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Anomalous Geomagnetic Variations on the Island of South Georgia

David BEAMISH

Institute of Geological Sciences, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland

Observations of geomagnetic variation fields on South Georgia, in the Scotia Sea, have revealed an unusual polarisation anomaly in the horizontal components, whose characteristics cannot be accounted for by an ocean-edge effect model. In addition, vertical field transfer functions have been calculated in the period range $10-10^4$ s. Although the data obtained from only one station allows only a limited analysis, it is suggested that the anomalous geomagnetic response on South Georgia can be accounted for by lithospheric conductivity contrasts between the Scotia and South American Plates.

1. Introduction

High resolution geomagnetic data have been obtained on South Georgia from a rubidium vapour magnetometer at the British Antarctic Survey's station at King Edward Point (54.26°S, 36.50°W, geographic; −44.04, 25.89, centred geomagnetic). The magnetometer records digitally on cassette, sampling the magnetic NE, NW and vertical components at 2.5 s intervals (RIDDICK *et al.*, 1976). A preliminary analysis of such data by HAMILTON (1979) revealed an unusual geomagnetic polarization anomaly in the horizontal components. The present study extends the analysis of the horizontal components and includes an assessment of the anomalous vertical field recorded on South Georgia.

The geomagnetic response observed on deep ocean islands is termed the Geomagnetic Island Effect (GIE) and is essentially a special case of the Geomagnetic Coast Effect (GCE) observed on the landward side of continental margins. A review of the subject is given by PARKINSON and JONES (1980). Both the GCE and GIE are characterised by a large increase in the vertical field as the continental edge is approached while the horizontal component perpendicular to the continental edge undergoes a more modest increase. Such anomalous fields are produced by the contrast in conductivity between ocean and continent. Additional current concentrations may occur in the highly conducting layer of sea-water defining the continental slope and/or at great depths in the upper mantle where lithospheric conductivity contrasts may produce large lateral conductivity gradients. The separation of the two effects, shallow from deep, is a matter of some debate (PARKINSON and JONES, 1980), however the GCE, on a global scale, has provided a degree of classification of the geomagnetic response of different (ie. active and passive) continental margins (eg. EDWARDS and GREENHOUSE, 1975). Geoelectric soundings of oceanic lithosphere, were, until recently, restricted to deep ocean islands (SASAI, 1968; HONKURA, 1971; KLEIN and

LARSEN, 1978) however much valuable data has, in recent years, been obtained from ocean-bottom experiments (FILLOUX, 1980; COX *et al.*, 1980).

The polarisation anomaly observed on South Georgia is unusual. The data obtained from only one site precludes separation of shallow from deep effects. A comparison of the vertical field response obtained on South Georgia with that calculated from thin-sheet (ie. ocean-edge effect) models suggests, that while such a model can adequately explain the observed frequency dependence of the vertical field, the cause of the horizontal field polarisation anomaly must be sought at greater depths.

2. Tectonic Relationships

South Georgia is a detached block of continental crust separated from its former position adjacent to the Southern Andes (DALZIEL *et al.*, 1975). The distribution of plate boundaries in the region together with their motion is summarised by BARKER and DALZIEL (1980) and by BARKER and HILL (1981) as shown in Fig. 1. The Scotia Sea is thought to have formed over the past 40 Ma as an increasingly intricate modification of the South American (SAM) and Antartic (ANT) plate boudaries. Marine geophysical investigations (BARKER, 1972; BARKER and HILL, 1981) have shown that active sea-floor spreading is taking place some 440 km west of the South Sandwich Trench. Such back-arc extension has given rise to the Scotia and Sandwich plates as defined by BARKER and DALZIEL (1980). The South Georgia continental block lies on the northern margin of the Scotia Plate (Fig. 1).

