Natural Environment Research Council
Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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An airborne geophysical survey of the Whin Sill between Haltwhistle and Scots' Gap, south Northumberland

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Mineral Reconnaissance Programme Reports

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SUMMARY

A detailed airborne geophysical survey was made of part of south Northumberland, at a flying height of 75 m with magnetic, electromagnetic (VLF-EM) and radiometric equipment mounted in a helicopter. The area of 440 km^2 covered by the survey includes the outcrop of the Whin Sill, its down-dip extension and the Haydon Bridge mining district. There was some indication from available data of a spatial relationship between magnetic anomalies, attributable to faulting in the Whin Sill, and some of the known mineral veins, as well as evidence from 'Landsat' imagery of a broader structural control to the distribution of the mineral occurrences of the area. Particular importance was therefore attached to the magnetic results and their structural interpretation.

Details are given of the equipment, survey procedure and map compilation based on information supplied by the geophysical contractor for the survey (Sander Geophysics Limited). General aspects of the interpretation of the magnetic and electromagnetic data are discussed, and detailed consideration is given to the principal features revealed by the magnetic data.

The aeromagnetic map shows a clear correlation between the distribution of anomalies and the mapped outcrops of the sill, and in drift-covered areas allows more accurate delineation of the subcrop of the sill. The magnetic data also indicate that the outcrop pattern consists of a series of linear segments and it is suggested that the form of the sill was controlled during intrusion by the pre-existing joint or fault system, as well as being extensively modified by later faulting. Linear magnetic anomalies occur over the down-dip extension of the sill though it is not clear if these are necessarily entirely due to faulting. In the Settlingstones Mine area the magnetic anomalies are clearly related spatially to the known veins and have been used to guide the search for vein extensions, while comparable anomalies elsewhere suggest new sites to be considered for detailed exploration.

The VLF and radiometric data provide little obvious additional information at this stage, but further more detailed interpretation is desirable.

All maps and data are available for inspection by arrangement with the Head of the Applied Geophysics Unit of IGS, Keyworth, Nottingham, NG12 5GG.

INTRODUCTION

An airborne geophysical survey of part of south Northumberland was carried out in September 1978, using the magnetic, VLF electromagnetic (VLF-EM) and radiometric methods. The location of the survey area is shown in Figure 1. The survey formed part of the Mineral Reconnaissance Programme being conducted by the Institute on behalf of the Department of Industry, and was preliminary to more detailed ground geophysical and geochemical surveys, begun in 1979.

The survey was carried out under contract to the Natural Environment Research Council by Sander Geophysics Limited, who were also responsible for reduction of the survey data and for presentation of the results in map form (with the exception of the radiometric data which remain in the form of digital and analogue records).

This report provides a description of the survey and an initial appraisal of the results. Detailed ground surveys — geophysical and geochemical — have subsequently been carried out, both within and beyond the area of the airborne survey, as part of a mineral reconnaissance of the Northumberland Basin, and the results of this work will be reported separately.

OBJECTIVES

A number of old mines and trials in the Lower Carboniferous of south Northumberland together constitute the northernmost of the Pennine-type orefields (Figure 2). The airborne geophysical survey was directed towards obtaining an improved structural interpretation of this area, much of which is drift-covered, to help identify further localities likely to be mineralised. In addition, it was hoped that any significant concealed sulphide mineralisation might be detected directly.

The Whin Sill underlies almost the whole of the survey area and much of the mineralisation worked in the past is clearly related to the Whin Sill and to structures within it. Since the Whin Sill has a significant magnetisation, the survey provided two methods for locating mineral concentrations: directly by the detection of conductivity anomalies with the VLF-EM equipment, and indirectly by detection with the magnetometer of magnetic anomalies due to structure and/or alteration in the Whin Sill. The latter approach offers an opportunity for locating mineralised bodies

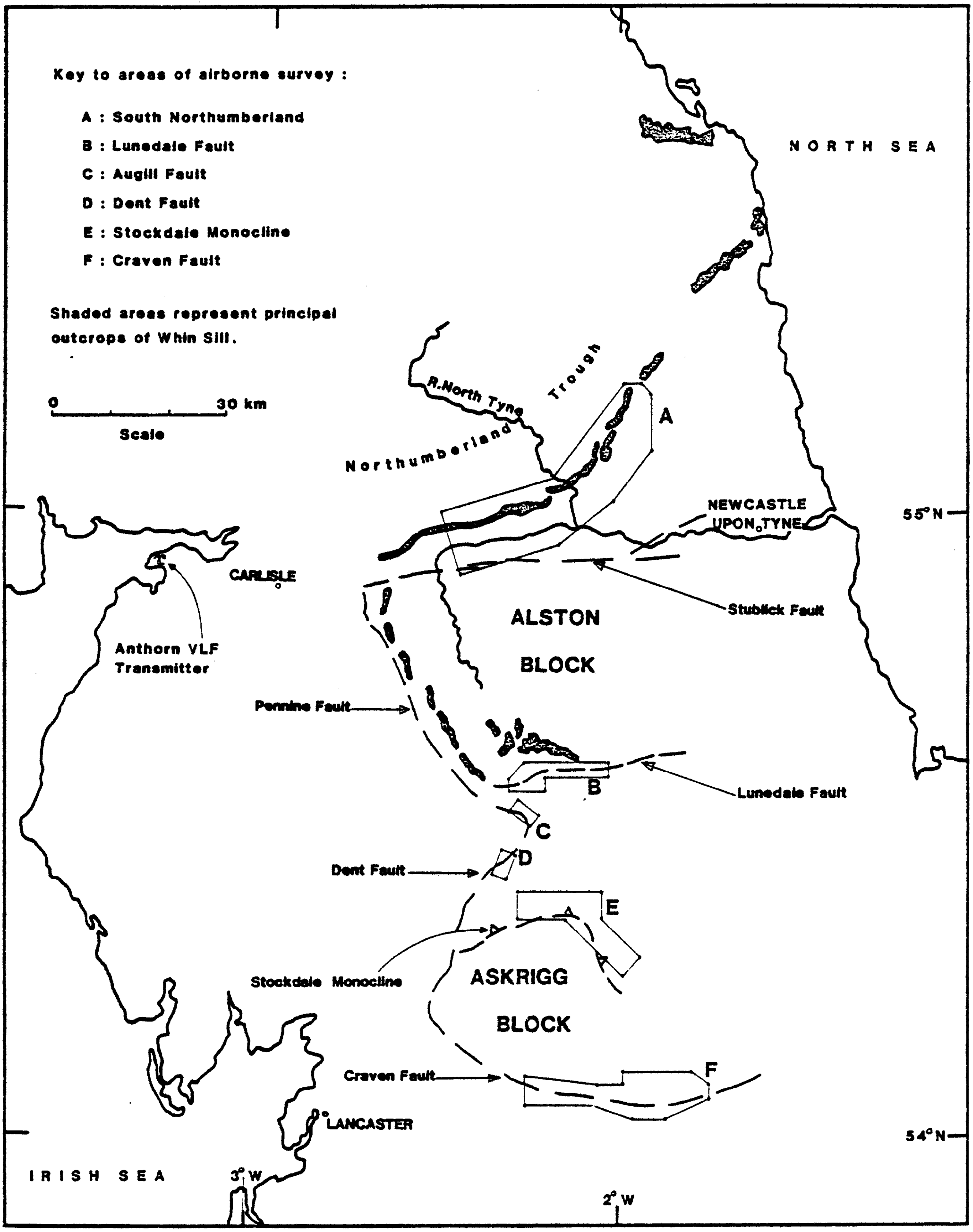


Fig. 1 : Principal elements of structure in the northern Pennines, and areas of airborne survey.

irrespective of their conductivity. This is useful for non-conductors such as barite and witherite, which have been mined in the area in the past, and sphalerite, which is a constituent of some of the known deposits. The VLF-EM method has been shown from the results of ground surveys at several sites in the Pennines to be a useful tool in mineral exploration.

The boundaries of the area for the airborne survey were selected to meet two principal criteria:

i To include all the significant known mineral occurrences north of the Stublick Fault, in the Whin Sill and adjacent strata.

ii To cover the area where existing geological data indicate that the Whin Sill occurs as a fairly continuous stratigraphic unit dipping relatively gently away from its outcrop. This condition is necessary since the Whin Sill, as well as apparently acting as a preferential host for mineralisation, should, because of its regular dip, provide a fairly uniform background magnetic field against which anomalies due to structures are well defined. To the west of the selected area the sill appears to dip beneath the overlying strata rather too rapidly, whilst to the north-east its occurrence appears to be sporadic.

A number of other factors supported the choice of survey area:

i Proximity to the southern margin of the Northumberland Trough offers a possible environment for the emplacement of Irish-type ore deposits. Similar basin margin areas on the flanks of the Pennine 'blocks' (Figure 1) have been investigated in previous years by means of airborne geophysical surveys (Cornwell and others, 1978; Cornwell and Wadge, 1980).

ii Inspection of 'Landsat' imagery of the area shows a pattern of lineations which suggested that, if they represent a fracture/joint system, then ore solutions might be expected to migrate towards an approximately triangular area extending north-east to east from an apex in the Haltwhistle area.

iii From an earlier airborne geophysical survey (Institute of Geological Sciences, 1972), flown at a height of 305 m, a weak magnetic 'high' had been identified which coincided with the principal mineral occurrences of the Haydon Bridge mining field (Figure 3). Before the present survey was carried out, several test traverses were made to determine the expression of this anomaly on the ground, and its relationship, if any, to the known mineralisation.

GEOLOGY

The Northumberland Trough is a tectonic downwarp with a Caledonoid trend in which some 2500 m of sediments accumulated during the Lower Carboniferous, the greater proportion being of Viséan age. The trough is bounded to the north and south by the stable areas of the Southern Uplands and the Alston Block respectively, the latter being submerged by the latest Viséan transgression whilst the former probably survived as a positive belt throughout the Carboniferous. Many authors have examined aspects of the Carboniferous of Northumberland, but Leeder (1974, a, b) has considered the development of the trough as an entity.

The area covered by the airborne survey lies on the southern margin of the trough, with the north-eastern part of the survey area extending some distance into the trough itself. The southern edge of the area just includes the Stublick Fault zone, which marks the northern boundary of the Alston Block (Figure 2).

The succession of Lower Carboniferous (Dinantian) sediments is most conveniently divided into five groups, of which the Lower Border Group, partly of Tournaisian age, is the oldest. This group shows a progressive change from generally non-marine beds to the east of Cheviot through a succession of algal limestones of a lagoonal sequence further south, to a more marine fossiliferous sequence in the west, as seen in the Bewcastle–Canonbie area where the group is some 500 m thick.

The succeeding Viséan sedimentation commenced with the deltaic–estuarine sands of the Middle Border Group, with a few local marine incursions, notably in the south-west. The overlying Upper Border Group, comprising mudstones and sandstones, with thin limestones and coals, contains only a restricted marine fauna. The Lower and Upper Liddesdale Groups which follow are represented by successive limestone–mudstone–sandstone units known as Yoredale cyclothems which indicate repeated marine transgressions into the area, followed by delta progradation during the periods of regression. The influx of terrigenous material from the north and east shows that the Southern Uplands massif was still a positive feature being actively eroded. Sedimentation continued, with a decreasing marine influence, in the Namurian and Westphalian. Outcrops of the latter are restricted to small isolated areas along the line of the Stublick Fault zone.

Within the airborne survey area the stratigraphy ranges from the top of the Lower Liddesdale Group (Asbian) near Barrasford to the Lower Coal Measures (Westphalian A) along the Stublick Fault. The strata of principal interest are the alternating sandstones, limestones and shales of the Upper Liddesdale Group (Brigantian). The reported mineral occurrences (Appendix 1) have each been wholly or partly worked within this group, with the exception of the Thornbrough deposit.

The sediments of the Northumberland Trough have been intruded by two principal groups of

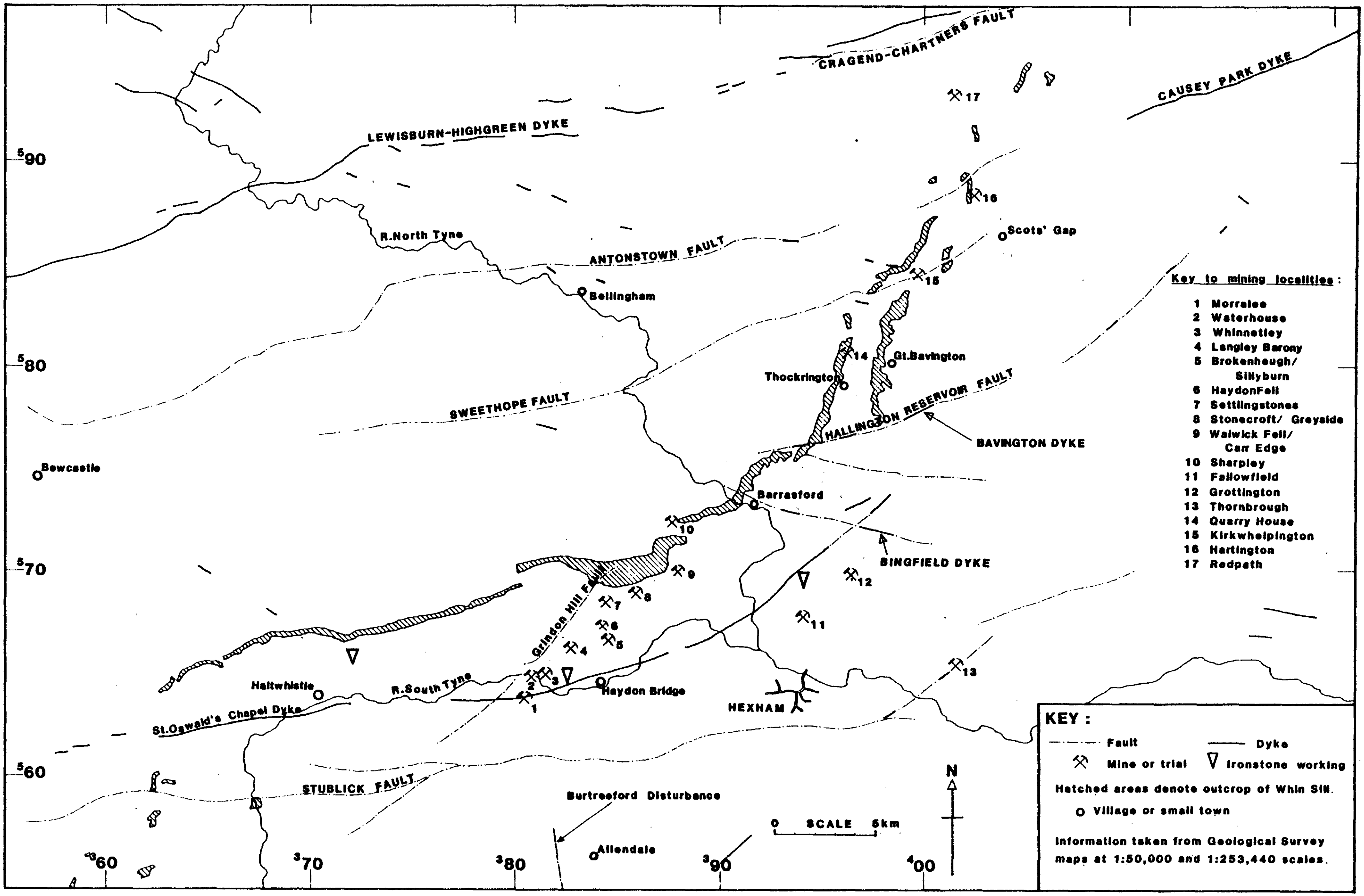


Fig 2 : Geology of part of the Northumberland Trough : Principal structures and intrusions.

