Exploration Geophysics (1986) 17, 22

Geomagnetic Induction

The study of geomagnetic induction physics

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Fluctuating electric currents, flowing external to the earth in the ionosphere, the magnetosphere, and beyond, act as primary source fields which cause electromagnetic induction in the solid earth. Secondary electric currents (or 'eddy currents') are thus induced to flow in the earth's oceans, crust, and upper mantle. The horizontal distances over which the primary and secondary currents flow are of the order of thousands of kilometres.

The flow patterns of the secondary currents are controlled by the electrical conductivity structure of the earth. The phenomenon of natural geomagnetic induction may thus be exploited to study the electrical conductivity structure of the earth from the surface down to depths of the order of hundreds of kilometres.

Two horizontal length scales

There are two important horizontal length scales to the phenomenon of geomagnetic induction. One length scale is the horizontal distance over which the source field can be considered to be uniform. The other length scale is the horizontal distance over which the geological structure can be considered to be laterally uniform. The relative sizes of these two length scales indicate whether induction can be approximated as 'one-dimensional', for which geological structure is horizontally layered relative to source field non-uniformity, or 'two- or three-dimensional', for which source fields may be considered uniform relative to geologic non-uniformity.

Whether the induction taking place is one-dimensional, or two- or three-dimensional, strongly affects the geophysical characteristics which will be observed in field observations, and also affects the style of the geophysical information which can be obtained by interpretation of the observations.

Geomagnetic induction approximated as one-dimensional

In a one-dimensional situation, observed data may be interpreted to give a vertical profile of electrical conductivity varying with depth into the earth. The data may be observed by single-site magnetotelluric instruments, which measure the horizontal components of the fluctuating magnetic field, and of the fluctuating electric field at the earth's surface. On a larger (but still continental) scale, observations of the fluctuating magnetic field with arrays of recording magnetic variometers may be interpreted by the 'horizontal spatial gradient' method to give profiles of electrical conductivity with depth. Such arrays themselves detect the horizontal length scale of the geological structure, and also obtain a measure of the non-uniformity of the primary source fields. On a global scale, the interpretation of magnetic fluctuation data from the world-wide network of magnetic observatories has traditionally been in terms of an earth in which electrical conductivity varies with radius only, and so is 'one-dimensional'.

Geomagnetic induction in two-dimensional and three-dimensional geological structures

The most spectacular geomagnetic induction observations are those from situations where the induced secondary or eddy electric currents flowing in the ground are strongly concentrated along particular paths. Such paths must be geological structures of increased electrical conductivity and are referred to as 'conductivity anomalies'. In such cases it is not uncommon for the vertical component of the magnetic fluctuating field to be reversed between two different observing sites perhaps only tens of kilometres apart in horizontal distance.

The mapping of electrical conductivity anomalies in the earth is thus a method for obtaining geological information not available by other means. For much of the earth (including Australia) the work is just commencing, with large parts of continents not yet explored for their basic electrical conductivity structure. Exploration of the ocean basins is even more at a pioneering stage, involving as it does the extra technical challenge of making electromagnetic fluctuation measurements on the deep-sea floor.

An example and an application

Figure 1 shows the areas covered by major magnetometer array studies in Australia, and the main regions of anomalous

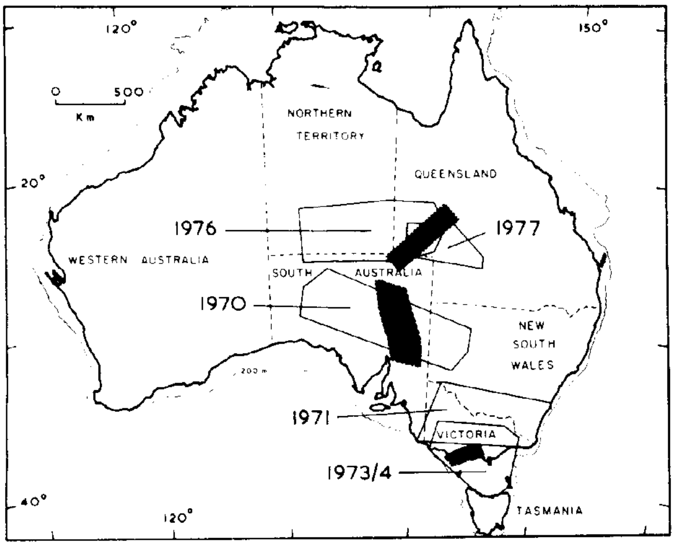

Fig. 1 Areas covered by magnetometer array studies in Australia. Hatched regions mark the zones of strongest spatial non-uniformity in magnetic fluctuation patterns. In addition a 'coast effect' may be expected to be present everywhere around the edge of the continental shelf. The areas away from the marked zones are not necessarily regions of completely uniform magnetic fluctuation patterns.

geomagnetic induction mapped by them. Some further electrical conductivity anomalies are now known, notably in South Australia and Tasmania. Figure 2 shows simultaneous records of a simple magnetic substorm event as recorded at the sites of the 1977 array in western Queensland (carried out by D. V. Woods). The fluctuation signals in the amplitude of the total magnetic field, denoted F, have been computed from the other scalar components observed: north, east, and vertically downwards. Figure 2 shows that across the array area, even between sites only tens of kilometres apart, there are major differences in the vertical component (Z) of the fluctuations, which carry across to the total field amplitude (F).

