Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

D. Ostle
Programme Manager
Institute of Geological Sciences
Keyworth,
Nottingham NG12 5GG

No. 33

Mineral investigations at Carrock Fell, Cumbria. Part 1–Geophysical survey

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Mineral investigations at Carrock Fell, Cumbria. Part 1 - Geophysical survey

D. J. Patrick, PhD, MIMM

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SUMMARY

A geophysical survey was conducted in the vicinity of the Carrock tungsten mine, Cumbria. The object of the survey was to establish an optimum geophysical exploration procedure for the location of the style of mineralisation known at Carrock. The VLF–EM method recorded only weak or indistinct anomalies over much of the known mineralisation but a weak anomaly coincident with the Emerson vein was traced northwards for one km. Several similar linear features were recorded in the area on trends favourable for mineralisation and two, at Poddy Gill in the east and Arm o' Grain in the west, are coincident for part of their strike with exposed mineralisation.

Resistivity measurements indicated that most fault structures have coincident low resistivity zones; a detailed traverse across the Emerson vein showed a minor high resistivity peak within the low zone.

Induced polarisation, magnetic and self potential anomalies were recorded only within the gabbro on the extrapolated positions of the Smith and Wilson lodes. It is concluded that these anomalies are caused by discontinuous near-surface lenses of pyrrhotite which have little VLF response.

The VLF method is identified as the best tool for the location of structures which may carry mineralisation in this environment. Incidentally to the main objectives of the work, three VLF anomalies are identified which appear to warrant investigation by drilling; the Arm o' Grain anomaly, the Emerson vein extension and the Poddy Gill feature.

INTRODUCTION

A study group has been established within the Mineral Reconnaissance Programme to examine well-documented mineral occurrences (including working mines) in order to evaluate and refine exploration methods and interpretation techniques as an aid to the discovery and preliminary assessment of further mineralisation in the same area or similar occurrences elsewhere.

The Carrock Fell tungsten mining area meets the geological requirements of the project. An active mine provides detailed information on the controls and nature of mineralisation. The geology, geochemistry and mineral paragenesis have been the subjects of recent studies, which conclude that the area has definite mineral potential (Appleton and Wadge, 1976, Shepherd et al., 1976). The present report describes the results of a survey which was aimed at establishing the best geophysical exploration procedure to detect and study this style of mineralisation.

REGIONAL SETTING AND GEOLOGY

The Carrock Mine is situated some two miles to the west of Mosedale, Cumbria, in Grainsgill Beck, a tributary of the River Caldew. The area is one of high relief and rugged topography and in the summer months the lower slopes of the steep valleys are heavily vegetated with bracken and heather.

The geology of the area is detailed in the works mentioned above and the mining history is described in Anon (1977). Only a brief summary of the geology is given here and the solid geology is shown in Fig. 1.

The southern part of the area is underlain by the Lower Ordovician Skiddaw Group sediments, which are commonly highly deformed. Fold axes have an east-north-easterly trend. In the north of the area a thick, near-vertical sequence of volcanic rocks strikes east-west and has been correlated with the Borrowdale Volcanic Series. The central part of the area is dominated by two major intrusions. To the north the Lower Palaeozoic Carrock Fell gabbro complex trends roughly along the east-west regional strike and is in steep contact with the surrounding rocks. To the south, separated from the gabbro by a few hundred feet of hornfelsed sediments, lies the northernmost part of the Caledonian Skiddaw Granite. This has been greisenised in the Grainsgill Beck area.

The mineralisation is in the form of quartz veins which strike north-south and dip steeply to the west. The veins carry tungsten as wolframite and scheelite, together with lesser amounts of arsenopyrite, pyrrhotite and pyrite which increase northwards. The mineralisation is closely associated with the greisenisation of the Skiddaw Granite and it is considered that both the tungsten mineralisation and the greisen are the result of circulation of saline fluids through and around the hot granitic intrusion (Appleton and Wadge, op. cit.). The circulation was especially active on the northern margin of the granite where joints and fractures in the gabbro and the granite provided channelways for the fluids. The Skiddaw Group sediments, in contrast, were hydrologically much "tighter", so that circulation was limited in the south.

SURVEY DESIGN

The survey area was geographically defined to include the harder fractured rocks to the immediate north and west of the present workings. The southern area was not tested in detail. The geophysical methods used were selected on the basis of the following considerations:

i The nature of the veins – tight, continuous quartz lodes of 1.5–3 m average width, with fracture controlled orientation – suggested that they would not form good electromagnetic targets in themselves. Thus exploration procedures using EM methods were aimed at their indirect detection by the identification of favourable structures. The VLF–EM method has a history of successful location of faults and fissures in a variety of geological environments (Phillips and Richards, 1975; Coney and Myers, 1977; Telford et al., 1977; Patrick et al., in prep.) and was considered to be the most suitable method of locating fractures in this area.

ii The quartz lodes should have a considerably higher resistivity than the country rocks (see Table 1), and resistivity methods might thus be expected to detect the veins. The small widths, however, would require the use of small array spacing for optimum resolution.

iii Pyrrhotite has been observed within the gabbro close to the veins and this could be expected to produce an

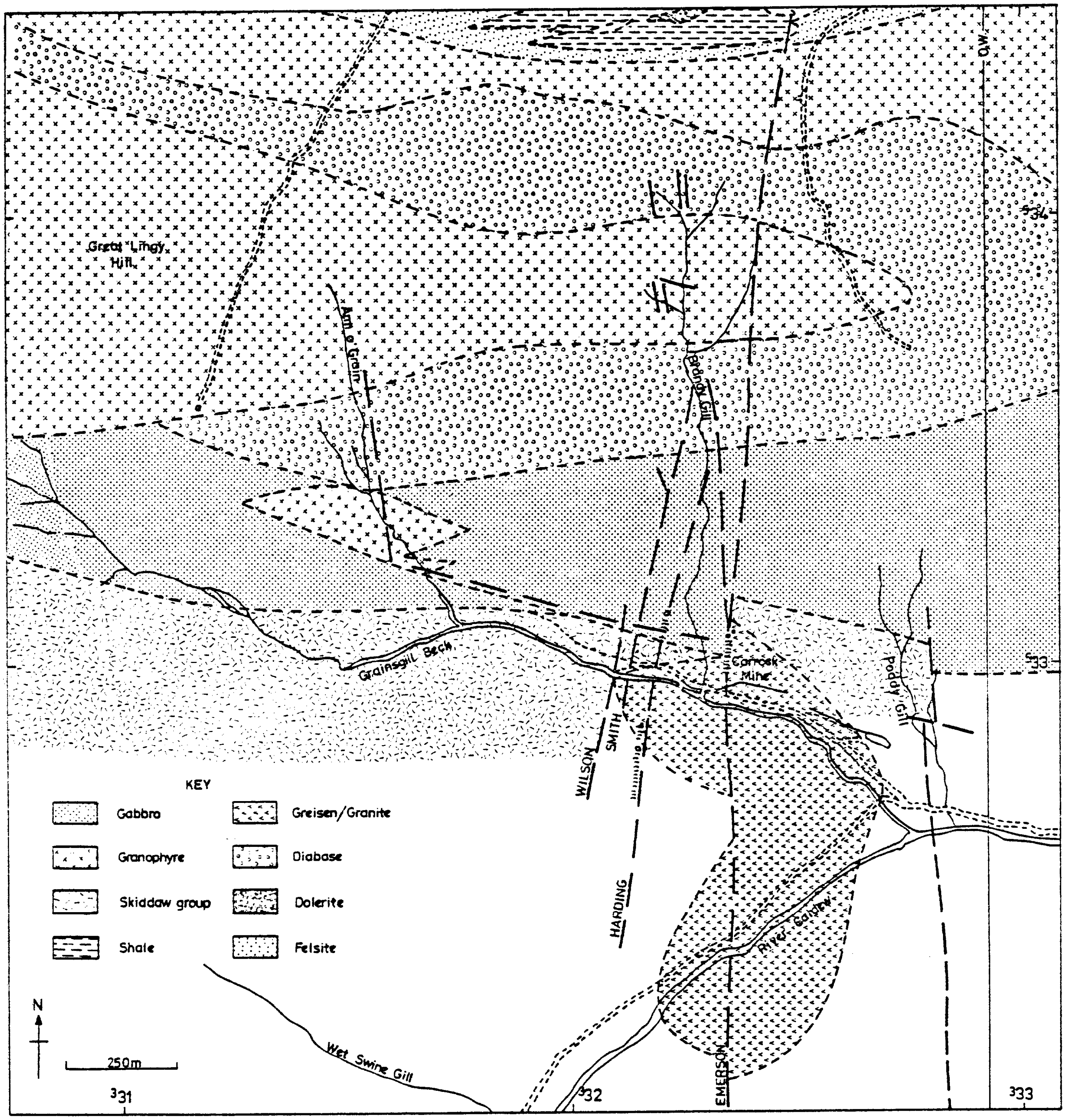

FIG. 1. GEOLOGY OF THE CARROCK FELL MINING AREA

anomalous induced polarisation response. The ground resistivity would be determined as a matter of course in an IP survey.

