Natural Environment Research Council
Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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No. 54

Copper mineralisation near Middleton Tyas, North Yorkshire

INSTITUTE OF GEOLOGICAL SCIENCES

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The Institute of Geological Sciences was formed by the incorporation of the Geological Survey of Great Britain and the Geological Museum with Overseas Geological Surveys and is a constituent body of the Natural Environment Research Council

Bibliographical reference
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SUMMARY

Historical accounts of copper mining near Middleton Tyas in the 18th century show that small tonnages of very rich ore were dug from veins, flats or irregular cavities in the Underset Limestone. The mineralisation probably originated from metalliferous brines migrating from the Stainmore Trough or a similar Lower Carboniferous sedimentary basin to the east. The possibility that the mineralisation was syngenetic has been investigated but is now discounted; similarly, boreholes through the local Permian succession to test whether a Kupferschiefer facies of the Marl Slate is present locally, gave negative results. The primary copper sulphides were subsequently enhanced in grade by supergene enrichment under arid conditions during early Permian times.

Much of the outcrop of the Main and Underset limestones within the Middleton Tyas anticline is heavily drift-covered. Anomalous copper values in soils have been found over about 6 sq km, but it is not known whether these are due to ice dispersion or whether they mark hidden copper deposits. An IP survey in the area was hampered by the presence of strong artificial conductors.

INTRODUCTION

The Middleton Tyas area of North Yorkshire is mixed dairy and arable farmland lying close to the Great North Road (A1) (Figure 1a). The ground is undulating and rises gradually westwards to the moors above Swaledale. The area is traversed by the Swale–Tees watershed but relief is low and drainage towards both rivers is sluggish. The village of Middleton Tyas is distinguished from neighbouring agricultural villages by the presence of several large houses built from the wealth of the local 18th-century copper mining industry. During the 19th century, limestone was extensively quarried around the village for use in the iron and steel industries of Teesside. The local market town and agricultural centre is Richmond, at the foot of Swaledale.

GEOLOGY

The primary geological survey of the area by W. Gunn was carried out during the 1870s and published in 1889, though without a descriptive memoir. The map outlined the Sleightholme–Middleton Tyas anticline (Figure 1b), trending eastwards near Sleightholme but plunging gently to the south-east near Middleton Tyas. The stratigraphy and structure of the fold were described by Wells (1957) and during the present work, the 1:10 000 geological maps (NZ 20 NW and SW) have been revised. As an aid to this revision, Middleton Tyas No. 1 borehole (Figure 2 and Appendix 1) was drilled to establish the local Dinantian succession in the mining area east of the village.

The Carboniferous rocks underlying most of the Middleton Tyas area are upper Dinantian (up to the base of the Main Limestone) and lower Namurian in age and, at outcrop around the village, range from the Underset Limestone up to the Richmond Cherts (Figure 2). Drilling has extended knowledge of the local succession down to the Middle Limestone. The limestones are generally biomicrites with debris from broken brachiopods, corals, foraminifera and bryozoa, denoting accumulation in the high-energy environment of a shallow sea. Crinoid-debris grainstones are common especially in the Underset. The limestones usually have low inter-granular porosity due to extensive re-crystallisation of the carbonates. The limestones are typically succeeded by mudstones, siltstones and then sandstones, with perhaps a thin seatearth and coal developed above, the entire rhythmic unit comprising a cyclothem of Yoredale type. The Namurian rocks show similar rhythmic deposition but are also characterised by widespread syn-sedimentary cherts at certain levels. The thickest development is the Richmond Cherts which are siliceous limestones and cherts lying above the Little Limestone (Wells, 1955). They appear to have accumulated in rather turbulent conditions like the carbonates and are thought to be due to the co-precipitation of silica gel and carbonate on the shallow sea floor. Secondary flinty chert is also common in the form of nodules along the bedding.

The sequence of Carboniferous rocks around Middleton Tyas differs from that generally found on the Askrigg block to the west in several respects. The Main Limestone is unusually thin (about 8 m) whilst the Underset Limestone is much thicker (20–25 m). The Five Yard Limestone is also surprisingly thick (about 14 m) and lies very close above the Middle Limestone. These changes from the normal Swaledale sequence may

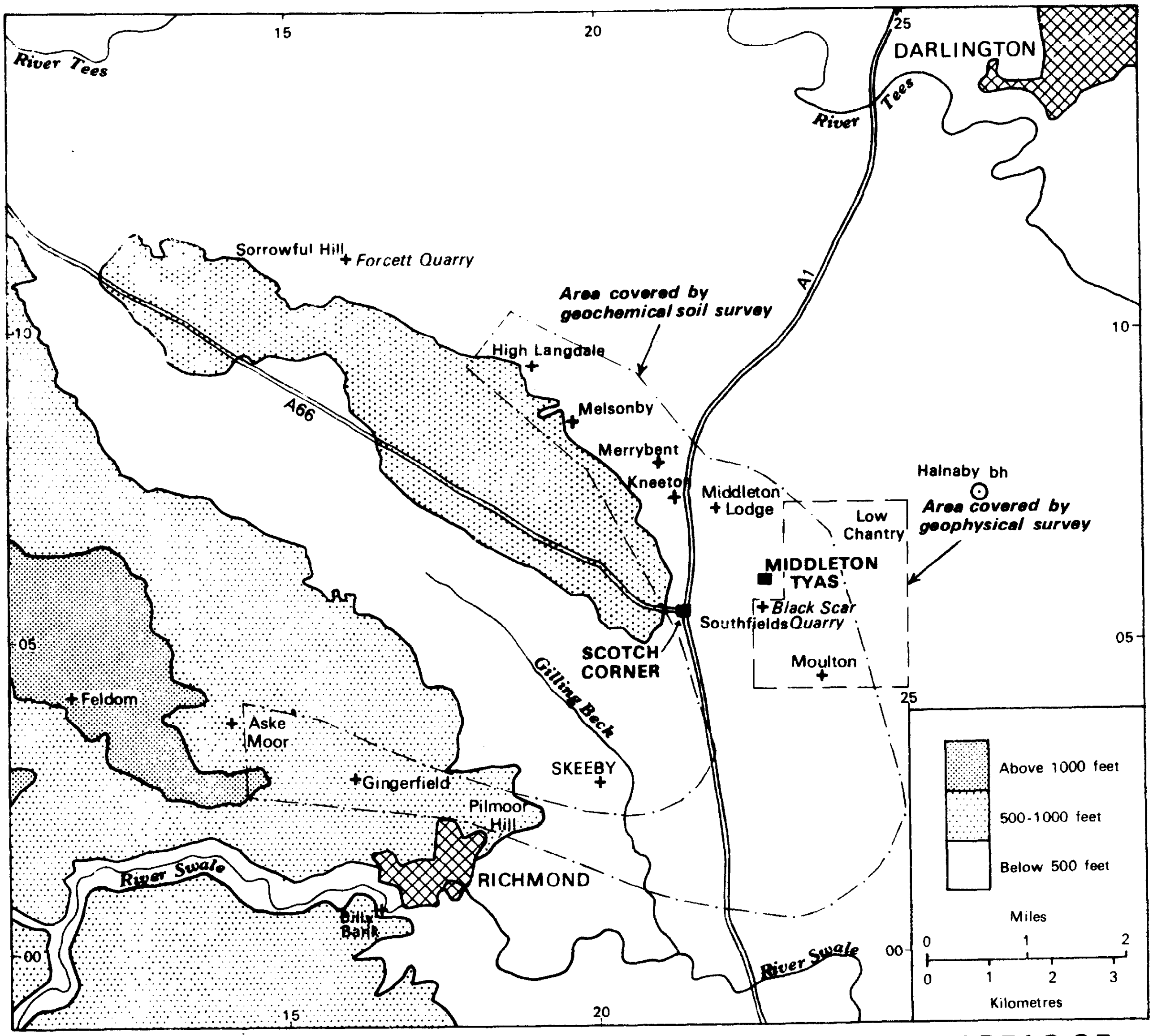


FIG. 1a TOPOGRAPHY AROUND MIDDLETON TYAS AND THE AREAS OF GEOCHEMICAL AND GEOPHYSICAL SURVEY.

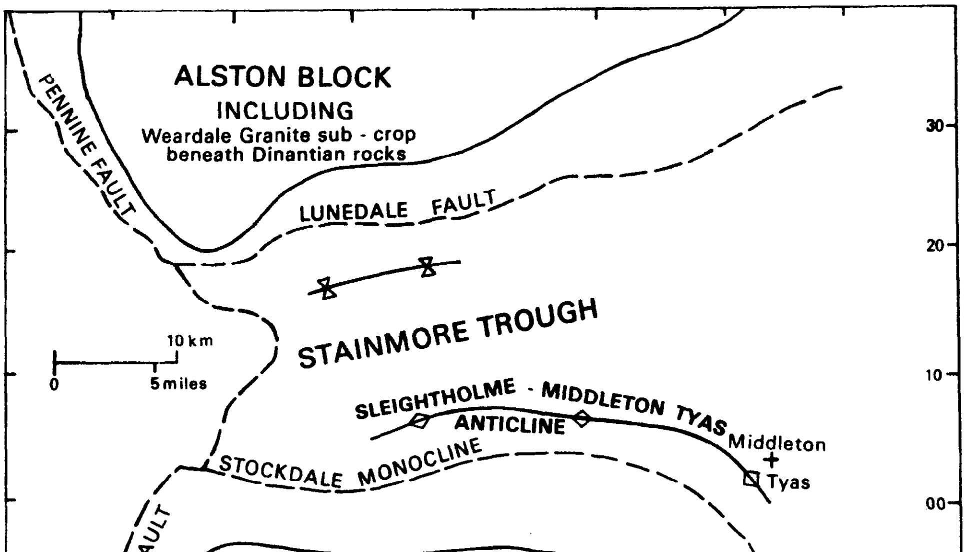


FIG 1b REGIONAL STRUCTURE OF DINANTIAN BLOCKS AND BASINS

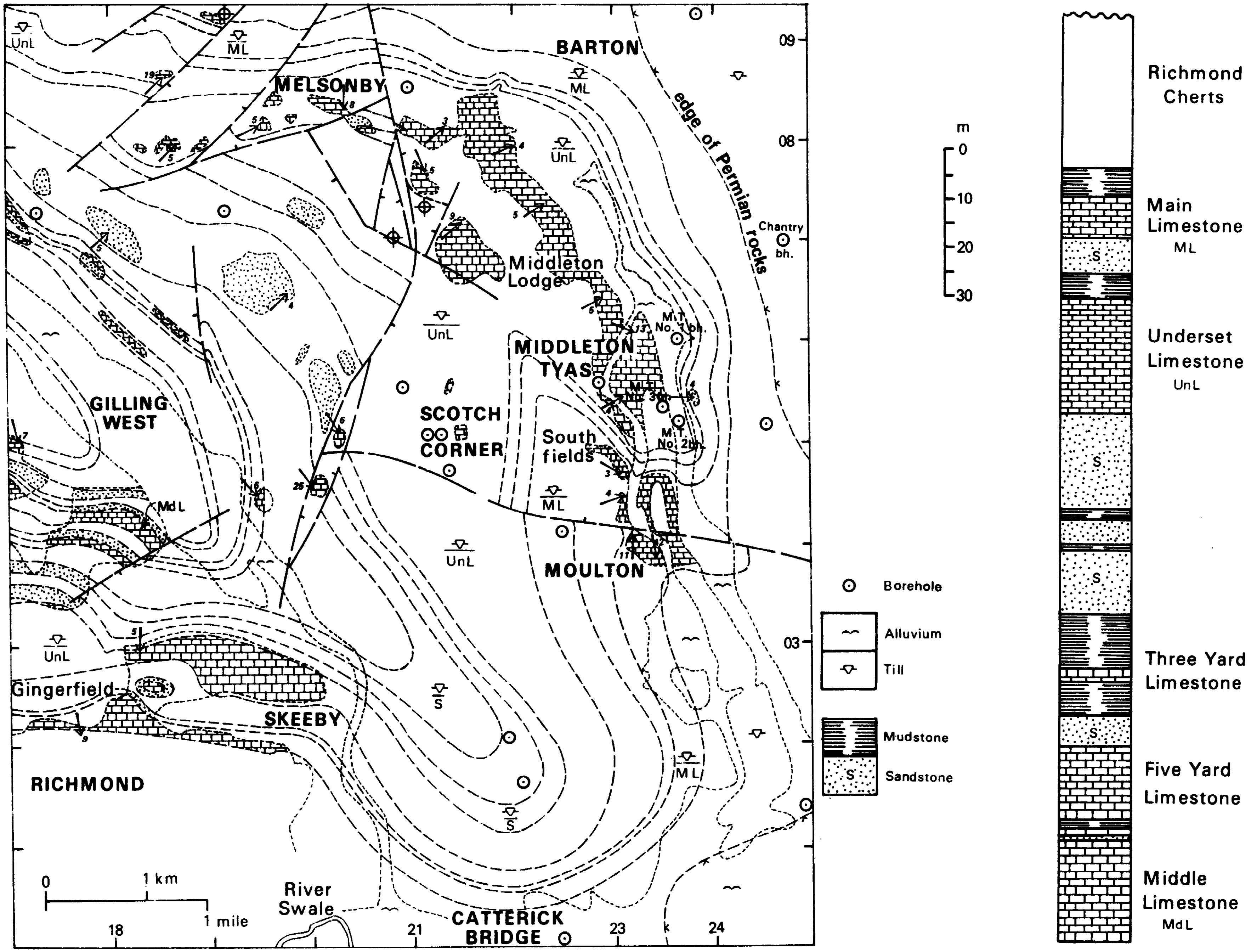


FIG. 2 GEOLOGICAL MAP AND VERTICAL SECTION OF MIDDLETON TYAS

presage a lateral transition to a basinal Dinantian facies to the north or east. Indeed, it seems likely that the anticline approximately marks the edge of the Askrigg Block, although this cannot be demonstrated with certainty since the lower Dinantian succession hereabouts is unproven.

