

British Geological Survey



Mineral Reconnaissance Programme

A review of detailed
airborne geophysical
surveys in Great Britain

Department of Trade and Industry

MRP Report 136

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J D Cornwell, S F Kimbell, A D Evans,
and D C Cooper

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Authors

J D Cornwell, MSc, PhD
S F Kimbell, BSc
A D Evans, BSc
D C Cooper, BSc, PhD, CGeol
BGS Keyworth

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BRITISH GEOLOGICAL SURVEY

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Keyworth, Nottingham NG12 5GG

☎ 0115-936 3100

Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA

☎ 0131-667 1000

Telex 727343 SEISED G
Fax 0131-668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London, SW7 2DE

☎ 0171-589 4090

Fax 0171-584 8270

☎ 0171-938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF

☎ 0131-667 1000

Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX

☎ 01392-78312

Fax 01392-437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 01232-666595

Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800

Telex 849365 HYDROL G
Fax 01491-25338

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire

SN2 1EU

☎ 01793-411500

Telex 444293 ENVRE G
Fax 01793-411501

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Dr D C Cooper
Minerals Group
British Geological Survey
Keyworth
Nottingham NG12 5GG

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SUMMARY

Detailed airborne geophysical surveys, with flight line spacings of a few hundred metres, low terrain clearance and a combination of magnetic, EM and radiometric instruments, provide high-resolution data that are particularly valuable for mineral exploration purposes. The British Geological Survey (BGS) holds data for 17 of these airborne mineral exploration surveys, covering a combined area of approximately 16,000 km², carried out in Britain since 1957. The survey areas are distributed across the country, mainly over rocks of Precambrian, Lower Palaeozoic and Carboniferous age. Significant mineral deposits within these areas include the granite-related mineralisation of south-west England, the volcanogenic massive-sulphide deposit at Parys Mountain in Anglesey and stratabound mineralisation in the Dalradian of central Scotland.

This report has been compiled to increase awareness and promote usage of these valuable datasets. It includes information on the survey locations, geophysical methods and equipment, and a brief geological background for each area. Of the many datasets originally recorded in analogue form, the largest and those of most interest have recently been converted to digital form to allow full use to be made of state-of-the-art presentation and interpretation software. Conversion of the analogue data will be continued in order to provide coverage of further areas. These digital datasets can be integrated readily with other digital geoscience data to optimise the appraisal of prospective areas.

INTRODUCTION

One of the functions of the Mineral Reconnaissance Programme (MRP) is to provide a comprehensive, easily accessible exploration database for Great Britain. Included in the geophysical component of this database are the results from various detailed, low-level airborne geophysical surveys, many of which were carried out for MRP projects and involved multi-method data acquisition. There are several reasons why the results of such surveys are valuable, and will retain their value as basic datasets for exploration in the future:

- detailed airborne surveys provide a valuable comprehensive data coverage intermediate in scale between those of national surveys and ground surveys aimed at specific targets;
- initial survey costs were high, and improvements in instrumentation are seldom sufficient to justify complete re-surveying;
- interpretations at the time of the survey mainly concentrated on specific types of target, which are often replaced as exploration interests and models change;
- improvements in data presentation have been considerable in recent years and new information is often extracted from old data;
- the systematic data coverage provided can be integrated effectively with other datasets.

The continuing value of detailed airborne geophysical surveys to exploration projects is widely recognised and has been recently reviewed by Hanna (1990) and Fitterman (1990).

Although many of the UK surveys were originally recorded in analogue form, an MRP project to digitise these data is well advanced and the results are being incorporated into a databank established by the BGS Regional Geophysics Group. The creation of these digital datasets means that advantage can be taken of state-of-the-art software for interpretation and presentation. In parallel with this development have been advances in digital databasing for geological, geochemical and remotely-sensed data, which means that the geophysical data can be interpreted more readily in the broadest possible context.

The main purpose of this report is to summarise the availability of all data, both digital and analogue, from detailed airborne surveys. The report also provides a brief account of the exploration context and the principal features of the results from each area surveyed.

AIRBORNE GEOPHYSICAL SURVEYS

Airborne surveys have played an important part in mineral exploration programmes in many parts of the world over the past 40 years. The high resolution required in such surveys is achieved by a low terrain clearance (Figure 1) and flight line spacings of a few hundred metres. The methods used nearly always include magnetic, radiometric and electromagnetic (EM) measurements. These can be effective both directly, as in the location of massive sulphides using the EM method, or indirectly, by providing indications of lithological and structural features favourable to mineralisation. The latter approach can be particularly important in areas of poor geological exposure, or where the minerals sought occur in economic concentrations which generate no significant geophysical response (e.g. gold, platinum group elements and diamonds).

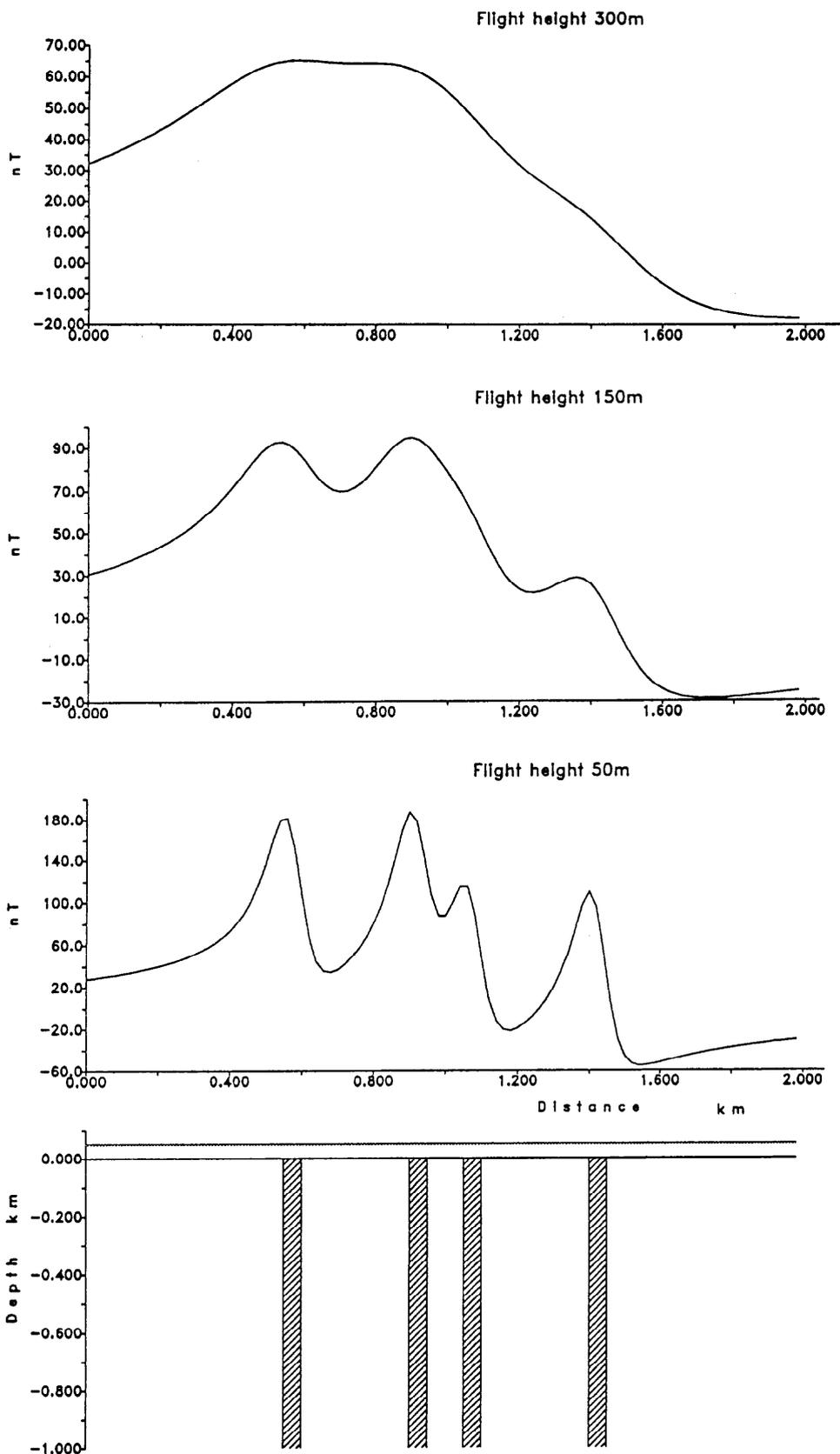


Figure 1 Effect of flight height on resolution for aeromagnetic data. The model curves for the different heights have been calculated for the same sets of identical dyke-like bodies (magnetisation 0.95 A/m, inclined 68° north) along a north–south profile. Note change in anomaly amplitude scale.

National Survey

The aeromagnetic survey of Great Britain was carried out for the Geological Survey of Great Britain (now the BGS) between 1955 and 1965. This national survey was flown with a flight-line spacing of 2 km and a terrain clearance of 305 m in nearly all areas. The data are published as contour maps at scales of 1:625 000 and 1:250 000 covering the UK, including much of the offshore area. The original survey worksheets have been digitised (Smith and Royles, 1989) and the data are held in the BGS Regional Geophysics databank. This dataset provides a uniform coverage suitable for regional assessment but is usually inadequate for the detailed interpretation required for mineral exploration.

Detailed surveys

BGS's first high-resolution survey in Great Britain was flown over south-west England in 1957-59 as part of a uranium exploration programme. Flight-lines were spaced 400 m apart and the terrain clearance was 150 m. Subsequent high-resolution airborne surveys have been carried out for the MRP between 1972 and 1978. Surveys by exploration companies, for which the BGS holds data, cover large areas of the Grampian region of Scotland. Details of all these surveys, including instrumentation used and availability of data, are summarised in Table 1.

The BGS also holds airborne geophysical data gathered for purposes other than metalliferous mineral exploration, and these are summarised in Table 2. They include two surveys flown in north-west England (Formby and Fylde) under a Commission of the European Communities (CEC) contract to investigate the application of high-resolution aeromagnetic surveys in the direct detection of hydrocarbons (Busby et al., 1991), and one near Maldon in Essex for sand and gravel (Bristow, 1985). Table 3 lists other airborne surveys known to the BGS but for which data are not currently available. Figure 2 shows the locations of all detailed airborne surveys known to the BGS.

TECHNICAL DETAILS OF SURVEYS SUPERVISED BY THE BGS

1957-59 Airborne survey of south-west England

The airborne geophysical survey of south-west England was flown as part of a uranium exploration programme carried out by the Geological Survey of Great Britain (now the BGS) and the UK Atomic Energy Authority. In 1956 a trial radiometric survey was flown over a 100 km² area where detailed ground surveys had previously been made. All known anomalies were detected by the airborne survey and some new ones noted. This led to a larger survey being flown in the following years. The aircraft used was a Douglas DC3 carrying radiometric, magnetic and EM sensors. Flying height was 150 m (± 30 m) and the line spacing 400 m (± 200 m). The survey contractor was Hunting Geophysics Ltd. The survey was carried out in two parts: Cornwall, from Lands End to National Grid line 220E, flown in 1957; and from 220E to 310E, flown in 1958/9. Geophysical equipment used differed in the two phases:

Equipment 1957

Magnetometer. PSC fluxgate magnetometer recording total magnetic field, housed in the tail of the aircraft

EM. Dual frequency PSC MKI EM system operating at frequencies of 400 Hz and 2,300 Hz. The horizontal transmitting loop was mounted on the aircraft and a vertical detecting coil was towed behind in a "bird". This measured the out-of-phase components of the resultant EM fields, which were recorded continuously for both frequencies on two separate channels.

