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EXAMPLES OF HORIZONTAL LOOP ELECTROMAGNETIC ANOMALIES CONTROLLED BY GEOLOGICAL FAULTING

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ABSTRACT

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Examples of horizontal loop (slingram) electromagnetic anomalies associated with geological faults in the English Peak District are described, and interpreted in terms of the geology defined by detailed mapping, bore holes and resistivity measurements. Each anomaly is interpreted as being due to the edge effect of thin, horizontal sheets of low-resistivity strata, rather than to conductive material in the fault zone. The anomalies presented are controlled more by the shallowness of the conductor responsible than by high conductivity-thickness products. The implications of the results for geological mapping and mineral prospecting are considered, the latter by means of a laboratory scale model.

INTRODUCTION

This paper describes initial results of research aimed at developing the use of the electromagnetic prospecting method for geological mapping. Horizontal loop, moving source-receiver (slingram) measurements have been made over faults covered by glacial drift at 4 sites in the English Peak District. At each site electromagnetic anomalies have been found, which can be related to the presence of the fault.

Frischknecht (1966) demonstrated that conducting strata, such as black slates, may be mapped by slingram measurements, the response being mainly out-of-phase. His examples involved steeply dipping strata rather than faulted junctions; however, both structures present a similar target for the EM method. VLF electromagnetic measurements over faults frequently reveal anomalies due to contrasts in bedrock resistivities (e.g., Telford et al., 1976, p. 598).

Currently, the slingram method is used mainly to prospect for massive mineralisation. Such mineralisation is commonly found in, or near to fault zones. It is well known that if a fault zone contains conductive material such as metal sulphides or ground water, it may become amenable to detection by electromagnetic induction methods. If the conducting material can be assumed to form a thin half plane, good estimates can be made of its conductivity-thickness product (σt), and the depth to its top, from the negative peak in-phase and quadrature values of the electromagnetic response, using appropriate Argand diagrams (Strangeway, 1966a; Parasnis, 1971).

The effect of conducting overburden and conductive host rock on the form of an anomaly due to a conductive thin sheet has been studied by Lowrie and West (1965), and Verma and Gaur (1975), using scale models. All considered thin sheet models either covered, or surrounded by isotropic, conductive media. Lowrie and West demonstrate that the response of a dipping sheet, underlying but not in galvanic contact with horizontal, conducting overburden, will undergo a phase rotation. They present approximate expressions which may be applied to eliminate this overburden effect. Verma and Gaur show that any asymmetry due to the dip of a conducting sheet is rapidly lost when the sheet is surrounded by, and in galvanic contact with, a conducting host rock. Geyer (1976) shows that short wavelength anomalies due to localised thickening or increase in conductivity of an electrically anisotropic, thin overburden, occurs mainly in the quadrature component for most real cases.

THE SURVEYS

Horizontal loop profiles over known faults at four sites in the English Peak District (Fig. 1) were made. The geology at each site was known from detailed outcrop mapping, resistivity surveys, and in addition, at site 1, from bore hole records.

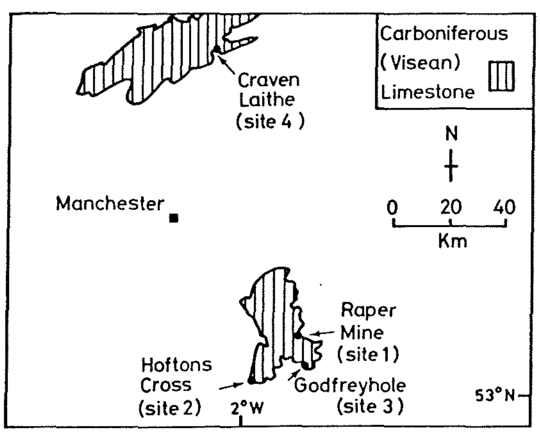

Fig. 1. Locations of fieldwork sites. The English Peak District.

A two frequency, horizontal loop unit (ABEM Demigun DMG 251), operating at 880 and 2640 Hz was used, with a coil spacing of 60 m. Readings of the in-phase and quadrature values of the vertical component of the resultant induced magnetic field were taken at intervals varying from 5 to 20 m, along lines normal to the strike of the faults.