To the east of Middleton Tyas, Upper Permian and Triassic beds lie unconformably upon the folded Carboniferous rocks. The junction is entirely hidden by thick drift but the Chantry and Halnaby boreholes (Appendix 1) show that the Permian rocks dip gently eastwards at 2° to 4°. At Chantry, the basal breccia is overlain by a thin Lower Magnesian Limestone, while at Halnaby the basal breccia is much thicker and is succeeded by Middle Permian Marls. There was locally considerable on-lap at the base of the Permian on to an irregular land-surface produced by the erosion of the Carboniferous rocks of the Middleton Tyas anticline.

MINING

MIDDLETON TYAS

No detailed plans of the Middleton Tyas mines exist but a brief account by Raistrick (1936) and a full historical treatment of the local industry by Hornshaw (1975) ably summarise the available information. Indeed, so thorough is Hornshaw's research into the surviving documents that a detailed and fascinating picture of the principal personalities and way of life of the people of Middleton Tyas in the 18th century emerges from his account. The first discovery of copper ore was made in 1733 during the working of the limestone quarries just west of Layberrys (Figure 3), and by 1742 sufficient ore had been proved to sustain profitable workings. Copper was discovered on glebe lands around the church in 1750 and by the time of the Rector's death in 1763, the value of ore won amounted to about £40 000, a sizeable sum for those times. By 1763 the copper mines were approaching exhaustion and mining ceased altogether about 1779. Two contemporary accounts by foreign visitors to the copper mines are extant (Angerstein, 1755; Jars, 1781) and two crude sketch-maps of the shafts and underground workings by the mine managers of the time have survived. It is upon these sources that the reconstruction shown in Figure 3 is based. During the primary geological survey, Gunn mapped two north-west trending faults through the mineralised ground. Though there is no evidence either on his field map or in his manuscript notes to show why he thought the faults were necessary, the principal one has been retained in Figure 4.

Numerous spoil heaps can still be seen marking the old shafts but there is no access underground. There were said by Angerstein to be two vertical veins or 'pipes' and a flat in the mine he visited. Hornshaw estimates that one flat, developed along the bedding of the Underset Limestone below the glebe land between Church Field and Goosehill, may have been 27 m wide, 275 m long and about 0.4 m thick. The pipes apparently contained gouge with malachite and azurite, together with cavities filled with limonite-coated secondary Cu sulphides. The flats occurred both within the Underset and in the 'underbed', the sandstone immediately below the limestone. Many of the deposits lay below the water-table and it proved difficult to keep the water at bay with the rudimentary pumps of the time, although the deepest shafts, near the church, were only about 15 m deep.

The total tonnage of ore dug from the mines is difficult to estimate but it cannot have been large. A maximum of 3500 tonnes of ore seems reasonable (Dunham and Wilson, *in preparation*) from the fragmentary evidence. The grade of the ore was high, perhaps as much as 66% Cu in some of the deposits. Even with inefficient beneficiation, the overall grade may have averaged 45% Cu, so that the total production of Cu metal may have been about 1500 tonnes (Dunham and Wilson, *op. cit*).

ADJACENT AREAS

The Middleton Tyas mines were the most productive of a series of Cu occurrences around the nose of the Sleightholme–Middleton Tyas anticline, from Sorrowful Hill in the north-west, via Middleton Tyas and then westwards to Feldom (Figure 1a). This Cu area is in contrast to the Swaledale mining field farther west in which Pb, Zn, Ba and F ores predominate. The small mines and trials are briefly described below.

Sorrowful Hill–Forcett Quarry

A small north-east trending vein was formerly tried for Cu on the Main Limestone outcrop at Sorrowful Hill and is exposed as a 2-m fault in the large Forcett Quarry working the Limestone to the north. Within the Limestone, chalcopyrite, witherite and barite are found in the vein, together with small amounts of sulphides formed by secondary enrichment, such as bornite and chalcocite. In the shales beneath the Limestone are layers of pyrite nodules also replaced by secondary Cu sulphides as seen in the following section [1556 1066]:

MAIN Limestone, grey, fine-grained, dolomitic with azurite traces	2.0 m
Siltstone, dark grey, calcareous with sulphide nodules	0.1 m
TUFT Sandstone, grey, fine-grained calcareous with malachite and chalcocite	0.6 m
Mudstone, dark grey, silty, micaceous, stained with malachite	2.0 m

The sulphide nodules, up to 7 cm in diameter,

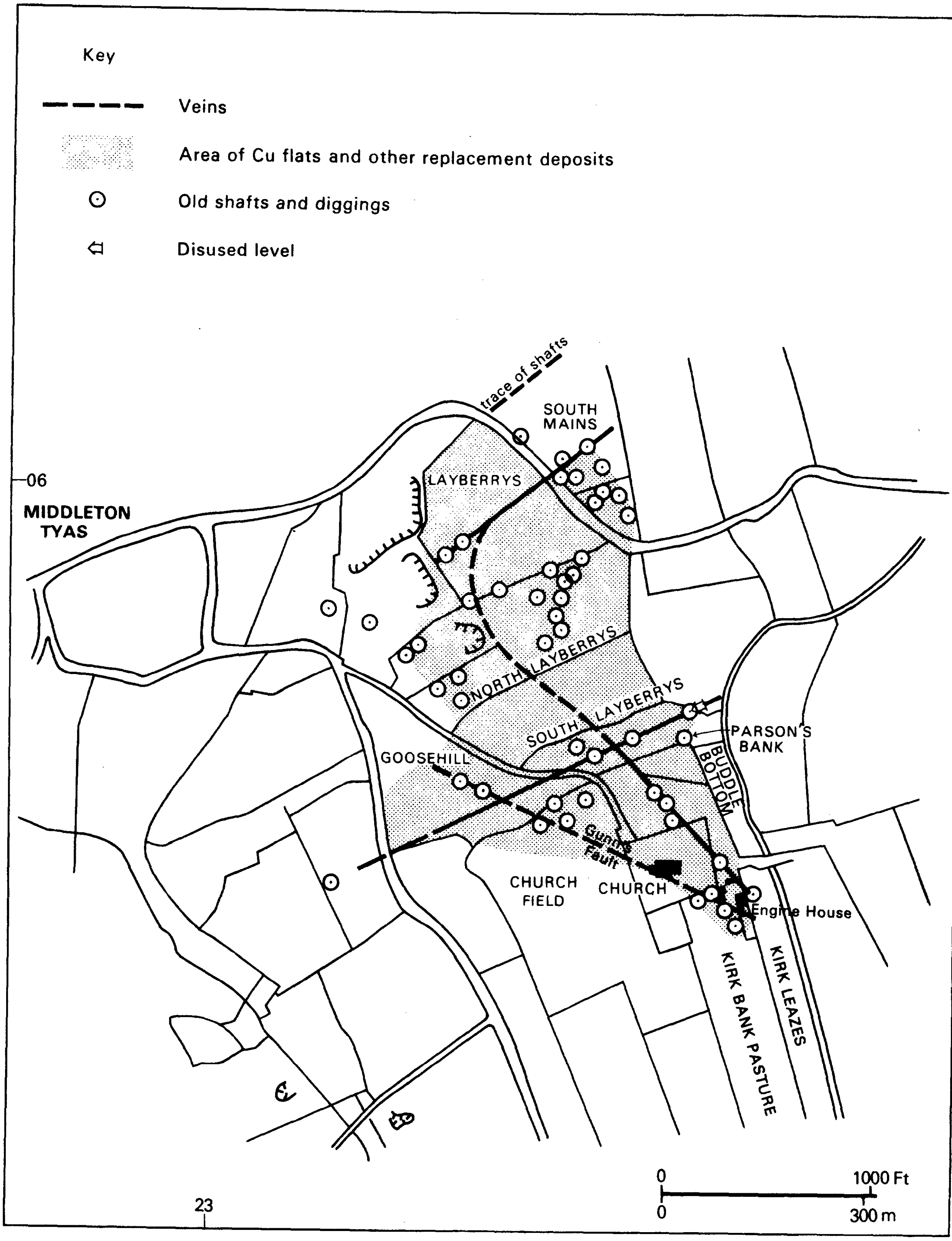


FIG. 3 18th-CENTURY WORKINGS FOR Cu AT MIDDLETON TYAS.
(after T.R.Hornshaw 1975)

assayed at 42% Cu, 20% Fe and 32% S. The green-stained shales and sandstone in the dispersion zone below the layer of nodules show 2–5% Cu on analysis.

Close by in Forcett Quarry [1575 1067] the small fault is exposed in a face of Main Limestone, where the fracture is rich in chalcocite, chalcopyrite, covelline and malachite, but the mineralisation ceases at an earthy parting. The fault can be traced north-eastwards across the quarry but there is no further sign of mineralisation other than dolomitisation in this direction.

High Langdale
An overgrown trial [1911 0927] lies close to a north-east trending fault cutting the Main Limestone outcrop. Apart from some malachite-stained limestone debris, there are no tips.

Melsonby
The Underset Limestone is exposed in a small quarry [1975 0818] and carries thin north-east trending veins of calcite and malachite. A trial shaft on the south side of the digging was probably sunk during the 18th century.

Merrybent
Mining of Cu and Pb at these mines dates from the 19th century and began in 1856 (Hornshaw, 1975). Production was continuous between 1863 and 1874 although the small tonnage of ore won always made this a marginal enterprise. The principal Engine Shaft [2106 0737] was 91 m deep and commanded several small faults trending either north-east or north-west and cutting the Underset Limestone and the underlying beds. Two such faults were penetrated by the shaft itself. Driveage was carried out on three levels, at about 10 m, 42 m and 91 m below ground respectively although little was done on the lowest level. The minerals worked included galena and chalcopyrite, as well as the replacement copper sulphides and carbonates, giving high ore grades. More details of the workings and drainage levels are given in Dunham and Wilson (*op. cit.*).

Gingerfield
Trials were made along the outcrop of the Main Limestone to the east and west of the farm in about 1762, by miners from Middleton Tyas (Hornshaw, 1975). The workings consist of shallow shafts and adits into the steep bank of the outcrop wherever green-stained or dolomitic limestone was seen. The easternmost workings were at Pilmoor Hills [1834 0213] and near Bend Hagge. The latter occurrence is now part of the Richmond Golf course and has been extensively landscaped, but Gunn's 19th-century field map shows an extensive quarry with two east-trending, and a north-east trending, 'vein or swell'. The outcrop south of Gingerfield farm was tried by several shafts [1653 0236, 1634 0232, 1620 0231, 1606 0233] but there are no signs of large tips. One trial was made in the underlying Tuft sandstone near the farm [1603 0276], again without apparent success. Farther west there are shafts on Rasp Bank [1555 0265, 1546 0258, 1522 0265, 1513 0274], and an adit near High Coalsgarth driven south-westwards into the Limestone. Gunn drew strike faults and veins along much of the 4 km-cupriferous outcrop of the Main Limestone but there is no demonstrable throw along much of this length. It seems more likely that the mineralisation is similar to that at Middleton Tyas and that secondary dispersion of Cu from small veins has produced the widespread anomalies hereabouts (Figure 4).

Billy Bank
Probably the oldest Cu mine of the area is situated on Billy Bank, on the south bank of the River Swale, south-west of Richmond. This may have been the 'copper mine in Richmond' referred to in the State Papers of the late 15th century (Hornshaw, 1975). Disused shafts were recorded here by Gunn during the primary geological survey published in 1878, but mining was renewed in 1906 and continued until 1916. Two adits were driven from just above river level [1650 0062 and 1649 0057] along the WSW-trending Richmond Fault for about 240 m. Details of the underground workings have been established by a caving group from Newcastle (Moldywarps Speleological Group Journal, 1968–1970) and are described in Dunham and Wilson (*op. cit.*). The veins worked here seem to have carried calcite and chalcopyrite, together with malachite, azurite and chrysocolla. The occurrence is atypical in that it lacks minerals indicative of supergene enrichment.

Feldom
This vein, situated 7 km WNW of Richmond (Figure 1b), carried both Cu and Pb and trends north-east across the outcrop of the Main Limestone. It more closely resembles the veins of the Swaledale mining field than the Cu occurrences farther east. The tips show galena, chalcopyrite, barite and calcite, plus oxidation minerals. It seems to have been worked in the late 17th and early 18th centuries, along a strike length of about 900 m.

MINERALISATION

It is difficult to obtain useful specimens of minerals from many of the disused workings but a good collection was made some years ago by Dr T. Deans at Black Scar quarry. He found nodules of bornite enclosed by chalcocite and chalcopyrite with covelline, with an outer layer of bornite and oxidation minerals such as malachite, azurite and limonite (Deans, 1951). In sandy pockets in the limestone, chalcocite, covelline, malachite, barite and limonite occurred with tiny crystals of native copper. At Merrybent, samples of chalcocite and covelline replacing galena were found.

P. R. Simpson of the IGS Applied Mineralogy Unit has examined this material and additional specimens collected during this survey. He considers that the primary sulphides were chalcopyrite and djurleite, and that digenite, bornite and covelline were produced by secondary enrichment. Subsequent oxidation led to the dispersion of malachite and azurite; local reduction to native copper probably took place in the presence of organic matter. Gangue minerals such as calcite, barite and witherite are very rarely present.

The lack of access to the workings at Middleton Tyas and the ambiguity of contemporary accounts of the mineralisation has made the origin of these deposits problematical. At least three ideas have been canvassed:

i the copper sulphide mineralisation was syngenetic with the deposition of the Underset and Main limestones.

ii the sulphides originated in a Kupferschiefer facies of the Marl Slate near the base of the Permian succession and were carried down into the Carboniferous limestones by downward-percolating groundwater (Deans, 1951).

iii the sulphides were carred from adjacent Lower Carboniferous sedimentary basins by hypersaline brines.

