Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

INSTITUTE OF GEOLOGICAL SCIENCES

Natural Environment Research Council

Mineral Reconnaissance Programme

Report No. 65

Geophysical investigations in Swaledale, North Yorkshire

Airborne geophysics
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SUMMARY

An airborne geophysical survey was carried out over part of upper Swaledale and the adjacent moorland. The area has a long history of mining and the geology and style of mineralisation are representative of most of the north Pennine orefield. The survey employed magnetic, electromagnetic and radiometric methods, and provided a test of the applicability of airborne geophysical exploration in this environment. Eleven airborne electromagnetic anomalies were followed up with detailed ground surveys; more limited surveys were employed to check several smaller airborne indications. At two sites the follow-up surveys recorded anomalies sufficiently significant to be considered possible indications of mineralisation. One of these, at Oxnop Gill, was tested by core drilling, but no evidence of significant mineralisation was found. The other site, Whirley Gill, was not drilled, and the anomalies, although promising, remain unexplained. Of the remaining airborne anomalies, some were not detectable on the ground and others were considered to be due to stratigraphical or artificial conductors. It is concluded that the particular airborne EM system employed is not an effective tool in exploration for new mineral veins of the kind known in the northern Pennines.

INTRODUCTION

Swaledale was one of six areas in the northern Pennines to be covered by airborne geophysical surveys aimed at establishing further base metal potential in the districts and effective means of identifying favourable indications of deposits. Whilst other airborne surveys covered parts of the major fault lines bounding the Alston and Askrigg blocks (Cornwell and Wadge, 1980; Cornwell and others, 1978; Wadge and others, 1983), the survey in the Swaledale area covered part of the extensive mining field of the Keld–Reeth–Askrigg district, where vein-type mineralisation, generally Pb and Zn, has been worked in Lower Carboniferous sediments. The elevated moorland which predominates in the survey area, carrying a thin cover of drift deposits, was considered a suitable environment in which to test the response of the airborne electromagnetic system to geological features which are typical of the mining districts of the northern Pennines. The airborne survey also offered the possibility of locating previously unrecorded mineral veins, as well as extensions to those exploited in the past. Furthermore, part of the survey area was oriented along the line of the Stockdale Monocline. This structure is considered to mark the boundary between the Askrigg Block to the south and the Stainmore sedimentary basin to the north (Figure 1), thus inviting comparison with the structural setting of some of the major base metal deposits in the Lower Carboniferous rocks of Eire.

GEOLOGY

As elsewhere in the northern Pennines, the stratigraphy of the Dinantian rocks in the Swaledale area is determined by the disposition of contemporaneous blocks and basins. In the north, the Stainmore Trough is characterised by a thick succession containing a relatively high proportion of clastic rocks. Although the lower part of the Dinantian sequence is not exposed, comparison with similar areas suggests that sedimentation began early and that thick evaporites may well have accumulated in the basin. To the south, the Askrigg Block is overlain by a thinner Dinantian succession. The Wensleydale Granite forms the core of the block and, although it is not exposed at the surface, it was proved in the Raydale borehole about 6 km south-west of Askrigg (Figure 1). The granite is end-Silurian in age and is marked by a strong Bouguer gravity anomaly low (Dunham, 1974) which suggests that it extends beneath the Lower Carboniferous rocks as far north as Askrigg. The boundary between the Stainmore Trough and the Askrigg Block is not well defined, but it probably lies close to the Stockdale Monocline (Figure 1) which is aligned E–W approximately through Muker in upper Swaledale. Certainly this structural line appears to lie along the eastward continuation of the margin of the Ravenstonedale trough, west of the Dent Fault.

Across both block and basin, the rocks are generally flat-lying and the regional north-easterly dip rarely exceeds 5°. Near to faults, however, the beds may be more steeply inclined, with dips locally close to vertical. Faults are commonly aligned E–W or NW–SE, with a subsidiary set trending NNW–SSE, and throws are rarely substantial. Most mineral veins occur along faults,

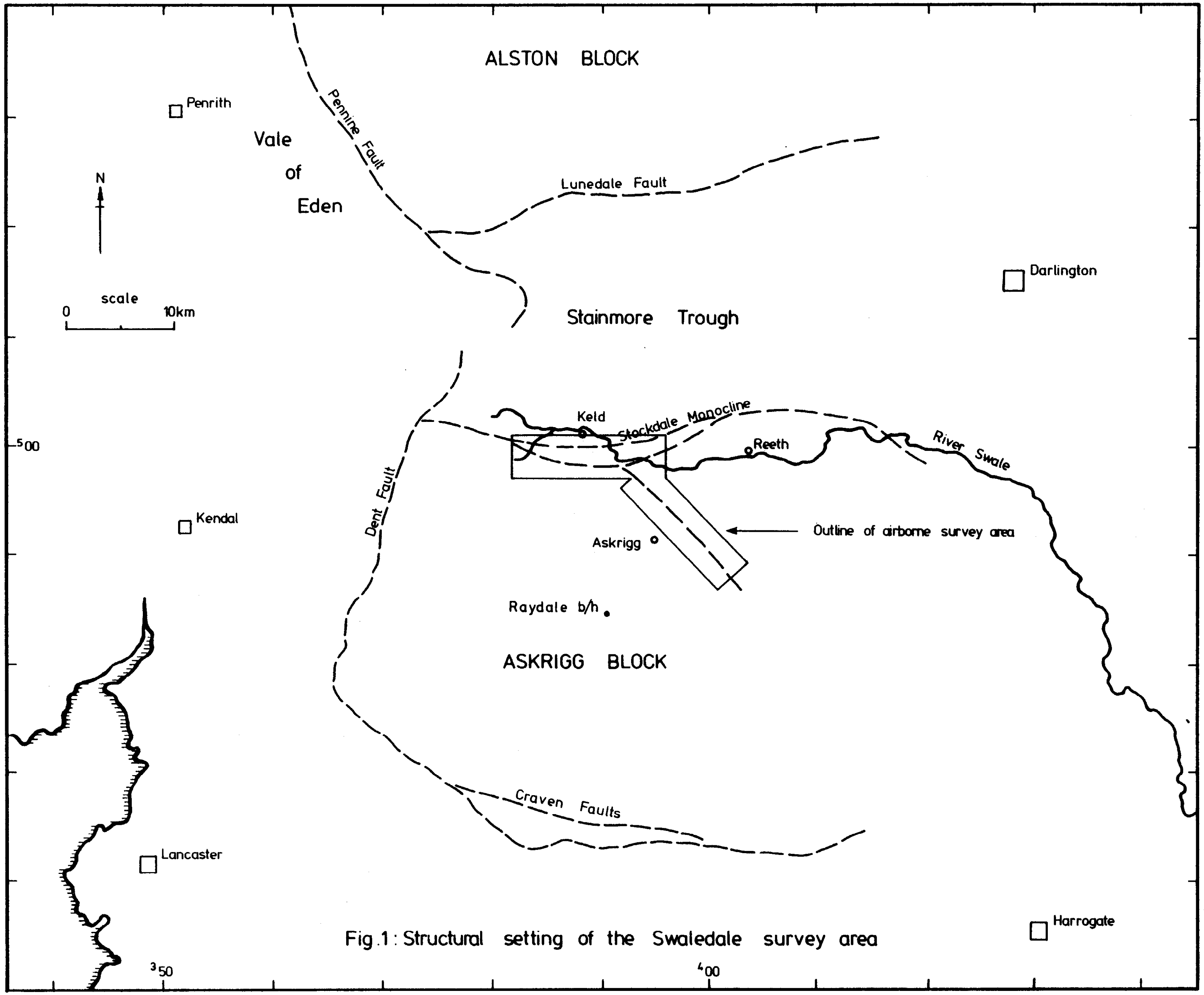


Fig.1: Structural setting of the Swaledale survey area

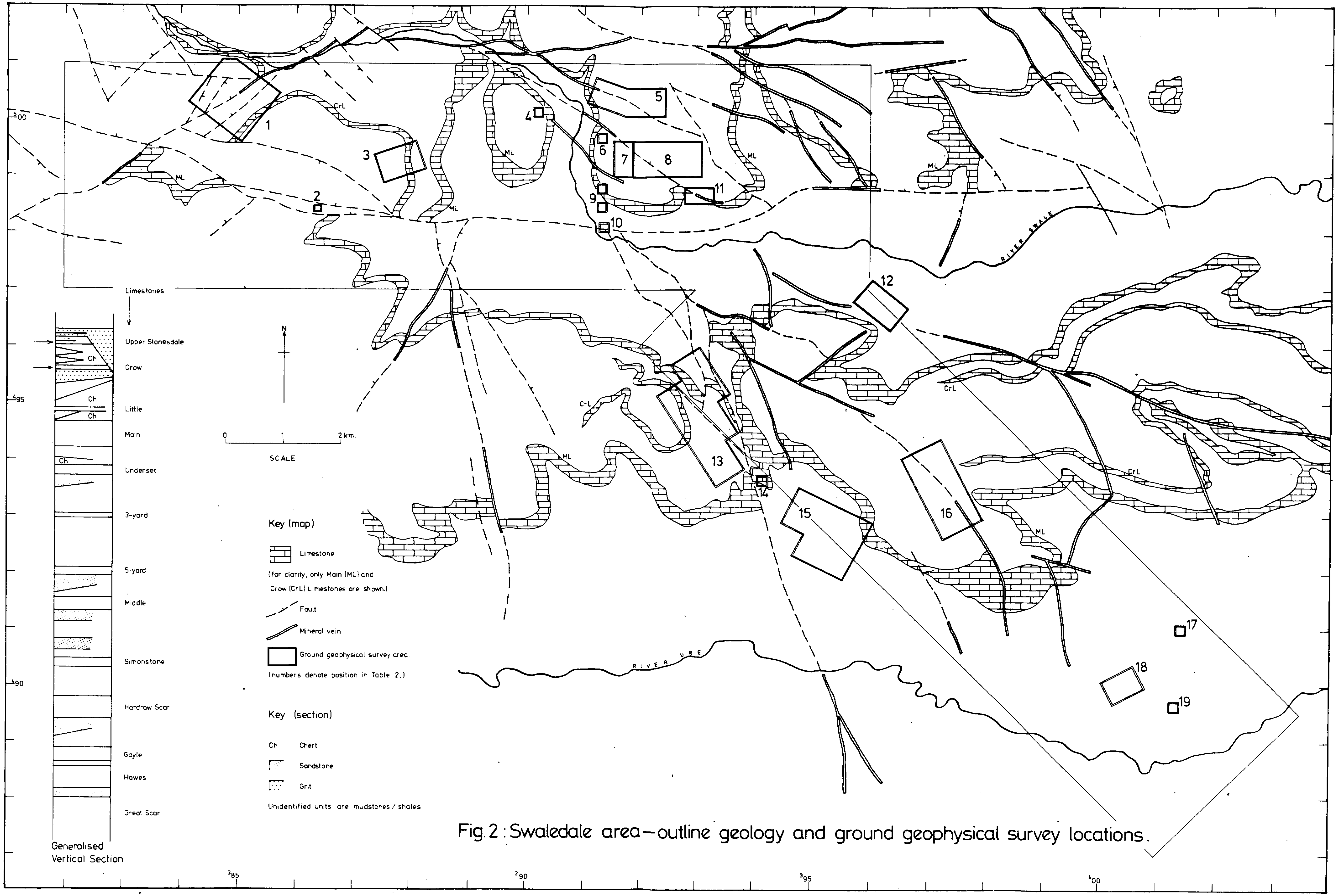


Fig. 2 : Swaledale area—outline geology and ground geophysical survey locations.

although some appear to be located on major joints.

The stratigraphy of the area is shown in Figure 2 and comprises the upper part of the Dinantian Alston Group and the lower part of the overlying Namurian Millstone Grit. The sequence is cyclical and, since the early days of geology, it has been known as the Yoredale facies (Phillips, 1836). Each cyclothem contains a marine limestone, generally a biomicrite or calcilutite with abundant crinoidal debris or reefal growths, and locally calcarenites or pseudobreccias may be developed. Calcareous, silty mudstones generally overlie the limestones and pass up gradually into pyritic mudstones. These are succeeded by finely banded siltstones and then sandstones, with perhaps a seatearth and thin coal developed at the top of the cyclothem. Each cycle represents a marine carbonate incursion followed by the re-establishment of brackish or non-marine, deltaic, clastic sedimentation. Syn-sedimentary chert is widespread, scattered in irregular patches and developed concordantly along the bedding, particularly just above the Main Limestone (Main Chert) and above the Little Limestone (Richmond Chert).