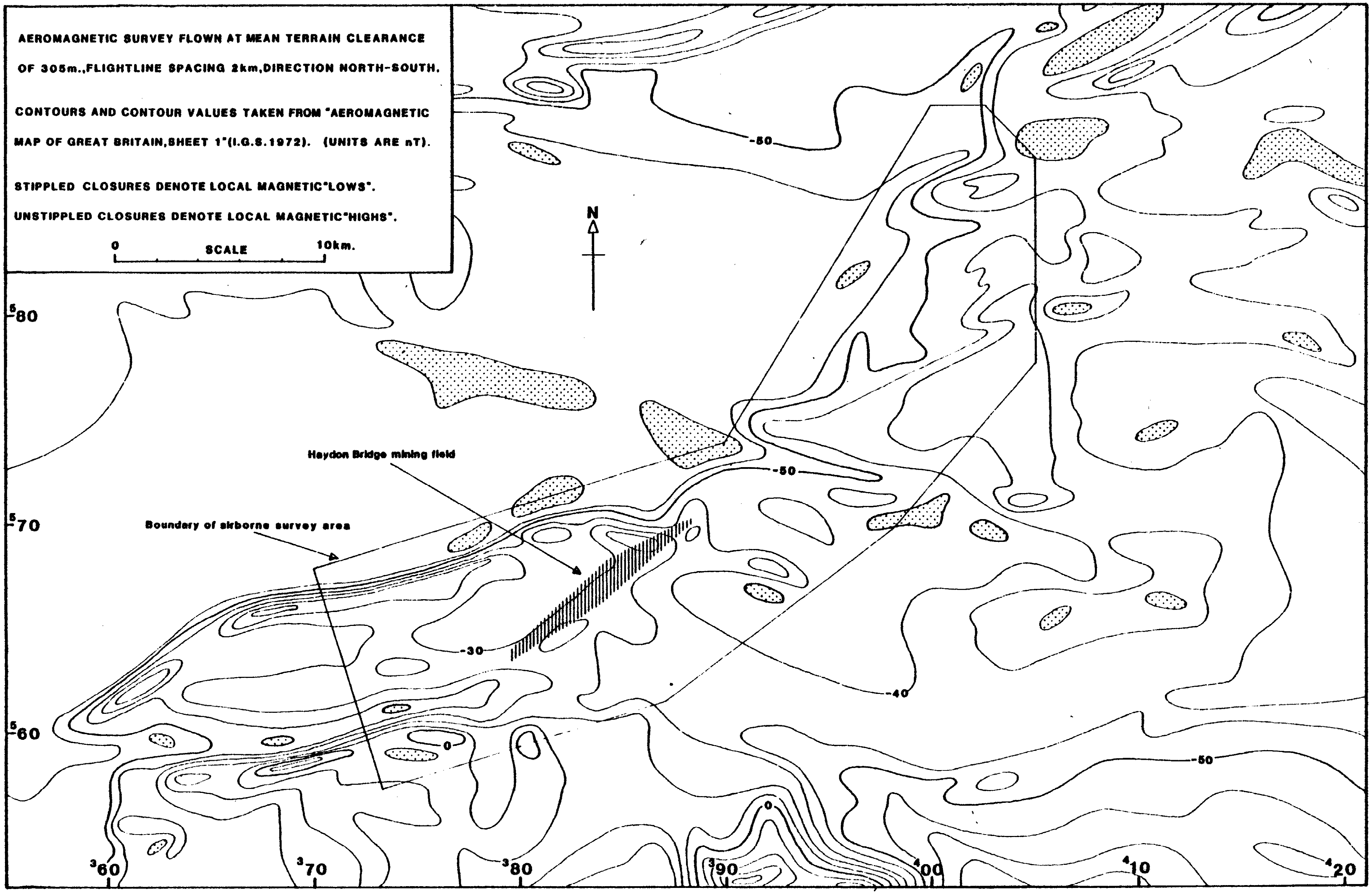


Fig.3 : Aeromagnetic map of part of the Northumberland Trough showing area of south Northumberland airborne survey.

igneous rocks, of late Carboniferous and Tertiary age respectively. The dolerite intrusives of the earlier group are the more extensive, being represented by the Whin Sill and a number of related dykes. The Whin Sill at outcrop is almost everywhere confined to the Upper Liddesdale Group, generally occupying a position towards the middle of the group. On a broad scale, notably within the area of the airborne survey, the sill appears conformable with the sedimentary succession, but on a local scale it shows numerous minor changes in stratigraphic level, some considerable changes in thickness (from a few metres to several tens of metres), and sporadically it occurs as a pair of superposed sills at different stratigraphic levels. In addition to the Whin Sill a number of Whin dykes are seen in the area, including two of considerable lateral extent, the St Oswald's Chapel and Lewisburn-High Green dykes (Figure 2). An age of approximately 295 m.y has been derived for the 'Whin' intrusions (Fitch and Miller, 1967).

Structurally the sediments show a reasonably consistent regional dip in a south-easterly direction, but within this overall pattern it is possible to identify two deformational events which occurred during post-Carboniferous, pre-Tertiary orogenic phases. The earlier gave rise to gentle folding of moderate amplitude along east-west axes related to a phase of south to north compression. It is possible that some of the movement along the north-east faults was initiated by the tensional phase which followed this compression. More intense folding in some areas, such as in the west around Bewcastle, occurred during a second phase of compression during which the resultant direction of pressure was normal to that of the earlier phase, producing folding about north-east–south-west axes. Tension faulting in a NNE direction succeeded this phase. Some of the faulting activated by the later movement was probably initiated in the very early development of the basin, when hinge lines associated with the accumulation of sediments developed as fault lines. The Stublick–Ninety Fathom Fault line is a major example of this.

The faulting in the area has played a significant role with respect to the mineralisation. All of the known major deposits, as well as some of the minor ones, are spatially related to faults. In some cases the fault planes themselves carry the mineralisation, whilst in others the 'open' nature of the faulting has allowed hydrothermal fluids access to the Whin dolerite. In the latter case the resulting altered dolerite, known as 'White Whin', provides a favourable host for mineralisation.

FORMER MINING

A number of mineral occurrences in the survey area have been exploited in the past, from small trials considered uneconomic for further development, to the major Settlingstones Mine (Trestrail, 1931) which produced some 17 000 tons of lead concentrates and approximately 550 000 tons of witherite between 1849 and its closure in 1969. Details of the mines and trials are tabulated in Appendix 1, and their locations are shown on Figure 2.

Sedimentary iron ores have been worked from ironstone horizons near Haltwhistle, near Haydon Bridge and north of Hexham (Figure 2). These appear to be unrelated to the lead–baryte mineralisation elsewhere and are not discussed further. Full details of these ores are given in Gibson and Sherlock (1920).

The mineral occurrences and mines listed in Appendix 1 have been described by Wilson and others (1922) and by Smith (1923), with the important Haydon Bridge mining field receiving more detailed attention from Dunham (1948). A number of general points are discussed below.

The bulk of the production came from two principal localities:

i the adjacent properties of the Langley Barony–Settlingstones–Stonecroft–Greyside mines.
ii the Fallowfield Mine.

Workings further afield to the south-west and north-east have been small developments and trials, probably yielding a total of only a few hundred tons of ore (statistics are incomplete). Production statistics for the Haydon Bridge mining field and for other fields in the northern Pennines have been compared by Dunham (1944).

A division of the known deposits can be made into those where the mineralisation occurs in, or is spatially closely related to, the Whin intrusives, and those where it is not. The latter group includes the Whinnetley, Waterhouse, Langley Barony and Fallowfield deposits, all of which occur at stratigraphically higher levels than the Whin Sill. In none of these was exploratory development extended down to the Whin Sill, as its depth posed technical problems which could not be resolved economically at the time. It is thus possible that all of the deposits listed have some relationship to the Whin Sill (with the exception of Redpath, where the mineralisation occurs stratigraphically below the level of the sill).

It is probably significant that those deposits which have been worked in, or are closely related to, the Whin intrusives (Figure 2, Nos. 1, 7, 8, 9, 10, 14, 15, 16) all lie less than 1 km from a straight line, 35 km long, aligned approximately 042°. The Langley Barony, Whinnetley and Waterhouse deposits, although having a different geologic setting, also lie on this line. This distribution strongly suggests that mineral deposition was related to a major linear zone of fracturing, and this view is supported by evidence from 'Landsat' imagery, which indicates a major lineament close to the line of mineral occurrences.

Galena and *witherite* were the principal ore minerals mined in the area, each of the known mines having been worked for one or both of these. The *silver* content of the galena justified its extraction, varying from around 2.5 oz per ton of lead in the Langley Barony, Settlingstones and Stonecroft–Greyside mines to 4 oz/ton at Fallowfield and 7 oz/ton at Morralee and Waterhouse. Collins (1972) provides a number of references to the witherite–baryte production.

Sphalerite has never been produced from any of the mines in the survey area, in contrast to the mines of the Alston field to the south. Its occurrence was reported only from Settlingstones, Langley Barony and Stonecroft–Greyside and then only in small quantities. At Langley Barony and Stonecroft–Greyside the sphalerite was intimately mixed with the barytes and difficulty in gravity separation of the two minerals resulted in the low barytes recoveries from these two mines.

Pyrite, together with quartz, accompanies the galena at the Quarry House mine.

Copper minerals are unknown in the area.

Available evidence suggests that the known oreshoots at each of the mines in the area are exhausted, with the exception of that at the Fallowfield Mine where there was reported (Dunham, 1948) to be no impoverishment of the grade of ore in the deepest levels. Trials were invariably made at all the mines to test any immediate extension of the known oreshoots both along strike and in depth, though exploration was usually insufficient to eliminate entirely the possible reappearance of the veins and was often hampered by drainage and ventilation difficulties. For example, the ground between the south-western limit of the Settlingstones workings and the north-eastern limit of the Langley Barony workings, although having some features favourable to mineralisation, appears not to have been thoroughly tested. Also untested is the possibility that mineralisation is present at depth beneath the Langley Barony workings (and adjacent mines to the south-west) at the favoured horizon of the Whin Sill, though development would demand deepening of the existing shafts (if accessible) by as much as 150 m.

AIRBORNE SURVEY EQUIPMENT AND PREPARATION OF MAPS

The airborne geophysical survey of the south Northumberland area was carried out on contract by Sander Geophysics Limited. Most of the equipment had been developed by the same firm and was installed in an Alouette II helicopter.

The area of 440 km^2 covered by the survey is shown in Figure 4, with the National Grid co-ordinates of the points which define the area. A total of 1939 km of survey line was flown. The western and central parts of the area were covered by flight lines aligned 340°, but this was changed to 315° for the north-eastern part. The form of the survey area was determined by the criteria given above, with the flight line direction being chosen so as to be appropriate to as great a proportion as possible of the known structural trends. The flying height of the helicopter was 75 ± 20 m throughout the area, at a line spacing of 250 m.

The following description of the survey equipment is based mainly on the report prepared by Sander Geophysics Limited (Broome, 1979), and photographs illustrating the installation of the equipment are published elsewhere (Institute of Geological Sciences, 1979, p. 82).

MAGNETOMETER

The total magnetic field intensity was measured with a Sander NPM-5 high resolution proton precession magnetometer with a quoted accuracy and resolution of 0.1 nT. Measurements were made at 1 s intervals and the data recorded digitally, along with data from the other equipment, at this interval. The precession head and preamplifier were carried in a small bird towed about 20 m below the helicopter.

A second NPM-5 magnetometer with a chart recorder was used as a base station and the results synchronised with the airborne magnetometer through the use of crystal clocks. With this system diurnal variations in the magnetic field could be corrected for on the airborne magnetometer record.

VLF EQUIPMENT

The Sander VLF-EM II equipment used for the surveys had three orthogonal receiver coils mounted on a boom outside on the skid of the helicopter. The three coils allow the determination of the entire ellipsoid of polarisation of the EM field emanating from the selected radio transmitter. As the signal strength depends upon the orientation of the coils, the attitude of the helicopter in the air during surveying was monitored with a vertical gyro and corrections applied during data processing.

Four channels of information were recorded:

- H_1 signal amplitude recorded by the maximum-coupled coil.
- H_2 signal amplitude recorded by the minimum-coupled coil.
- V_{IP} signal amplitude of the in-phase component recorded by the vertical coil and compared with H_1.
- V_{OP} signal amplitude of the out-of-phase component recorded by the vertical coil, again compared with H_1.

These four channels of information, together with two channels for the gyro, were recorded

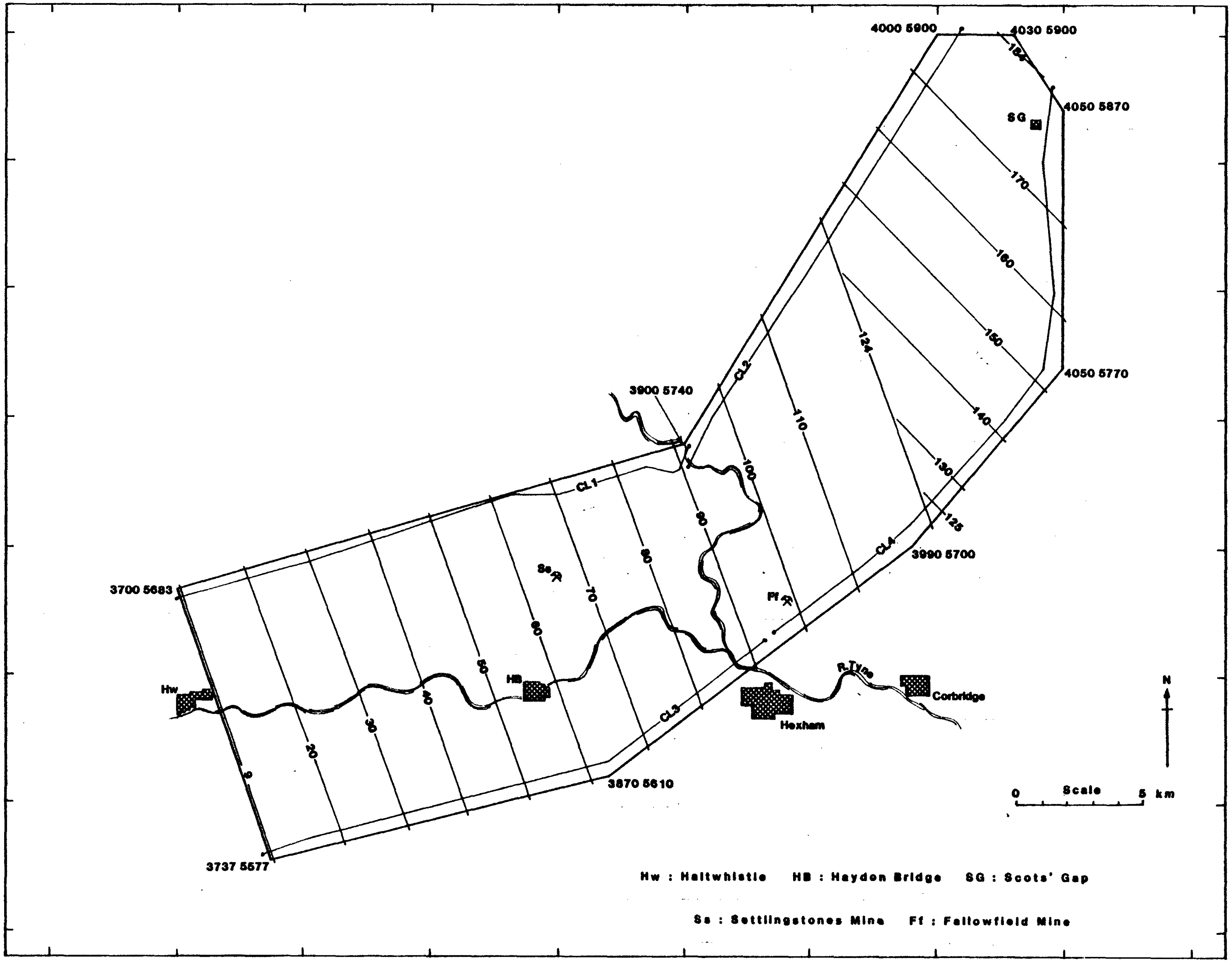


Fig.4 : South Northumberland airborne survey - area boundary, position and orientation of flightlines and control lines.

digitally every 1 s.

The VLF radio transmitter at Anthorn (GQD), operating at 19.0 kHz, was used. Situated 22 km west of Carlisle (Figure 1), this transmitter is almost ideally located relative to a flight line direction perpendicular to the main strike direction of the Whin Sill in the south Northumberland area, but will produce little response from conductors aligned about a north to south direction.

The direction of the transmitter, relative to that of the flight lines, varies between 90° and, in the north of the survey area, 55°. As the transmitter lies only 52 km SSW of the western end of the south Northumberland area its field strength is high. It varies significantly within the survey area, although this effect is removed by the data processing procedure.

GAMMA SPECTROMETER

The Sander SPM-12 gamma-ray spectrometer was connected to two 9 inch by 4 inch cylindrical NaI(T1) crystals (with a total volume of 500 cubic inches). The crystals were kept in thermostatically controlled containers mounted on the floor of the helicopter. The signals from each of the 128 channels were processed using a fast analogue-to-digital recorder and the energy divided into the following windows:

Recording window	Energy width MeV
K	1.31–1.61
U	1.62–1.94
Th	2.47–2.97

Before each day's flying the calibration of the equipment was tested by presenting an artificial source to each of the two detectors and recording the response on each of the four recording windows (total count, K, U and Th). The medium channel on the thorium energy peak was also checked.

ADDITIONAL EQUIPMENT

The altitude of the helicopter was recorded by two radar altimeters, a Honeywell HG 7605 4403 and a Bonzer, and the output of the latter was recorded digitally.

A Sander CM3-12 16 mm tracking camera produced continuous coverage of the flight path for subsequent plotting on 1:10 560 scale maps.

All the survey data were recorded in analogue and digital form. For the digital data a Sander ADR-11 data acquisition system recorded onto standard cassette tape at 800 b.p.i. in a special code. Analogue records were made from the digital data after each flight using a tape reader and a Brush chart recorder, but for in-flight data checks a Century 444 light-spot galvanometer recorder was used to produce small-scale analogue records.

DATA PROCESSING

The channels used in the digital recorder, all with a 1 s sampling rate, were as follows:

Channel	*Type of data*	*Chart*
1	Magnetometer (high sensitivity)	1
2	Fiducials	1 & 2
3	Time in seconds	–
4	Time in hours	–
5	Magnetometer (low sensitivity)	–
6	Total count	2
7	Potassium	2
8	Uranium	2
9	Thorium	2
10	Radar Altimeter	2
11	Pitch	1
12	Roll	2
13	H_1 (VLF horizontal component 1)	1
14	H_2 (VLF horizontal component 2)	1
15	V_{IP} (VLF vertical in-phase)	1
16	V_{OP} (VLF vertical out-of-phase)	1

These data were used to produce the analogue records in the form of sets of profiles on two separate charts (1 and 2 above).

