Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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

No. 30

Porphyry style copper mineralisation at Black Stockarton Moor, south-west Scotland

INSTITUTE OF GEOLOGICAL SCIENCES

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Porphyry style copper mineralisation at Black Stockarton Moor south-west Scotland

Geochemistry
M. J. Brown, BSc

Geology and Mineralisation
R. C. Leake, BSc, PhD

Geophysics
M. E. Parker, BA

Mineralogy
N. J. Fortey, BSc, PhD

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Mineral Reconnaissance Programme Reports

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SUMMARY

Reconnaissance soil sampling within the catchment of streams containing anomalous levels of copper in drainage samples led to the discovery of disseminated copper mineralisation in the Black Stockarton Moor area of Galloway, Scotland. Analysis of aeromagnetic data and of a gravity survey of the area, previously mapped as an irregular complex of dykes, suggested that the region was underlain by laminar bodies of granodiorite. Geological mapping revealed the presence of a major Caledonian multiphase subvolcanic complex intruding Lower Palaeozoic turbidites, to the west of the Criffel granodioritic plutonic complex. An induced polarisation survey delineated an arcuate anomaly about 6 km long and the results of a simultaneous geochemical soil survey showed a zone with anomalous levels of copper (> 140 ppm to 5500 ppm) in the southern part of the area to be essentially parallel to the IP anomaly but partially displaced to the east. A series of three deep angled drill holes and nine shallow holes sited on geochemical and geophysical anomalies confirmed the widespread presence of both veinlet and disseminated pyrite and copper mineralisation of the porphyry type.

The Black Stockarton Moor subvolcanic complex is a composite of minor intrusive rocks, the earliest phase of which, comprising porphyrite dyke swarms, granodiorite sheet intrusions, small granodiorite stocks, breccia pipes, vent agglomerates with plugs of basic rock and a few basic dykes, predates the adjacent multiphase Criffel plutonic complex. The second phase of subvolcanic activity postdates the plutonic rocks and comprises intense en-echelon sigmoidal swarms of porphyrite dykes sharply discordant to the earliest phase rocks. A minor third phase consists of linear porphyrite dykes closely associated with faulting.

Chemical analysis and mineralogical examination of the borehole material indicates that regular zonation can be observed in the style and intensity of both mineralisation and hydrothermal alteration. This zonation is regular from west to east across the IP and soil anomalies. A propylitic alteration zone with the development of chlorite, epidote and minor sericite in igneous rocks and of calcite, quartz, jasperoid, chlorite, amphibole, epidote and albite in sedimentary rocks occurs to the west. Within this zone hematite gradually gives way to increasing amounts of pyrite from west to east. The propylitic zone passes into a sericitic alteration zone where sedimentary rocks are frequently bleached and igneous rocks pink or orange-coloured containing secondary quartz, chlorite and muscovite. Pyrite is most conspicuous within rocks of the outer sericite zone, the outcrop of which coincides roughly with the axis of the IP anomaly. Further east pyrite decreases but chalcopyrite and bornite with some chalcocite become relatively conspicuous and copper levels are the highest attained (in the 400 ppm to 1100 ppm range), save for isolated highly brecciated sections. Chemical zonation shows relative enrichment in Mn, Zn, As and Pb in the outer propylitic zone, Ba in the sericitic zone and Cu in the inner sericitic zone while As, Sb and Au are markedly concentrated with Cu and Mo in isolated brecciated sections.

INTRODUCTION

The area described covers 20.5 km^2 of the Dumfries and Galloway Region and lies 6 km north-east of Kirkcudbright and 8 km south-west of Castle Douglas (Fig.1). The area falls within the Ordnance Survey 1:50,000 Dumfries (84) Sheet and the Kirkcudbright (5W) Sheet of the 1:50,000 geological map of Scotland. The altitude of the area varies from 15 m along the River Dee to 174 m on The Fell. The area is dominated by poorly drained moorland and rough pasture with arable land occurring around the margins of the moor. The area was covered by ice during the period of maximum glaciation, the transport direction being from north to south as indicated by striae on rock surfaces and the alignment of drumlins. The depth of till over Black Stockarton and Culdoach Moors averaged 1.66 m with a maximum of 6 m in boggy ground. The main river draining the area is the Dee which rises in the Galloway Hills and runs southwards into the Solway. Streams draining the area form a radial pattern either flowing northwards into the River Dee or in a southerly direction into the Solway.

Previous work

A regional reconnaissance drainage survey was undertaken by IGS over the Criffel-Dalbeattie area during 1970 as part of an exploration programme for uranium sponsored by the UKAEA (Gallagher et al, 1971). Further drainage sampling was undertaken during 1972 as part of the Mineral Reconnaissance Programme undertaken on behalf of the Department of Industry and geochemical maps were produced (Leake et al, 1978). The distribution of metalliferous minerals in stream sediments and heavy mineral concentrates showed that samples from some streams flowing from the Black Stockarton Moor area contained anomalous levels of copper. Based on these results, follow-up drainage sampling and reconnaissance soil sampling were carried out. Encouraging levels of copper in soil led to the initiation of a further follow-up programme.

Present investigation

Detailed follow-up work within the area included geological mapping and geophysical and geochemical investigations. Mapping was carried out over an area of 34 km^2 based on Ordnance Survey 1:7000 and 1:7500 aerial photographs, using 1:10560 topographic maps for ground control. The geophysical reconnaissance work consisted of a gravity survey over an area of 40 km^2 and reference to aeromagnetic data. Induced polarisation (IP), resistivity and magnetic surveys were undertaken over an area of 6 km^2 centred on targets outlined by the geological mapping. Geochemical work consisted of the collection of 2267 soil samples over areas outlined by the geological mapping and IP survey. This was supplemented in some areas of anomalous copper in soil and areas of deep overburden by the collection of 235 samples of basal till using a mechanical auger. A total of 12 drill holes were cored, sited on the basis of geophysical and geochemical anomalies. Three deep holes were drilled under contract and the remainder were drilled by an IGS team using a portable rock drill.