Each of these hypotheses has been tested as follows:

The idea of syngenetic Cu mineralisation was initially attractive since the principal occurrences almost invariably lie close to the bases of either the Underset or Main limestones, and the background levels of Cu are generally higher in these cyclothems hereabouts than is usual elsewhere. In addition, there were several records of Cu-rich nodules lying along the bedding at these horizons, particularly at Forcett quarry. It was only after a mineralogical examination of these minerals that it became clear that the syngenetic mineral had been pyrite and that the Cu was introduced subsequently. Furthermore, several cored and rotary percussion boreholes were drilled through these horizons and failed to prove syngenetic Cu sulphides. The high background levels of Cu are also accounted for by the third hypothesis so the idea of syngenetic mineralisation has been abandoned.

The Marl Slate of south-east Durham is enriched in Pb over a wide area (Hirst and Dunham, 1963) and, as Deans had found both Pb and Cu in these beds in northern Germany (Deans, 1950), it seemed likely to him that a cupriferous facies might be present to the east of Middleton Tyas. The mineralised ground lies close to the sub-Permian unconformity but the idea could not be tested by field observation since there is a complete cover of thick drift over the outcrop for at least 15 km along strike. Accordingly, two cored boreholes were drilled, at Chantry (see Figure 2) and Halnaby, nearly 1.5 km east of Chantry (Figure 1a) to prove the Permian succession. These boreholes intersected neither Marl Slate nor other cupriferous sediments in the Permian succession (Appendix 1), so the Marl Slate can therefore be discounted as a source for the mineralisation in the Carboniferous rocks.

It seems most likely that the Cu minerals were deposited from hypersaline brines. The Middleton Tyas area lies immediately east of the Swaledale Pb–Zn mining field and veins at Feldom and Billy Bank, which contain both Cu and Pb sulphides, appear to be transitional between the types characteristic of the two areas. It has been suggested (Small, 1978) that the Swaledale minerals originated from low Na:K ratio brines derived from the Mallerstang area of the Askrigg block and, further, that the Middleton Tyas mineralisation was derived from brines with high Na:K ratios originating as formation waters. On this view the veins of transitional type at Feldom and Billy Bank represent mixing of the two sorts of brine.

Fluid inclusion studies (Rogers, 1978) from the Swaledale mining area show that the Pb–Zn ores were deposited at low mineralisation temperatures (92–159°C). No fluid inclusion data has been obtained from Middleton Tyas minerals but one sample of calcite from the nearest part of the Swaledale field indicates temperatures of 'less than 70°C plus pressure correction' (Small, 1978).

The source of the Middleton Tyas brines is most likely to be the deep Lower Carboniferous sedimentary basin of the Stainmore Trough, although a similar, but as yet unproven, basin may underlie the Permo-Triassic rocks to the east and south-east. It is envisaged that the brines originated as formation waters and migrated upwards through suitable aquifers and faults towards the flanks of the basin, under compaction pressures. Sulphide minerals were then deposited where the brines met local S-rich pore-fluids. This process accounts not only for the rich veins and flats in the limestones but also for the widely disseminated Cu minerals which characterised all the lithologies of the Underset and Main cyclothems in the area.

The emplacement by brines probably took place in late-Carboniferous or early-Permian times since the subsequent processes of supergene enrichment are most likely to date from the period of arid climate which characterised this region during the early Permian. This type of enrichment takes place most effectively when the water table is low. Copper is leached from the upper part of the deposit and carried downwards in acidic sulphate solutions to be re-deposited by reaction with sulphides near the water table. The process is probably enhanced by the dolomitisation of parts of the limestones, giving cavities for the circulation of solutions, and by the presence of diagenetic pyrite nodules in the mudstones beneath the Main and Underset limestones. The mineral suite bornite–covellite–digenite–chalcocite is characteristic of the process.

GEOCHEMICAL SURVEYS

At the reconnaissance stage, soil samples were collected along traverses roughly normal to the strike of the beds around the Middleton Tyas anticline (Figure 4). The sampling interval varied between 50 m and 200 m, and the soils were collected from depths of 20 cm to 100 cm. All the soils collected were analysed by AAS techniques for Cu; two traverses were also analysed for Pb and Zn by similar techniques in order to provide some background data on their occurrence. Only the Cu values are reported here, the levels of Pb and Zn being at the background values expected. The results obtained from the Cu analyses are indicated in Figure 4 on which only values in excess of 50 ppm (a figure that approximates to the background value) are indicated.

High Cu values, in some cases in excess of 5000 ppm, were obtained from Gingerfield and Pilmoor Hill. Values up to 2300 ppm were obtained not only around the worked area of the Underset Limestone near Middleton Tyas, but also farther north near Middleton Lodge and to the south near Southfields Farm. The latter anomalies continue southwards through the thick drift south of Moulton towards the flood-plain of the River Swale, and appear to coincide broadly with the sub-drift crops of the Underset and Main Limestones. Nonetheless, Cu values generally in the soils were lower where the drift is thick.

In the Gingerfield and Pilmoor Hills areas the soil anomalies are related to bedrock mineralisation beneath a thin soil cover; elsewhere, particularly to the east, the increased thickness of glacial material obscures this relationship. In order to test the anomalously high Cu soil values, five of the reconnaissance lines were re-sampled at the overburden/bedrock interface by means of a power auger. For the same reasons additional basal till sampling was undertaken in the Southfields Farm area (Figure 5).

The augering was carried out by Mr M. McGlashan and the holes ranged in depth from 0.8 to 9.0 m, averaging 3.7 m. In most of the holes the Cu content of the till markedly increased with depth; the ratio between basal till and soil values varied from 1.1 up to 11. Some samples showed an initial decrease in Cu just below the soil (e.g. Figure 8) before increasing steadily downwards toward the bedrock. Values as high as 2000 ppm Cu were reached in some basal till samples, but these are not necessarily the most promising occurrences if they are isolated. Of greatest interest are those groups of holes showing a steady increase in Cu content towards bedrock. Five such areas emerged from the reconnaissance soils and power auger surveys, at Gingerfield, Southfields, Middleton Lodge, to the south-east of Middleton Tyas church, and just to the north of Moulton village. The first three areas were investigated using a rotary percussion rig. The fourth area coincides with an IP anomaly and two cored boreholes were sunk here. (Middleton Tyas Nos. 2 and 3, p. 25 and Appendix 1.) The last area was given a lower priority of investigation since the drift around Moulton is drumlinised and much thicker than in the other areas and would make extension of exploration away from the local outcrops more difficult. The high Cu values here appear to lie along an east-trending fault and parallel fold in the Main Limestone.

In concert with the rotary percussion drilling programme, the metal content of the Underset Limestone in Black Scar quarry (Figure 6) was tested, by channel sampling and analysis by atomic absorption spectrometry. The quarry provides a good section through the Limestone close to the 18th century mines, and in its south-western corner (locality 3 in Figure 6) groundwater leakage along a small fault gives vivid green Cu staining of the Limestone and underlying mudstones. Analysis shows 7.5% Cu along this fracture. Elsewhere in the quarry, where there is no sign of faulting, Cu values are still high in the Limestone and fine grains of malachite and azurite are visible along joints and bedding surfaces. The analyses for Pb and Zn are at much lower levels than for Cu, but are still higher than is usual for these lithologies.

The programme of rotary percussion air-flush drilling was supervised by J. M. Hudson. The method produces samples of rock as small chips and fine dust brought to the surface by the circulating flow of compressed air lubricating the drilling bit. Using a 4-inch bit, a large volume of powder was obtained from one metre of bedrock but it was generally sufficiently homogeneous for analysis of grab samples to be representative. All the powders were analysed for Cu, Pb and Zn by atomic absorption spectrometry. The logs of most of the boreholes and their analyses are shown graphically in Figures 7 to 9. It was usually intended to drill to a maximum depth of 40 m, but in some cases the water table stopped the hole at shallower depths. To maximise the likelihood of intersecting steeply-inclined faults and veins, the holes were generally drilled at 45 degrees, but it proved difficult sometimes to obtain a satisfactory return of chippings from an inclined hole and in these cases the borehole was drilled vertically. Poor returns of powders were experienced where open joints or bedding cavities in the limestones allowed the air flush to be dissipated.

SOUTHFIELDS

The distribution of auger holes and 10 rotary percussion boreholes is shown in Figures 5 and 7. Both the Main and Underset limestones were proved, separated by about 20 m of mudstone, siltstone and sandstone.

For this location a total of 215 samples (each representing approximately 1 m of bedrock in the