Detailed geophysical surveys of the structure of the South Georgia continental shelf are presented by SIMPSON and GRIFFITHS (1981). A plate boundary traverses the northern margin of the South Georgia block. Relative motions are uncertain but in the region of

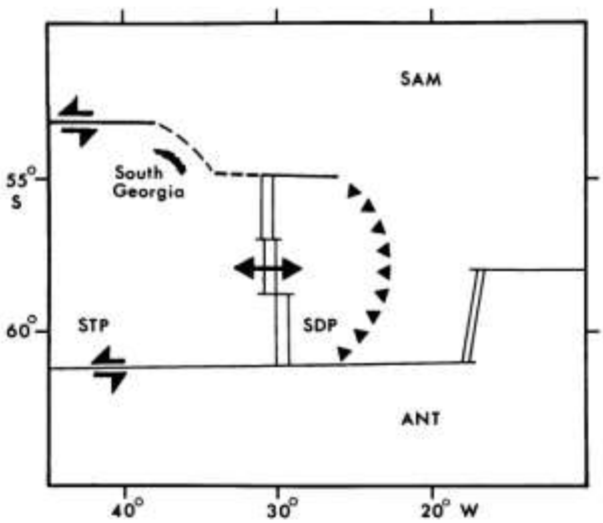

Fig. 1. Plate boundaries and present motions in the region of the Scotia Sea, redrawn from BARKER and DALZIEL (1980); FRANKEL and MCCANN (1979). SAM: South American Plate, ANT: Antartic Plate, STP: Scotia Plate, SDP: Sandwich Plate. Serrated arc is a subduction zone with teeth on the overthrust plate.

South Georgia, motion is thought to be sinistral strike-slip with a possible convergent component of old ocean floor underthrusting the NW margin of the block (Barker, personal communication, 1980). From the point of view of the present discussion the location of the South Georgia block as being transitional between old (~ 100 Ma) and young (10–20 Ma) oceanic lithosphere is emphasised. The implications of lithospheric age on the conductivity structure of the oceanic upper mantle have been recently discussed by FILLOUX (1980) and OLDENBURG (1981). It appears likely that there exists a correspondence between the age of oceanic lithosphere and the depth to a conductive zone of partial melt. If this hypothesis is accepted, the South Georgia continental block represents a region of strong lateral conductivity gradients at upper mantle depths.

3. The Anomalous Horizontal Field

A preliminary analysis of the horizontal field polarisation anomaly on South Georgia has been reported by HAMILTON (1979). The study revealed that the horizontal field variations are consistently polarised in the geomagnetic azimuth range $0° < \theta < 40°$, over a wide range of variation periods. The data have been reanalysed using complex demodulation in an attempt to further quantify the polarisation anomaly observed. Complex demodulation of geomagnetic data (BANKS, 1975) is a convenient spectral technique for the determination of the polarisation characteristics of both harmonic and band-averaged data. For the data under consideration, data lengths of 3 hours were used to enable a universal time (U.T.) dependence to be retained. Each complete day (24 hours) provide eight, 3 hour data files. The major axis (θ) of the horizontal field polarisation ellipse was determined in the usual manner (LILLEY and BENNETT, 1972) from complex demodulates determined over six period bands obtained from each 3 hour data file. The period bands (B1–B6) together with the number of polarisation states sampled in each band are given in Table 1.

In order to obtain an effective sampling population of polarisation states, 20 days of data were analysed in the above manner. The only selection criterion employed was to choose data from days with a moderate K_p index over the 24 hour period. The procedure obtains the azimuth of the major axis of the polarisation ellipse irrespective of amplitude and therefore admits noise.

The results showing the normalised distributions of azimuths in 10° sectors as a function of U.T. and period band are shown in Fig. 2a. The results confirm the findings of

Table 1. Period bands and number of polarisation states sampleddin each band (NP) for the analysis of the observed horizontal field.