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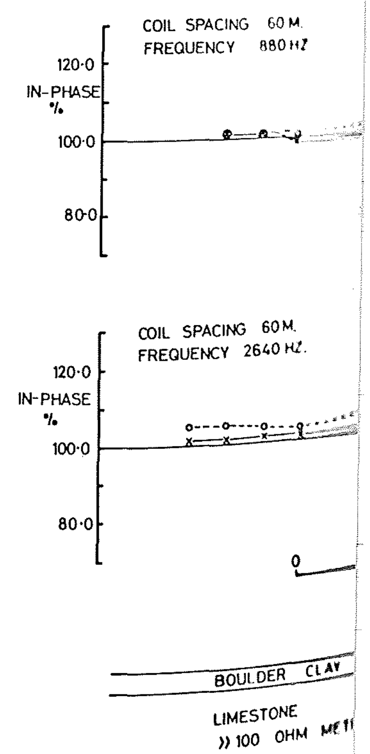


Fig. 2. Electromagnetic profiles

Electrically neutral ground over which to set the in-phase dial to 100% was not always available, consequently some of the values obtained may differ by up to ± 10% from absolute values. The shape of the profiles, however, will not differ significantly from those defined by the absolute values.

Profiles were made on level ground, except on one side of the fault at site 2. Here the anomaly occurs largely over level ground, and so a terrain correction has not been applied. Details and electromagnetic results for each site are plotted in Figs. 2—5. The geology at all sites consists of Lower Carboniferous (Visean) sediments and Quaternary drift deposits. The results for site 1 come from Sirikci (1976).

At each site, Schlumberger resistivity expansions were made to obtain resistivity values of rocks on each side of the faults, and drift thicknesses. The resistivity surveys were made far enough from the faults to avoid spurious, fault controlled, current distributions. Interpretation was by curve matching, using curves computed by the method of Mooney et al. (1966), and type curves (Rijkswaterstaat, 1969).

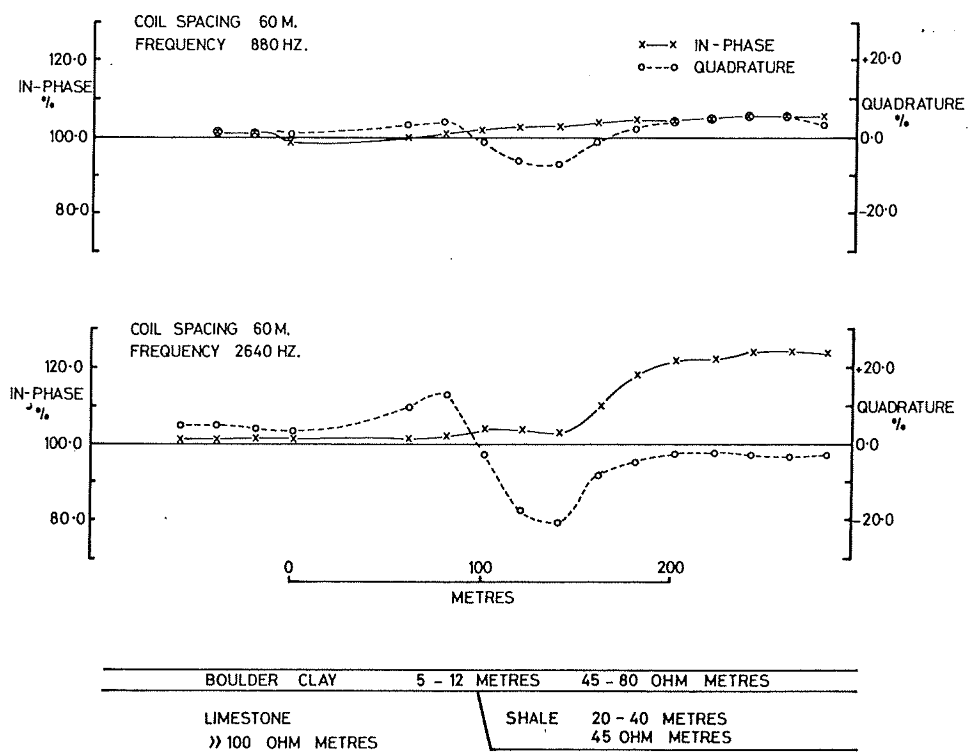


Fig. 2. Electromagnetic profiles and geologic section, site 1.