iv Local concentrations of pyrrhotite within the veins might be detected by the magnetic method. Examination of the 1:63 360 aeromagnetic map of the area (IGS, 1959) indicates that the gabbro is not significantly more magnetic than the adjacent rocks, although only one flight line crossed the complex in the area of interest. The gabbro lies on the flank of an intense aeromagnetic anomaly which coincides with the Eycott Group of lavas (Collar and Patrick, 1978). No systematic remanence has been found within the metamorphic aureole of the Skiddaw Granite, NRM intensities varying between 20 and 70 nT. (Faller and Briden, 1978.) A small south-to-north increase in background of 10 nT per km would be expected due to the effect of the Eycott Group, but local concentrations within the veins should be detectable in both the granitic and gabbroic rocks.

v Studies elsewhere have indicated considerable SP effects over a quartz lode with scattered sulphides (Patrick, et al., in prep.), so this method was tested over the veins.

The instruments used in the survey are listed in Table 2. Details of their operation may be found in Burley et al. (1978).

The gravity method was not used in the present survey although it is recognised that it would give useful information on the geometry of the granite and thus pinpoint areas of potential mineralisation. Levelling data in the area are scant, so a sufficiently detailed gravity survey would be time consuming and outside the scope of the present work.

VLF–EM SURVEY

A reconnaissance conducted prior to the detailed survey demonstrated that the veins would produce a VLF response. Anomalies were also located on possible vein continuations (Patrick, et al., in prep.). Readings taken at 5 m intervals on an initial traverse showed that the anomalies over the veins were broad enough to be detected at a station spacing of 20 m. The latter was used for the major part of the survey. Three line km of combined VLF and Radiohm resistivity (Collett and Becker, 1968) stations could be occupied during the working day.

Figure 2 is a plot of the measured in-phase profiles with the known mineralisation superimposed. The profiles were interpreted according to the method of Karous and Hjelt (1977), which uses a general form of the well-known Fraser filter (Fraser, 1969). A simple numerical filter smooths raw in-phase data to remove high frequency noise and generates a theoretical model of the apparent current density distribution which would give rise to the same magnetic field as that represented by the in-phase measurements. By considering progressively wider spaced data points, apparent current densities at progressive depth increase are calculated. An indication of dip is given by the migration down-dip of the apparent current density maximum as the spacing between data points increases. The results obtained are plotted as apparent current density pseudosections which may be contoured to give an indication of the conductivity distribution in a vertical plane beneath the traverse. The method may also be applied to the out-of-phase (quadrature) component with more complicated results.

The depth to the conductors is not satisfactorily determined by this interpretation method, but a first approximation for depth to a tabular conductor may be obtained from the anomaly half-width. The accuracy of this is impaired by conductive overburden and topography. Whittle (1969) has shown that topography produces long wavelength anomalies which need not obscure 'real' anomalies. Baker (pers. comm.) has demonstrated, by model experiments, that readings taken on downhill traverses require correction by the addition of a value which varies with slope; and that uphill readings require the subtraction of this value. He has quantified this factor for simple cases, but the Carrock Fell situation, while requiring similar treatment, is too complicated for the correction procedure to be effective.

Of the anomalies described below, only one has a maximum peak to peak width of 100 m (11–11) and few exceed 50 m. Estimates based on half width suggest that most of the anomalies have a near-surface source. In the interests of clarity, the quadrature response is not shown on the diagrams but is described in the text. A "positive" quadrature has the same sign as the in-phase; the significance is discussed below. Paterson and Ronka (1971) demonstrate theoretically that a good conductor in less conductive ground has a negative quadrature response, while a positive response is generated by a poor conductor in non-conductive ground. Phillips and Richards (1975) show that a mineralised fault zone acting as a moderate conductor has a strongly positive response. Telford et al. (1977) have analysed the VLF response to a vertical fault and show that the in-phase will have a single positive peak when passing from a high conductivity to a low conductivity zone and the flank in the low conductivity zone will

Table 1 Typical resistivity values for the range of rock types occurring at Carrock Fell (After Telford et al., 1976)

Rock	Resistivity range (Ω m)	
Granite	3×10^2	$- 10^6$
Gabbro	10^3	$- 10^6$
Hornfels	8×10^3 (wet)	$- 6 \times 10^7$ (dry)
Slate	6×10^2	$- 4 \times 10^7$
Quartzite	2×10^8	$- 10 \times 10^8$
Quartz	4×10^{10}	$- 2 \times 10^{14}$

