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INTRODUCTION

The Amberley magnetic observatory near Christchurch in New Zealand has been the basis of several important studies of the time-varying magnetic field. Baird (1927) and Skey (1928) recognised a proportionality between the amplitudes of the vertical and eastwards components of magnetic fluctuations. A similar phenomenon was also detected by these authors at other magnetic observatories in the Australasian region, with differences occurring in the strengths of the proportionality from place to place. Parkinson (1959), in a later analysis of magnetic observatory records, defined for each observatory a "preferred plane" within which the magnetic fluctuation vector is always likely to lie.

Parkinson represented a preferred plane on a map by an arrow given by the horizontal projection of the downwards-directed normal to the plane. Using this method, Parkinson (1962) determined an arrow for Amberley for fluctuations in the period range 20–60 min. Arrows for a wider period range were later determined for Amberley by Lawrie (1965).

The present paper derives a set of arrows for the modern magnetic observatory at Eyrewell (Fig. 1), which replaced the Amberley Observatory in 1978. Eyrewell lies 43 km to the southwest of Amberley, and is some 40 km from the east coast of the South Island of New Zealand. The data analysed in this paper are from four months of magnetograms from Eyrewell, for the interval 1 December 1983 to 31 March 1984 inclusive. This particular interval was chosen for digitisation in order to give data from Eyrewell which would be simultaneous with magnetic and telluric observations of the Tasman Project of Seafloor Magnetotelluric Exploration (Ferguson et al. 1985). During this experiment, instruments were positioned on a line across the east Australian continent and the Tasman seafloor. The

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Magnetic field fluctuations at the Eyrewell Observatory, Christchurch, New Zealand

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Abstract Four months of magnetic records from the Eyrewell Observatory near Christchurch, New Zealand, have been digitised, and analysed to produce Parkinson response arrows. The magnitudes and azimuths of both the real and quadrature arrows are smooth functions of period. Real arrows at three particular periods are similar to arrows published previously for the earlier observatory at Amberley, some 43 km northeast of Eyrewell. Differences between the Eyrewell and Amberley arrows are consistent with effects due to the closer proximity of Amberley to the ocean, the different analysis techniques employed in the various studies, and possibly with some local geological effects.

The magnitude of the real arrow at Eyrewell has a narrow peak at a period of about 1000 s. At longer periods, the Eyrewell real response decreases sharply, a characteristic which is interpreted as being due to the limited width of the New Zealand landmass, and the balancing effect of the Tasman Sea on its western side. At intermediate periods (500–4500 s) the Eyrewell quadrature arrow has a northerly component. Part of this northerly component could be associated with the strong electric current through Cook Strait, some 320 km to the north.

Keywords electromagnetic induction; Parkinson arrows; Earth-current surveys; Eyrewell Observatory

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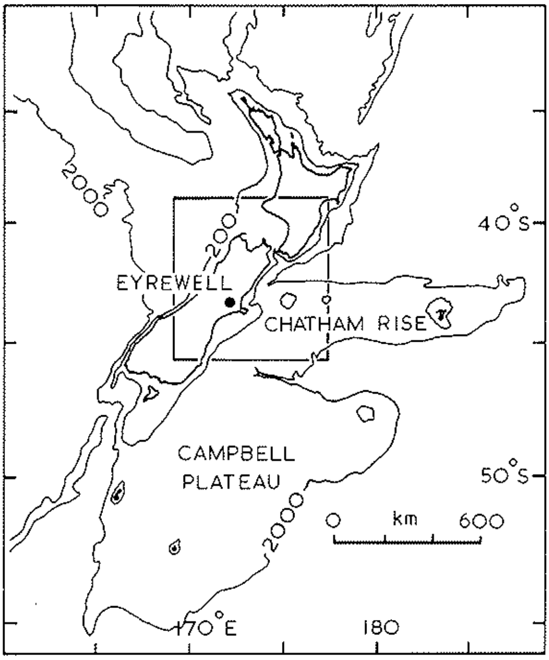


Fig. 1 New Zealand and the surrounding bathymetry (metres). The position of the Eyrewell Observatory is shown. The box indicates the area covered in Fig 3.

DATA ANALYSIS

Regular Eyrewell magnetograms for the 121 days of the Tasman experiment were digitised using a modern digitising tablet. The data were digitised at a density of 32 points (i.e. 2^5) per hour of record, which set the Nyquist frequency of the variations studied to 2^4 cycles per hour (i.e., period 225 s).