The data were transferred to standard nine-track tapes and digitised information on the location of the flight path added to a map file for subsequent processing.

The magnetometer results were corrected for diurnal variations and an overall correction for secular variation made of -750 nT for the south Northumberland area. This value was based on observed changes since 1955.5 in the regional geomagnetic field recorded at geomagnetic observatories. The magnetic field readings were corrected for differences in values at intersections of flight lines and tie lines. Finally the residual magnetic field values were calculated by removing a normal geomagnetic field, similar to that applied to the national aeromagnetic survey (Institute of Geological Sciences, 1972), defined by a linear field equation which implies a regional field increase northwards of 2.1728 nT/km and westwards of 0.259 nT/km and a datum value of 47033 nT at the National Grid origin (epoch 1955.5). The final magnetic field maps were produced by computer from values at a grid of points with an interval of 0.1 inch (2.54 mm). The values at points between flight lines were estimated using a cubic spline.

Processing of the VLF data involved applying corrections for the attitude of the helicopter and variation in the strength of the EM field of the VLF transmitter. The vertical gyro mounted in the helicopter provided information for the first correction while the strength of the VLF field was estimated by averaging the values along a flight line. This normal field strength is represented as 100% on the horizontal intensity maps.

DATA PRESENTATION

The geophysical data for the south Northumberland area were presented by the contractor as three sets of maps at a scale of 1:10 560 showing (a) total magnetic field anomaly contours, (b) contours of the normalised intensity of the horizontal component of the VLF field, and (c) stacked profiles of the normalised in-phase and out-of-phase values of the vertical component of the VLF field. The two modes of presentation of the related VLF data were chosen to provide maps giving both a good regional picture of the conductor distribution and the detailed information available in the stacked profile form.

The original 1:10 560 scale maps (*see* Plate 1 for key) were superimposed on a subdued topographic base. Photographic reductions of the maps have been made to scale of 1:25 000 and 1:50 000. The radiometric data are in the form of analogue records only.

All data and maps are deposited with the Applied Geophysics Unit of IGS, and are available for inspection by arrangement with the Head of Unit. Dyeline copies of all the maps are available.

RESULTS

The magnetic results are presented in Plate 1. This is a compilation at 1:50 000 scale of the photo-reductions of the individual magnetic anomaly maps supplied by the contractor. Plate 1 shows a large number of anomalies; the more prominent are in most cases of geological origin and many of these are considered structurally significant. A general, largely qualitative interpretation was made of the magnetic map, and this is presented in map form as Plate 3.

The VLF-EM results are presented in Plate 2. This is a compilation, as for Plate 1, and shows the variation of the horizontal VLF field intensity. Artificial and topographic effects contribute to the anomaly pattern and significant anomalies of geological origin are not readily discernible; a broad interpretation of the VLF map has not been attempted.

The radiometric data were inspected during the course of the survey, but no significant anomalies were evident. A more detailed treatment of the data would be desirable.

General aspects of the interpretation of the magnetic and VLF data are considered below, followed by detailed discussion of specific features seen on Plates 1 and 2.

MAGNETIC INTERPRETATION: GENERAL

MAGNETISATION OF THE IGNEOUS ROCKS

Within the survey area the only magnetic rocks known at surface are the Whin Sill and Whin dykes of late Carboniferous age, and a second group of dykes of Tertiary age. There is no indication from the aeromagnetic map of Great Britain (Institute of Geological Sciences, 1972) of the presence of older magnetic rocks, except at considerable depth, and the gradient of the regional magnetic field is low. Interpretation of the magnetic data from the present survey can therefore be made in most cases in terms of the properties of the Whin Sill alone, with allowances where appropriate for the effect of dykes, Tertiary or Whin, which occur along certain of the structures affecting the Whin Sill.

The Whin Sill and the dykes of both Whin and Tertiary ages are characterised by strong remanent magnetisations which are greater in intensity than the magnetisation induced by the present geomagnetic field. The magnetic anomalies of these intrusions therefore have characteristics determined largely by the direction and intensity of the remanent magnetisation.

Using data on the remanent magnetisation and susceptibility by Creer and others (1959), Cornwell and Wadge (1980) estimated a total magnetisation for the Whin Sill of 2.3×10^{-3} emu with a direction of 185° (declination, measured from geographical north), 4° inclination downwards. This assumes that the sill was horizontal when it acquired its magnetisation; the present total magnetisation for the intrusion at any given site can be determined from the amount of subsequent movement. This is illustrated by Figure 6, which shows both the intensity and inclination of the total magnetisation for east to west striking portions of the sill as functions of the post-magnetisation dip of the intrusion, in a north to south plane. For example, in the western part of the south Northumberland area, where the sill has an easterly strike and a dip to the south of about 10°, the total magnetisation will have an intensity of 2.5×10^{-3} emu and an inclination of +15° (measured from south).

In the eastern part of the survey area the strike of the Whin Sill approaches north-to-south. Here the magnetic anomaly at the outcrop of the sill will be comparatively weak because the vertical components of the induced and remanent magnetisation vectors are anti-parallel and roughly of the same intensity, while the horizontal components are parallel with the strike of the sill.

The magnetisation of the Whin Sill is due to magnetite and it is estimated that about 1% (vol.) is necessary to give rise to the observed susceptibility of about 2×10^{-3} emu. Like (1966) has examined the magnetic properties and crystal lattice parameters of magnetite from the Whin Sill and found it exists in a form fairly close to pure Fe_3O_4. Dunham (1970), however, notes that the Whin dolerite contains 7% iron-titanium oxides, with the magnetite in solid solution with titanium minerals.

Remanent magnetisation also plays a major part in determining the direction and intensity of the total magnetisation of Tertiary dykes, examples of which occur within the south Northumberland survey area. Nearly all the Tertiary dykes in the British Isles seem to have been formed when the geomagnetic field had a polarity opposite to that existing at the present time. The strong 'reverse' remanent magnetisation retained by these dykes results in the formation of negative magnetic anomalies. Bruckshaw and Robertson (1949) carried out ground magnetic surveys over Tertiary tholeiite dykes in the north of England and also made measurements on dyke samples of the magnetic susceptibility and remanent magnetisation. The susceptibility values vary between 1 and 3×10^{-3} emu (i.e. similar to the Whin Sill) while the remanence intensity shows a greater variation of between 1 and more than 10×10^{-3} emu. The Q-values (the ratio between the remanent and the induced magnetisation) therefore also show a large variation but are nearly all greater than 1. The direction of the remanence was found to be almost opposite in direction to that of the present geomagnetic field and it would then be expected that the magnetic anomalies due to dykes with these magnetic properties would be negative. However, in the case where the Q-value is 1, the anti-parallel remanence and induced magnetisation vectors will cancel and it is possible that no magnetic anomaly will occur over the dyke. Bruckshaw and Robertson (1949) also noted that the samples from the margins of the dykes exhibited higher Q-values than those from the central portions.

One of the Tertiary dykes – the Acklington Dyke (Figure 9) – has been traced over a distance of 24 km in north-west Northumberland using a magnetometer (Robson, 1964). The dyke produces anomalies up to 700 nT in amplitude and although the anomalies are mostly negative, some traverses revealed positive anomalies or no magnetic field variation at all. It was concluded that the variable magnetic response was due to differing weathering characteristics, although the same effect could be produced by variation in the Q-values of the dyke rocks. It was also concluded from an examination of the course of the dyke revealed by the survey that the dyke had been interrupted by nearly all the faults crossing its path, particularly those trending to the north-east. Robson (1964) preferred this explanation of the displacement of the dyke to that involving the deflection along faults during the intrusion of the dyke.

MAGNETIC DATA

The magnetic data obtained from the survey area are of good quality. It was evident from the paper chart records, checked during the course of the survey, that the magnetic noise level was generally very low. The automated system for the reduction and contouring of data has provided maps of reasonable clarity, which are suitable for immediate use. There are some minor shortcomings in the automated contouring system and these are discussed below.

The magnetic data are contoured at an interval of 4 nT. Because of the low noise level, some significance can be attached to even the weakest features – anomalies of as little as 10 nT – particularly where these have some linear persistence. Indeed, if the magnetic contour map is 'simplified' by increasing the contour interval to 20 nT, then a large proportion of the significant new information seen in Plate 1 is lost. The strongest anomalies are recorded over the Whin Sill outcrop in the western part of the area, these being commonly of around 200 nT amplitude, locally reaching almost 400 nT. Anomalies with these amplitudes are consistent with the intensity of magnetisation obtained as shown in Figure 6.

As a means of mapping the extent and form of the igneous rocks, the magnetic data can be viewed with some confidence since most of the previously known structures are seen to have some magnetic expression closely corresponding with their positions on the ground. In particular, a number of structures mapped over only limited areas, because of drift cover, can be confidently extended for distances of up to several kilometres using the magnetic data. Conversely, there are a few instances in which conjecturally mapped features can be shown to be probably in error on the basis of the magnetic anomalies (or their absence).

As well as providing information which confirms or amends the locations of the known geological structures, and extensions to them, several magnetic features indicate the presence of geological structures and features whose existence was uncertain or unsuspected, and these are discussed below.

Many artificial anomalies are evident on the magnetic contour map. The majority of these occur over farms and can be attributed to silos and steel-framed or iron-clad barns. They generally occur only on single flight lines and are of short wavelength. Fortunately in most cases they do not interrupt any real anomalies. The remaining artificial anomalies can also be readily identified as such, because they occur over road or railway bridges, or sites of industrial activity. It was necessary to check only two artificial anomalies on the ground because the 1:10 560 scale map gave no indication of their causes – these were found to be a recently laid gas pipeline and machinery at a recently developed sand and gravel working.

The automated contouring system used by the contractor to compile the magnetic maps from the processed data has resulted in a few instances of anomalies on separate flight lines being contoured together when they are probably unrelated. This arises because the automation is based on the assumption that the flight lines will have been oriented normal to the direction of geological features and that the data should therefore be contoured to give preference to trends normal to

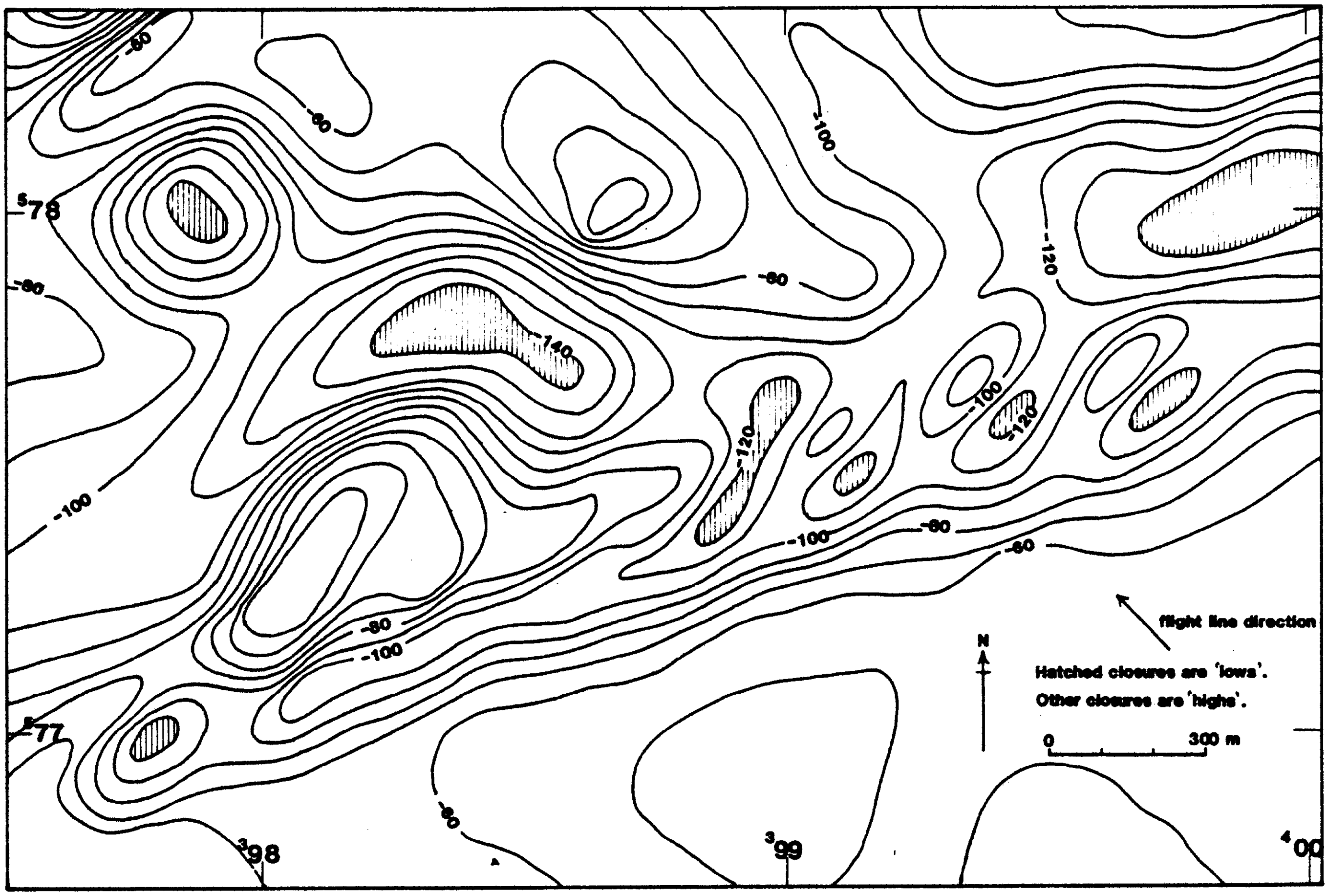


Fig.5a : Airborne magnetic anomalies over part of the Bavington Dyke - machine-drawn contours at 10nT intervals.

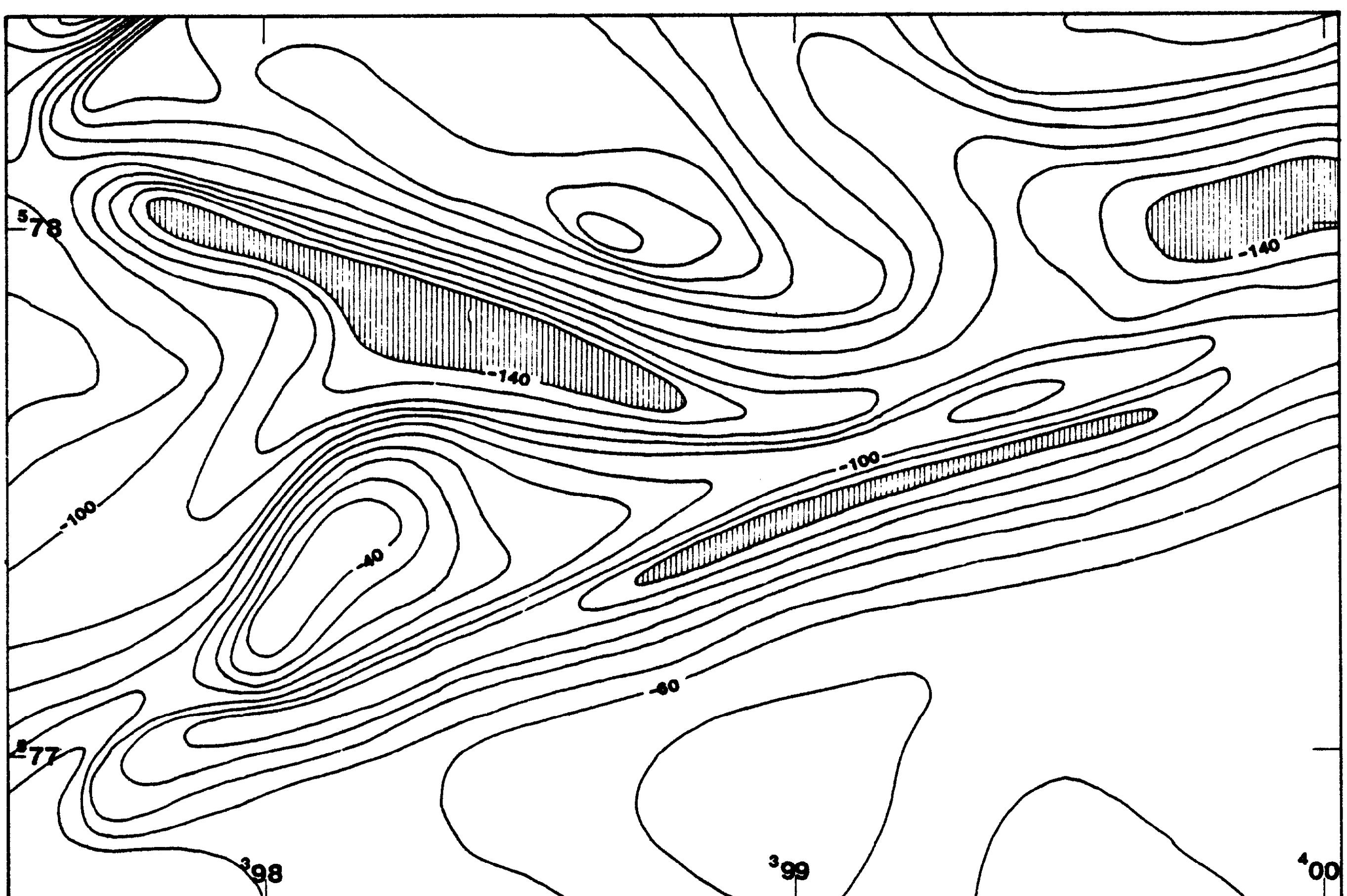
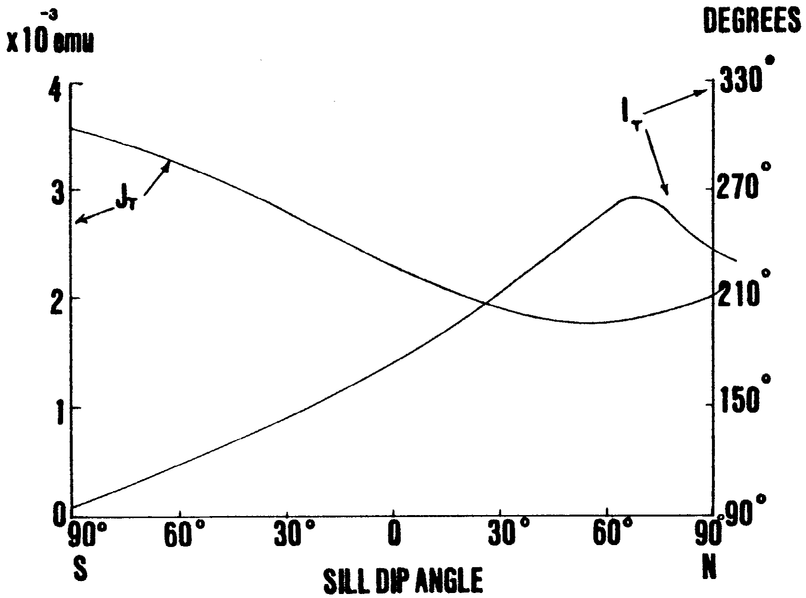


Fig.5b : As Fig.5a - manually-drawn contours.