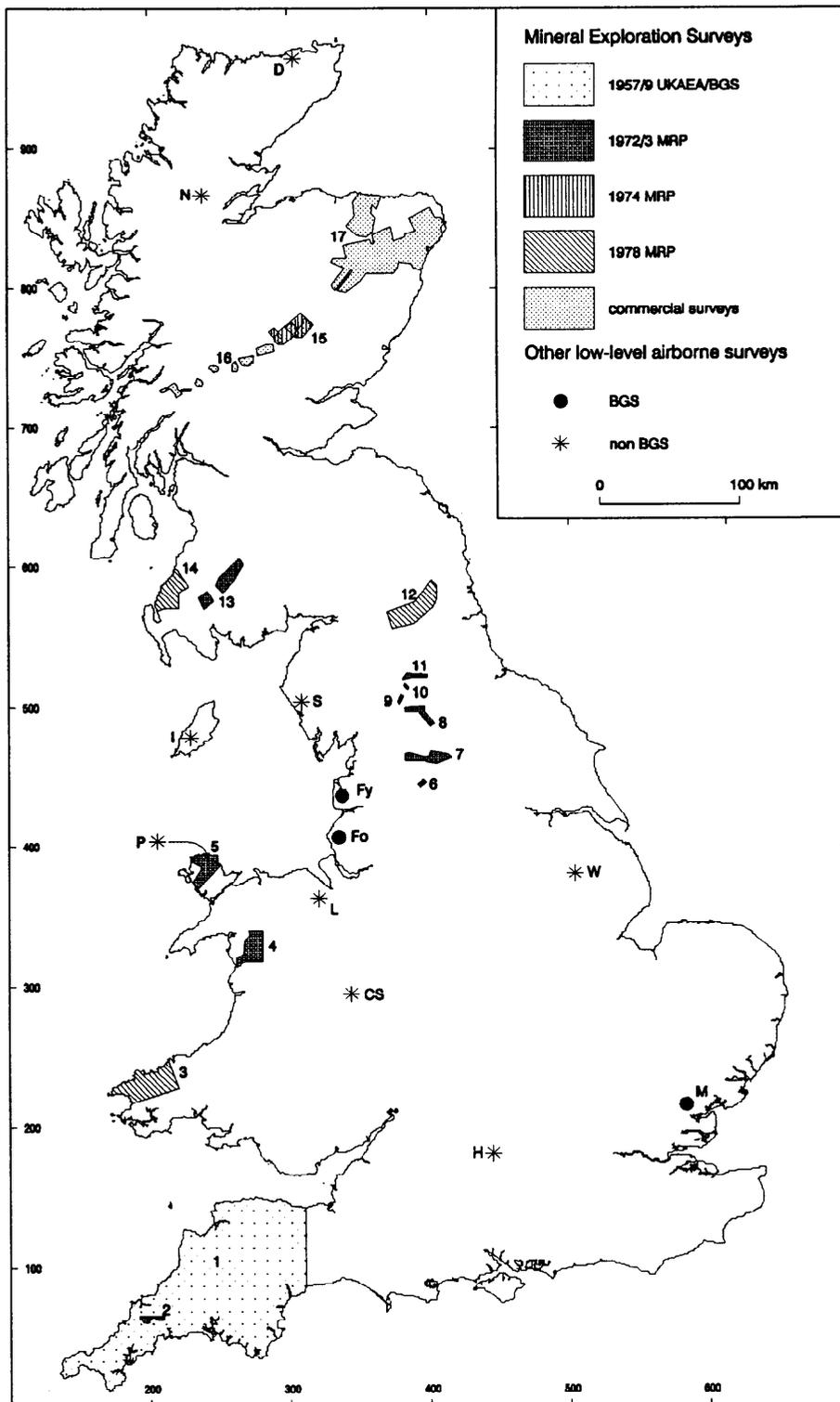


Figure 2 Locations of detailed airborne surveys.

Ticks at margins indicate British National Grid (in km). 1 - SW England, 2 - Bodmin, 3 - SW Dyfed, 4 - Harlech Dome, 5 - Anglesey, 6 - Lothersdale, 7 - Craven, 8 - Stockdale, 9 - Dent, 10 - Augill, 11 - Lunedale, 12 - S Northumberland, 13 - Doon-Glenkens, 14 - Girvan-Ballantrae, 15 - Blair Atholl, 16 - Middle Dalradian, 17 - Aberdeenshire, M - Maldon, Fo - Formby, Fy - Fylde, H - Harwell, CS - Church Stretton, L - Llanferries, P - Parys Mountain, I - Isle of Man, S - Sellafield, N - NE Scotland, D - Dounreay.

Table 1: Airborne surveys for mineral exploration in Great Britain: data held by the BGS

Area	Year	Contractor ¹	Line spacing (m)	Terrain clearance (m)			Total area (km ²)	Instruments			Data records ²		
				Aircraft & spectrometer	EM	Mag		Magnetometer	EM equipment	Spectrometer	Magnetic	EM	Radiometric
S W England	1957-9	H	400	150	150	150	10,000	PSC & GULF MK3	PSC MK1	AERE 1444A & 1531A	AMd	AM	AM
Bodmin	1973	H	200	61	30	46	60	MAP2	HEM 701 (1600 HZ)	NE 8420	AM	AM	A
Harlech Dome	1972-3	H	100 & 200	61	30	30 & 46	315	GULF MK3 & MAP2	LHM 250 (1000HZ)	NE 8420	AMd	AMd	A
Anglesey	1972	H	100 & 200	61	30	30	230	GULF MK 3	LHM 250	NE 8420	AMd	AM	A
Dent	1973	H	100	61	30	46	6	MAP 2	HEM 701	NE 8420	AM	AM	A
Augill	1973	H	100	61	30	46	12	MAP 2	HEM 701	NE 8420	AM	AM	A
Doon-Glenkens	1973	H	200	61	30	46	275	MAP 2	HEM 701	NE 8420	AMd	AMd	A
Lunedale	1973	H	200	61	30	46	50	MAP 2	HEM 701	NE 8420	AMd	AMd	A
Stockdale	1973	H	200	61	30	46	100	MAP 2	HEM 701	NE 8420	AM	AM	A
Craven	1973	H	200	61	30	46	175	MAP 2	HEM 701	NE 8420	AM	AM	A
Lothersdale	1973	H	200	61	30	46	16	MAP 2	HEM 701	NE 8420	AM	AM	A
Blair Atholl	1974	S	200	61	45	35	325	NPM-4	HEM-3A (1000HZ)	SPM-11	AMd	AMD	AMD
S Numberland	1978	S	250	75	75	60	440	NPM-5	VLF-EM II	SPM-12	AMD	AMD	AD
Girvan-Ballantrae	1978	S	250	75	75	60	365	NPM-5	VLF-EM II	SPM-12	AMD	AMD	AD
S W Dyfed	1978	S	250	75	75	60	670	NPM-5	VLF-EM II	SPM-12	AMD	AMD	AD
Aberdeenshire (EVL)	1970	B	320	61	30	49	2,500	AM 104	HEM & VLF	-	Md	M	-
Dalradian (Exxon)	1983	D	200	?	35	50	430	G803	DIGHEM 3 TOTEM-VLF	-	Md	Md	-

¹ H - Hunting Geology & Geophysics Ltd B - Barringer Research Ltd
S - Sander Geophysics Ltd (Canada) D - Dighem Ltd

² A- analogue flight record; D - digital flight record
d - survey data digitised M - map

Table 2: Airborne surveys for non-metalliferous mineral exploration: data held by the BGS

Area	Contractor	Year	Target	Terrain clearance (m)	Line spacing (m)	Total area (km ²)	NGR at centre of survey area	Methods
Maldon	Barringer Research Ltd	1973	Sand and gravel	61-76	161	158	584 214	E-phase resistivity
Formby	Global Earth Sciences Ltd	1987	Hydrocarbons	130,100 (mag. bird)	200	100	335 408	Magnetic and radiometric
Fylde	Global Earth Sciences Ltd	1987	Hydrocarbons	130,100 (mag. bird)	200	100	340 438	Magnetic and radiometric

Table 3: Other airborne surveys: data not held by the BGS

Area	Client	Contractor	Year	Target	Terrain clearance* (m)	Line spacing (m)	Total area (km ²)	NGR at centre of survey area	Methods
Church Stretton	---	Hunting G & G Ltd	1955	Trial	150	400	160	348 292	Magnetic
Isle of Man	Island Exploration Co	Hunting G & G Ltd	1956	Mineral exploration	150 (M.R.) 90 (EM)	400	500	235 485	Mag., EM, radiometric
Parys Mountain, Angelsey	Consolidated Denison Mines Ltd	Hunting G & G Ltd	1956	Mineral exploration	150	200	93	245 386	Mag., EM, radiometric
Llanferries (Halkyn)	?	Hunting G & G Ltd	1956	Mineral exploration	?	?	60	324 362	EM, radiometric
Harwell	UKAEA	Hunting G & G Ltd	1959	Background radioactivity	150	radii 24, 48, 72 km from site	-	448 187	Radiometric
Aberdeenshire	EVL	Faireys Survey Ltd	1969/70	Mineral exploration	150	400	2,700	Same as 1970 EVL survey	Magnetics
NE Scotland	Esso Minerals	Hunting G & G Ltd	1972/73	Mineral exploration (uranium)	150	800 & 1600	26,000	Orkneys-Aberdeen	Magnetic, radiometric
Welton	BP (UK) Ltd	?	?	Hydrocarbons	200 150 & 100 (M)	500	260	505 378	Mag. (total field & gradient) radiometric
Sellafield	Nirex	Aerodat Ltd	1990/91	Geology	130 (R) 115 (V) 100 (M)	200	500	310 505	Mag. (total field & gradient), VLF-EM, radiometric
Dounreay	Nirex	Global Earth Sciences Ltd	1990	Geology	125	200	400	300 970	Magnetic, radiometric

* M - magnetic sensor
R - spectrometer
V - VLF-EM sensor

Radiometrics. Two scintillation counters were installed in the aircraft: i) AERE 1444A, comprising one 4.7 inch by 1 inch cylindrical, thallium-activated NaI crystal (total volume 17 cubic inches); and ii) AERE 1531A, comprising three thallium-activated NaI crystals (total volume 50 cubic inches). The number of counts per second (cps) were recorded continuously on two separate chart recorders, with full scale deflections of 1,000 cps (AERE 1444A) and 3,250 cps (AERE 1531A).

Auxiliary Equipment. A 35 mm Vinten positioning camera and an STR30 radio altimeter.

Equipment 1958/9

Magnetometer. Airborne Gulf MK3 fluxgate, housed in a bird towed behind the aircraft.

Radiometrics. AERE 1531A and experimental AERE 1531B scintillation counters, mounted inside the aircraft.

Auxiliary Equipment. Vinten 35 mm positioning camera and an APN-1 radio altimeter.

No EM system was deployed on the 1958/9 survey.

Data processing and presentation

Control of the aeromagnetic data was achieved by terminating both ends of each line over common tie points which were connected by independent tie lines, and by flying other tie lines across the area. These allowed adjustments for instrumental drift and diurnal variation. A base recording magnetometer was used to check for any magnetic storms which might have required lines to be re-flown. The repeatability of data and performance of EM and radiometric equipment were checked by control lines flown at the beginning and end of each sortie. The magnetic data were presented as contour maps of total field anomalies relative to a local reference field for the UK at epoch 1955.5, which has a value of 47033 nT at the National Grid origin and increases northwards at 2.1728 nT/km and westwards at 0.259 nT/km, with a correction made for the secular variation from 1955.5 to the date of the survey. This dataset was integrated with the National Survey to form part of the 1965 aeromagnetic map of Great Britain.

The flight lines were plotted from the camera records onto overlays of Ordnance Survey (OS) maps at a scale of 1:25,000, and related to the flight records using fiducial marks. Intercepts were read from profiles at maxima, minima and at set intervals (5 nT, 2° phase shift, 50 cps (AERE 1444A) and 83½ cps (AERE 1531A). The intercepts were transferred to the overlays to produce contour maps of total magnetic intensity, total count and phase difference, plus a map of flying height for use in interpretation.

Further processing

The aeromagnetic data have been digitised with the rest of the National Survey and incorporated into the BGS Regional Geophysics databank. Trial digitisation of a subset of the aeroradiometric records is planned by the MRP, to test whether significant new information useful for mineral exploration is obtained. No further work has been done on the EM data.