The following notations for the components of the fluctuating magnetic field are used: H for the horizontal component to the magnetic north, D for the horizontal component to the magnetic east, and Z for the component vertically downwards. An example of 10 days of the H, D and Z digitised series for Eyrewell is given in Fig. 2. The diagram shows a range of levels of geomagnetic disturbance including storm activity during the middle 2 days of the 10 day period. In analysing the observed data, the usual approach of geomagnetic induction studies has been followed in seeking a best fit to the empirical relationship

$$Z = AH + BD \qquad (1)$$

which represents a linear relationship between the fluctuating components of the magnetic field at the observatory. In equation (1), all quantities are now functions of frequency and may be complex, with real and quadrature parts.

It is generally accepted for work in mid-geomagnetic latitudes that the functions A and B depend on terrestrial electric conductivity structure only (see Parkinson & Jones 1979 for a discussion on the validity of equation 1).

To estimate the functions A and B for Eyrewell, the time series of 4 months duration were divided into equal-length subseries of approximately 10 days duration. The technique of analysing large sections of the data which include quiet days, substorms, and storms, is preferred to the technique of analysing only short events, because it reduces any possible bias in the transfer functions due to source-field characteristics. Each subseries was transformed into the frequency domain using the Fourier transformation

$$g(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{+i\omega t}\, dt \qquad (2)$$

where ω denotes angular frequency and g(ω) is the transform of the time series f(t). A time dependance of $e^{-i\omega t}$ is thus understood for all quantities in equation (1).

A least squares fit to equation (1) was calculated using the equations given by Everett & Hyndman (1967):

$$A = \frac{S_{ZH} S_{DD} - S_{ZD} S_{DH}}{S_{HH} S_{DD} - |S_{DH}|^2} \qquad (3)$$

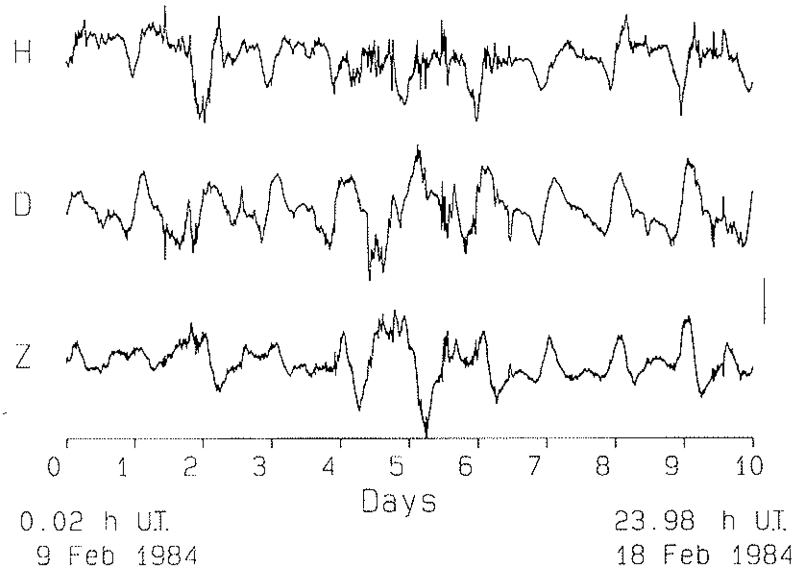
$$B = \frac{S_{ZD} S_{HH} - S_{ZH} S_{HD}}{S_{HH} S_{DD} - |S_{DH}|^2} \qquad (4)$$

where S_{xy} denotes the cross-power spectrum between components x and y (or the auto-power spectrum where x=y). The power spectra were derived from the Fourier transforms using

$$S_{xy} = \frac{[g_x \cdot g_y^{*}]}{T_0} \qquad (5)$$

where T_0 is the length of the subseries, the asterisk denotes a complex conjugate, and the brackets denote averaging over a frequency band and over different subseries.

Fig. 2 Digitised magnetic fluctuation records from the Eyrewell Observatory: H data, D data, Z data. The 10 day interval starts on 9 Feb 1984 and finishes on 18 Feb 1984. Marks on the horizontal axis are for individual days. The vertical bar on the right-hand side of the graph gives the scales of 50 nT for H, 50 nT for D, and 30 nT for Z.



PARKINSON ARROWS

The A and B functions determined for a site may be plotted graphically in a variety of ways. One method is to plot the real parts (A_r, B_r) and the quadrature parts (A_q,B_q) separately, in the form of arrows. A suite of such arrows is shown in Fig. 3, in which the real parts have been plotted with A_r as the component to the south and B_r as the component to the west. Such "real" arrows (referred to as Parkinson arrows) point to the more conductive side of a horizontal conductivity contrast.