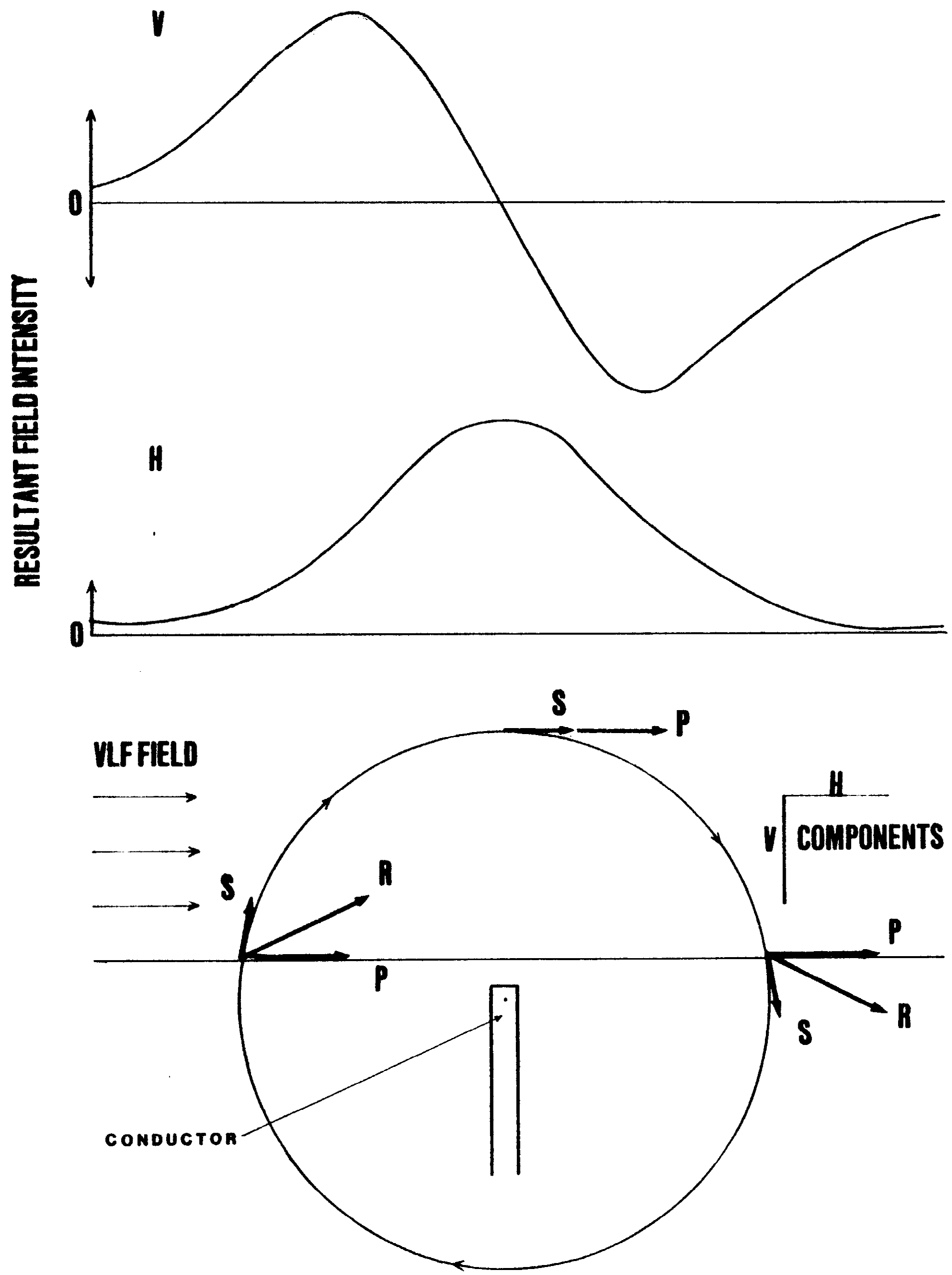


Fig. 6 (above): Diagram illustrating the variation of intensity (J_T) and inclination (I_T) of the total magnetisation of the Whin Sill for various dip angles between 90°N and 90°S. The sill is taken to strike east-west and to have a susceptibility of 2×10^{-3} emu, a mean remanence of 184°(D),-15°(I) and 2.7×10^{-3} emu intensity (J_T). The angle of inclination (I_T) varies between 90° (vertically downwards, measured from the horizontal north direction) to more than 270° (vertically upwards).

Fig. 7 (right): Diagram illustrating the variation of the horizontal (H) and vertical (V) components of the field intensity over a conductor. The resultant (R) is formed from the constant primary VLF field (P) and a variable secondary field (S) produced by secondary current flow in the conductor as shown in the lower diagram.

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MINERAL RECONNAISSANCE PROGRAMME REPORTS

Herewith reports nos. 47 and 48. Copies of these reports will be placed on Open File here and at other IGS offices on Monday, 14th December, 9181.

Catherine Collingborn

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pp. D. Ostle. Programme Manager

the flight lines. A good example of this occurs over the Bavington Dyke and is illustrated in Figure 5a. Here the geological feature trends at 070°, yet the contouring has been arranged to give a series of isolated highs and lows oriented at 90° to the flight line direction of 045°. Keeping the contour line–flight line intersections the same, the contours can be re-drawn to produce the more realistic pattern shown (Figure 5b). Several other similar examples are to be found. In most instances, as with the example given, the true trend of the anomaly is readily apparent.

There are a few examples on the maps of contour closures which occur between flight lines. These occur because the contouring programme uses magnetic field values on a square grid, and between lines these values can only be interpolated.

Overall, the choice of flight line direction has been justified by the marked linear pattern of anomalies and the distribution of preferred anomaly trends, the incidence of anomalies aligned between N–S and NW–SE being very low.

GEOLOGICAL CONSIDERATIONS

It is considered reasonable to assume, for the purposes of interpretation, that large-scale changes in the magnetic properties of the Whin Sill do not occur within the area, and that the airborne magnetic anomalies therefore represent, for example, faulting, folding, transgression or changes in thickness of the sill. The linear trends of many of the anomalies can therefore be regarded as an expression of the significant structural features affecting the rocks within the area. Thus there is evidence from the magnetic map of, amongst other features, an extensive system of linear structures throughout the survey area which not only are evident in the Whin Sill where it is concealed, but also strongly influence the magnetic pattern at the sill outcrop. Of the latter, there is evidence of such features both along the line of the outcrop, and extending down dip from displacements of the outcrop.

The dominant structural trends indicated by the magnetic data are aligned between 090° and 110°, and between 080° and 065°. There is a smaller number of anomalies with trends approaching NE, and progressively fewer with more northerly trends. No anomalies of note have trends between NNE and NNW. The pattern is completed with a few anomalies with trends between NNW and NW. This distribution of anomaly trends is in close agreement with the distribution of the trends of faults and folds in the Bellingham district (Frost and Holliday, 1980).

Quantitative interpretation of the airborne magnetic data needs, for simplicity, to assume the Whin Sill to exist as a single sill, generally conformable with the adjacent strata (so that its dip may be inferred from the dip of the strata seen above it at surface), and not changing significantly in thickness other than over long distances. While these conditions can reasonably be expected to apply, at least approximately, over much of the area, there are probably instances of more complex situations. For example, the Whin Sill is recorded as being 68 m thick in the Carr Edge West shaft [880 700] *, only a little less than its maximum known thickness (at sites in Weardale and Teesdale) of around 73 m, yet within a kilometre of the shaft to the east the sill appears to pinch out completely, to be replaced by a thinner sill at a lower stratigraphic level, possibly with some overlap between the two sills. The possibility of superposed sills is apparent elsewhere, though even in the Thockrington/Great Bavington area (Figure 2), where there is good evidence of a pair of sills occupying different stratigraphic levels over a considerable strike distance, there is in fact no information as to the extent to which the sills persist as a pair down dip of outcrop.

Minor departures from the ideal setting of the sill as a uniform unit are described by Randall (1959), though the small scale of the features referred to would preclude their being resolved by the airborne magnetic data. Similarly, local, possibly tropical, deep weathering of the sill, reported in the Roman Wall area by Hornung and Hatton (1974) would probably also be undetectable by the airborne survey.

VLF-EM INTERPRETATION: GENERAL

The VLF-EM method utilises the signal emitted by radio transmitters in the range 15.0–25.0 kHz. The magnetic component of the EM signal is polarised cylindrically about the transmitting antenna parallel to the ground surface. Secondary fields are produced by currents formed in electrical conductors in the ground and the resultant is the field measured with VLF equipment on or above ground level. Most VLF anomalies appear to be caused by current flow in the ground and can be used to trace this flow over large horizontal and even vertical distances. The method is particularly sensitive to large conductive structures, such as faults, and does not have the selective response to smaller, highly conductive structures which is a characteristic feature of EM methods using a moving transmitter.

VLF anomalies are usually measured with ground equipment by recording the in-phase component and out-of-phase component of the resultant field. With the VLF system used for this airborne survey the in-phase and out-of-phase components of the vertical field and the intensity of the total horizontal component of the magnetic

*National Grid References are given in this form throughout. Figures with eastings between 700 and 999 relate to places in 100 km square NY (or 35), those with eastings between 000 and 050 to places in 100 km square NZ (or 45).

field were estimated from recordings made with the orthogonal coil system. The relationship between these measurements is that the horizontal field intensity should reach a maximum at the same point as the vertical field intensity passes through the 'normal' value when changing from a maximum to a minimum value directly over the conductor (the 'crossover' – Figure 7).

The interpretation of the airborne VLF results is basically the same as that for ground measurements and estimates of the dip and depth of conductors can be made using published material (e.g. Baker and Myers, 1979).

One of the advantages of the VLF method over most other airborne EM methods available is that the signal decreases less rapidly with height, allowing the survey helicopter or aircraft to fly further away from the ground. A VLF survey, however, often produces numerous anomalies, and interpretation of these can be difficult, particularly if the geological control is not good. In the south Northumberland area, however, recent mapping and a relatively simple geological structure were considered to provide fairly good geological control.

The depth of penetration using the VLF method is set by the 'skin depth' (δ):

$\delta = \sqrt{2\rho/\omega\mu}$

where ρ is the ground resistivity (ohm metres), ω the frequency (19 kHz for the south Northumberland survey) and μ the magnetic permeability of the ground. There are no measurements of ground resistivity available for the survey area but estimated values and the corresponding skin depths are as follows:

	Resistivity (ohm metres)	Skin depth (metres)
Shales	50	26
Sandstones and drift	100	37
Limestones	1000	115

These estimates suggest that unless exceptionally thick drift occurs (more than say 20 m) the VLF map should reflect changes in the bedrock. However, the resistivity contrast between the shales and limestones is itself large enough to give rise to VLF anomalies close to boundaries between the two lithologies.

The earth itself is always conductive to a certain degree and is, therefore, capable of producing VLF anomalies over topographic features (Whittles, 1969). A typical effect is the production of a 'crossover' in the vertical component or a maximum in the horizontal intensity over the top of a hill. Steep sided valleys are indicated on some of the airborne VLF maps by pronounced 'lows' in the horizontal intensity. Topographic effects, however, can often be recognised on the VLF maps by an obvious correlation with a topographic feature or the wavelength of the anomalies, which will be greater than those of anomalies due to variations in the bedrock resistivity. A quantitative method of estimating the terrain effect on VLF observations is described by Karous (1979).

MAGNETIC INTERPRETATION: DETAILS

The magnetic anomaly map is shown in Plate 1, and in Plate 3 a summary of the interpretation of this map is presented. The magnetic interpretation map (Plate 3) shows the more readily identifiable magnetic anomalies and includes relevant geological information, notably the outcrops of igneous intrusions, all of the faults recorded on the 1:50 000 scale maps, and all the known mineral occurrences. Although more detailed ground magnetic surveys have been made in certain areas, the information in Plate 3 is based largely on the airborne survey results. Where appropriate, brief reference is made to certain ground survey results, but these will be described in detail in a later report. It is likely that a more complete, combined interpretation of the airborne and ground survey data would suggest some modification to the information on the interpretation map.

The main features of interest in Plate 1 are the many magnetic linear features, and, less commonly, anomalies indicating shallow extensions of outcropping igneous material and other concealed intrusions. The origin of the linear features is not clear since faulting in the Whin Sill, transgression of the sill from one horizon to another along joint planes, or the appearance or disappearance of a second sill can all produce similar magnetic effects with a linear pattern. (For convenience, however, the origin of the linear features will be described as faults in this report, although this does not imply that the structures have a significant throw.) Nevertheless, several of the linear magnetic features can be considered significant from the mineral exploration point of view, on the basis of their location alone. Near-surface extensions of the Whin intrusions are generally easily recognised, by comparing the outcrop pattern on the geological maps with the magnetic map. For the indicated concealed intrusions, the form and trend of the anomaly can identify either a Whin or Tertiary dyke or other body as the cause.

The observed anomalies can be grouped into three broad categories, depending upon their relationship to the surface geology:

i Anomalies corresponding to known geological features. Within this group are almost all the anomalies caused by outcrop or subcrop of the Whin Sill, plus those anomalies caused by known dykes and by the few known major faults.

ii Anomalies indicating extensions of known features. Particularly significant within this group are several anomalies indicating extensions to known mineralised structures, while others demonstrate the continuity of dykes between widely spaced outcrops and the extension of faults beneath drift cover. There are some indications of extensions to the outcop of the Whin Sill; though these are few since the outcrop generally gives rise to marked topographic features and its position is consequently already well known.

iii Anomalies indicating previously unknown features. This group includes most of the anomalies occurring downdip of the Whin Sill outcrop, as much of the geological control, on the Hexham and Morpeth map sheets in particular, is hampered by the extensive drift cover. The detection of anomalies in this category was one of the principal objectives of the survey, and the number recorded, together with the possible significance of certain of them, is satisfactory justification for the survey. Anomalies in this category appear to indicate features such as faulting in the Whin Sill, unrecorded Whin and Tertiary dykes, and several other less specific structures, some of these anomalies having considerable linear extent. Also in this category are a few instances, such as around [850 700], where the sill is poorly exposed and where the magnetic data indicate a subcrop form different from that mapped.

There appear to be no spurious anomalies due to noise, and only a few ambiguous anomaly patterns resulting from the automated contouring of the data (see above).

Outside the above categories are areas of low magnetic gradient with a marked absence of anomalies. These will naturally occur where the Whin Sill is undisturbed, but the more likely explanation for those shown in Plate 3 is that they indicate particularly deep-lying parts of the intrusion. This explanation is supported by the fact that these areas tend to coincide with the outcrop of Namurian sediments, a notable example being the syncline around [800 660].

In the following discussion, the relationship of the magnetic data to groups of features (sills, dykes, faults, mineralisation) is considered, with the confirmed, extended and newly-revealed features in each group examined in turn.