Band	Period Range (s)	NP
B1	2,000–1,000	16
B2	1,000–500	32
B3	500–250	64
B4	250–125	128
B5	125–62.5	256
B6	62.5–31.25	256

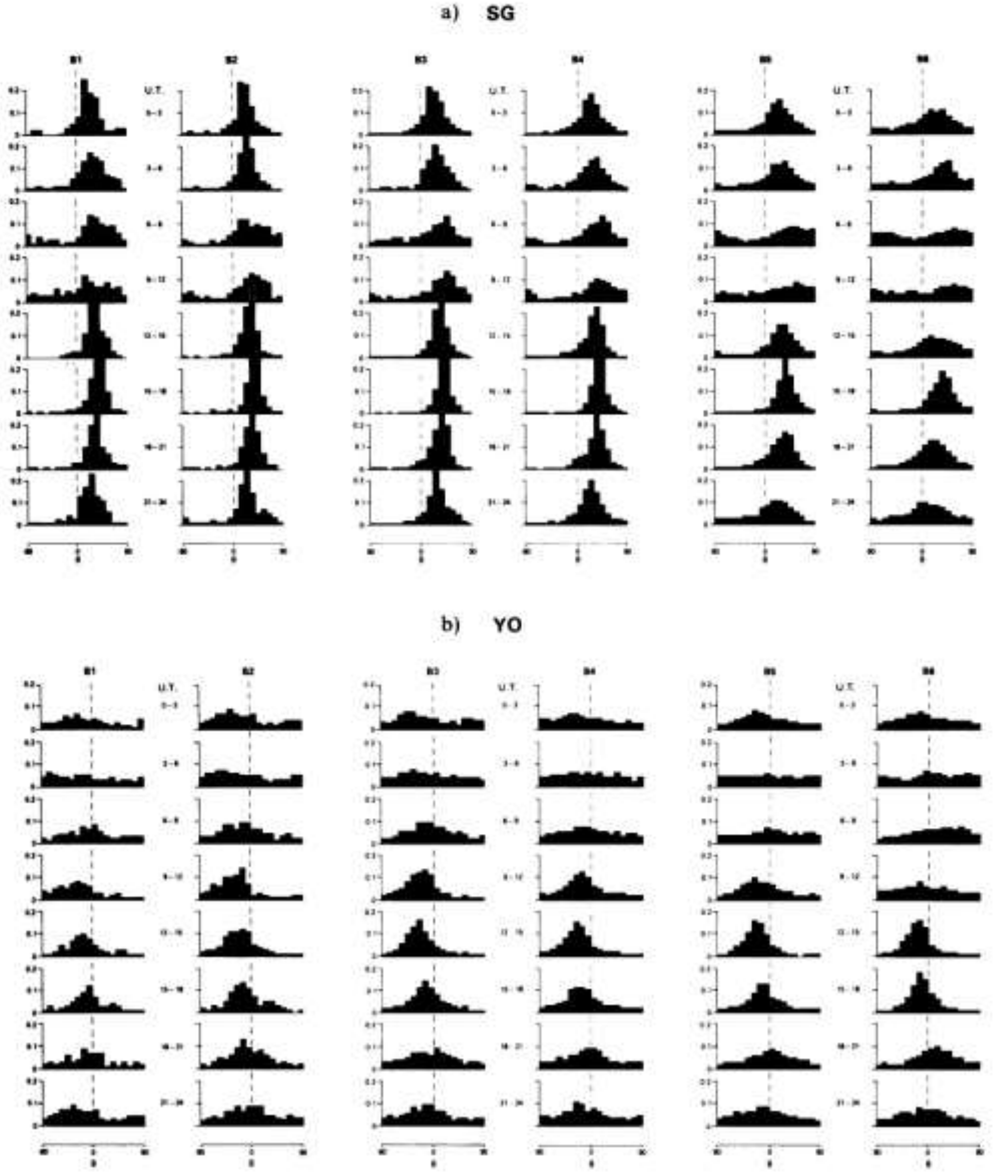

Fig. 2

the preliminary analysis. A highly skewed distribution is apparent throughout the period range. The major axis is largely confined to the geomagnetic azimuth range $10^\circ < \theta < 50^\circ$. The only modification introduced as a U.T. dependence is a tendency towards a more uniform distribution during 06.00–12.00 U.T. (08.30–14.30 L.T.). The likely cause of such a feature is a local time (L.T.) minimum in the source field amplitudes. If the distributions are summed over U.T., it is apparent from Fig. 2a that the distributions for the longest period bands exhibit the most skewed form.