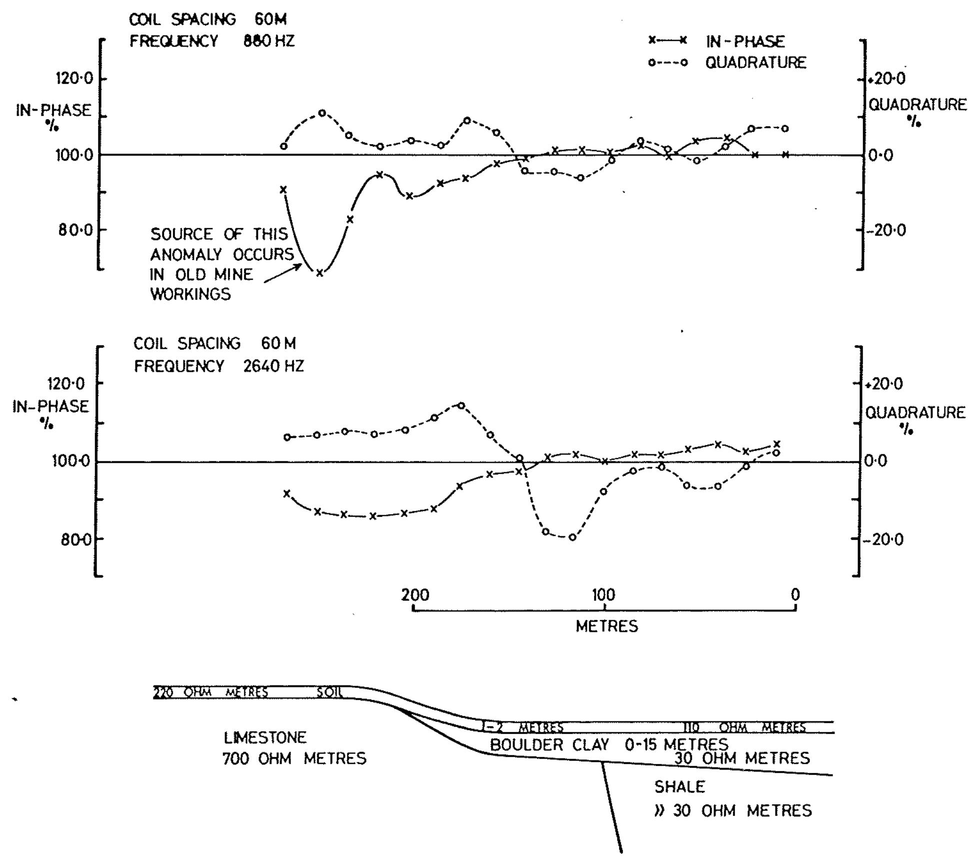


Fig. 3. Electromagnetic profiles and geologic section, site 2. N.B.: real components in region of slope uncorrected for height differences.

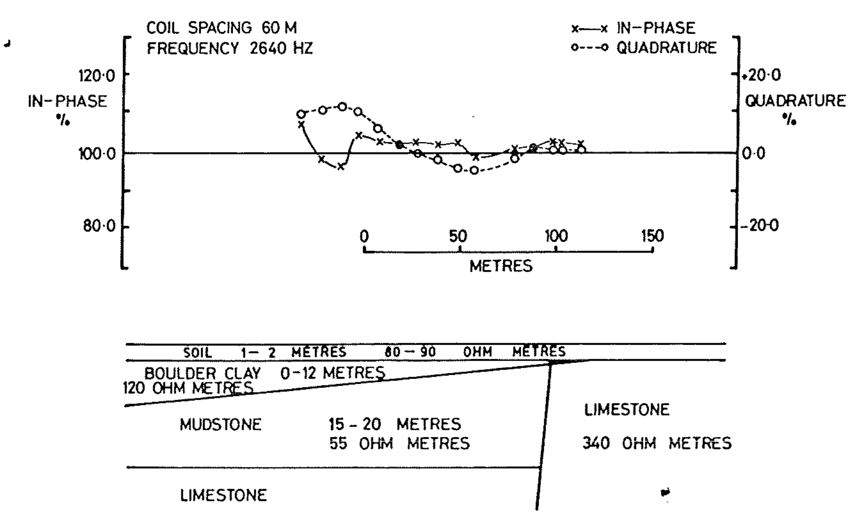
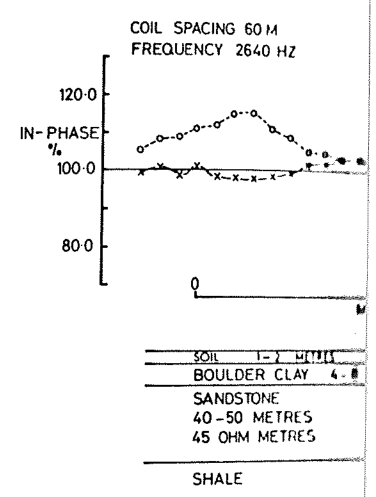


