Local and regional induction in the British Isles

Banks, R.J. & Beamish, D., 1984. Local and regional induction In the British Isles.
Geophys. J. R. astr. Soc., 79, 539-553.

DOI: 10.1111/j.1365-246X.1984.tb02239.x

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Summary. Electric currents induced in the shallow seas and deep ocean around the British Isles have a profound effect upon the electromagnetic fields observed at stations on the land. The configuration of anomalous currents changes with frequency, and causes corresponding changes in the geomagnetic transfer functions. Magnetic variations have been recorded at a dense network of sites in southern Scotland and northern England. Single-station transfer functions have been used to generate hypothetical event maps of the anomalous vertical field, and hence to infer the configuration of the anomalous internal currents. At periods exceeding 2000 s, the vertical field is dominated by the effects of electric currents to the west, presumably in the Atlantic Ocean. In the period range 400–2000 s, anomalous currents are concentrated in a thin sheet comprising the shallow seas, the thick sequences of post-Caledonian sedimentary rock which underlie them, and the extensions of the sedimentary basins into the land. The response of the individual basin is determined not only by its local conductivity structure, but also by the extent of its connection to the shallow seas, i.e. its regional importance within the conductive sheet. At periods less than 200 s on the other hand, the anomalous fields at inland sites are principally determined by the *local* geological structure. These results confirm conclusions reached from theoretical studies of electromagnetic induction in a heterogeneous surface layer (Park, Orange & Madden); that electromagnetic response data measured in a 3-D environment such as the Northumberland Basin must be interpreted using 3-D models. If one or 2-D models is used, the data must be corrected on the basis of regional measurements.

1 Introduction

The Atlantic Ocean and the shallow seas around the British Isles (Fig. 1) must strongly influence the electromagnetic fields observed on the land. Electric currents induced in the

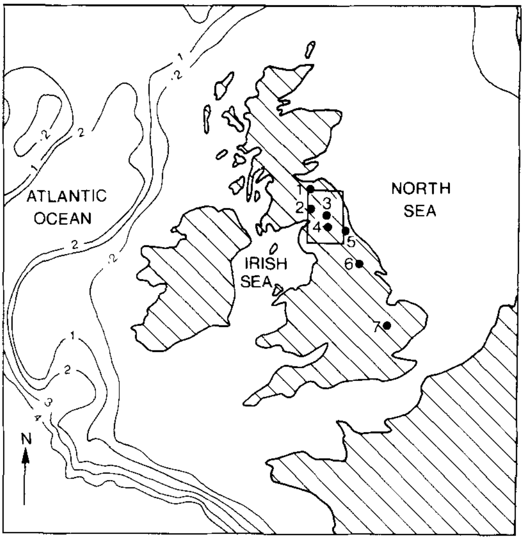

Figure 1. Location of the area investigated in relation to the shallow seas around the British Isles. Numbered stations are: 1 – Earlyburn, 2 – Eskdalemuir, 3 – Wark, 4 – Sinderhope, 5 – Durham, 6 – York, 7 – Cambridge. Bathymetric contours are labelled in kilometres.

sea-water produce magnetic fields which may contribute significantly to the total field at an inland site. In addition, the configuration of the shallow seas may modify the electric field within the land, and affect the response of bodies of conductive rock. Our aim in this investigation is to try to assess the effect of the seas on magnetic field variations with periods of 20–6000 s, and in particular to decide whether they must be included as an essential component of any model which attempts to simulate the electromagnetic fields at inland sites.

Edwards, Law & White (1971) determined single-station transfer functions at sites throughout the British Isles, and used an induction vector representation of their data to infer the approximate location of anomalous currents. At a period of 2400 s, they detected current concentrations in the Atlantic Ocean, in the North and Irish Seas, and also through the land beneath southern Scotland. Bailey & Edwards (1976) used the hypothetical event technique (Bailey *et al.* 1974) to represent the same data in a different way. They emphasized the distinction between the current systems generated in response to orthogonal polarisations of the horizontal magnetic field. With a northward magnetic field, the regional current flow should be from east to west, involving a significant component through the land, and exciting anomalous structures within the land. The regional current associated with an eastward field is approximately parallel to the coastline of the British Isles, and is most effective in exciting anomalous currents in the shallow seas.

More recently, Dosso, Nienaber & Hutton (1980) have used an analogue model to investigate the response of the British Isles to electromagnetic fields with periods in the range 1000–10 000 s. Their results confirmed the importance of both the period and polarization of the horizontal magnetic field in determining the configuration of the anomalous currents. The E-polarization case (magnetic field east–west) produces the most straightforward results. At the longest period (10 000 s) the vertical component of the magnetic field observed over the land is dominated by the induced currents in the Atlantic. As the period is reduced, there is a decrease in the spatial scale of the magnetic fields they produce. Consequently, at sites some distance from the continental edge, e.g. in Scotland and England, the relative importance of the current in the shallow seas increases, and is dominant at a period of 1000 s. When the magnetic field is north–south (the *H*-polarization case), the vertical field produced by the currents in the seas is much less important. There is some evidence that the varying geometry of the islands influences the amount of current which flows through different parts of the land. However, since the land has a uniform conductivity in the model, the effects of conductive structures such as sedimentary basins are not predicted.

We have used the analogue model results to help predict the frequency response of single-station transfer function data collected at a dense network of sites in northern England and southern Scotland. The area straddles the mainland from coast to coast (see Fig. 1). On its western side, the northern end of the Irish Sea is almost closed by southern Scotland, leaving only the narrow passage of the North Channel between Scotland and Ireland. It is possible that the constriction may cause more current to flow through the land between the Irish and North Seas than would be otherwise expected. This purely geometric effect may be enhanced further by the presence of a sedimentary basin, running east–west across northern England, linking the North and Irish Seas (Fig. 3).