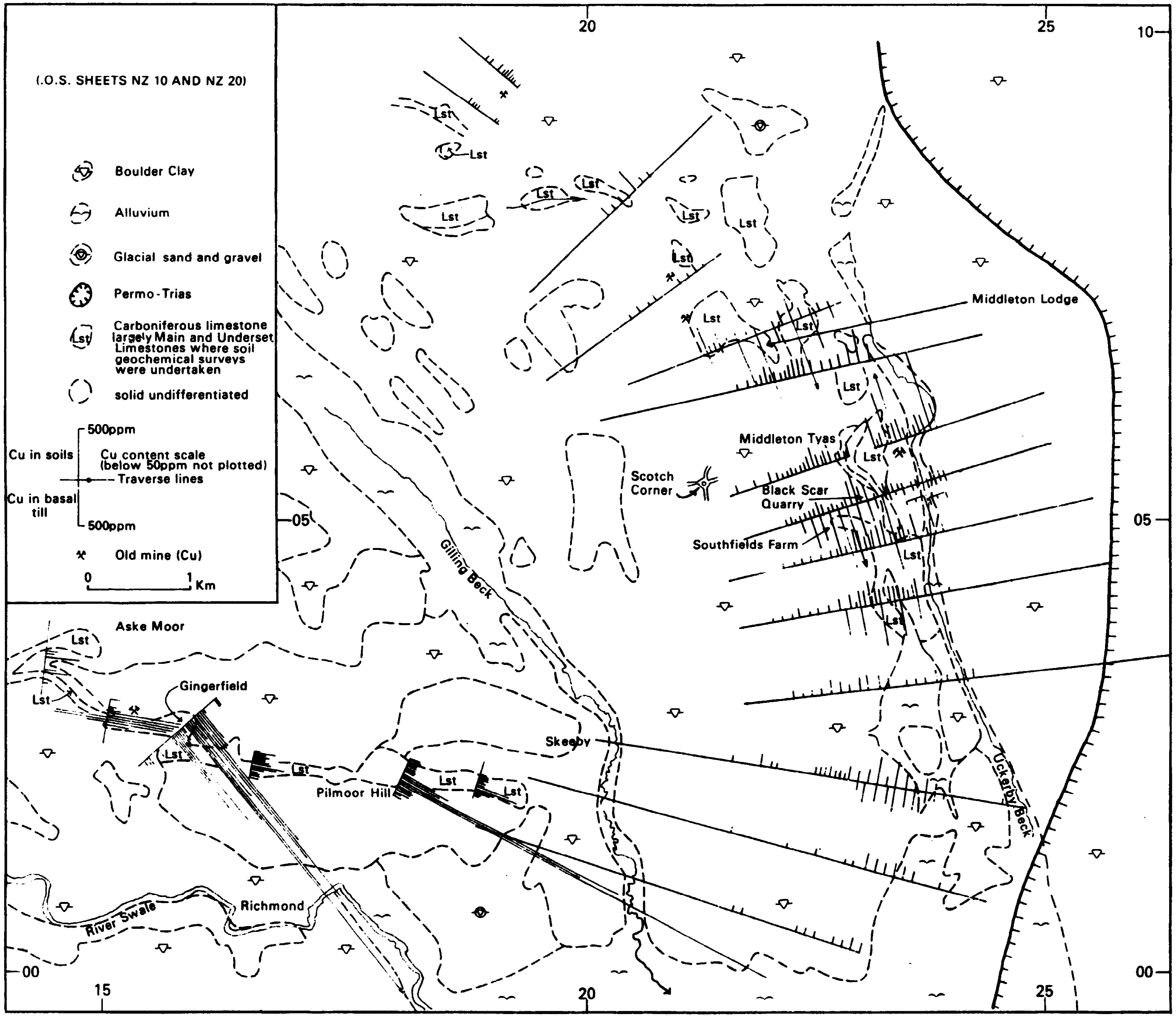


FIG. 4 SOIL SAMPLE TRAVERSES AND ANOMALOUS Cu VALUES

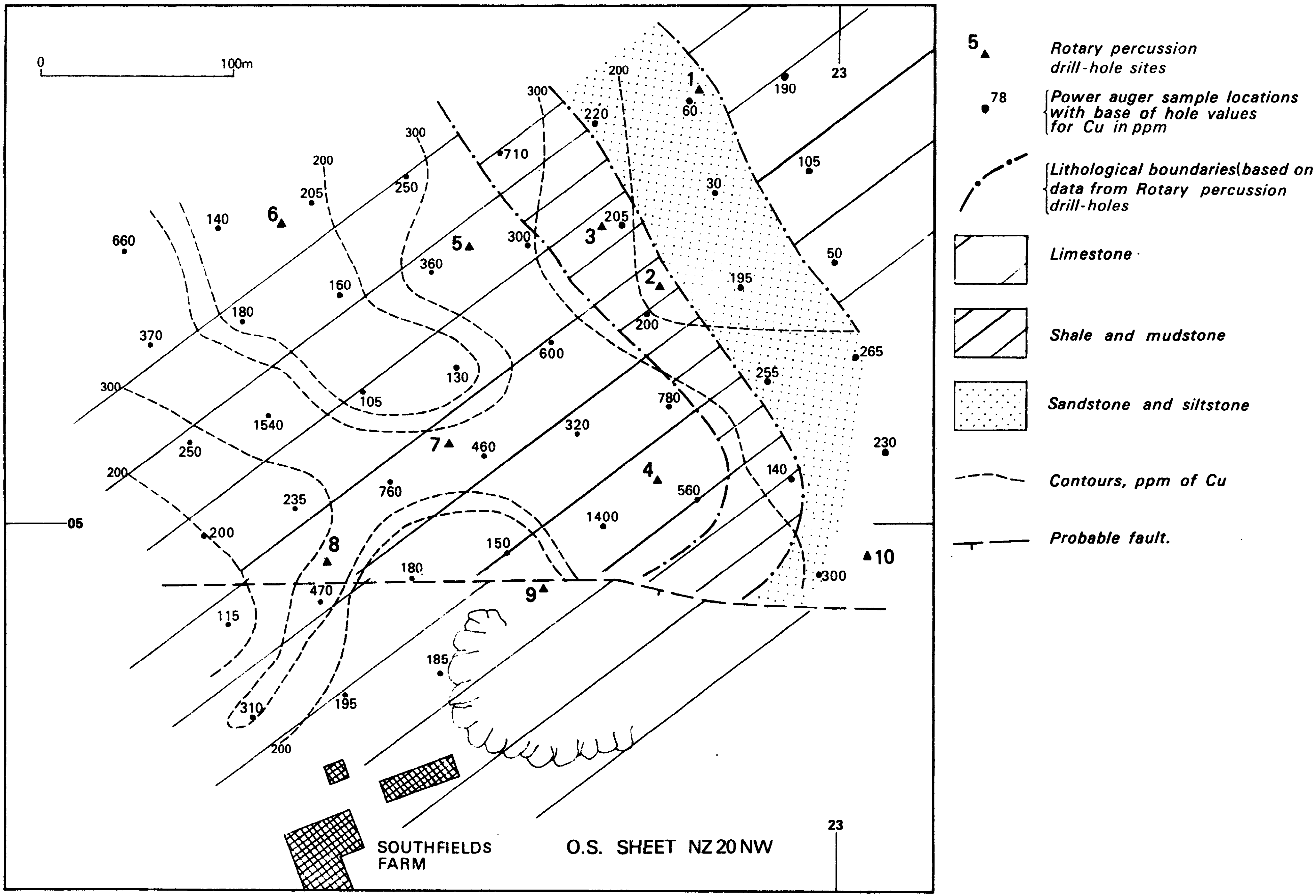
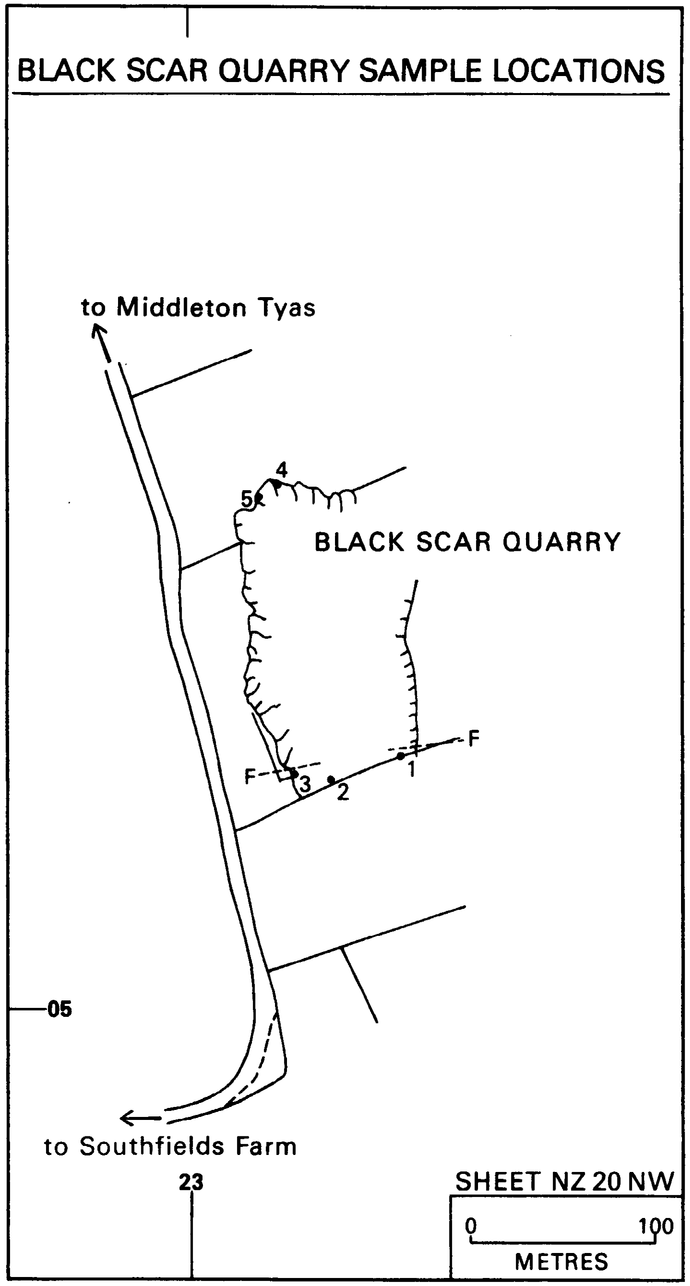


Fig. 5 SOUTHFIELDS FARM: ROTARY PERCUSSION AND POWER AUGER SAMPLING



Location	Sample No.	Cu	Pb	Zn	Lithology	
		Values in ppm				
1	RSR 501	5,600	90	60)	Grey part dolomitised	0.70m
	RSR 502	40,000	40	20)	lmst.	
	RSR 503	17,500	20	10	Fractured chert.	0.15m
	RSR 504	15,000	40	15	Calc. siltstone	0.28m
	RSR 505	1,700	40	20	Brown shale	0.30m
	RSR 506	900	40	30	Black shale	0.40m
2	RSR 511	140	980	400	Composite shale	1.30m
3	RSR 507	10,000	40	30	Massive lmst.	0.45m
	RSR 508	56,250	40	20	Fractured chert.	0.20m
	RSR 509	75,000	40	30	Shaley lmst.	0.65m
	RSR 510	15,000	40	50	Calc. shale	0.56m
4	RSR 512	5,000	50	10	Bulk crinoidal lmst. N. end of quarry	7.00m
5	RSR 601	250			Crinoidal lmst.	2.00m
	RSR 602	900			" "	5.50m
	RSR 603	210			" "	2.50m
	RSR 604	480			Thin bedded lmst. and chert.	3.00m
		Ca	Mg	Fe		
		Values in ppm				
1	RSR 501	70,000	5,400			
	RSR 505			20,000	As above	
3	RSR 507	230,000	600		"	
	RSR 508	66,000	600		"	
	RSR 512	7,900	3,600		"	

Fig. 6. BLACK SCAR QUARRY - CHANNEL AND CHIP SAMPLES

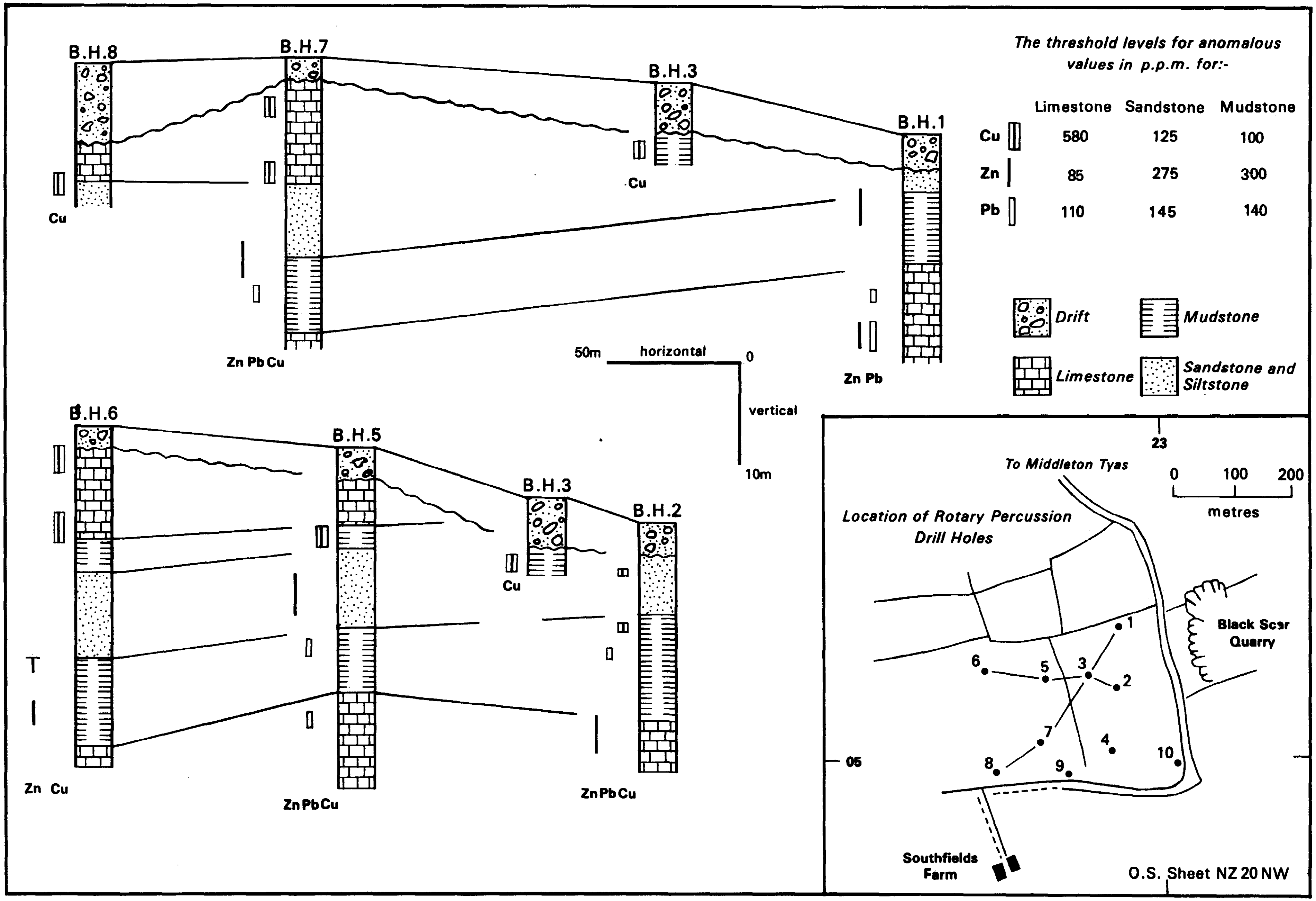


FIG. 7 ROTARY PERCUSSION DRILLING AT SOUTHFIELDS

ppm	Limestone	Sandstone	Shale
Copper	5–20	10–40	30–150
Lead	5–10	10–40	20
Zinc	4–20	5–20	50–300

	Cu				Pb				Zn			
ppm	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range
Limestone (n = 68)	183	198	579	15–6000	68	63	195	30–4000	64	68	200	10–370
Sandstone (n = 55)	43	43	129	10–290	81	73	227	10–410	79	96	270	10–320
Mudstone (n = 89)	57	21	95	15–6750	67	34	135	10–200	169	124	415	10–800

hole) were analysed. The total population was subdivided into three groups to represent the main lithologies present, limestone, sandstone/siltstone and mudstone. Individual statistical tests were applied to each lithological population. In order to obtain more meaningful statistical data the highest (and obviously anomalous) values were not included in the treatment to determine the mean and standard deviation. The mean plus two standard deviations has been taken as background. Comparison is made with the range of expected values for each element, as quoted by Hawkes and Webb (1962) (see table above).

This treatment allows direct comparison between the metal contents of the different lithologies and enables anomalously high values to be identified with respect to their stratigraphical position. The high values for Cu are largely restricted to the Main Limestone and those for Zn to the underlying sandstone. Anomalous Pb levels occur in the Underset Limestone and also in the overlying mudstones. All these values for Cu, Pb and Zn are anomalous in comparison with generally recognised average levels (Hawkes and Webb, 1962) and show enrichment between three and nine times.

MIDDLETON LODGE

This area was tested by seven rotary percussion boreholes on a single traverse (Figure 8), drilled into the Underset Limestone and the underlying sandstones and mudstones. Of these, one hole (No. 5) failed completely to provide material for analysis due to waterlogged conditions. Values obtained in the area are given in the table below.

Anomalous Cu values occur only in the east, whilst Pb and Zn are high only in holes 2 and 4 (Figure 8) towards the western end of the traverse. There is little to suggest that the lithological control seen at Southfields has operated here, although the general level of values is again higher than normal by factors from 1.5 up to 15. Lead content in sandstones and Zn and Cu in mudstones are, however, the exceptions to this situation – the levels in these lithologies being at background values.