Fig. 4. Electromagnetic profile and geologic section, site 3.



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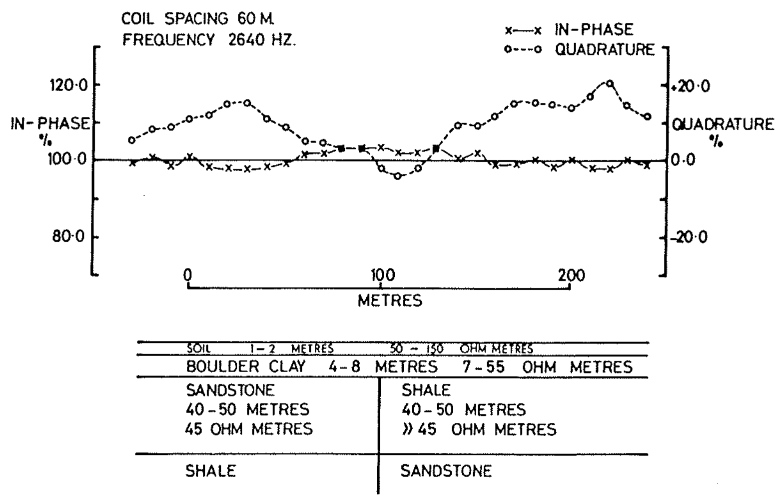

Fig. 5. Electromagnetic profile and geologic section, site 4.

RESULTS

The electromagnetic anomaly profiles at sites 1, 2 and 3 have a similar form. The response is mainly in the quadrature component, and is characterised by a peak on the more resistive side of the fault, and a trough about one coil spacing from it on the more conductive side. The exact position of the fault in relation to the anomaly varies, and is controlled by its dip, depth and the control it exerts on conductive overburden. Beyond the minimum, quadrature values become increasingly positive, up to a maximum which is not symmetrical with the other peak either in position or magnitude. In-phase values are positive over the more conductive side, and drop to zero in the region of the fault.

The asymmetrical nature of the anomalies at sites 1, 2 and 3 suggests that they are unlikely to be due to high conductivity material in the fault zones. Verma and Gaur (1975) show that a dipping half plane in conductive host rock will tend to produce a symmetrical anomaly, indicative of a vertical conductor, regardless of its actual dip. Their study did not include cases where the host rock has a different conductivity on each side of the dipping conductor. In such cases, the anomaly due to a dipping half plane could either be accentuated or diminished. As the exact modification of the anomaly in such a situation is not known, the possibility of the anomalies at sites 1, 2 and 3 being due to conducting material in the fault zone cannot be totally dismissed.

The general shape of the anomalies resembles that expected over the edge of a shallow, horizontal, poorly conducting thin sheet (Strangeway, 1966b). The results for sites 1 and 2 demonstrate this particularly well. Using a criterium for thinness developed by Mayr (1925), a sheet is thin if its thickness is less than $300\sqrt{1/\sigma f}$, where f = frequency (Hz) and σ = conductivity (mho m^{-1}). This criterium breaks down if the coil spacing is less than the actual thickness of the sheet (Keller and Frischknecht, 1966). On this criterion the strata causing the anomalies are all thin. One or more thin sheets of strata are thought to produce the anomalies at all four sites, though these sheets may not always be uniform in thickness and resistivity.

