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No. 20

Geophysical field techniques for mineral exploration
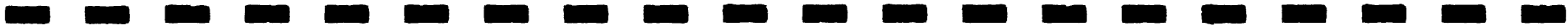
Mineral Reconnaissance Programme

Report No. 20

Geophysical field techniques for mineral exploration

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London   1978   *A report prepared for the Department of Industry*

Mineral Reconnaissance Programme Reports

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LIST OF ILLUSTRATIONS

SUMMARY

In areas as intensively explored as much of the British
Isles, new mineral deposits are only likely to be found
concealed beneath overburden or barren rock. Geophysical
and geochemical methods therefore have important roles
to play in any exploration programme. A wide variety of
geophysical methods has been used for the Department
of Industry Mineral Reconnaissance Programme and the
selection of the method has been determined mainly by
the type of mineralisation expected.

In this report a brief general outline of the different
geophysical methods used is given but further details are
included where these are particularly relevant to the
Mineral Reconnaissance Programme. Included in this
latter section are details of the airborne surveys, noise
studies made in connection with EM surveys and examples
of field surveys illustrating the use of different methods.

GENERAL

Introduction

The geophysical techniques suitable for mineral
exploration have developed rapidly over the last 20 years
and there is now a wide range of methods available,
several of which have not been used extensively in
Great Britain. The general principles, range of methods
available and case histories are described in several text-
books (for example, Parasnis (1973) and Morley (1970)).
This report deals in greater detail with topics directly
relevant to exploration in Great Britain for the Mineral
Reconnaissance Programme sponsored by the Department
of Industry (Dunham, 1973). The material included is
intended to serve as an introduction to the geophysical
work described in other reports in this series on specific
areas. The instrumentation used for both ground and
airborne methods is described.

In areas as heavily populated as much of England,
Scotland and Wales, interference by man-made sources
of 'noise' is bound to be a problem. To assist in the
selection of equipment and planning of the surveys using
electromagnetic methods, a special study was made of
the sources of man-made noise and the results of this
survey are included as an appendix.

The report deals with geophysical methods up to the
stage of data presentation but largely omits the next
important stage of data interpretation. This is because
the problems of interpretation are complex and varied
and are best described in relation to the specific areas
covered by individual reports

Physical properties of minerals and rocks

All geophysical techniques depend upon detecting
variations in one or more of the physical properties of
rocks. These properties vary within wide limits and it
is usually desirable to make measurements on samples
from within the area to be surveyed; but it is also
essential to have some prior knowledge of the limits in
order to decide what type of geophysical survey is
required to solve a particular problem.

In Table 1 the physical properties relevant to mineral
exploration (density, magnetic susceptibility and
resistivity) have been listed for the more common ore
minerals and rock types. These data have been extracted
from a more comprehensive list published by ABEM,
Stockholm (Parasnis, 1971). They provide a guide to the
ranges expected; results for specific areas are given in
individual reports.

It is clear from the data listed in Table 1 that nearly

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D of I Mineral Reconnaissance Programme Report Series

Herewith reports nos 20, 21, 22 and 23. Copies of these reports are to be placed
on Open File here and at the other IGS Offices on Monday, 4 September.

pp. D Ostle
Programme Manager

Table 1. Density, magnetic susceptibility and resistivity of some common ore and gangue minerals and rock types

MINERALS

Type		Saturated density g cm^{-3}	Magnetic susceptibility K x 10^6 (SI)	Electrical resistivity ohm metre
Arsenopyrite	FeAsS	5.9-6.2	2.10^3	$10^{-4} - 10$
Barite	BaSO$_4$	4.3-4.6		
Bornite	Cu$_5$FeS$_4$	5.0	-	$1.6.10^{-6} - 6.10^{-3}$
Calcite	CaCO$_3$	2.7	-12	5.10^{12}
Cassiterite	SnO$_2$	6.8-7.0	-	$5.10^{-4} - 10^{+4}$
Chalcocite	Cu$_2$S	5.5-5.8	-	$10^{-4} - 4.10^{-2}$
Chalcopyrite	CuFeS$_2$	4.3	$4.10^2 - 2.10^3$	$3.10^{-5} - 5.10^{-2}$
Chromite	FeOCr$_2$O$_3$	4.5-4.8	$8.10^3 - 12.10^5$	10^6
Copper	Cu	9.0	-10	2.10^{-8}
Galena	PbS	7.6	-33	$3.10^{-5} - 6.10^{-1}$
Graphite	C	2.3	$-224 - -608 /\!/c$ $- 6 - -79 \perp c$	$4.10^{-7} - 10^{-6} /\!/c$ $3 \cdot 10^{-5} - 10^{-2} \perp c$
Haematite	Fe$_2$O$_3$	5.1	$4.2.10^2 - 10^4$	$10^{-3} - 10^4$
Ilmenite	FeOTiO$_2$	4.4-5.0	-	$10^{-3} - 4$
Lead	Pb	11.3	-17.1	21.10^{-8}
Magnetite	Fe$_3$O$_4$	5.2	15.10^6	$5.10^{-5} - 10^{-3}$
Malachite	CuCO$_3$Cu(OH)$_2$	3.9-4.5	430	-
Manganite	MnO(OH)	4.2-4.4	$4.10^3 - 6.10^3$	$2.10^{-2} - 5.10^{-1}$
Molybdenite	MoS$_2$	4.9	-	$7 - 10^4$
Pyrite	FeS$_2$	5.1	35 - 60	$10^{-5} - 10^{-2}$
Pyrrhotite	Fe$_7$S$_8$	4.6	$10^4 - 25.10^4$	$2.10^{-6} - 1.6.10^{-4}$
Quartz	SiO$_2$	2.65		$2.10^{14} \perp c$ $10^{12} /\!/ c$
Sphalerite	ZnS	3.5-4.2	-13100	$2.10^{-2} - 4.10^4$
Wolframite	(Fe,Mn)WO$_4$	7.2		$10^3 - 10^7$

ROCKS

Type		Saturated density g cm^{-3}	Magnetic susceptibility K x 10^6 (SI)	Electrical resistivity ohm metre
Andesite		2.55-2.65	$3.10^3 - 6.10^4$	5.10^4
Basalt		2.90-3.05	$3.10^2 - 10^5$	$10^2 - 10^4$
Clay		1.5-2.5	$50 - 6.10^2$	$10 - 10^2$
Dolerite		2.8-3.3	$4.10^2 - 9.10^4$	
Dolomite		2.8	-13 - +44	$4.10^2 - 5.10^3$
Gabbro		2.85-3.00	$0 - 10^5$	$10^5 - 10^6$
Gneiss		2.6-2.9	$0 - 3.10^3$	$10^3 - 7.10^4$
Granite		2.65	$10 - 5.10^4$	$10^3 - 2.10^4$
Granodiorite		2.72		
Greywacke		2.55-2.75		$4.10^3 - 10^5$
Limestone		2.7	$10 - 3.10^3$	$10^2 - 10^5$
Marl		2.4		12 - 40
Peridotite		3.15-3.28		10^3
Phyllite		2.65-2.80	$0 - 10^3$	
Sandstone		2.15-2.65		$20 - 10^3$
Schist		2.7-3.0		$5.10^3 - 10^5$
Mica schist		2.74		
Glaucophane schist		3.05		
Serpentinite		2.5-2.7	$3.10^3 - 8.10^4$	
Shale		2.4-2.8		$1 - 10^4$

all the ore minerals which provide the targets for a mineral exploration programme have very low electrical resistivities compared with the rock types with which they are associated. This characteristic is used in the electrical and electromagnetic methods. The ore minerals also typically have high densities but this is seldom of use for the direct location of ore deposits in the UK using the gravity method because the concentration of ore is usually too low or the ore bodies too small. With both the gravity and magnetic methods use if often made of contrasts in the physical properties of rock types associated with the ore deposits, so that exploration is guided in an indirect way by the interpretation of the geophysical data in terms of geological structures or host rocks likely to be favourable to mineralisation.

AIRBORNE SURVEYS

Introduction

At an early stage in the Mineral Reconnaissance Programme eleven areas, totalling about 1000 km^2, were selected on geological evidence as possible targets for mineral exploration. The relatively large area involved meant that the geophysical reconnaissance had to be made from an aircraft or helicopter if the work was to be completed within a reasonable time.

The electromagnetic response to electrical conductors decreases rapidly with the height of the detector above the conductor and it is desirable to fly surveys at the minimum ground clearance compatible with safety. A fixed wing aircraft would have been unable to maintain such a clearance in the rugged topography of areas such as the Harlech Dome and south-west Scotland and a helicopter-borne system was therefore selected. Even in comparatively flat areas, such as Anglesey and Newquay-Withiel, the presence of numerous obstacles such as power lines and buildings would make low flying by aircraft hazardous.

The main contract for the airborne survey was awarded to Hunting Geology and Geophysics Ltd. The areas surveyed are listed in Table 2 and are shown in Fig. 1. The initial proposal also included another six areas in the Orkneys and the north of Scotland but these were eventually abandoned because delays in the earlier surveys prevented them from being surveyed before the onset of winter. The ground clearance for the EM equipment was set at 100 feet (30.5m) and the survey flight lines were originally planned at 100m intervals, although this was subsequently increased to 200m. Departures of more than 200 feet (61m) from the planned flight line and 25 feet (7.6m) from the planned ground clearance required re-flying under the terms of the contract. It was also required that instrumental noise levels should not exceed 3 gamma for the magnetometer and 10 ppm for the electromagnetic equipment (in-phase and out-of-phase components).

The choice for airborne electromagnetic equipment rested between two-frequency out-of-phase component equipment and the single frequency in-phase and out-of-phase type of equipment. Two commercially available sets of the latter type of equipment (Lockwood and Scintrex) were used. Magnetic and radiometric measurements were made simultaneously with the electromagnetic measurements.

A summary of all the equipment used in 1972 and 1973 is given in Table 3 and further details, consisting mainly of parts of a report by Hunting Geology and Geophysics Ltd., are given below. A separate survey of the Blair Atholl area was carried out by Sander Geophysics Ltd. (Ottawa, Canada) and is to be described in a report for that area (Michie and others, in preparation).

Table 2. Summary of airborne surveys flown in 1972 and 1973

Area	Flight Line Direction	Period flown	Total line Miles (km)
Area A Cornwall	NE - SW	11. 5. 73-26. 5. 73	393. 3 (632. 7)
Area B Harlech Dome	E - W NW - SE	7. 12. 72-17. 12. 72 and 4. 6. 73-26. 6. 73	1162. 0 (1869. 7)
Areas C/K Anglesey	N - S	16. 10. 72-28. 11. 72	1417. 0 (2280. 0)
Area D Dent Fault	E - W	1. 7. 73-3. 7. 73	85. 0 (136. 8)
Area E Augill Fault	NE - SW	26. 6. 73-3. 7. 73	46. 0 (74. 0)
Area F Kirkcudbrightshire	NW - SE	5. 7. 73-8. 7. 73	272. 5 (438. 5)
Areas G/M Kirkcudbrightshire	NW - SE	10. 7. 73-27. 7. 73	648. 0 (1042. 6)
Area P Lunedale, Yorkshire	N - S	1. 7. 73-3. 7. 73	207. 0 (333. 1)
Areas Q/R Stockdale, Yorkshire	Q. N - S R. NE - SW	28. 7. 73-31. 7. 73	359. 3 (578. 0)
Area S Craven, Yorkshire	N - S	1. 8. 73-13. 8. 73	583. 5 (938. 9)
Area T Lothersdale, Yorkshire	N W - SE	1. 8. 73 and 12. 8. 73	60. 0 (96. 5)
			Total 5233. 6 (8420. 8)