The principal valleys of the area were occupied by valley glaciers during Devensian times, and overconsolidated ground moraine is widespread on the low ground. In addition, morainic mounds, eskers and spreads of fluvioglacial sand and gravel remain from the de-glaciation of the valleys. The moors are largely free of extensive sheets of till but solifluction debris is widespread. Blanket peat covers much of the moors, especially where the drainage is poor, and is generally 1 to 3 m thick although local hollows may hold much thicker accumulations.

During much of the 19th century Swaledale supported a vigorous lead-mining industry. Between 1860 and 1870, annual production averaged about 5000 tons of Pb, an output comparable at the time with that of any of the other Pennine mining fields. Subordinate Zn and minor amounts of Ba and Cu were also produced from the veins and flats. The most productive host-rock was undoubtedly the Main Limestone but ore was also found in some of the underlying limestones and in the thick sandstones higher in the sequence. By the turn of the century, mining had largely ceased. Those veins most accessible by adit from the steep-sided valleys had been largely worked out, although many veins remained unproved across the broader interfluves. It appears from the old records that the mineralisation tended to die out downwards although the Middle Limestone and limestones underlying it, which should be suitable host-rocks, are almost entirely untested.

It seems likely that the base metals were deposited from metalliferous chloride-rich brines derived from the deep Lower Carboniferous sedimentary basin to the north (Small, 1978; Vaughan and Ixer, 1980). The low temperatures at which the minerals were emplaced (92–159°C) (Rogers, 1978) are consistent with this view. The brines were presumably concentrated at about the horizon of the Main Limestone under fluid pressure and were able to circulate and react with the source of sulphur within the massive, well-jointed and faulted rock. The broad circulation of brines from the basin on to the block may have been driven by the relatively high heat-flow through the Wensleydale Granite. The Stockdale Monocline, as a probable basin-margin structure, presents two types of target for mineral exploration. Firstly, it is likely that there are veins, as yet undetected, within suitable host-rocks on the upthrow side of the structure. These are probably best sought on the flatter parts of the moors or on the broad interfluves, where their outcrops may be obscured by thin superficial deposits. Secondly, it is possible that there are disseminated sulphides occurring low in the sequence on the downthrow side of the structure. The penetration of the geophysical techniques used here is too shallow to detect that type of mineralisation.

AIRBORNE GEOPHYSICAL SURVEY

SURVEY METHODS

The airborne survey was carried out by Hunting Geology and Geophysics Limited, using helicopter-borne equipment. The latter comprised a magnetometer, gamma spectrometer and co-axial vertical loop electromagnetic (EM) system, together with radio altimeter and positioning camera. The ground clearance of the helicopter was a nominal 61 m. The magnetic and EM equipment was suspended by cable beneath the helicopter to give an effective ground clearance for these systems of 46 m and 30 m respectively; the spectrometer was carried on board. Full details of the instrumentation are given in Burley and others (1978).

A total of 578 km of survey line was flown, including tie lines, with flight lines spaced 200 m apart. The area covered (approximately 98 km^2) was divided into two blocks (Figures 1, 2), to follow the local structural features as these trend east-west then south-east along the line of the Stockdale Monocline. The flight lines in each block were oriented approximately normal to the predominant trends of the known mineral veins. Thus, in the western part of the survey area north-south flight lines cover part of the major fault known as the Stockdale Vein; in the eastern part, flight lines aligned at 045° cover the belt of mineralised ground extending from Muker in Swaledale to Carperby in Wensleydale.

The full National Grid References of the points defining the boundaries of the survey area are as follows:

i area of N–S flight lines: [^{3}820 ^{4}970, ^{3}930 ^{4}970, ^{3}945 ^{4}985, ^{3}960 ^{4}970, ^{3}960 ^{5}010, ^{3}820 ^{5}010].

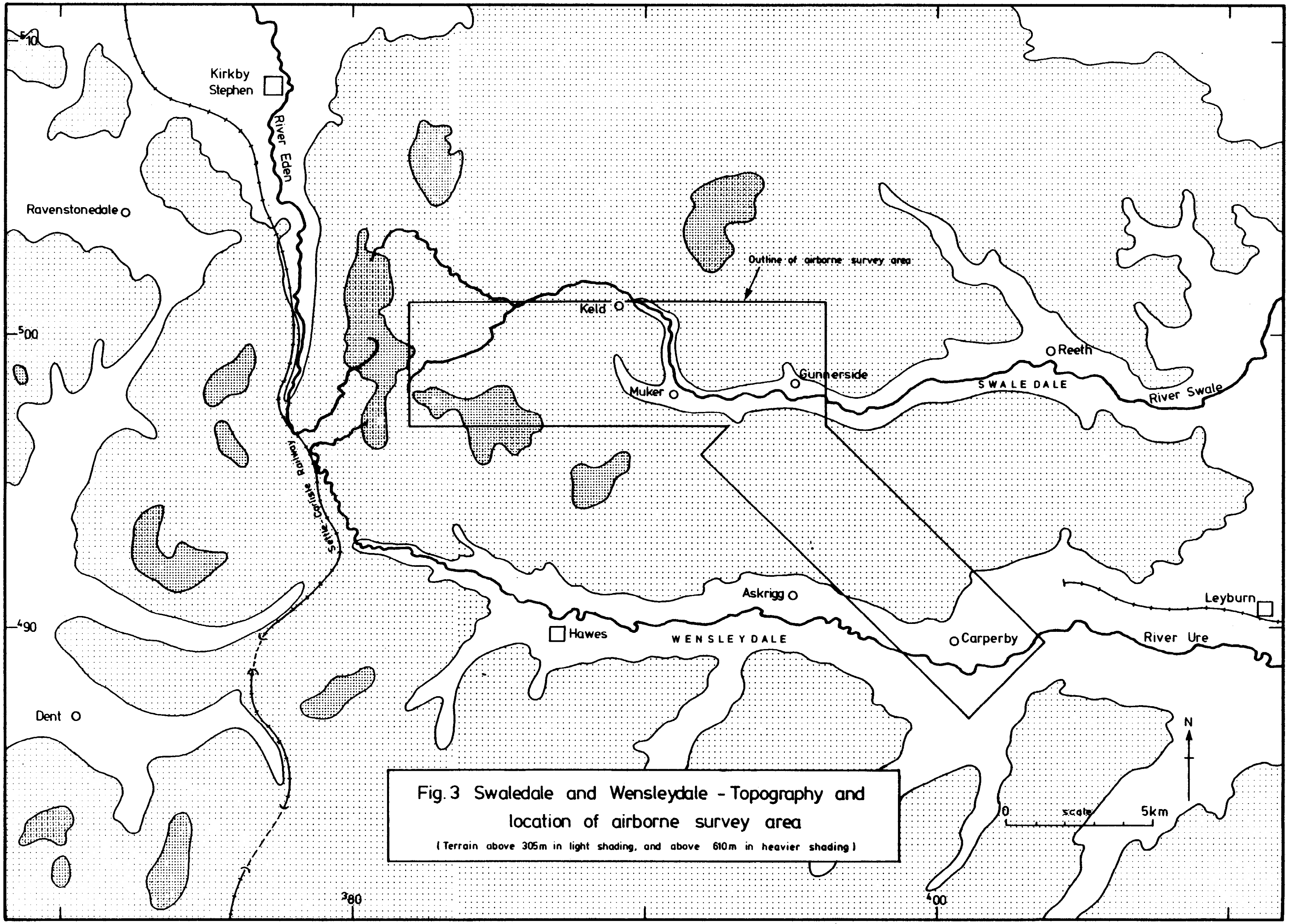


Fig. 3 Swaledale and Wensleydale - Topography and location of airborne survey area

(Terrain above 305m in light shading, and above 610m in heavier shading)

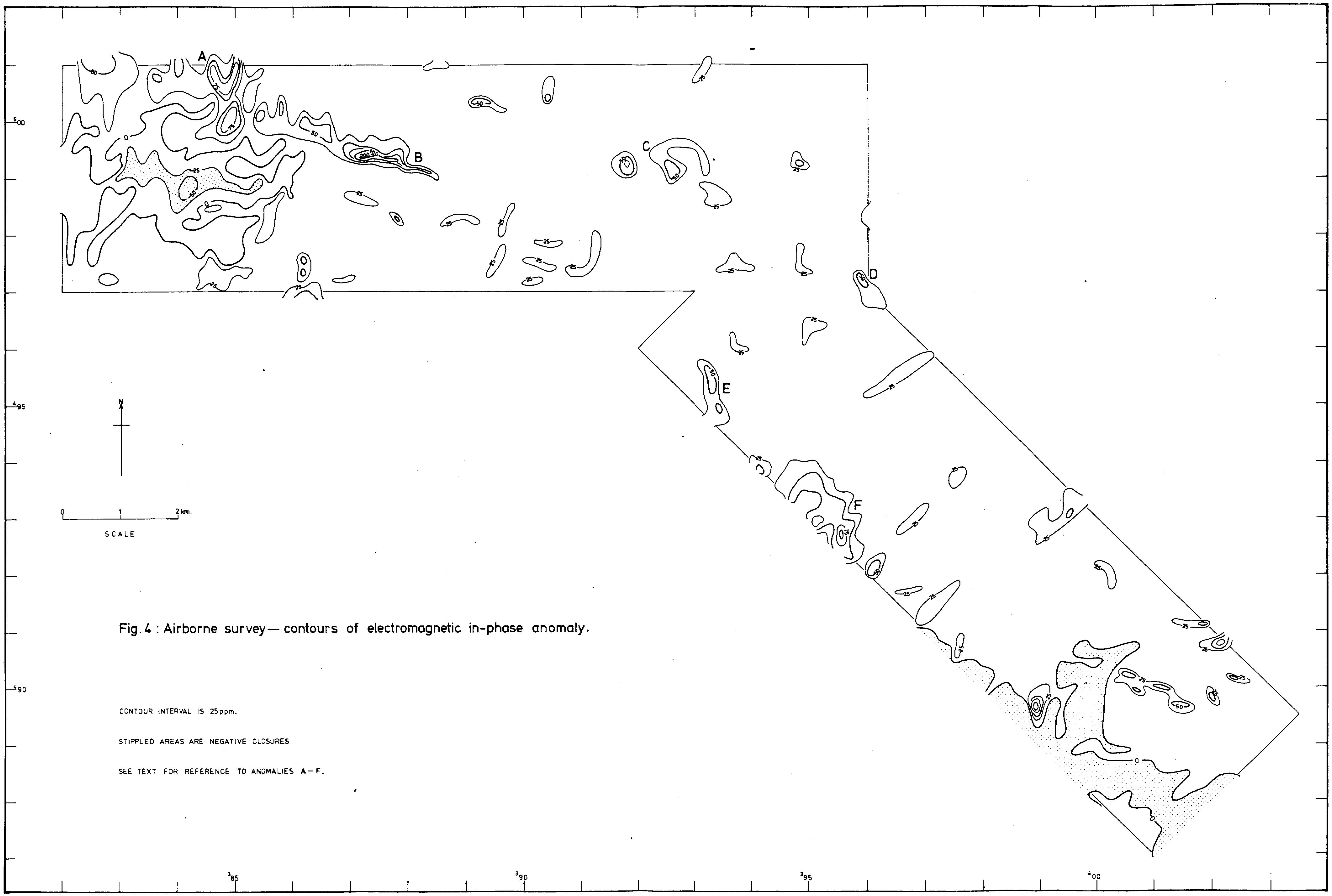


Fig. 4 : Airborne survey— contours of electromagnetic in-phase anomaly.

ii area of NE–SW flight lines: [^{4}010 ^{4}870, ^{4}034 ^{4}895, ^{3}945 ^{4}985, ^{3}920 ^{4}960].

The topography of the area (Figure 3) presented no serious problems for the survey. Elevations ranged from about 150 m above OD near Carperby to about 700 m on Great Shunner Fell [850 970] though slopes are generally fairly smooth, particularly on the higher ground. The valley sides of the deeply-incised River Swale around Muker and Gunnerside provide the steepest terrain. Habitation is confined to the valley bottoms of Swaledale and Wensleydale, as are the common sources of artificial geophysical anomalies such as power lines and water pipes.

MAP COMPILATION

Magnetic, electromagnetic (EM) and radiometric data were measured continuously along each flight line, and were recorded and annotated in flight on analogue paper charts. The magnetic and EM data were compiled into map form at the 1:10 560 scale by manual processing of the flight records by the survey contractor. The magnetic maps show contours of total force magnetic anomaly at intervals of 5 nT. Contour values represent departures from the normal field used for the published 1:625 000 map (Geological Survey of Great Britain, 1965), adjusted to compensate for secular changes. The EM maps show contours of the in-phase component of the EM anomaly in ppm of the primary field. Contours are at intervals of 25 ppm, and are relative to a datum level selected by inspection of the records. The locations of individual anomaly peaks are also shown, and are classified by the sign and magnitude of the ratio of in-phase component to out-of-phase component. Both sets of maps are superimposed on a subdued topographic base. Thirteen maps cover the area, each corresponding to a 5 km × 5 km Ordnance Survey map sheet. The radiometric data remain in the form of original analogue flight records.