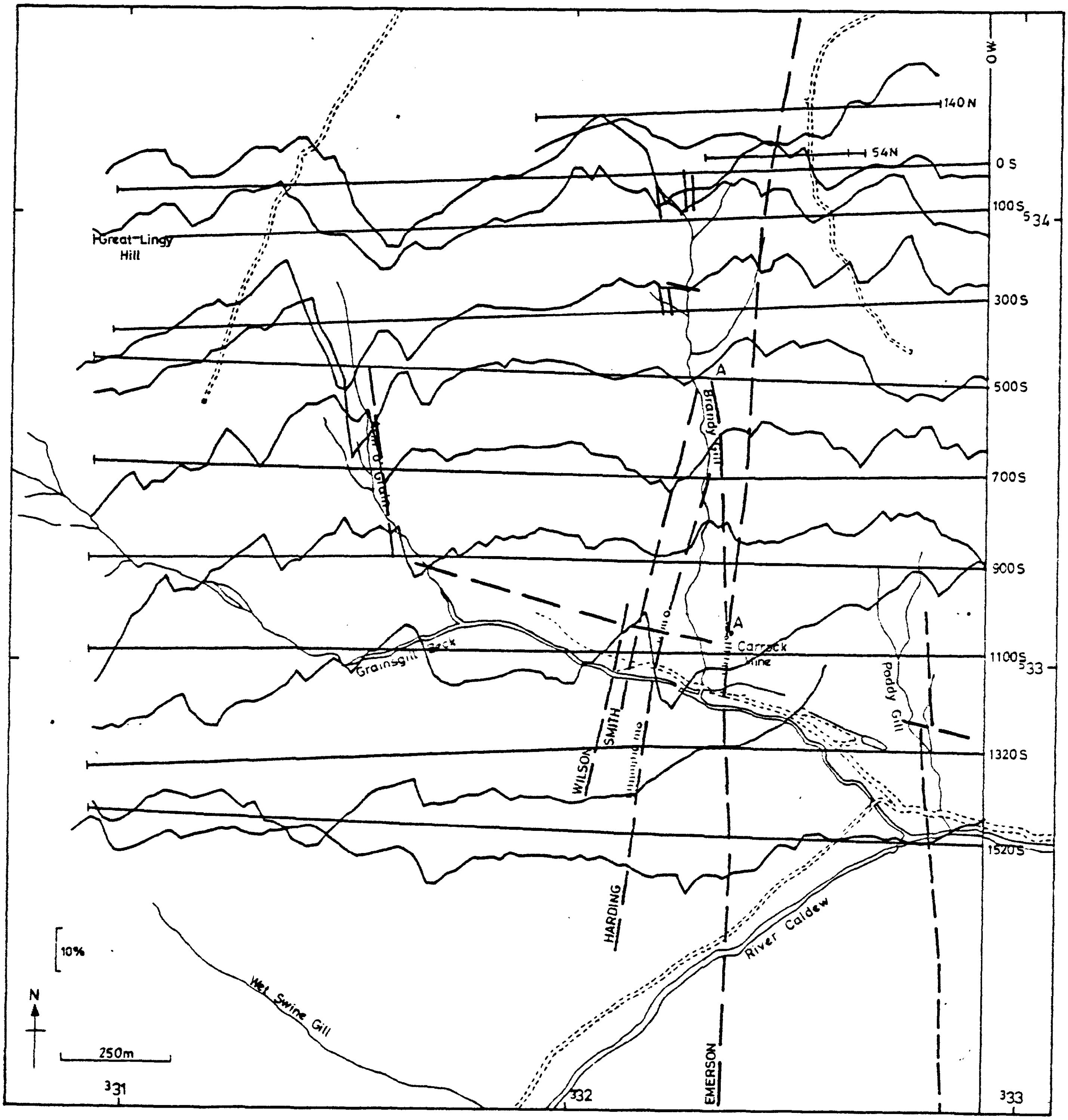

FIG. 2. IN PHASE PROFILES FROM VLF-EM MEASUREMENTS

Table 2 Instruments used in the Carrock Fell survey

Method	Instrument
VLF–EM	Geonics EM16 tuned to GBR (Rugby), operating at 16 kHz
Resistivity	i Geonics EM16R radiohm method tuned at 16 kHz
	ii Huntec MKIII IP receiver with
	(a) LOPO MKIII transmitter – dipole-dipole array
	(b) 2.5 kW Huntec transmitter – Gradient array
Magnetics	Geometrics G816 Proton magnetometer
	Kappameter – for in-situ susceptibility determination
Self Potential	Schlumberger digital millivoltmeter

be steeper. The quadrature will be broadly positive with a negative 'cusp' immediately above the fault. Field measurements presented by the authors do not consistently show this feature.

Figure 3 is a contour map of the apparent current density distribution for depth = 20 m. To avoid the contouring bias introduced by the layout of the grid, only anomalies whose shape could be traced to an adjacent profile were contoured together. The resulting map shows a number of linear features which parallel the major trends of mineralisation and faulting. The features are discussed from east to west, anomalies on individual traverses being described in terms of the measured in-phase amplitudes shown on Fig. 2.

RESULTS

Anomaly 1–1

This linear feature can be traced from 100 N to 1100S. It has a north-south strike and it coincides with a mapped fault on 1100S at Poddy Gill. The feature is possibly represented by a minor (4%) anomaly on 1300S, although disturbance from an artificial source swamps the results to the immediate west. The anomaly is strongest on lines OS, 100S and 300S, where its average amplitude is 25%. Here the filter indicates an essentially vertical conductor. The form of the anomaly on 300S is similar to that described by Telford et al. (1977) for a vertical geological contact with the less resistive rock to the east, and it occurs at the contact mapped between granophyre and diabase. It is possible that this contact is fault controlled, not concordant as mapped. The quadrature response is strongly positive. On 500S the anomaly is represented by a weak (3%) inflexion on the flank of a stronger anomaly to the west. The conductive feature has a steep westerly dip on 700S and 900S and the amplitude of the anomaly is 20%. These data indicate that the fault mapped at 1100S continues at least as far as 100N. A tungsten-bearing quartz vein has been recorded along the strike of this feature at Poddy Gill (Andrew, 1976).

Anomaly 2–2

This feature is strongest on 500S and 700S, but does not appear to the north of 300S although the anomaly becomes progressively weaker to the south, having an amplitude of 7% on 900S and 3% on 1100S. No known structure is mapped here, but the anomaly trend suggests the presence of a weakly conductive geological feature. The dip of the structure is interpreted as westerly, and the quadrature response is positive.

Anomaly 3–3

This feature extends from 110N to 500S and possibly converges with 2–2 farther south. It has an amplitude of 20% in the north, decreasing to 5% on 500S. A westerly dip is indicated. The quadrature response is broadly positive.

Anomaly 4–4

A weak (maximum 10%) anomaly with a weakly positive quadrature response can be traced from 100N to 900S. On 0S and 100S it falls on the flank of 3–3 but the two anomalies diverge further south. To the north of 0S the two anomalies converge to form a single sharp peak at 100N. A series of short traverses (not shown on Fig. 3) traced the combined anomalies a further 100 m north. From 900S to 0S anomaly 4–4 coincides exactly with the known outcrop and mapped extension of the Emerson vein, and the interpreted structure has a vertical to westerly dip. The weak nature of the anomaly and its positive quadrature response indicate that the vein is nowhere strongly conductive, and the VLF response is unlikely to be due to massive sulphides. A zone of relatively low resistivity correlates broadly with 4–4, although the peak of the filtered VLF anomaly and the Emerson vein are displaced from the centre of this zone.

Anomaly 5

This anomaly occurs immediately above the adit on the Harding vein and is caused by iron rails and electric cables in the mine. Small slope changes occur on its western flank at the position of the Smith and Wilson veins, but the artificial noise could be expected effectively to mask any anomalous response from the veins.

Anomaly 6–6

Both this zone of broad positive anomalies with superimposed sharper features and the adjacent negative zone are considered to be due to topography. The sharp, superimposed features coincide with mapped veins at 6a, 6b, 6c and 6d. The last is a large amplitude (25%) anomaly on 0S and 100S which is caused by a manganese bearing vein of little economic significance. Anomaly 6b is on the

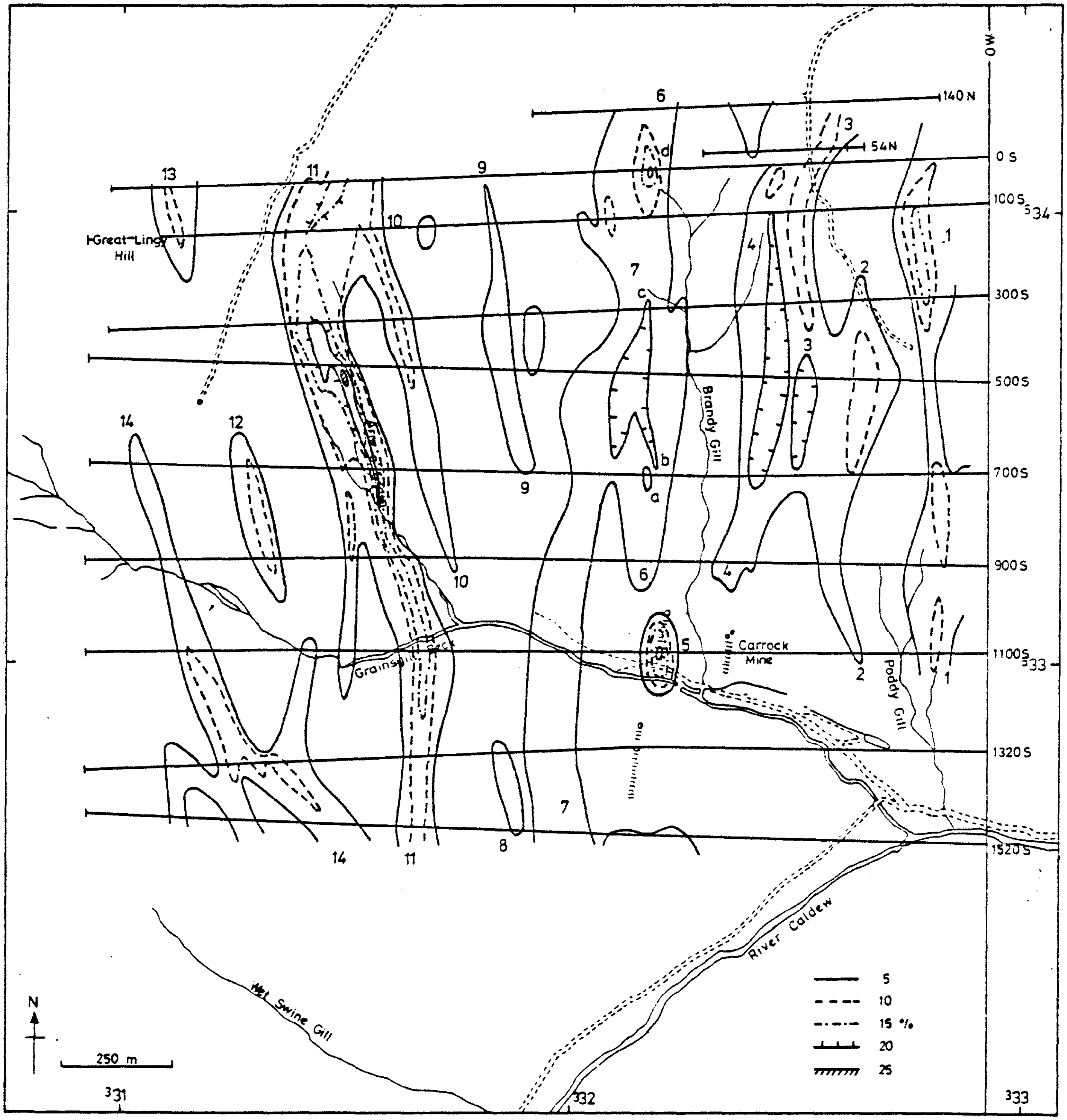

FIG.3. APPARENT CURRENT DENSITY RATIO DISTRIBUTION FROM VLF-EM MEASUREMENTS

mapped extension of the Smith vein, but only has an amplitude of 5% and the anomaly cannot be traced on adjacent lines. No vein is mapped at anomaly 6e, but the form suggests the presence of a minor structure.