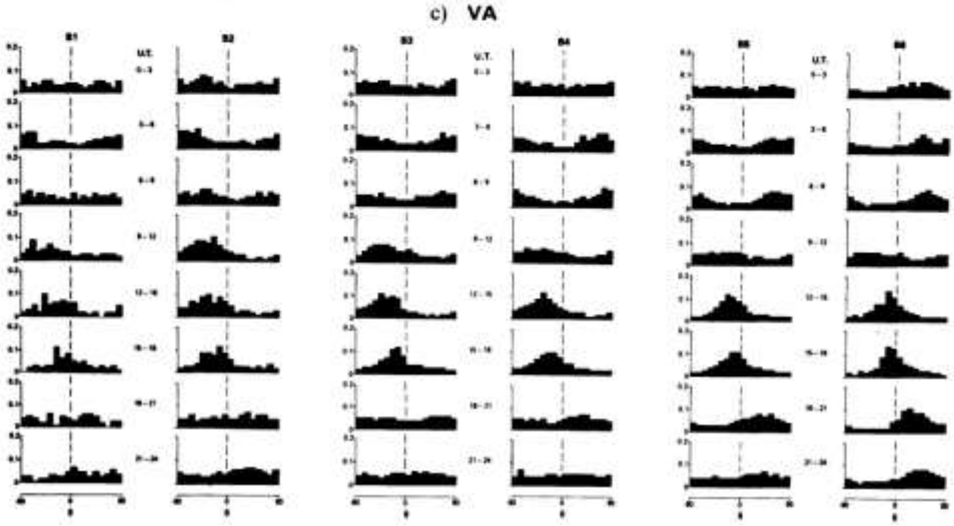

Fig. 2. Normalised distributions of the azimuth of the major axis of the horizontal field polarisation ellipse as a function of U.T. and period band (B1–B6). The azimuth is defined positive clockwise from geomagnetic north. (a) At SG (South Georgia), (−54.26°, [36.50); (b) At YO (York), (53.95°, −1.05); (c) At VA (Valentia), (51.93, −10.25).

To emphasis the anomalous nature of the horizontal field polarisation on South Georgia, the above analysis was repeated at two stations in the U.K. at which identical magnetometers are installed, but which are some 10° higher in geomagnetic latitude. The two stations lie approximately at the same geomagnetic latitude of 54° but possess characteristically different geomagnetic response functions in the period range considered. One station (VA) is situated on the west coast of Ireland and is a typical GCE site (ie. influenced by the European continental shelf) while the second station (YO) is a typical U.K. mainland site.

The above analysis was repeated using 20 days of data from the two U.K. sites. The results are presented in Figs. 2b and 2c. A comparison of these two figures reveals that there are no significant differences in the distributions of the major axes of the horizontal field polarisation ellipse, either as a function of period band or U.T. Clearly the distributions exhibit their most skewed form between 12.00–18.00 U.T., however there is no suggestion, at this higher geomagnetic latitude, that the azimuths are highly constrained independently of period and U.T. as is the case at South Georgia.

It is unlikely that we can account for the anomalous horizontal field polarisation on South Georgia in terms of consistently anomalous source field characteristics over the period range considered. The unusual horizontal field characteristics are considered to result from induced currents flowing along a lateral boundary in conductive structure, and which therefore act continuously. If normal (derving from layered Earth structure) horizontal field variations are small then the polarisation anomaly observed on South Georgia can be accounted for by the presence of largely anomalous (deriving from lateral structure) horizontal field variations. The observed horizontal field variations would thus derive from a locally two-dimensional boundary striking perpendicular to the preferred azimuth range of the polarisation ellipse. Equally one can view the preferred azimuth range on South Georgia as defining a direction in which local conductivity structural gradients are a maximum.