Note:
Details of the geophysical investigations in those areas underlined have been included in Mineral Reconnaissance Programme Reports which are on Open File at offices of the Institute of Geological Sciences. Those for other areas will be available as the appropriate Open File reports are issued.
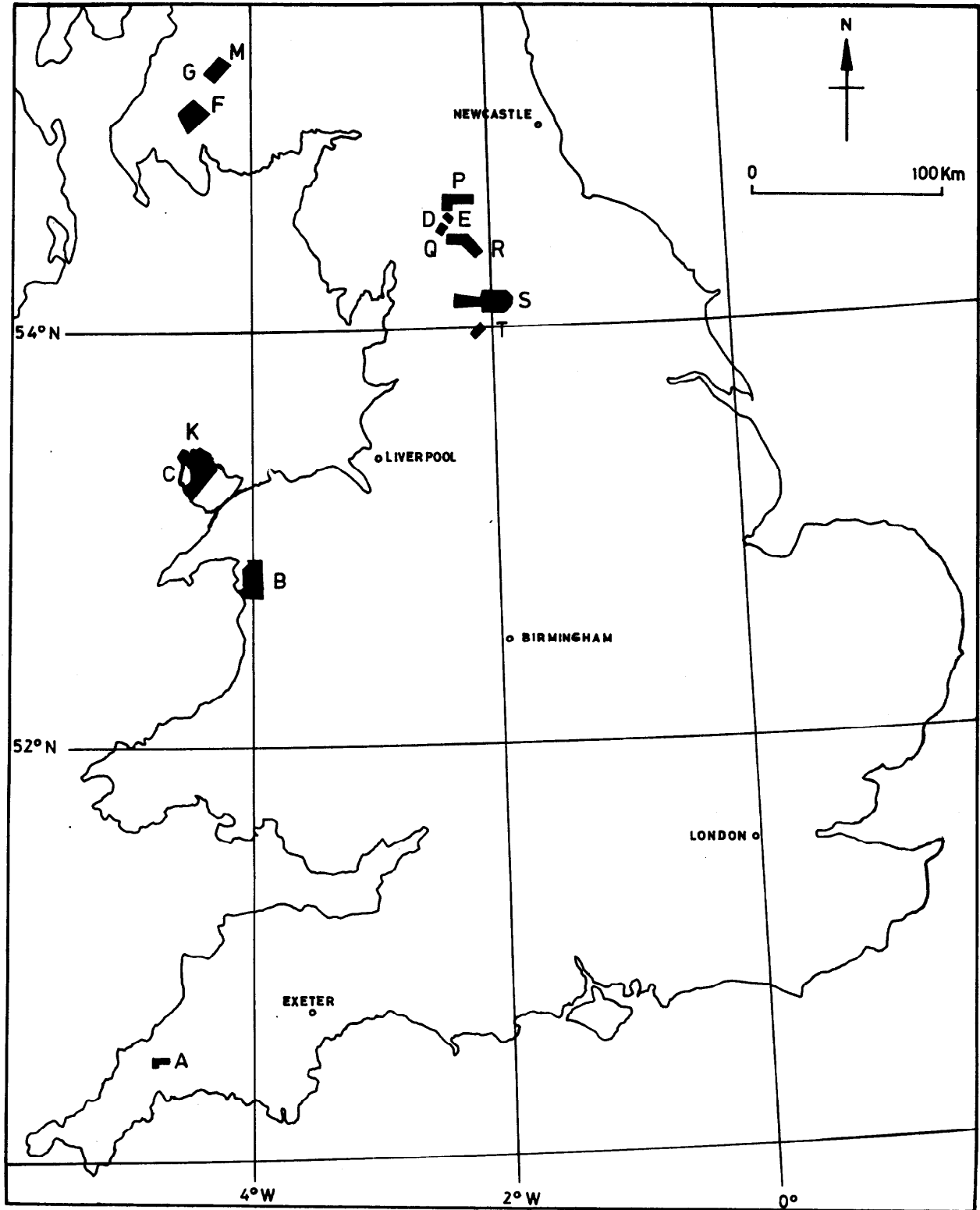
Fig. 1.   Location of airborne survey areas.
Letter notation as in Table 2.

Table 3. Summary of equipment used on airborne surveys

Equipment	Type	Recorder	Chart Speed	Chart scale/width	Supplier & Areas of Operation
Air Magnetometer*	Gulf MK III Analogue	Moseley 7100B (2 Channel)	6 in. per minute	10 in. 0-600 gammas	1. Lockwood Survey Corp 2. Areas D (Part) C/K
Air Magnetometer	M.A.P.2 Analogue	Moseley 7100 B (2 Channel)	6 in. per minute	10 in. 0-1000 gammas	1. Scintrex Limited 2. Areas A. b(Part) D.E.F.G./H.PQ/R S&T
Electromagnetometer*	LHM 250 (1000 HZ)	M.F.E. (3 Channel) Inphase/Out of phase	6 in. per minute	50 mm per channel 400 ppm	1. Lockwood Survey Corp 2. Areas B (Part) C/K
Electromagnetometer	HEM 701 (1600 HZ)	M.F.E. (6 Channel) Inphase/Out of phase	5 in. per minute	50 mm per channel 500 ppm	1. Scintrex Limited 2. Areas A. B(Part) D.E.F.G/M.PQ/R S & T
Spectrometer	NE 8420 Analogue	Moseley 7100 B (2 channel)	6 in. per minute	10 in. channel 1 6000 cps (see Table 3)	1. Hunting Geology & Geophysics Ltd 2. All Areas
Ground/Storm Magnetometer	Gulf Analogue	Esterline Angus	10 in. per hour	6 in. 0-250 gammas	1. Hunting Geology & Geophysics Ltd 2. All Areas
Positioning Camera*	Vinten 35 mm	400 ft Magazine	1.5 secs	35 mm	1. Lockwood Survey Corp 2. Areas B (Part) C/K
Positioning Camera	Automax Gi/3	400 ft Magazine	1.2 secs	35 mm	1. Scintrex Limited 2. Areas A.B (Part) D.E.F.G/M. PQ/R S & T
Radio Altimeter	Bonzor TRN 70	MFE 3/6 Channel	6 in. per minute / 5 in. per minute	150-500 ft 0-600 ft 0-700 ft / 0-700 ft	1. Lockwood Survey Corp & Scintrex Limited 2. All Areas
Helicopter	Allouette II		50 knots per hour approx		1. Helicopter Hire Ltd 2. All Areas

*Alternative used in 1972
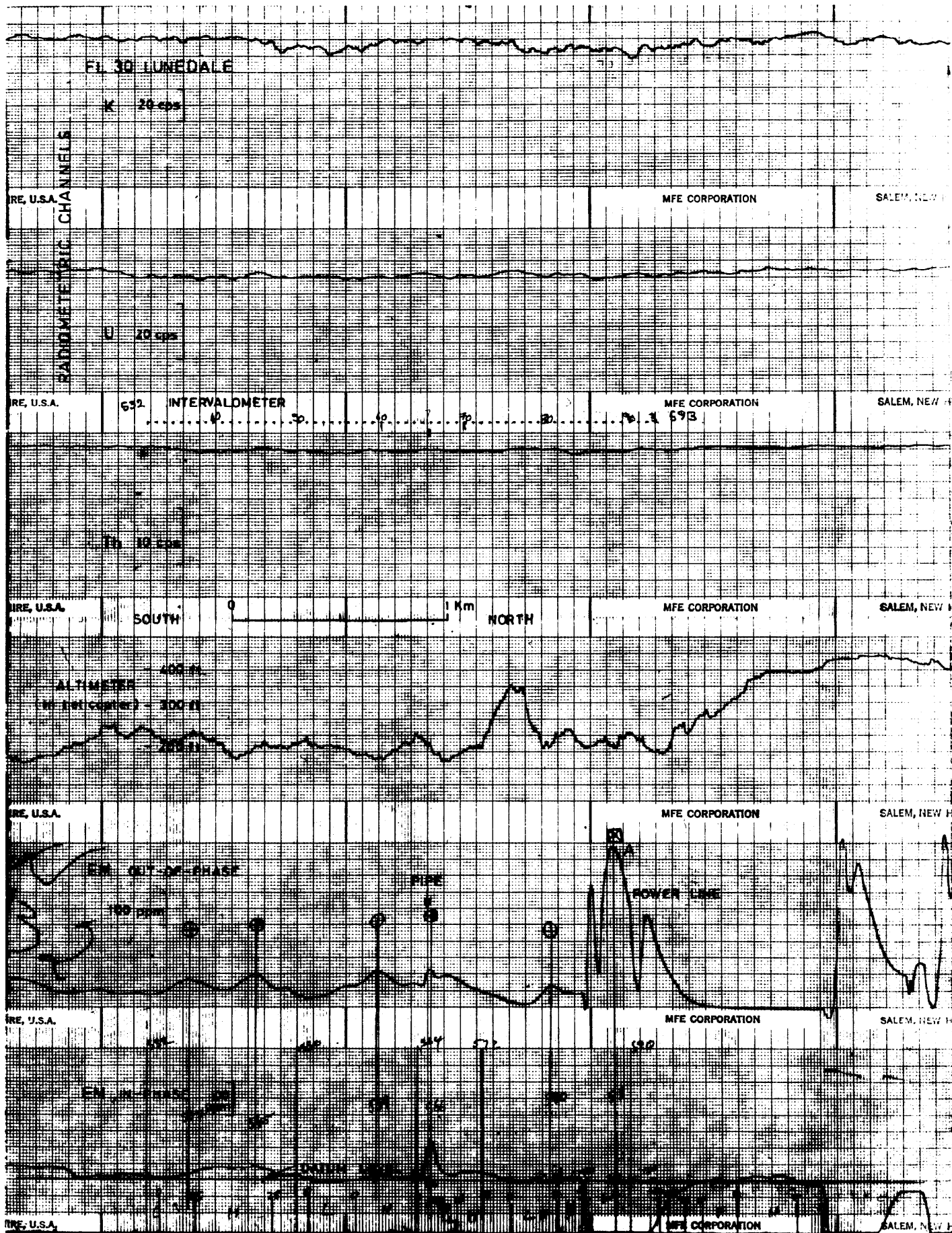
Fig. 2. Copy of part of a record from one of the chart recorders used in the airborne surveys.

Geophysical and ancillary equipment

Gamma Ray Spectrometer

The spectrometer used throughout the total survey period was Model NE 8420 manufactured by Nuclear Enterprises of Edinburgh to Huntings' specific requirements. Gamma radiation was detected by two sodium iodide (Thallium-activated) crystals, each with a matched, integrally mounted, 5 inches diameter photomultiplier tube, type EMI 9583A. Each crystal was 6 inches in diameter and 4 inches thick, giving a combined crystal volume of 226 cubic inches. The two crystals were placed outboard on shock-proof mountings as far away as possible from radioactive sources in the helicopter. The detectors were thermally insulated and moisture proofed.

The energy of the incident gamma radiation was recorded over the range 1.0 to 2.9 MeV for the total count trace on the chart recorder. Using pulse height analysers the energy spectrum was also sub-divided into energy windows and the corresponding count rate recorded separately. The energy channel widths and the normal full scale sensitivity of each channel were as follows:

Channel		Energy Width (MeV)	Range (Counts /sec)
Total Count	1	1.0 to 2.9	0-6000
K	2	1.31 to 1.61	0-100
U	3	1.61 to 2.2	0-60
Th	4	2.2 to 2.9	0-30

Electromagnetic equipment

LHEM 250

The LHEM 250 EM System used throughout the first field season (1972) (Table 3) was developed and manufactured by Lockwood Survey Corporation of Toronto and the Huntec Division of Hunting Exploration Services Ltd. The transmitter and receiver are housed in an aerodynamically designed 'bird' towed 100 ft (30.5 m) below the helicopter. They comprise two vertical co-axial coils fixed 30 ft (9.1 m) apart. The transmitter coil generates a primary field (frequency 1000 Hz). The receiver coil measures the in-phase and out-of-phase components and records these, in parts per million (ppm) of the primary field, on a 3 channel, MFE analogue recorder. The in-phase and out-of-phase profiles are adjacent to one another on the record, together with the radio altimeter trace and the synchronised 35 mm positioning camera fiducial (Table 3).

HEM 701

The HEM 701 EM system, used for all areas surveyed during the second flying season, was developed and manufactured by Scintrex Limited, Downsview, Ontario. The transmitter and receiver coils were again housed in a 'bird' towed 100 ft (30.5 m) below the helicopter and comprised two vertical, co-axial coils spaced 30 ft (9.1 m) apart. A primary field of 1600 Hz was generated by the transmitting coil. The in-phase and out-of-phase components, received by the receiving coil, were recorded

on a 6-channel MFE recorder (Fig. 2), together with the altimetric and spectrometric data.

