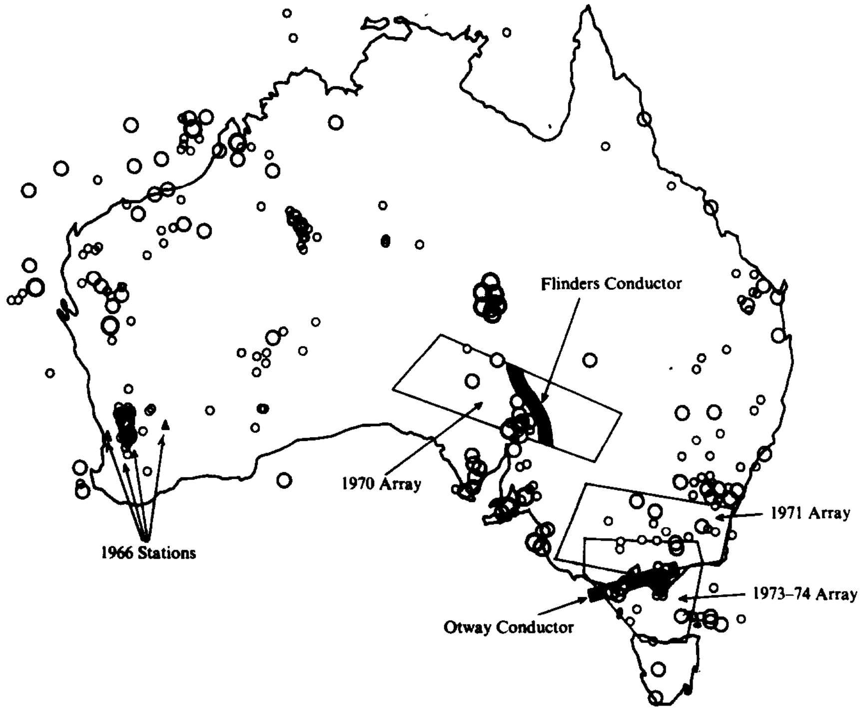

Fig. 6. The Flinders and Otway conductivity anomalies plotted on a map of Australian seismicity (from Lilley 1975).

departures from uniform layering. They have discovered within the continent two major anomalies, which have been called the Flinders and Otway anomalies respectively, and which are interpreted as zones of high electrical conductivity. They are shown in Fig. 6 from a paper which discusses the possibility that they occur in association with zones of seismicity.

The anomalies may be part of a geodynamic pattern for the whole Australian continent, and the 1976 array was carried out in part to seek the possible northward extension of the Flinders anomaly. Reduction of the data is currently in progress, but something of the excitement of discovery can be sensed by examining the examples of basic record shown in Fig. 7. Between two stations in western Queensland, there is a clear reversal of vertical magnetic fluctuation trace, indicating that a body of good conductor has been straddled by the two stations. Further work will tell whether this is a northern continuation of the Flinders conductor occurring in the 1970 array area.*

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* *Footnote added March 1979:* The reversal of the vertical component of magnetic fluctuations shown in Fig. 7 was further investigated by additional stations occupied in the area in 1977. A report of this subsequent work is now in preparation.

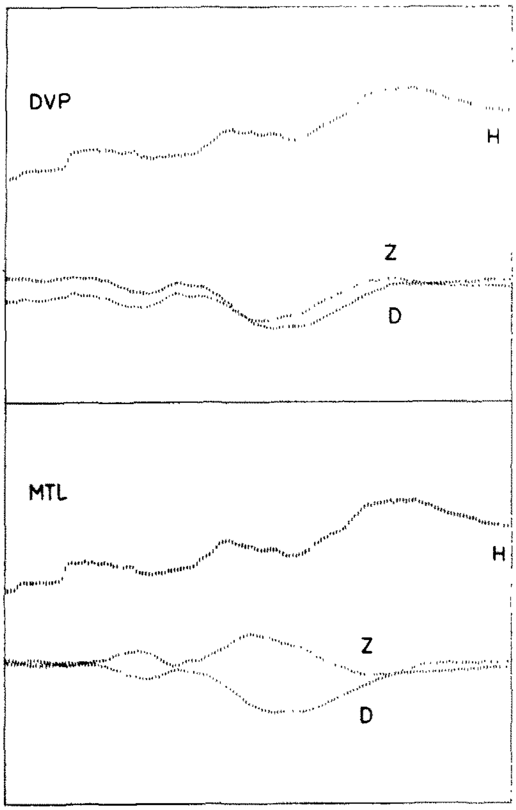

Fig. 7. Examples of the basic film records obtained from the 1976 array operation, showing a reversal in the vertical fluctuation component (*Z*) between the two west Queensland stations, Davenport Downs (*DVP*) and Mt Leonard (*MTL*). The records shown are of approximately 2½ hr duration.

CONCLUSION

Studies of natural electromagnetic induction indicate areas of gross earth anomalous conductivity, which cannot at present be found in any other way. The development of techniques to fully exploit this phenomenon is still proceeding, with the basic physics being continually better understood, and the possibilities and limitations becoming better defined. The positive effects the method shows in geodynamic regions emphasize its potential for the future.

ACKNOWLEDGEMENT

The 1976 array is a joint project of the author with a colleague, Mr D.V. Woods. Figure 7 is an example of the data obtained in this project, which is so far otherwise unpublished.

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