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

RESULTS

Magnetic data

The magnetic data show no significant anomalies. Indeed, over parts of the area there is no measureable magnetic gradient. Only in the area of map sheet SD89NW is there signficant gradient, rising to approximately 10 nT/km in a south-south-west direction. This pattern is consistent with the results of the aeromagnetic survey of Great Britain (Geological Survey of Great Britain, 1965) which show the Swaledale area to lie close to the centre of a broad magnetic low; which passes southwards onto the northern flank of the sharp Ribblehead anomaly centred some 16 km south-west of Hawes. This magnetic evidence suggests that the basement rocks in the Swaledale area are probably non-magnetic Lower Palaeozoic sediments.

Electromagnetic data

The electromagnetic maps supplied by the contractor were reduced and simplified to produce the map shown in Figure 4. To preserve clarity, the flight lines and the symbols indicating the anomalous in-phase/out-of-phase ratios are omitted. The 'zero' contour has been omitted from most of the map, as this generally defines areas – up to approximately 1 km^2 – of irregular shape, where the background level of EM response falls slightly below the selected datum. The delineation of these areas generally has no geological significance. The zero contour has, however, been retained where it defines two rather larger areas. The first is centred on [842 988], and is a low of considerable extent, with a minimum of less than -50 ppm and a clear linear trend indicated by the -25 ppm contour. The second low is in the extreme south-east of the area, where the area within the zero contour is occupied entirely by strong negative anomalies related almost certainly to artificial features (most probably power lines) in the vicinity of the villages of Carperby and Aysgarth.

Also omitted from Figure 4 are near-circular closures (generally at 25 ppm) representing isolated anomalies on single flight lines. They have no evident relationship to nearby anomalies and are therefore of no apparent geological significance. Similarly, anomalies identified by the contractor (with an 'A' symbol on the original maps) as having characteristics indicative of a non-geological origin are also omitted from the electromagnetic map.

INTERPRETATION OF ELECTROMAGNETIC DATA

The compiled maps of EM in-phase component and anomaly ratio were not sufficient alone to permit satisfactory appraisal of the significance of the various anomalies recorded; interpretation of the maps necessitated reference to the original flight records. With the in-phase component contours spaced at 25 ppm, anomalies are often defined by only two or three contour closures, whilst the classification of anomalies by the ratio symbols often indicates several minor peaks within a single contour closure. The flight records were thus examined to identify such individual anomaly peaks. In addition, they were examined to classify anomalies, for example by shape, so that weaker anomalies, not of sufficient amplitude to appear as contour closures, could be correlated between flight lines. Examination of the flight records also provided an appreciation of the relative characteristics of the in-phase and out-of-phase responses.

Interpretation also demanded reference to the geological maps (Sheet Nos 40 and 41, 1:63 360

scale) to assess the extent to which the presence of particularly conductive stratigraphical horizons has influenced the anomaly pattern.

The following sections offer a general discussion of the interpretation of the EM data, dividing the anomalies into three categories.

Stratigraphical anomalies
There are indications that some of the airborne EM anomalies are related to particular stratigraphical members, although these correlations are local and do not apply to the whole survey area. Those anomalies which seem to arise most clearly from the stratigraphy are seen in the north-western part of the area. For example, the broad anomaly extending WNW from Skeugh Head coincides with the position of the mudstones immediately above the Crow Limestone [854 998 to 880 996]. Further west, in Keld Calf Pasture [848 008] the outcrop of the same mudstones is approximately outlined by the 25 ppm contour. Since these mudstones do not crop out so broadly elsewhere within the survey area, the correlation cannot be tested further. Also of interest in this category of anomaly is the negative feature centred at [842 988]. Its extent is such as to suggest a broad zone of anomalous conductivity that might be expected from a shallow-dipping member of the sedimentary succession. The location of the anomaly precludes either an artificial source or a topographical effect. The breadth of the anomaly makes it unlikely that it is caused by a narrow linear feature, though the anomaly is approximately bounded to the north by the line of the Stockdale Vein. Comparison with the geological map shows that the centre of the anomaly coincides approximately with a broad outcrop of the Main Limestone in upper Great Sleddale. However, no anomalies of this extent and amplitude occur elsewhere along the outcrop of the Main Limestone.

The relatively low incidence of possible stratigraphical anomalies provides an interesting contrast with the results of the airborne survey in the Craven area (Wadge and others, 1983), where a broad correlation between AEM response and stratigraphy is apparent. This contrast can probably be attributed to two factors. The Bowland Shales and the limestone outcrops in the Craven area occur over broad areas, readily resolvable in terms of their respective EM responses, whereas in the Swaledale area the responses of the succession of thin limestones, sandstones and mudstones cannot easily be resolved. Secondly, the shale-limestone contacts in the Craven area, particularly along the line of the Craven faults or on the flanks of the steeply sided reef-knolls, provide a moderately to steeply dipping conductivity contrast more readily detected by the coaxial loop airborne EM system than the nearly horizontal discontinuities between the beds of the Swaledale area. However, particular circumstances may provide exceptions to the above general observations. For example, a thin conductive bed turned up along a fault would give rise to a narrow linear anomaly, belying the essentially stratigraphic cause. Flanking beds of more resistive rocks would serve better to define the response from such a feature.

Artificial anomalies
There are numerous anomalies on the EM maps which are artificial, arising from man-made features. The two principal and readily identifiable sources of such anomalies are metal water-pipes and high voltage overhead power-lines. The former give rise to positive anomalies (both in-phase and out-of-phase) not always distinguishable from anomalies due to geological features, and power-lines produce characteristic, usually very strong anomalies (in-phase negative, out-of-phase positive) which can be recognised from the chart records as being of non-geological origin. The power-line anomalies have thus been identified by the survey contractor at the data compilation stage and are indicated on the contour maps. Such anomalies are omitted from the compilation map (Figure 4), though the '0' contour north and east of Aysgarth [002 884] defines the position of a large group of such anomalies.

Anomalies of possible economic significance
There are no instances of anomalies coincident with known veins and which are sufficiently well defined to suggest the possibility of mineralisation still existing *in situ*. Without detailed information on the levels of extraction at the numerous mines in the area, it is not possible to assess the likelihood of quantities of ore remaining along each of the known veins. It is nevertheless considered probable that such un-mined ore does remain, especially across watersheds. The absence of anomalies may indicate that mineralisation is sparse or that signficant quantities of ore are present only at too great a depth for detection. However, there are several airborne EM anomalies which seem to be related indirectly to known mineral veins. They either trend parallel to proved veins or branch from them. Several of these anomalies can be distinguished on the EM anomaly contour map (Figure 4), and these are listed and described briefly below (see Table 1 for grid reference):

Anomaly A (Keld Calf Pasture) A local high occurs within the possible stratigraphical anomaly (already described), in the immediate vicinity of a group of ENE-trending veins, and may indicate further veins hereabouts.

Anomaly B (Skeugh Head) A strong ESE-trending anomaly lies within the possible stratigraphical anomaly described above. Both anomalies are approximately parallel to the Stockdale Vein 1 km to the south.

Anomaly C (Gunnerside Pasture) The western limb of this arcuate anomaly lies close to an ESE-

Table 1 Ground geophysical surveys

Area [NGR]	*Target*	*Methods*	*Line km*	*Line separation*
Keld Calf Pasture [848 006]	Broad AEM anomaly up to 75 ppm in previously mined area	Slingram EM, 1600 Hz, 30 m stns.	12	100 m
		Turam. 220 & 660 Hz, 40 m stns.	5	160 m
		VLF-EM. 25 m stns.	1	100 m
Stockdale [864 985]	25 ppm AEM anomaly	Slingram EM, 1600 Hz, 30 m stns.	1	100 m
Skeugh Head [878 993]	Intense elongate 100 ppm AEM anomaly	Turam, 660 Hz, 30 m stns.	5	100 m
North Gang Scar [904 001]	Small AEM anomaly coincident with mapped vein	VLF-EM. 15 m stns	1	100 m
Ivelet Moor [916 003]	Weak AEM anomaly coincident with mapped fault	Turam. 220 & 660 Hz, 40 m stns.	3	160 m
		VLF-EM 15 m stns	4	100 m
Iveletside (1) [913 997]	Small AEM anomaly coincident with mapped vein	VLF-EM. 5 m stns	0.25	–
Peat Moor Rigg [918 993]	25 ppm AEM anomaly	VLF-EM. 15 m stns	1.75	100 m
Gunnerside Pasture [925 995]	Scattered AEM anomalies up to 25 ppm	Slingram EM, 880 & 2640 Hz, 60 m stns.	5	200 m
Iveletside (2) & (3) [914 987]	Small AEM anomalies	VLF-EM. 15 m stns	2.5	–
Iveletside (4) [924 981]	25 ppm AEM anomalies	EM-15 continuous monitoring	0.5	–
Ivelet Beck [931 986]	AEM anomalies on line of fault	VLF-EM. 15 m stns	1	–
Crackpot Moor [961 969]	Elongated AEM anomalies up to 50 ppm	Turam, 660 Hz, 40 m stns.	3	160 m
Oxnop Gill [935 949]	AEM anomalies up to 75 ppm	Turam, 220 & 660 Hz, 30/40 m stns.	17.5	100 m
		VLF-EM. 15 m stns	5	100 m
		Slingram EM, 880 & 3520 Hz, 30 m stns.	1	–
Askrigg Common [942 938]	Scattered AEM anomalies up to 50 ppm	VLF-EM. 15 m stns	1.5	100 m
Green Mea [955 928]	Broad AEM anomalies up to 100 ppm	Turam, 220 & 660 Hz, 30/40 m stns.	10	100 m
Whirley Gill [971 937]	25 ppm AEM anomalies	Turam, 220 & 660 Hz, 40 m stns.	3	160 m
		VLF-EM. 15 m stns	4.5	100 m
West Bolton [016 911]	Intense AEM anomaly	EM-15 continuous monitoring	0.5	–
Carperby (1) [005 902]	Small scattered AEM anomalies	Slingram EM, 1600 Hz, 30 m stns.	3.5	100 m
Carperby (2) [015 897]	Small scattered AEM anomalies	EM-15 continuous monitoring	0.5	–

trending branch of the major E–W vein system, 2 km to the north, and may mark undetected veins with a similar trend.

Anomaly D (Crackpot) A SSE-trending anomaly is approximately aligned with similarly-trending veins some 2 km distant on the opposite (north) side of the Swale valley.

Anomaly E (Oxnop Gill) A SSE-trending anomaly coincides with a major fault. Similarly-trending faults approximately 1 km to the east at Summer Lodge are mineralised.

Anomaly F (Green Mea) A broad high is approximately aligned with the extension of a group of SSE-trending veins at Summer Lodge.

Anomalies in several other areas, apparent only from inspection of the flight profiles, were also considered to be of possible economic significance, though rather less promising than the anomalies listed above because of their smaller amplitude and limited linear extent. These areas are as follows:

Ivelet Moor and Whirley Gill At these two localities, rather irregularly distributed anomalies of less than 25 ppm broadly mark mapped faults which extend from known veins.

Ivelet Beck Well defined in-phase anomalies of small amplitude coincide with a mapped vein on two adjacent flight-lines.

At *North Gang Scar* and *Ivelet Side* 'single point' in-phase anomalies coincide with mapped veins. Other comparable anomalies occur also on Ivelet Side further south, and at *Stockdale* on the line of the Stockdale Vein.

Other anomalies with a favourable strong in-phase response are seen at *Carperby* and *West Bolton,* though the proximity of these anomalies to buildings suggest an aritificial source such as a water pipe.

GROUND GEOPHYSICAL SURVEYS

Following assessment and preliminary interpretation of the airborne EM data, areas were selected for ground survey to confirm the presence of specific EM anomalies and to define them more accurately. The areas selected included those described above where there was some indication that the airborne anomalies were related to known mineralised structures; and other areas were selected to test possible correlations between the airborne anomaly pattern and the stratigraphy. Several weak, though discrete, anomalies were thought likely to have artificial causes and these were checked on the ground. They were not characterised as artificial by the contractor but were thought likely to be water pipes because they occured close to buildings. A small number of anomalies, again quite discrete but appearing on only single flight lines, was also checked to assess whether they were due to instrumental noise.