RELATIONSHIP OF MAGNETIC DATA TO SILLS AND DYKES

Within the limitations imposed by the flight line spacing and by the automated contouring of the data, the magnetic contour map clearly defines the position of the edge of the Whin Sill. There is much variation in the observed anomaly, since the dip of the sill, its thickness and the presence or absence of an accompanying topographic feature all influence the anomaly signature. These variables can be determined for a given location, but the magnetisation vector, which also influences the anomaly signature, cannot conveniently be determined since it is not known whether, at a given locality, any post-magnetisation movement of the sill has taken place. However, theoretical magnetic profiles over a typical sill outcrop (Figure 8b), modelled on the basis of published remanence and susceptibility values, show that the magnetisation vector is not critical, for a small range of values, in determining the qualitative characteristics of the magnetic anomaly. The observed magnetic profiles over such outcrops are broadly consistent with the theoretical profiles.

The magnetic contour map indicates a few localities, principally in the northern part of the area, where the Whin Sill appears to extend further along strike than has been mapped. These extensions to the edge of sill are shown on the interpretation map. The sill in this northern area is thinner and more disjointed than elsewhere, forming less topographically pronounced outcrops more easily obscured by drift, thus accounting for these extensions to the sill being unrecorded.

Though the magnetic map essentially only confirms the already well known outcrop pattern, some features of this are seen which had not previously been apparent from the geological map. In particular, the magnetic map resolves anomalies close to the sill outcrop which suggest the presence of strike faults unrecognised in the course of surface mapping. For example, near Hotbank Farm, anomalies in the airborne data, confirmed by ground measurements, indicate that the Whin outcrop between [753 673] and [800 694] is a fault scarp. A mapped fault extending west from this line supports this. The alignment of the outcrop between [800 700] and [895 730] suggests that here too a fault defines the outcrop, with the outcrop being displaced southwards near Settlingstones by the intersection of the anticline (this too possibly fault controlled) running northeast from west of Haydon Bridge. The two faults postulated above have a similar trend (073°) but are offset at Moss Kennels [800 695]. The displacement in the outcrop here is mapped as a transgression, though ground VLF-EM anomalies at this locality suggest that a fault is present which could account for the displacement. To the east the anomaly associated with the Hallington Reservoir Fault has an identical trend to the two features described above, but is offset from them to the north. It appears likely that these three features are all expressions of a single major structure, possibly of greater significance at depth than is apparent at surface. Such a structure, together with the Stublick Fault to the south and the Sweethope, Antonstown and Cragend-Chartners Faults to the north (Figure 2), would complete a pattern of similarly aligned structures, approximately equally spaced north to south across the Northumberland Trough. Other structures with this trend are occupied some 40 km to the south by the Hett Dyke and some 70 km to the north by the Holy Island Dyke, these two dykes marking the southern and northern known limits of the Whin Sill respectively. Recent mapping in the Bellingham district (which includes a large part of the airborne survey area) has also shown the dominant direction of fault and fold axes to be ENE.

To the north of the Hallington Reservoir Fault, as far as the Sweethope Fault, the Whin appears as two sills, their outcrops following a NNE trend. This trend is contained between these two faults and it does not appear from the magnetic data that there is any underlying NNE structure persisting to the north or south.

North of the Sweethope Fault the outcrop becomes more disjointed, but clearly follows a north-east trend. The lower of the two sills seen to the south is no longer in evidence, either at surface or from the magnetic data. On the eastern margin of the survey area the magnetic map confirms the occasional appearance of dolerite a little below the horizon of the Great Limestone. The north-east trend of the principal intrusion seems to be a reappearance of that anomaly trend along which are located the Settlingstones and Langley Barony mineral veins. A major structure, approximately coinciding with this magnetic trend, is seen on the Landsat imagery of the area.

The geological map indicates in certain areas the presence of additional thin sills above or below the principal intrusions, notably north-west of Chollerton [924 730], south-west of Thockrington [953 785] and west of Great Bavington [975 800], though none of these occurrences is reported to be extensive. There is no clear magnetic evidence to confirm these occurrences, nor to suggest their persistence along strike.

The few exposures of Whin and Tertiary dykes within the survey area (Figure 2) are seen generally to have coincident magnetic anomalies. The magnetic map reveals the extent of the dyke system which these exposures represent. Only in the case of the St Oswald's Chapel Dyke have conjectural extensions to the exposures been mapped, and these conjectural lines are confirmed by the magnetic data.

St Oswald's Chapel Dyke

This dyke is seen at only a few isolated localities, and its position and continuity on the geological map (Figure 2) were based on interpolation and conjecture. The magnetic map confirms the conjectural position of the dyke, generally to within 100 m, and it is therefore not necessary to show separately the mapped position of the dyke on the interpretation map. The break in the dyke previously thought to occur between Haltwhistle and Haydon Bridge (Figure 2) evidently does not exist. However, a major break in the dyke is apparent in the Haydon Bridge area, where a prominent magnetic 'high' and accompanying 'low', both of limited linear extent, occur across the line of the dyke (Plate 3). It is possible that this feature is caused by a 'plug' of dolerite, perhaps a feeder for the St Oswald's Chapel Dyke and for the sill itself. The proximity of this feature to the Haydon Bridge mining field is of uncertain significance; and there are no comparable magnetic features elsewhere within the survey area.

Another break, or displacement, in the position of the dyke is seen at [915 678], possibly related to an extension of the magnetic feature extending down dip from [885 713]. The dyke is again interrupted by the ENE-trending magnetic feature along which has been intruded the Tertiary Bingfield Dyke. The St Oswald's Chapel Dyke dies out to the north of this feature.

The course of the St Oswald's Chapel Dyke is seen from the magnetic map to be not, as it first appears, a gentle curve, but a succession of linear segments, probably reflecting a series of structures at depth. For example, the course of the dyke between [845 648] and [880 660] appears to be determined by a structure whose existence is evident west of [810 636] as the dyke diverges from it to the north; the magnetic effect of this structure being a result of its effect on the deep-lying Whin Sill.

The anomaly due to the dyke has been interpreted using the profile from flight line 84, which lies within 100 m of a parallel ground traverse. The airborne profile is shown in Figure 8a together with a closely-fitting model curve. The dyke is assumed to be vertical; the generally straight course of the dyke regardless of topography supporting this. The airborne anomaly is assumed to be due only to the dyke, with any contributed anomaly from a feature at depth in the Whin Sill being negligible. Comparison of the airborne and ground survey profiles supports this assumption. Also shown in Figure 8a is the anomaly which would result from the same dyke using the remanence data of Creer and others (1959) to derive the dip of the total magnetisation vector (assuming no post-intrusion movement of the dyke). Clearly the magnetisation thus derived is far removed from the true value for the dyke, the very close fit shown being obtained by using a dip of 90° for the magnetisation vector. A detailed interpretation of the ground survey profile has not been made, but by comparison with sets of model curves the indicated dip of the magnetisation vector lies between 90° and 105°, supporting the interpretation of the airborne anomaly. This conclusion could have particular geological significance for it implies that the remanent magnetisation of the dyke differs from that of the sill, due to either a different age of intrusion or different magnetic properties.

The Bavington Dyke

This dyke also is seen at only a few localities, but its continuity is demonstrated by the airborne magnetic data. It appears not to extend as a magnetic feature west of [980 772], although there are isolated exposures of the dyke west of this point. This Dyke, unlike the more substantial St Oswald's Chapel Dyke, has recorded widths of about 1 m, and it is possible that its westernmost

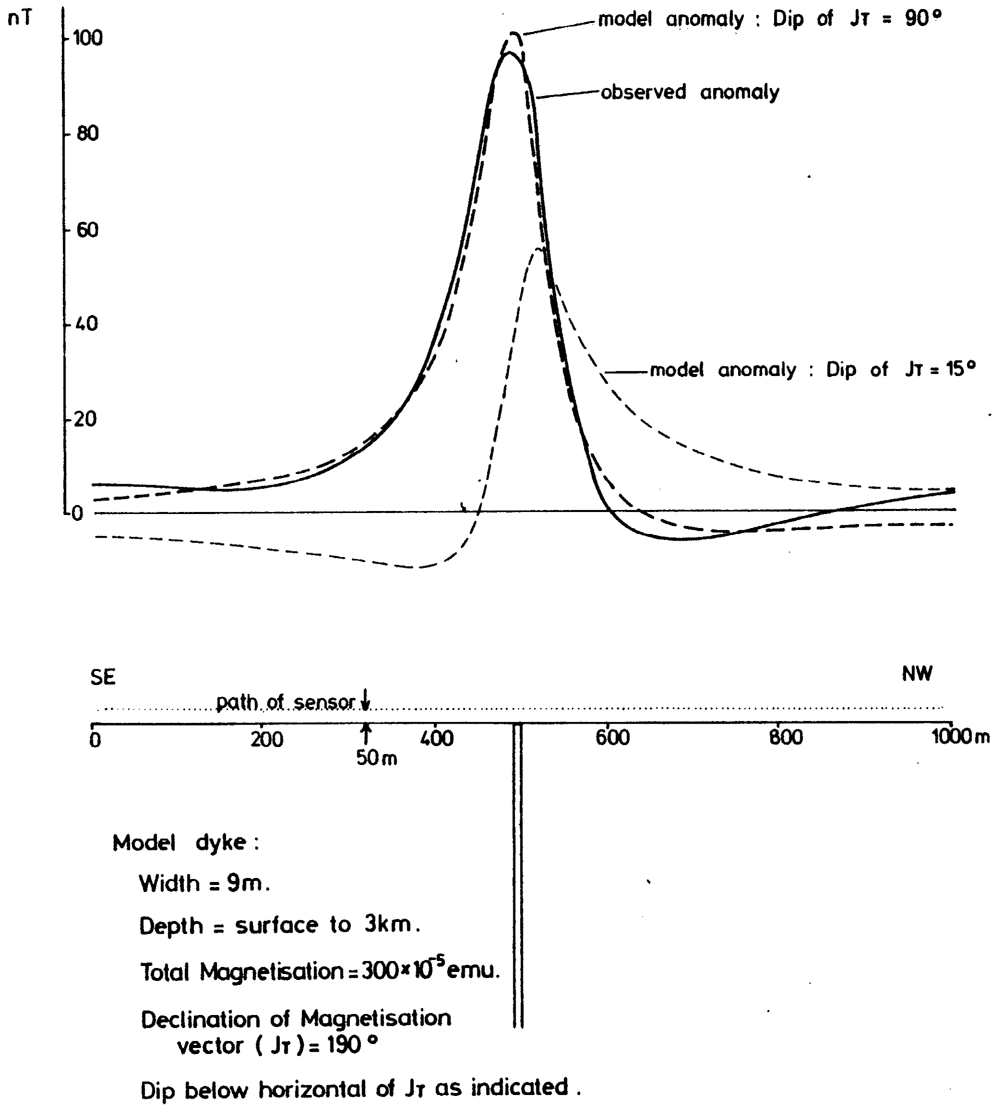

Fig 8a : Observed and theoretical airborne magnetic profiles over the St.Oswald's Chapel Dyke.

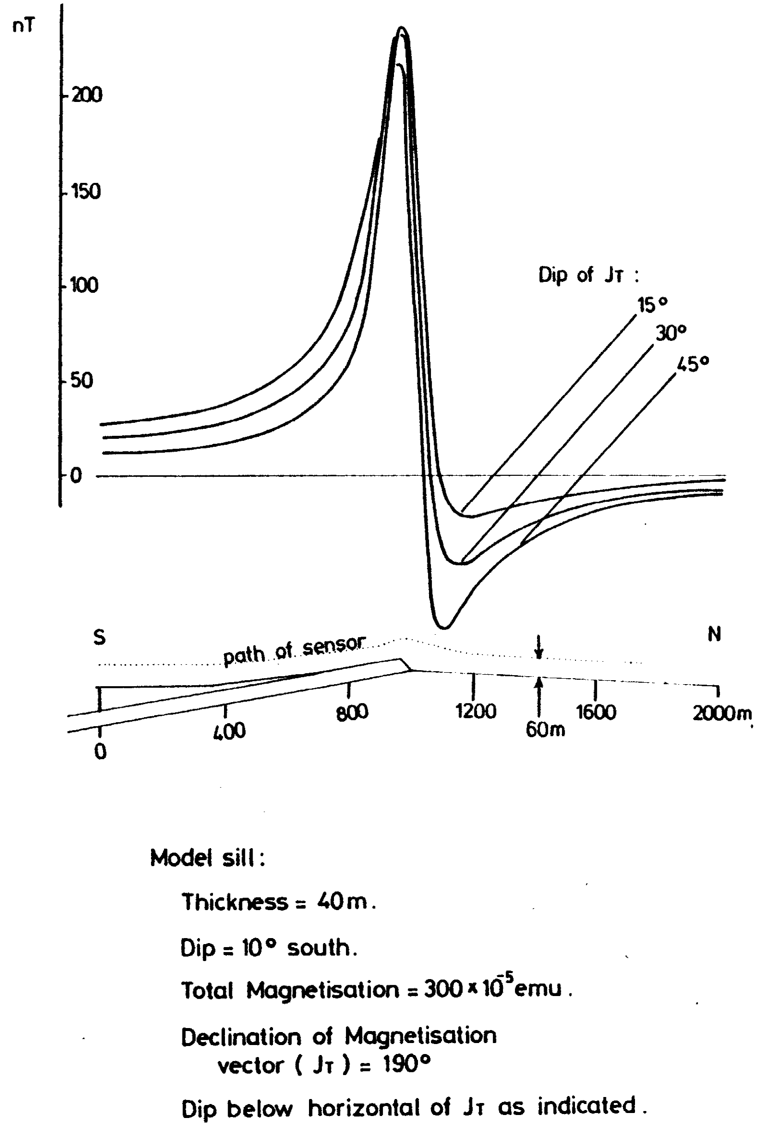

Fig 8b : Theoretical airborne magnetic profiles over a typical outcrop of the Whin Sill.

exposures are too insignificant to provide a detectable airborne anomaly. The dyke is coincident with the Hallington Reservoir Fault (Figure 2) which displaces the Whin Sill at shallow depth, and the anomaly along the structure reflects both the faulted sill and the presence of the dyke.

Dyke at Prior Hall

A weak but well defined magnetic anomaly extending north-east from Prior Hall [030 852] was checked with a test ground traverse, and an anomaly indicative of a Whin dyke was observed. The trend of the anomaly also suggests a Whin dyke as a likely cause. If this is the case then the dyke does not align with any other exposures to the south-west or north-east. There are no indications that this dyke occupies a major fault in the Whin Sill.

Tertiary dykes

The locations and trends of several magnetic anomalies suggest that they are related to Tertiary dykes of the Mull swarm. There are five such anomalies (Figure 9) and, of these, four are marked negatives (1, 2, 3, 4 in Figure 9) which extend down dip of the sill outcrop. Three of the four anomalies, and the fifth (2, 3, 4, 5 in Figure 9), appear to extend beyond the outcrop of the sill to the north-west, though as the survey boundary closely follows the edge of the sill these weak features can be seen only over a short distance. Whether the remaining anomaly (1 in Figure 9) behaves similarly is not known since the anomaly leaves the survey area before it crosses the sill outcrop. Also shown in Figure 9 are the known outcrops of Mull dykes in northern England and southern Scotland. The correlation of the anomalies described above with the alignment of the known dykes is ample evidence that the magnetic anomalies are in some way related to the dykes. This relationship is almost certainly complex, with a number of factors possibly combining to modify any anomalies due to the dykes themselves. Thus it is necessary to consider the magnetic effect of any displacement of the Whin Sill by faults which the dykes may occupy, and the effect of any local change in the magnetisation of the Whin Sill caused by the intrusion of the dykes through the sill. Also to be considered is the possibility that the Tertiary dykes are rather more substantial at depth than at surface; their persistence over considerable distances, as well as the appearance in some cases of corresponding negative anomalies on the regional aeromagnetic map (Figure 3) supports this suggestion.

RELATIONSHIP OF MAGNETIC DATA TO FAULTING

For the faults shown on the geological map (Figure 2) there are features on the magnetic map which can be considered to confirm all of them, with the exception of the Grindon Hill Fault. This 'fault' lies within the area of some of the ground surveys and the data from these are also unable to support the existence of a fault affecting the Whin Sill in this position.

One of the places where the effect of faulting in the Whin Sill can be clearly demonstrated is in the south-western corner of the area. Here the Stublick Fault downthrows to the north, but a second fault has produced a small graben containing productive Coal Measures of Westphalian age (the Midgeholme Coalfield). There is reasonable agreement between the observed and theoretical magnetic profiles (Figure 10) and the model used to derive the latter fits most of the geological evidence for the structure. The VLF anomalies are not particularly pronounced in this area and there are no features associated with the faults (Figure 10). The magnetic map also indicates that, compared with the slightly sinuous course at surface, the main Stublick Fault at depth consists of a series of segments displaced 'en echelon' by a series of intersecting NE-trending faults. The Stublick Fault is shown thus, rather than as mapped, in Plate 3.

With the exception of the features referred to below in relation to mineral veins, there is only one magnetic anomaly which suggests a significant extension to a known fault (possibly because some faults may already have been conjecturally extended on the geological map). This anomaly extends from [998 812] to [050 803] and coincides with the probable line of a Tertiary dyke.

The magnetic map reveals a number of other linear anomalies comparable to those related to known faults. These features cannot necessarily be ascribed to faults in the Whin Sill, but, should the sill not be faulted, then the causative feature in the sill (e.g. transgression, pinching out) will probably be related to pre-intrusion faulting or jointing, and the linear magnetic features will, therefore, still be structurally significant.