Magnetometer Equipment

Gulf Mk III Magnetometer

The standard Gulf Mk III Fluxgate Air Magnetometer, supplied by Lockwood Survey Corporation, was manufactured by the Gulf Research and Development Company, Pittsburgh, U.S.A. and installed in the centre section of the LHEM 250 bird. This instrument produced a continuous profile recording of variations in the earth's magnetic field with a sensitivity of 1 gamma. The detector head comprised a detector and an orientor element mounted in a gimbal system.

Map 2 Magnetometer

The Map 2, a nuclear-resonance lightweight proton magnetometer, manufactured by Scintrex Ltd., was used throughout the second season (1973). The detector head was located some 50 feet below the helicopter in a separate bird attached to the HEM 701 cable and was operated at its design sensitivity of 1 gamma. The magnetic profile was recorded on a Moseley 7100B twin channel recorder with a full scale deflection of 1000 gammas. As with all other recorders 35 mm camera fiducials were recorded on this chart (Table 3).

Other equipment

Tracking cameras

A continuous record of the flight paths was obtained from a tracking camera mounted in the floor of the helicopter. The exposure of the individual frames of the 35 mm film was controlled, by the intervalometer, to occur at intervals of 1, 1.5, or 2 sec. A Vinten Mk 7 camera was used for the surveys in 1972 and an Automax G1/3 low level camera in 1973.

Radio altimeters

In addition to the standard barometric altimeter a Bonzer radio altimeter type TRN 70 was used for all the helicopter surveys to maintain ground clearance and to provide a continuous profile of the actual ground clearance. The altimeter was calibrated daily.

Data compilation

The output of the magnetic, electromagnetic and radiometric equipment was recorded continuously in the helicopter as 8 traces on two chart recorders. Part of a typical set of traces is shown in Fig. 2 and includes the electromagnetic, altimeter and radiometric (K, U and Th) data. The magnetic field and radiometric total count data were plotted by a second chart recorder.

The magnetic data were presented as contour maps showing departures from a 'normal' geomagnetic field. The normal field changes linearly with distance and is the same as that used in the published 1;625,000 scale aeromagnetic maps of Great Britain [Institute of Geological Sciences, 1965 (Sheet 2) and 1972 (Sheet 1)] but adjusted to compensate for secular changes

since that date.

The electromagnetic data were presented in two forms:
1 - contour maps of the in-phase component, relative to
datum levels selected by inspection of the records (Fig.2).
2 - anomaly ratio (in-phase to out-of-phase component)
maps with symbols representing various ratios. The keys
to the ratio symbols used are shown on each map and
several examples can also be seen in Fig. 2. This
diagram also shows an example of a non-geological
conductor ('A' on the EM out-of-phase component) which
in this case was a power line.

In areas of complicated electromagnetic responses
the two types of data presentation have been reproduced
as separate maps.

No processing was carried out on the radiometric data
which is available only in the form of flight records.

All the geophysical data presented in map form
were compiled on a 1:10,560 scale and superimposed
on the corresponding Ordnance Survey National Grid
Series topographic maps.

GROUND SURVEYS

Introduction

Ground geophysical surveys were carried out for one or
more of the following reasons:

a) Follow-up to airborne surveys
An examination of the flight records and the maps was
carried out for each area and electromagnetic anomalies
selected for ground "follow-up" on the basis of either
their character (e.g. large amplitude or a large in-
phase to out-of-phase ratio) or their occurrence in a
promising geological environment. "Follow-up" was
carried out with one of the electromagnetic methods
to confirm the existence of the anomaly and to locate
its position accurately.

b) Investigation of an exposed mineral occurrence or of
a favourable geological environment.

c) Investigation of a geochemical anomaly

d) On a regional scale, as with gravity surveys, to define
promising structures or environments (e.g. buried granite
cupolas).

The method used for b and c depended upon the nature
of the mineralisation, such factors as the likely form,
depth and composition of the target being taken into
account.

Numbering of stations and lines for ground surveys

Most detailed geophysical surveys on the ground were
carried out on a rectilinear grid on which the position
of measurement ('station') was specified in relation to
the position of a base point. This base point should be
easy to re-locate from local topographic or man-made
features.

Survey lines or traverses are given a number
according to their distance and approximate direction from
the base point along a base line (Fig. 3). Stations on a
traverse are then numbered according to their distance and
approximate direction from the base line. Thus point
A in the example is station 310 W on line 500 N where the
numbers represent distances in metres and 'W' and 'N'
indicate 'to the west' and 'to the north' (not necessarily
'due west' or 'due north'). Where possible the base line
is positioned so that it lies along, or parallel to, the
structure being investigated.

In some cases, where several separate and independent
survey lines are required in a small area (as in the ground
follow-up of some aerial surveys) lines are identified by
the 10 m grid co-ordinates of their origin.

Electromagnetic methods
Introduction
The electromagnetic (EM) methods of geophysical
exploration depend upon the detection of a change in
amplitude and/or phase of an alternating EM field.
The transmitter of the field can be either fixed or
moving but the receiver, as it is moved along traverses
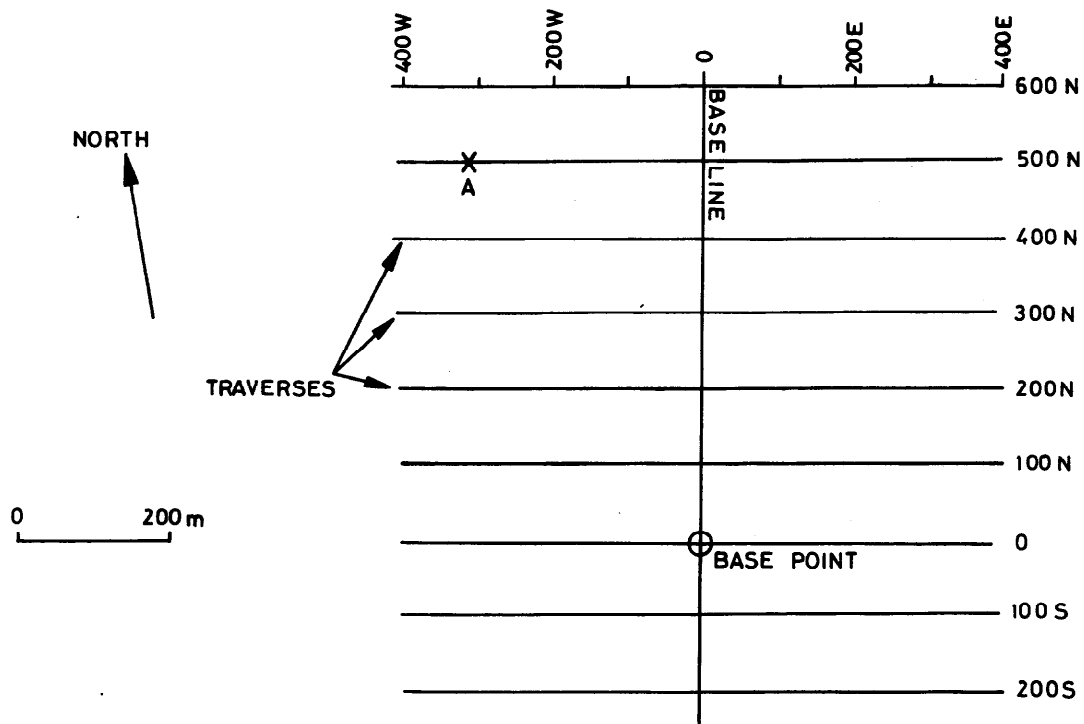compares the signal received with that transmitted.

9

Fig. 3. Example of grid system of measurements used for ground surveys.

Like the airborne surveys, the ground EM methods are susceptible to 'noise', but this was not found to present problems at most localities.

Table 4 is a summary of the different types of EM equipment in use.

Slingram

This was the most frequently used type of EM equipment and consists of a transmitter with a coil, a reference cable and a receiver with a second coil. With the equipment used, the two coils were orientated with their axes of rotation vertical and advanced together in line along the traverses. The separation of the two coils partly determined the depth of investigation possible and could be varied to suit the requirements of a particular survey. A coil separation of 60 m was commonly used and readings were taken at intervals equal to the coil separation or simple fractions of this distance. During survey operations the coil separation must be kept constant to avoid introducing spurious in-phase anomalies. An Abney level was used on most surveys to measure any elevation difference between the two coils and the corresponding corrections made.

The receiver coil records a field which is the resultant of the primary field, due to the transmitter coil, and a secondary field arising from eddy currents induced in any conductors in the ground. Measurements are made of the in-phase and out-of-phase components of the resultant field and these are expressed as percentages of the normal field. By convention, the in-phase component of the normal field is 100% and the out-of-phase component 0% (e.g. Fig. 4B). The point of measurement is taken to be midway between the two coils for plotting purposes.

The Geonics EM 1 5 (Table 4) is an adaptation of the Slingram equipment for quick, shallow penetration surveys such as the location of buried pipes or cables.

Turam

With the Turam equipment the signal is transmitted from a fixed source, in the form of either a rectangular loop of cable or a straight cable grounded at the ends. The moving part of the equipment consists of two receiver coils connected by a reference cable, 20 m or 40 m long. The coils measure the difference in the phase of the two signals received and the ratio of their field strengths. Because the field strength is dependent upon distance from the transmitter cable, a correction must be applied to produce 'reduced field ratios' which, together with the phase differences, are used to produce profiles (e.g. Figs 4A and 9) and contoured maps.

The Turam method has a greater depth of penetration and a greater sensitivity than the more rapid Slingram method and suffers less from topographic errors.

VLF

The VLF method makes use of very low frequency radio signals from one or more radio transmitting stations. The Geonics EM16 instrument (Table 4) has two small receiver coils at right angles which are rotated together until minimum signal is received. In this position estimates of the in-phase and out-of-phase components of the field at that point (compared with the normal field) are possible, providing the secondary field is not too large.

The small size of this instrument makes it suitable for quick reconnaissance surveys but it has also been found to be a useful method to complement other types of surveys.

The observations made with the EM16 can be plotted directly as maps or profiles (e.g. Figs 9 and 10) but it has been found that filtered data are more readily interpreted. The method described by Fraser (1969) has been used in which the inflexion point on the original data (assumed to occur directly over the

Table 4 Equipment used for EM exploration

Method	Equipment	Operating frequency (Hz)	Coil separation (metres)
Slingram	Geonics EM15	16000	0. 83
	Geonics EM17	1600	30-122
	ABEM Demigun	880, 2640	60
	ABEM 35/88	880, 3520	60
Turam	ABEM 2S	220, 660	20-40
VLF	Geonics EM16	Optional radio transmitter frequency e.g. 17,800 (NAA) 16,000 (GBR)	Effectively infinite
	Geonics EM16R (attachment for ground resistivity measurements)		

conductor in the gournd) is converted into a peak and long wavelength anomalies are attenuated. The filtered reading (S) is obtained by averaging adjacent pairs of dip-angle readings:

$$S_{2,3} = (R_1 + R_2) - (R_3 + R_4)$$

where R_1 to R_4 are four consecutive readings taken at equal intervals along a traverse.

Although the 'skin effect' limits the depth of penetration possible with the comparatively high frequency (for prospecting equipment) used in the VLF method, this is partly compensated for by the large separation of the transmitter (i. e. radio station) and receiver.

Resistivity and induced polarisation (IP) methods

Introduction

If an electric current is passed into the ground through two electrodes on the surface a potential gradient is set up and a voltage can be measured between a second pair of electrodes nearby. From a knowledge of the current, the voltage and the geometrical arrangement of the four electrodes, an apparent ground resistivity (ρa) can be calculated. This is a volume average value but is commonly taken as referring to a particular point (the plotting point), whose location depends on the electrode configuration. Lateral variations in resistivity can be detected by moving the whole electrode array while keeping its dimensions constant: known as a constant separation traverse (CST). Vertical variations are detected by expanding the array about a fixed centre: called a depth sounding, depth probe or vertical electrical sounding (VES). The most commonly used electrode arrays are discussed briefly below.