Most of the data analysed in this paper are derived from an investigation of the Alston Block and Northumberland Basin (Beamish & Banks 1983). The single-station transfer function estimates are of particularly good quality, derived from large amounts of data, and covering a wide period range (20–7200 s). The reliability of the data can be judged from the fact that it is possible to generate smooth hypothetical event maps with a spacing of only 0.02 nT between contours for a horizontal field amplitude of 1 nT. The station spacing averages 10–15 km, enabling us to locate the internal currents very precisely, and to relate them with some confidence to known geological structures.

2 The frequency dependence of the transfer functions

The azimuth of the induction vector provides a useful indication of the geometry of the internal current system responsible for the anomalous vertical magnetic field (Banks 1973). Fig. 2 shows the frequency dependence of the azimuth of the real vector for representative stations in the area mapped in detail (numbers 1–4), and also for some widely separated sites on a north–south line parallel to the east coast of England (numbers 5–7).

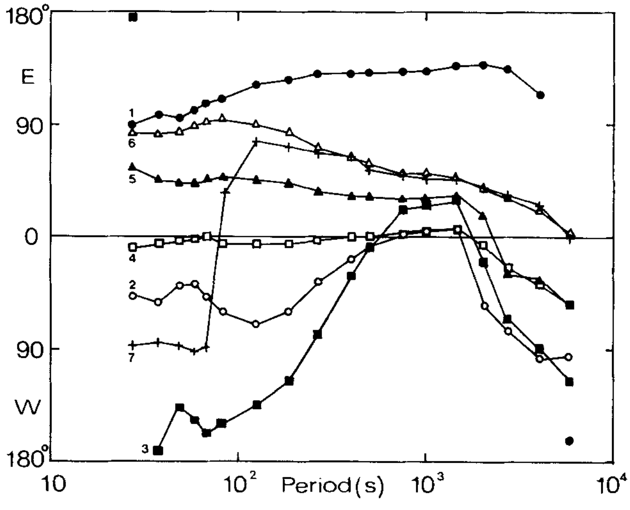

Figure 2. Azimuth of the real induction vector as a function of period. Station numbering as in Fig. 1.

At periods greater than 400 s, the frequency dependence of the azimuth is very similar at all the stations, with the exception of Earlybur [illegible] the period decreases from 10 000 to 1000 s, the vectors rotate from the NW to the NE quadrant. This behaviour agrees with that observed in the analogue model (Dosso *et al.* 1980). At 10 000 s, the magnetic fields are dominated by the current system in the deep ocean to the west and SW. As the period decreases, so does the spatial scale of the fields produced by the current in the Atlantic. The currents to the east in the North Sea are much closer, and their relative importance increases. The induction vectors at the most easterly stations (6 and 7) are the first to rotate as the period decreases, with the most westerly (3 and 4) the last to respond. The similarity in the behaviour of the real vector at all these sites strongly suggests that a common process controls the current which generates the magnetic fields. It is most unlikely that the strike of the local conductivity structure in the vicinity of each of these widely spaced stations is the same. It is much more probable that the common factor at all the sites is the dominant effect of currents induced in the shallow seas. However, the current system may not be confined to the seas alone, but extend inland by way of the sedimentary basins.

As the period falls to less than 400 s, the azimuths of the real vectors diverge, and below 100 s they stabilize around distinctly different directions. Such behaviour indicates that the local geological structure at each site controls the electromagnetic fields in the period range 30–100 s.

This simplified analysis of the frequency response of the magnetic field variations implies the existence of two distinct induction processes. Between 30 and 100 s, the induced current is controlled only by the *local* geological structure. In the range 400–2000 s, induction is a *regional* process involving the whole of a thin sheet comprising the shallow seas and conductive sediment both beneath the sea and on land. There is no sharp cut-off in the frequency ranges of the two modes of induction; their effects will overlap to some extent. The period ranges we are quoting are those in which each mode dominates the anomalous internal magnetic field at the majority of our sites.

To test the model, we need to investigate more closely the spatial correlation between the magnetic fields (and by implication the induced currents) and the local conductivity structure, in an area where the latter can be inferred from geological and other geophysical data. Fortunately, the structure of the region we have mapped in detail is relatively well known, both in terms of the surface geology, and from aeromagnetic, gravity and seismic surveys.

3 Spatial structure of the anomalous fields at intermediate periods

The area investigated in detail is shown in Fig. 3. It is bounded by the North Sea to the east and the Solway Firth to the west. Rocks of Ordovician and Silurian age, which were metamorphosed and folded in the Caledonian Orogeny, outcrop in the NW (the Southern Uplands), around the Cheviot volcanic centre in the NE, and in the SW (the Lake District). They are also present at very shallow depths in the SE, on the Alston Block. The Lake District, Alston Block, Cheviots and parts of the Southern Uplands, were all intruded by granite batholiths towards the end of the Caledonian Orogeny, and have subsequently formed relatively bouyant blocks of crust. The tendency of the Alston Block to rise relative to the surrounding areas has created major systems of faults along its northern, western and southern margins. By contrast, the crust in the areas between the granite-centred blocks has tended to subside, forming basins containing sediments of Upper Devonian to Permo–Triassic age. The thickness of the sediments is a maximum immediately to the north and west of the Alston Block, in the Northumberland Trough and Vale of Eden respectively. In both areas, the depth of the Caledonian basement is believed to reach 2–3 km (Lee 1982;