MRP phase I: 1972/73 surveys

At the commencement of the MRP, airborne geophysical surveys were used in the initial assessment of the prospective terrains chosen for investigation. Eleven areas, totalling about 1200 km² were selected. The surveys were flown using a helicopter carrying magnetic, EM and radiometric sensors and the data were recorded continuously on annotated paper charts. Specified flying height was 61 m

(200 ft) and line spacing 200 m (100 m in two small areas). A tracking camera was used to record the flight paths, which were subsequently plotted onto 1:10,560 or 1:10,000 OS maps, and barometric and radio altimeters were used to maintain and record ground clearance. Deviations of more than 61 m from the planned flight line and 7.6 m from planned ground clearance required re-flying, if requested by supervising staff. The survey contractor was Hunting Geology and Geophysics Ltd.

Equipment

EM. The airborne EM equipment chosen for these surveys was a single-frequency, rigid co-axial vertical-loop system. The transmitter and receiver coils were spaced 9.1 m apart and housed in a bird towed 30.5 m below the helicopter (mean terrain clearance 30.5 m). A primary field (1000 Hz for the 1972 surveys and 1600 Hz in 1973) was generated by the transmitting coil. The in-phase and out-of-phase components of the resultant field detected by the receiver coil were recorded as ppm of the primary field.

Magnetics. For the first two surveys (Anglesey and part of the Harlech Dome) the total magnetic field was measured with a fluxgate magnetometer mounted in the centre section of the EM bird. Subsequent surveys used a Scintrex MAP2 nuclear-resonance proton precession magnetometer, with the sensor attached to the EM cable 15 m below the helicopter (Table 1).

Radiometrics. The radiometric data for all these surveys were collected using a 4-channel gamma-ray spectrometer comprising two thallium-activated NaI crystals. Each crystal had a 6 inch diameter and was 4 inches thick, giving a combined crystal volume of 226 cubic inches. The crystals, thermally insulated and moisture-proofed, were installed outside the helicopter on shock-proof mountings.

The spectrometer was set to record 4 channels of information from the following level set-ups:

Total count	1.00 – 2.90 MeV
K	1.31 – 1.61 MeV
U	1.61 – 2.20 MeV
Th	2.20 – 9.00 MeV

Data processing and presentation

The magnetic and EM data were compiled into map form at 1:10,560 or 1:10,000 scale by manual processing of the flight records by the contractor. The magnetic data were presented as contour maps of total field anomalies relative to the local reference field for the UK. This enables maps to be directly compared with those for the National Survey.

The EM data were presented in two ways:

1. Contour maps of the in-phase component in ppm, relative to datum levels selected by inspection of the records.
2. In-phase / out-of-phase anomaly ratio maps with symbols representing the various ratios of all distinct EM anomalies (e.g. in-phase + ve, out-of-phase -ve, ratio 2.0–3.0).

In some areas the two formats were combined (Harlech Dome, Doon–Glenkens, Stockdale and Craven).

Radiometric data were not processed and were left in the form of flight records which were visually inspected.

Further processing

Some of these datasets have been digitised by the MRP in recent years (see Table 1).

MRP phase II: 1974 survey

This survey was flown over part of Perthshire, using magnetic, EM and radiometric equipment as part of the MRP investigation of strata-controlled mineralisation in the Middle Dalradian. The helicopter speed was approximately 80 km/hr and data were recorded digitally onto tape at a rate of 2 samples per second, and in analogue form for in-flight control. Specified flying height was 61 m (200 ft) and line spacing 200 m, but, as the region is very mountainous, this was difficult to maintain in many areas. Flying height and flight paths were recorded using a Honeywell HG radar altimeter and a 16 mm tracking camera. The flight paths were plotted onto the 1:10,000 or 1:10,560 OS maps of the area (17 in total) and used as bases for presenting the results. The survey contractor was Sander Geophysics Ltd.

Equipment

Magnetics. Measurements of total magnetic field were made with a Sander NPM-4 proton precession magnetometer towed 26 m below the helicopter (mean terrain clearance 35 m). Records from a ground-level station were used to correct in-flight data for diurnal variations.

EM. The EM system used was the Sander EM-3A co-axial vertical loop system, with coils 7.5 m apart operating at a frequency of 1000 Hz. The bird housing the system was towed 16 m below the helicopter, giving an average sensor height of 45 m. Because of the steep topography encountered in the survey area, data processing included correcting EM data for variations in flying height, assuming a vertical-slab geometry for conductive sources.

Radiometrics. The gamma ray spectrometer used a single 9 inch by 4 inch cylindrical thallium-activated NaI crystal (total volume 254 cubic inches). It was set to produce 4 channels of information from the following energy level setups (values from the contractor's report):

Total count	0.70 – 3.00 MeV
K	1.36 – 1.56 MeV
U	1.56 – 1.86 MeV
Th	2.28 – 1.68 MeV

The crystal was kept in a thermostatically controlled container (35°C) mounted inside the helicopter.

Data processing and presentation

The total magnetic field data were processed by the contractor and presented as contour maps at 1:10,000 or 1:10,560 and 1:63,360 scale, without removal of the National reference field.

EM data were presented at 1:10,000 or 1:10,560 scale as in-phase and out-of-phase profiles, where data showed anomalous response, and summarised as a 1:63,360 scale map showing areas of anomalous EM response defined by:

1. In-phase anomalies (>10 ppm) with corresponding out-of-phase anomaly.
2. In-phase anomalies (>10 ppm) with little or no out-of-phase response.
3. Small in-phase anomalies (5–10 ppm).
4. Anomalous areas marginally above noise level.

The radiometric data were presented as profiles of total count, plotted on 1:10,000 or 1:10,560 scale OS maps.

MRP phase III: 1978 surveys

Three surveys were flown in 1978 to investigate additional areas of potential economic interest. The survey contractor was Sander Geophysics Ltd. Specified flying height was 75 m, with a line spacing of 250 m and the speed of the helicopter was approximately 115 km/hr. All data were recorded in analogue and digital form. Additional analogue records were made from the digital data after each flight for checking. The same equipment was used on all these surveys.

Equipment

Magnetics. Measurements of total magnetic field were made with a Sander NPM-5 proton precession magnetometer, with the sensor mounted on a small bird approximately 15 m below the helicopter giving a mean terrain clearance of 60 m (allowing for displacement of the bird in flight). The data were recorded digitally at a rate of 1 sample/sec. A second NPM-5 magnetometer, connected to a chart recorder, was used as a ground base station.

EM. The EM equipment used was the Very Low Frequency (VLF-EM) type. Compared with conventional EM, the VLF method is sensitive to laterally extensive resistivity contrasts and therefore emphasises geological structure rather than pin-pointing good conductors. In each area a VLF transmitter was selected which lay roughly along the regional geological strike.

A Sander VLF-EM II receiver with 3 orthogonal coils, mounted on the helicopter skid measured the following parameters:

H_1 - signal amplitude of the horizontal, maximum-coupled coil

H_2 - signal amplitude of the horizontal, minimum-coupled coil

V_{ip} - amplitude of the in-phase component recorded by the vertical coil and compared with H_1

V_{op} - amplitude of the out-of-phase component recorded by the vertical coils and compared with H_1

As signal strength is dependent on the orientation of the receiver coils, the attitude of the helicopter was measured with a vertical gyro to allow for corrections of pitch and roll during processing. Data from the VLF-EM receiver and the gyro were recorded in digital form every second.

Radiometrics. The Sander SPM-12 gamma-ray spectrometer used was connected to two 9 inch by 4 inch cylindrical NaI (Tl) crystals, giving a total crystal volume of 509 cubic inches. The crystals were kept in thermostatically controlled containers mounted on the floor of the helicopter. The signals from 128 channels were processed using a fast analogue-to-digital recorder and the energy divided into the following windows:

Total count	0.70 – 3.00 MeV
K	1.31 – 1.61 MeV
U	1.62 – 1.94 MeV
Th	2.47 – 2.97 MeV

Counting time was set to 1 second and the raw data recorded unstripped on the digital cassettes. Calibration checks were made before and after each flight.

Auxiliary Equipment. The helicopter was equipped with two radar altimeters: a Bonzer to record terrain clearance and a Honeywell to monitor the Bonzer. A Sander CM3-12 16 mm tracking camera was used to provide continuous coverage of the flight path.

Data processing and presentation

Magnetics. The aeromagnetic data were corrected for diurnal variation and the National reference geomagnetic field was removed (as for the 1957/9 and 1972/3 surveys) before data were edited and gridded. Results were plotted as total magnetic field anomaly contours on 1:10,560 or 1:10,000 scale OS base maps (Evans and Cornwell, 1981).

VLF-EM. Data were corrected for the pitch and roll of the helicopter and for variation in the signal strength of the EM field of the VLF transmitter. This was estimated using a 49 multi-point moving averaging of values along each flight line, which was then represented as 100 % on the horizontal intensity maps. VLF-EM data were presented in map form in two ways:

1. Contours of the normalised intensity of the horizontal component of the VLF field.
2. Stacked profiles of the normalised in-phase and out-of-phase values of the vertical magnetic field component of the VLF field (V_{ip} and V_{op}).

Radiometric data. The digital radiometric data were not processed further by the contractor and were presented to the MRP as uncorrected channel counts. They have subsequently been reprocessed by the BGS for various projects. This involved position recovery (to convert data to NGR format), spectral interaction corrections, low-pass filtering to suppress statistical noise, and correction for atmospheric attenuation using empirically derived coefficients.

COMPILATION OF DIGITAL DATASETS

With the growth of digital databases and increasing use of digital techniques for interpretation and presentation of data in the mid-1980's, two tasks presented themselves in respect of the archiving of the data from the surveys described above. First, to convert to digital format all of those data which were recorded in analogue form; and second, to re-work those datasets which had been acquired digitally, but for which suitable digital data had not been originally specified.

Financial support, from BGS's programme to enhance information systems, funded digitisation of the EVL aeromagnetic maps for north-east Scotland (area 17). The results of this work proved of value to BGS's mapping and mineral exploration projects and led the MRP to support digitisation of its own maps of airborne survey data, giving priority to those areas where the data would be of use to active mineral exploration projects.

Analogue-to-digital conversion

There were three options for a methodology for this conversion: (i) digitise the contours from the fair-drawn maps; (ii) digitise only the intersections between contours and flight-lines; or (iii) digitise the in-flight chart records.

Digitising contours has no advantages other than allowing reasonably faithful reproduction of the original maps, while digitising the in-flight chart records is a complex procedure. The method selected – digitising the intersections between contours and flight-lines – has the advantages of ease of digitising, relatively straightforward quality control and a simply-structured dataset with minimal data

redundancy. This method proved to be satisfactory when used for digitising the national aeromagnetic survey (Smith and Royles, 1989). The disadvantages are that signatures too weak to be represented by contouring cannot be captured (though in most cases these would be eventually smoothed out by gridding), and that any large contour-free areas will be devoid of data points necessary to constrain gridding. Scrutiny of data grids indicates that the latter problem has not arisen in datasets digitised to date.

The selected digitising method has been used, so far, for analogue-to-digital conversion of maps of magnetic and electromagnetic data for those survey areas with the greatest geological information content. Survey areas with few geophysical features, or where the data are dominated by cultural anomalies, have not been digitised.

The radiometric data for the analogue-recorded surveys have never been compiled into map form, so that any digitising of these will have to be done from the in-flight chart records.

The digitising process

The survey data have been digitised map by map, using mylar master copies where these are available. On completion of a map, or portion of a map, the 'drawing file' is converted into an ASCII text file within which each record describes a contour/flight-line intercept. Each record has five fields, which are, from left to right: flight-line number; contour value; British National Grid (BNG) easting; BNG northing; flying height. The Fortran format is (i3,i7,1x,2f10.0,f7.0).

On completion of all of the maps for a survey, the text files are linked and the data sorted so that the data are sequential (increasing easting or northing) along each flight-line, and the flight-lines are also sequential (increasing line number). Checking of the data can then be carried out using a range of specially-written software and by generating test plots.

Quality control

The colour monitor used during digitising allows a measure of real-time quality control, and test plots enable positional precision to be checked. The data values themselves are, as noted above, checked with a range of software routines to identify the most likely errors, which are : (i) mis-keying of contour values; (ii) incorrect identification of unlabelled contours; (iii) contour labelling errors on the original map; (iv) mis-keying and/or incorrect identification of flight-line number. Other routines allow tidying (such as elimination of duplicated points at map edges), generation of vector files (to produce flight-line maps) and statistical analysis (useful in deciding upon suitable contouring when producing maps from gridded versions of the data).