Arrays

(a) Wenner array. The four electrodes are equally spaced along a straight line. Current is transmitted through the two outer electrodes and the voltage measured between the two inner. The plotting point is at the centre of the array at a depth which is not defined but which increases with the separation. This array is often used for both CST and VES; interpretation is by comparison with computed model curves.

(b) Schlumberger array. This is similar to the Wenner array except that the inner electrodes are placed close together and measure essentially the voltage gradient. Strictly, for CST all four electrodes must be moved (cf. gradient array); but for VES it is only necessary to increase the current electrode separation until the voltage across the potential electrodes becomes too small to be measured accurately.

(c) Gradient array. This is a modification of the Schlumberger array in which the current electrodes are maintained a fixed distance, AB, apart and the closely-spaced potential electrodes are traversed along the line joining the current electrodes and along parallel lines. Two-dimensional coverage over a square of side (0.6 x AB) can be achieved without moving the current electrodes. The plotting point is halfway between the potential electrodes. The results, normally presented in contour form, are diagnostic of near-surface dip and give good horizontal resolution, but no information on the depth of an anomalous structure.

(d) Collinear dipole-dipole array. A current dipole is formed by placing electrodes a distance l apart. A similar potential dipole is positioned so that the distance between the dipole centres is nl where n is an integer (>1), all four electrodes being in a straight line. The plotting point is the intersection of 45° lines in a vertical plane through the dipole centres. (By the reciprocity theorem the result should be the same if the two dipoles are interchanged). By using p fixed current electrodes switched to give (p.-1) dipoles, data can be quickly accumulated for different values of n giving, in effect, a somewhat distorted electrical cross-section beneath the traverse line (e.g. Figs. 4c, 9, 10). In qualitative interpretation of such a "pseudo-section" it is often useful to realise that an anomaly can be caused by a source anywhere between the dipoles; and it follows that an apparent widening of an anomaly with depth is not necessarily of real significance. The main advantage of this array is that it gives information on the depth, location and extent of a structure and reduces coupling between the current and potential electrode wires by separating them on the ground.

In mineral prospecting surveys, if minerals exist in such concentration that conductive paths of appreciable length occur, the resistivity will be lowered.

Resistivity measurements are normally made in conjunction with IP measurements, discussed below. The ABEM Terrameter which is occasionally used in AGU mineral surveys, records resistivity only at a signal frequency near 4 Hz.

IP effects

If a sustained current is applied to the ground and suddenly switched off, in the presence of a concentration of conductive mineral grains the voltage decay occupies a period of the order of a few seconds. This is because double layers of charge built up at interfaces between electronic conductors (mineral grains) and ionic conductors (pore fluids) break down slowly. This induced polarisation effect is a function of the number of interfaces and is therefore sensitive to disseminated mineralisation which may have no effect on bulk resistivity. The voltage remaining at a certain time after switch-off, V_s, divided by the voltage while current is flowing, V_p, gives a dimensionless quantity known as chargeability, m. It can also be expressed as an integral between two times and in this case has the dimension of time. The Huntec Mk III receiver used in AGU surveys records V_p and also four quantities p_1 to p_4, defined as

$$m_n = \frac{\overline{V}_{sn}}{V_p} \times 100, \quad n = 1 \text{ to } 4$$

where V_{sn} is V_s averaged over the time interval
$(t_d + (2^{n-1}-1) t_p)$ to $(t_d +(2^n-1) t_p)$ after switch off.
t_d and t_p are pre-set by the operator. For example,
with $t_d = 75$ ms and $t_p = 60$ ms, the signal is sampled over
the period 75 to 975 ms after switch-off and m_1 to
m_4 are approximations to the chargeabilities at the
centre of each sampling interval, i.e. 105, 195, 375
and 735 ms. The quantity

$$m_c = \frac{\sum_{n=1}^{4} 2^{n-1} m_n \times t_p}{100}$$

is an approximation to the integrated chargeability over
the total sampling time. In the example above,

$$m_c = (m_1 + 2m_2 + 4m_3 + 8m_4) \times 0.6 \text{ ms} = m \frac{975}{75}$$

where the subscript and superscript denote the lower
and upper limits of integration. m_c may give a better
measure of conducting mineral content than any
individual m value. A chargeability pseudo-section
can be plotted in the same way as for resistivity. In a
porous rock of low pore fluid resistivity, many conduction
paths including mineral grains will be bypassed by paths
through electrolyte and the chargeability will be lowered.
A parameter called specific capacitance (SC), obtained
by dividing chargeability by resistivity, makes some
allowance for this effect and is sometimes considered to
be a better guide to mineral content. It should be noted
that only ρ a and m_c are independent quantities.

The IP method responds to minerals which conduct
by electron flow. These include pyrite, chalcopyrite,
pyrrhotite, galena and graphite. Attempts to
distinguish between minerals by studying the shape
of their decay curves have so far been generally
unsuccessful.

Clay minerals also cause an IP effect, due to a
different mechanism. Its magnitude is generally
lower than that due to conductors and it commonly
defines a background value for an area, which may show
considerable local variations. Variations in charge-
ability above the background reflect differences in
mineral concentration or proximity of a conductor to
a dipole.

IP equipment used in AGU surveys comprises the
Huntec Mk III IP receiver mentioned above, with
either a Huntec LOPO Mk III transmitter with an
output power of 250 watts, or a 2.5 kW or 7.5 kW
Huntec transmitter. The transmitted signal is a
sequence of alternating positive and negative pulses
each of length t_1 separated by off periods of length
t_2 (t_1 and t_2 are pre-set; common values are $t_1 = t_2$
$=25$). A measurement is made for each pulse and
the receiver automatically displays the average of
many measurements. Metal stake transmitter electrodes
and porous pot receiver electrodes are normally used.
On occasions a Geoscience variable frequency IP set has
been used. This measures the IP effect expressed as the
change in apparent resistivity with frequency (usually at
at 0.3 and 3 Hz), or per cent frequency effect (PFE). This
quantity can be taken as roughly proportional to chargeability.

Problems with electrical surveys
Although radio transmitters have not led to any serious
problems with EM prospecting on the ground (and are
in fact made use of with the VLF method), many
difficulties have arisen due to the presence of buried
metal pipes, cables and wire fences. These artifacts
are very common in several of the survey areas and
have produced misleading results, particularly in the
case of pipes, whose presence can not always be
confirmed by reference to other sources of information.
Typical airborne and ground profiles (Figs. 2, 4) show
that the effects of pipes disturb readings over a
considerable distance. In the cases of the Turam and
IP results, readings over distances of several hundred
metres are affected. The possibility of a pipe is
suggested by the large and variable anomaly peaks for
the Slingram and Turam profiles. For the IP pseudo-
section (Fig. 4C), however, the resistivity is only
slightly affected due to the fact that the pipe is
intersected at right angles by the traverse, but the
chargeability values are still anomalous at $n = 5$, more
than 100 m away from the pipe.

Metal fences also give rise to spurious anomalies using
electrical methods but the effect is not always recognisable
and detailed measurements are sometimes necessary to
resolve ambiguities.

Magnetic methods
The geomagnetic field in Great Britain
The elements of the earth's magnetic field in Britain lie
within the following ranges (1976 data, excluding local
variations):

Total field strength	47,600 to 50,100 gamma increasing northwards
Vertical field strength	44,000 to 47,500 gamma
Inclination (dip)	68.0° to 71.3° below the northern horizon
Declination	6°W to 12°W of true north (1 gamma = 10^{-5} oersted = 1 nanoTesla – nT)

(Source: U.S. Navy Hydrographic Office charts)

Induced and remanent magnetisation
When a body capable of magnetisation lies in a magnetic
field, it will acquire an additional 'induced' field producing
a disturbance of the inducing field in its vicinity. The
size of the disturbance depends on the 'susceptibility' of the
material of the body, that is, its ability to be magnetised.
Magnetic materials become magnetically polarised, or
magnetised, such that the induced field augments the
inducing field. The effect of this induction in British
latitudes over a uniformly magnetised steeply dipping
body extending to depth (in which all magnetisation is
induced) is to give a positive magnetic anomaly whose
peak value is displaced to the magnetic south of the
centre of the body with a corresponding negative anomaly
displaced to the north. The negative anomaly will
normally be of smaller amplitude and broader than the
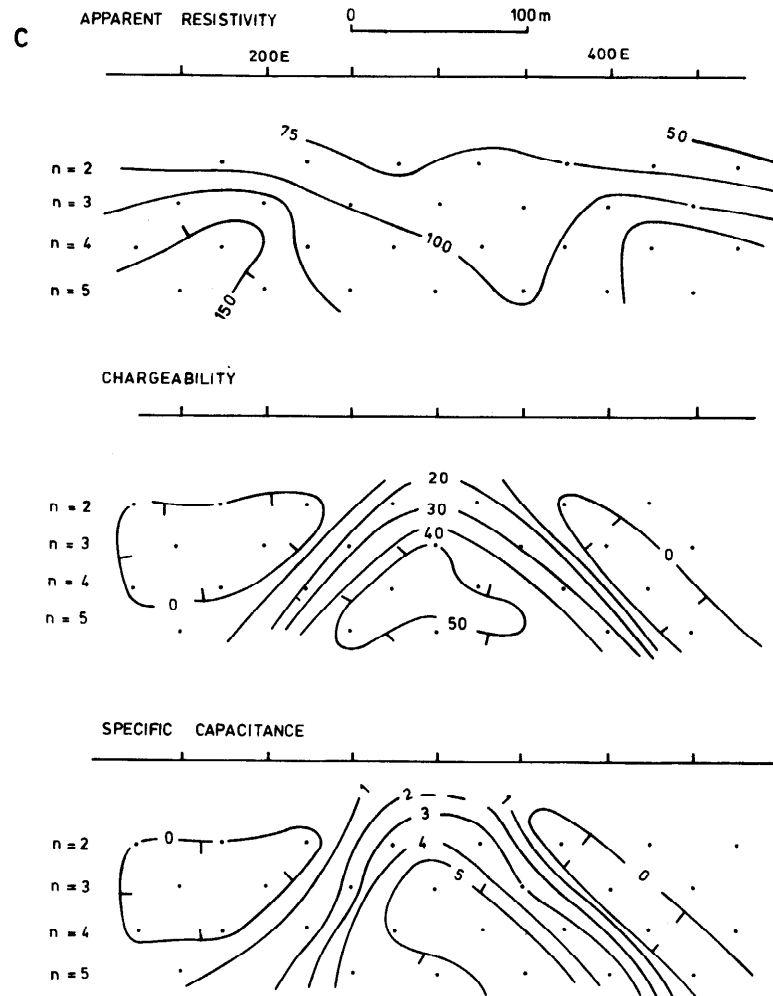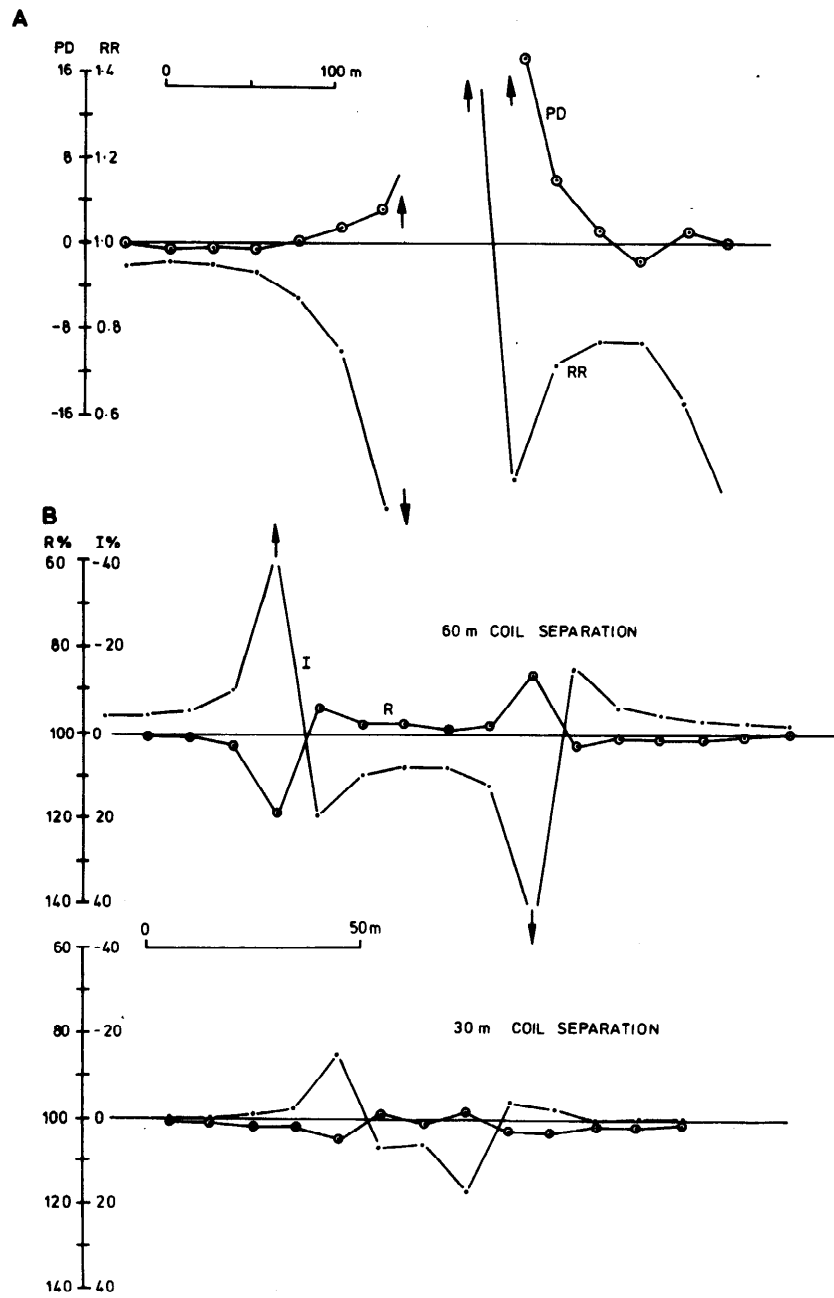positive, to an extent which depends partly on the relative