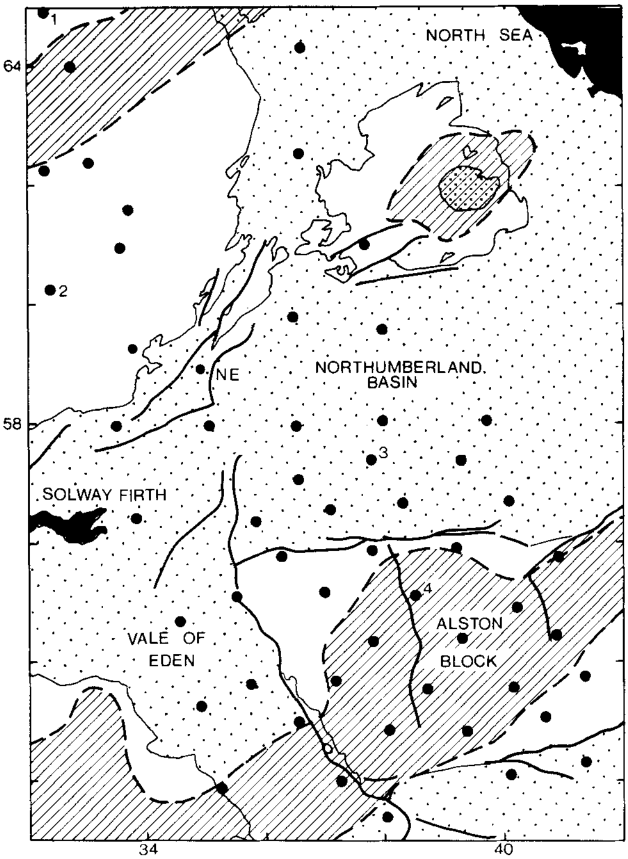

Figure 3. Station locations and geology. ● Magnetometer sites. — Major faults. Shading indicates areas underlain by granite batholiths. Stippled areas are underlain by substantial thicknesses of post-Caledonian sedimentary rock.

Bott 1974). The Carboniferous and Permo–Triassic sedimentary basins on the land are continuous with similar, but much thicker and more extensive basins beneath the North Sea and Irish Sea. The Caledonian metamorphic rocks, intruded by granite batholiths, can be expected to form a higher resistivity basement, over which there is a thin sheet of material with a high but laterally variable conductance, comprising both conductive sedimentary rocks and sea-water.

Two-frequency bands, centred on 750 and 60s, were chosen on the basis of the frequency dependence of the real induction vector discussed in Section 2. Hypothetical event analysis (Bailey *et al.* 1974) was used to generate maps of the anomalous field associated with horizontal magnetic fields in the magnetic north and magnetic east directions (9°W and 81°E respectively). The azimuths are approximately parallel and perpendicular to the nearby east coast of England, and should correspond to H and E polarization induction in the North Sea. Single-station transfer functions (Banks 1973) are available at all the sites marked in Fig. 3. The data at 48 of the sites are derived from surveys by the authors and their colleagues (Beamish & Banks 1983; Grimes 1977); the remaining five are taken from Hutton & Jones (1980) and Ingham & Hutton (1982). The only anomalous field maps which can be generated from single-station transfer functions are of the real and imaginary parts of the vertical field. Unfortunately, the maps are only accurate if the horizontal field is uniform across the area, i.e. if the anomalous horizontal fields are only a small fraction of the total. Stations in the south of the area were operated simultaneously with a Rubidium magnetometer at Durham (see Fig. 1), and inter-station transfer functions were computed, linking the horizontal fields at each site to those at Durham (Beamish & Banks 1983). They showed that the anomalous horizontal fields at 750 s were generatlly less than 20 per cent of the total. At 60 s, however, the spatial variations in the horizontal fields are up to 100 per cent of the total field at Durham. These results suggest that hypothetical event maps based upon single-station transfer functions will given an adequate picture of the anomalous fields at 750 s, but that at 60 s the maps may be significantly distorted, and should be interpreted with care.

Fig. 4 is a map of the real part of the anomalous vertical field produced when the hori-