At site 1 the anomaly is considered to be principally due to the faulted edge of the shale, with a smaller contribution from boulder clay cover. A shallow resistivity traverse (Wenner configuration) over the fault, with a 5-m electrode spacing, showed that the position of the fault could be quite accurately estimated from variations in drift resistivity. This variation in drift resistivity is attributed not to a noticeable difference in material but mainly to a difference in physical properties and internal structure, produced by different permeabilities in the underlying strata. A difference in permeability of the bedrock will control the water content of the drift, by affecting drainage, porosity and clay mineral content. Since the more resistive drift occurs over the high resistivity limestone, the overall effect of the drift is to enhance the electromagnetic anomaly due to bedrock.

The anomaly at site 2 is very similar in form to that at site 1. The position of the fault at site 2, however, does not coincide with the position which would be suggested were the EM anomaly due to the edge of the shale. While the strata at both sites are of similar age and lithology, the anomaly at site 2 is considered to be due principally to the boulder clay overlying the shale, rather than the shale itself. A significant thickness (10—15 m) of low resistivity boulder clay (30 ohm.m) has accumulated on the low ground occupied by the shale. Waterlogging over the shale in winter demonstrates that the impervious shale inhibits drainage, and thus keeps the water content of the boulder clay high.

The range of conductivity-thickness products for the shale at site 1 (0.44 - 0.88 mhos) overlaps the range for the boulder clay at site 2 (0.33 - 0.5 mhos). This explains the similarity of the anomalies. If the edge of the shale at site 2 causes an anomaly, its magnitude is too small to enable it to be convincingly distinguished from that due to the boulder clay.

Site 3 presents a combination of the previous two cases. The small quadrature anomaly over the fault is considered to be due to the edge of the low resistivity mudstone. The larger positive values of both components, which occur over the mudstone in Fig. 4 and on adjacent profiles, are considered to be a response to drift, which thickens markedly away from the fault, from 4 m to 12 m. Variations in drift resistivity are likely as its water and clay content are known to be variable.

Variations in the thickness and resistivity of the drift at site 4 make interpretation complex. Even so, a distinct trough occurs in the quadrature component, within 10 m of the known position of the fault. The sandstone side of the fault is the less resistive. However, as Gaur et al. (1972) demonstrate, the conductive overburden is likely to make the anomaly more symmetrical than would be the case if the sole cause of the anomaly was the edge effect of the sandstone. It is probable that the anomaly is principally due to the edge of the sandstone, but is modified by the inhomogeneous cover of boulder clay, and to a small extent by the shale.

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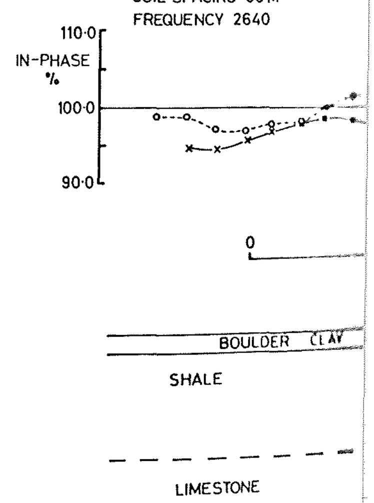

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A further point of interest arises from measurements made 500 m further along strike of the fault at site 1, where shale is faulted against shale. A small but distinct anomaly was measured over the fault, the quadrature component being asymmetric. The anomaly is considered to be due to different thicknesses of shale on each side of the fault. The geology and electromagnetic results are shown in Fig. 6.