The software allows speedy identification of errors, with minimal recourse to hard copy. A final dataset, after running all checking routines and making necessary edits, can be assumed for all practical purposes to be error-free.

Re-processing of digitally recorded data

New methods of computer analysis and display of geophysical datasets can extract a great deal more information and have led to most of these data being re-processed by the BGS. A suite of computer routines were written for position recovery, radiometric data analysis and processing, and data reformatting. The reprocessed data can now be displayed and manipulated with a variety of software display packages (Plates 1-3).

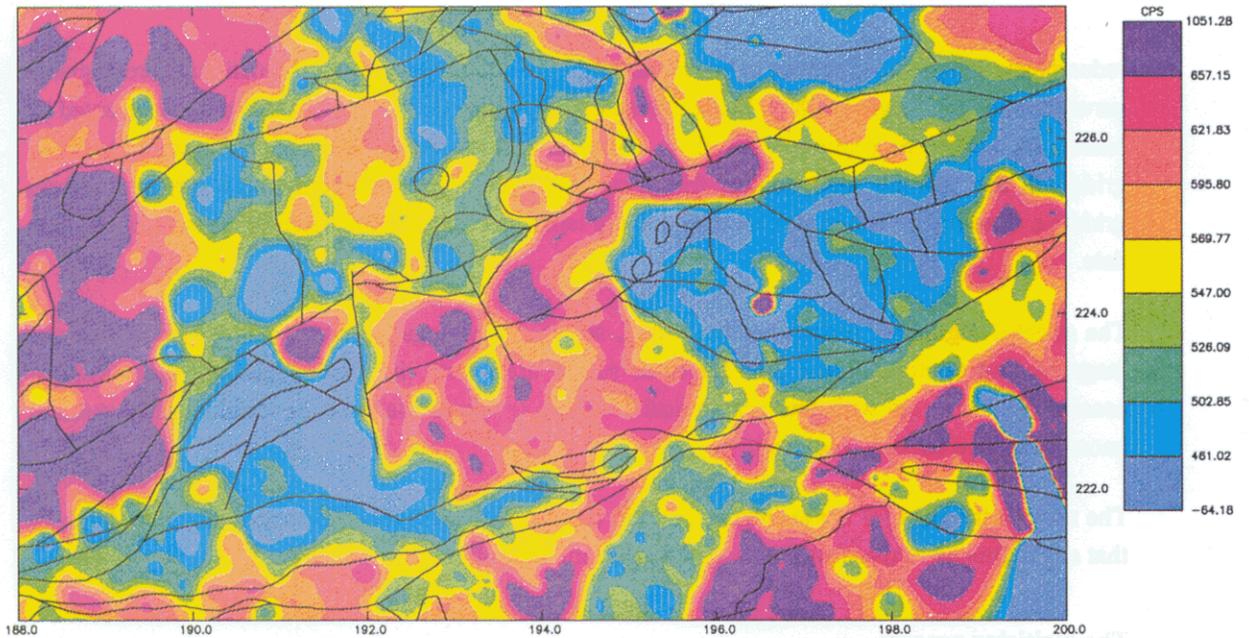


Plate 1 Total count radiometric data for the Treffgarne area, south-west Dyfed, with main geological boundaries shown as black lines. Equal-area presentation with a total range of 1000 cps: red - highs, blue - lows.

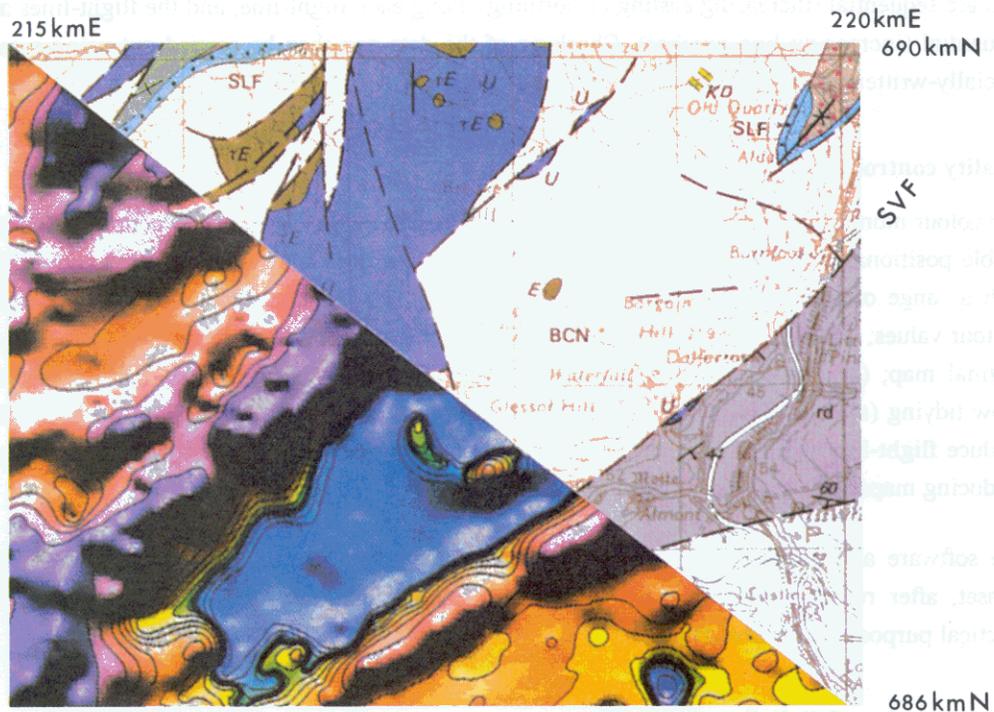


Plate 3 Composite geological and aeromagnetic map for part of the Girvan area. Magnetic data presented as coloured shaded relief plot (illumination from north) showing anomalies associated with ultrabasic rocks and greywackes containing locally derived magnetite. (BCN - Balcreuchan Group (volcanic rocks of the Ballantrae complex), U - seppentinite, E - diorite and gabbros, rd - Tappins Group greywackes, SVF - Stincher Valley Fault.)

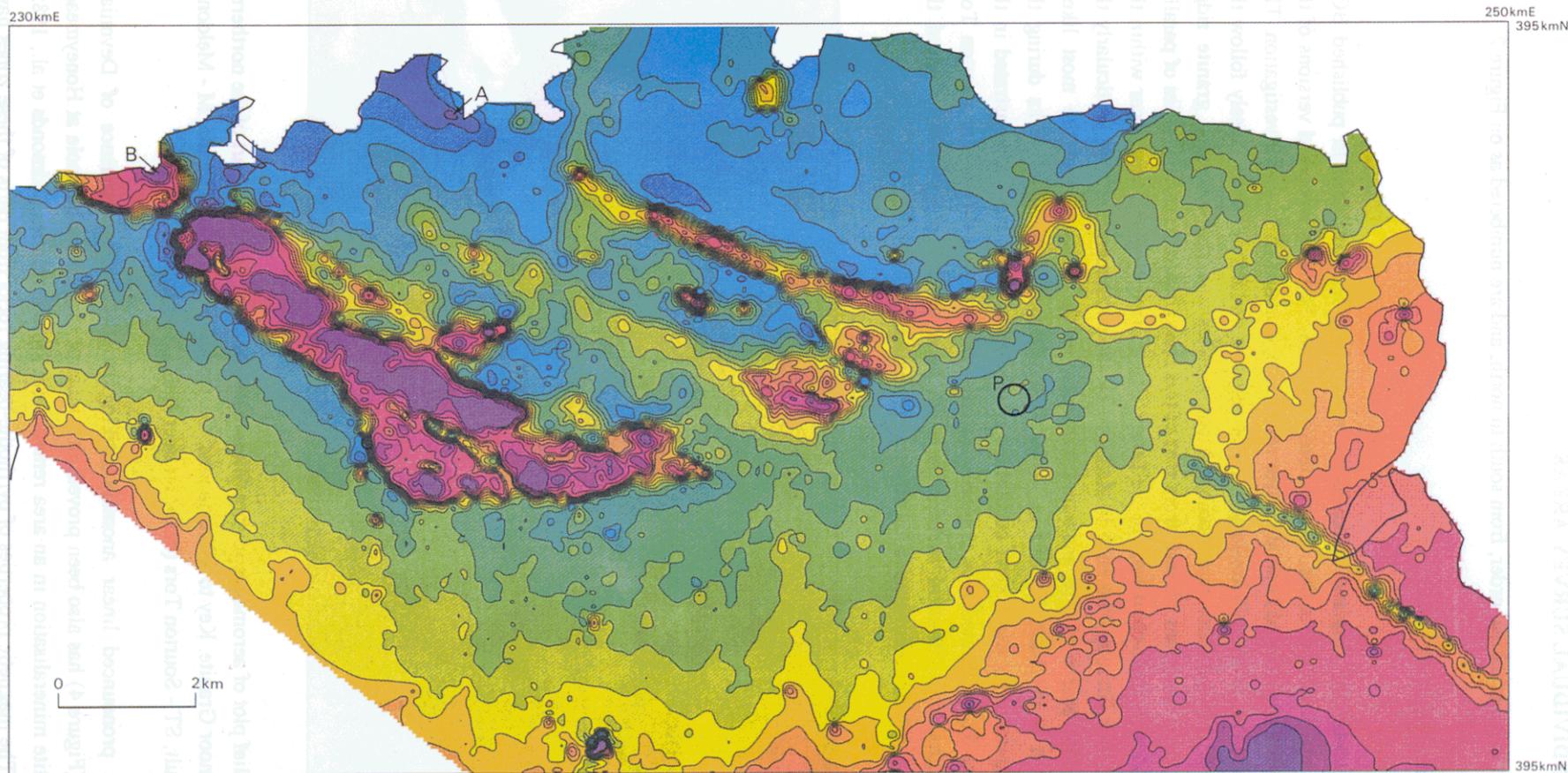


Plate 2 Contours of total field magnetic anomaly from airborne survey data over the northern part of the island of Anglesey. Contour range is from -150nT (closure A) to +50nT (closures at B and southeast thereof). Circle 'P' marks the location of the recently-discovered extension of the Parys Mountain orebody.

RESULTS FOR INDIVIDUAL SURVEY AREAS

These are discussed in geographical order, from south to north, and are numbered as on Figure 2.

1 South-west England (1957-59)

Aeromagnetic data

The results of the south-west England aeromagnetic survey have been included in published BGS maps at 1:250,000 and 1:625,000 scales. These contour maps are based on smoothed versions of the data, and reveal several pronounced anomaly zones which have encouraged further investigation. The most pronounced of these is the 100 km-long zone of negative anomalies which closely follow the northern margins of the Dartmoor and Bodmin Moor granites and the concealed granite ridge between the two exposed intrusions. Results from part of this zone (Figure 3) show a series of parallel anomalies associated with shale-chert beds in the Lower Carboniferous, where they occur within the aureole of the Dartmoor Granite. The zone is displaced by the subsequent faulting, particularly the Sticklepath Fault. The source of the anomalies has been much discussed, but the most likely explanation is that it is pyrrhotite formed in Lower Carboniferous sedimentary rocks during the intrusion of the granites. The widespread occurrence of this mineral has been demonstrated in the Meldon area (Figure 3) by detailed rock magnetism studies (Cornwell, 1967) and at Sourton Tors (Figure 3) where ground geophysical surveys, followed by a drilling programme, revealed the presence of extensive pyrrhotite mineralisation (Beer and Fenning, 1976).