There were no difficulties in obtaining access to the selected survey areas. The main valleys are farmed, but the extensive moorlands are used mainly as rough grazing for sheep and for rearing of grouse. Access to the grouse moors is restricted during the breeding and shooting seasons – early spring and August–September respectively. The main valleys are served by minor roads, and several cross the watershed between Swaledale and Wensleydale. Rough tracks allow vehicle access to some of the high ground away from these roads, but over the areas of thick, heavily-dissected peat access is possible only on foot.

Table 1 lists all the areas at which ground geophysical surveys were carried out. The areas of greatest interest are described in the text.

METHODS

The ground surveys employed a range of electromagnetic methods, fixed source (Turam and VLF-EM) and moving-source (Slingram) (Burley and others, 1978). At some sites, traverses were measured with two or three different systems, while at others a single system was considered sufficient. For the more extensive surveys, traverses were laid out where possible on a grid pattern.

Details of the methods used at each site, together with traverse spacing and total line-km measured, are given in Table 1. Further details of the equipment used are listed in Table 2.

For each of the survey sites, traverse location maps at a scale of 1:10 560 (6″ to 1 mile) are available for inspection at the Applied Geophysics

Table 2 Instruments used for ground survey

(a) Fixed source

Turam:	ABEM TS. Operating frequences 220 Hz and 660 Hz. Receiver coil separation 30 m or 40 m. Grounded transmitter cable, length 1 km.
VLF-EM:	Geonics EM-16. Tuned as required to transmission from NAA (17.8 kHz), GBR (16.0 kHz) or FUO (15.1 kHz).

(b) Moving source

Slingram:	Geonics EM-17. Operating frequency 1600 Hz. Transmitter–Receiver coil separation 30.5 m or 61 m.
	ABEM Demigun. Operating frequences 880 Hz and 2640 Hz. Transmitter–Receiver coil separation 60 m.
	ABEM 35–88. Operating frequences 880 Hz and 3520 Hz. Transmitter–Receiver coil separation 60 m.

Slingram (hand-held, single unit): Geonics EM-15. Operating frequency 15 kHz. Transmitter–Receiver coil separation 0.83 m.

Unit of IGS at Keyworth, Nottingham, by arrangement with the Head of Unit. Survey data and accompanying unpublished reports are also available.

OXNOP GILL

The EM in-phase and out-of-phase flight profiles for this area are shown in Figure 5. They include several parallel anomalies, up to 180 ppm out-of-phase and 70 ppm in-phase, the smaller anomalies lying to the south-west. The initial ground follow-up comprised a Turam survey of limited extent which located a strong linear anomaly (A in Figure 6). Extending the area of Turam survey defined further anomalies (B and C on Figure 6) and increased the proven length of anomaly A to about 1.2 km. Note that whilst the airborne anomaly corresponding to A has a strong out-of-phase expression, it is the airborne anomaly corresponding to B and C, with a stronger in-phase response, which is seen on the airborne contour map (anomaly E, Figure 4). Anomaly A has maximum reduced ratios of 1.38 at 660 Hz, 1.28 at 220 Hz with corresponding negative phase differences of -11.9° at 660 Hz and -6.0° at 220 Hz against average background values of about 1.00 (ratio) and -1.0° (phase difference). A steeply dipping, near-surface, moderately good conductor is indicated. Anomaly B is similar in amplitude to A whilst anomaly C is strongly asymmetrical. On the north-eastern side of anomaly C, reduced ratios decrease rapidly from 1.375 to 0.878 at 660 Hz and from 1.203 to 0.913 at 220 Hz. The phase differences across this part of the anomaly increase from -18.0° to +8.5° at 660 Hz and from -8.3° to +0.5° at 220 Hz but part of this effect may be due to interference from the adjacent anomaly.

A VLF-EM survey was conducted across anomaly A (Figure 7) and filtered in-phase data were obtained using the method of Fraser (1969). The areas of high conductivity indicated by the positive linear features in Figure 7 correlate well with anomaly A and indicate a steeply inclined, moderately conductive body. It lies no deeper than 50 m, using a half-width approximation depth estimate. Both Turam and VLF anomalies vary in intensity along the strike of anomaly A, and the strongest points do not necessarily coincide (Figure 8, 9). This may be due in part to the masking effect of the peat which particularly affects the VLF measurements, but it also appears that the conductor itself is inhomogeneous.

A second VLF anomaly to the east of the Turam anomaly A on lines 250N to 450N (Figures 7, 8) marks the shales below the Little Limestone. A VLF traverse across anomalies B and C (Figure 6) gave a profile indicative of shale outcrops (Figure 10). The geology of the area is shown in Figure 11. The rocks are generally flat-lying and range in age from the Underset Limestone up to the Crow Limestone. Anomaly A coincides on the ground with a fault trending NNE though Seavy Bottom (Figure 11). Parallel to the fault, which throws down to the west, is a tight east-facing monocline. This fold forms a prominent scarp feature since the Little Limestone crops out in its core. The fold is well exposed in Nigh Black Hole and other streams southwards towards Whitfield Fell, but the fault is entirely covered by drift and thick peat. After the geophysical work was completed and the area had been geologically mapped in detail, it seemed likely that mineralised ground with a strike-length of about 1.5 km had been detected, particularly since a similar fault of comparable trend passing through Oxnop Beck Head had been extensively worked for Pb.

Accordingly it was decided to test the interpretation by drilling. The considerable problem of transporting a drilling rig across the peat bogs of Seavy Bottom was solved by placing the rig on a broad sledge pulled by a 'Snowcat' tractor with broad caterpillar tracks. Two boreholes were drilled and their logs are summarised in Figure 11. Borehole 1 [9340 9437] was inclined at 60° to the horizontal on a bearing of 280° true, and borehole 2 (approximately 400 m NW of borehole 1) was similarly inclined on a bearing of 200° true, the bearings of the holes being approximately normal to the trends of the anomalies at the respective sites. Borehole 1 intersected faulting at several levels but did not prove any mineralisation apart from scattered grains of pyrite and galena at the horizons shown on the graphic log. The upper part of the section lies in the Richmond Cherts and the lower part, including a seat-earth at about 25 m, probably correlates with the Coal Sills just below the Little Limestone. Borehole 2 just missed the fault, due to an unusual thickness of till beneath the peat, and proved the sequence on the upthrow side down to the beds below the Main Limestone. Again there was little sign of mineralisation.

An experimental EM probe was lowered down borehole 2 when the drilling was completed, as part of a test programme of down-the-hole measurements by Dr M. H. Worthington of the Department of Geology and Mineralogy at Oxford University. The probe was used to check the source of the ground EM anomaly. This work confirmed that the anomaly did not result simply from the contrasting resistivities of the different lithologies, but was probably due to a narrow, sub-linear source. This is almost certainly the fault but it is not clear from these measurements whether or not the structure is mineralised.

WHIRLEY GILL

Several small EM anomalies, up to 25 ppm (in-phase), were defined by the airborne survey. The flight profiles show a number of anomalies with in-phase to out-of-phase ratios of less than

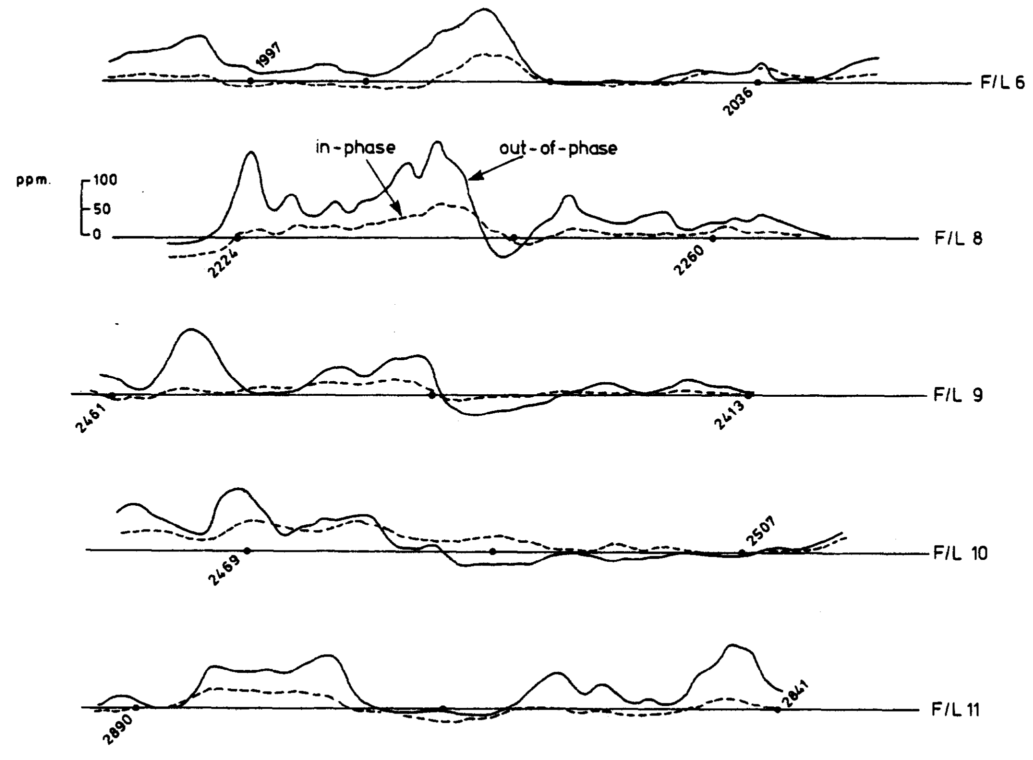
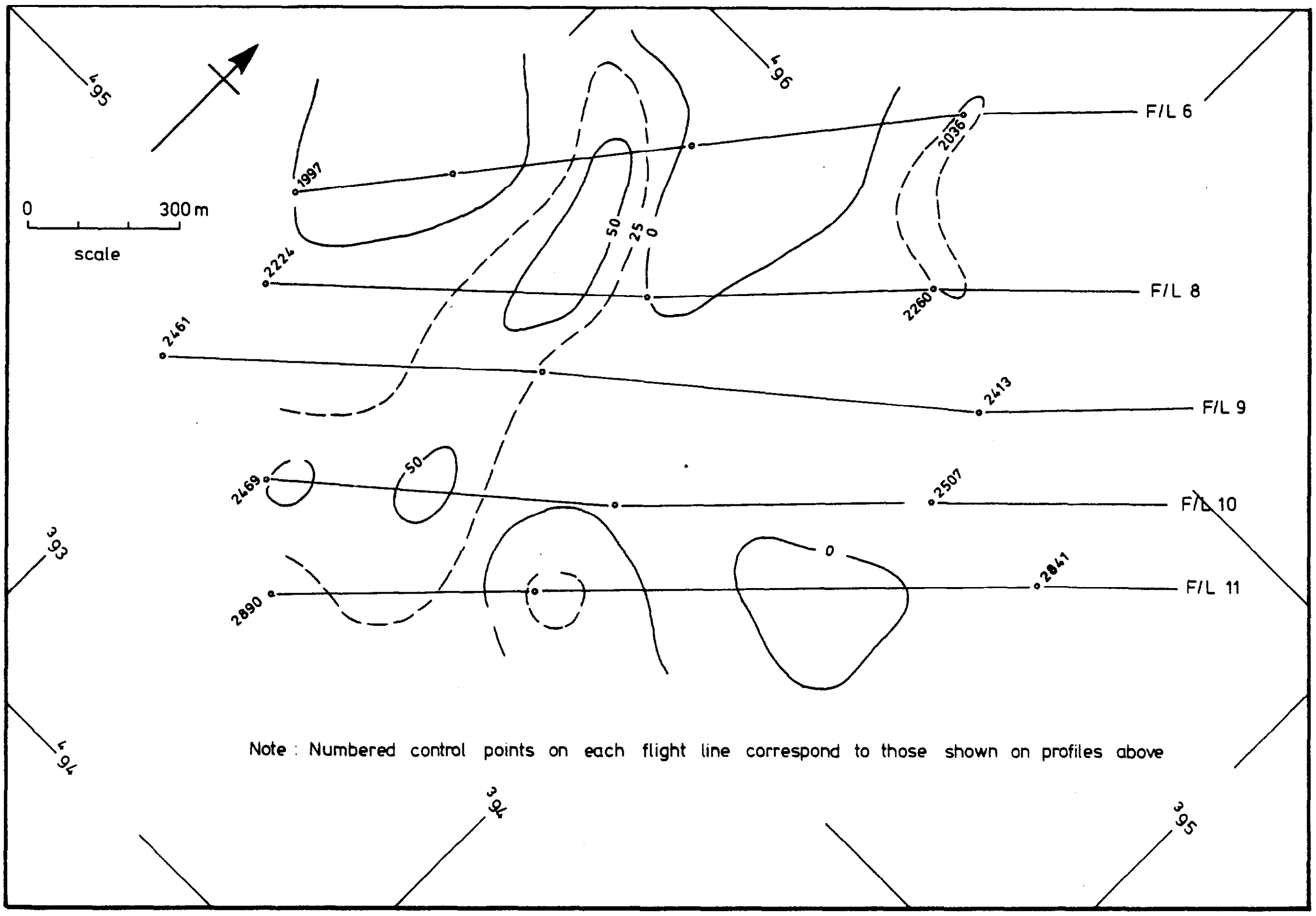