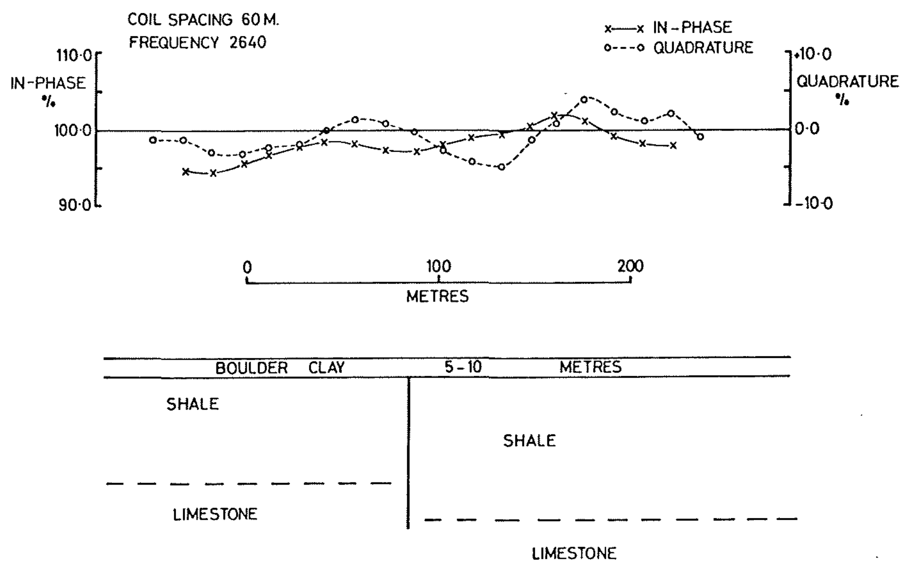

Fig. 6. Electromagnetic profile and approximate geologic section, site 1. In-phase values have been smoothed by averaging three consecutive values. This is to eliminate short wavelength noise.

The small amplitude of the anomaly makes it noteworthy. It shows that anomalies with an amplitude of less than 10%, and which might be discarded in horizontal loop surveys, can be useful in studying shallow geological features. While short wavelength noise, due to localised inhomogeneities, might inhibit confident use of such small anomalies for mapping where no previous knowledge of the geology exists, slingram measurements can enable the line of a known feature to be traced rapidly.

THE SIGNIFICANCE OF FAULT CONTROLLED ANOMALIES IN GENERAL EXPLORATION

A simple laboratory model has been used to simulate the effect that fault controlled anomalies, such as those cited in this study, are likely to have on the anomalies due to underlying ore bodies. The conditions for electromagnetic scale modelling, which are summarised in Negi and Gupta (1968), are obeyed. A thin sheet of stainless steel was used to represent a horizontal conductive stratum, with a σt product of the same order as for the stratum discussed in the examples given above. An ore body, dipping at 60°, was simulated by a thin copper sheet. The response parameter $(\sigma.w.\mu_0.t.l.)$, where $w = 2\pi f$, l = coil spacing (m), and μ_0 = permeability of free space, and the relative depth (d/l) are summarised in Table I. The operating frequency was 876 Hz.

TABLE I

Summary of model parameters, both actual and interpreted from EM measurements

Model	$(\sigma.w.\mu_0.t.l.)$ known	Interpreted from 60° Argand diagram	d/l actual	Interpreted from 60° Argand diagram
Stainless steel (horizontal)	0.4	—	0.1	—
Copper (dipping 60°)	44.0	44.0	0.28	0.28
Combined model	—	10.0	—	0.1

The results of this model study are shown in Fig. 7. The conductive bedrock model alone, causes an anomaly which is dominantly out-of-phase. The ore model, however, produces a dominantly in-phase anomaly. The anomaly due to the combined model contains elements of the anomalies due to the separate models. The in-phase component is similar in magnitude and position to that of the ore model alone, though it fails to return to 100% over the conductive stratum. The quadrature response, however, is principally due to the horizontal conductor.

These laboratory experiments suggest that if an attempt were made to interpret anomalies due in part to conducting host rock, in terms of just a single dipping ore body, the interpretation (summarised in Table I) would be highly erroneous.

The interpreted conductivity-thickness product of the ore body would be less than 25% of its actual value, and its apparent depth only $\frac{1}{3}$ of its true depth. Such errors clearly have profound significance.