Those linear features which simply coincide with known faults are not discussed further, while the remainder are described in turn below.

i [803 692] to [811 681]. This feature extends SSE from the outcrop of the sill, where the sill is observed to transgress through one cyclothem down the sedimentary sequence. The anomaly is consistent with a sharp change of level of the sill along this SSE line, with displacement being down to the east. It is possibly significant that, were the Burtreeford Disturbance to be extended along the trend it has in the Allendale area (Figure 2), it would intersect the Whin Sill at the site of the transgression described, though there is no evidence from the magnetic data for such a connection. The locality has been described in detail by Johnson (1959).

ii [885 713] to [896 692]. A feature with the same trend as i and, similarly, its location relative to the sill outcrop suggests that the anomaly marks

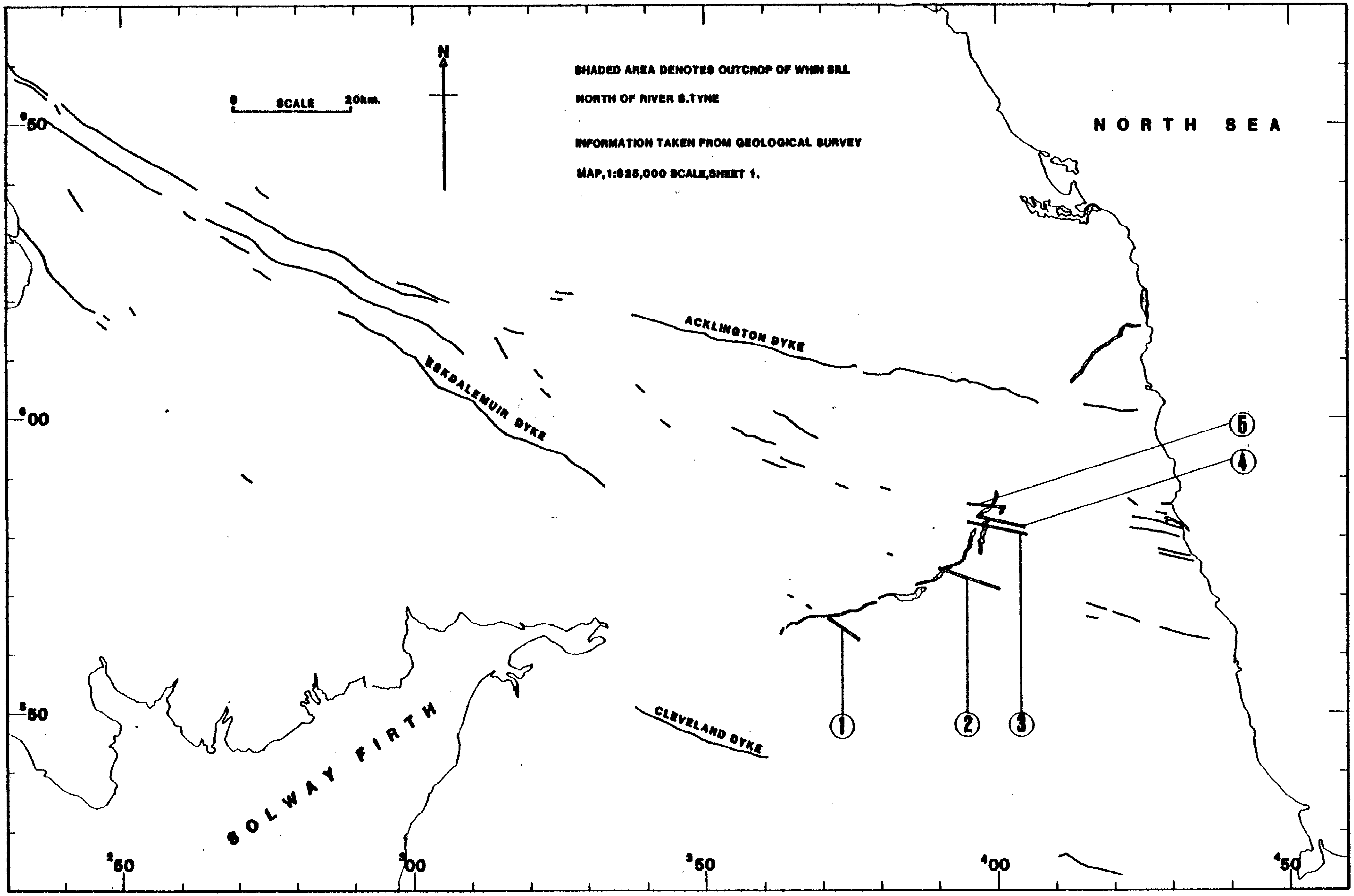

Fig.9 : Tertiary dykes in northern England and southern Scotland ,and locations of ESE-trending magnetic "lows" (① to ⑤).

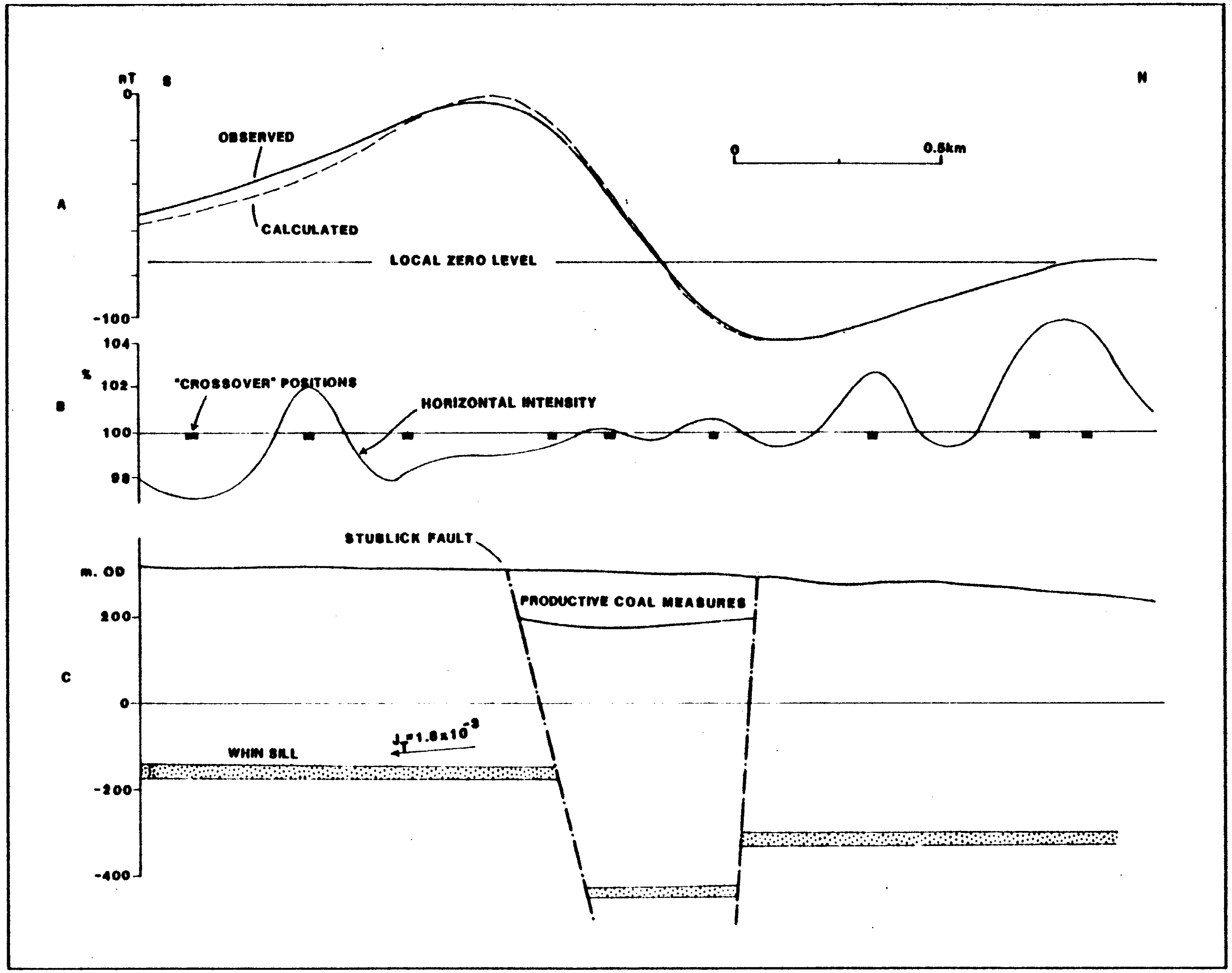

Fig.10 : Airborne magnetic (A) and VLF (B) profiles across the Stublick Fault.
The model for the Whin Sill (C) produces the calculated magnetic profile shown in (A).

a line of transgression, or alternatively a line along which the thick sill of the Settlingstones district pinches out, the intrusion re-appearing at a lower horizon as the rather thinner sill of the Barrasford district. Extension of this anomaly to the south-west leads to a point on the St Oswald's Chapel Dyke where this dyke appears from the magnetic data to be displaced [915 678], indicating the presence of a fault which has, therefore, presumably controlled the emplacement of the sill. No such fault is mapped, but this interpretation of the magnetic data indicates a length of some 5 km for such a structure.

iii [886 725] to [914 720]. This feature is approximately parallel with the Barrasford Fault 1.5 km to the north and, as with feature ii, may have had some influence on the behaviour of the intrusion and hence on the present outcrop pattern in the vicinity of [875 720]. The structure may extend much further to the ESE to link with the fault which is mapped as terminating the Fallowfield Vein at [973 702]. This possibility could account for the marked weakening of the anomaly due to the St Oswald's Chapel Dyke north-east of [953 708].

iv [960 792] to [990 776]. A fault is mapped where this feature intersects the lower of the two sills in this area. The local change in strike of the upper sill (through some 60°), where the magnetic feature intersects, supports the existence of some previously unmapped structural control here.

v [985 790] to [998 779]. A feature with a similar trend to iv, lying close to a mapped fault at its north-west end. Again some relationship to a change in the local strike of the Whin is suggested.

vi [935 736] to [959 764] and [977 786] to [990 802]. This feature is quite unrelated to any mapped structures or trends in the vicinity, and it intersects, uninterrupted, several known faults. The feature has possible significance for mineralisation, as described below.

RELATIONSHIP OF MAGNETIC DATA TO MINERALISATION

Two of the features which led to the initiation of the airborne magnetic survey were the relationship of the Haydon Bridge mining field to the existing aeromagnetic data (Figure 3), and the coincidence of a weak but significant ground magnetic anomaly with the vein system worked at the important Settlingstones Mine. The present survey has confirmed that not only does the Settlingstones vein system coincide with an anomaly but that the Stonecroft/Greyside vein system, with veins trending ENE and ESE (both extensively worked), is also followed by elongated anomalies (Figure 11). This correlation has been examined in detail on the ground and the results will be published in a future report. There is also some suggestion that the airborne VLF has distinguished part of this vein system, but these particular anomalies are not sufficiently distinct from others in the survey area.

Attention has already been drawn to the distribution of a large proportion of the mines and trials along a narrow belt trending 042° through Settlingstones, having a close correlation with a 'Landsat' feature of regional scale. A magnetic anomaly extending from the northern limit of the Fallowfield vein follows a similar trend (Plate 3) and the Thornborough deposit lies on a branch of the Stublick Fault which turns to follow a similar line (Figure 2). Of consequent significance is the linear magnetic anomaly (feature vi, this page) with a very similar trend (040°) some 3 km to the south-east of the 'belt' of mineral occurrences, also coincident in part with a 'Landsat' lineament. This magnetic feature is seen in two parts (Plate 3) with a combined length of some 6 km. It appears to be unrelated to any of the known mineralisation, but its apparent conformity to a possible regionally-controlled distribution of mineral occurrences suggests it is worthy of more detailed investigation. This possible model of lineaments of regional scale contributing to the control of mineralisation invites comparison with work by Carter and Moore (1978) who suggest evidence for a series of broad linear features traversing the orefield of the Alston Block, along which there are more than the average number of veins per square kilometre.

Thus it appears that the pattern of linear features revealed by the aeromagnetic map, whilst complex and of uncertain relationship to possible mineralisation, can provide starting points on both local and regional scales for detailed ground exploration in the area.

The magnetic anomalies in the vicinity of the more important mines are described in turn below. The other known mineral occurrences are (or were) generally of very limited extent and thus not demonstrably related to larger scale features. It would therefore be unreasonable to speculate on possible extensions to these deposits on the basis of the magnetic data.

Langley Barony (Figure 2, No. 4)

The magnetic contours show a marked break of slope along a line with a trend of 043° lying approximately parallel to the Settlingstones vein, some 400 m to the south-west of the vein (Plate 3). The Langley Barony main vein extends south-west along the same trend from the south-west end of the magnetic feature. The feature is sufficiently marked for it to appear significant in its own right rather than being simply a consequence of the Settlingstones 'low' (see below). Thus a possible reappearance of the Langley Barony structure in the area to the south-east of the Settlingstones vein seems to deserve investigation.

Extrapolation of the 'break-of-slope' magnetic feature to the north-east suggests persistence of the causative structure since the sharp deviation of the

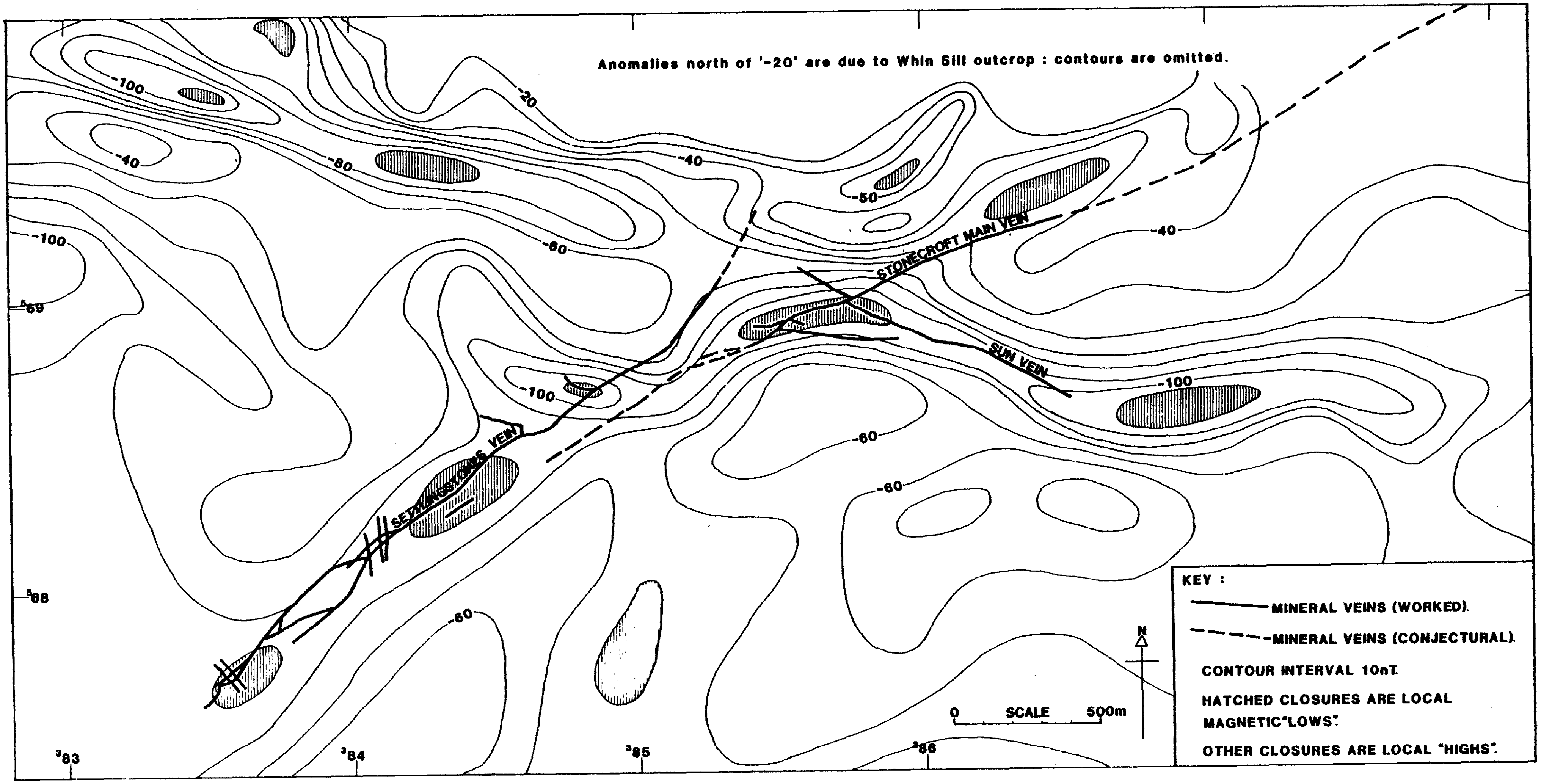

Fig.11 : Airborne magnetic contours (manually smoothed) in the Settlingstones area, and location of mineral veins.

sill outcrop to a north-east trend at [865 705] occurs on the same alignment. As already discussed, it is possibly significant that the Whin Sill outcrop resumes a north-east trend where the NNE-trending outcrop meets the production of the line of the magnetic feature described above [965 820].