Fig. 5. Airborne EM profiles (above) and contoured in-phase data (below), in the Oxnop Gill area



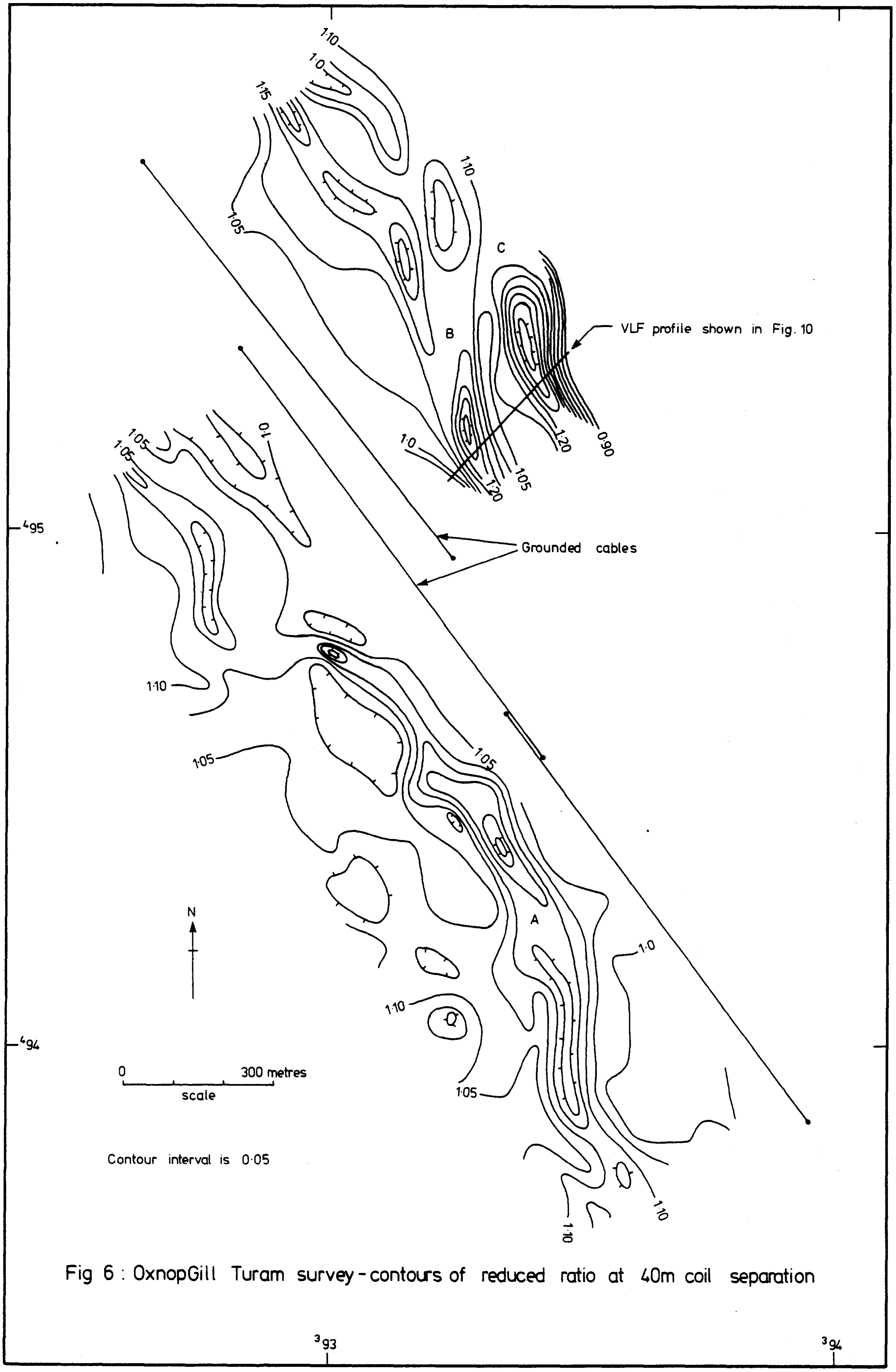


Fig 6 : OxnopGill Turam survey - contours of reduced ratio at 40m coil separation

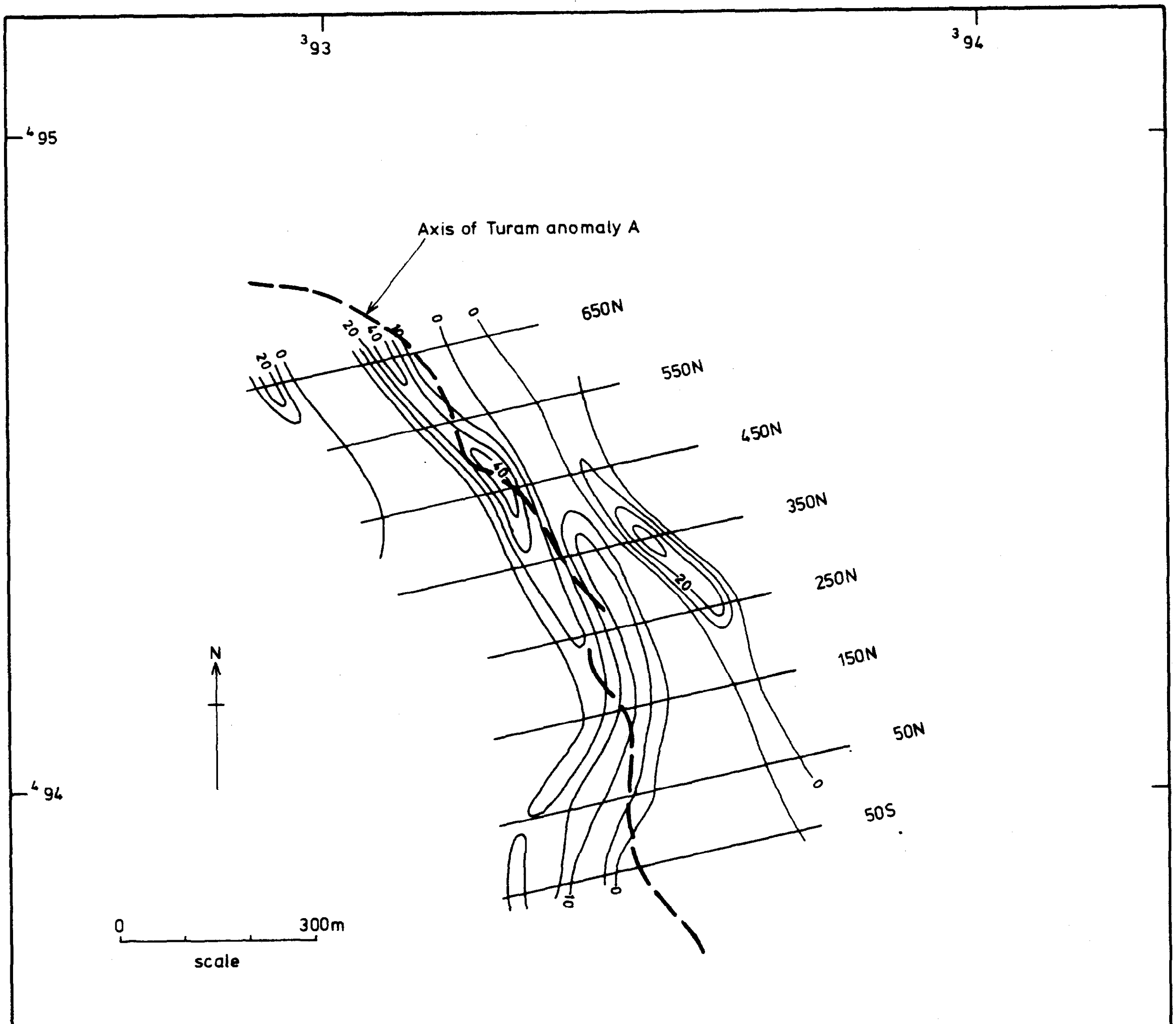


Fig.7 : Oxnop Gill VLF-EM survey — filtered in-phase data — Bordeaux transmitter.

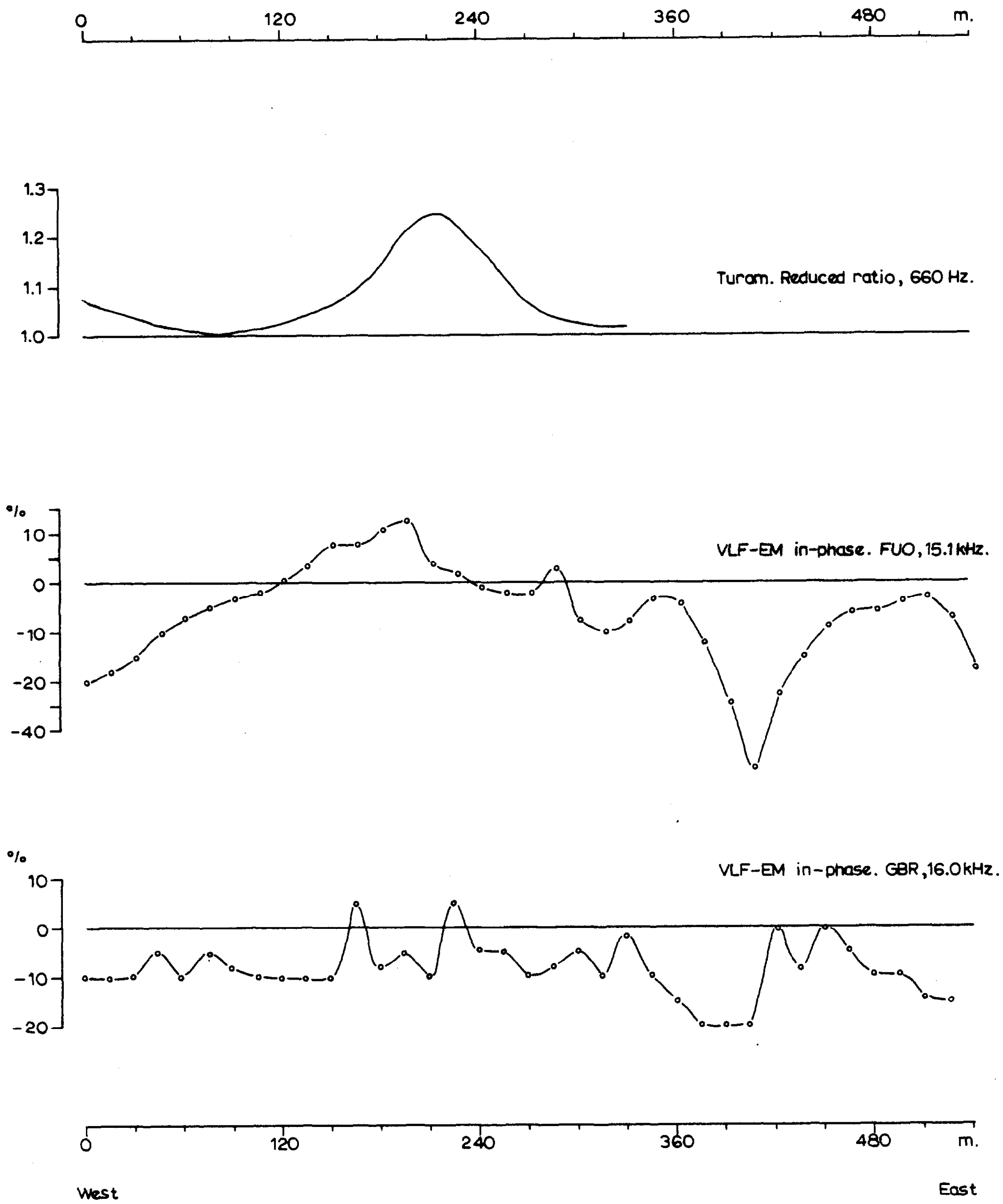


Fig. 8 : Profiles on VLF Traverse 350N at Oxnop Gill.