This one example is merely intended to demonstrate the possible magnitude of the problem. The large number of permutations of relative resistivity, depth and position, in the ore body — horizontal conducting strata situation, would make a complete study, with quantitative conclusions impractical. Recognition of an anomaly due to two causes is important if misinterpretation is not to occur. Fortunately, the presence of an edge effect anomaly can often be inferred from the anomaly profiles. With conducting strata on only one side of a fault, background values of one or both components away from the fault will

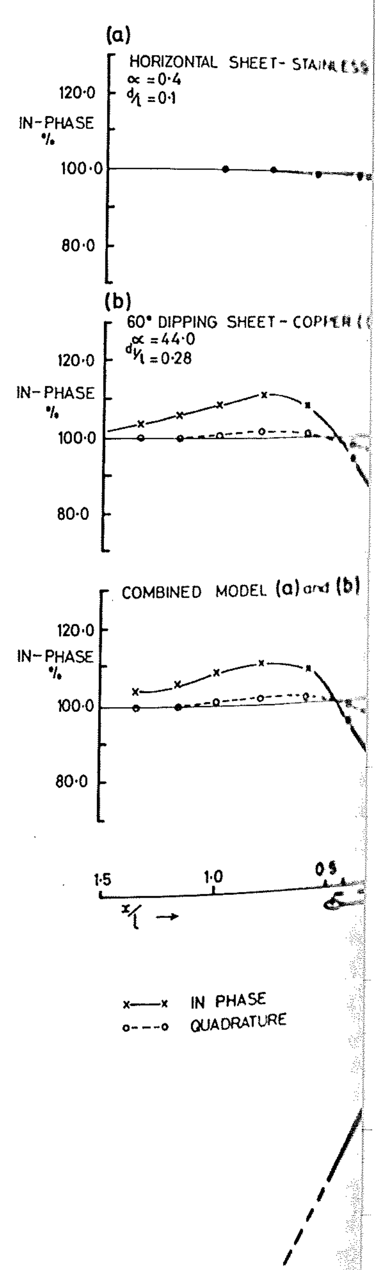

Fig. 7. Model profiles to demonstr
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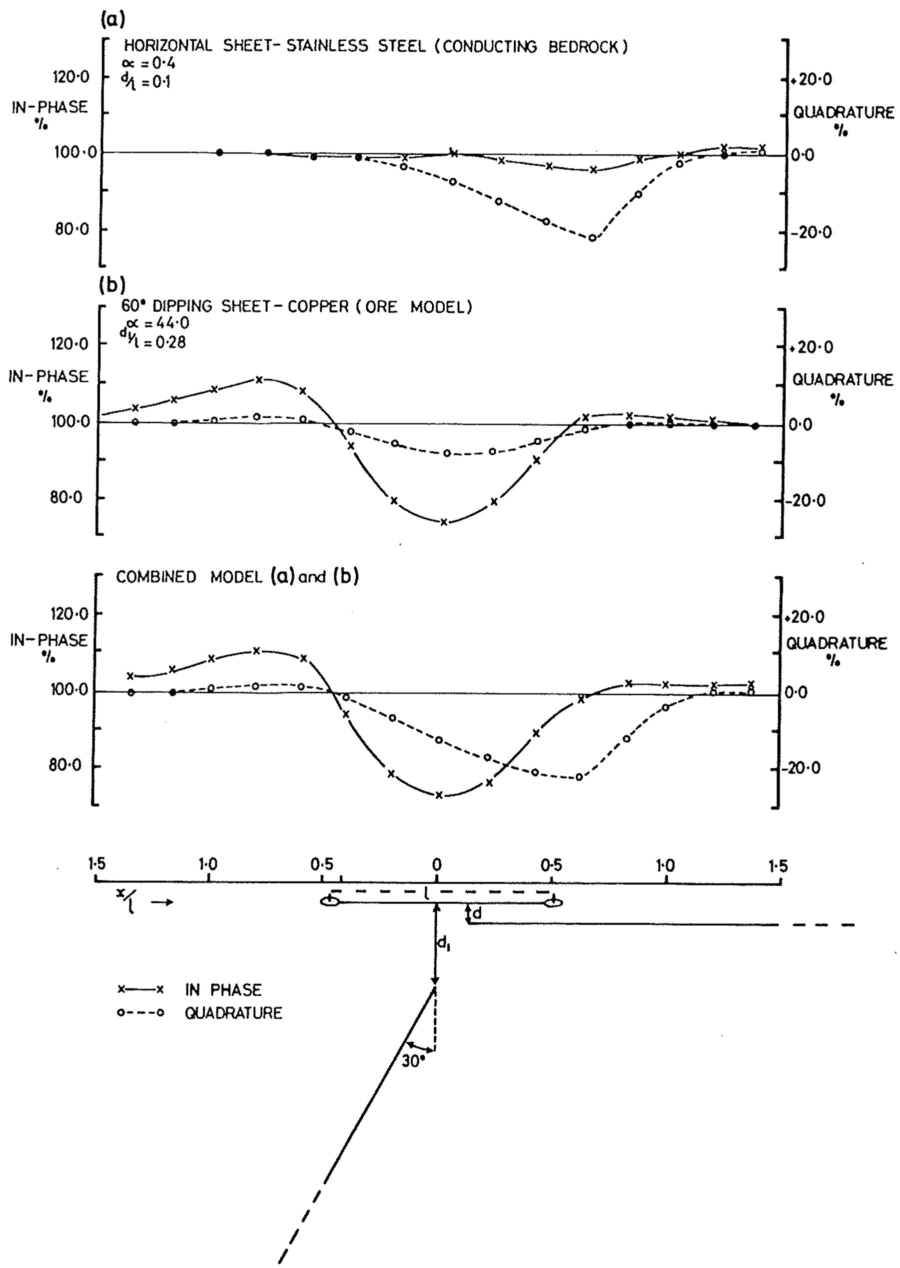