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Fig. 4. Example of ground survey profiles over metal pipes in different areas using (A) Turam, (B) Slingram and (C) IP equipment.

depths of the upper and lower faces of the body. The shape and size of the anomaly is of course determined by the shape of the body and its susceptibility relative to that of the surrounding rock and it is because of this that interpretation of a magnetic anomaly can provide an indication of the shape of the source. This simplified situation can be modified in practice for several reasons. Firstly, the body may have a permanent, or 'remanent' magnetisation of its own, acquired at the time of its formation when the Earth's field had a quite different direction from the present. In quantitative interpretation of a magnetic anomaly this effect can only be determined by measurements on orientated rock samples. Secondly, this 'ideal' anomaly is only produced if the surrounding rock is uniformly magnetised or of low susceptibility. In sediments, this condition is usually satisfied, but rarely, for instance, in volcanic rocks. Thirdly, the body itself may not be uniformly magnetised and, fourthly, there may be interference from other magnetic bodies nearby.

In most cases in the programme, quantitative interpretation of a magnetic anomaly is carried out only where these interfering factors can be assumed to be inapplicable. Calculations are simplest for an essentially two-dimensional structure (e.g. a dyke) where its width, dip, depth and susceptibility can be estimated. Even in such a simple case there is some ambiguity in the interpretation unless there is other evidence available: for instance, a change in susceptibility can produce an effect which is similar to that produced by a change in the ratio of depth to width of the body. If the magnetisation is not solely induced the total polarisation direction must be known before the dip of the dyke can be deduced.

Sources of magnetic anomalies
The principal magnetic minerals are magnetite, pyrrhotite and, to a lesser extent, ilmenite and some forms of hematite. In Britain they are not generally of economic importance in themselves, but they may be associated with other minerals which are. Since the main magnetic minerals are also conductive they can give rise to resistivity, EM and IP anomalies. It is therefore usual to carry out a magnetic survey at the same time as any of these other types of measurement, in order simply to indicate the presence or absence of magnetic material. Coincident anomalies indicate that the conductive source includes a magnetic mineral and is therefore unlikely to be clay.

Instruments and field procedure
Two types of instrument are used, the proton precession magnetometer (either Geometrics or Elsec) and the fluxgate magnetometer (either Jalander or Sharpe). Proton magnetometers measure the magnitude of the total field to an accuracy of 1 gamma but suffer from the disadvantage that they cannot operate in very steep magnetic gradients. In areas where there are steep gradients, a fluxgate instrument is preferred, which measures the vertical component of the field to an accuracy of about $\pm$ 25 gamma.

The usual field procedure with either type of instrument is to measure the field at intervals along traverse lines, usually between 5 and 30 metres, with additional measurements where significant variations are observed. At intervals of about an hour a reading is taken at a fixed point, called a magnetic base, so that field measurements may be corrected for fluctuations with time in the Earth's field. At times of magnetic storms these fluctuations may be such that readings are not repeatable and it is impracticable to continue surveying. It is, of course, important to avoid taking measurements near man-made metallic objects, such as fences, water tanks etc, which can produce large magnetic anomalies.

Uses of magnetic surveys
These have been mentioned above: the determination of the presence or absence of magnetic minerals in an area showing other types of anomaly can help to indicate the nature of the source. If the magnetic anomaly is of a simple type (e.g. Fig. 10) a rough estimate of the size, depth and shape of the source can be made. Contoured maps plotted from the individual measurements can be a useful aid to geological interpretation; strike directions and faults can often be identified, as in aerial surveys, but in much more detail.

Gravity methods
The gravity method is used to investigate the shape of structures which have a density contrast with their surroundings. The scale of the survey may be 'regional', such as that over the granites in south-west England, or 'detailed', such as that to investigate barytes deposits in the Teign Valley. In a regional survey the standard mean coverage is usally one gravity meter reading (or 'station') per square kilometre, but in a detailed survey the stations may be only a few metres apart.

This section explains the significance of gravity bases and summarises the process by which field data are reduced to a form suitable for interpretation in terms of geological structure.

Base network
Gravity meters are capable of very accurate measurements of gravity differences, but are unsuitable for absolute measurements. For this reason all measurements in a given area are made relative to a local base which, in turn, is related to a network of bases throughout the U.K. called the NGRN 73 (National Gravity Reference Net, Masson Smith and others, 1974). Hence, unless otherwise specified, all gravity measurements made in this programme are directly comparable with each other and with IGS gravity maps published after 1972.

The Bouguer anomaly
This is the quantity which reflects changes in the density of rocks (Table 2) and hence is related directly to geological structure. The Bouguer anomaly is normally presented in reports and maps. It is derived from the observations of gravity obtained in the field by a series of calculations made for each field reading:
1) Tide and drift calculation. The difference between

the field reading at a station and the local base reading
is corrected for instrumental drift and for the effect
of the gravitational tide (arising from the changing
positions of the moon and sun). The correction due to
the tidal effect is obtained from an AGU computer
programme and that due to instrumental drift is estimated
by linear interpolation between successive readings at the
local base (made before and after each series of field
measurements). The time between base readings is
determined by the instrument being used; it is usually
at intervals of not more than 3 hours for Worden meters,
but can be much longer for La Coste and Romberg meters
which are thermostatically controlled.
2) Calibration. Each meter has its own calibration
factor for converting readings from ' dial divisions' to
'milliGals', or 'gravity units'. One milliGal (the unit
commonly used in this programme) is 10^{-3} cm sec^{-2},
ie very roughly one millionth of the acceleration due
to gravity at the earth's surface. One gravity unit =0.1
milliGal. The difference in milligals between the
field measurement (corrected for drift) and the base
measurement is added to the base gravity value to produce
the 'observed gravity' at the station.
3) Normal gravity, or 'latitude' correction. This is
applied using the International Gravity Formula, 1967
(otherwise known as the Geodetic Reference System, 1967)
to take account of the variation of gravity with latitude.
4) Height correction. This includes both 'free air'
and 'Bouguer' corrections and takes account of the
variation of gravity with height. Reduction is generally
to mean sea level and depends on the density of
rocks between this level and the point of observation
(gravity station). This density is usually taken to be
that of the country rock in the area. Because gravity
measurements are particularly sensitive to changes
in height, accurate height determination is important
(see below).
5) Terrain correction. This is applied to allow for the
effect of topography in the area around the station. In
detailed surveys, over only a few square kilometres,
corrections are usually made for Hammer zones A to H
(i. e. for terrain up to 2.6 km from the station) but for
regional surveys, corrections out to a distance of 50 km
from the station are needed. The corrections are
laborious, involving height estimates in segments from
topographic maps. In rugged areas the corrections are
larger and less accurate than in flat areas, leading to
less reliable Bouguer anomaly values. Where possible,
stations are not sited on rugged local topography such
as on, or near, spoil heaps or pits where the terrain
effect may be both significant and difficult to estimate.
    When all of these calculations have been carried
out, the resulting Bouguer anomaly is plotted and
interpreted.

Height measurements
The accuracy required depends upon the size of the
anomaly being measured, but is normally within 1 foot,
or 0.3 m (roughly equivalent to a Bouguer anomaly
accuracy of 0.06 milliGal at normal densities). For
regional surveys, benchmarks and spot heights are

usually sufficiently plentiful to establish the standard
mean regional coverage of one station per square
kilometre, though in areas of difficult access this may
be as low as 1 station every 4 km^2. For detailed
surveys it is usually necessary to survey each station
using a theodolite or level.

Interpretation
The approach to this depends on the type of structure
being investigated, and is described in reports on
individual surveys. A first step which is common to
most cases is the subtraction of one or more 'regional
gravity fields' with the object of obtaining a 'residual
field' which can be interpreted solely in terms of the
structure of interest. Simple, two-dimensional models
can be computed using a desk calculator, but for
three dimensional models, or iterative interpretations,
a computer is required.

Borehole methods
Geophysical methods have been used for many years to
log boreholes drilled for petroleum exploration,
providing estimates of features such as porosity,
permeability and the fluid or gas content of reservoir
rocks. In mineral exploration, information is usually
required from boreholes either on the location and
grade of mineralisation intersected or on the location
of possible mineralisation adjacent to the borehole.
Measurements in boreholes can be made at discrete
intervals, say 0.5 or 1 m, or sometimes continuously,
using a chart recorder.
    A down-hole adaptation of the IP method
has been found to be generally most useful in mineral
exploration (one example of data obtained is given in
Fig. 8). For this, the Huntec time-domain equipment
is used with two or three electrodes fixed in a small
diameter sonde, to form a pole-pole or pole-dipole
configuration. Coupling between potential and current
wires occurs in the cable and this problem has restricted
the use of frequency domain IP equipment in borehole
logging. Measurements of resistivity made simultaneously
with the chargeability determinations can often provide
a guide to the lithologies intersected by the borehole.
Using the same IP sonde and a high impedance voltmeter,
measurements of self-potential (SP) can also be made
rapidly and provide a useful secondary method of checking
out some zones of mineralisation.
    Measurements of the natural gamma radiation levels
in boreholes can be helpful, for example in determining
the presence of clay minerals in rocks (related to the content
of ^{40}K), as well as for the detection of any uranium and
thorium content. Discrimination of the three main
radioactive elements occuring in rocks (^{40}K, U and Th)
can be effected by the use of a borehole gamma.
spectrometer in boreholes of sufficient diameter to
enable use to be made of a large enough detector to
provide statistically significant counts.
    'Mise à la masse' and 'round-the-hole' methods
are modifications of ground methods in which use is
made of a suitable borehole to place one current
electrode closer to the mineralised zone while

measurements are made with the other electrodes at the surface. In the former method, measurements are made only of the potential field around the current electrode placed in the ore zone intersected by the borehole. In the second method IP measurements are made with arrays orientated in different directions at the surface but with one current electrode in the borehole.

CASE HISTORIES

The selection of the ground geophysical methods to be used in a particular area is usually determined by the nature of the mineralisation expected (e. g. disseminated sulphides are usually more amenable to detection by an IP survey). When there is insufficient information to make a confident choice, several methods may be tested until one is found which responds to the mineralisation. In practice it is often a great advantage to obtain data from two or more methods.