One application of such data (besides its fundamental use in mapping earth conductivity structure) is to the procedures of accurate magnetic surveying, especially airborne and seaborne. Accurate magnetic surveys are important both in the exploration for minerals, and also of sedimentary basins for structures of possible hydrocarbon significance. Because such surveys measure the steady part of the earth's magnetic field (arising from crustal magnetization) fluctuations in the field from the process of geomagnetic induction are a spurious signal to be removed. Such removal may be carried

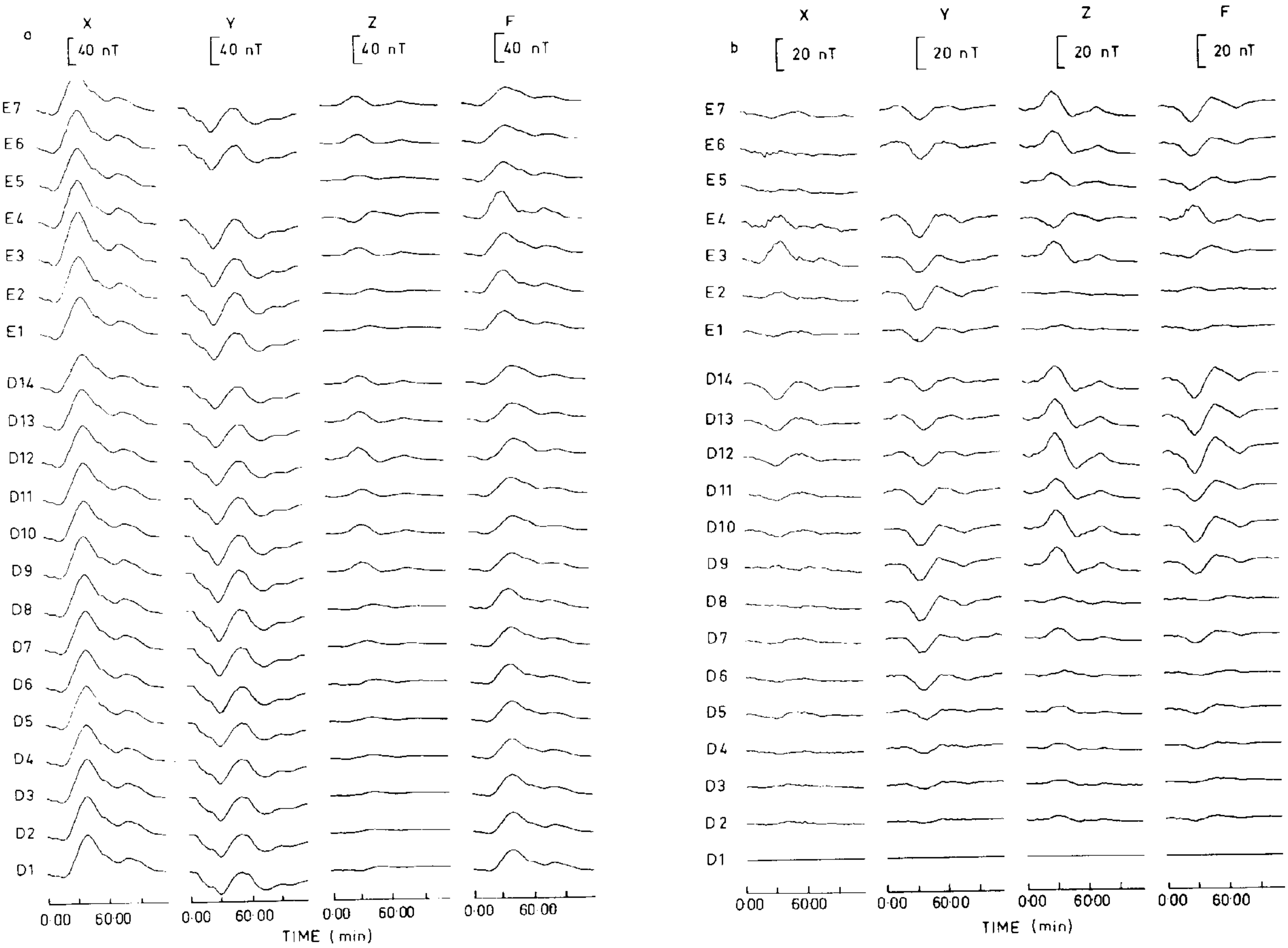

Fig 2 (a) Stacked profiles from the observations of the 1977 array of a magnetic substorm event commencing at 1105 h on 13 September 1977 UT and lasting for 115 min. (b) The difference profiles for the same event, obtained by subtracting the records of station D1 from all other station records.