Fig. 7. Model profiles to demonstrate the effect of combining an anomaly controlled by a fault, with that due to an ore body.

not be symmetrical about it. Also, if the position of the peak values for the two components differs markedly, this may indicate that the observed anomaly represents the combined effect of two sources. This second criterion is, however, a function of the geometry of the two conductors, rather than their electrical properties, and so will not always apply.

DISCUSSION AND CONCLUSIONS

It has been shown that electromagnetic anomalies occur when EM measurements are made over, or near to, geological faults. The anomalies are considered to be due to edge effects of thin sheets of horizontal strata whose position is fault controlled. The response of these sheets is controlled more by their shallowness than their conductivity-thickness products. The ratio of depth to coil spacing is less than 0.3 in all cases.

Four different ways in which an anomaly can arise have been demonstrated. These are: (1) good bedrock conductor faulted against poorer bedrock conductor; (2) thickness of conducting bedrock different on each side of the fault; (3) water content, and hence resistivity of drift, different on each side of the fault; and (4) different thicknesses of conductive drift on each side of the fault. Thicknesses are controlled by resistance of underlying bedrock to weathering, prior to drift formation.

Any of these four geological situations may produce an anomaly either on its own, or in combination. With (3) and (4) the resistivity and thickness of drift may vary gradually across the fault with the result that the interpreted position of the fault is offset from its actual location.

These results are significant for two main reasons.

(1) Bedrock faults may be readily traced under a significant thickness of drift using the slingram method, if any of the above conditions prevail. The method can therefore be used to investigate poorly conducting mineral deposits commonly associated with faults, e.g. fluorite, even though the deposit itself does not produce an electromagnetic anomaly.

(2) Gross misinterpretation of electromagnetic anomalies due to conducting features, such as ore bodies along fault zones, may result if the possibility of fault controlled modification of anomalies is not considered.

If the fault alone is the feature of interest, each of the faults cited here could probably have been traced using the VLF method. Brzozowski (1975) has shown a strong correlation between VLF anomalies and solid geology. There are, however, certain drawbacks with the VLF method; the receiver is at the mercy of a commercial transmitter both for the quality of signal, and its coupling with conductive features. A generator-driven transmitter may be used (Tilsley, 1976) to overcome these problems, but the inherent advantage of portability is then lost. If the strata are much more conductive than those studied here, the skin depth will become sufficiently small to significantly attenuate a VLF signal, and hence reduce the depth of penetration obtained.

To reduce the effects of fault-controlled anomalies in slingram ore prospecting, the coil spacing, and frequency should be kept small. Several of the large

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Finally it is noted that groundwater, and/or conducting clay minerals, commonly accumulate in fault zones. This source of EM anomalies is widely recognised and is commonly invoked to explain EM anomalies over fault zones. The results presented here show that this is not a universal explanation of such anomalies.

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