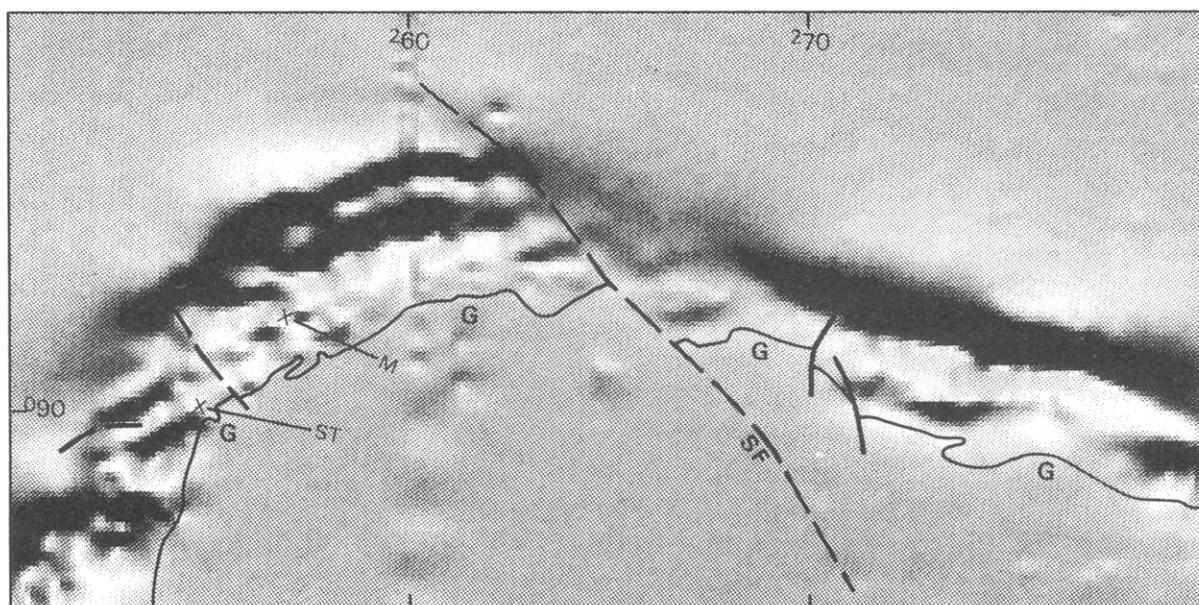


Figure 3 Shaded relief plot of aeromagnetic data (illuminated from the north) for part of the northern margin of the Dartmoor Granite. Key to abbreviations: G - margin of Dartmoor Granite, M - Meldon, SF - Sticklepath Fault, ST - Sourton Tors (based on Beer et al., 1989 figure 2b).

In north Devon a pronounced linear anomaly striking parallel with a sequence of Devonian sedimentary rocks (Figure 4) has also been proved, in a mineral exploration borehole at Honeymead, to be due to pyrrhotite mineralisation in an area remote from known granites (Edmonds et al., 1985; Jones et al., 1987). The magnetic properties of pyrrhotite-bearing rocks from parts of these zones have been investigated by Thomson et al. (1991). Other sources of magnetic anomalies in south-west

England include Devonian volcanic rocks south of Dartmoor and, in the pre-Devonian basement, peridotite and gabbro intrusions in the Lizard Complex (Rollin, 1986) and metamorphic rocks at Start Point.

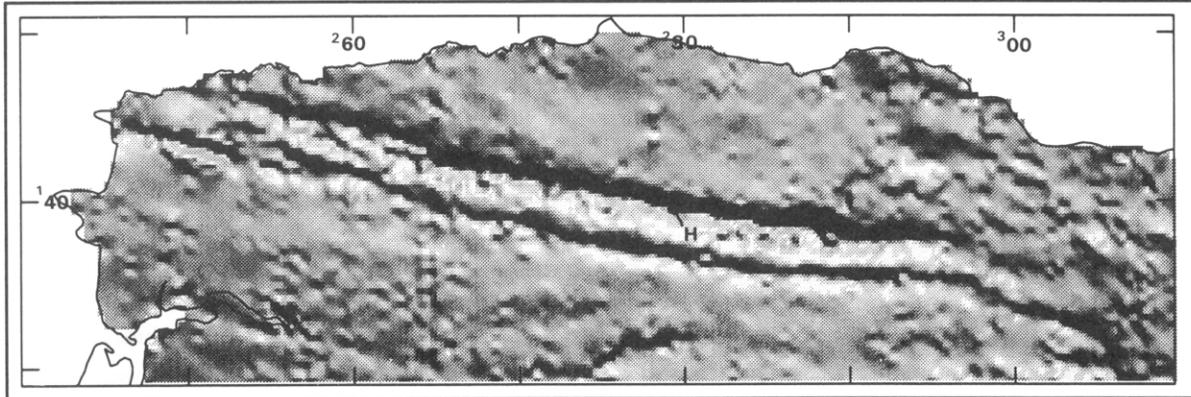


Figure 4 Shaded relief plot of aeromagnetic data (illumination from south) for part of Exmoor.
H - Honeymead Borehole (Jones et al., 1987)

In many other parts of south-west England the anomaly pattern is characterised by the presence of isolated, low amplitude features or subtle changes in gradient. These are not well represented in contour map form but their full significance can be assessed from the digital dataset. A preliminary examination of some of the data is included, for example, in a recent assessment of the diamond potential of Great Britain (Leake et al., 1995). This involved a rapid search to isolate 'point' anomalies which might be indicative of small pipe-like intrusions.

Radiometric data

The target of the gamma-ray survey was uranium and thorium mineralisation. Iso-rad maps show good correlation with geology over the granites, surficial concentrations of radioactive mineral and mine dump material. All anomalies more than three times the standard deviation of background were considered to be significant and ground follow up of all interesting anomalies resulted in the discovery of five virgin lodes (Bowie et al., 1958).

EM data

No comprehensive interpretation of the 1957 EM data is available, but an examination was made of results from the Boscastle area (McKeown et al., 1973). Many of the anomalies there appear to be topographical in origin, or due to power lines, but a geological origin for one 2 km-long zone was confirmed by ground surveys. Subsequent drilling proved the source to be dark, pyrite-rich Lower Carboniferous shales.

2 Bodmin (1973)

The target for this MRP survey was granite-related copper-tin-tungsten mineralisation. The area, which lies to the south and south-west of the town of Bodmin, was selected for the following reasons:

1. The northward concealed extension of the Hensbarrow Granite, with known mineral associations, lies at shallow depth throughout the area.

2. The northern part of the area lies over metamorphic calc-silicate rocks (the calc-flintas) which contain worked copper lodes and over which geochemical sampling has proved copper and zinc anomalies.
3. The southern part of the area covers the granite cupolas of Belowda Beacon and Castle-an-Dinas, their associated tin-tungsten mineralisation and part of the major iron lodes of Retire and Lanjew.

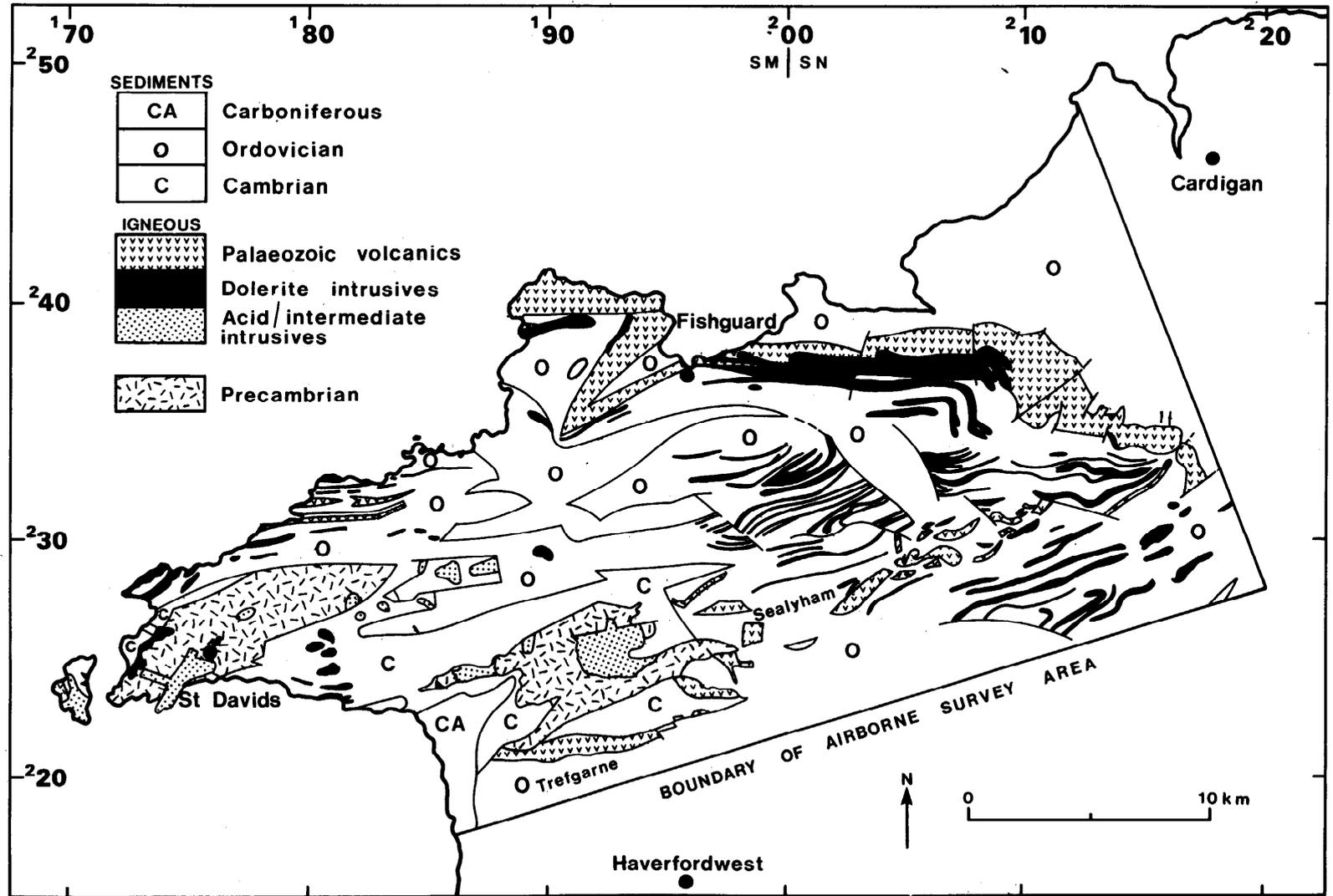
The survey gave no indications of significant new ore bodies, nor of extensions to known lodes. Ground follow-up of airborne anomalies with magnetics, EM and Induced Polarisation (IP) proved, in most cases, man-made sources such as pipes and power lines (Tombs, 1978).

3 South-west Dyfed (1978)

This survey area covers most of the northern part of Dyfed to the west of Cardigan. It includes the Precambrian rocks (mainly volcanic rocks and acidic intrusions) in the St. David's and Hayscastle anticlines, the extensive Lower Palaeozoic (Cambrian to Ordovician (Caradoc)) outcrop and a small area of Carboniferous rocks (Figure 5). The Cambrian succession is dominated by clastic sedimentary rocks (sandstones, siltstones and shales) whilst the Ordovician rocks comprise a succession of siltstones and mudstones, interrupted by several volcanic suites, the most extensive being the Fishguard Volcanic Group. There are also numerous high-level intrusions, ranging from acid to basic in composition, associated with the volcanism (Cornwell and Cave, 1987). There are few indications of previous mining activity in south-west Dyfed, but the area was selected for investigation because of the perceived potential for volcanic-hosted massive-sulphide deposits and porphyry-style mineralisation. The airborne geophysical data provide much new information on the concealed geology in this area where outcrops away from the coastline are sparse (Cornwell and Cave, 1987). Magnetic anomalies are associated in particular with the Precambrian volcanic rocks and the basic intrusions, the latter including a previously unrecognised 45 km-long dyke of probable Carboniferous age (Cave et al., 1989). VLF-EM anomalies are well defined and are largely associated with conductive shales in the Ordovician sequence, particularly where these abut resistive dolerite intrusions. In the Llandeloy area, where ground resistivity data are available from an IP survey (Allen et al., 1985), there is a good correlation between the resistive units defined by the two methods (Figure 6). Radiometric values and bedrock geology also correlate well, although the effect of the drift cover is apparent. In the example shown in Plate 1, an equal-area distribution of values has been used to emphasise low-amplitude anomalies. The high in the centre of the area occurs over sedimentary and volcanoclastic rocks in the area of stratiform pyrite mineralisation at Treffgarne (Brown et al., 1987).