The following short case histories illustrate the use of different methods and the advantage of using more than one method in a particular area. They are described more fully in other reports in the Mineral Reconnaissance Report Series (referred to in text by report numbers, e. g. MRP Report No. 9).

The first and second examples illustrate the applications of the gravity method on a regional and detailed scale respectively. The third and fourth case histories illustrate the use of the IP method for a ground survey and for logging in a borehole; and in the fifth and sixth examples (from near Woodhall, Cumbria, and Vidlin in the Shetlands) several methods have been used along the same traverses.

South-west Cornwall (MRP Report No. 1)
Fig. 5 shows the Bouguer anomalies and exposed granites in south-west Cornwall. The presence of a granite ridge trending south-westwards at shallow depth from near Camborne was inferred from the Bouguer anomaly. Boreholes "A" and "B" were drilled to test this hypothesis and to determine the thickness of overlying metasediments. Rough predictions of the expected depths to granite were made in advance from the Bouguer anomaly. Borehole A, at Bosworgy, entered granite at 173 m depth (prediction: 350 m), whilst borehole B, at Parbola, was drilled close to the steeply dipping flank of a granite ridge without penetrating the igneous body before termination at 665. 5 m (prediction: 540 m). The main reasons for the rather large errors in prediction were a lack of accurate subsurface density information; relatively unsophisticated interpretation techniques (these have since been improved) and, probably, the presence of short-wavelength undulations in the granite roof which were unresolvable by gravity surveys.

Teign Valley (MRP Report No. 12)
An example of an application of detailed gravity survey of only marginal usefulness is shown in Fig. 6. Theoretical calculations had shown that large tabular bodies of baryte (density 4. 3-4. 6 g cm^{-3}, Table 1) could give rise to small but detectable Bouguer anomaly 'highs'. The results of trial traverses over outcropping and inferred baryte bodies east of Dartmoor show small anomalies over two known lodes, but none over inferred lode positions. These small anomalies are superimposed on the regional gradient due to the nearby Dartmoor granite. The station
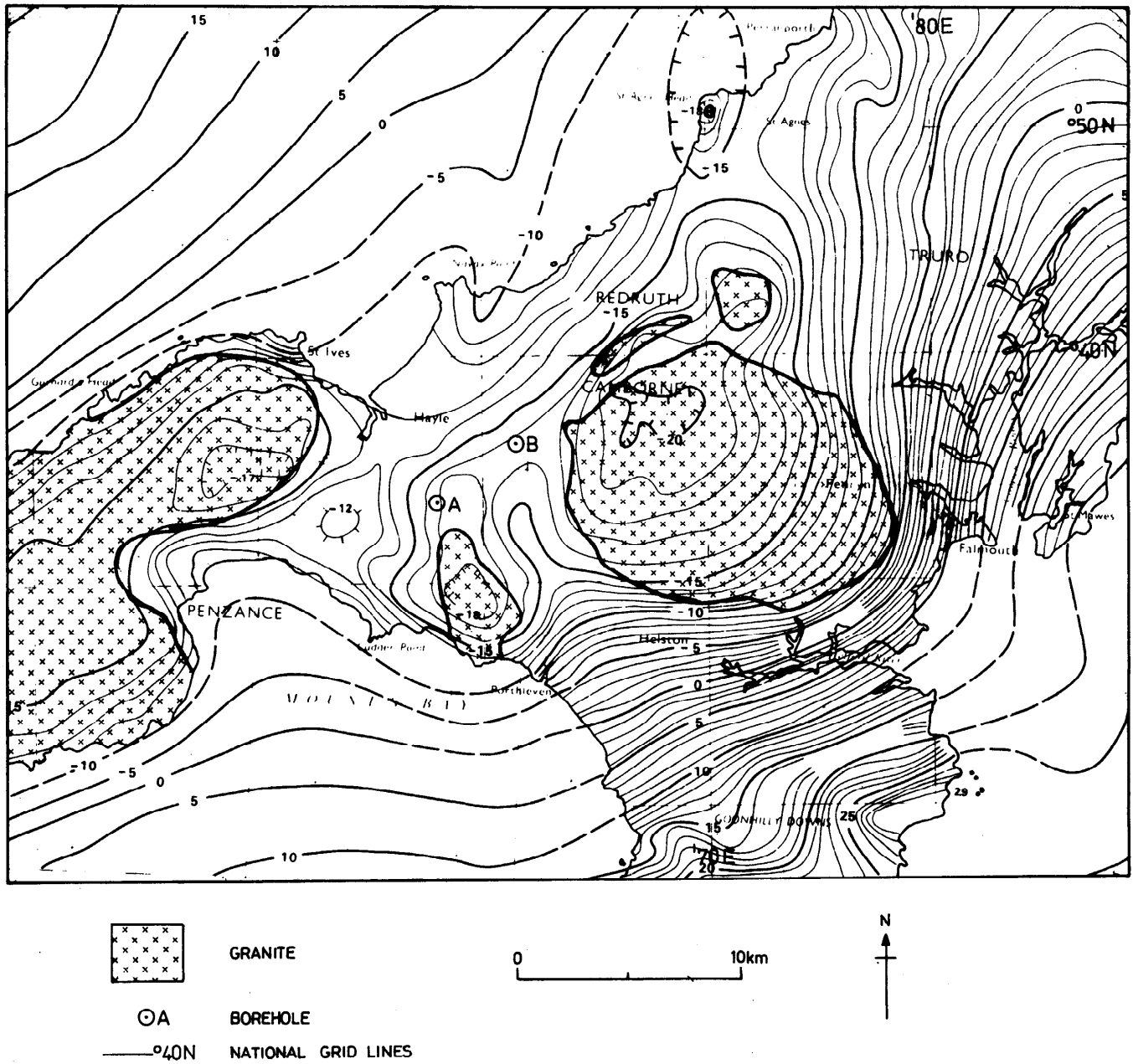
Fig. 5. Bouguer anomaly map of south-west Cornwall, outcrop of
granite intrusions and borehole sites A and B.
Bouger anomaly contours based on parts of the
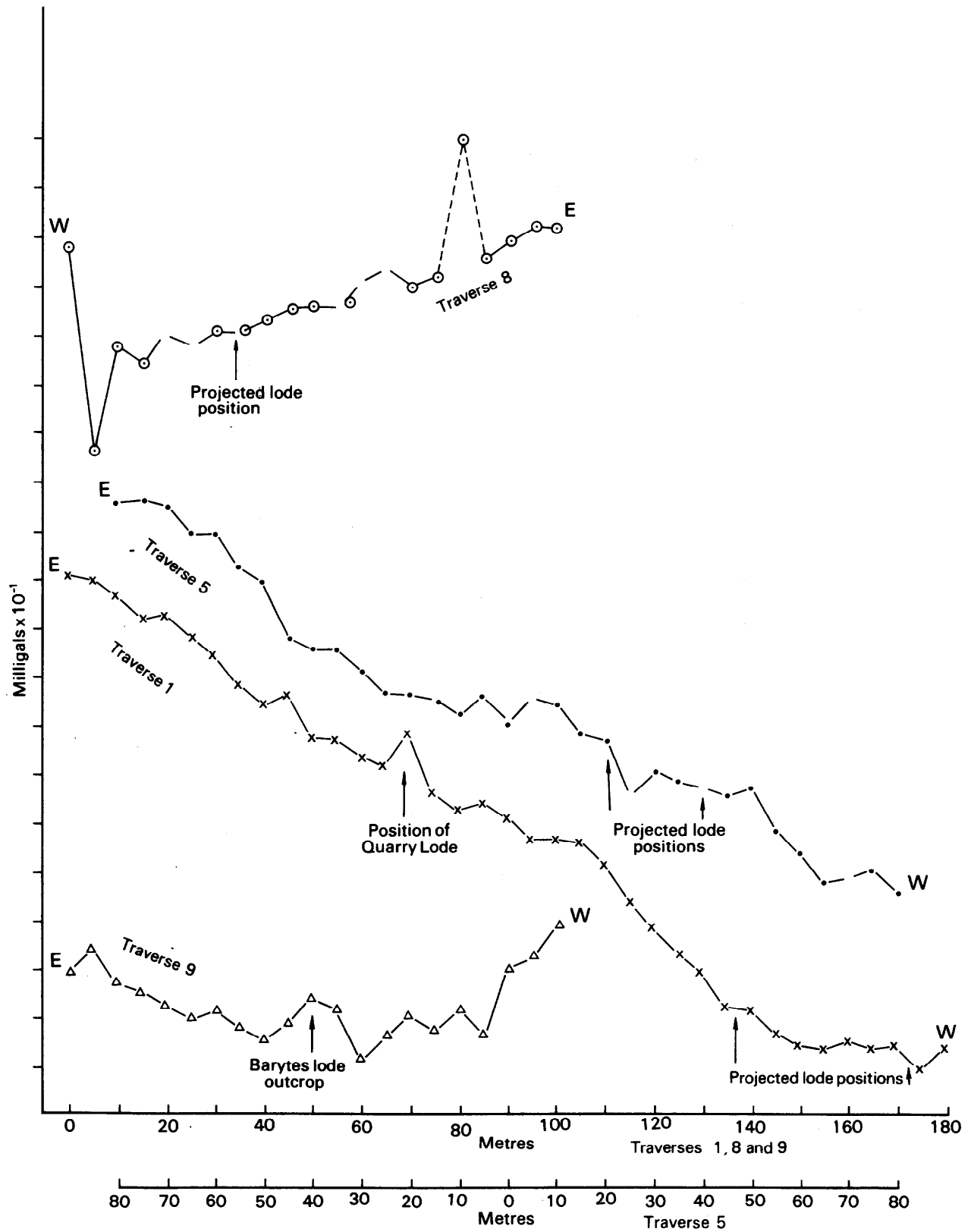Land's End 1:250 000 sheet, published by IGS in 1975.

Fig. 6. Bouguer anomaly profiles for four traverses in the Teign Valley

spacing was 5 m, which would have rendered systematic coverage of the area slow and expensive; but even with a spacing as small as this, evidence for one anomaly depended on one reading only, and the other was only slightly above the "geological noise" level. It was decided that gravity surveys would not be cost-effective and no production surveys were undertaken.

Meall Mor, Argyll (MRP Report No. 15)
Measurements of chargeability and resistivity were carried out using time-domain IP equipment in an area of disused copper mines. Profiles were made using a constant separation dipole-dipole array (dipoles 30 m long and 90 m centre-to-centre separation, i. e. n=3) producing a rapid survey of a large area, but without giving any information on dip or depth of the sources. Chargeability anomalies were found along a strike length of 6.5 km (Fig. 7) and detailed geological and geochemical examination defined a zone of sulphide enrichment closely associated with the anomalies. Boreholes were drilled where there was a good coincidence of chargeability anomalies and high copper values in the soils. The cores showed that pyrite was the predominant sulphide and therefore most likely to be responsible for the main geophysical anomalies; but in addition there was up to 1% copper present in associated chalcopyrite, as well as minor galena and sphalerite.

Kilmelford, Argyll (MRP Report No. 9)
Downhole measurements of resistivity and chargeability were carried out in two boreholes at Kilmelford using the time-domain Huntec Mark III equipment and a pole-dipole electrode array. IP measurements were taken at 1 m intervals down the hole, with one current electrode at the base of the sonde, two potential electrodes 0.5 m and 1.0 m above this, and the second current electrode on the ground surface approximately 50 m from the borehole. The purpose was to compare the borehole results with chargeabilities measured on the surface and with geological and geochemical borehole logs. Fig. 8 shows that high copper values generally correspond with high chargeability values. Disseminated chalcopyrite and pyrite are both visible in the core and both contribute to the measured IP effect. Very high chargeability values occur between 105 and 110 m where the hole intersects two dolerite dykes, but the dolerite itself was not analysed. The dolerite dyke between 126 and 130 m is not associated with high chargeability values.