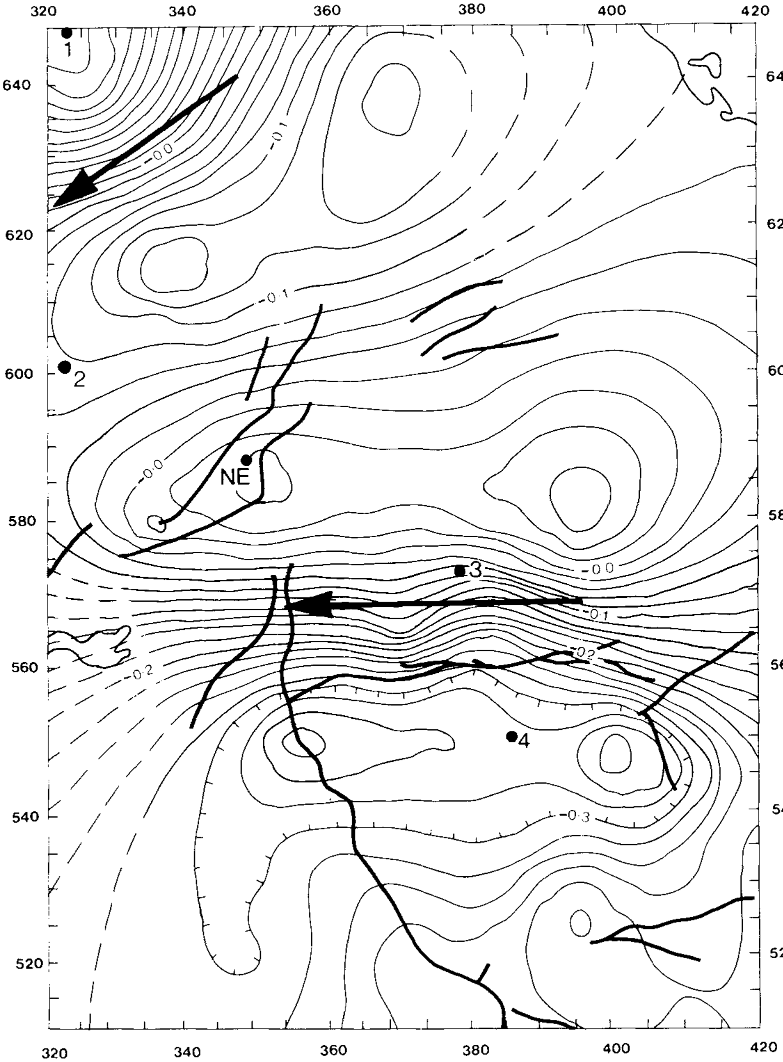

Figure 4. Hypothetical event maps of the anomalous vertical field. Period $(T) = 750$ s. Amplitude of the regional horizontal field = 1 nT. Azimuth (θ) of the regional field relative to magnetic north = 0°. Phase (ϕ) of the vertical field = 0°. Contour spacing = 0.02 nT. Heavy lines are major faults. Arrows indicate current concentrations.

zontal field at each site is directed magnetic north. The period is 750 s. The results for the imaginary part, which is very much smaller, are displayed in a different fashion in Section 5. A horizontal magnetic field with this azimuth should drive the current in the surface sheet from east to west through the land. Because the magnetic field is parallel to the coastline, no coast effect is expected, and none is observed. Instead, two intense anomalies are created over the land. The first of these, in the extreme NW of the map, is part of a NE to SW trending anomaly which runs across the entire width of Scotland beneath the Southern Uplands (see for example, Ingham & Hutton 1982). The second feature runs east–west, parallel to the southern margin of the Northumberland Trough, its maximum amplitude above the northern part of the Alston Block. The anomaly is asymmetric, possibly because of interference on its northern side from the other structure. The maximum current concentration is presumed to be in the position marked by the arrow, where the spatial gradient in the vertical field is greatest, and it coincides with the location of the greatest thickness of sediment in the Northumberland Trough. The steepness of the horizontal gradients in the magnetic field can be used to place constraints on the depth of the current. Alternatively, the vertical field map can be modelled by an equivalent current system in a thin sheet (Banks 1979). It turns out in this case that the sheet cannot be placed any deeper than 5 km; if it is, the current stream function is unstable. We interpret this to mean that at least a part of the current must be shallower than 5 km. The top 3 km of the crust is known to be formed from relatively conductive sedimentary rocks, which lie on top of a resistive metamorphic basement. A magnetotelluric station in the Northumberland Trough detected the surface conductor, which masked the deeper structure (Jones & Hutton 1979b). There is no positive evidence for the presence of any other conductive rocks in the upper crust, and, in view of the correlation between the anomalies and the near-surface structure, it seems most likely that the bulk of the current is flowing in the surface layer of sedimentary rock.

This superficial conductor is not isolated, but is linked at each end to more extensive bodies with greater conductivity–thickness products: the Irish and North Seas, and the underlying sedimentary basins of Permo–Triassic to Tertiary age. The question which naturally arises, is, whether the amplitudes of the anomalous fields around the Northumberland Basin would be as great as those observed if it were electrically isolated at both ends. If the connection to the rest of the sheet has no effects, the electromagnetic fields in and around the basin will be determined only by the 'local' geological structure, in this case the thickness, conductivity and horizontal extent of the Carboniferous sedimentary rocks. The Northumberland Basin runs east–west, and responds most strongly to a northward-directed horizontal magnetic field, just as we would expect if the induction were purely local. The very similar sedimentary basin in the Vale of Eden is aligned north–south, and if the induction is a local process, its response to an east magnetic field should be as strong as that of the Northumberland Basin to a northward field. However, if the link to the seas is important, the 'regional' situation of the conductor as part of the surface sheet should be just as important as the local conductivity structure in determining the basin's response. The Vale of Eden basin is linked at its northern end to the Solway Firth, but is an electrical dead-end to the south. Although it appears to connect to the Stainmore Trough, the sediment in both basins thins towards the junction, and the two conductors are effectively separate. There is, therefore, a significant contrast in the regional significance of the Vale of Eden and Northumberland Basins.