Settlingstones (Figure 2, No. 7, and Figure 11)
The Settlingstones main vein coincides with a pronounced magnetic 'low', which parallels the break-of-slope feature mentioned above. This 'low' is terminated at the south-west limit of the vein by a weak NW–SE feature, and to the north-east assumes a more easterly trend, turning to follow the Stonecroft main vein. Of interest is a second prominent 'low', the trend and magnitude of which are clarified by re-contouring a series of disjointed anomalies resulting from the automated data contouring. This low extends WNW for some 2 km from the north-eastern end of the Settlingstones main vein. The trend and position of this 'low' suggest that it may be related to an extension of the WNW-trending Stonecroft Sun Vein (Figure 11). Some 500 m to the south a second WNW-trending 'low', of only limited extent, coincides with the mapped position of a minor branch of the Settlingstones main vein, suggesting that this branch may have a rather greater extent than had been thought. Another 'low', some 300 m to the north of the Stonecroft main vein and apparently isolated, may represent a reappearance of the structure carrying the Settlingstones main vein. The magnetic 'lows' described are consistent, at least qualitatively, with the faulting of southerly downthrow, affecting the Whin Sill, to which the mineral veins in the Settlingstones area are known to be related.

Ineson (1972) has described the occurrence of altered dolerite, or 'White Whin', in association with the Settlingstones mineralisation. The alteration of the dolerite can much reduce, or destroy, its characteristic magnetisation, and this offers a second possible cause for the observed magnetic anomalies. However, computer modelling suggests that when in combination with faulting, alteration on the small scale described by Ineson can be expected only to contribute to, rather than dominate, the magnetic anomaly pattern.

Clearly, the magnetic anomalies in the Settlingstones area, though having two possible causes, can be considered in either case to indicate zones in which ascending hydrothermal fluids may have penetrated the Whin Sill, and thus provide a useful pointer to areas worthy of detailed ground surveys. Furthermore, the eastward continuation of the Settlingstones anomalies suggests that this reasoning can be applied equally in the vicinity of the Stonecroft and Carr Edge mines. These areas are described below.

Stonecroft–Greyside (Figure 2, No. 8)
Both the ENE-trending Stonecroft Main Vein and the ESE-trending Stonecroft Sun Vein coincide with magnetic 'lows' (Figure 11). The correlation with the main vein is most evident in the area where the vein has already been worked (and exhausted). To the ENE the mapped course of the vein is conjectural and the accompanying magnetic anomaly both weakens and shows some divergence. However, the Stonecroft Sun Vein very closely follows the axis of a magnetic low which extends as a well defined feature for well over a kilometre to the east of the last known position of the vein. This magnetic anomaly clearly indicates the continuity of the structure carrying the vein, with a marked change in its direction beyond the limit of the old workings.

Carr Edge (Figure 2, No. 9)
The workings at Carr Edge exploited a vein with a trend which suggested its being an extension of the Stonecroft Main Vein, though the lack of success of a number of trials over the intervening ground casts doubt on the conjectural position of the vein shown in Figure 11. The magnetic map shows a 'low' coincident with the vein in the Carr Edge area, which diverges from the conjectural extension to the WSW (Plate 3), turning slightly north to an east-west trend, running out to the point where the Whin Sill outcrop turns sharply from an east-west to a NNE trend. The eastern extension of the anomaly at Carr Edge is terminated abruptly by the SSE-trending feature which probably marks a pinching out of the sill at one horizon and its reappearance as a thinner sill at a lower horizon.

Fallowfield (Figure 2, No. 11)
The Fallowfield Vein occurs in an area where the Whin Sill lies at an estimated level of -0.2 km OD. The magnetic anomalies here are therefore of low amplitude and there is no simple relationship between these and the course of the Fallowfield Vein. The vein, however, appears to lie along an ENE line across three separate negative anomalies, each with a more east-to-west elongation. These negative anomalies could represent 'steps' in the sill with downthrow sides to the south (Figure 12), the individual anomalies perhaps being separated by another set of faults with an approximately north-south direction. The course of the vein at surface could represent the result of later faulting in the sediments overlying the zig-zag pattern of faults in the sill. The Grottington Mine (No. 12, Figure 2) is located close to a point on the Fallowfield Vein where it is intersected by another fault system trending to the WNW, a direction which is also reflected by the magnetic contours.

The magnetic contour map gives some indication of a structure, possibly several kilometres in length, which may represent a north-eastwards extension of the structure carrying the Fallowfield Vein, or of the structure at depth which determined the course of the vein (Plate 3). The Whin Sill in this area can be expected to occur at a depth of

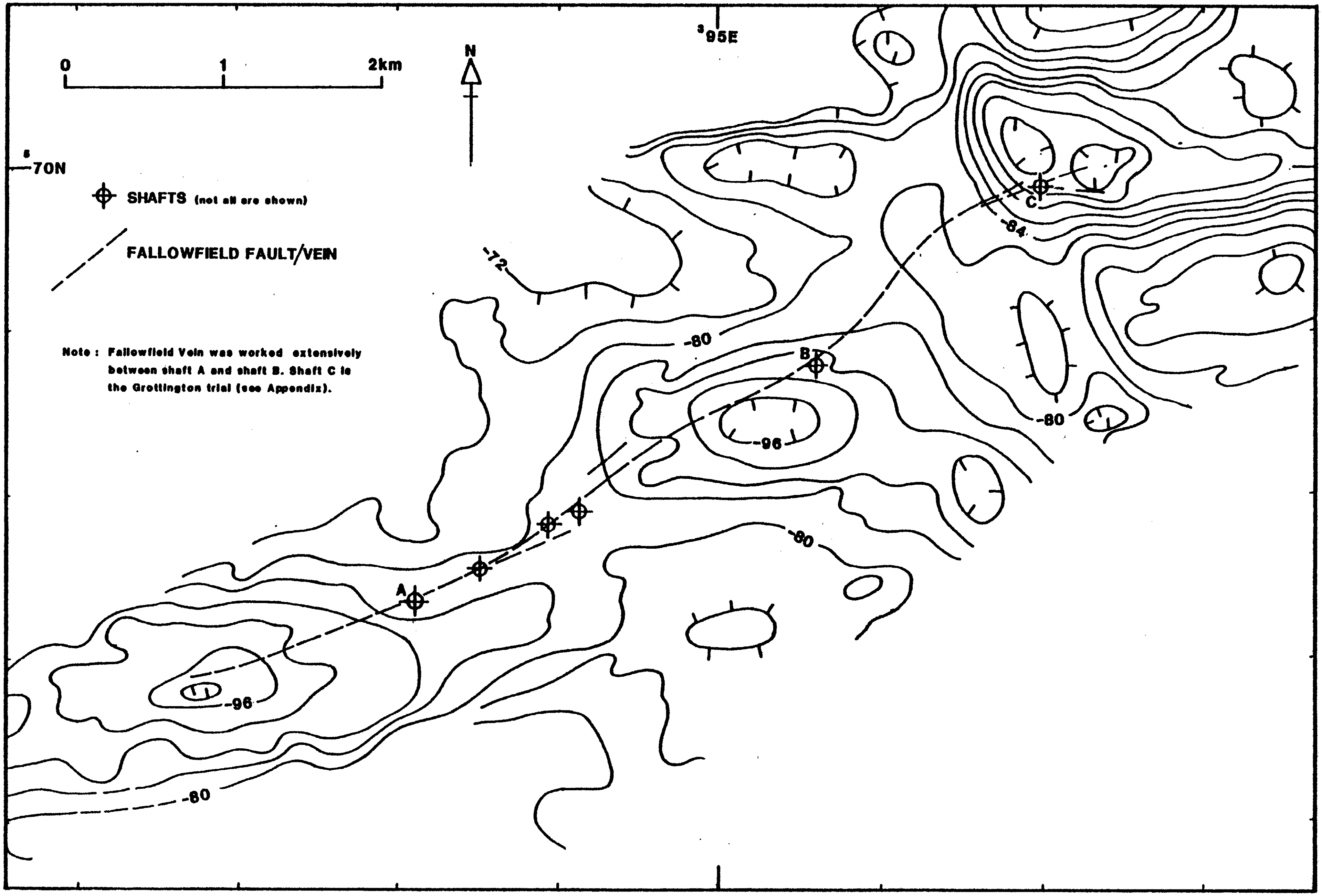

Fig. 12 : Aeromagnetic map for the Fallowfield mining area, with contours at 4nT intervals.

perhaps 0.3 km and ground surveys could not be expected to detect mineralisation (geophysically or geochemically) if this was located at the horizon of the sill. The possibility that this magnetic feature represents one of a series of approximately parallel mineralised 'belts' has been discussed above.

VLF-EM INTERPRETATION: DETAILS

The contoured maps of the VLF horizontal component intensity have been compiled at 1:50 000 scale and are presented as Plate 2. A large number of anomalies, both positive and negative, are seen. Generally, these are rather broad features, discrete anomalies of short wavelength being uncommon. A number of general points can be made regarding the anomaly pattern.

i Topographic effects. There is a marked correlation between the VLF anomalies and the topography. This is particularly evident in the western part of the survey area, where there is a well developed drainage pattern approximately normal to the flight line direction. Valleys in general give rise to negative anomalies and ridges to positive anomalies. However, the abruptness of a topographic feature in several cases seems to have more influence on the corresponding anomaly than simple consideration of its prominence as a topographic maximum or minimum. Thus a sharp break of slope some distance downslope of the crest of a broad ridge can have a rather greater corresponding anomaly than the ridge itself. The situation at the western edge of the survey area is illustrated by Figure 13. Here, the 25 ft (7.6 m) contours on the O.S. 1:25 000 map have been interpreted to define 'break of slope' lines along which a significant change could be expected in the flight path of the helicopter, either as a sharp reduction in the rate of ascent, or as a sharp increase in the rate of descent. These lines have been superimposed on the VLF horizontal intensity contours and a considerable measure of correlation between the two is apparent.

ii Artificial anomalies. There appear to be few anomalies due to man-made features, though one artificial anomaly in particular is of considerable linear extent. This is due to a 275 kV National Grid power line, extending from the western boundary of the survey area at [713 650] approximately eastwards to leave the area at [970 681]. The anomaly is seen as a well defined positive in Plate 2, and provides a good example of a crossover in both in-phase and out-of-phase components on the vertical field stacked-profile maps. Thus this anomaly is of a type which would be of interest if the cause were thought to be geological. Part of the anomaly can be seen running approximately east-west across the centre of Figure 13.

There are no other comparable anomalies on the map which are clearly visible. However, in the course of inspecting the individual 1:10 560 scale profile and contour maps, a number of similar anomalies were identified, these however being of smaller amplitude and only limited linear extent. They were of interest because of their short wavelength relative to the numerous broad anomalies seen elsewhere, and because of the well-defined nature of the crossovers seen on the profiles. Unfortunately, checking against local electricity distribution line maps showed that each of these anomalies corresponded closely with a power line. These are local power lines supplying only 11 kV but it is not known why only a few of the considerable number of these lines produce discernible VLF anomalies.

iii Stratigraphic anomalies. There are few clear examples of anomalies having geological causes. However, in the western part of the survey area in particular, the apparent influence of the local stratigraphy on the drainage pattern leaves open the possibility that certain anomalies which appear to be topographic may be due to conductivity contrast, or to a combination of both factors; the thin south-dipping limestones and sandstones in the succession appearing as marked ridges with north-facing scarps, with the more conductive areas of drift-covered mudstones occupying the intervening hollows. A similar correlation is provided by the often dramatic scarp of the Whin Sill. In this case, however, a continuous sequence of profiles across the feature is available over several kilometres and a better estimate can be made of the influence of topography. It appears that, after an estimated allowance for topographic effects, the exposure of a broad dip slope of dolerite can provide corresponding negative anomalies, almost certainly as a result of its poor conductivity relative to the succeeding predominantly-mudstone strata.

iv Other anomalies. There are no clear examples of distinctive anomalies corresponding with known faults or mineral veins, or indicating extensions to them. As mentioned elsewhere, there appears to be some local correlation between VLF 'crossovers' and a part of the Settlingstones Vein, but the proximity of the National Grid power line and other local lines confuses the interpretation in this area.

There are no examples of correlation over a significant length between VLF anomalies and the numerous linear magnetic features.

Because of the difficulties of interpretation and identification of anomalies possibly indicating mineralisation, ground VLF surveys have largely been restricted to profiles complementing magnetic surveys. A further important consideration in the planning of ground VLF surveys is the distribution of local power lines, since whilst it may be possible to eliminate these as the cause of a given airborne anomaly, close proximity of power lines may adversely influence any ground survey data, preventing satisfactory follow-up of the airborne anomaly.

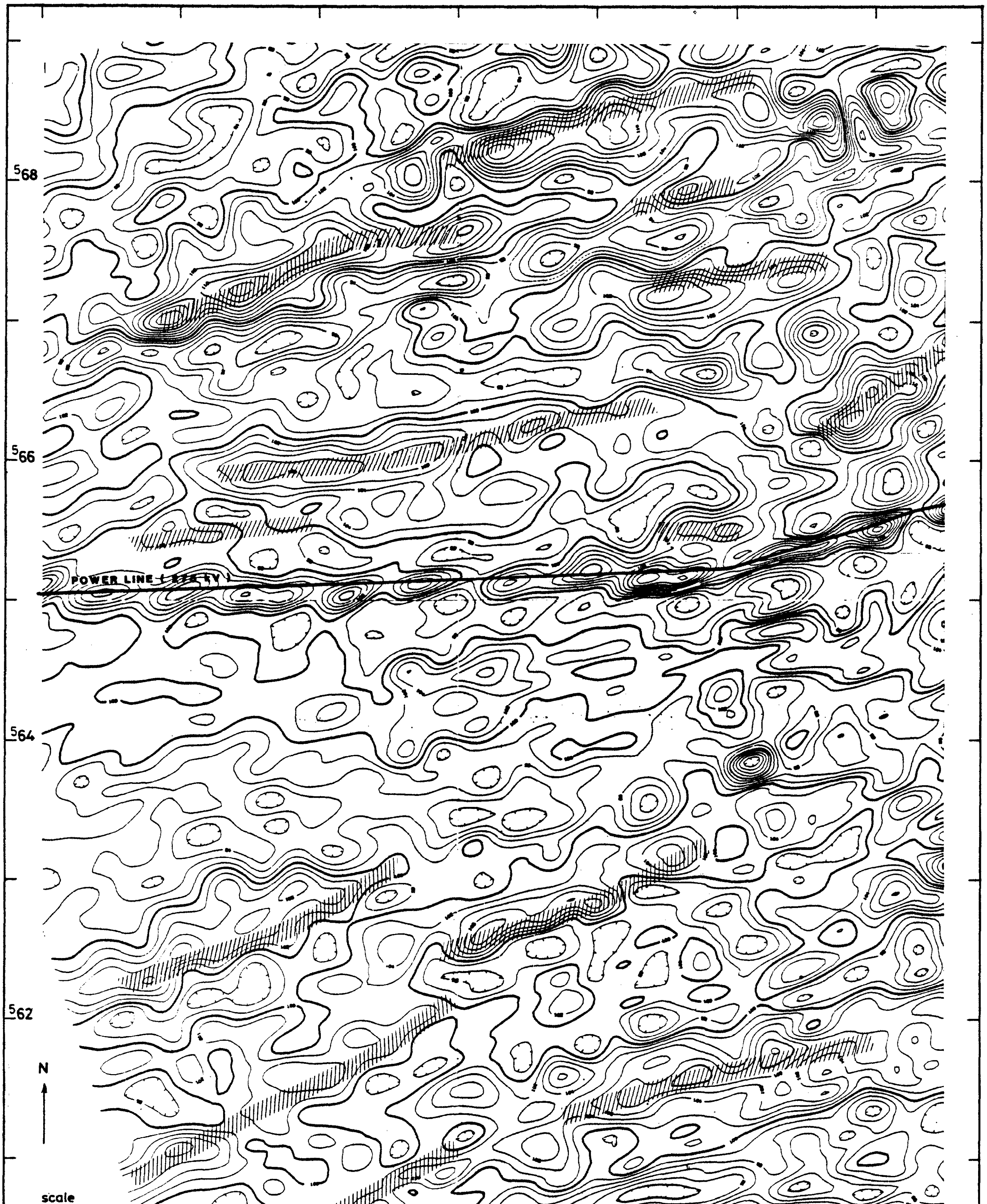

Fig. 13 : Airborne VLF-EM in-phase component contours and positions of topographic features.

(Hatched features mark lines of prominent breaks of topographic slope.)

CONCLUSIONS

The detailed aeromagnetic map of the Haltwhistle –Scots' Gap survey area shows a large number of anomalies associated with the outcrop of the Whin Sill, with both Whin and Tertiary dykes and with structures in the down-dip continuation of the Whin Sill. The form of the anomaly over the outcropping sill is consistent with a direction and intensity of magnetisation determined mainly by the strong reversed remanent magnetisation known from palaeomagnetic studies.