Anomalies 7–7, 8, 9–9
A series of weak (5%) in-phase anomalies extends from 300S to 1100S. Extensions to the north and south are indefinite. Anomalies 8 and 9–9 are similar weak features.

Anomaly 10–10
This feature is strongest on 300S and 500S, although it can be traced as far as 900S where it has an amplitude of 3%. Vertical to steep easterly dips are indicated, although the anomaly may be distorted by a topographic effect. The quadrature response is weakly positive. In the north the anomaly merges with 11–11.

Anomaly 11–11
This major feature can be traced across the whole survey area, although in the north it appears to change direction and become broader and less definite. Steep westerly dips are indicated on lines 0S to 900S but, south of this, the anomaly changes character, weakens, and has an interpreted easterly dip. This probablyreflects the passage out of the hard igneous rocks into the Skiddaw Group sediments. On 900S it coincides with an outcropping quartz lode which carries manganese, although the mapped continuation of this lode diverges from the anomaly on 500S. The anomaly here coincides with wet ground between the main Arm o'Grain stream and its western tributary and its amplitude is 70%. A very steep slope is superimposed on a weaker, longer wavelength feature. The quadrature response is strongly reversed on 100, 300 and 500S, and the anomaly is similar in form to a theoretical anomaly generated by a good conductor in weakly conductive ground (Paterson and Ronka, 1971). It is possible that a restricted band of thick conductive overburden occurs here, as the anomaly shows both a near surface contribution and deeper features.

Anomalies 12, 13
These weak anomalies fall on the same trend, although a vertical conductor is interpreted from anomaly 13, while anomaly 12 has an interpreted steep westerly dip. The quadrature response is weakly positive.

Anomaly 14–14
This anomaly can be traced from 700S to 1320S, with weak indications on 1520S. It nowhere exceeds 15%, and the interpreted dip of the conductive feature is steeply to the west. Quadrature response is positive.

DISCUSSION
A series of near-surface, weakly conductive structures, probably representing unmapped fractures, has been indicated by the VLF survey. The major failure of the method is the lack of a distinctive VLF response over the known producing lodes.

The amplitudes of anomalies recorded over the veins during the winter reconnaissance survey were considerably greater than those recorded in summer, particularly over high ground. This may be due to a seasonal variation in water table height, the same phenomenon having been observed elsewhere (Patrick, et al., in prep.)

The response of the Harding vein is affected by noise caused by artificial conductors, and weak responses over the Smith and Wilson veins are swamped by this noise at adit level. Farther north, the Smith vein may have a very weak coincident anomaly (see anomaly 6a). The Emerson vein has produced a weak but definite anomaly and it appears to have a considerable northwards extension. The major ankerite-bearing fault (A–A in Fig. 2) coincides with anomaly slope changes or minor troughs on lines 800S to 1500S, but these are not enhanced by the filtering process. Discrete anomalies coincide with small manganese-bearing veins of little economic interest. The main veins are disturbed by cross faulting and show a tendency to split into stringers to the north. The lack of VLF response may indicate a lack of linear continuity, particularly to the north of the ankerite fault. However, any fracture in this area has potential for mineralisation and of the numerous anomalies found on the present survey, three are considered to have particular significance. Anomalies 1–1, 4–4 and 11–11 lie in part on outcropping mineralisation and are continuous for at least one km. Anomalies 1–1 and 11–11 are stronger than 4–4 and probably indicate more open fractures which may carry water.

RESISTIVITY SURVEY

The Radiohm method was patented by Collett and Becker (1968). Based on the wave impedance theory, it involves the determination of the ratio and phase difference between horizontal orthogonal electric and magnetic field components produced by a plane wave radiated from a VLF transmitting station. A clip-on unit converts the EM16 to the resistivity mode. A pair of ground electrodes 10 m apart and aligned in the direction of the station are connected to the EM16 console and receive the electric field; the reference coil of the EM16 is horizontal and orthogonal to the electrode spread and is thus maximum coupled to the magnetic field. In homogeneous ground, the electric field leads the magnetic field by 45° and the measured value of resistance is the true ground resistivity. Interpretation curves are available for two layer cases, and in general, the phase decreases from 45° if the upper layer is more conductive and increases for a resistive upper layer. The method provides a rapid and convenient means of mapping lateral resistivity changes, although as the geology of the Carrock area is complicated, the two layer curves have little relevance and quantitative interpretation is not usually possible.

RESULTS
Fig. 4 is a contour map of the measured apparent resistivities. The profiles of adjacent traverses were sufficiently similar to permit contouring of the widely spaced data. Several regions have been distinguished for discussion.

Area A
This area of general low resistivity ($< 500\ \Omega$ m) coincides with the peat covered southern flanks of Miton Hill. The peat cover is thin (generally less than 2 m thick) and the phase angle falls away below 45° to the west, indicating a conductive upper layer. To the south the resistivity rises to greater than 1000 Ω m as the drift cover thins, and phase rises slightly above 45°. Areas of higher resistivity form embayments within the lower resistivity areas and the low resistivity ridges thus formed correlate with VLF anomalies 1–1, 2–2 and 3–3.

Area B–B
A linear low resistivity zone extends from 900S to 100S, and the Emerson vein falls on its eastern flank. A detailed traverse (Fig. 5) on 700S across the zone demonstrated that the Emerson vein gives rise to a small (100 Ω m) peak within low B–B which also correlates broadly with VLF anomaly 4–4, although the peak of the latter follows the Emerson vein.