GINGERFIELD

The thirteen rotary percussion boreholes drilled penetrated the Main Limestone and underlying sediments (Figure 9). Locally the higher water table terminated some holes at 5 m, but others

	Cu				Pb				Zn			
ppm	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range
Limestone (n = 82)	233	267	767	10–9000	33	19	71	40–180	33	26	85	10–290
Sandstone (n = 17)	66	71	208	15–600	16	17	50	10–230	17	8	33	10–230
Mudstone (n = 5)	84	93	270	30–235	25	21	67	20–100	17	15	47	20–70

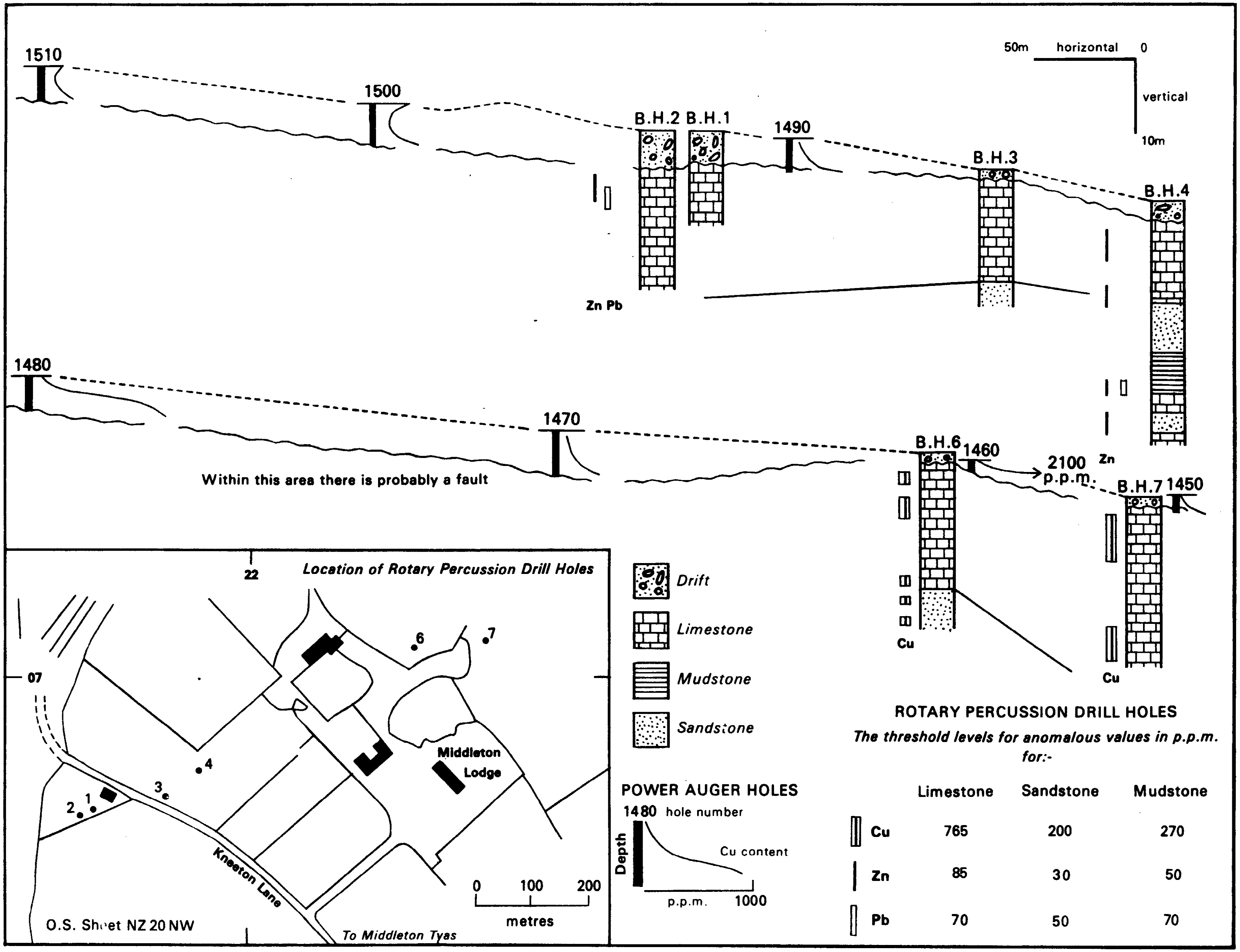


FIG. 8 ROTARY PERCUSSION DRILLING AT MIDDLETON LODGE

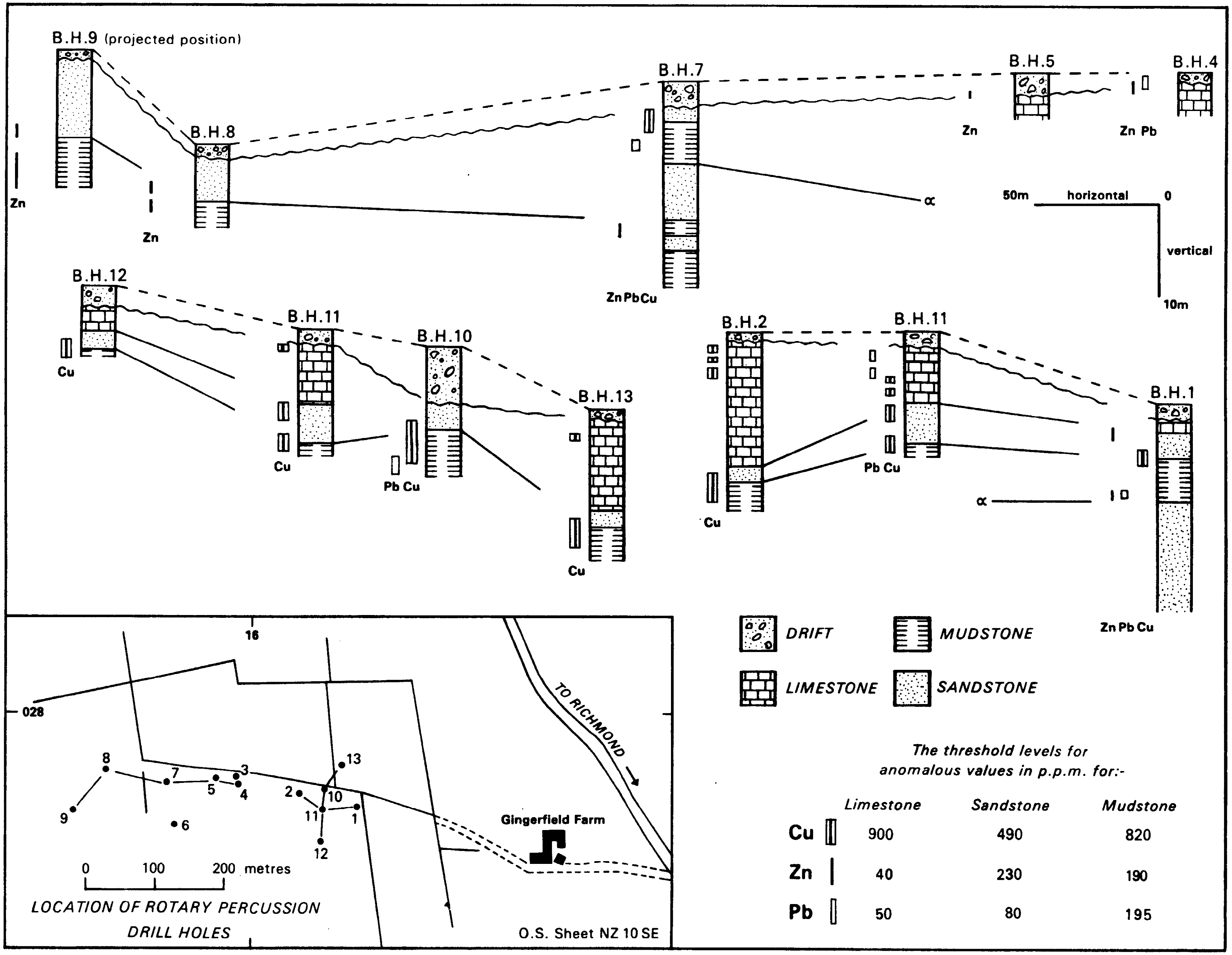


FIG.9 ROTARY PERCUSSION DRILLING AT GINGERFIELD

	Cu				Pb				Zn			
ppm	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range	$\bar{x}$	s	$\bar{x}+2s$	Range
Limestone (n = 50)	465	226	917	120–1350	26	11	48	10–40	23	13	49	10–40
Sandstone (n = 58)	268	111	490	5–25000	45	25	95	10–80	101	59	219	10–240
Mudstone (n = 45)	273	273	819	20–9000	117	76	269	20–700	99	57	213	10–260

were drilled deeper to a maximum of 23 m (see table above).

The highest Cu values occur in the sandstone just below the Main Limestone, although some similar Cu levels were found in the Limestone itself in holes 2 and 11. Anomalous Zn was associated with the lower part of this sandstone in holes 7 and 8, whilst the highest Pb values (still only at background levels) occur in the sandstone in hole 1 and in the limestone in holes 4, 11 and 13.

At Gingerfield the background values for Cu show considerable enrichment compared with the average figures quoted in Hawkes and Webb (1962). It is increased by a factor of 23 in the limestones and is also increased in the other lithologies. Both the other elements (Pb and Zn) also show increases in metal content.

CORED DRILL HOLES

The objective of two of these holes was primarily to provide stratigraphical information on the nature of the Permian succession to the east. To this end the holes at Chantry and Halnaby demonstrated that there was no indication of a copper-rich facies in the Permian succession. Analyses on a limited number of drill sludge samples from Halnaby, covering approximately 20 m of Permian mudstone with subordinate silts and sands passing downwards into a carbonate sequence, show values for Cu, Pb and Zn to be only in the normally expected range for these lithologies.

Sludge samples were not available for analysis from the other holes and visual examination of the cores did not indicate the likelihood of significant mineralisation requiring chemical analysis.

GEOPHYSICAL SURVEYS

The geophysical survey in the Middleton Tyas area covered an area of some 6 km^2 immediately to the east of the village. The induced polarisation (IP) method was used along a number of approximately east-west traverses over a strike length of almost 3 km. Traverses were spaced about 200 m apart, with additional lines inserted where more detail was needed (Figure 10). In several places, traverses deviated from the regular grid pattern to avoid growing crops.

Geophysical equipment comprised a Huntec Mk. III time-domain IP system with a portable 250W transmitter. A dipole-dipole electrode configuration was used, with a four-way current switch to avoid frequent movement of the transmitter unit. Stainless steel stakes served as current electrodes and Cu/$CuSO_4$ porous pot electrodes were used for the receiver. Fifty-metre dipoles were used, to a maximum separation of 250 m between the dipole centres (n = 5). Details of the field methods and data presentation are given by Burley and others (1978).

The IP receiver measures the voltage across the potential electrodes (receiver dipole) which is induced by the square-wave current pulse applied to the ground through the current electrodes (transmitter dipole). Both primary (during the current pulse) and secondary (after current switch-off) voltages are measured. The secondary voltages are recorded as four voltage/time integrals (M_1, M_2, M_3, M_4) representing the areas under the voltage decay curve over the four intervals 240–300 ms, 300–420 ms, 420–660 ms and 660–1140 ms after current switch-off. Optimum values for the duration of the current pulse (2s), delay time (240 ms) and measuring period (900 ms) were obtained by investigation of decay curves in the area prior to commencement of the survey.

Apparent resistivity (ohm-metres) and chargeability, defined as 0.6 ($M_1 + 2M_2 + 4M_3 + 8M_4$) ms, were derived from these observations. They have been plotted as maps of values at n = 2 and n = 4 (Figures 11 to 14) and as pseudo-sections (Figures 15–17). Figures 11 to 14 also show the positions of known artificial conductors which may cause spurious results. These artificial conductors include cast-iron water mains, with diameters of 6 or 8 cm, at depths of 1 m to 1.5 m. They may be accompanied by telephone cable ducts. Overhead power lines (11 kV) are also marked.

The chargeability plots (Figures 13 and 14) show strong linear features aligned along the arti-

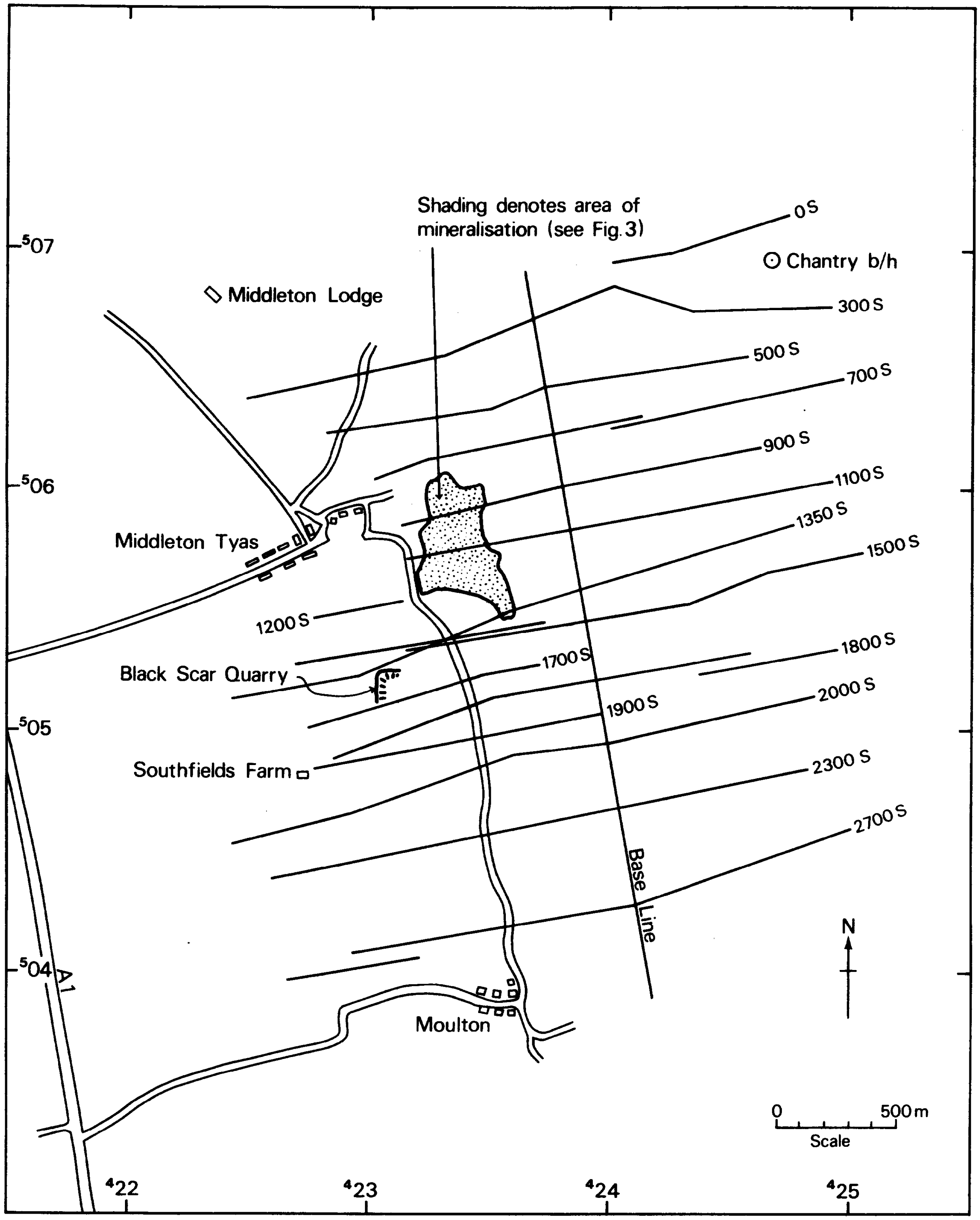


Fig. 10 Middleton Tyas IP survey — location of traverses.