Generally, geomagnetic studies have largely used the ratio of the verical and horizontal field components to infer lateral variations in conductivity structure. This ratio, determined from the data recorded on South Georgia, is now considered.

4. The Anomalous Vertical Field

The ratio Z/H is obtained using the transfer function relationship

$$Z(f) = A(f) \cdot H(f) + B(f) \cdot D(f) + E(f) \tag{1}$$

where quantities are complex and obtained from the recorded data ($\equiv H, D, Z$) by spectral analysis (eg. EVERETT and HYNDMAN, 1967). The transfer function (A, B) is determined in a least-squares sense by minimising the residual error term ($E(f)$) over an ensemble of events. The assumptions incorporated in Eq. (1) are discussed by SCHMUCKER (1970) and BANKS (1973). Induction arrows allow the complex response (A, B) to be presented in terms of an amplitude and azimuth which defines the normal to the strike of a local lateral conductive boundary. Two such arrows are defined for vertical fields responding in-phase (Real) and in-quadrature (Imaginary) with the horizontal component with which the vertical field possesses maximum correlation. The azimuths of the Real (θ_R) and Imaginary (θ_R) induction arrows are defined here as

$$\theta_R = \tan^{-1} - [\text{Re}\ (B)/(A)] \tag{2}$$

$$\theta_I = \tan^{-1} - [\text{Im}\ (B)/\text{Im}\ (\text{A})] \tag{3}$$

clockwise from geomagnetic north. The induction arrows determined at South Georgia in the period range $10-10^4$ s are shown in Fig. 3. The determination is made for 18 period bands distributed evenly in log period scale; the period ranges of individual bands are given in Table2.

Throughout the period range, the magnitude of the real arrow (G_R) is consistently larger than that of the imaginary arrow (G_I). The real response is strongly period dependent reaching a maximum value at 750 s. The azimuth of G_R is stable throughout the period range while the azimuth of G_I possesses a smooth transition from a northerly direction for $T > 1{,}000$ s to a southerly direction for $T < 200$ s the azimuthal results in relation to the South Georgia continental block are summarised in Figs. 4a and 4b. In Fig. 4a the azimuth range of θ_R is shown for the period range 5,000–20 s ie. all bands except B1. The stability of the azimuth response θ_R as a function of period is clearly displayed. Figure 4b shows the corresponding azimuth range of θ_I for two period ranges corresponding to $T > 1{,}000$ s and $T < 200$ s. In the intermediate period range the azimuth θ_I is transitional. Also shown in each figure is the range of horizontal field polarisation azimuths (mean $\pm$ 1 s.d.) determined from Fig. 2a.

The azimuth of the real induction arrow as displayed in Fig. 4a is unusual on two