Area C–C
This linear low follows the extrapolated Smith and Wilson

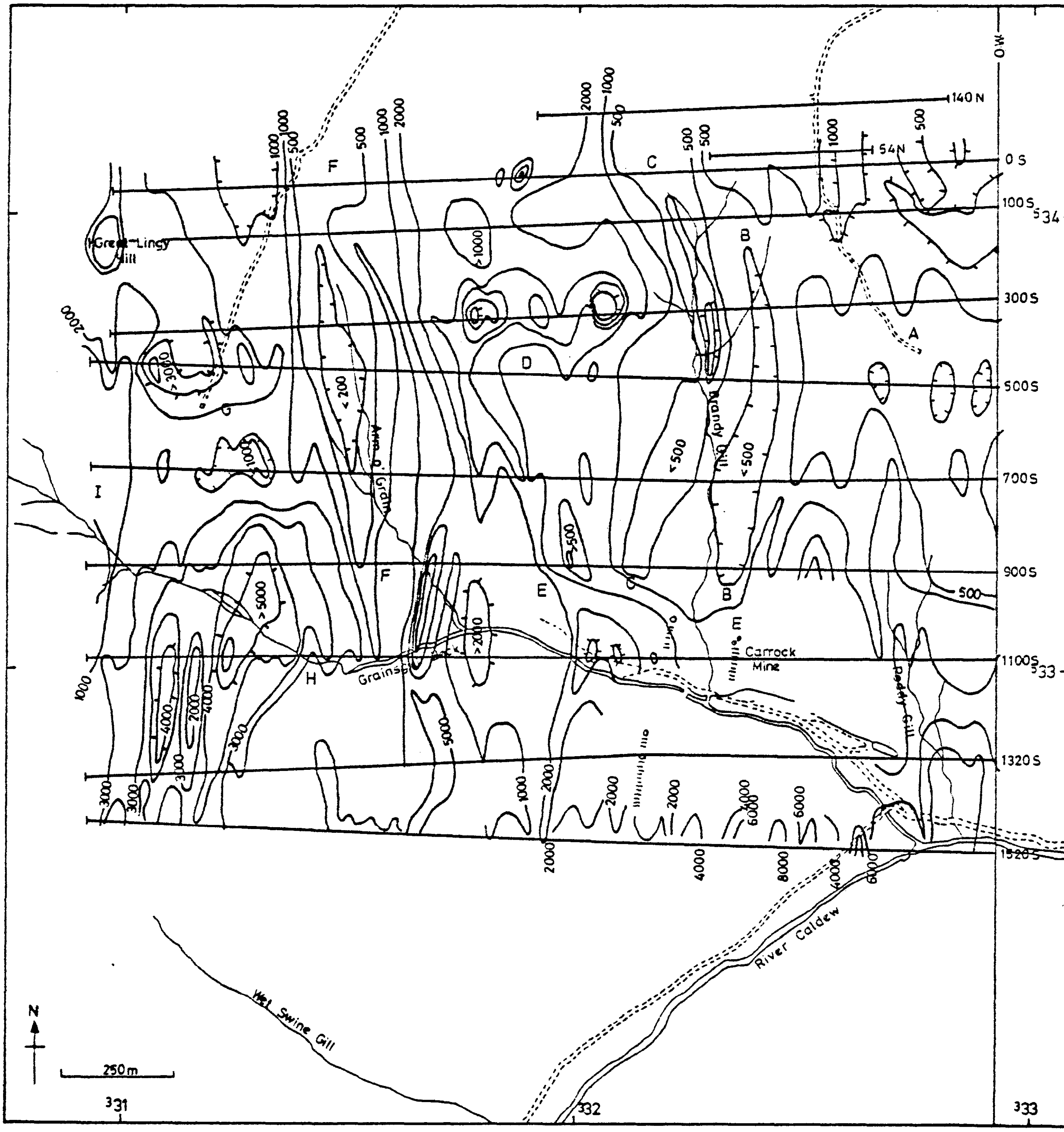

FIG. 4. APPARENT RESISTIVITY CONTOUR MAP IN OHM METRES

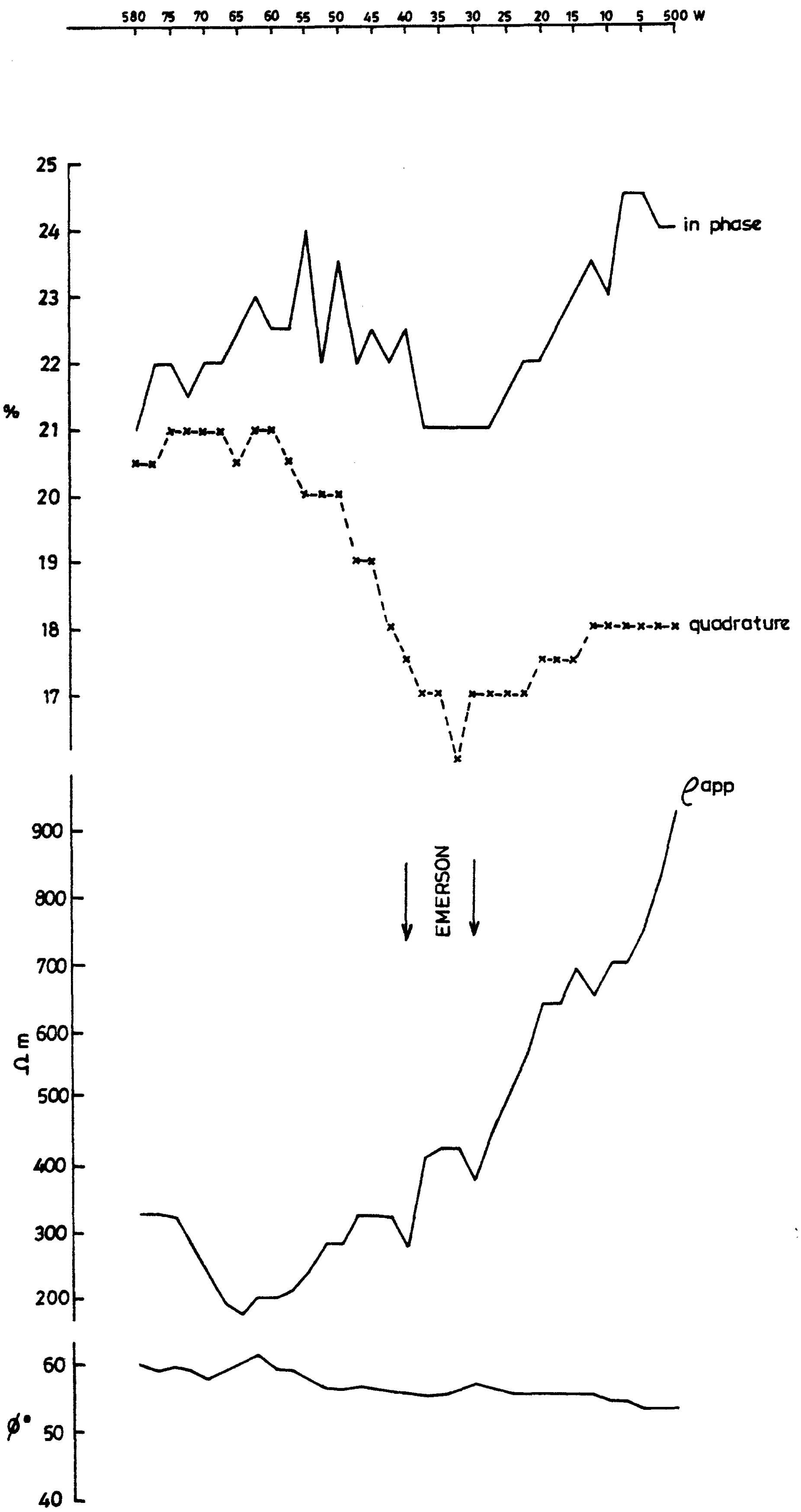

FIG. 5. DETAILED VLF AND RADIOHM RESISTIVITY PROFILES ACROSS THE EMERSON VEIN

veins to their convergence with the ankerite fault. It then swings to a north-westerly trend and follows the fault, a local high (> 1000 Ω m) occurring on the fault within the broad low feature. This high also has high phase angles, indicating a high resistivity upper layer such as desaturated scree.

Area D
High values here are due to outcropping granophyre. Phase angles close to 45° indicate homogeneity of the ground to a least 200 m depth and thin drift cover. Local resistivity peaks and troughs correlate with VLF anomaly 9–9.

Area E–E
Zones B–B, C–C and to some extent D are cut off by this cross cutting feature which correlates with the boundary between gabbro and the Skiddaw series. As B–B and C–C appear to be related to the faulting, these fractures must have a different character within the Skiddaw sediments and the greisen i.e. they must be tighter and less conductive in the sediments.

Area F–F
A linear low feature corresponding to VLF anomaly 11–11 extends across the survey area. Its minimum correlates with the maximum VLF anomaly on 300S and 500S. On 500S a value of 52 Ω m was measured with 45° phase; the low resistivity material extends from surface to at least 30 m. The resistivity on 300S is 200 Ω m and the phase is 40°, indicating the presence of a conductive upper layer. This zone of low phase extends from the western flank of the low resistivity zone to a point some 300 m east of the minimum. The resistivity minimum occurs 100 m west of the stream in Arm o'Grain. Although there is evidence of a conductive upper layer on most lines this appears to be wider than the low resistivity zone i.e. the latter represents a bedrock feature. On line 900S the main low lies to the west of Arm o'Grain, cutting across the topography, and it is unlikely that a restricted band of conductive overburden would follow such a trend. A ridge of high resistivity occurs within the general low south of 700S. Similarly a double low feature occurs on 0S and 100S. On 700S and 900S low phase angles (22°) coincide with the eastern low which may be related to the waterlogged ground near the stream. The general low feature F–F is considered to be caused by a relatively conductive geological feature, probably a fault zone, whose apparent resistivity is lowered by the presence of a conductive overburden on some lines.

Areas G and H
Outcropping rock is the main cause of these high resistivity zones, although on the steep slope above Grainsgill scree produced high apparent resistivities in linear zones.

Area I
This area of low values coincides with marshy ground which is the main catchment area for Grainsgill.