In Fig. 3 quadrature arrows are also given. In view of the implied time dependence of $e^{-i\omega t}$, these quadrature arrows have been formed by plotting A_q to the north, and B_q to the east, to also point towards regions carrying increased electric current flow (Lilley & Arora 1982).

Figure 3 includes the arrows for Amberley determined by Parkinson (1962) and Lawrie (1965). These arrows were originally published with their length given as the dip angle, β, of the preferred plane. In order to make the lengths of the Parkinson and Lawrie arrows comparable with the lengths of the Eyrewell arrows determined in this paper, the earlier arrows have been rescaled using the relationship given by Gregori & Lanzerotti (1980),

$$L = \tan \beta \qquad (6)$$

where L is the length of the arrow now plotted in Fig. 3 for Amberley. The graphical method used by Parkinson (1962) (and followed by Lawrie 1965) for arrow determination, produces an arrow that is equivalent to the combined magnitude of the real and quadrature parts of the arrows computed in this paper. Parkinson & Jones (1979) note, however, that the "preferred plane" method is only valid when the quadrature part is small compared to the real part.

In Fig. 3, Amberley and Eyrewell arrows may be compared for three period ranges. In the period range 1314–2063 s, the Amberley arrow (for period 1440 s from Lawrie 1965) shows good agreement with the real arrow at Eyrewell. At longer periods, the two Amberley arrows are longer and point further to the south than the corresponding Eyrewell real arrows.

Part of the greater length of the Amberley arrows may be attributed to the closer proximity of Amberley to the New Zealand coast and therefore to a stronger coast effect. Another factor which could be producing the differences between the arrows is the difference in the electric conductivity of the local geology at the sites. At periods longer than 3000 s, however, the effects of the oceans and of the conductivity structure of New Zealand should become comparable at the two sites. Because the arrow at Eyrewell has a quadrature part of the same length or longer than the real part, it is likely that the arrow at Amberley also has a significant quadrature part. The length of the Amberley arrow could have been poorly estimated by the "preferred plane" method. It is therefore probable that the difference between the Amberley and Eyrewell arrows results from the different techniques used to derive the arrows.