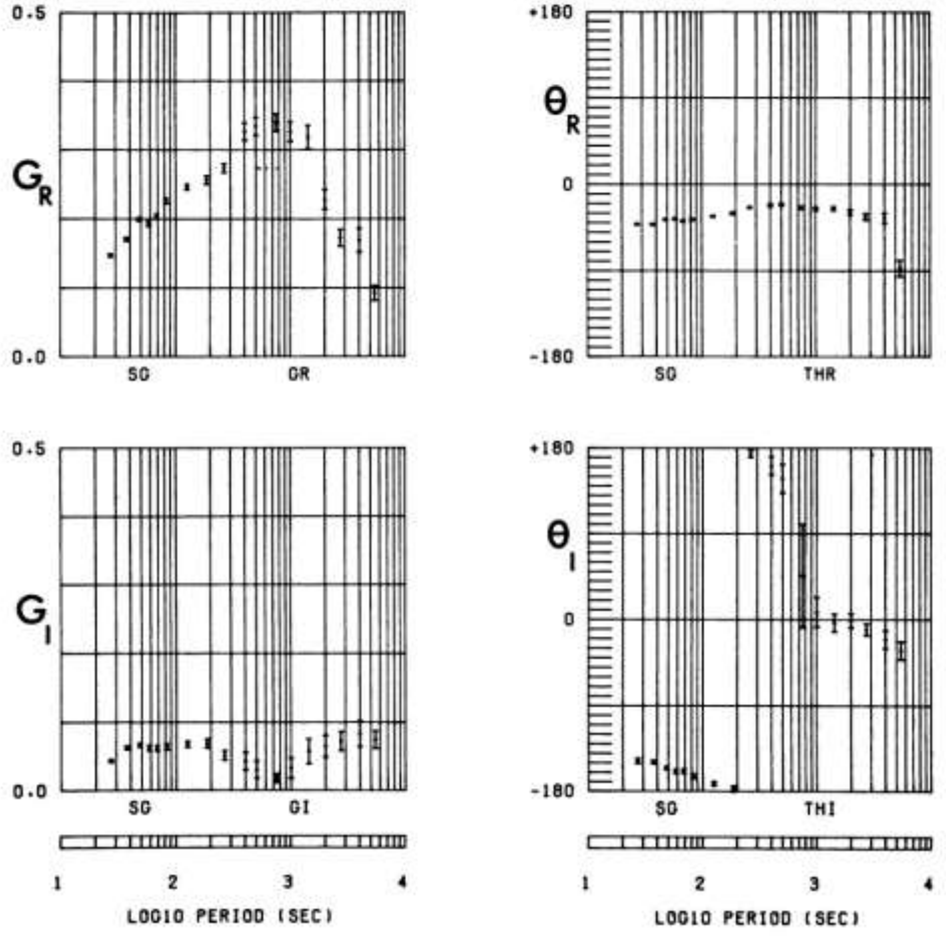

Fig. 3. Real (G_R, θ_R) and imaginary (G_I, θ_I) induction arrows on South Georgia, as a function of period.

accounts. In the first instance, considering the 'normal' geomagnetic island response (see next Section), we would anticipate a real induction arrow directed towards the nearest deep ocean. In the second instance we find in Fig. 4a that θ_R is rotated with respect to the preferred azimuth range of the horizontal field. We would normally anticipate allignment of the two azimuth ranges if both components of the anomalous field were derived from the same induced current system.

The two unusual features of the azimuthal range of θ_R may be reconciled by a consideration of the assumptions used in the application of Eq. (1), the assumption has been made that (H_a, D_a), the anomalous horizontal components, are small in relation to the total observed horizontal components. This is clearly not the case on South Georgia since the results of the previous Section suggested that the observed horizontal components must be viewed as largely anomalous. The consequences on the determination of (A, B), when

Table 2. Period bands and number of degrees of freedom sampled in each band (ND) for the analysis of the vertical field transfer function.

Band	Period Range (s)	ND
B1	7,200–4,000	32
B2	5,000–3,000	32
B3	4,000–2,000	64
B4	3,000–1,000	64
B5	2,000–1,000	64
B6	1,500–800	98
B7	1,000–600	128
B8	600–400	128
B9	500–300	128
B10	400–200	64
B11	250–150	64
B12	200–90	128
B13	100–70	128
B14	80–60	128
B15	70–50	128
B16	60–40	256
B17	50–30	256
B18	40–20	512

anomalous horizontal components are present, have been considered by BEAMISH (1977). The transfer function obtained in such circumstances is of smaller magnitude and induction arrows are rotated with respect to a determination made with normal horizontal components. When substantial anomalous horizontal components are present, the sense of rotation of the induction arrows is determined by the ration H_a/D_a. The results of the previous section indicate that although H_a and D_a may both be large, $H_a/D_a > 1$. In such circumstances the induction arrow tends towards a more E-W orientation. It is suggested that such an effect could account for the observed difference although the limited information available does not preclude separate causes for the two components of the observed anomalous field.