DISCUSSION
Most of the VLF anomalies have a corresponding low resistivity zone. In some cases (area A for example) the low resistivity contours are not continuous along the VLF anomalies but form an alignment of lows on individual traverses. This is due to the presence of conductive overburden which alters the background apparent resistivities between lines. The VLF filtering process enhances slope changes on the in-phase profiles so that an in-phase response which is attenuated due to conductive overburden will still have a positive apparent current density over a steep conductivity contrast. So a series of conductivity contrasts at different background levels will appear as separate low features on the resistivity map while the filtered VLF results show one continuous feature.

The detailed analysis of the low resistivity zone over the Emerson vein (Fig. 5) shows a local high over the vein, contained within a broad low zone. The reason for the latter is not clear; it may represent a zone of alteration and fracturing around the main lode-bearing fracture. Alternatively the vein may form a local subdrift topographic high, the surrounding low zone simply representing slight thickening of the overburden around this high. The second alternative is not, however, indicated by the phase measurements.

INDUCED POLARISATION SURVEY

The known mineralised zone was surveyed from line 300S to 1100S using Huntec MKIII time domain IP equipment. Initially a dipole-dipole array with an electrode separation of 20 m was used; dipole separations were n = 1 (20 m) and n = 2 (40 m). A 2 km gradient array was tried at a later stage, but practical difficulties restricted coverage only to line 700S and the array was abandoned.

The measured resistivity profiles are very similar in shape to the radiohm profiles, although the actual measured values are higher. This is to be expected as the radiohm method uses a very high frequency source. The resistivity map is unchanged except in contour magnitude; values measured at n = 1 and n = 2 are very similar, indicating homogeneity of the ground. As topographic variations can have a marked effect on resistivity measurements, a computer technique developed by Dey (Dey and Morrison, 1976; Dey, 1976) and modified by M. K. Lee of Applied Geophysics Unit (IGS, unpublished) was applied to the results. The effect on the dipole-dipole results was marginal, indicating that topographic effects were slight.

Chargeabilities are generally low (less than 4 milliseconds) except on 700S over the extrapolated continuation of the Wilson vein, coincident with a strong magnetic anomaly (see below). Here a zone some 50 m wide has chargeabilities of twice background with coincident low resistivity values. The chargeabilities within this zone are, however, very low and unlikely to indicate large concentrations of massive sulphides or extensive sulphide dissemination. Over the working lodes, no departure from background chargeability values were observed and the IP method is considered to have little potential for locating tungsten mineralisation in this area.

MAGNETIC SURVEY

Fig. 6 is a contour map of the total magnetic field measurements obtained in the Carrock Fell area. The results are reduced to an arbitrary base established on the north-south tie line B–B, and no regional correction has been applied as the gradient on B–B is negligible.

RESULTS
In the areas to the north of 800S and to the south of 900S the magnetic field is very quiet and uniform, averaging +50 nT relative to the base. The granite outcrop is picked out by the 0 contour line on 1100S. Between 700S and 900S a number of anomalies occur, and where the contours can be closed with certainty, the anomalies fall within the gabbro outcrop. The patch of granophyre mapped at Arm o'Grain coincides with a local low bounded by the +50 nT contour. A zone of intense (up to 3000 nT) anomalies occurs between 700S and 900S, the strongest anomalies occurring on line 700S (see Fig. 7). These features lie along the extrapolated positions of the

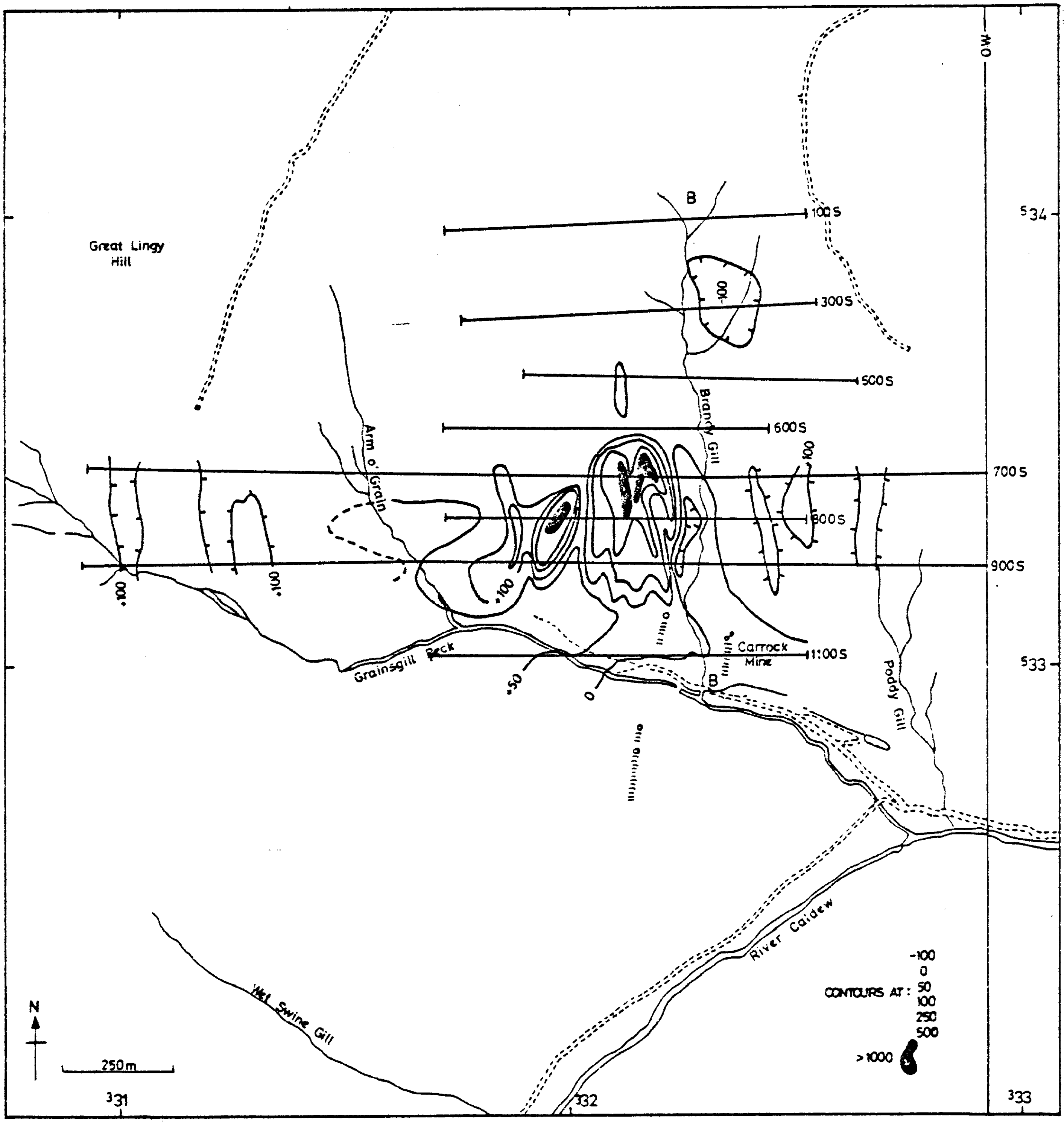

FIG. 6. TOTAL MAGNETIC FIELD MEASUREMENTS (NANOTESLA ABOVE AN ARBITRARY ZERO)