Fig. 5 shows the real part of the vertical field associated with a horizontal magnetic field directed eastward. The regional current should be driven from south to north, producing anomalous current concentrations in the North and Irish Seas. The resultant vertical field should be negative on the eastern side of the land, and positive on the west. The overall

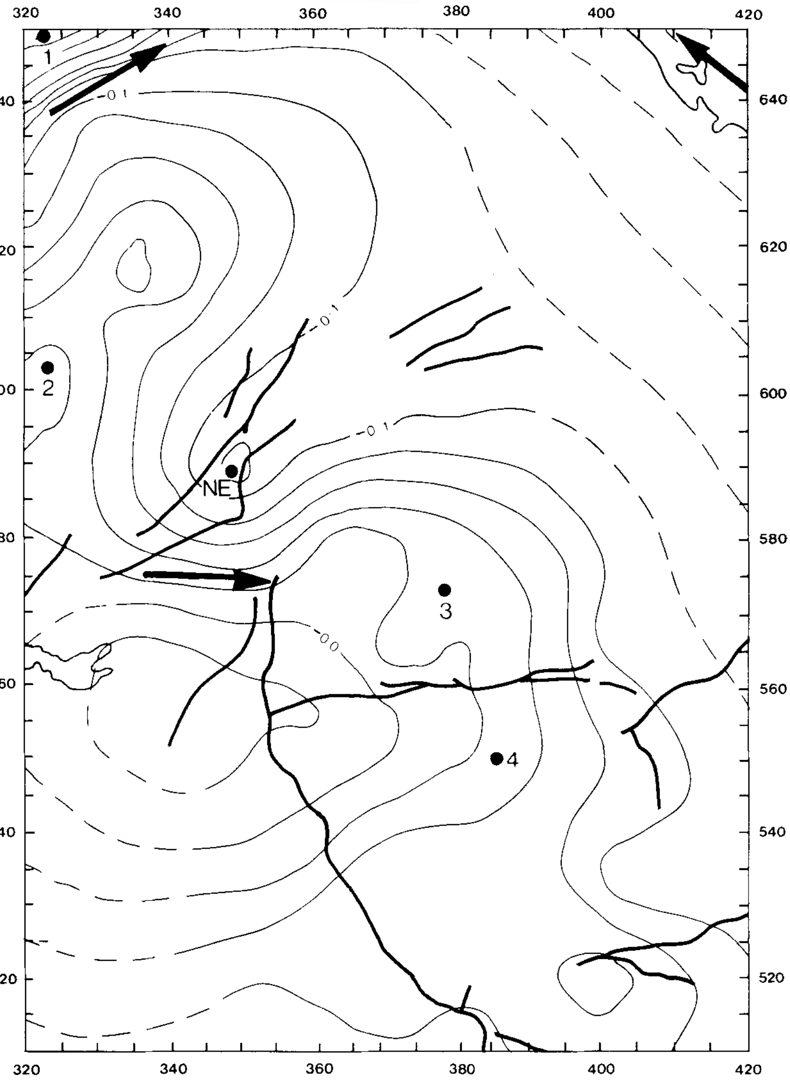

Figure 5. $T = 750$ s, $\theta = 90°$, $\phi = 0°$.

trend in the observations agrees with this prediction, although the field produced by the current in the North Sea is significantly stronger. However, superimposed on the broad pattern are features with much steeper spatial gradients. The Southern Uplands anomaly is still present in the NW corner, running from NE to SW. In addition, the influence of the conductor in the Northumberland Basin is plainly visible as an eastward bulge in the positive contours, indicating that the *eastward* magnetic field is able to induce a west-to-east current in the basin. Most significant of all, there is no sign of any anomaly running north–south along the eastern edge of the Vale of Eden, such as we would have expected if the local geological structure were the only factor determining the electromagnetic fields.

We conclude that, at a period of 750 s, the electromagnetic fields in northern England and southern Scotland are determined by induction in a thin sheet comprising both sea and sedimentary basins, and that the fields around a conductive structure on land are not only determined by its locally significant properties of conductance and lateral extent, but also by its regional importance with the sheet.

4 The spatial structure of the anomalous fields at short periods

Our analysis of the frequency dependence of the azimuth of the real induction vector led us to suggest that a profound change occurs in the mode of induction as the period of the magnetic field variations decreases to 100 s and less, and that the electromagnetic fields at shorter periods could well be much more closely related to the local geological structures. This assertion can be tested by investigating the fields around the two sedimentary basins at a period of 60 s.

Fig. 6 is a map of the real part of the vertical field associated with a northward horizontal magnetic field. The Southern Uplands anomaly in the NW has virtually disappeared, and the