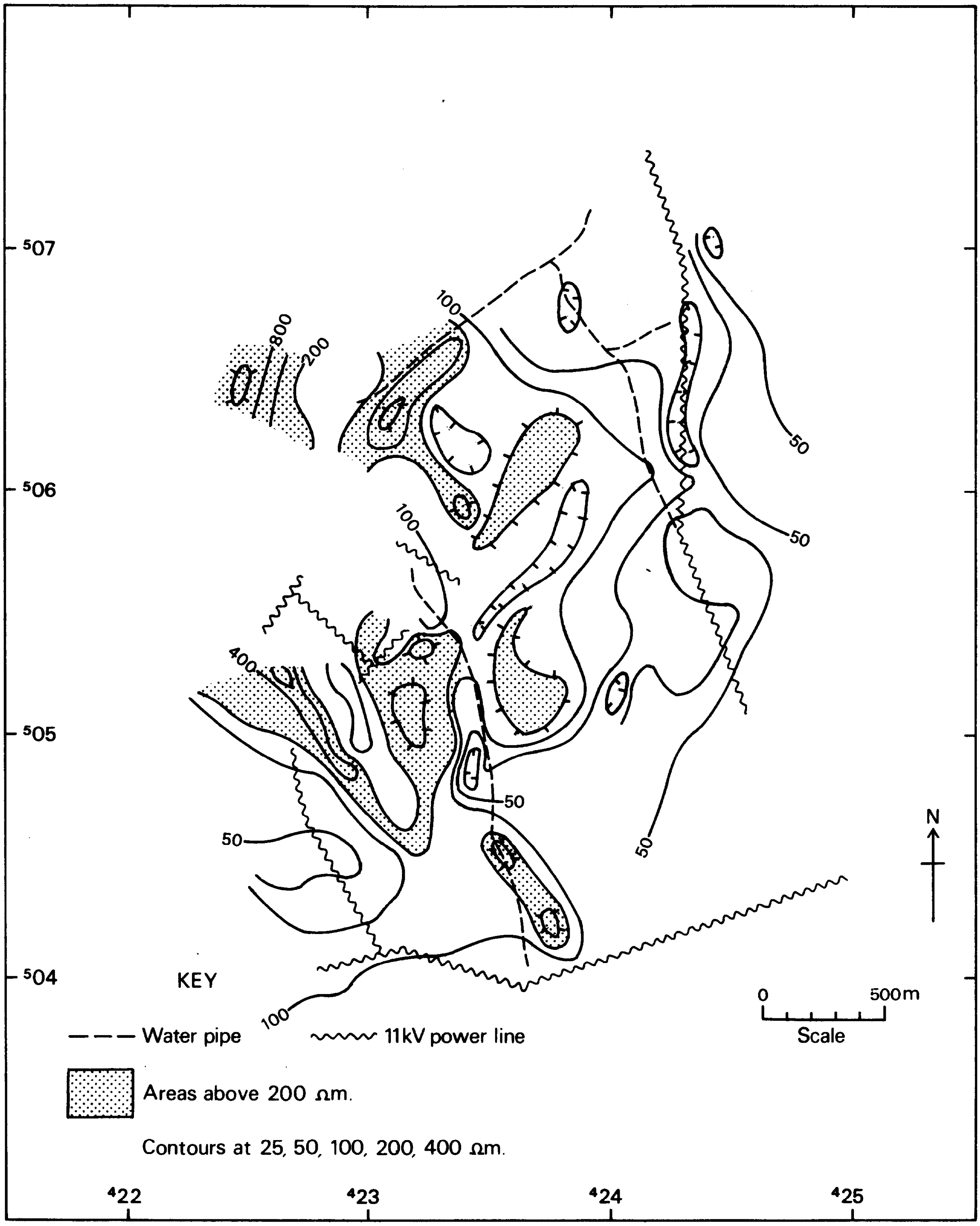


Fig. 11 Apparent resistivity at n=2.

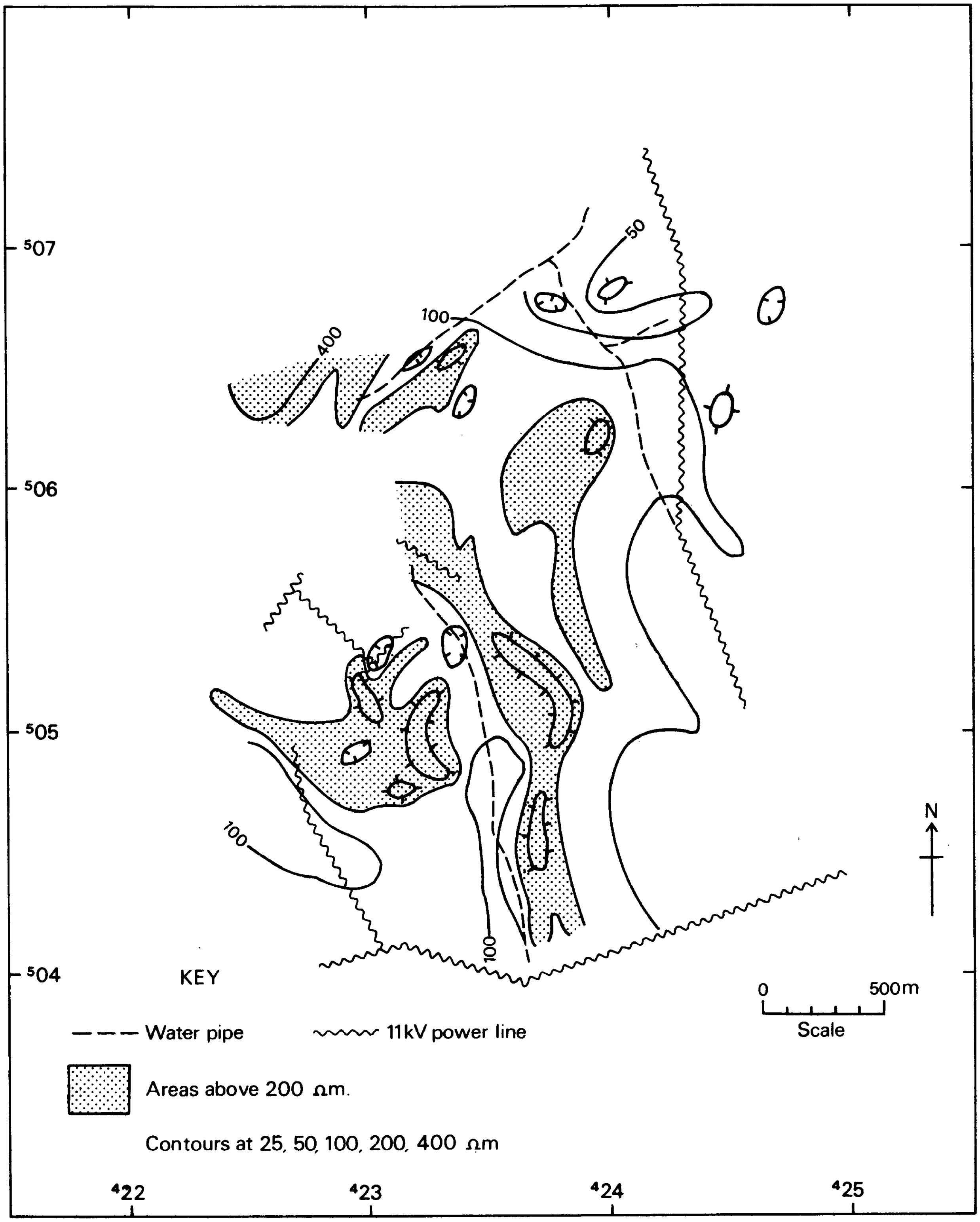


Fig. 12 Apparent resistivity at n = 4.