5. Models of the GIE and GCE

We now consider the observed variation of the induction arrows over the period range 7,200 – 20 s in relation to the general problem of electromagnetic induction in the ocean. The geomagnetic variation fields observed on an oceanic island are influenced by the distribution of induced currents in the surrounding ocean and by the underlying conductivity distribution. Since the seawater is highly conducting with respect to the landmass both the GIE and the GCE are commonly related to electromagnetic induction in a thin-sheet ie. a quasi-uniform current sheet (the ocean) being perturbed by the low conductivity of the island/shelf structure. The thin-sheet model is valid if two conditions relating to the thickness (d) of the surface sheet are met (SCHMUCKER, 1970). The first is that d should be several times smaller than the skin-depth of the incident field in the surface sheet. The second condition is that the depth of penetration of the field into the underlying material

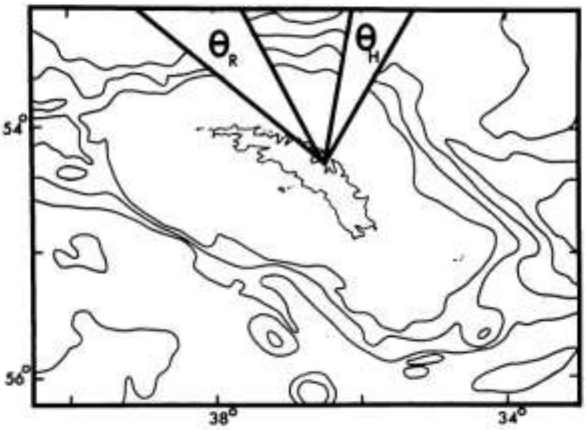

Fig. 4a. The azimuth range of the real induction arrow (θ_R) for the period range 5,000–20 s, together with the range of the major axis of the horizontal field polarisation ellipse (θ_H). Bathymetry at interval of 1,000 m.

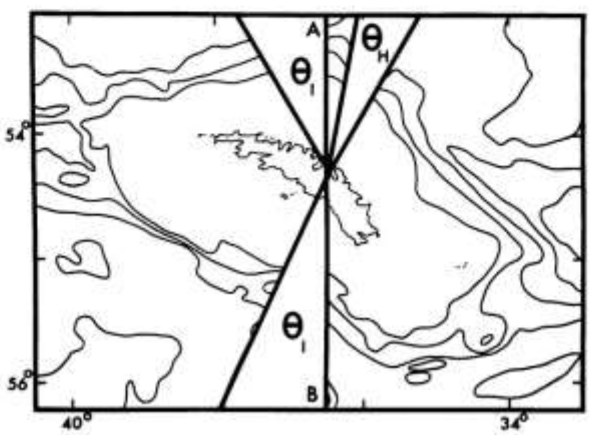

Fig. 4b. The azimuth ranges of the imaginary induction arrow (θ_I) for the period ranges A: $T > 1{,}000$ s and B: $T < 200$ s, together with the range of the major axis of the horizontal field polarisation ellipse (θ_H). Bathymetry at interval of 1,000 m.

should be large compared with d. Both conditions are functions of period, with the first usually being the more restrictive. The first condition is likely to be constant for the deep ocean requiring the period (T) of the incident field to be > 900 s (SCHMUCKER, 1971).

The GIE is a special case of the GCE. The GIE as examplified by the perfectly conducting thin-sheet model of SCHMUCKER (1970, p. 86) is a function of position across the island. For symmetric and isolated island structures there exists an inductive centre where the anomalous vertical field is zero. In common with thin-sheet models of the GCE, the anomalous horizontal field is pertubed only slightly across the island. Investigations using Eq. (1) on islands and thin-sheet models containing variable conductance, have observed both of these effects (SASAI, 1968; HONKURA, 1971, 1973; KLEIN and LARSEN, 1978). At perimeter sites these studies reveal that the azimuths of the real induction arrows are directed towards the nearest deep ocean in response to the shelving structure of the oceanic sheet.