Woodhall, Cumbria (MRP Report No. 14 and A. D. Evans, private communication)
At Woodhall, near Caldbeck in Cumbria, an IP survey was carried out to trace the extension of a known sulphide vein which runs north-westwards, passing from Borrowdale Volcanic rocks into Lower Carboniferous limestones resting uncomformably on the volcanics and locally faulted against them. Moderately strong chargeability anomalies (25-30 ms) were recorded (e. g. Fig. 9) in an area of thin drift cover approximately along the line of the expected

extension to the vein. A Turam survey was then carried out to measure the EM response from this target but no anomaly was obtained over the position of the chargeability anomaly, although a moderately strong anomaly, recorded approximately 100 m to the south-east, indicated the presence of a conductor dipping steeply to the south. VLF measurements made over the same area confirmed the existence of a good conductor, having a steep southerly dip, along this trend at a depth of several tens of metres. This conductor is likely to be a continuation of the known vein although the absence of an associated chargeability anomaly suggests that sulphide mineralisation is probably not extensive. The conductor coincides with the edge of a zone of lower resistivity (Fig. 9), suggesting that the vein occupies a fault in this area. The origin of the chargeability anomaly, which coincides with a small VLF anomaly only, is unknown, one possibility being a weak sulphide impregnation too dispersed to form an EM conductor.

No drilling was carried out at Woodhall because of the small size of the possible vein extension described above.

Vidlin, Shetland (MRP Report No. 4)
Trial geophysical surveys in October, 1974, over a strata-bound sulphide horizon on a promontory at Vidlin Ness, showed pronounced anomalies (Fig. 10) and indicated a minimum strike length for the mineralisation of 460 m. The zone runs parallel with and close to the sea shore which sets a physical limit to the lengths of traverse lines. The effect of the sea on the VLF results, especially those for the in-phase components, is clearly demonstrated at both ends of the profiles shown in Fig. 10. However, the 'cross-over' point of the 'in-phase' and 'out-of-phase' responses is well defined over the mineralisation and coincides with prominent magnetic, resistivity and chargeability anomalies. Although the source of these anomalies does not crop out on this traverse, it is close to the surface; but if the same source were a few tens of metres deep, instead of a few metres, the anomalies (particularly VLF and magnetic) would be much weaker and more poorly defined (c. f. Fig. 9).

Subsequent, more extensive, geophysical surveys in 1975 showed that chargeability and resistivity anomalies of varying amplitude and width extend over a total strike length of some 3 km but that corresponding magnetic and VLF anomalies are weak along all except about 1 km of this distance. It has not been established whether these anomalies arise from a different horizon or from the same horizon at greater depth and with perhaps less mineralisation. Drilling through the main anomalies proved massive sulphides (mainly pyrrhotite with some chalcopyrite, sphalerite and galena) extending in length for at least 500 m, in depth for at least 100 m, and varying in width between 2 m and 10 m. In the 6 boreholes drilled, average metal content ranged from a minimum of 0.46% Cu and 0.12% Zn to 1.19% Cu and 1.27% Zn.
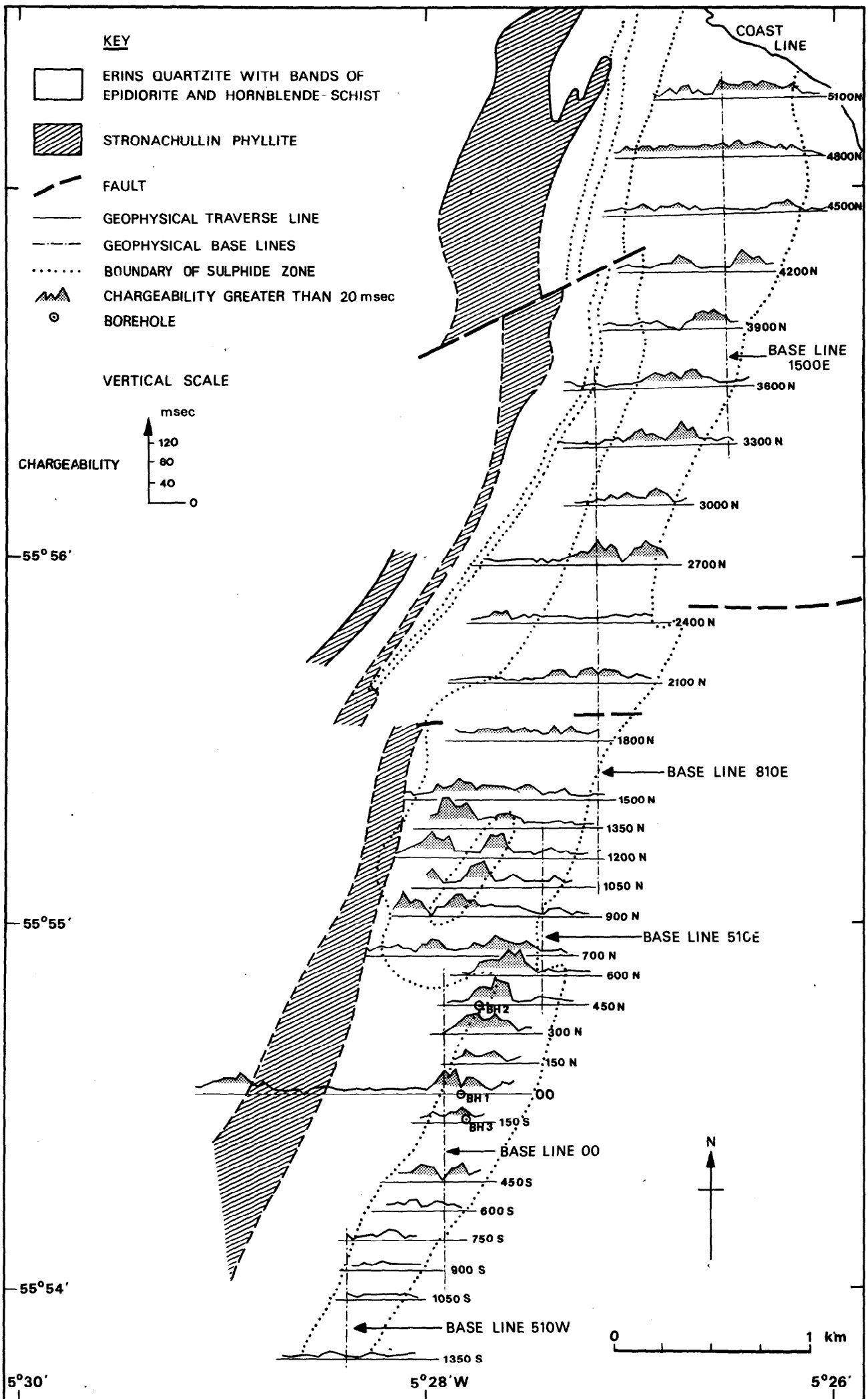
Fig. 7.   Chargeability profiles and main geological features
of the Meall Mor area, Argyll.

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GRAPHIC LOG. BH. 1

Metres

Histogram for *Cu.* in p.p.m
(Based on sample assays)

I.P. Log – Chargeability
(Milliseconds)

Geological
Summary Log

Histogram for Mo. in p.p.m
(Based on sample assays)

Alteration

SILICIFICATION

KAOLINITE

SECONDARY ORTHOCLASE

SERICITE / CARBONATE

SECONDARY MUSCOVITE

Strong Sericite and Calcite

Moderate overall Sericite/Carbonate alteration

NOT SAMPLED

150 Ms

Geological Legend

Dolerite
Crinanite

} Tertiary

Biotite Felspar Porphyry
Felspar Porphyry
Adamellite
Xenolithic Felspar Porphyry

} Caledonian

Hornfelsed Metasediment

} Dalradian

Breccia - zone
Quartz /Carbonate Vein Stockwork

F........F Fracture zone
Inclination 50°
Azimuth 352½°

Fig. 8.   Geochemical, geophysical and geological logs for
Borehole 1, Kimelford, Argyll.

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NW

SE

0   100 m

TURAM

+4°   1·10
P.D.   R.R.

reduced ratio

phase difference

0

−4°   0·90

V.L.F. E.M.

+30%

in-phase

out-of-phase

0

−20%

CHARGEABILITY (ms)

100 NW   0   100 SE   200 SE   300 SE   400 SE   500 SE

1   9   10   24   35   6   3   0   3   2   8

2   3   12   24   33   22   9   6   2   1   5   22

2   3   23   26   18   16   10   12   3   6   23

4   6   42   11   24   17   21   10   23   47

APPARENT RESISTIVITY (ohm m)

193   529   511   401   356   250   404   163   204   288   995

254   191   764   320   276   234   199   596   303   267   568   828

237   387   637   232   371   255   304   1330   872   460   643   615

270   443   475   360   390   382   688   690   397   372

Fig. 9.   Turam, VLF, chargeability and apparent resistivity profiles, Woodhall, Cumbria.

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300W 200W 100W 00

+40
+20
0
-20
-40

DIRECTION OF
MEASUREMENT

OUT OF PHASE

IN PHASE

V.L.F. RESPONSE : EM 16

+2000
+1000
0
-1000
-2000

GAMMAS
(ARBITRARY
DATUM)

VERTICAL MAGNETIC FIELD: JALANDER

CONTOURS AT 5, 10, 20,
50, 100, 200, 500, 1000

APPARENT RESISTIVITY : HUNTEC I.P.
(OHM METRES)

200W 100W 00

1019 1170 1191 1069 641 31 369
505 1503 1450 1073 405 17 19
(1065)
647 738 1614 1012 331 15
536 862 790 963 267 5
281 726 867 444 228 5

CHARGEABILITY : HUNTEC I.P.
(M.SEC)

200W 100W 00

17 17 17 24 26 40 29
33 26 26 32 67 54 63
(32)
44 36 36 41 51 65
39 48 43 69 60
26 39 54 55 68

SEA
SHORE
(WEST)

POSITION OF
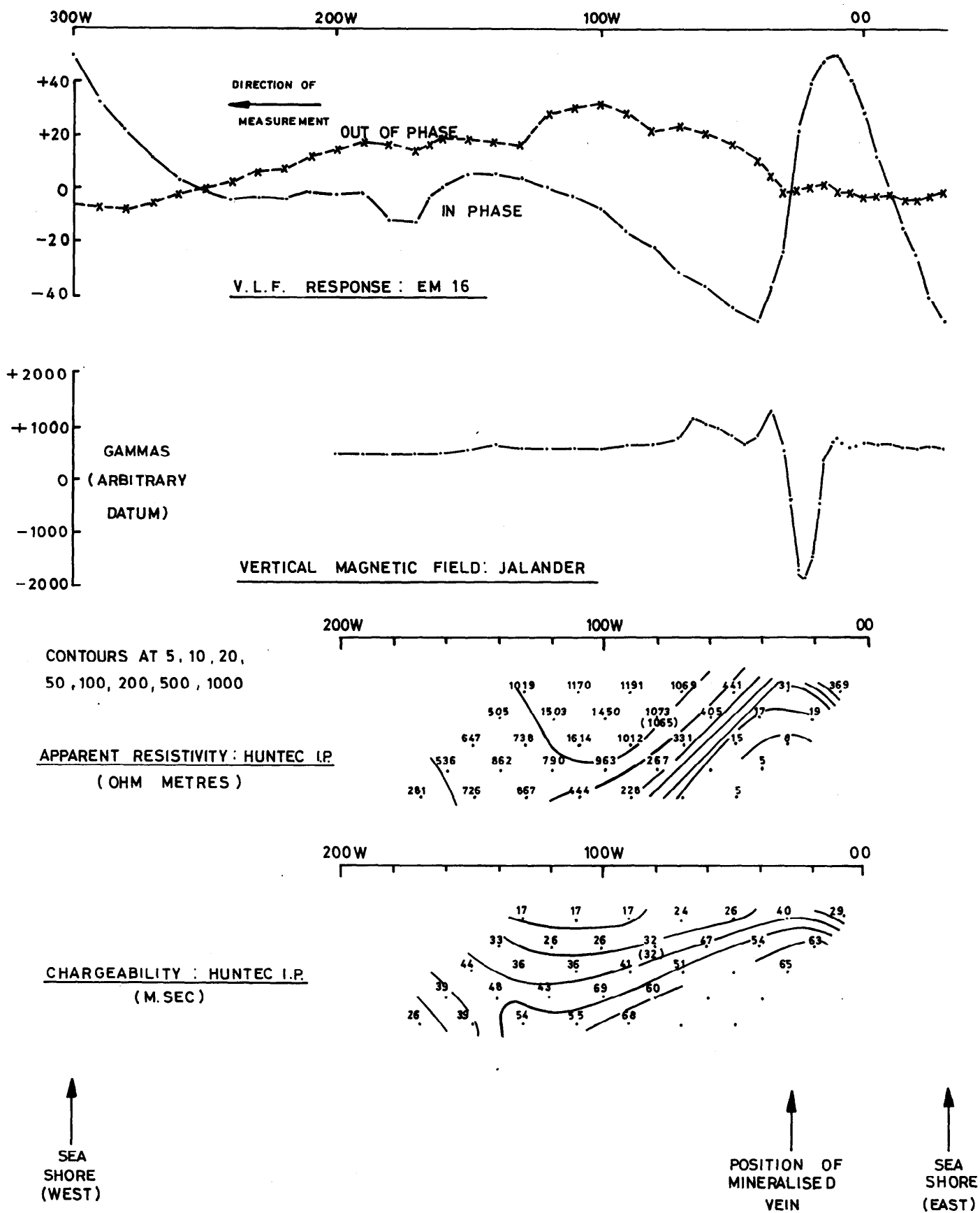MINERALISED
VEIN

SEA
SHORE
(EAST)

Fig. 10. VLF, magnetic, apparent resistivity and chargeability profiles
for traverse 150N, Vidlin, Shetland.