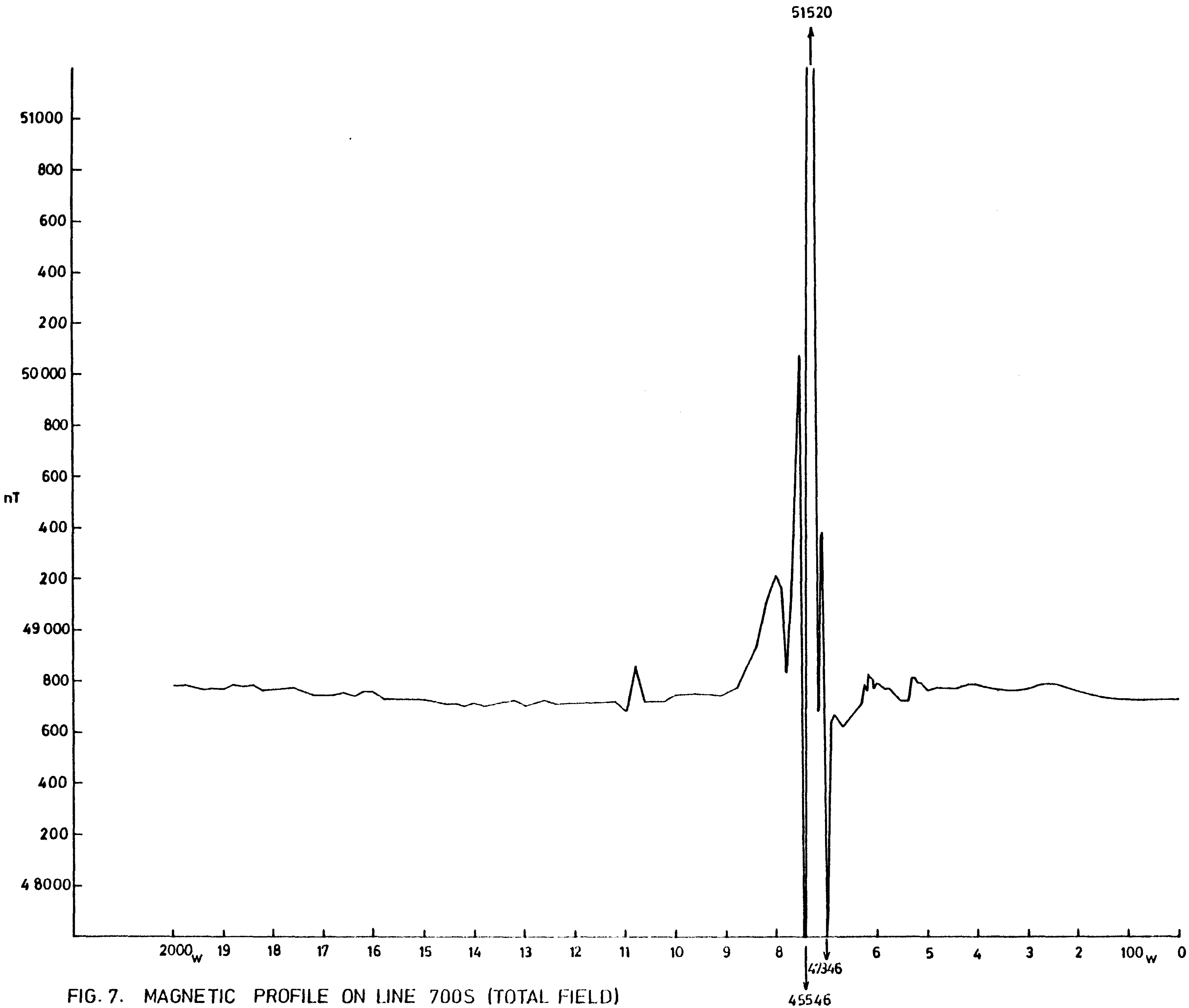

FIG. 7. MAGNETIC PROFILE ON LINE 700S (TOTAL FIELD)

Table 3 In situ susceptibility measurements at Carrock Fell

Rock type	Susceptibility range (x 10^6 emu)	Average
Greisen	15 – 100	55
Hornfels	150	150
Melagabbro	150 – 220	200
Leucogabbro	90 – 220	100
Quartz Vein	0	0
Pyrrhotite-rich Gabbro	1110 – 2625	1670

Smith and Wilson veins, but cannot be correlated exactly with the veins as the mapping is conjectural.

DISCUSSION

The very short wavelength of the high amplitude anomalies suggests that the causative bodies reach surface, although any outcrop is masked by a thin soil and vegetation cover. In situ susceptibility measurements on exposures both in Brandy Gill and underground show uniform low values except where the gabbros and veins are pyrrhotite rich, and even here the measured values are too low to explain the anomalies (see Table 3). The values must be regarded as minima as it was often difficult to expose a uniform fresh surface for accurate measurements. The observed anomalies are too complicated for satisfactory computer interpretation, but calculations show that susceptibilities of several orders of magnitude greater than the measured values are required to explain their amplitudes. This suggests almost pure segregations of pyrrhotite (average susceptibility 125 x 10^{-3}emu (Telford et al., 1976)). Magnetite is unlikely to occur in quantity as Eastwood et al. (1968) report that this mineral usually occurs in the gabbro peripheral to ilmenite of much lower susceptibility and within areas of hydrothermal alteration such as adjacent to veins where migration of iron has occurred with concomitant hornblendisation. Pyrrhotite has been observed within veins and in gabbro adjacent to veins and may form by the combination of iron leached from the gabbro and sulphide-rich hydrothermal fluids.

The anomalies are thus considered to represent discrete pyrrhotite lenses within, or adjacent to, fractures within the gabbro. The lack of coincident VLF anomalies indicates that the lenses have little depth extent, as more extensive pyrrhotite mineralisation has been shown elsewhere (Brzozowski, 1975) to produce strong VLF anomalies. Resistivity measurements on 700S and 900S (see below) show coincident low values of 500–1000 ohm metres, but the skin depths calculated from these values indicate that penetration of the VLF method would fall within the range 90–125 m, so the instrument would sample a considerable volume of ground. Any near surface body of restricted linear extent and depth would probably not produce a VLF response strong enough to be detected.

The magnetic method does not appear to be of value in tracing known mineralised structures, except within the gabbro outcrop, and no magnetic anomalies coincide with the VLF anomalies of Poddy Gill, the Emerson vein or Arm o'Grain. The increasing intensity of magnetic anomalies from 900S to 700S reflects the known northward increase of pyrrhotite seen along the worked vein within the gabbro.

SELF POTENTIAL SURVEY

Lines 600S, 700S, 800S and 900S were surveyed in the Brandy Gill area using the self potential method. One electrode was fixed at a base point and the other was moved to successive stations 20 m apart, thus measuring the potential with respect to the fixed base. The potentials between the lines were also determined.

RESULTS

Fig. 8 is a map of the equipotentials reduced to the base on 700S. A westerly gradient of -200 mV in 600 m is evident on the plotted profiles (Fig. 9), but this is unrelated to topography and is high for a regional gradient. Superimposed on this gradient are several short wavelength anomalies. On 700S a -250 mV anomaly is coincident with the strongest magnetic anomaly and appears to have a near surface cause. To the west of this a broader -50 mV trough coincides with a very weak magnetic anomaly. On 800S the strong anomaly has split into two -220 mV troughs coincident with the strongest magnetic anomalies. A -70 mV anomaly to the west coincides with a relatively strong magnetic feature. By 900S the two troughs are weaker (-100 mV) and are more widely separated by a positive peak of +180 mV. This positive peak coincides with a wide band of magnetic disturbance, the SP troughs coinciding with strong anomalies at each end of the disturbed zone. A wide trough of some -100 mV to the west coincides with a weak magnetic anomaly. On line 600S the SP anomalies are very weak, less than -30 mV and the magnetic anomalies are also extremely weak. Thus a zone of coincident SP and magnetic anomalies lies within the gabbro between 600S and 900S. Both represent bodies, possibly of pyrrhotite, which are almost at surface. The strong westerly gradient may indicate that Arm o'Grain has a very strong SP; unfortunately time did not permit investigation of this possibility.