Two areas of south-west Dyfed have been investigated in detail by the MRP. At Llandeloy, intrusions of intermediate composition were regarded as being of potential interest as sources of porphyry-copper mineralisation because of their similarity to those in the Harlech Dome. Detailed geochemical and geophysical surveys and drilling proved sub-economic porphyry-style mineralisation (Allen et al., 1985). At Treffgarne, geophysical and geochemical surveys, followed by drilling, proved baryte and extensive stratiform pyrite mineralisation in the highly altered volcano-sedimentary succession of the Roch Rhyolite Group (Brown et al., 1987). This area has been subsequently investigated in greater detail by a recent MRP project (Colman et al., 1995).

Figure 5 Simplified geology of the south-west Dyfed survey area (from Cornwell and Cave, 1987).



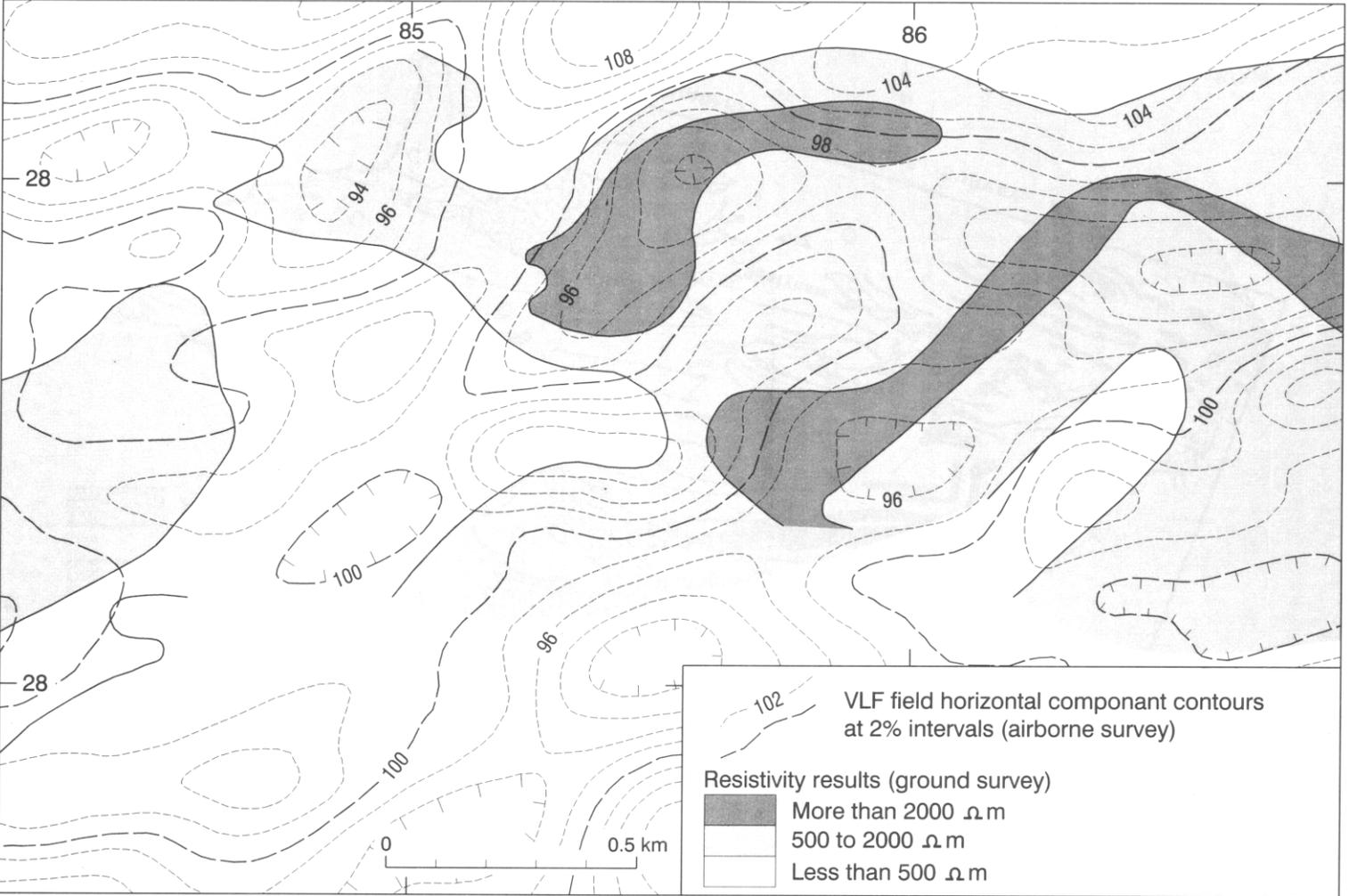


Figure 6 Airborne VLF-EM anomalies and ground resistivity results for part of the Llandeloy area, south-west Wales, (figure from Cornwell and Cave, 1987). VLF-EM anomaly minima indicate higher resistivity rocks.

4 Harlech Dome (1972/3)

This survey area includes the Cambrian sequence exposed in the core of the Harlech Dome and part of the flanking Ordovician sequence to the east. The volcanic centre of Rhobell Fawr (Tremadocian) occurs within the area, as do numerous extrusives and basic intrusions. Mineralisation includes the lodes of the Dolgellau gold-belt, the Coed-y-Brenin porphyry-copper deposit (Rice and Sharp, 1976) and bedded manganese deposits.

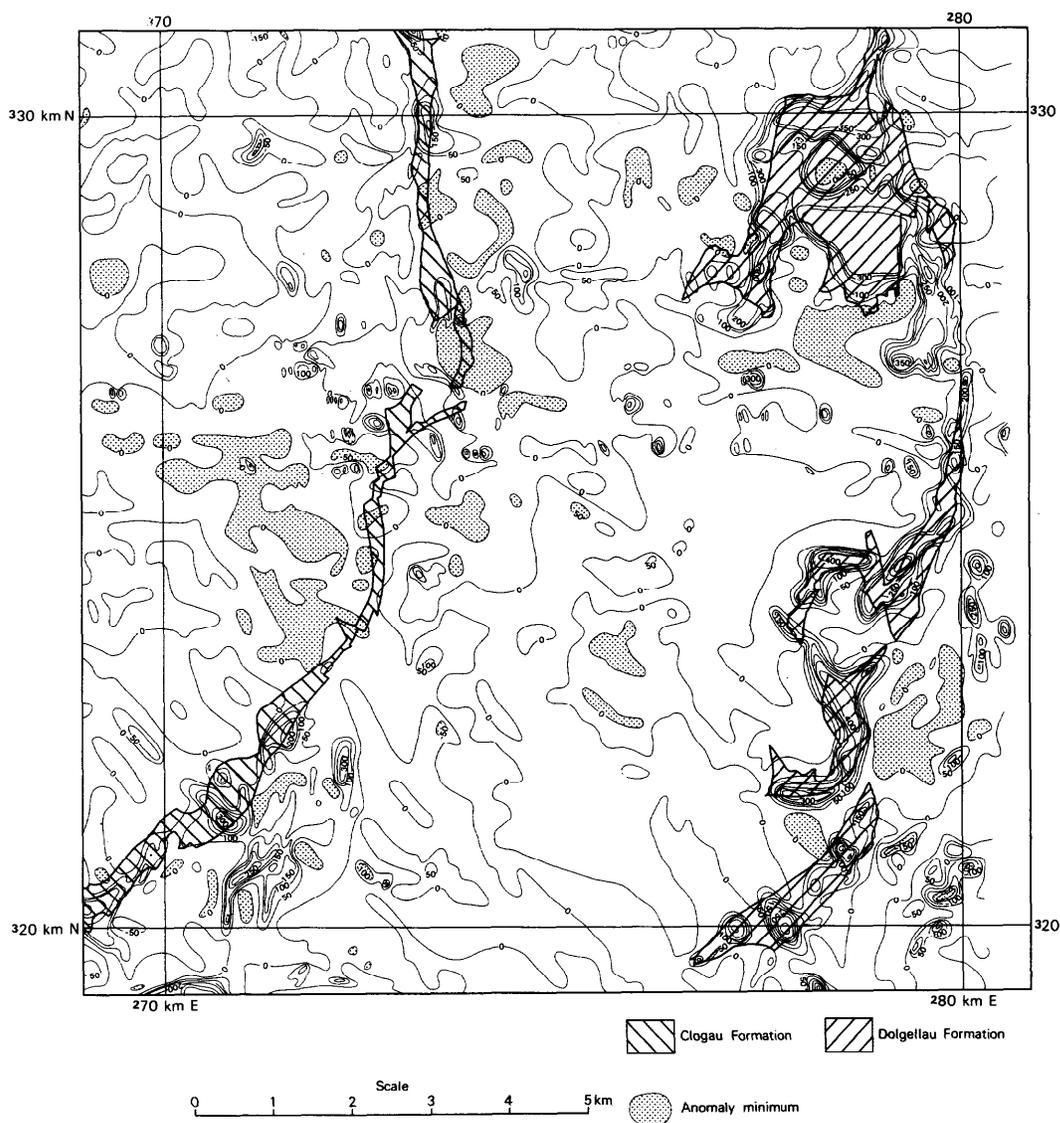


Figure 7 EM (in-phase component) map of part of the Harlech Dome airborne survey area with contours at intervals of 50 ppm. Many of the anomalies are associated with black mudstones of the Clogau Formation and the Dolgellau Member of the Cwmhesgen Formation (from Allen et al., 1985).

The MRP envisaged four main exploration targets (Allen et al., 1979):

1. Porphyry-style copper mineralisation similar to that at Coed-y-Brenin.
2. Vein-style base-metal and gold mineralisation.
3. Stratabound mineralisation associated with dark mudstones.
4. Massive sulphide deposits associated with the Ordovician volcanic rocks.

The airborne survey was carried out in two stages. The first, using 100 m line spacing (north of 337.5N), had to be curtailed because of weather conditions; the second, with 200 m spaced lines and covering a much larger area, was flown in the following year. The severe topography in parts of the area added to the difficulties of accurate survey navigation. The airborne survey was followed up by ground surveys in 26 areas (Allen et al., 1979).

A subsequent geochemical survey by the MRP work in the Ordovician periphery of the Harlech Dome confirmed the metalliferous mineral potential of the area and identified several targets meriting further investigation (Cooper et al., 1985).

5 Anglesey (1972)

The island of Anglesey hosts one of the largest known base-metal ore deposits in Great Britain at Parys Mountain, near Amlwch. The mineralisation is hosted in Ordovician volcanic and sedimentary rocks and comprises polymetallic, volcanogenic massive-sulphides, comparable with Avoca in Ireland. First deposits in the area were discovered in 1768 and produced over 130,000 tonnes of copper from around 3 million tonnes of ore. Recent evaluation of the results of many years' exploration drilling has indicated a new deposit at depth with a reserve of some 5 Mt of zinc-lead-copper ore (Swallow, 1990).

The MRP airborne survey, flown in 1972, covers the north and central parts of the island. The rocks here are of Precambrian to early Cambrian and Ordovician age, intersected by basic Tertiary dykes, and host the Parys Mountain deposit noted above. The possibility of discovering other such deposits concealed under the extensive Pleistocene cover was one of the survey objectives (Smith, 1979). The elongate tract of Coedana Granite at the south edge of the survey area was also considered a possible source of mineralisation. Other known mineralisation on the island includes copper-bearing veins in the Precambrian rocks, baryte (with galena) veins in Carboniferous rocks and oolitic ironstones in the Ordovician succession (Cooper et al., 1982). The island is low-lying, with little topographic relief and is largely given over to pasture farming with an attendant scatter of farms and villages.

In the southern part of the area the aeromagnetic data reveal strong linear negative anomalies associated with the south-east-trending Tertiary dykes, which had previously been known only from a few poor exposures. Plate 2 illustrates data from the northern part of the area, where strong anomalies are recorded over the overthrust rocks of the Mona Complex. The southern limit of these anomalies marks the course of the Carmel Head Thrust. It is possible that the broad positive anomaly in the western part of the image is due to the aggregate effect of a swarm of pre-Ordovician dykes. A weak negative anomaly in the south-east part of the image marks the inland course of the Tertiary Traeth Bychan Dyke. The Parys Mountain ore deposits lie close to an extension of this Tertiary lineament, though no magnetic anomalies arise from the deposits themselves as the main iron sulphide in the mineralisation is pyrite rather than pyrrhotite.