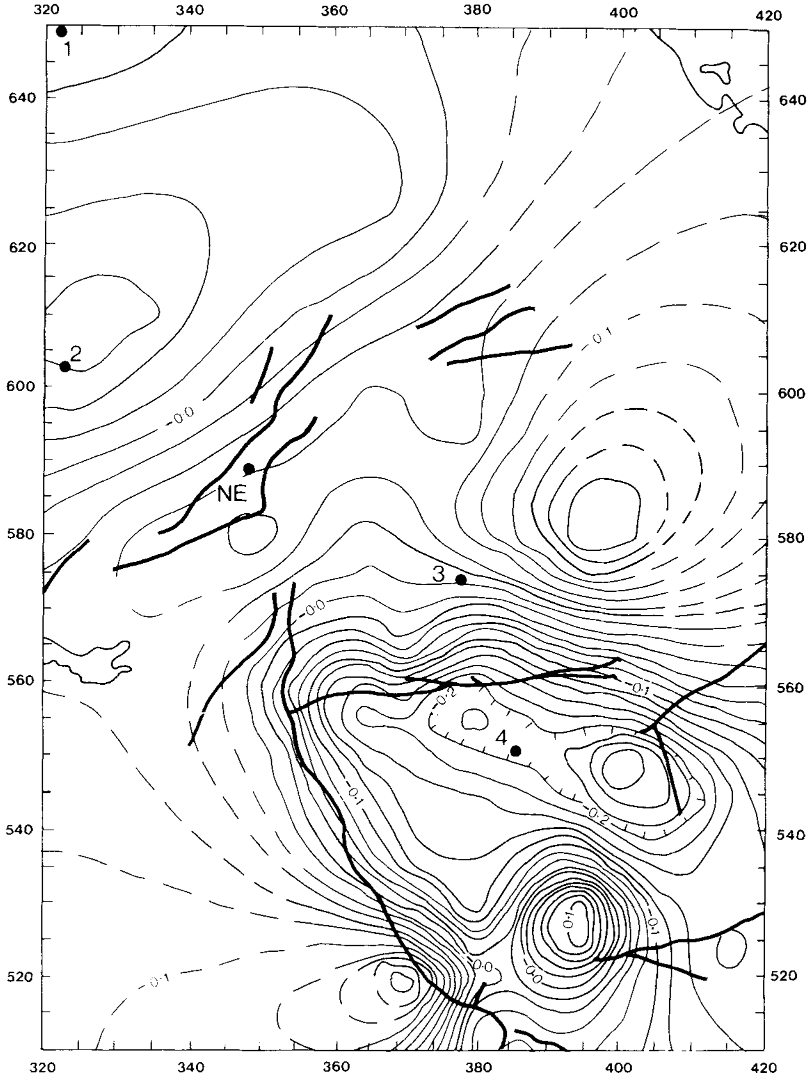

Figure 6. $T = 60$ s, $\theta = 0°$, $\phi = 0°$.

anomalies over the northern margin and centre of the Northumberland Basin are smoothly varying and of low amplitude. Intense anomalies running east–west are concentrated along the southern margin of the Northumberland Basin, where the sediment thickness is greatest, and where the boundary fault maximizes the contrast with the resistive rocks of the Alston Block. There is some indication of structures within the block, and a rather surprising apparent response from the western edge against the Vale of Eden. However, the station spacing of 10 km is barely adequate to resolve the structure over the southern part of the block, at the junction with the Stainmore Trough.

The response to an eastward magnetic field is shown in Fig. 7. The anomaly associated with the Northumberland Basin has virtually, though not entirely disappeared. However, at this frequency there is clear evidence of an anomaly running parallel to the western margin of the block, as we would expect if the induced fields in the Vale of Eden are determined by the local conductivity structure. The residual anomaly at the western end of the

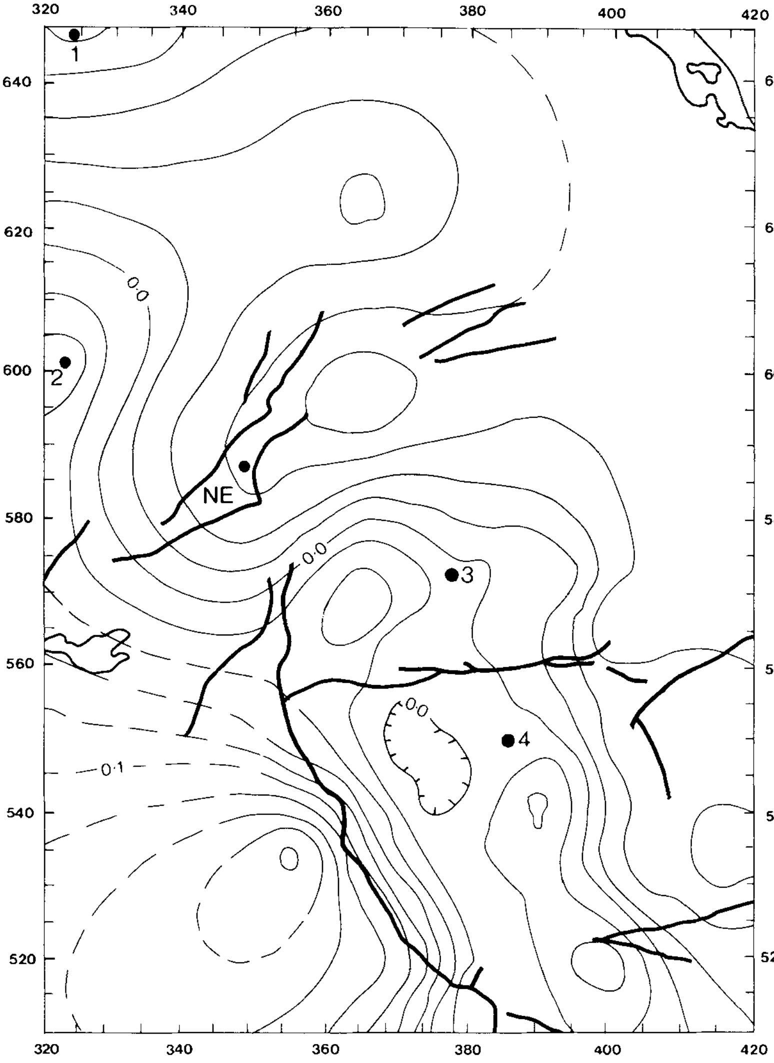

Figure 7. $T = 60$ s, $\theta = 90°$, $\phi = 0°$.

Northumberland Basin appears to correlate in position and trend with a SW to NE aligned anticline which causes the basement to shallow.

The observations of the Northumberland Basin and Vale of Eden at a period of 60 s support the view that electromagnetic fields with periods less than 200 s are predominantly determined by the *local* structure, and relatively uninfluenced by the regional setting of the basins within the surface sheet. It should therefore be entirely appropriate to model their response below 200 s by structures based upon the local geology.