out by subtracting a base station record made simultaneously with that of the moving survey instrument, but only if fluctuations at the base station and at the survey instrument are expected to be the same. Such information is precisely that supplied by observations such as those in Fig. 2. In places, in Australia, base station and survey instrument may correctly be separated by distances of approximately 100 km. In other places, and notably near coastlines, significant errors may be introduced by 'base station to survey instrument' distances of as little as 10 km. Knowledge of the geomagnetic induction patterns of a continent and of its coastal seas allow such errors to be minimized.

The spatial pattern of the daily magnetic variation over Australia, with application to the correction of magnetic survey data

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Time variations of the earth's geomagnetic field, with periods of a few seconds to the daily variation, can introduce errors of up to tens of nanoteslas into magnetic survey data (Lilley 1982; Riddihough 1971). These errors may be removed either by rapid looping methods similar to those used in gravity surveys, or, as is more usually the case, by subtracting from the survey data the record of a continuously monitored ground station. This latter method usually works well if the survey is undertaken relatively close to the base monitor, but when the distances involved become of the order of several hundred kilometres, as they may in aeromagnetic surveying in Australia, the assumption of uniform variations on this scale may not be valid. Since magnetic surveys are not usually undertaken on days of strong disturbance of the geomagnetic field, the main errors will arise from pulsation events (I. Hone & D. Pridmore, pers. comm.), and from the daily variation, which is further considered here.

Spatial non-uniformities in the daily variation can arise either from irregularities in the ionospheric current systems producing the primary external field, or from secondary fields produced by currents induced in the ground by the primary field. In general, the normal daily variation differs between observation sites with a simple local-time phase dependence, as the earth rotates beneath the source currents, which remain stationary with respect to the sun, and with a smooth latitude dependence observed in the amplitude (Lilley 1982).

Several anomalous zones have been defined in Australia by Lilley (1982, 1984), using arrays of magnetometers. The effects are most noticeable for short period events of up to a few hours duration, but significant lateral variations in the diurnal field are visible in the records from near Cobar, where current-channelling is postulated within the near-surface formations. The coast effect across south-east Australia is also prominent in the daily variation (Bennett & Lilley 1973). Anomalous zones in northern South Australia and south-west Queensland are most obvious for short-period events, and this is true again for the more southerly regions of South Australia, which have now been mapped in some detail (White & Polatajko 1978, 1985; White & Milligan 1985; Chamalaun 1985). It is interesting that a very strong anomaly at short periods on the southern Eyre Peninsula, South Australia (White & Milligan 1984), appears to have negligible effect on the daily variation. There are, however, still large areas of Australia, particularly in Western Australia, the Northern Territory, and eastern Queensland, where geomagnetic variation studies using arrays of magnetometers have not been undertaken; hence geological effects on the magnetic variations are unknown for these regions.

Some information regarding the spatial distribution of the daily variation across Australia is available from recordings made by the Bureau of Mineral Resources (BMR) as part of their first-order magnetic surveys for the production of epoch maps of the seven geomagnetic elements. Records of H, D, Z and F are available for at least 2 days in succession from a network of more than 60 repeat sites across Australia (Fig. 1). Although these data have not been simultaneously recorded, variations at each site may be compared with observatory data from Gnangara, Port Moresby, Toolangi and Canberra to give an estimate of the spatial distribution across Australia. As Lilley and Parker (1976) point out, the analysis of 1 day may be used to compare variations between two different sites, even though it may not give a reasonable estimate of the average daily variation at a single location.

Riddihough (1971) compared the records of seven sites across Ireland with the corresponding total field records derived from Valentia Observatory. He found that the errors involved in assuming uniformity in the daily variation lie between ± 2 and ± 6 nT, with a maximum station separation of approximately 300 km. Daily variations at each site were found to be highly correlated with those at the observatory, and it was concluded that while both time and amplitude differences affect the errors in reduction of magnetic survey data, the time variations have much less effect than the amplitude variations. A consistent geographical pattern of amplitude differences was contoured for Ireland, and subsequently used as a basis for estimating errors involved in reducing magnetic survey data. Srivastava (1971) described a similar analysis for the east coast of Canada, using