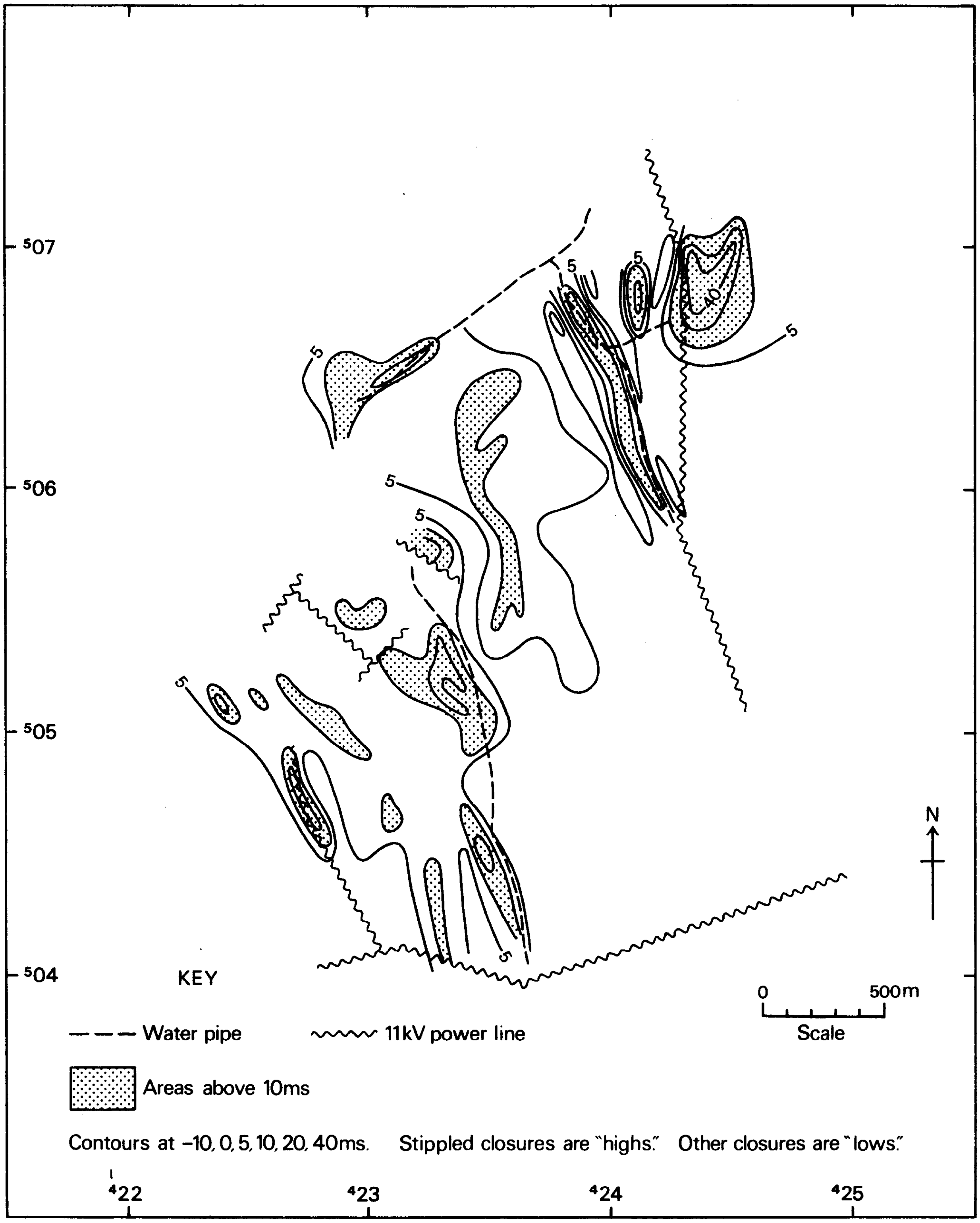


Fig. 13 Chargeability at n=2

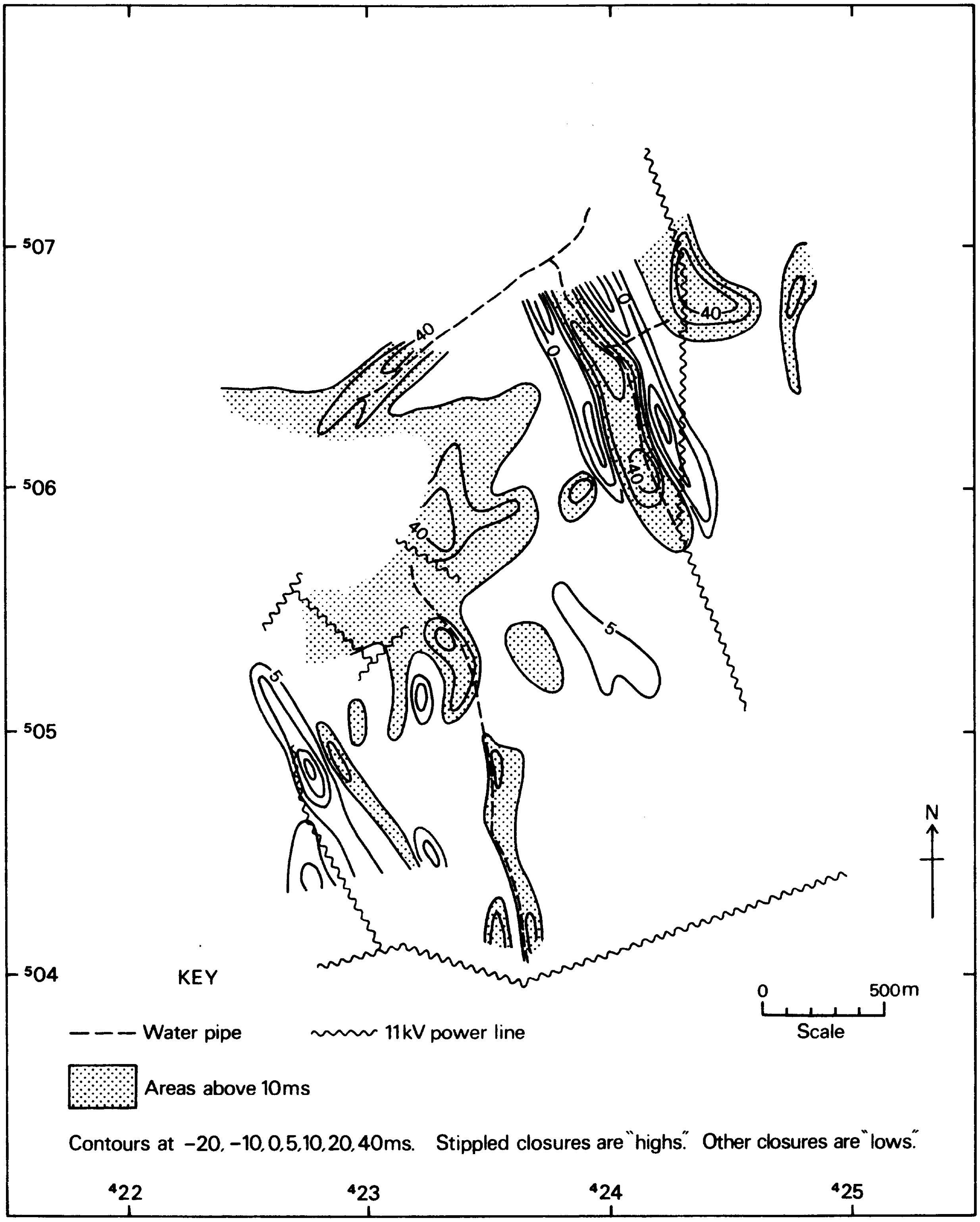


Fig. 14 Chargeability at n=4

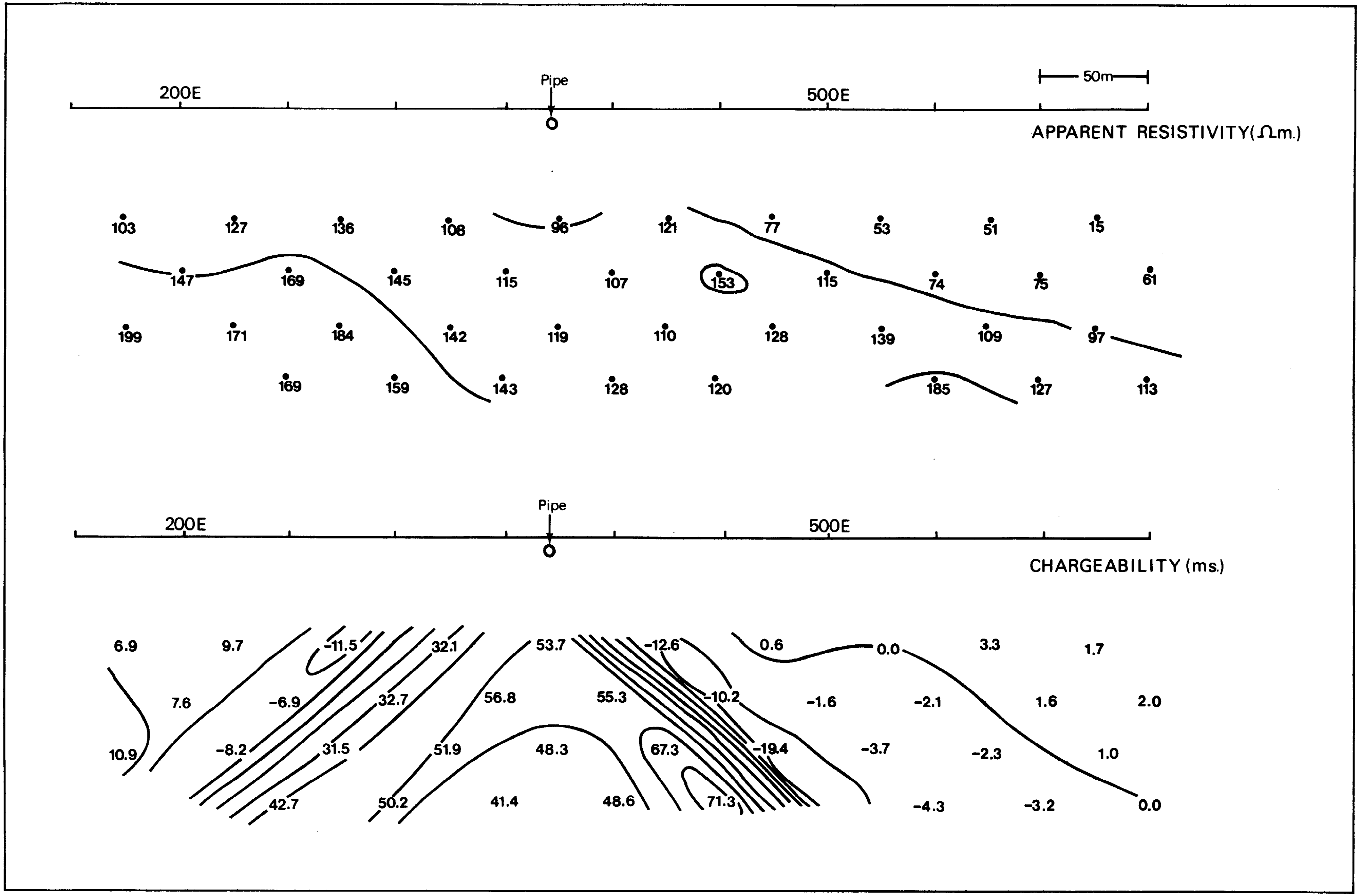


Fig. 15 IP dipole - dipole pseudo-sections for part of traverse 900S, illustrating effect of buried metal pipe.

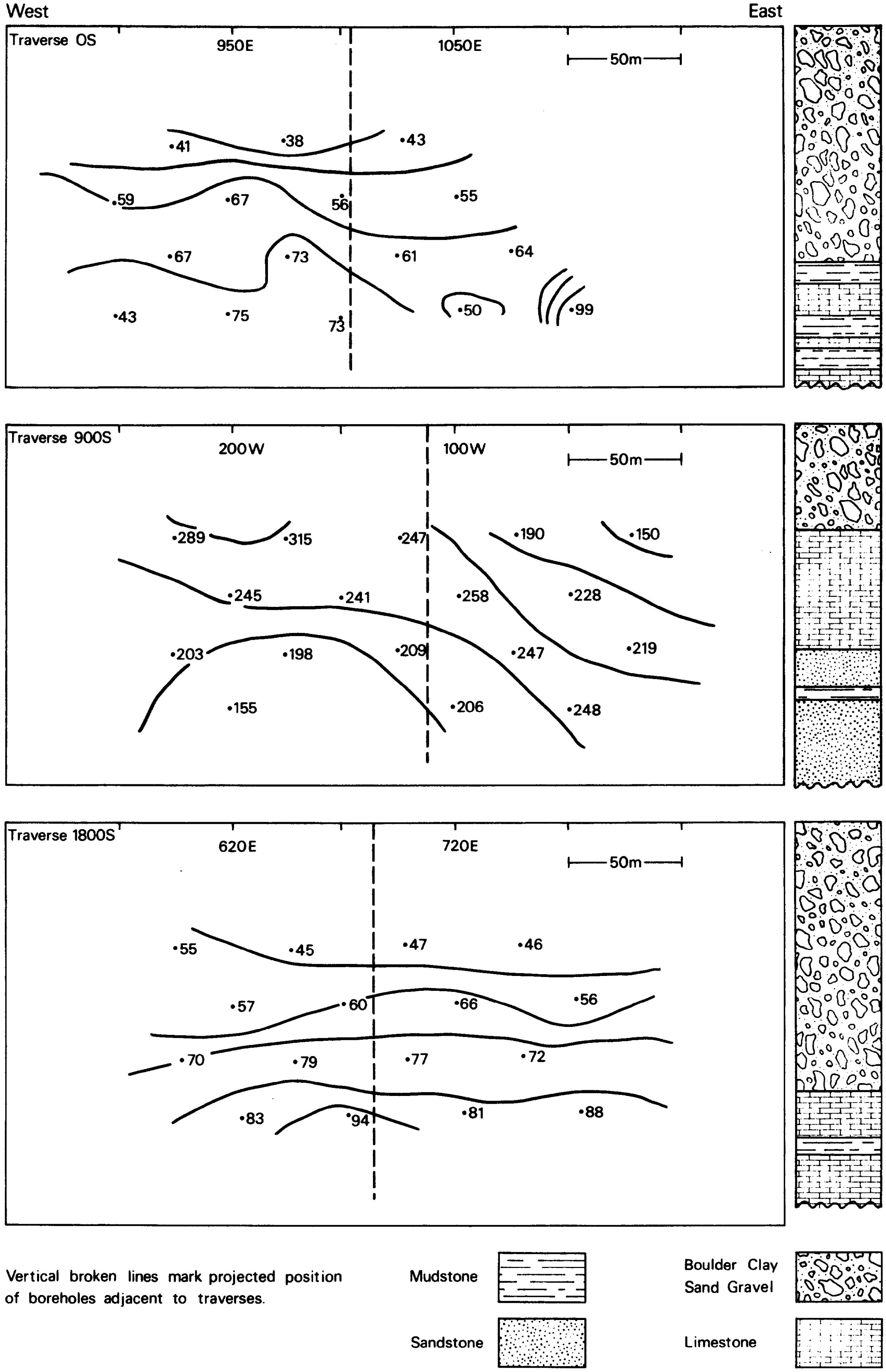


Fig. 16 Pseudo-sections of apparent resistivity for parts of traverses OS, 900S and 1800S

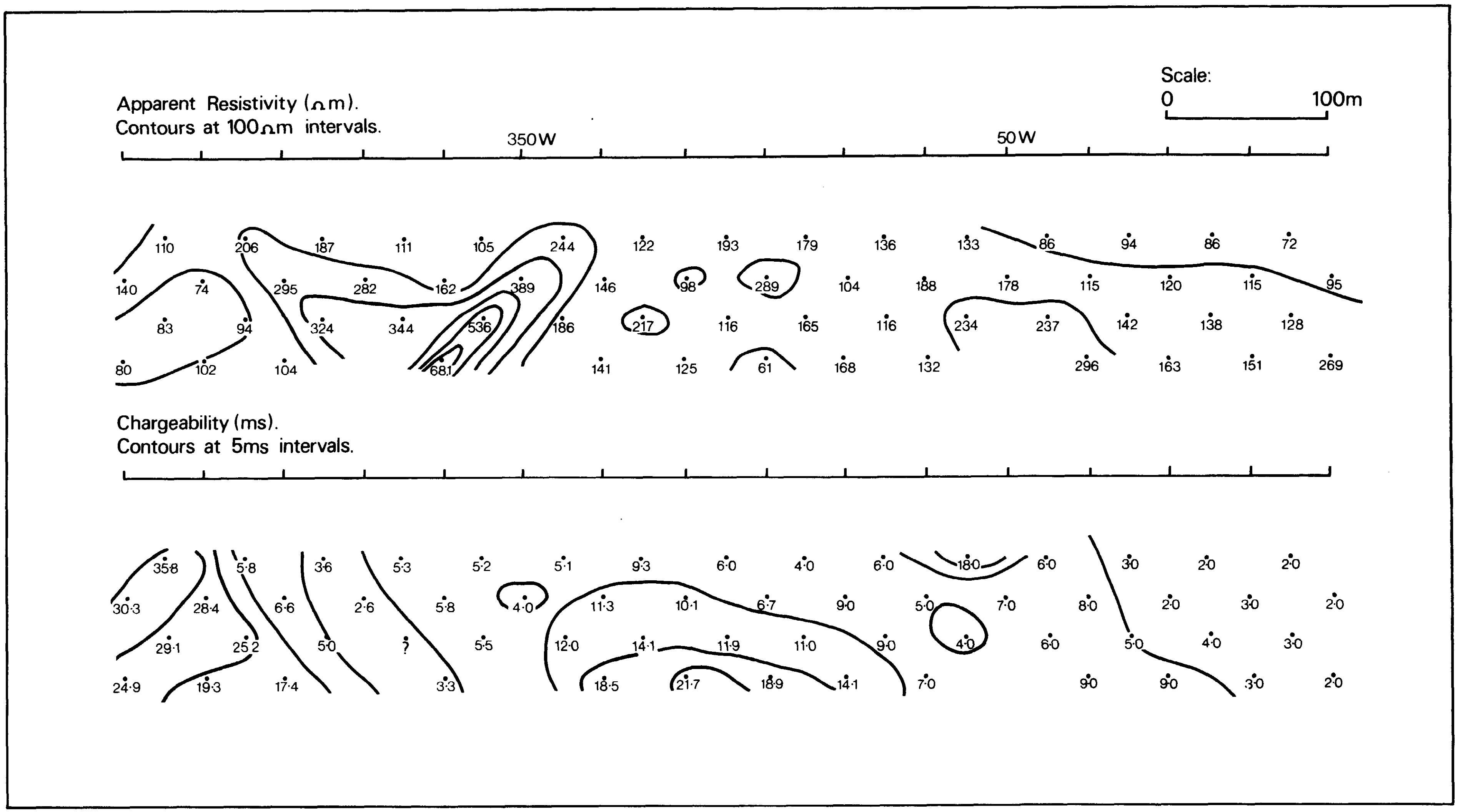


Fig. 17 IP dipole – dipole pseudo – sections for part of traverse 1500 S.

ficial conductors. At the n = 2 dipole spacing (Figure 13), the anomalies are 20 to 40 ms above background, 100 to 300 m wide and have flanking zones with low or negative values. At n = 4, the anomalies are as intense as at n = 2 but are 200 to 400 m wide with the flanking 'lows' being more pronounced (Figure 14). The anomalies caused by the artificial conductors are sufficiently strong to mask any electrical effects from mineralised bedrock, particularly since the latter would be weakened by the thick drift which covers much of the area. The resistivity plots do not display corresponding strong anomalies (Figure 15), although most of the low values of around 25 ohm-metres (Figures 11 and 12) occur over artificial conductors.