The EM data for much of the survey area are corrupted by the strong signals from two radio transmitters located in the north-east corner of the island. Other anomalies are due to power lines and other man-made sources. The radiometric data show no indications of uranium mineralisation.

Several of the airborne geophysical anomalies were followed up by ground surveys (Cooper et al., 1982; 1990). Base-metal vein-style mineralisation, locally containing appreciable gold, was found in several boreholes in the Carmel Head area (Cooper et al., 1989). Evidence from Bouguer gravity data has been used recently to postulate the existence of a concealed granite beneath north-west Anglesey and the adjacent offshore area (Cornwell and Smith, 1993).

North Pennine Surveys (nos 6-11)

The following six areas, numbered 6–11 in this report, were flown for the MRP to provide data that would assist in the evaluation of the potential for Lower Carboniferous rocks of the Pennines to host Irish-style base-metal mineralisation. The areas selected for airborne surveys covered major fault zones and structures at the margins of Lower Carboniferous basins, where mineral deposits could have formed by upward leakage from deep deposits analogous to those found in the Lower Carboniferous basins of Ireland.

6 Lothersdale (1973)

The 16 km² of the Lothersdale survey area covers the outcrop of the Chatburn and Pendleside limestones in the core of the north-east-trending Lothersdale Anticline, one of the major fold structures in the Carboniferous rocks of the Craven Basin. The nature of this structure and the occurrence of old workings for lead, manganese and baryte led to the inclusion of the area in the MRP Craven Basin project (Wadge et al., 1983).

The smooth aeromagnetic contours reflect the absence of magnetic source rocks in this area. Power lines are responsible for several of the EM anomalies (Wadge et al., 1983, figure 37) and others appear to be associated with conductive Bowland Shales. None of the EM anomalies was followed up with ground surveys. A trial frequency-domain IP survey carried out on the flanks of the Chatburn Limestone showed no indications of sulphide mineralisation.

7 Craven (1973)

The Craven area was the largest examined in the North Pennine MRP project. The airborne survey was carried out where mineralisation was known or thought likely to occur nearest to surface, namely along the Craven Fault Zone.

The airborne survey area covers most of the North Craven Fault and parts of the Mid- and South Craven faults between Settle and Pateley Bridge, a distance of 34 km. The fault zone forms the boundary between the thick Lower Carboniferous development of the Craven Basin and the thinner sequence on the Askrigg Block. The pre-Carboniferous basement of Lower Palaeozoic sedimentary rocks is exposed in inliers on the north side of the North Craven Fault to the west of Malham. The area also includes the historic mining districts of Grassington and Greenhow where lead-zinc-barium-fluorine ores were worked from extensive vein systems best developed in the Namurian Grassington Grit (Dunham and Wilson, 1985).

The magnetic data show no anomalies indicative of geological sources within the area, though magnetic basement rocks, which become shallower to the north, give rise to a marked regional gradient.

The airborne EM data were evaluated and 25 anomalies followed up by the MRP (Wadge et al., 1983). Many of these anomalies proved to have man-made sources, but at five sites the ground survey results were considered to have potential mineral interest.

The radiometric data show several prominent anomalies over, or at the margins of, knoll-reef (carbonate build-up) limestones (Figure 8). In some instances, these limestones show minor lead-zinc-copper mineralisation (Wadge et al., 1983; Arthurton et al., 1988). Elsewhere, these limestones exhibit high levels of radioactivity from uranium collophane concentration (Peacock and Taylor, 1966) as well as radon daughter anomalies resulting from high gas permeability of fore-reef facies rocks. Mineral veins frequently show enhanced levels of uranium, usually fixed in hydrocarbons and in collophane (T K Ball, personal communication, 1995).

8 Stockdale (1973)

The Stockdale survey, another of the six selected areas in the northern Pennines, covers part of the Stockdale Monocline in upper Swaledale and the Summer Lodge–Brownfield veins across the watershed into Wensleydale (Evans et al., 1983). The survey area covers part of the historic Keld–Reeth–Askrigg mining district, where vein-style mineralisation has been worked for lead and zinc in Lower Carboniferous sedimentary rocks since Roman times (Dunham and Wilson, 1985). The elevated moorland which dominates the survey area has only thin drift cover and was considered a particularly suitable environment in which to test the effectiveness of airborne EM in detecting Pennine-style mineral veins, especially as some of the veins in this area are known not to have been exploited at depth.

The airborne survey located a number of EM anomalies, of which 19 were followed up with ground surveys. Three of these anomalies were attributed to conductive mudstones and shale horizons, and artificial sources accounted for a further six. Eight were not found to be significant on the ground and were attributed either to noise from flexing of the EM bird, or to topographic effects. Significant ground EM anomalies at the two remaining sites were investigated more fully, including core-drilling at one site, but no significant mineralisation was found (Evans et al., 1983).

The aeromagnetic data showed no distinct anomalies, as expected from the regional data which show the survey area to be lying close to the centre of a broad magnetic low.

9 & 10 Dent and Augill (1973)

These two small surveys (combined area of 18 km²) cover a part of the Augill Fault system on the south-western side of the Alston Block, and a part of the Dent Fault which forms the western margin of the Askrigg Block (Cornwell et al., 1978).

In the absence of any near-surface magnetic rocks, the aeromagnetic data indicate only long-wavelength anomalies reflecting the regional field. Some EM anomalies occur over shale beds in the Lower Carboniferous sequence, but data are affected in many places by power lines and other man-made objects. Total count radiometric profiles show variations in background levels of 100–200 cps,

the most pronounced being along the line of the Dent Fault, which probably arise from shales immediately above the Great Scar Limestone.

Ground geophysical surveys were carried out to investigate twelve of the EM anomalies. Man-made sources accounted for five of these and a further five anomalies were attributed to conductive shale-mudstone units. The remaining two appeared to relate to faults and mudstone outcrops close to disused mine workings, but these targets were not sufficiently promising to justify drilling (Cornwell et al., 1978).

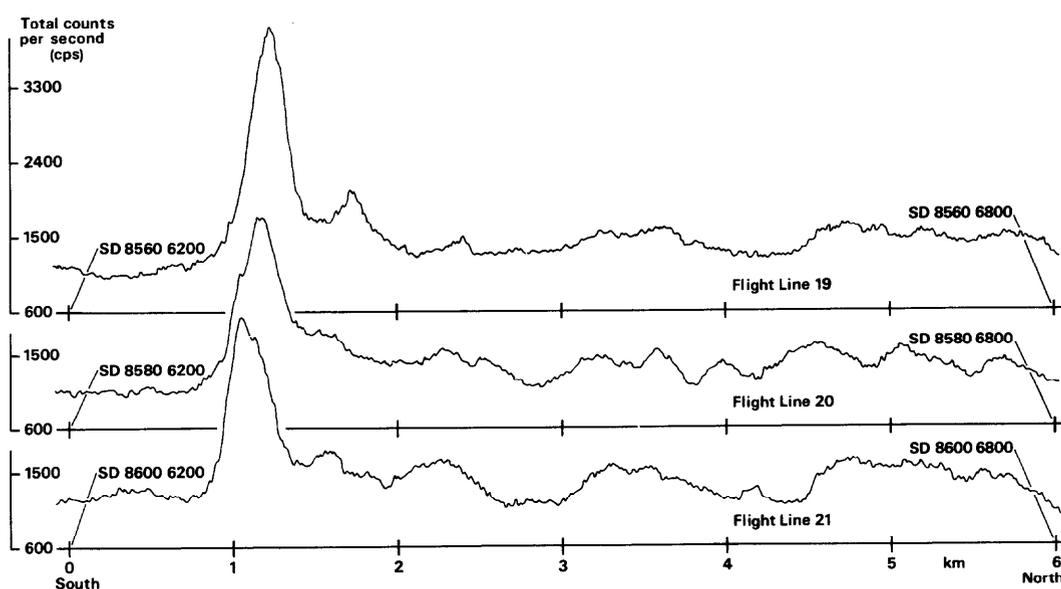


Figure 8 Total count radiometric profiles in the Craven area showing anomaly over High South Bank, an area of partly silicified Gordale Limestone (Arthurton et al., 1988).

11 Lunedale (1973)

This area includes part of the Lunedale Fault, which forms the boundary between the extensively mineralised Alston Block and, to the south, the Stainmore Trough. The structure was active during sedimentation in Dinantian times, thicknesses of these rocks increasing from 350 m on the block to more than 800 m on the downthrow side. Located on an extension of the Lunedale Fault is the major baryte deposit presently mined at Closehouse (Cornwell and Wadge, 1980). The mineralisation here is a massive replacement of Whin Sill dolerite. The Lunedale Fault also forms the boundary between structures with different styles and is the southern limit to the area intruded by the Whin Sill. The potential application of the airborne geophysical data is similar to that for the South Northumberland area (see below).

The aeromagnetic data provide detailed information on the form of the Whin intrusion (since this dolerite is the only significantly magnetised rock in the area), both at subcrop and where concealed. The presence of structural features can also be inferred (Cornwell and Evans, 1986).

Power lines and pipes are responsible for most EM anomalies, but several weaker features remain unexplained.

The radiometric profiles were examined briefly, but show only small anomalies; some are associated with the workings at Closehouse Mine and others with shales in the Lower Carboniferous sequence.

A limited amount of ground geophysical survey work was carried out, but Cornwell and Wadge (1980) consider that the mineral potential of the area remains largely untested.

12 South Northumberland (1978)

The purpose of this survey was to map structure, and thus potential locations for mineralisation, within the Whin Sill dolerite where this intrusion occurs at relatively shallow depth over a wide area. The area covered extends south and south-east from the northern margin of the sill, which in part forms a pronounced escarpment followed by Hadrian's Wall. The dolerite is intruded into a cyclic sequence of Lower Carboniferous (Brigantian) rocks, comprising sandstones, limestones and shales. It is generally conformable with these strata and is typically of the order of 30 m thick. The area is also intersected by east-south-east-trending Tertiary dykes of the Mull swarm.

The principal economic interest is barium mineralisation, the largest deposit being of witherite, which was mined at Settringstones as recently as 1969. The mineralisation here was deposited as fault veins, best developed in the Whin Sill, which is thus altered to White Whin. This alteration included the destruction of magnetite, and the combined effect of faulting and alteration is to give magnetically anomalous zones, which can be mapped at the surface along the course of the faults.

The airborne survey data thus reveal the magnetic signature of the Settringstones vein system, and provide detailed information elsewhere on structures in concealed parts of the Whin Sill (Evans and Cornwell, 1981). Some of these were selected for further mineral exploration under the MRP (Bateson et al., 1983; 1984; 1985; Cornwell and Evans, 1986). Drilling at Newborough (Bateson and Johnson, 1984) proved the interpreted faulting and alteration in the Whin Sill, with mineralisation representing an eastward extension of the Settringstones vein system. The magnetic data also indicate that, throughout the survey area, the present outcrop pattern of the sill largely reflects the control exerted during intrusion by the existing joint/fracture system.

Many of the VLF-EM anomalies appear to be related to the topography but as this also reflects lithological variations, interpretation of these data is difficult.

The radiometric variations are due largely to the effects of the variable drift cover but some correlation with bedrock geology is apparent.

13 Doon–Glenkens, Kirkcudbrightshire (1973)

Vein-style mineralisation within the Lower Palaeozoic rocks of the Southern Uplands of Scotland has been mined for centuries. Historically, the most productive district was Leadhills–Wanlockhead, which yielded lead, silver and zinc ores from near vertical-veins. Significant amounts of base-metal ores have also been produced from veins in the Newton Stewart district and from near Carsphairn.

The geology of the survey area, part of the Northern Belt of the Southern Uplands (Walton and Oliver, 1991), comprises a thick pile of steeply inclined Ordovician rocks, mainly greywackes, which are complexly folded and faulted with a predominantly north-east or east-north-east trend. These were

subsequently intruded by granitic plutons in Devonian times, the larger intrusions producing broad metamorphic aureoles within which the country rocks are highly altered (Dawson et al., 1977). Gravity surveying shows pronounced lows over the granitic plutons and indicates that they could be connected at depths of approximately 3–5 km, rising to less than 3 km towards Carsphairn, producing a large platform area. The area has potential for granite-related polymetallic mineralisation and slate-belt-hosted gold deposits, and earlier geochemical surveys in the Southern Uplands found lead, zinc and nickel anomalies over the black shale horizons which cross the survey area (Dawson et al., 1977).