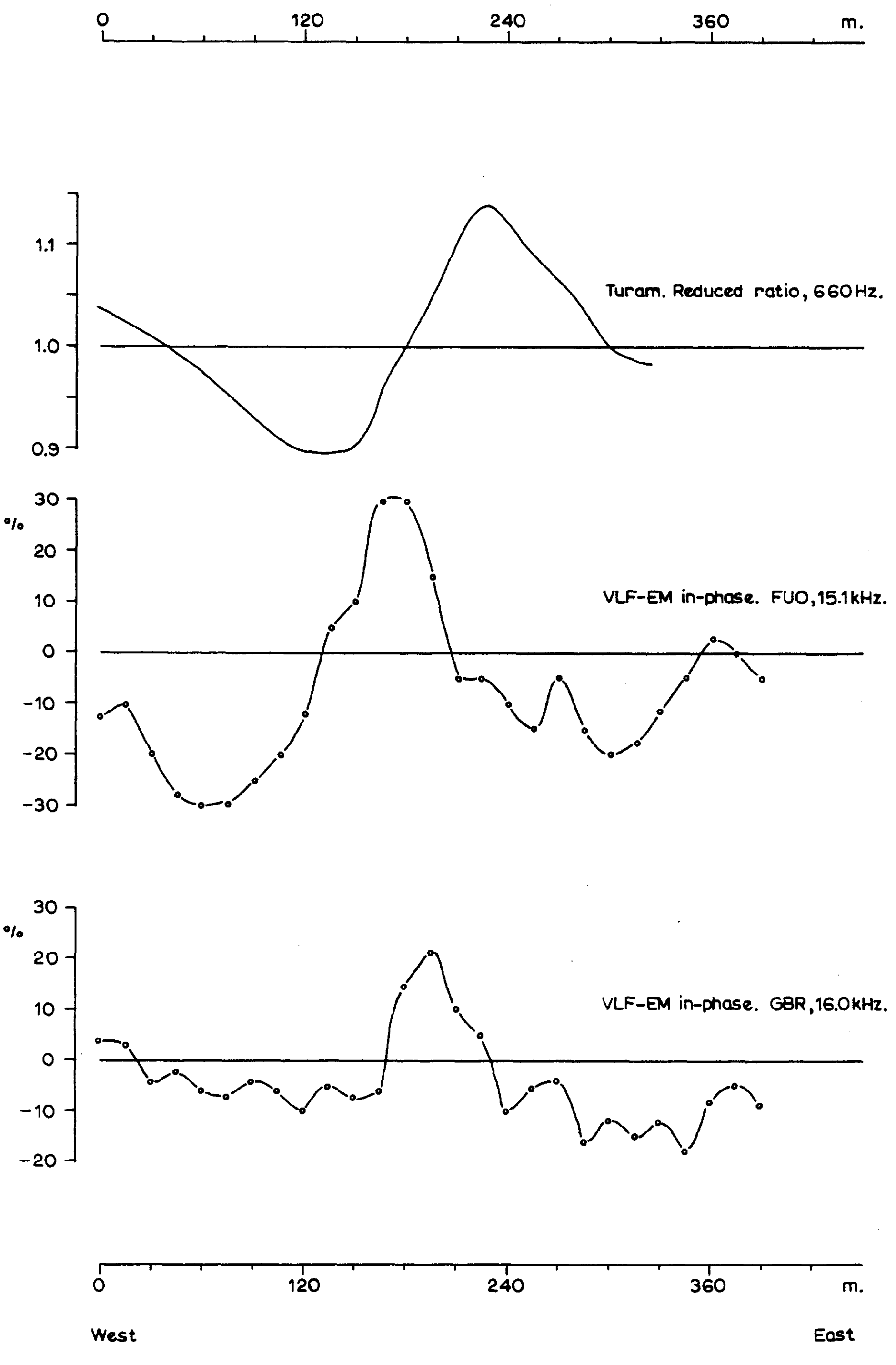


Fig. 9 : Profiles on VLF Traverse 650N at Oxnop Gill.

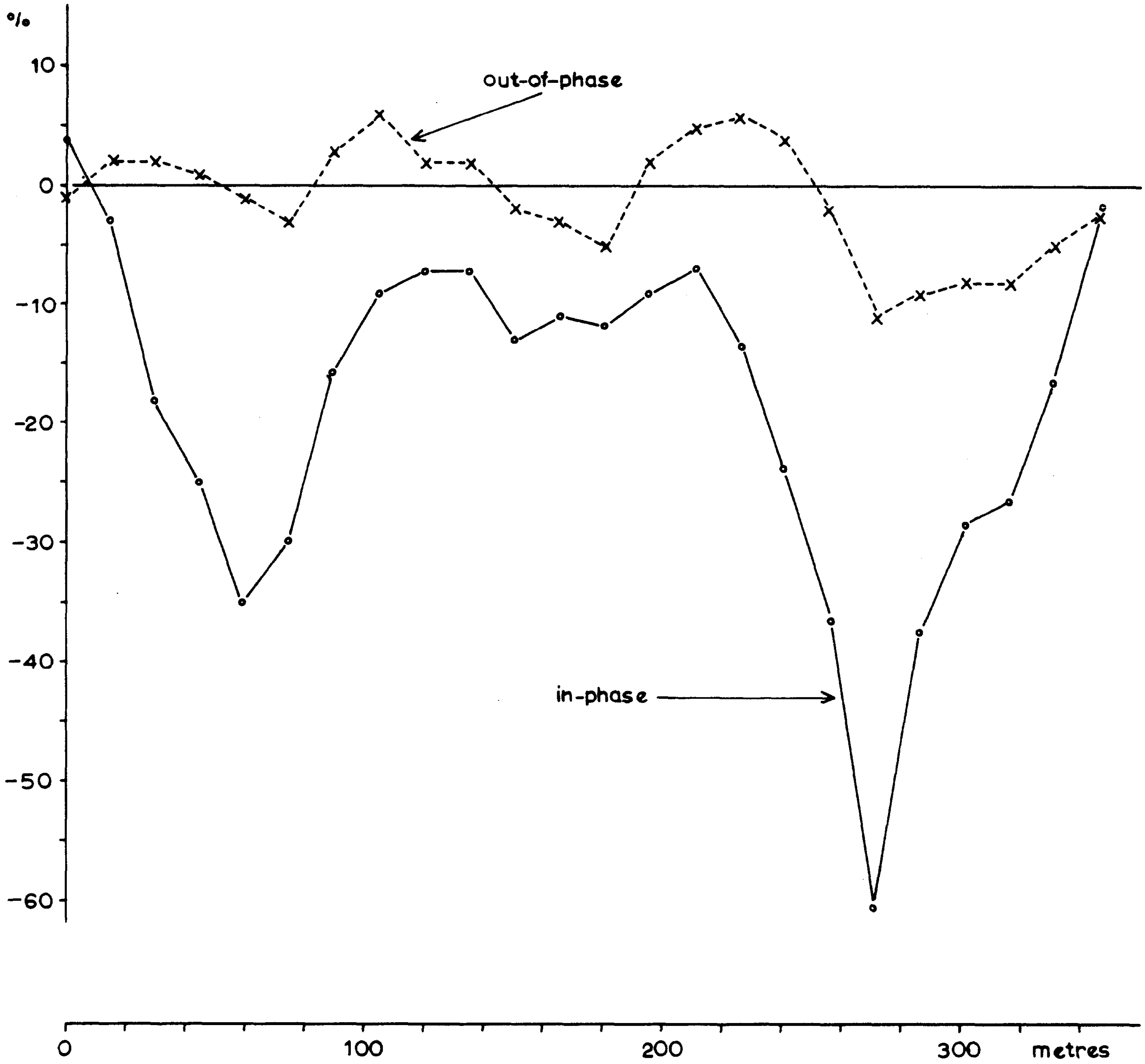


Fig.10 : VLF-EM profile at Oxnop Gill (Traverse indicated on Fig. 6).