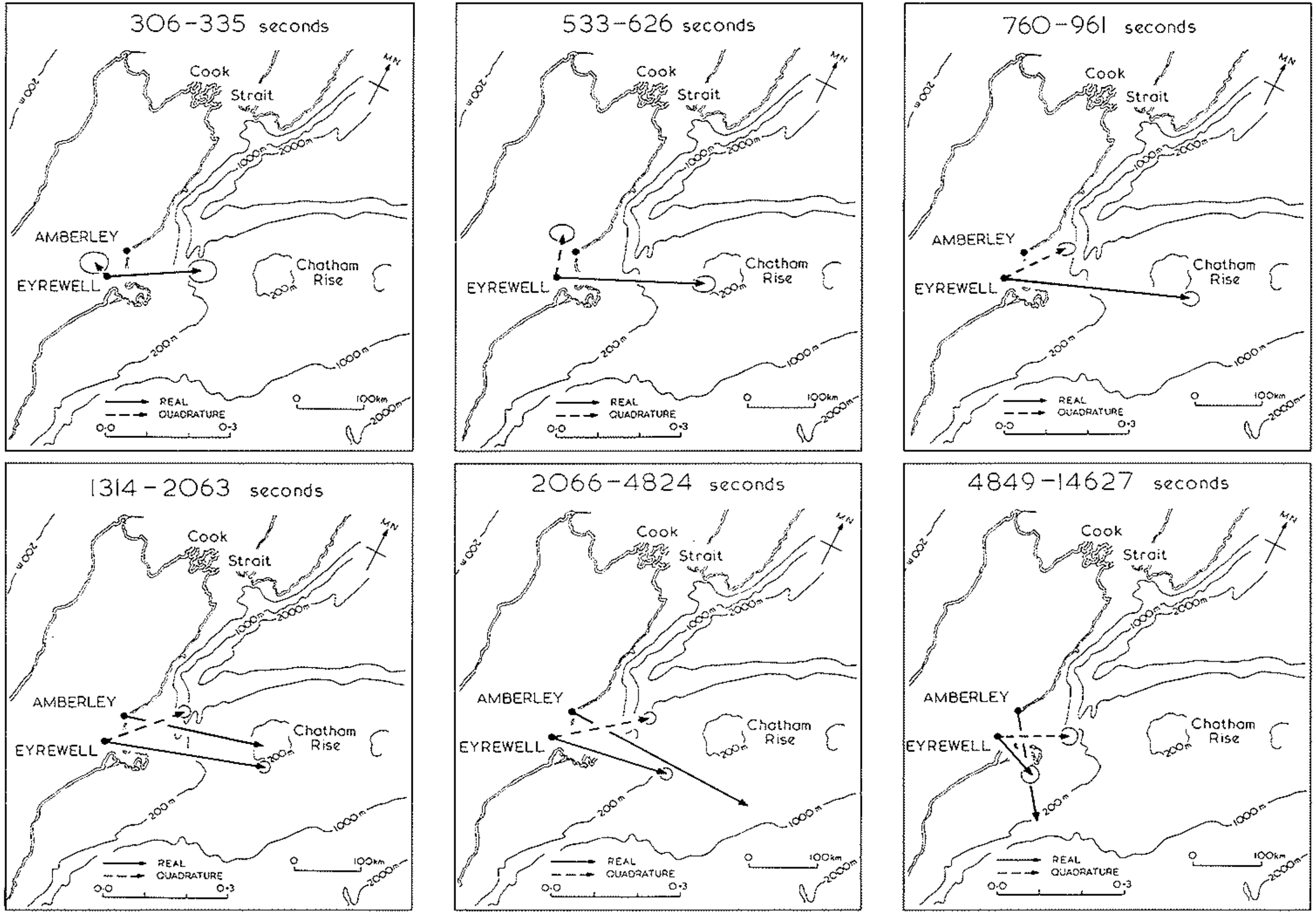


Fig. 3 Parkinson arrows for the Amberley and Eyrewell Observatories, for different period bands. The Eyrewell arrows are as determined in the present paper; the error ellipses represent 95% confidence limits. The Amberley arrows are from Lawrie (1965) for periods around 1440 s and 7200 s and from Parkinson (1962) for periods around 2400 s.

INTERPRETATION

The real arrows determined for Eyrewell substantiate the coast effect observed for Amberley by Parkinson (1962) and Lawrie (1965). In Fig. 3, the Eyrewell real arrow shows a rotation clockwise with increasing period. If the coast effect is considered to be a response to electric current flow in the seawater, then the rotation of the arrows can be simply attributed to arrows of longer period (>5000 s), pointing to the deep water off the Campbell Plateau to the south (see Fig. 1). In contrast, the shorter period arrows (300–1000 s) may be strongly influenced by more local concentrations of electric current. Such a concentration could occur in the seawater in the channel between the shallow banks at the western end of the Chatham Rise.

The magnitude of the real arrow at Eyrewell (Fig. 4) is a smooth function of period with a maximum at around 1000 s. Induction studies have shown that the frequency spectra for most recording sites situated near coasts are smooth functions (Parkinson & Jones 1979), and that significant variations occur in the shape of such spectra even for sites in similar tectonic settings (Beamish 1985). For sites near coasts, a maximum value for the amplitude of the real arrow is commonly seen at periods between 1000 s and 2000 s (Cochrane & Hyndman 1970; Parkinson & Jones 1979).

The peak for Eyrewell shown in Fig. 4A at period 1000 s is unusually narrow. It is interpreted as being due to the limited width of the New Zealand landmass, so that at long periods the Tasman Sea to the west has a coast effect which opposes that of the ocean to the east, thereby reducing the amplitude of the eastwards pointing arrow.

Parkinson & Jones (1979), in compilations of coast effect results from different continental shorelines, plot the length of the real arrow as a function of distance from the outer edge of the continental shelf. The tectonic structure of the continental shelf off southeast New Zealand differs from the structure of regions included in the Parkinson & Jones compilation for "non-shield" coastlines (California, southern and eastern Australia). Seismic surface wave dispersion studies (Adams 1962) suggest that, for this part of the New Zealand shelf, an area of anomalously thin continental crust extends beyond the shelf edge to the edge of the Campbell Plateau (Fig. 1). Using the nonshield results of Parkinson & Jones (1979, fig. 1), and taking a distance to the shelf edge of 100 km (see bathymetry in Fig. 3), one would predict a real arrow length for Eyrewell of approximately 0.5 ± 0.1. This value is in good agreement with the observed maximum coast effect value for Eyrewell (Fig. 4A) of 0.45 ± 0.02.