The airborne survey was flown over two areas separated by the Loch Doon igneous complex. The EM survey produced strongest anomalies over shales which are attributed to clay minerals, accompanied sometimes by graphite, pyrite or pyrrhotite. Where shales have been metamorphosed near intrusions they become less conductive (Dawson et al., 1977). Other less extensive EM anomalies are attributed to unmapped shale inliers; away from these rocks, most of the more prominent EM anomalies are caused by man-made objects.

The aeromagnetic data also reveal anomalies over shale beds, but these are not usually coincident with the EM anomalies and probably arise from ilmenite with minor amounts of pyrrhotite (Dawson et al., 1977). Other aeromagnetic anomalies relate to intrusive rocks at Carsphairn and Craig of Knockgray and, in the north-east part of the area, cross-strike Tertiary dykes.

Initial ground follow-up was carried out in four main areas using magnetics, VLF-EM, EM and some IP (Dawson et al., 1977). Subsequent investigations confirmed the presence of metalliferous mineralisation in the black mudstones and shales around the headwaters of Penkiln Burn, on the south-west flanks of the Loch Doon Granite (Stone et al., 1984). Soil sampling and geophysical surveys concluded with a drilling programme to investigate the extent of exposed base-metal mineralisation in depth and along strike. Results showed that disseminated stratabound mineralisation occurs in the Ordovician rocks of the Southern Uplands, although no ore-grade deposits were found. At Glenhead Burn, over the watershed to the north-west of Penkiln Burn, arsenic-gold vein mineralisation was also found (Leake et al., 1981).

14 Girvan–Ballantrae (1978)

The airborne survey of the Girvan–Ballantrae area of south-west Scotland was flown to provide data for mineral exploration in a poorly exposed area of Lower Palaeozoic igneous and sedimentary rocks. In the north-western half of the area is the Ballantrae Ophiolitic Complex, most of which consists of spilitic lava sequences and serpentinite bodies with related small basic and ultrabasic intrusions. The whole complex is highly dissected by faults (Stone and Smellie, 1988). The south-eastern half of the area comprises Ordovician sedimentary rocks of the Northern Belt of the Southern Uplands. These are predominantly greywackes with a north-east to south-west regional strike, steeply inclined and fault-bounded, as in the Doon–Glenkens survey area. The structure and paleogeographical environment of the survey area, which crosses both the Midland Valley and Southern Upland terranes, has been a matter of debate for some years, with a variety of models being proposed (McKerrow, 1987).

The aeromagnetic map shows strong contrasts across the region (Carruthers, 1980). Ground follow-up was carried out in 16 areas in order to aid geological interpretation of the aeromagnetic data, whilst checking its accuracy in terms of positioning and interpolation of anomalies between flight lines. Reprocessing of the aeromagnetic data using new imaging techniques has shown that the region can be divided into three zones (Figure 9):

1. High-amplitude, short-wavelength anomalies over the serpentinites of the Ballantrae Complex.

2. The flat magnetic field in the south-east (apart from anomalies over the south-south-east-trending Tertiary dykes) over the siltstone-shale greywacke sequence of the Leadhills Group.
3. The area between these two, bounded by the Glen App Fault and the Stinchar Valley Fault, showing discrete areas of high, intermediate and low amplitude magnetic anomalies which can be correlated to greywacke and lava units of the Tappins Group rocks (Floyd and Kimbell, 1995).

An example of the correlation between aeromagnetic data and geology is shown in Plate 3, with strong magnetic anomalies over the serpentinites and the Trayboyck Formation of the Tappins Group; a greywacke which commonly contains coarse-grained fragments of igneous rocks.

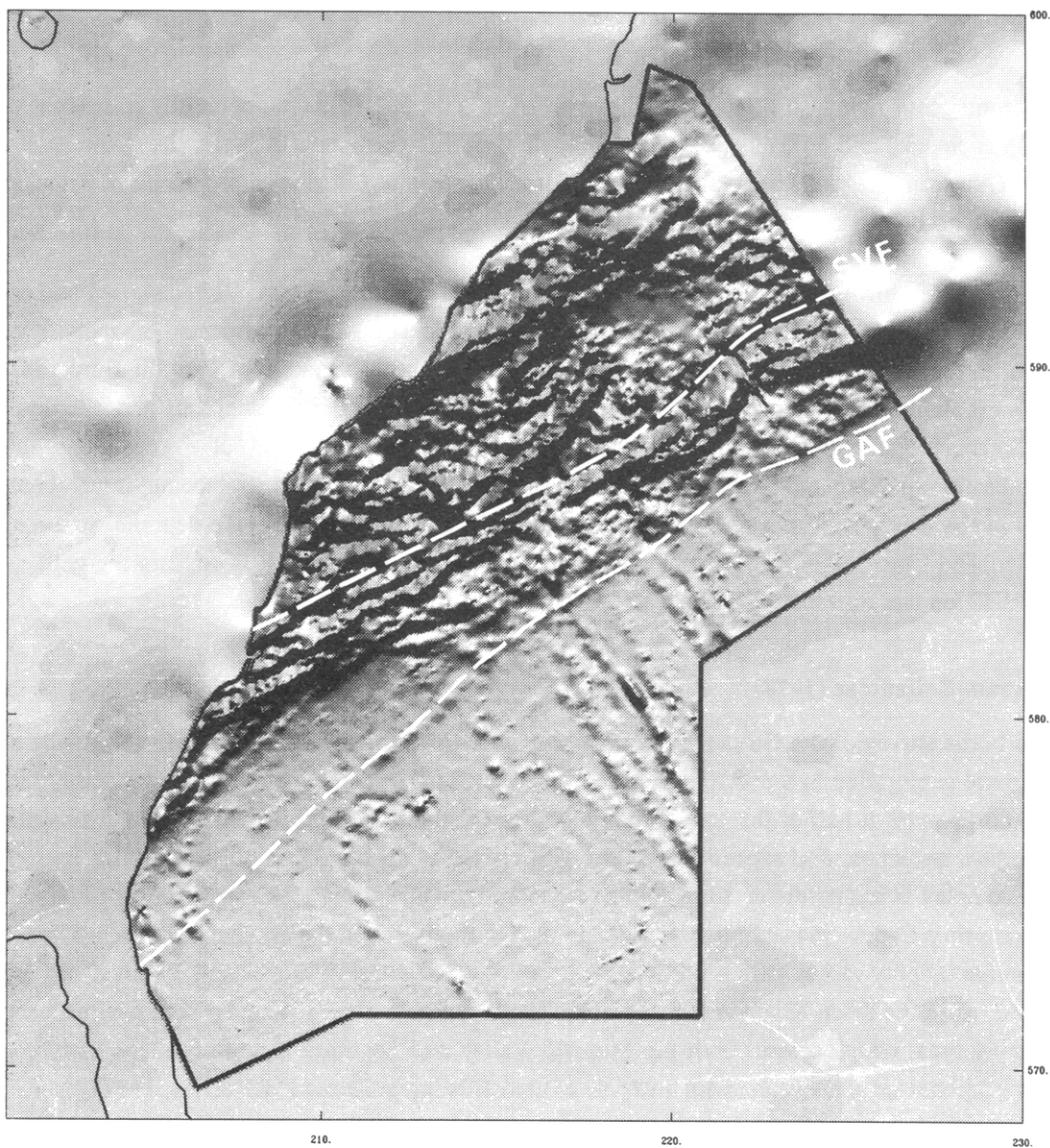


Figure 9 Aeromagnetic data from the Girvan-Ballantrae detailed survey superimposed on the national survey data. Grey-scale shaded-relief image illuminated from the north. SVF- Stinchar Valley Fault, GAF- Glen App Fault.

The VLF-EM survey data were not obviously helpful either in terms of indicating areas of mineral potential or for geological and structure mapping. This was attributed to the lack of distinctive electrical resistivity contrasts within the principal near-surface formations. The alignments observed were usually associated with topographic features. Similarly, data from the radiometric survey show most correlation to variations in topography and overburden (G S Kimbell, personal communication).

15 Blair Atholl, Perthshire (1974)

The Blair Atholl survey covers a rugged mountainous area in the southern Grampian Highlands of Scotland. Rocks of the late Precambrian–Cambrian Dalradian Supergroup make up most of the area.

The airborne survey was flown to investigate the mineral potential of the Middle Dalradian in the area from Blair Atholl to Glenshee. The principal target was strata-controlled base-metal and baryte mineralisation. Strong EM anomalies were found over the Ben Eagach Schist, often accompanied by negative magnetic anomalies. Initial ground follow-up was made in 14 areas in 1975 and most anomalies were attributed to graphite, with some associated pyrrhotite (Burley and Howard, 1976). Further MRP geophysical, geochemical and geological surveys in the 1980s revealed the presence of stratabound base-metal and baryte mineralisation (Coats et al., 1987).

Following the discovery of economic stratabound mineralisation around Aberfeldy there was considerable commercial interest in this area, and further airborne surveys were flown over the Middle Dalradian rocks of the Grampian Highlands in 1983 (see below).

AIRBORNE SURVEYS BY EXPLORATION COMPANIES

16 Middle Dalradian, Central Scotland (1983)

These surveys were flown in 1983 by Dighem Ltd for Fleethaven Ltd (a subsidiary of Exxon Minerals Company) under the Mineral Exploration Investment Grants Act 1972 (MEIGA). The target was stratabound mineralisation in the Middle Dalradian and followed MRP discoveries in the Aberfeldy area. Ten separate areas were flown, extending eastwards from the Dalradian rocks at Lochawe, along strike to Glenshee (area 16, Figure 2). Magnetics, VLF-EM and EM were recorded digitally and BGS holds copies of the processed contour maps (Table 1). The maps of enhanced magnetics and apparent resistivity have been digitised by the MRP. Some ground follow-up was done, but no economic deposits were found.

17 Aberdeenshire (1970)

This survey was flown in 1970 by Barringer Research Ltd for Exploration Ventures Ltd (EVL). Technical details are given in Table 1. The principal target was copper-nickel mineralisation in the ultrabasic masses. There are five contiguous areas with varying flight line directions, the coverage tailored closely to geology. BGS holds 1:25,000 scale maps showing position and type of EM anomalies and aeromagnetic contour maps at a scale of 1:25,000 which have been digitised by the BGS. Ground follow-up of anomalies was carried out by EVL in the early 1970s using a variety of geophysical and geochemical methods. Part of this work was made using funds from the MEIGA scheme. Some mineralisation was found, though not of ore grade.

CONCLUSIONS AND RECOMMENDATIONS

1. High-resolution airborne survey data held by the BGS provide detailed coverage of a total of 16,000 km² in 17 areas in Great Britain. These areas contain a wide range of geological environments and styles of mineralisation.
2. The survey results, acquired over a period of 40 years, remain of considerable value as they provide basic datasets which are available for re-interpretation.
3. In order to take advantage of state-of-the-art software, older analogue datasets have been converted to digital form. Where this has been done, important new information has been revealed which has proved to be of use in recent exploration initiatives.
4. The value of these datasets is enhanced when they can be examined and interpreted in combination with other digital datasets. The BGS now has an increasing number of digital datasets: regional geology; remotely-sensed imagery; boreholes and, for much of the country, the geochemical survey results from the MRP and G-BASE (formerly the Geochemical Survey Programme).
5. Aeromagnetic data have provided a great deal of new information on the geological structure of the areas flown allowing the precise tracing of magnetised rocks at sub-crop. This has proved particularly useful in areas of poor bedrock exposure and difficult access.
6. The EM data have been useful in areas where mineralisation is associated with conductive mudrock units and in the search for fault-controlled mineralisation; however, the value of the data has been reduced in many places by interference from man-made sources.
7. The radiometric data collected before 1974 is still in the form of flight line chart records and has not been converted to digital form. Where there is evidence that the radiometric signatures have geological sources, digitisation of the data may be merited for mineral exploration purposes.
8. Although flown principally for mineral exploration purposes, the surveys provide a substantial database for other applications where detailed information on geological structure or radiation levels is required.

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