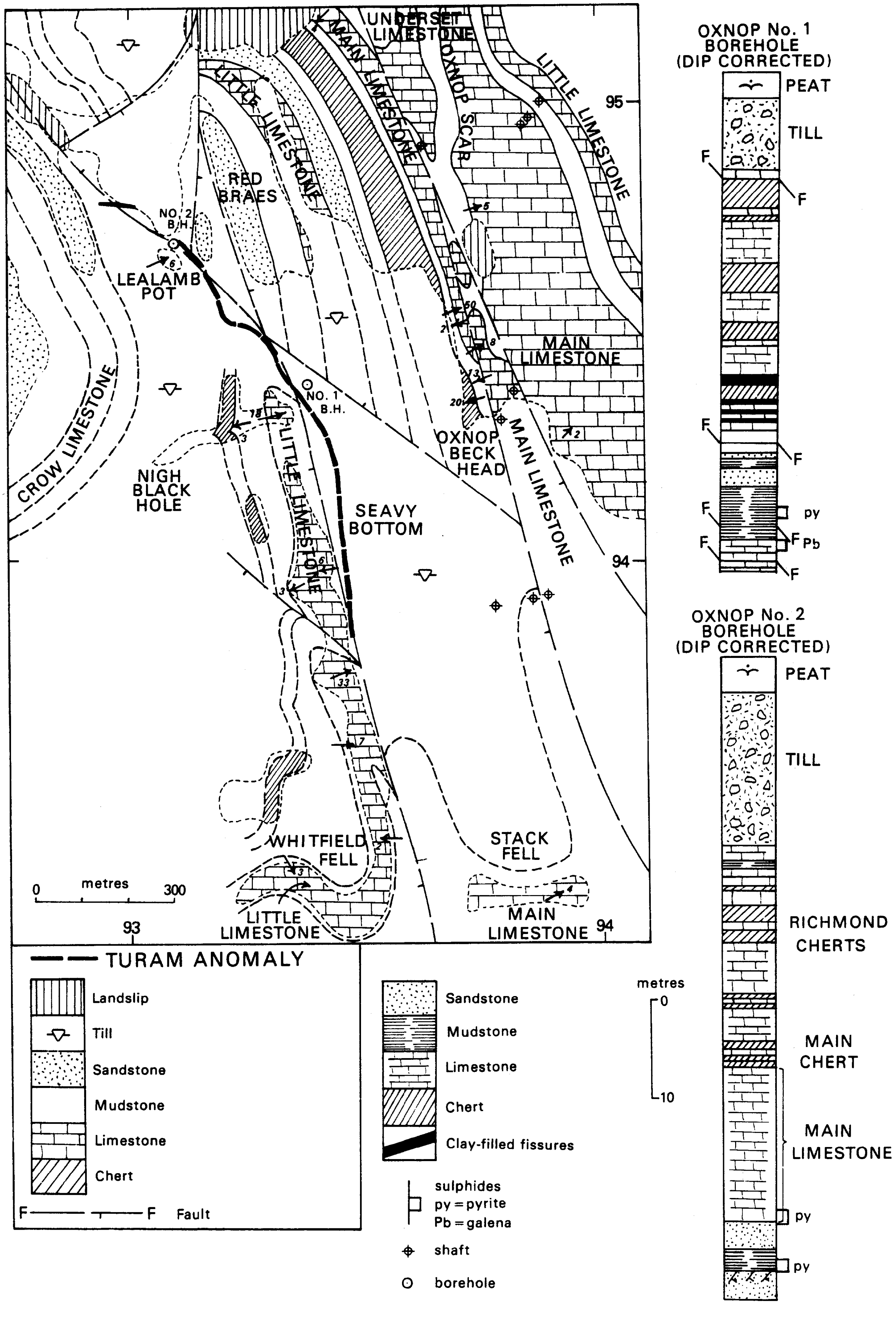


FIG 11 GEOLOGICAL MAP OF OXNOP GILL WITH BOREHOLE SECTIONS

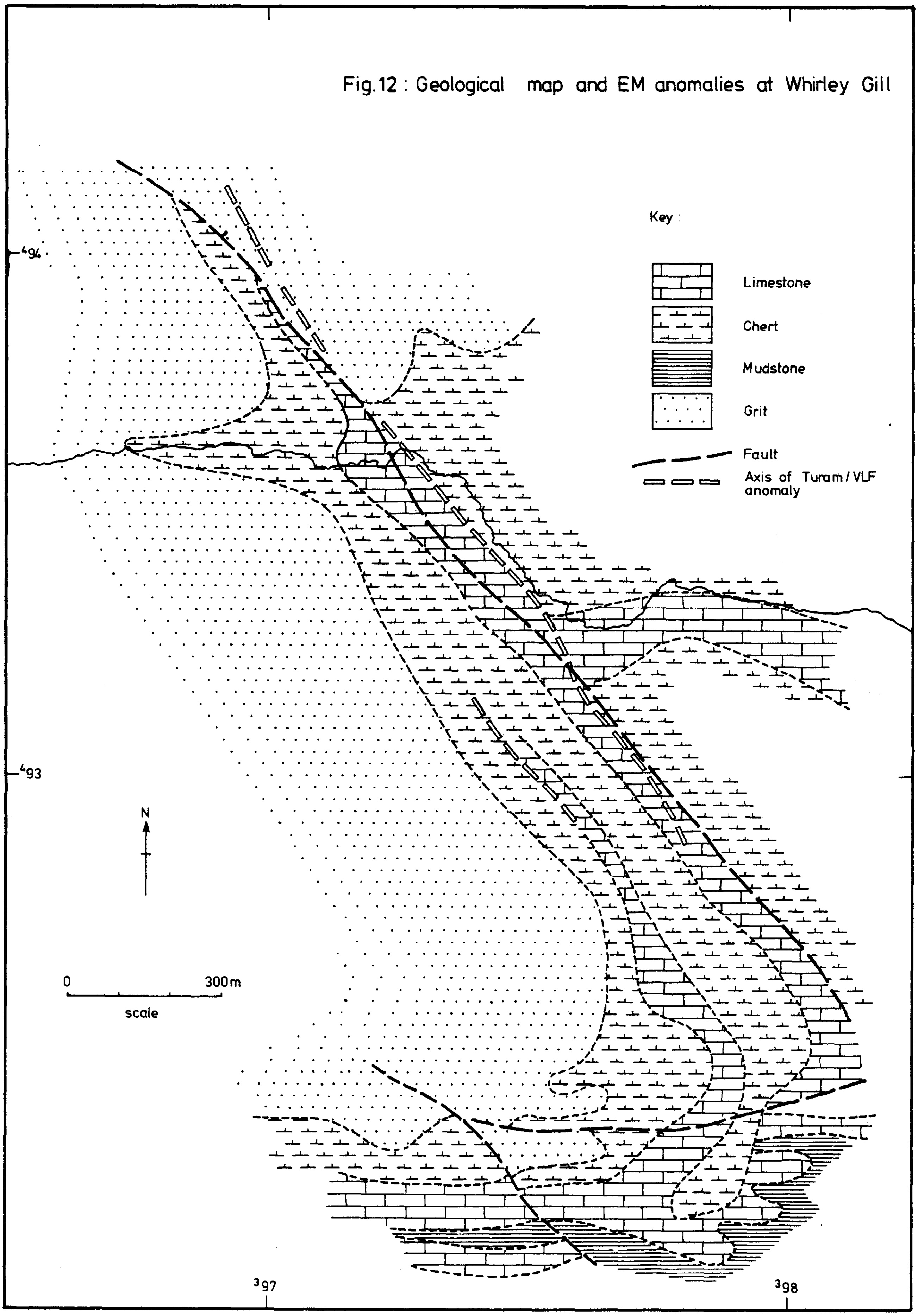


Fig. 12 : Geological map and EM anomalies at Whirley Gill
Key :
Limestone
Chert
Mudstone
Grit
Fault
Axis of Turam / VLF anomaly
⁴94
⁴93
³97
³98
N
0
300m
scale

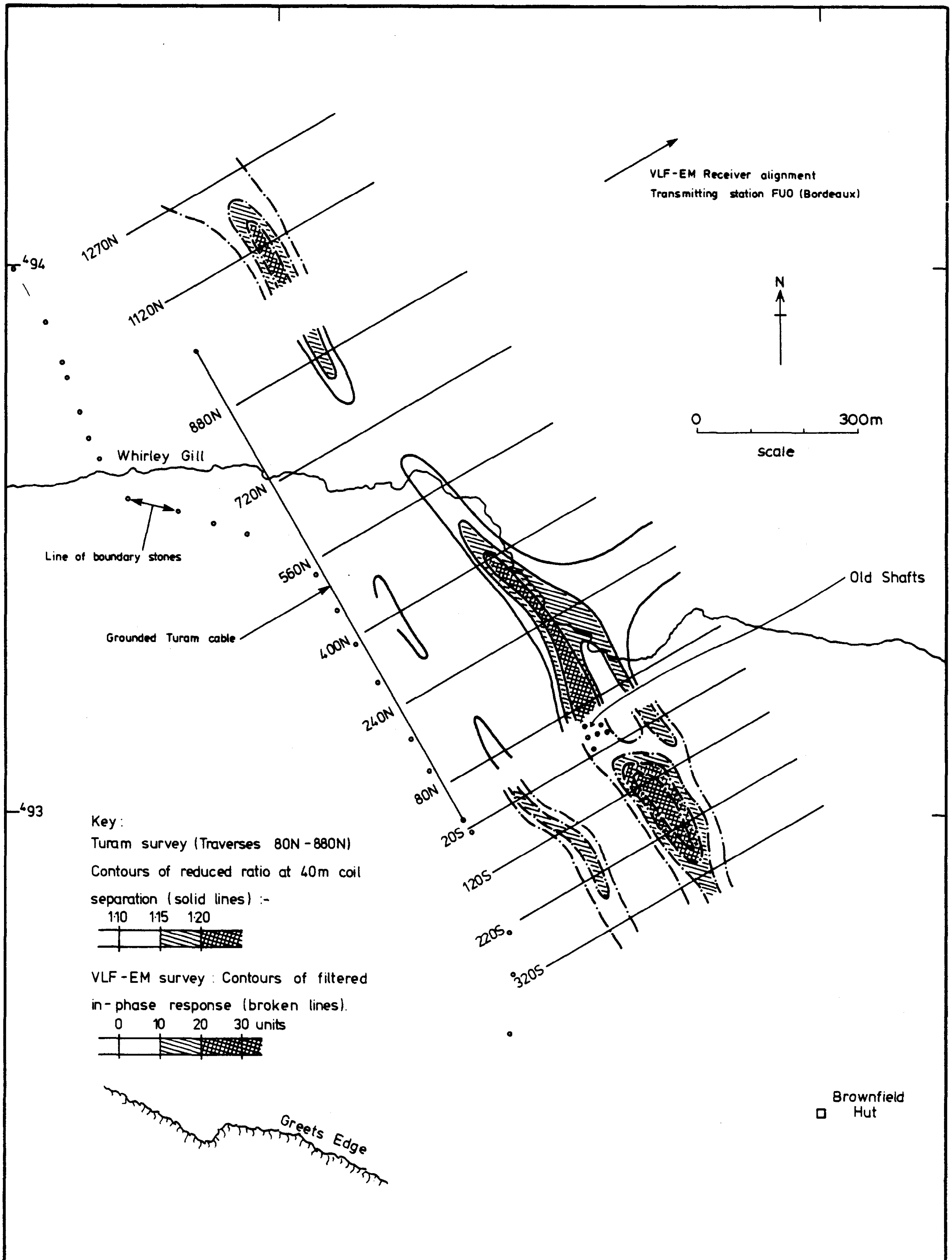


Fig. 13: Turam and VLF-EM traverse locations and anomaly contours at Whirley Gill

0.5 and these generally lie along the NW-trending fault traversing the area but they do not appear on every flight line.

The fault throws about 20 to 45 m down to the north-east and brings Main Limestone against Richmond Cherts in the south-eastern part of the area (Figure 12). The fault is mineralised here and has been worked at the Brownfield lead mine. The Turam survey, instituted to check the airborne anomalies, defined a good anomaly running parallel with, and offset about 50 m to the north-east of, the Brownfield vein. The anomaly continues to the north-west beyond the worked ground parallel to the fault. The Main Limestone is slightly deeper in this direction as the Coal Sills come on above but the characteristics of the anomaly suggest that its cause lies at least 40 m down and that it is not due to near-surface conductors. This increases the chance that the anomaly is caused by mineralisation within the faulted Main Limestone.

Subsequent traverses using VLF-EM equipment confirmed the position of the conductor indicated by the Turam anomaly, and showed extensions to this conductor to the NW and SE, with an anomaly maximum near the Brownfield mine. Other VLF anomalies in the south-west (Figure 13) coincide with shale bands.

It seems likely that the Brownfield vein continues north-westwards beneath shallow cover and that the Main Limestone carries sulphides here. The difficulty of access for drilling equipment prevented further testing of this prospect within the resources of the Mineral Reconnaissance Programme.

IVELET MOOR

An airborne EM anomaly up to 25 ppm with in-phase to out-of-phase ratios of less than 0.5 coincides with a fault. The fracture is extensively mineralised to the north-west where it crosses upper Swaledale. It throws a few metres down to the south bringing the mudstones below the Lower Howgate Edge Grit against the lower part of the Grit across much of the moor (Figure 14).

A Turam survey detected several linear anomalies, the largest coinciding with the fault (Figure 14). West of traverse 1000W the terrain is very steep with extensive landslips so that the survey could not be continued into the mined area in the valley. A subsequent VLF survey confirmed the Turam anomalies but encountered excessive noise in the landslipped area. The VLF anomaly along the fault was strong and negative, both in-phase and out-of-phase. Both methods indicated a shallow source less than 30 m below the surface, and the VLF profiles (Figure 15) suggested that it had only a shallow dip. It seems probable, therefore, that the main anomaly is due to the shales below the Lower Howgate Edge Grit on the up-throw side of the fault. The other anomalies nearby probably mark thin shale bands or conductive horizons in the drift.

OTHER AREAS

For the remaining areas where ground surveys were carried out the results can be classified as follows: (1) areas where the observed anomalies are indicative of stratigraphical conductors, (2) areas where the anomalies (or visual evidence) indicate that artificial conductors are the cause of the airborne anomalies, and (3) areas where anomalies are weak or irregularly distributed, and are thus of uncertain relationship to the respective airborne anomalies.

Stratigraphical conductors are indicated at Keld Calf Pasture (Table 1), where strong anomalies located at the edge of the initial Turam survey area were confirmed by further traverses (Figure 16). The anomalies have a more north-south trend than the faulting in the area, and show some correlation with the strike of the mudstones which overlie the Crow Limestone. VLF-EM measurements indicated that the conductor causing the anomalies was shallow-dipping, supporting the suggestion of a stratigraphical conductor. As already noted, the mudstone above the Crow Limestone has been identified as probably a significant conductor from the airborne data.

Anomalies at Crackpot and Green Mea, less well defined than those at Keld Calf Pasture, also probably have a stratigraphical cause, suggested by the anomaly trends. However, at these sites the ground anomalies are of uncertain relationship to the airborne anomalies.

Artificial conductors were identified at six sites, and these would account for the corresponding airborne anomalies. These conductors were all pipes of various kinds, with the exception of Carperby (2) (Table 1), where buried telephone cables appear to be the cause. At this site, and at West Bolton, brief checks were made with the EM-15 (see Table 2) since the anomaly setting — near habitation — suggested an artificial source before traverses were measured. At Ivelet Beck and at Ivelet Side (4), artificial sources were identified visually at an early stage.

At both Skeugh Head and Carperby (1), several traverses were measured before an artificial source was identified. At Skeugh Head stronger anomalies than could be measured with the Turam equipment were observed. The anomaly pattern clearly indicated an artificial source despite the unlikely setting. Unfortunately, pipes may be installed by private estates and so are not recorded by water authorities. Advance checking of areas on paper is, therefore, not definitive. Other pipes may be related to old mine workings or associated activity, providing an easy source of misinterpretation of favourable anomalies.