The resistivity variations show a close correlation with the geology (compare Figure 12 with the geological map, Figure 2). At n = 2, the 100 ohm-metre contour divides an eastern area of low resistivities and thick drift from a western area of higher values elongated around the limestone outcrops. At n = 4, the pattern is similar, although the 100 ohm-metre contour lies further east because of the greater depth penetration of the wider-spaced dipoles. In Figure 16, resistivity pseudo-sections for traverses 0S, 900S and 1800S are plotted against the logs of three boreholes lying close to these lines. Traverses 0S and 1800S show a steady increase in resistivity with depth, consistent with boulder clay resting on a higher-resistivity sequence of Main Limestone, Richmond Cherts and Magnesian Limestone. Along traverse 900S the higher resistivities mark the Underset Limestone at a shallow depth, but overlain by boulder clay which increases in thickness to the east. The resistivity values on traverse 900S at the greater dipole separations are generally lower than for the intermediate separations, this probably reflecting the influence of the water table at depth.

Two areas of anomalous chargeability do not show any clear relationship to artificial conductors, and are therefore probably due to geological causes. The first lies around the disused tile works east of Chantry [245 068] and is distinct from the anomaly produced by the water-pipe leading to Chantry Farm. At n = 2, chargeabilities reach 40 ms in the centre of the anomaly (Figure 13) and resistivities fall to between 25 and 50 ohm-metres (Figure 11). At n = 4, the orientation of the chargeability anomaly is rather different (Figure 14), while resistivities are between 50 and 100 ohm-metres (Figure 12). It is considered likely that this anomaly is due to the relatively pure deposits of laminated clay within the drumlinised drift sequence, these deposits having been worked in the past for making tiles and field drains. The nearby power line may contribute to the anomaly, although there are no related anomalies over the rest of its length.

The second anomalous area lies south-south-east of Middleton Tyas church, along the Kirk Beck valley [237 052]. At n = 2 it is seen as the southern limit of a linear feature some 200 m wide, which extends and becomes stronger to the north. At n = 4, the anomaly is broader and forms a separate closure (Figure 14). The pseudo-sections of apparent resistivity and chargeability, along traverse 1500S and through the anomaly, are shown in Figure 17. The chargeability values increase with depth to a maximum of 21.7 ms at n = 5 (at 250W), whilst the apparent resistivities are lower than background, reaching a minimum of 61 ohm-metres at n = 5. The high resistivity values in the vicinity of 350W mark outcrops of the Underset Limestone on the west side of the valley. The well-defined increase in the chargeability anomaly with depth indicates that the cause of the anomaly lies within the bedrock. The anomaly occurs just south of the 18th century mining area, close to workings below the church where extensive 'flats' of copper sulphides were mined in the lowest part of the Underset Limestone and in the underlying sandstone. Accordingly, two shallow, vertical cored boreholes (Middleton Tyas Nos. 2 and 3 – see Figure 2 and Appendix 1) were drilled on the anomaly [2373 0522 and 2360 0537] to test these horizons. Extensive dolomitisation was encountered, but apart from a few scattered grains of chalcopyrite and azurite, no metallic minerals were present. Logs for the boreholes are given in Appendix 1. Thus the cause of the chargeability anomaly remains unproven. Possible alternative explanations include the existence of mineralisation in the Three Yard Limestone, though this would be at a depth (30 to 35 m) possibly at the limit of detection for the equipment and electrode array size employed. Thus a more likely explanation may be the presence of clay minerals in one of the sandstones of the Three Yard cyclothem; such a lithology is known to be able to cause significant chargeability anomalies.

CONCLUSIONS AND RECOMMENDATIONS

The initial soil-sampling results confirmed the presence of high values for Cu in the area generally – apparently related, spatially at least, to the limestones. Subsequent rotary precussion drilling showed that the anomalous metal values were dispersed within the limestones, in addition to the concentrations in faults and joints as at Black Scar Quarry.

The geochemical data, taken in conjuction with the evidence provided by the mineralogical study (p. 7) and core drilling, assisted in the recognition of the mineralising process.

It is likely that the copper mineralisation around Middleton Tyas owes its origin to the interaction of local sulphur-rich solutions with metal-bearing brines expelled from the Stainmore Trough or a similar Lower Carboniferous basin to the east. Subsequent secondary enrichment under early Permian desert conditions substantially enhanced the grade of the ore, which near Middleton Tyas was mined in veins, flats and cavities within the Underset Limestone. Both the initial deposition of the metal ores and their subsequent enrichment took place at relatively low temperatures – which is in keeping with the available experimental data.

No evidence has been obtained to indicate that the Cu originated as syngenetic Lower Carboniferous mineralisation, and the absence of Kupferschiefer facies of the Marl Slate in the area discounts the derivation of the copper from that source.

Efforts to locate further sulphides by geophysical means were vitiated by the presence of strong artificial conductors, but reconnaissance geochemical surveys outlined an area of about 6 km^2 of anomalous Cu values in the soil to the south of the mined area at Middleton Tyas. It is not clear whether this is due to dispersion of copper-rich drift by ice moving southwards over the Middleton Tyas deposits or whether the anomalies mark further deposits along the sub-drift outcrops of the Underset and Main limestones. Testing the latter possibility is a logical next step in the exploration of the area but it would require an extensive drilling programme since the drift is consistently thick.

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	Thickness (m)	Depth (m)
Mudstone, *Lingula sp.* and fish remains	0.30	47.75
Sandstone, fine-grained	1.65	49.40
Mudstone, dark grey, brachiopod and fish fragments	2.00	51.40
Sandstone, fine-grained, with two seat-earth horizons alternating with runs of mudstone with plant fragments	6.50	57.90
Sandstone, fine-grained, mudstone pebbles near base	13.70	71.60
Mudstone, dark grey with gastropods, brachiopods and bivalves passing up into siltstone	11.10	82.70
Three Yard Limestone		
Limestone, packstone-grainstone pale grey, bioturbated at many levels, thin chalcopyrite vein at top	2.40	85.10
Beds of Five Yard cyclothem		
Mudstone, gastropods and brachiopods near base, siltstone bands upwards	6.55	91.65
Limestone, wackestone, medium dark grey	0.54	92.19
Sandstone, fine-grained, with cross-lamination and ripple marks, two seatearth horizons and three runs of sandstone	7.01	99.20
Five Yard Limestone		
Limestone, wackestone, dark grey with several runs of fossiliferous mudstone	2.90	102.10
Limestone, wackestone, packstone chiefly medium grey	12.60	114.70
Mudstone, dark grey, crinoid stems	1.03	115.73
Limestone, wackestone, medium pale grey	1.82	117.55
Beds of Middle cyclothem (presumed)		
Sandstone, fine-grained on mudstone	0.75	118.30
Middle Limestone		
Limestone, pale grey mottled with medium grey, *Gigantoproductus* at base	3.15	121.45
Limestone, grainstone with crinoid stems, chiefly grey	6.25	127.70
Limestone, mostly grainstone; abundant crinoid debris, pale grey	11.43	139.13

Middleton Tyas No. 2 Borehole [2373 0522], logged by J. M. Hudson

	Thickness (m)	Depth (m)
Quaternary		
Alluvium resting on fluvioglacial alluvium and possibly boulder clay	13.94	13.94
Brigantian		
Underset Limestone		
Limestone, grey, medium-grained, with dolomitic patches stained pinkish-brown and yellow. Shaley partings	7.26	21.20
Limestone, grey-brown, medium-grained, strongly dolomitic in irregular patches coloured pink and yellow. Thin veins of deep red hematite(?)	1.30	22.50
Beds of Three Yard cyclothem		
Sandstone, pale grey, fine-grained, feldspathic, poorly cross-bedded, pink stained in places and with thin mudstone partings	8.79	31.29

Middleton Tyas No. 3 Borehole [2360 0537], logged by J. M. Hudson

	Thickness (m)	Depth (m)
Quaternary		
Till, unsampled	3.30	3.30
Brigantian		
Underset Limestone		
Limestone, medium grey, fine- to medium-grained bioclastic, chert in thin bands; rare scattered grains of chalcopyrite	1.48	4.78
Limestone, pale brown and cream, fine-grained, dolomitic, with irregular patches of dark brown chert; rare flakes of azurite	0.57	5.35
Limestone, medium to dark grey, medium-grained, dolomitic, with argillaceous partings; malachite and azurite on joint and bedding surfaces	1.25	6.60
Siltstone, calcareous, dark grey, rubbly	0.15	6.75
Limestone, pale to medium grey and brown, fine- to medium-grained with cherty bands, dolomitic patches; specks of azurite towards top	13.75	20.50
Limestone, grey, cherty, fine-grained, dolomitic	2.20	22.70
Limestone, fine- to medium-grained, strongly dolomitised, pink, cream and purple	1.25	23.95
Beds of Three Yard cyclothem		
Sandstone, pale grey, fine-grained, silty, poorly bedded (dip about 6°)	8.73	32.68
Sandstone, alternating pale and dark grey, striped-bedded, silty, cross-bedded, with pyrite crystals on joints	1.73	32.41
Coal, dirty, with mudstone partings	0.03	34.44
Sandstone, pale and dark grey, striped-bedded, micaceous, silty (dip about 6°)	13.46	47.90

APPENDIX 1

BOREHOLE LOGS

Chantry Borehole [2469 0705], logged by A. A. Wilson

	Thickness (m)	*Depth (m)*
Quaternary		
Devensian till		
Stony clay	25.95	25.95
Permian		
Upper Magnesian Limestone		
Dolomite, fine-grained, yellowish grey	3.95	29.90
Middle Permian Marl		
Mudstone, structureless, chiefly reddish brown, some brecciation	1.80	31.70
Mudstone, brecciated due to evaporite solution, reddish brown	0.95	32.65
Lower Magnesian Limestone		
Dolomite, chiefly yellow, with some chert clasts in middle (dip 11°)	1.10	33.75
Carboniferous (Namurian)		
Richmond Cherts (dip 10–11°)		
Chert with some cherty limestone, buff and purple colouration, *Zoophycos*, anchoring spicules of *Hyalostelia*, some core loss in upper beds	13.75	47.50
Mudstone, grey, crinoid columnals	0.40	47.90
Chert, grey streaky, *Zoophycos*, anchoring spicules of *Hyalostelia*	5.05	52.95
Limestone, cherty in part, crinoidal	3.40	56.35
Mudstone, grey, crinoid columnals	0.80	57.15
Limestone, mostly cherty with some streaky cherts, vertical borings 1.25 m above base	6.40	63.55
Beds of Main cyclothem (dip 5°)		
Mudstone, dark grey, brachiopods abundant near base, scattered higher up	5.82	69.37
Main Limestone		
Limestone, wackestone, medium grey, bioturbated in top 1.30 m and from 76–77 m, 0.02 m-wide quartz, calcite, chalcopyrite vein at 73.74 m	8.88	78.25
Brigantian		
Beds of Underset cyclothem (dip 5°)		
Mudstone, dark grey, bioturbated, productoids	0.50	78.75
Seatearth sandstone	0.25	79.00
Sandstone, fine-grained, ripple-marked in part	7.75	86.75
Mudstone, silty, striped with siltstone bands	3.73	90.48
Underset Limestone		
Limestone, chiefly grainstone rich in crinoid debris including thick stems at several levels, chiefly pale grey, *Gigantoproductus* at several levels from 91.50–100.40	16.22	106.70
Limestone, wackestone with some calcite mudstone, pale and medium grey, scattered crinoid debris in parts	8.25	114.95
Beds of Three Yard cyclothem (dip 8°)		
Sandstone, fine-grained	2.14	117.09

Halnaby borehole [2607 0717], logged by D. B. Smith

	Thickness (m)	*Depth (m)*
Quaternary		
Till, unsampled	43.71	43.71
Permian		
Permian Upper Marl		
Mudstone, red-brown silty with siltstone bands and subordinate bands of pale red-brown fine-grained sandstone. Partly brecciated by collape below 53.61 m	16.00	59.71
Residue of Billingham Main Anhydrite		
Limestone, mottled red, brown and grey, partly brecciated	0.29	60.00
Seaham Formation		
Dolomite and limestone, grey and pale brown, mainly fine-grained but partly oolitic in upper part with abundant bivalves and *Calcinema*	16.21	76.21
Permian Middle Marl		
Mudstone, mainly grey but partly red-brown, silty with abundant gypsum veins in lower part	5.29	81.50
Dolomite, grey, fine-grained, gypsiferous	0.24	81.74
Anhydrite, grey, with grey mudstone partings	8.96	90.70
Mudstone, interbedded red and grey, silty, with bands and nodules of anhydrite	5.06	95.76
Basal Breccia		
Sandstone, grey and brown, coarse-grained with bands of breccia. Clasts of limestone, chert, sandstone and mudstone. Secondary gypsum veins common	12.64	108.40
Unconformity		
Carboniferous		
Namurian		
Mudstone, grey, red and purple, silty, strongly oxidised	1.60	110.0

Middleton Tyas No. 1 Borehole [2371 0603], logged by A. A. Wilson
Dip in core varies from 4–6°

	Thickness (m)	*Depth (m)*
Quarternary		
Alluvium resting on fluvioglacial alluvium		
Sand, silt and pebbles	13.22	13.22
Brigantian		
Underset Limestone		
Limestone, wackestone, grey	3.85	17.07
Limestone, chiefly packstone but upper beds are grainstone containing *Gigantoproductus*	12.13	29.20
Beds of Three Yard cyclothem		
Sandstone, fine-grained, cross laminae and ripplemarks at several levels with several thin siltstone and mudstone partings, seatearth sandstones occur at six separate levels, nodules of chalcopyrite at 36.01–36.05 m	18.25	47.45