5 The phase of the response at intermediate periods

So far, we have ignored the imaginary part of the anomalous field because its amplitude is generally much smaller than that of the real part. However, the phase of the fields observed at intermediate periods (i.e. 750 s) should be particularly significant if the model that has been proposed is correct. We have envisaged the anomalous fields at periods of 400–2000 s as arising from the perturbation of a regional current flow in a thin sheet of laterally variable conductance. The observed vertical field will be in phase with the perturbation currents created by the inhomogeneities. Provided the horizontal dimensions of the conductivity anomalies are small compared with the skin depth of the electromagnetic field, the perturbation current will itself be in phase with the regional current, which is common to all parts of the sheet. Consequently, the model predicts that the phase of the anomalous vertical field should be the same at every station, and only its amplitude will vary. The most direct approach to testing this idea is to plot an Argand diagram showing the real and imaginary components of the vertical field at each site which are produced when the horizontal field has a specified azimuth. If the phase is uniform, points for different sites will plot along a straight line which passes through the origin, and whose phase is that of the regional current.

Fig. 8 is an Argand diagram of the vertical fields associated with a northward horizontal field of amplitude 1 nT. Stations in the survey area are not labelled, but the more widely-spaced sites in Fig. 1 are indicated by their numbers. With three exceptions, the complex

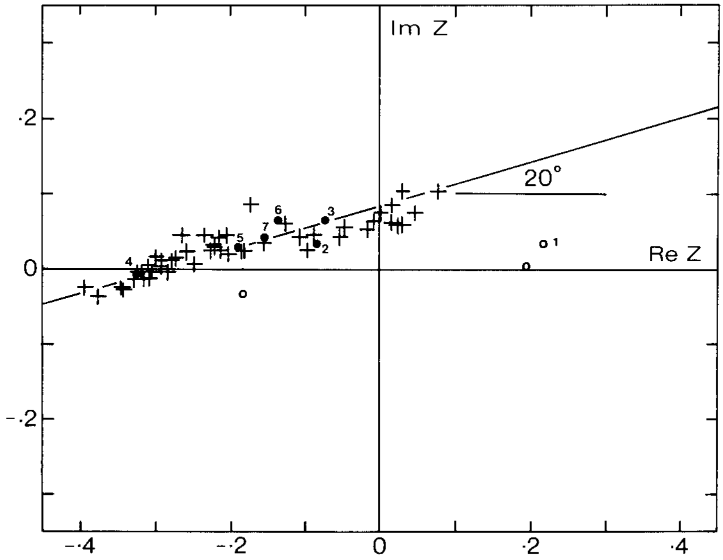

Figure 8. Argand diagram for the vertical field. $T = 750$ s, $\theta = 0°$. Numbers correspond to sites in Fig. 1.

values plot on a straight line. The exceptions are sites located in the extreme NW of the map, which are those most strongly influenced by the Southern Uplands anomaly. The distinction between the fields produced by this current, and those measured at the remaining sites, including some as far away as 300 km, is a strong indication that two quite separate current systems are involved. For instance, the Southern Uplands conductor may be significantly deeper than the surface sheet, and electrically isolated from it.

Although there is a linear relationship between the imaginary and real parts of the vertical field at the majority of the sites, the best-fitting line does not pass through the origin, as the sheet induction model would predict. The slope of the line corresponds to a phase of 20°. If a hypothetical event map is plotted with phase references of 20 and 110°, instead of the customary 0 and 90°, the map with 110° phase is essentially featureless, since all the stations display the same vertical field of approximately 0.08 nT. If the sheet model had been correct, this field at 110° phase would have been uniformly zero. A possible explanation of this behaviour is that the anomalous vertical field over the survey area is generated by two separate current systems. The major part is derived from the perturbation currents in the thin sheet, which are themselves in phase with a regional sheet current whose phase relative to the horizontal north magnetic field is 20°. The second part is a field of indeterminate magnitude and phase which is spatially uniform on a scale of several hundred kilometres.

Fig. 9 is an Argand plot of the vertical field associated with an eastward magnetic field. The amplitudes are much smaller in this case, and the points more scattered, but there is a hint of a correlation between the imaginary and real parts similar to that observed for the north magnetic field. Also, the magnitude of the offset created by the uniform field has diminished. This behaviour suggests that, by rotating the azimuth of the horizontal field, it may be possible to eliminate, or at least minimize the contribution of the uniform field, leaving only that of the current sheet. Experiment shows that a horizontal field with an azimuth of 115°E (i.e. 106°E geographic) comes closest to producing a set of data which plots along a straight line through the origin (see Fig. 10). The phase of the current sheet remains approximately 15–20°.

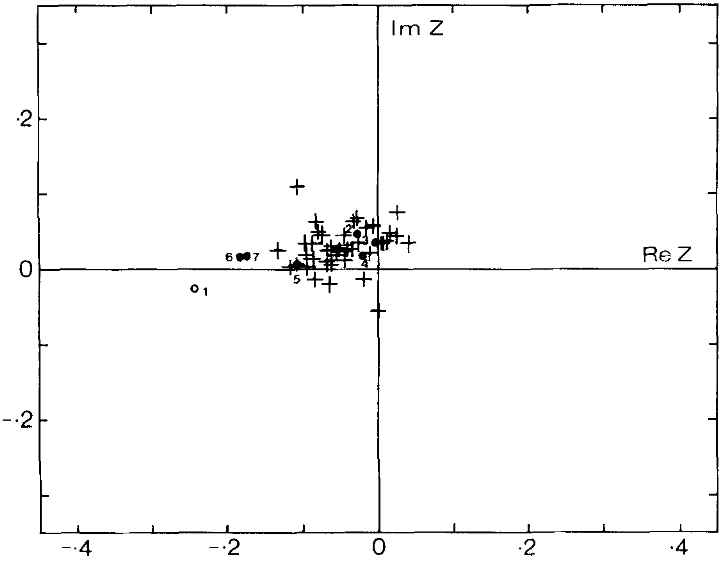

Figure 9. Argand diagram for $T = 750$ s, $\theta = 90°$.