At the remaining eight sites not referred to above, the observed ground anomalies are probably best regarded as noise, because of their small

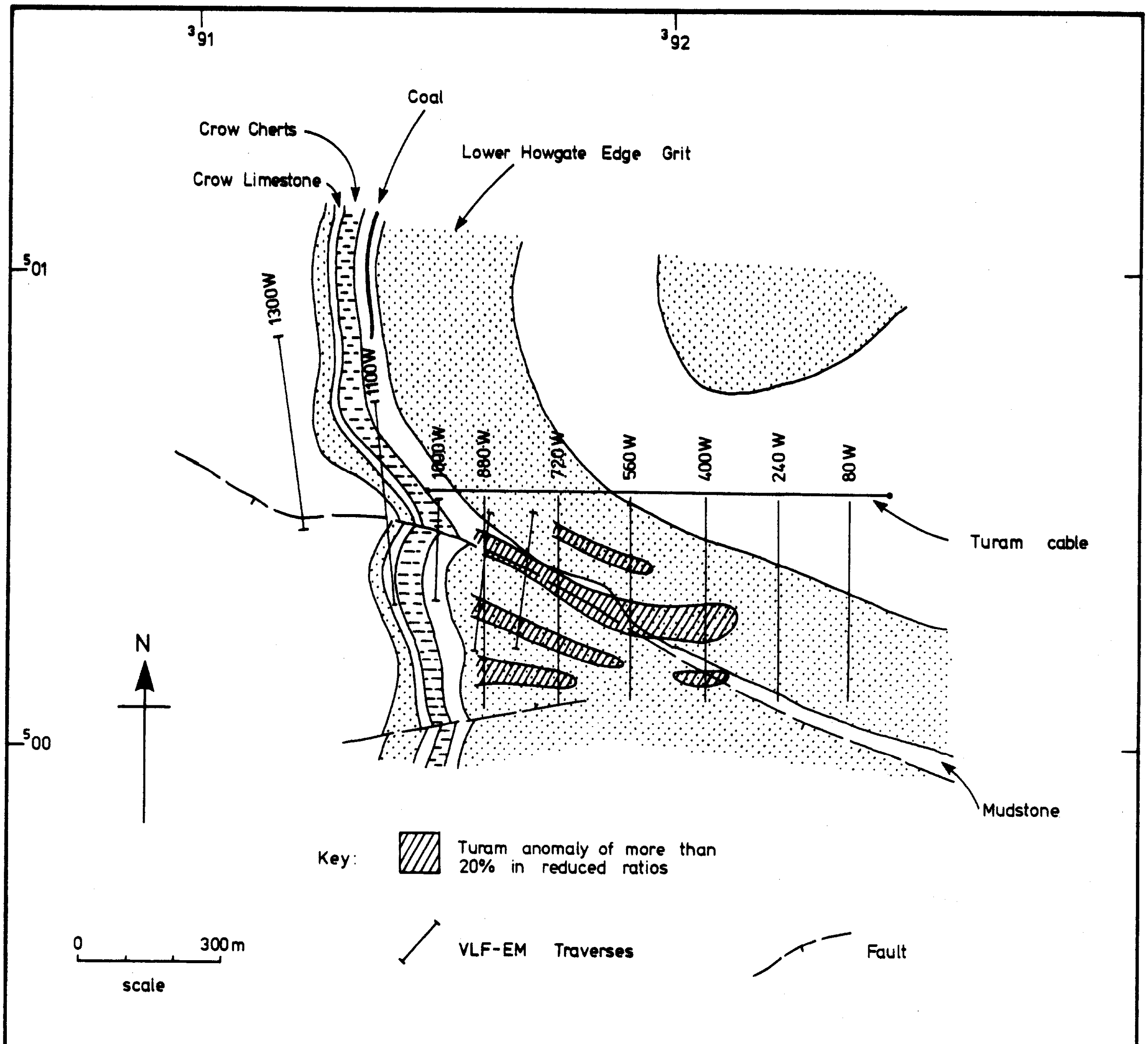


Fig. 14 : Geological map and Turam anomalies on Ivelet Moor

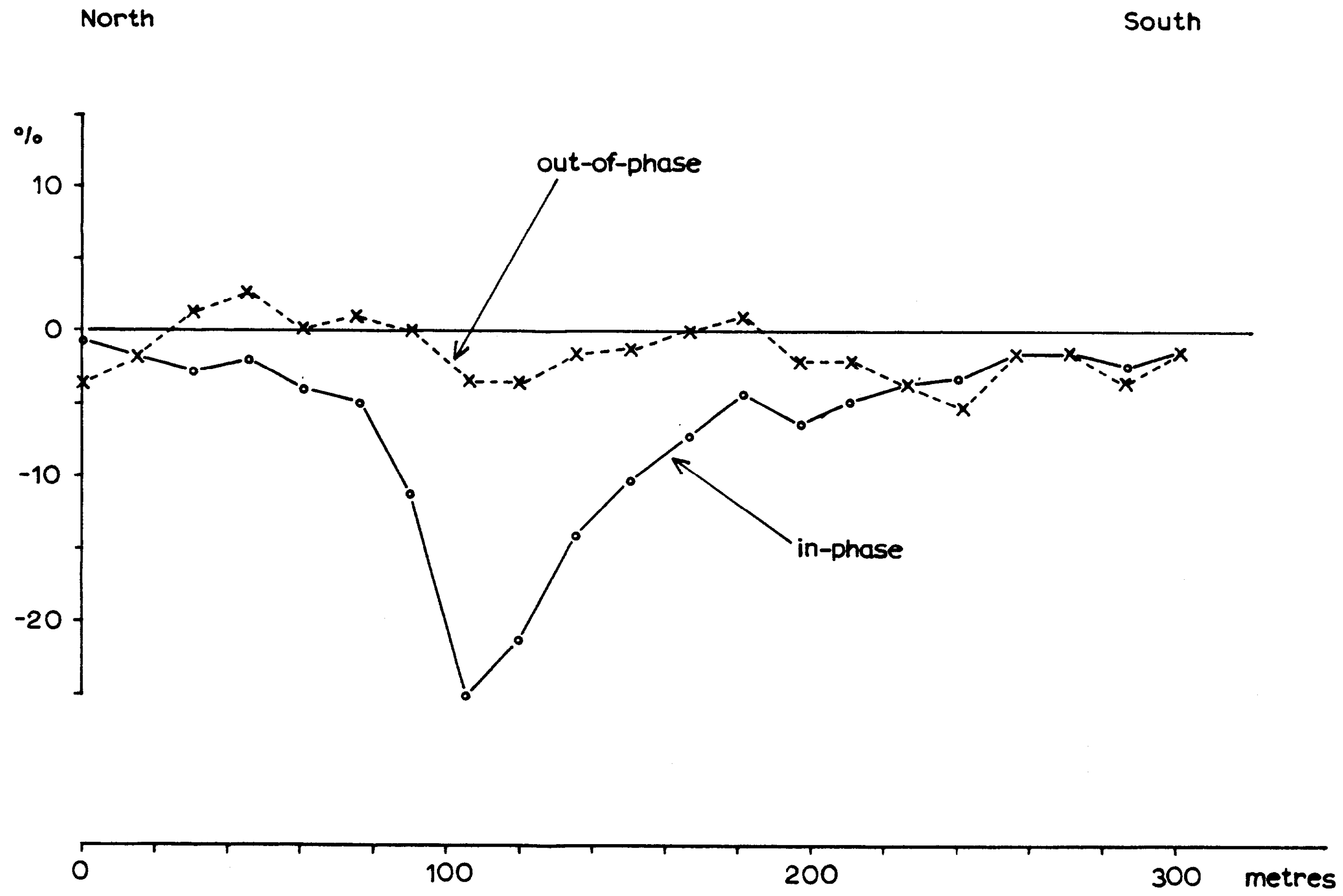


Fig.15 : VLF-EM profile at Ivelet Moor (Traverse 900W).

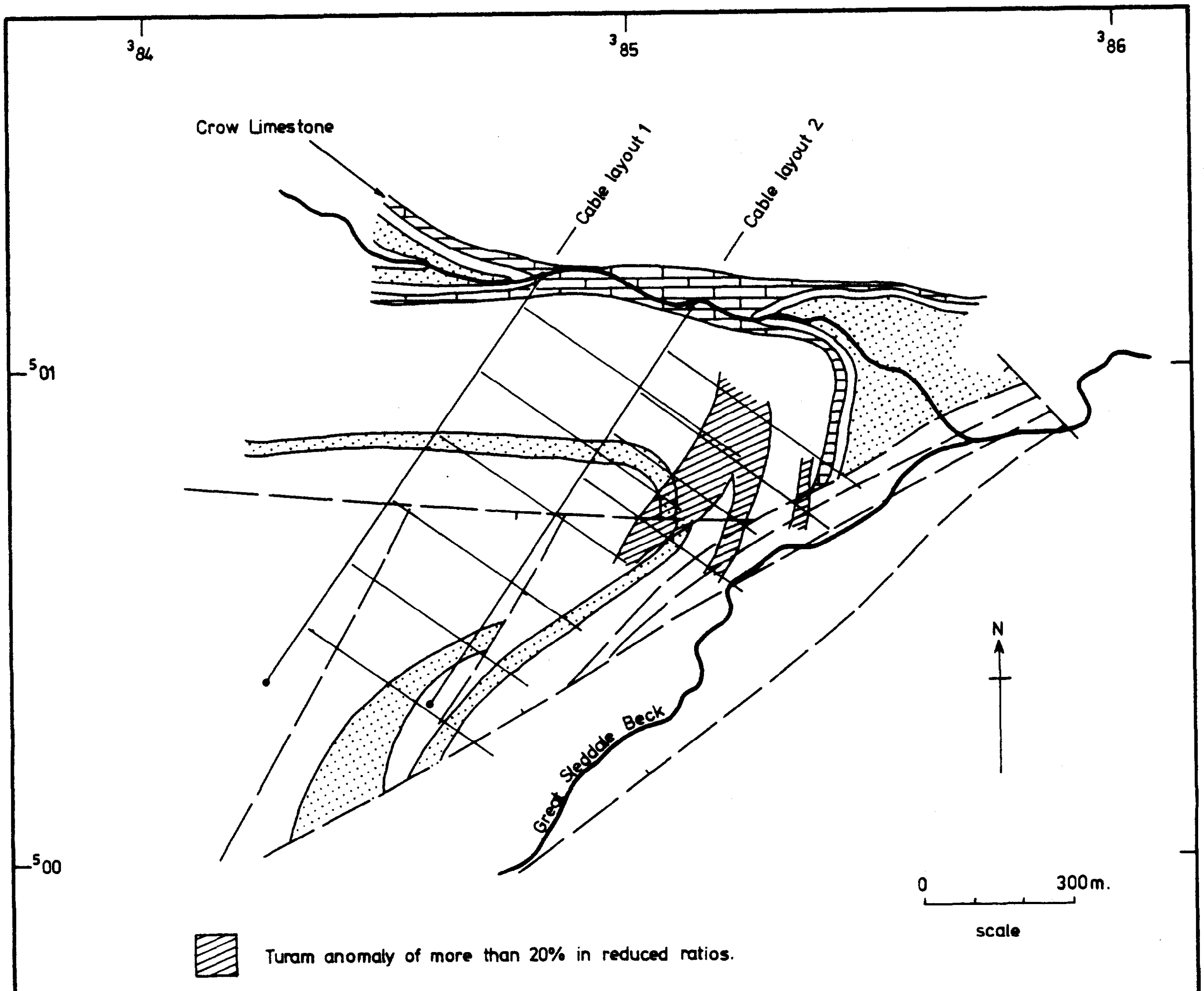


Fig.16 : Geological map and Turam anomalies at Keld Calf Pasture.

amplitudes and irregular distribution. The respective airborne anomalies at these sites might be accounted for in two ways. Shorter wavelength anomalies may be instrumental; caused, for example, by flexing of the EM system 'bird' when changing height rapidly over a topographic feature. Longer wavelength anomalies may be caused by broadly anomalous surface features, such as areas of poorly drained ground or landslip, which are better resolved from the air than by ground measurement.

CONCLUSIONS

The airborne survey located a number of EM anomalies. All of the more significant anomalies identified on the contour maps have been followed up with ground surveys, as have several others from the flight profiles.

The area contains a large number of geological features which might have been expected to provide some EM response; for example faults, both mineralised and unmineralised, and several thick mudstone beds within the sedimentary succession. It is, therefore, discouraging from an exploration viewpoint that there are only occasional local correlations, many of them uncertain, between these geological features and the observed EM response. It has not been possible, for example, to characterise, and so eliminate from consideration as exploration targets, anomalies due to stratigraphical conductors. Similarly, anomalies with an artificial cause cannot be clearly identified as such from the airborne data (with the exception of power-line anomalies), though the proximity of anomalies to habitation suggest such a cause in some cases. Anomalies over the numerous known mineral veins are limited to single-point features too small to enable these characteristics to be defined. There are no anomalies which provide good evidence of the extension of any of the veins.

The best example of a favourable AEM anomaly is in the Oxnop Gill area, where a markedly linear anomaly coincides with a fault with a SSE trend which reflects that of nearby mineral veins. Ground surveys here indicated that the principal AEM anomaly was due to shales, though a sub-parallel anomaly observed with the Turam survey was considered of sufficient interest to merit drilling. However, the two drill holes sited on the anomaly gave no indication of the presence of significant quantities of sulphides along the feature. The source of the EM anomalies remains unresolved.

The results from the Whirley Gill area over the Brownfield vein demonstrate that ground surveys may detect favourable anomalies which are not well defined from the air. Thus the absence of significant airborne anomalies over the many other known veins does not necessarily eliminate them as possible targets.

It is concluded, therefore, that airborne EM surveys are unlikely to prove effective in exploring for new mineral veins in other comparable mineral fields of the northern Pennines. Detailed ground geophysical measurements along the extensions to worked veins would probably prove the better method of locating new mineralisation, though the considerable number of known veins would demand that this be done selectively.

ACKNOWLEDGEMENTS

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