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APPENDIX 1

Electromagnetic noise frequency spectrum surveys
Introduction

Most electromagnetic geophysical prospecting methods
depend on the detection of small variations in amplitude
and phase of an artificially generated magnetic field of
fixed frequency, usually in the audio range. One factor
to be taken into account in choosing an operating
frequency for survey work must therefore be the optimi-
sation of signal-to-noise ratio in the presence of natural
and artificial noise fields. An element of the surveys
under review was the measurement of the frequency
distribution of the noise fields in areas selected for
airborne EM surveys as part of the DI Mineral Reconnaissance
Programme.

The areas surveyed were Newquay-Withiel (SW England);
Anglesey and the Harlech Dome (N Wales); Dent (Pennines);
SW Scotland; and Helmsdale, Strathhalladale, Wick and
Orkney (N Scotland). Further details can be found in
individual reports for these areas.

Expected nature of noise fields

Audio-frequency electromagnetic noise is partly natural,
partly man-made, in origin. Natural noise arises
mostly from distant thunderstorms, covers a broad
frequency spectrum, and is usually of an amplitude
insufficient to disturb geophysical instruments (although
even distant lightning produced 'spikes' on the airborne
electromagnetic records). Man-made noise can arise
from several sources:

(a) Mains interference. Power lines radiate at the mains
frequency (50 Hz) and its harmonics (100, 150 ... Hz).
Since power line currents are approximately balanced,
the field is that of a dipolar line source, i. e. it decreases
as the inverse square of the distance from the power line.

(b) VLF radio transmitters. These powerful transmitters
radiate signals at fixed frequencies in the audio-frequency
range which are detectable over many thousands of miles.
The most powerful VLF source in the UK is GBR (Rugby)
at 16 kHz.

(c) Other radio transmitters. These transmit signals
above the audio-frequency range, but see below.
Radio transmitters are operational in or near the
Newquay-Withiel, Anglesey and Wick areas.

Effect on instruments

All modern geophysical instruments have filters
designed to reject signals outside the wanted range.
Whether rejection is satisfactory or not depends on the
differences in strength and frequency between the
wanted and unwanted signals, and the sharpness of the
filters. In some designs a broadband amplifier stage
is present before the filter. In this case an unwanted
signal strong enough to saturate the amplifier will cause
non-linearity and the generation of inter-modulation
products, ie output signals of frequency $(mf_1 \pm nf_2)$,
where f_1 and f_2 are the frequencies of any two input
signals and m and n are small integers. The

demodulation of radio signals is mathematically equivalent: if a radio carrier wave is amplitude modulated with an audio frequency signal, that signal will appear at the output of a non-linear amplifier. Intermodulation and demodulation products will be troublesome if they occur within a filter's passband.

Instrumentation

The sensing device used for these frequency spectrum surveys was on air-cored Slingram coil about 60 cm in diameter of DC resistance about 20 Ω. The output was fed to a battery-powered low-noise preamplifier based on an Analog Devices integrated circuit type AD 504 J. A simple diode detector could be switched into the circuit between the coil and the preamplifier to detect intermodulation and demodulation products. The output from the preamplifier was at first fed directly to a spectrum analyser unit incorporated in a Tektronix oscilloscope, but it was later found more convenient to record the signals on a cassette tape recorder and play them back to the spectrum analyser subsequently. The overall sensitivity at the aerial was 0.1 μV. The records were photographed on Polaroid film.

Results

Typical results from the surveys are shown in Fig. 11.

Fig. 11-1A, from the Newquay-Withiel area (NGR SX 033654), shows sharp peaks at mains frequency (50 Hz) and mains harmonics at 150, 250, 350, 550 and 650 Hz at levels well above the background.

Fig. 11-1B is a composite record of several "sweeps" from the Newquay-Withiel area (NGR SX 022634) which shows diffuse noise sources at 0-200 and 750-1000 Hz and sharp peaks at 1200 and 2000 Hz which are believed to derive from the GPO transmitter nearby. (The apparent spread at the base of the sharp peaks is in fact mostly due to the response bandwidth of the spectrum analyser).

Fig. 11-1C from the Harlech Dome area (NGR SH 649 181) shows an intense broad peak near 570 Hz, the cause of which is uncertain. (The upper trace is a calibration trace with peaks at 0, 100, 300, 500 .. Hz).

Results for all areas are summarised in Table 5. For many reasons it is difficult to quantify the results more precisely. It is probable that, in practice, interference would occur at any frequency in the Newquay-Withiel and Anglesey areas in the immediate vicinity of the transmitting stations.

Table 5. Degree of risk of interference within the frequency range of most airborne and ground electromagnetic prospecting equipment.

Area \ Frequency (Hz)	340	400[2]	500	800	918	1000	1070	1600	2000
Newquay-Withiel	L[1]	L	M	H	H	H	M	L	H
Harlech Dome	L	L	M	M	D	M	M	M	L
Dent	D	D	M	L	L	L	D	D	M
S W Scotland	D[1]	D	D	M	D	L	M	M	M
Helmsdale	L	L	L	L	L	L	L	D	L
Strathhalladale	L[1]	L	L	D	M	M	M	L[3]	L
Wick	L	L	M	M	M	D	L	L[3]	L
Orkney	L	L	M	L	L	L	L	L	M

L = low risk. D = definite, but small, risk. M = moderate risk. H = high risk.

Notes
1. Many power lines in these areas. Possibility of interference from 7th harmonic (350 Hz) depending on sharpness of filters
2. Eighth harmonic of mains frequency (400 Hz) is usually weak.
3. Strong demodulation signal at 1400 Hz may be troublesome, depending on sharpness of filters.

RELATIVE AMPLITUDE ⟶

FIG. 1A

0   1000 Hz

FIG. 1B

0   2500 Hz
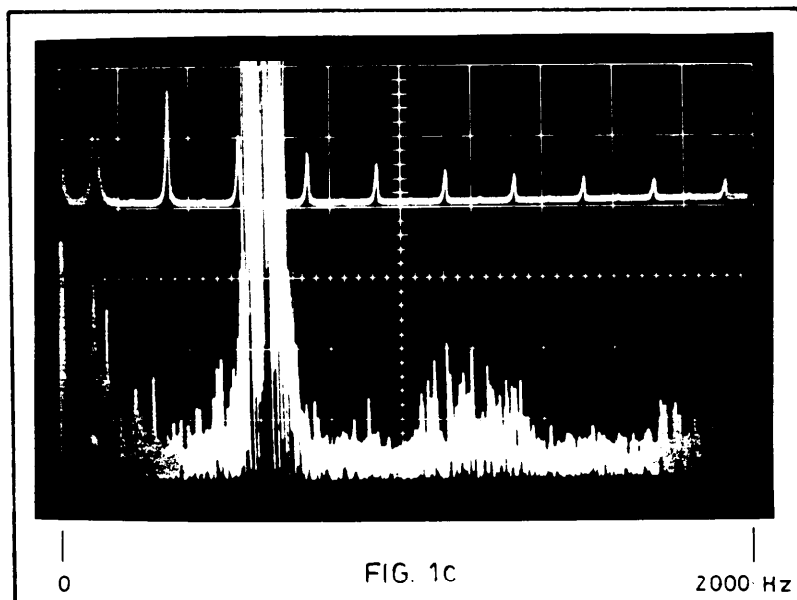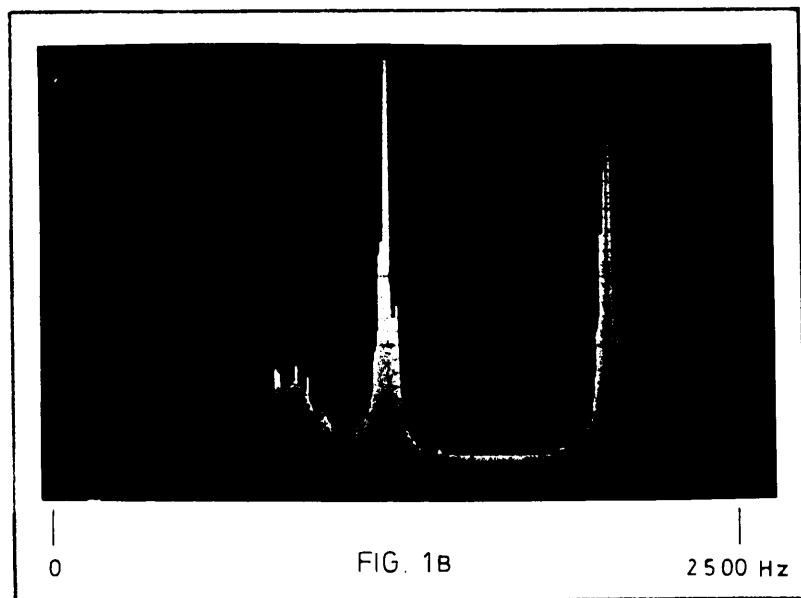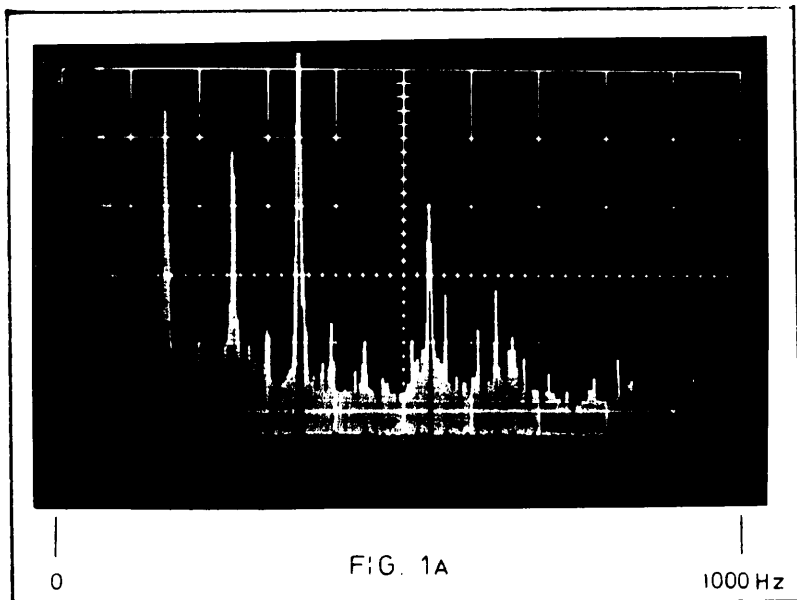
FIG. 1C

0   2000 Hz

FIG. 11 FREQUENCY SPECTRUM RESULTS FROM SURVEYS IN THE
NEWQUAY-WITHIEL AREA (A AND B) AND THE HARLECH DOME AREA (C)