When more than one station is available, it is possible to obtain a measure of the spatial distortion of the fields across the island and to separate this effect (that of quasi-static induction in a non-uniform thin-sheet) from that produced by the deep mantle conductivity structure (HONKURA, 1973; KLEIN and LARSEN, 1978). The availiability of only single-station data precludes such an analysis on South Georgia.

Using the thin-sheet approximation the effect of the ocean edge as a function of period has been studied by a number of authors (eg. BULLARD and PARKER, 1968; QUINNEY, 1979). The anomalous vertical field at a coastal location is found to decrease with increasing period. Referring to Fig. 3 we observe that the magnitude of the real arrow is consistent with such behaviour in the period range 7,200–800 s (B1–B6). The maximum anomalous vertical field occurs in the period range 1,000–600 s (B7) where the response is largely in-phase. The maximum vertical field response defines the transition from quasi-static induction in the ocean to a response at shorter periods determined by self and mutual induction in the ocean, the continental shelf and the underlying conductivity structure. The observed variation with period of the induction arrows are thus considered compatable with an acceptable model of electromagnetic induction in the deep ocean surrounding South Georgia.

As noted above, the thin-sheet models for both the GIE and GCE give rise to only a moderate anomalous horizontal field on the continental side of the ocean edge. Such models cannot therefore explain the observed anomalous horizontal field polarisation which appears to act continuously over the period range 7,200–30 s. To explain this observation a sub-oceanic conductivity anomaly is required.

6. Discussion

With the limited data available on South Georgia it is inevitable that any discussion of the results obtained in this study remain tentative. As a comparative measure we note that a similar polarisation anomaly in the horizontal field has been reported at Alert on Ellsemere Island off the NW coast of Greenland (WHITHAM, 1965; WHITHAM and ANDERSEN, 1965). An extensive examination of the Alert anomaly was carried out by NIBLETT *et al.* (1974). The authors suggest that an anomalous conductor 100 km wide and located in the crust at depths between 10 and 20 km can account for the geomagnetic variation anomaly observed. The authors note that the high conductivity zone seems more likely to be caused by hydration and structural changes deep in the crust which may be related to an ancient plate boundary.

The tectonic framework in the vicinity of South Georgia has already been summarised. The geotectonic relationships and geology of the South Georgia landmass are considered by DALZIEL *et al.* (1975) and BELL *et al.* (1977). Most of the island consists of 2 sequences of folded volcanoclastic turbidites largely of late Mesozoic age. One of these sequences (the Cumberland Bay formation) is thought to be derived from an andesitic island arc to the south-west. The sequence was deposited in a marginal basin on a composite platform consisting of an ophiolite sequence, representing oceanic crust, emplaced into metasedimentary continental crust. The ophiolites, mapped only in the SE portion of South Georgia, possess a NW-SE trend (BELL *et al.*, 1977). Such a strike direction is orthogonal to the polarisation anomaly and therefore represents an appealing possible local correlation.

Apart from this possibility, it is apparent from the tectonic relationships in the area (Fig. 1) that regional lithospheric contrasts exist in the region of South Georgia between the old South American and younger Scotia Plates. If the hypothesis that lithospheric conductivity structure is a function of lithospheric age is accepted (FILLOUX, 1980; OLDENBURG, 1981) then the anomalous fields on South Georgia may well represent an observation of one of the many lateral consequences of such a model. It is worth noting that marginal back-arc oceanic basins such as the Scottia Sea and the Philipine Sea (HONKURA *et al.*, 1981) provide islands on which to base electromagnetic experiments. Crustal accretion is in many cases, similar to that occurring at the world's mid-oceanic ridge systems (VINE and SMITH, 1981). Islands within such basins therefore provide an alternative platform (c.f. ocean bottom experiments) for electromagnetic studies of the geophysical processes governing crustal accretion.

The vertical resolution of geoelectric structure provided by single-station geomagnetic data is minimal. Magnetotelluric recording equipment has recently been installed on South Georgia by the British Antarctic Survey to allow a more complete analysis of the geoelectric structure to be undertaken.

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