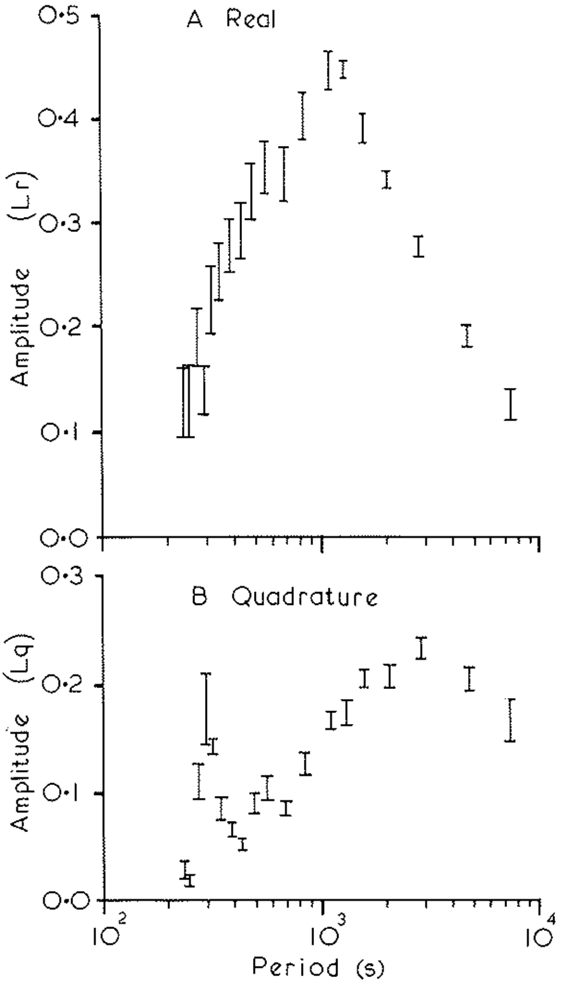


Fig. 4 Amplitudes Lr (A) and Lq (B) of the real and quadrature Parkinson arrows, respectively, for the Eyrewell Observatory as functions of period. The error bars represent the major axis of the 95% confidence ellipse.

Quadrature arrows are important as they can separate out a reactive response from a conductive response, and thus provide extra information on Earth electric conductivity structure (Lilley & Arora 1982). For Eyrewell, the quadrature arrows (Fig. 3) are smaller than the real arrows over most of the available period range. The quadrature arrows change direction systematically and substantially with increasing period. At periods below 2000 s, the quadrature arrows have a significant northerly component. This northerly component is not predicted by simple coast effect models and therefore warrants further explanation.

It is possible that the Eyrewell quadrature arrow is responding to some undefined geological feature of the South Island of New Zealand. However, the northerly quadrature response may also be due to the channelling of electric currents through the Cook Strait, some 320 km distant between the North and South Islands of New Zealand, as observed by Ingham (1985) in a geomagnetic study on the North Island, and Boteler et al. (1987) in a study of voltage in a cable across the strait. Ingham found that these currents affected both the real and quadrature arrow response at intermediate periods (800–1500 s) and the quadrature arrow response at long periods (2000–5000 s), at sites on the southern quarter of the North Island. Using a simple d.c. line current model, Ingham (1985) was able to reproduce the observed pattern of real vertical field responses for intermediate periods (800 s).

A similar line current model can be used to determine the effect at Eyrewell of a large quadrature-phase current in Cook Strait. At a period of 3000 s, the arrow in Fig. 3 indicates that a northwards horizontal field change of 100 nT would be observed to produce a quadrature vertical response at Eyrewell of c. 20 nT. Under the Biot-Savart law, this vertical field change at Eyrewell could be caused by an electric current in Cook Strait of c. 2×10^4 A. Such a model may be checked for consistency with Ingham's (1985, fig. 2, period 3162 s) quadrature results for the North Island. Ingham's results indicate that a northwards horizontal field change of 100 nT should be accompanied by a quadrature electric current in Cook Strait (again using the Biot-Savart law) of c. 1×10^4 A. The order of magnitude agreement of this current with the current calculated from the Eyrewell data indicates that the northwards component of the Eyrewell quadrature arrow may be explained by large quadrature phase currents being channelled through Cook Strait.

CONCLUSION

The results of an analysis of magnetic fluctuations at the Eyrewell Observatory generally agree with the earlier arrow determinations for Amberley, which showed a coast effect for the eastern side of the South Island of New Zealand. For Eyrewell, the Parkinson arrow-length has a distinctive frequency response. The long-period behaviour is interpreted as resulting from the presence of deep water both to the east and the west of the narrow New Zealand continental landmass. At shorter periods, the Eyrewell real arrow may indicate channelling of electric current in the seawater through deep troughs at the western end of Chatham Rise.

The quadrature-response arrows determined for Eyrewell have a northerly component. More observations on the northern part of the South Island may be necessary to determine its cause, though this effect may be due in part to induced electric current channelled through Cook Strait.

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