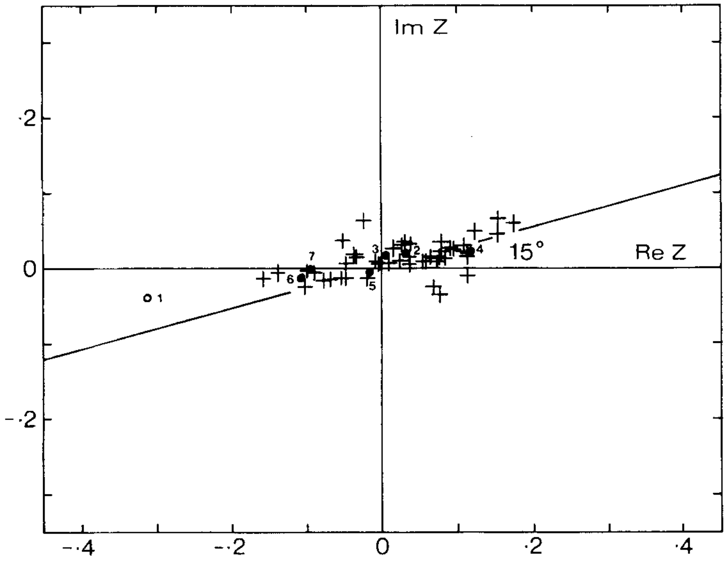

Figure 10. Argand diagram for $T = 750$ s, $\theta = 115°$.

The fact that the uniform field can be eliminated by choosing a magnetic field azimuth of 106°E gives a possible clue to its origin. The configuration of the continental edge around the British Isles is quite complex (see Fig. 1). Although the water depth is substantially greater to the west of Ireland than over the shelf, it is very variable, and never reaches anything like the full depth of the Atlantic. Only to the SW of the British Isles is there a true continental edge where the water depth increases very rapidly from 200 to 4000 m. It is this edge, with an azimuth of 110–120°E, which is likely to be the most important factor in controlling the induced current in the Atlantic Ocean. The vertical field of the Atlantic currents will be a minimum over the British Isles when the horizontal magnetic field is parallel to this edge, i.e. has an azimuth of 110–120°E. The stations we have analysed are nearly 1000 km from the edge, and at this distance the fields will be relatively uniform. We suggest therefore that the spatially uniform fields over north and eastern England at a period of 750 s are the residual direct fields of the current in the Atlantic Ocean.

6 Conclusions

Three distinct modes of induction control the electromagnetic fields observed in southern Scotland and in north and eastern England. The influence of each mode is most easily recognized in a specific period band, although the bands which the modes affect must overlap substantially. At periods greater than 2000 s, the transfer functions at the vast majority of sites are determined by electric current flowing to the west and SW in the Atlantic Ocean. This effect becomes more important with increasing period. In the period range 400–2000 s, the transfer functions are determined by currents induced in a thin sheet of laterally varying conductance, comprising the shallow seas and their underlying sediments, together with the landward extensions of the sedimentary basins. Other sources with different characteristics are locally important, such as the Southern Uplands anomaly, which is distinguished by its phase. At periods less than 200 s, the transfer functions are compatible with an induction process which is controlled only by the local geological structure.

We have called the intermediate period mode *regional induction*. We believe that our data show that the electromagnetic fields and transfer functions corresponding to this mode are not only determined by the local conductivity structure, but also by the role of the local conductor in the surface sheet which includes the shallow seas. The first step in attempting to interpret data from this band must involve a 3-D thin sheet model (e.g. Park, Orange & Madden 1983) which incorporates realistic estimates of the lateral variations in its conductance, based upon hydrographic, geological, and other geophysical data. Our results indicate that the choice of boundary to the area modelled may be rather critical, and the effects of placing it at different distances from the Northumberland Basin must be carefully investigated. In a 3-D environment such as the Northumberland Basin, magnetotelluric sounding curves covering this period band may be significantly distorted. It is not always obvious from impedance measurements at a single station that such distortion has occurred, and low values of skew and approximately isotropic apparent resistivity curves may tempt the interpreter to fit a 1-D model. The result may be false features in the resistivity profile at intermediate depths (Park *et al.* 1983). Response data from Newcastleton (station NE in Fig. 3) has been interpreted using a 1-D model to give a depth profile for the Northumberland Basin (Jones & Hutton 1979b). We think our results emphasize the importance of supporting an individual station response by an adequate *regional* coverage of soundings, so that the effects of the heterogeneous surface layer can be estimated and corrected for in the manner advocated by Park *et al.* (1983).

We have labelled the short-period mode, *local induction*. At most of the stations in our survey, it should be safe to interpret the response data from this and shorter period bands using models based on the geological structure in the immediate vicinity of the measurement sites. However, we must stress that this conclusion is specific to the area we have investigated. What is important is the relationship between the sheet thickness, the skin depth, and the 'adjustment length' (Park *et al.* 1983) of the electromagnetic fields, and these parameters are dependent on the particular geological structure.

Acknowledgments

We gratefully acknowledge support from the UK Natural Environment Research Council in the form of grant GR3/2371 and a grant from the Deep Geology Project. This paper is published with the approval of the Director, British Geological Survey (NERC).

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