The magnetic anomaly pattern associated with the outcrop of the Whin Sill consists of a series of segments separated by abrupt displacements, which in some cases can be correlated with known transgressions of the sill. The magnetic contours show a linearity of these segments at outcrop which is rather more marked than inspection of the mapped outcrop positions suggests. This feature, together with the persistence of some lineations over considerable distances, is interpreted to indicate that the form of the sill was determined by a rectilinear system of joints and faults existing at the time of its intrusion. Post-intrusion faulting has also affected the sill, though the magnetic evidence alone does not necessarily permit discrimination between this and the contemporaneous features.

A number of other magnetic anomalies occur down-dip of the outcrop of the Whin Sill, commonly as linear features up to several kilometres in length. It is probable that these indicate faults affecting the sill at depth, the distribution of their trends being similar to that of faults and folds mapped at surface.

The magnetic anomalies in the vicinity of the Settlingstones and Stonecroft Mines are consistent with the faulting to which the mineralisation is known to be related, although contributory to these anomalies could be the development of 'White Whin', an altered, demagnetised form of the dolerite, formed by the action of ascending hydrothermal fluids. The correlation between the known veins and the magnetic anomalies is sufficiently good for extensions of the latter to be considered as useful guides in the search for further mineralisation. Comparable linear magnetic features occur in the Whin Sill elsewhere within the survey area, and these too could be important to mineral exploration when the relationship between the magnetic anomalies and the source of the mineralisation is more clearly understood from detailed investigations which have been carried out near Settlingstones.

On a regional scale, the magnetic data, viewed together with Landsat and geological evidence, suggest that the Haydon Bridge mining field may form part of a major faulted mineralised belt extending to the north-east. This possibility is supported by evidence of similarly aligned structures to the east which may thus also be of economic significance.

Two sets of dykes, one formed contemporaneously with the Whin Sill, the other during Tertiary time, can also clearly be traced on the aeromagnetic map, and appear in some cases to occupy faults which displace the underlying Whin Sill. This invites comparison with the Closehouse Mine, Co. Durham, where the mineralisation occurs near intersections of the Whin Sill and the fault-controlled Whin dykes, though unfortunately the comparable environment in the Haltwhistle–Scots' Gap area is in most cases too deep for convenient exploration.

Apart from the principal structural and exploration aspects of the results, the airborne survey has indicated other features which invite more detailed investigation, notably the distinctive anomaly near Haydon Bridge on the course of the St Oswald's Chapel Dyke and the apparently anomalous magnetisation of this dyke.

The VLF-EM survey data have failed to identify any distinctive electrical conductors which could be related to known or postulated faults or mineral veins. Power lines are responsible for the strongest VLF anomalies recorded and many others are due to topographic effects. No significant radiometric anomalies were recorded, but a more detailed examination of these results, as well as the VLF data, is desirable.

Thus the airborne geophysical survey of the Haltwhistle–Scots' Gap area achieved its principal objectives. Despite continued economic and academic investigations in the area in the past, the interpretation of the magnetic data has provided much new detailed structural information, valuable on both the local and regional scales as a starting point for future mineral exploration work in the area.

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APPENDIX 1

MINES AND TRIALS

This appendix provides brief details relating to the recorded sites of lead, barytes and witherite workings within, and in the immediate vicinity of, the area covered by the south Northumberland airborne survey. Data have been taken principally from Wilson and others (1922), Smith (1923), Dunham (1948) and Frost and Holliday (1980). Some minor inconsistencies are apparent between these sources. Each of the sites listed is shown in Figure 2, and all but site 17 are indicated on Plate 3. For the more extensive workings, grid references relate to the principal shafts.

The details given for each site provide an indication of the size of the deposit and of any significant related structure, where known. This latter information is of use in an assessment of any magnetic anomalies in the vicinity of the deposit.

Where production figures are given, the dates correspond to those figures. Where no production figure is given, dates refer to the approximate period of working or development. The term 'no returns' indicates that there is thought to have been a period of production (rather than only trial activity), with actual tonnage figures not appearing in official statistics.

Tonnages for lead (Pb) refer to concentrates.

Figures for silver (Ag) relate to the recovery of silver from the lead, either as a total weight or as an average yield per ton.

'Ba' indicates barytes.

'Ba(W)' indicates witherite.

Location (Number refers to Figure 2)	*Grid Reference*	*Product, tonnages, dates*	*Description*
1 Morralee	804 636	Pb 119T 1856–64, 80–81 (+Ag, 7 oz/ton)	Worked one of four small NE-trending faults. Workings are in immediate vicinity of St Oswald's Chapel (Whin) Dyke
2 Waterhouse	810 647	Pb ~500T 1861–65, 80–81 (+Ag, 7 oz/ton)	Worked a probable extension of Langley Barony's Bewick Vein, over approximately 300 m.
3 Whinnetley	815 648	Pb 136T 1858–60	Worked probably the Bewick Vein between Langley Barony and Waterhouse.
4 Langley Barony	828 664	Pb 41 000T 1873–93 (+Ag, 46 000 oz) Ba 397T 1882–87	Worked the Bewick Vein, with three minor associated veins. Bewick Vein is in a fault, downthrow north ~11 m, trending NE. Worked over ~1400 m. Workings are all above the Scar Limestone.
5 Brokenheugh/ Sillyburn	848 660	Pb No returns. c1860	Very limited working of a NE vein in the Great Limestone and from near surface in an adjacent 'flat'.
6 Haydon Fell	845 665	Ba Not known.	Probably a trial for lead, but only a little barytes reported from a NE vein in the Great Limestone.
7 Settlingstones	850 688	Pb 17 000T 1849–73 (+Ag, 20 000 oz 1854–73) Ba(W) ~550 000T 1854–1969	Worked the Main Vein, small cross-veins and 'loops' over ~2.4 km. Main Vein is in a fault, downthrow south up to 30 m, trending NE and up to 11 m wide. Separate galena and witherite zones have been worked, principally in the Whin Sill.
8 Stonecroft/ Greyside	860 689	Pb 74 000T 1853–96 (+Ag, 95 000 oz 1854–82) Ba(W) 104T 1880/82/96	Worked the Stonecroft Main Vein over 900 m, NW Cross Vein over 300 m and Sun Vein over 800 m. Main Vein trends ENE, Sun Vein ESE, both in faults downthrow south ~30 m. Workings were principally in the Whin Sill.
9 Walwick Fell/ Carr Edge	880 700	Ba No returns. 19th cent.	On a probable extension of the Stonecroft Main Vein. Workings were at the horizon of the Whin Sill–Scar limestone, probably for barytes; reported uneconomic for lead.
10 Sharpley	878 724	Pb Probably 18th cent.	Workings very limited, probably only at surface. No record of a vein; mineralisation possibly dissemination in Oxford limestone.
11 Fallowfield	940 678	Pb 11 000T 1848–1907 (+Ag, 28 000 oz 1854–82) Ba(W) 100 000T 1855–1912	Worked the Fallowfield Vein over nearly 3 km, the vein up to 12 m wide in a fault trending NE, downthrow south up to 90 m. Workings were mostly at or above the horizon of the Great Limestone. The

Location (Number refers to Figure 2)	*Grid Reference*	*Product, tonnages, dates*			*Description*
					Whin Sill lies perhaps 200 m below the deepest workings.
12 Grottington	970 698	Pb	40T	1852–56	Trial shaft to test NE extension of Fallowfield Vein. Limited production; evidence of vein splitting up.
13 Thornbrough	015 655	Pb	1872–85		Limited development to test vein occupying NE fault. Fault also reported occupied by basaltic intrusion, and may be an extension of Stublick Fault. Workings perhaps 200 m above Great Limestone.
14 Quarry House	965 808	Pb	No returns. Mid-19th cent.		Worked a NNE vein in the Whin Sill. Development of several shafts and levels reported.
15 Kirkwhelpington	996 842	Pb	Early 19th cent.		Trials to test vein seen in limestone above the Whin Sill. No known production.
16 Hartington	023 881	Pb	Early 19th cent.		Trial shafts to test ENE vein reported in the Whin Sill. No known production.
17 Redpath	011 928	Pb	No returns. 18/19th cent.		Worked N–S vein in stream section in Oxford Limestone. Extensions to the vein reported unproductive.

INSTITUTE OF GEOLOGICAL SCIENCES

Applied Geophysics Unit

SOUTH NORTHUMBERLAND AIRBORNE GEOPHYSICAL SURVEY AREA

SCALE 1 : 50000

AEROMAGNETIC MAP

Contour values represent the total force magnetic anomalies in nanoteslas (nT) at epoch 1955.5 relative to a local reference field for the British Isles which has a value of 47,033 nT at the British National Grid false origin and increases in the direction of grid north and grid west at the uniform rates of 2.1728 nT km^{-1} and 0.259 nT km^{-1} respectively.

Anomalies on this map may be related (to within 1 nT) to the International Geomagnetic Reference Field at epoch 1976.0 by applying the following correction at the grid points stated and by linear interpolation for intermediate positions.

370 560 : -695 nT   410 590 : -701 nT
410 560 : -700 nT   370 590 : -696 nT

Magnetic field measured by proton precession magnetometer (Sander NPM-5); mean terrain clearance 60 m. Flight line separation 250 m. Fiducial points plotted from 16 mm photography.

The data for this map were recorded digitally and edited, compiled and contoured by automatic computer process. The observed magnetic values were interpolated to a square grid of 2.54 mm before contouring.

Topographic base provided by 1:10,000 or 1:10,560 scale maps published by the Ordnance Survey. © Crown Copyright.

Flying, data reduction and map compilation by
SANDER GEOPHYSICS LIMITED
On contract to N.E.R.C. in 1978

Broken contour lines are at 4nT intervals. Solid contours are at 20nT intervals, and are thickened at 100nT intervals. The '0' contour is doubly thickened. Local magnetic lows are indicated by ticked closures. Data were not recorded over the Haydon Bridge built-up area [840 645].

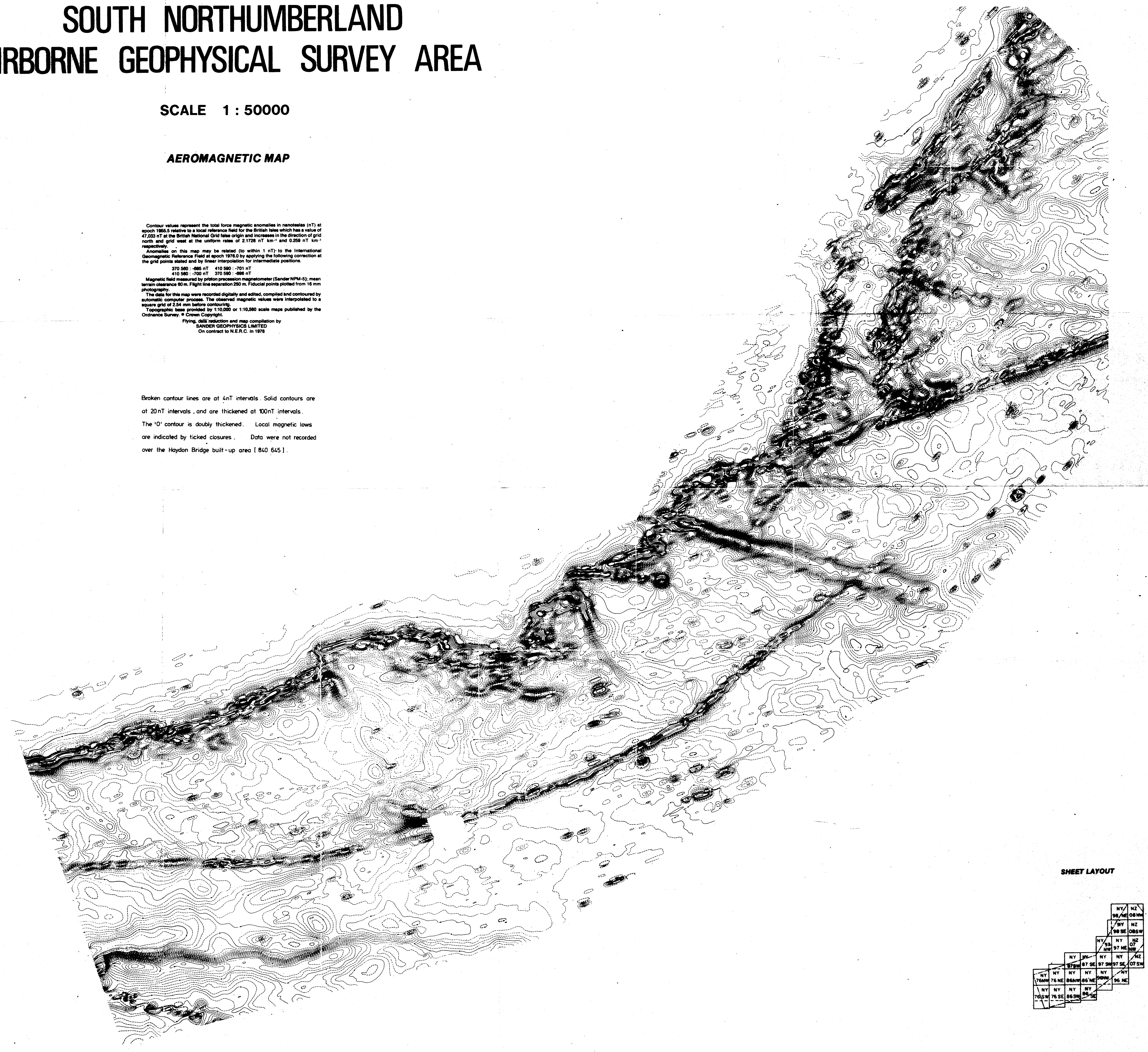

Plate 2

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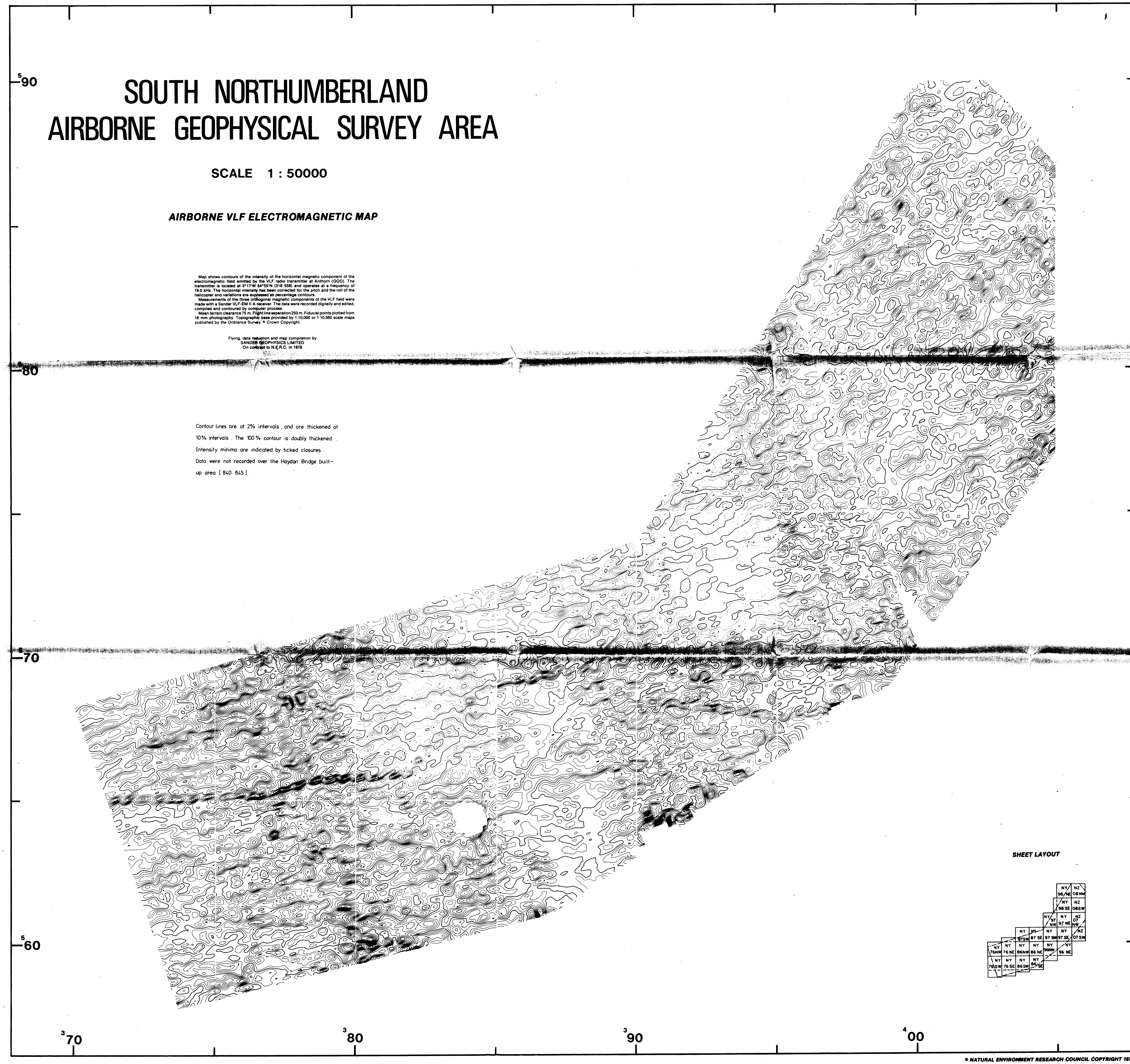

Plate 3

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