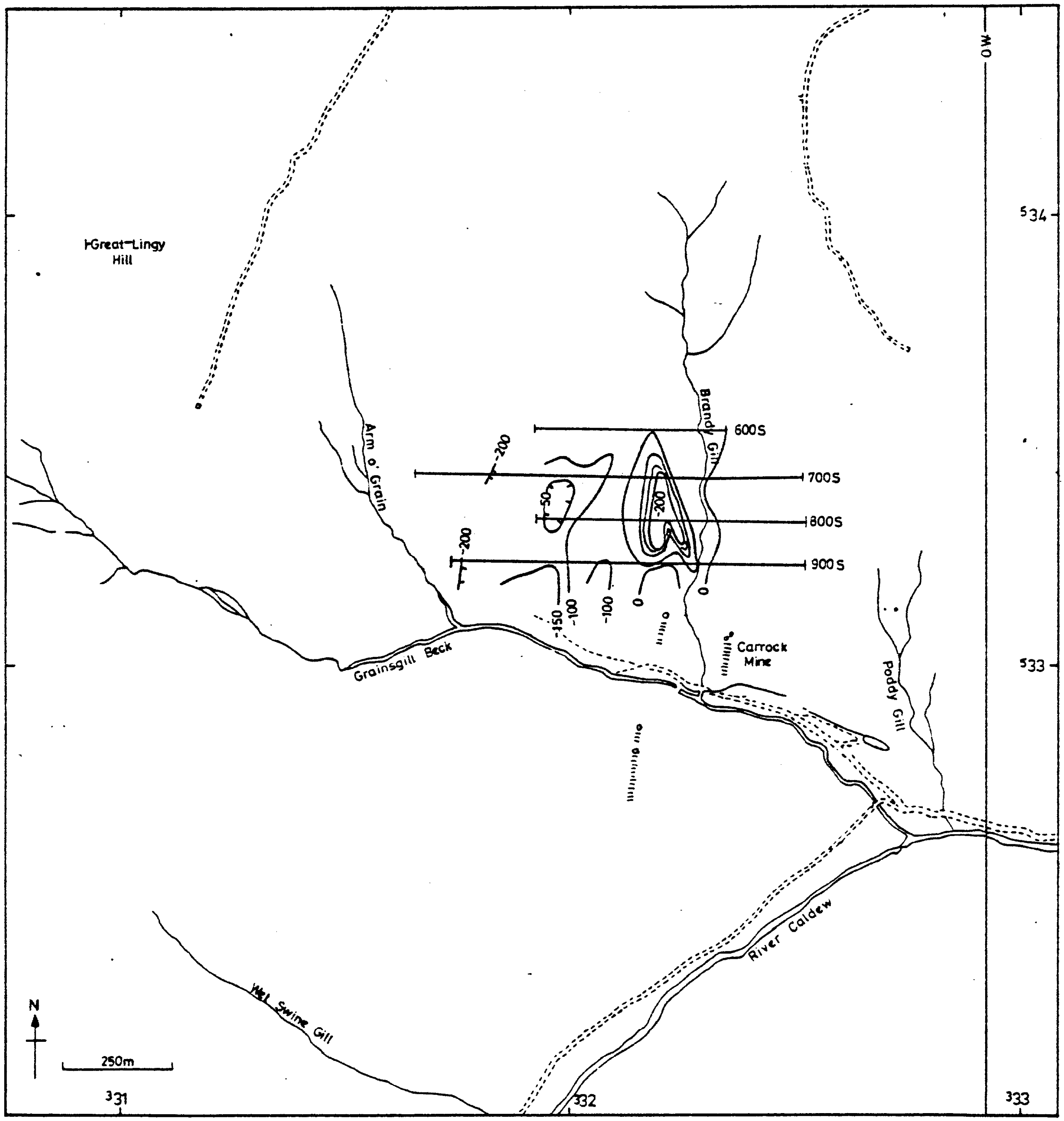

FIG.8. SELF POTENTIAL CONTOUR MAP (MILLIVOLTS)

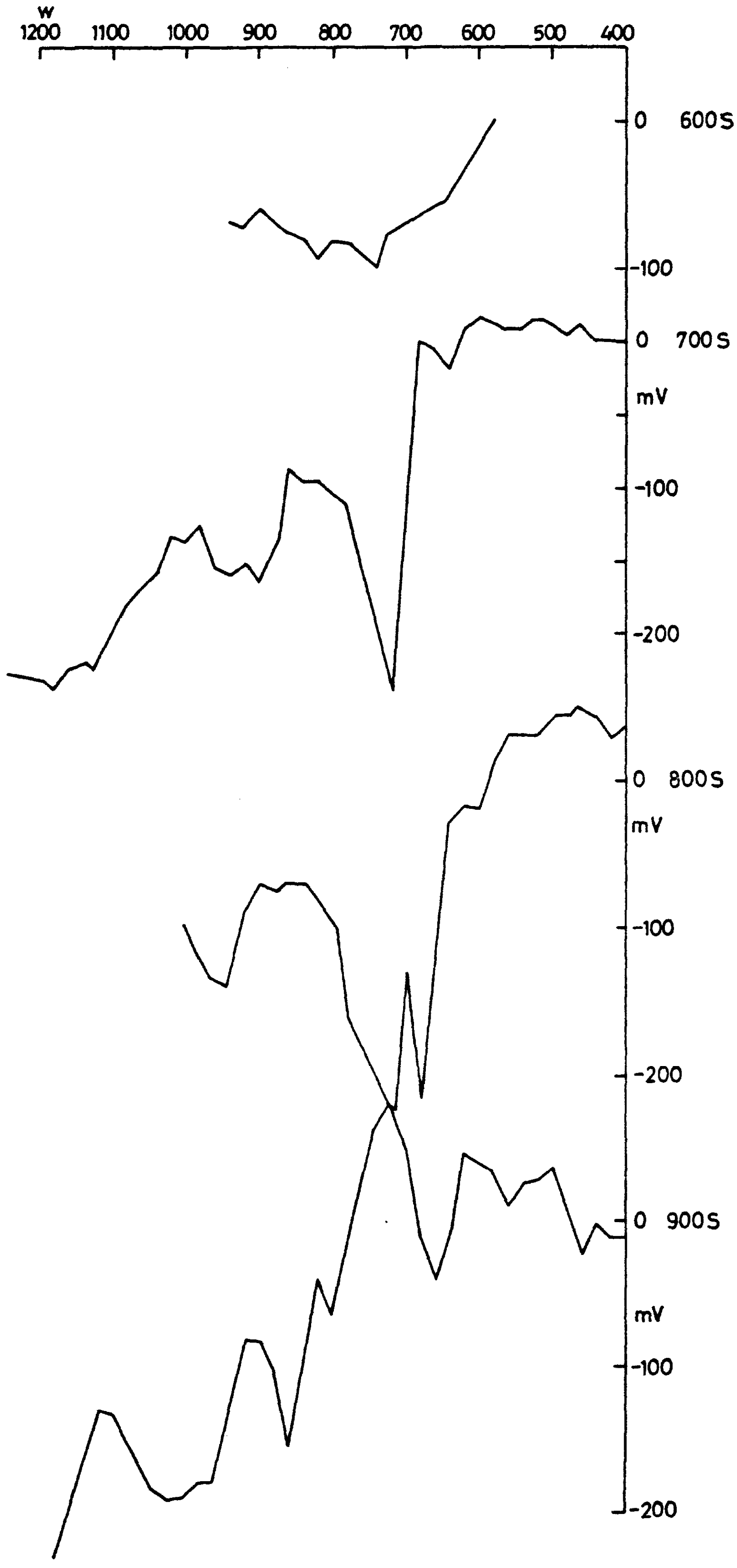

FIG. 9. SELF POTENTIAL PROFILES

CONCLUSIONS

Two distinct sets of anomalies have been outlined in this survey. The first, and possibly more significant, is a set of VLF anomalies which probably represent extensive linear fractures. The trend and distribution of these features are favourable for mineralisation. The strongest VLF anomaly occurs at Arm o'Grain where manganese mineralisation has been recorded; while this need not necessarily be related to tungsten mineralisation this anomaly warrants further studies. The continuations of the Emerson lode and the Poddy Gill structure are probably more interesting economically. The remainder require geochemical indication of mineralisation before further investigation is undertaken.

The second set of anomalies comprise coincident SP and magnetic features within the gabbro to the west of Brandy Gill on the continuation of the Smith and Wilson lodes. These are thought to represent lenses of pyrrhotite in a convergent set of fractures. Their near surface nature and lack of linear extent render them unlikely VLF targets, although they fall within a broad relatively low resistivity zone. A small zone of higher than background chargeabilities coincides with the anomalies; this was measured on a 20 m dipole-dipole array at n = 1 i.e. within the top few metres of ground. These anomalies are of more academic interest as they are unlikely to represent significant concentrations of economic minerals; however, a small programme of shallow drilling could usefully be conducted to prove their source.

Thus, of the techniques tried, VLF—EM appears to be the best geophysical method for the indirect location of mineralisation in the Carrock Fell environment. Resistivity results are likely to be confusing due to the variable thickness of conductive overburden, although most linear VLF features have coincident resistivity lows. Detailed resistivity traverses across the low zones might be expected to demonstrate the presence of a quartz lode as a localised high feature (see Fig. 7). The magnetic and self potential methods outline areas of near-surface local segregations of magnetic material and appear to have little success in tracing vein extensions.

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