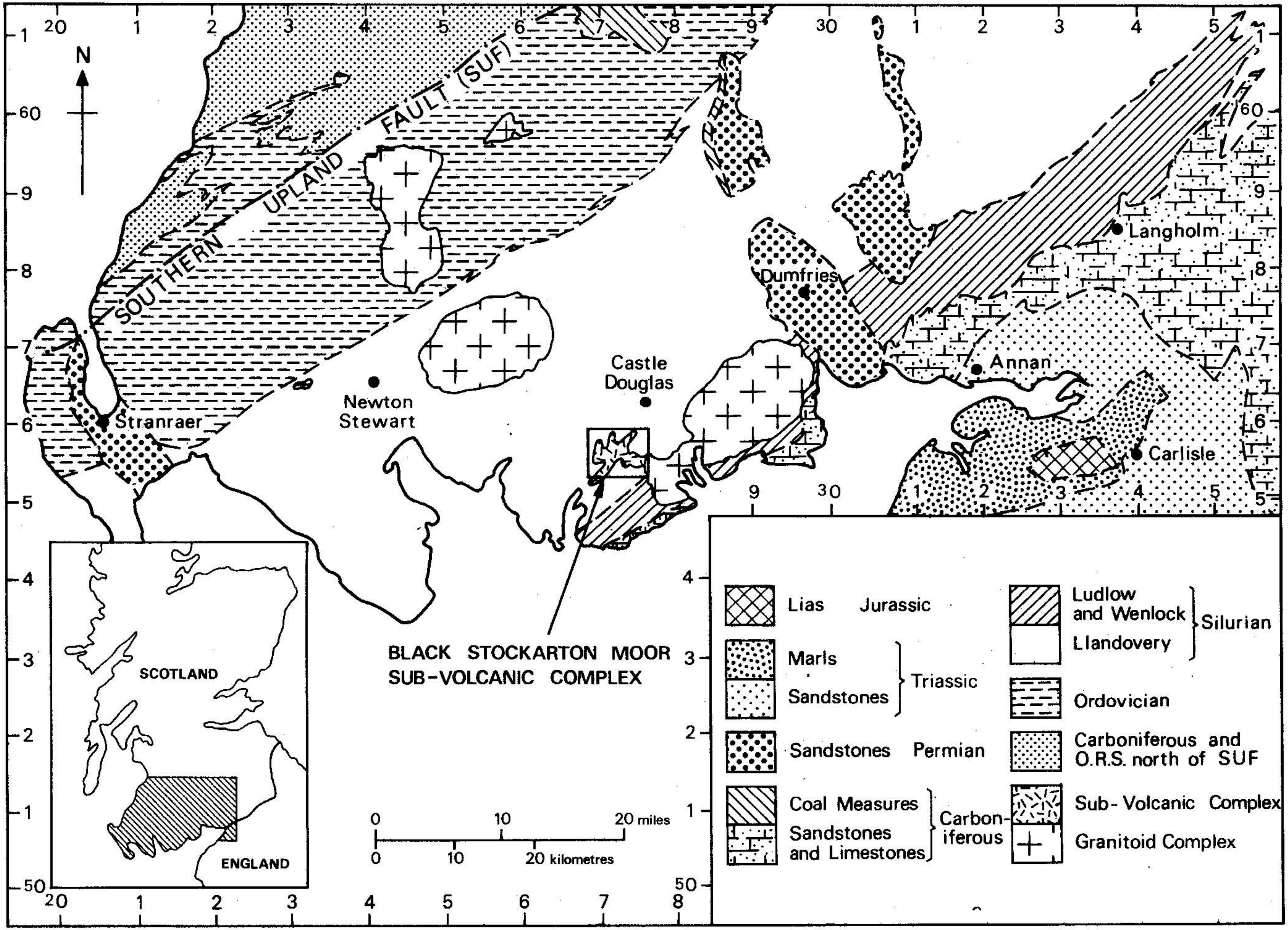


Figure 1 Location of survey area

GEOLOGY

The Black Stockarton Moor area is situated within the Southern Uplands of Scotland, a belt of Lower Palaeozoic turbidite sediments and inliers of black shale, chert and volcanic rocks (Fig. 2). The sedimentary rocks exposed within the area are considered to be either Wenlockian or younger (Craig and Walton, 1959; Walton, 1965), or Llandoverian (Clarkson, Craig and Walton, 1975). They consist of turbidites grading upwards from greywacke to mudstone, in units which vary in thickness from a few centimetres to approximately 2 metres. The structure of the sedimentary rocks appears superficially simple as throughout the area there are only small and gradual variations in strike while the dip is usually high angle. In boreholes the turbidites mostly dip steeply to the west-north-west and young in the same direction (Figs. 25 and 26). There are local deviations with flexures, fold noses and overturned beds but in most cases there is also evidence of adjacent faulting. In one respect the Black Stockarton Moor area appears structurally anomalous within the Southern Upland belt, as there is a sigmoidal deviation of strike through the area from the regional north-north-east trend to a northerly one. Into these sediments are intruded complexes of both subvolcanic minor intrusions and plutonic granodioritic rocks.

The Black Stockarton Moor subvolcanic complex

The Black Stockarton Moor subvolcanic complex (Fig. 3) refers to a multiphase centre of minor intrusive rocks which outcrops largely to the west of the Criffel pluton (Fig. 2). The main features of this complex are summarised here but a more detailed description and discussion of its geology and tectonic setting are given in Leake and Cooper (in prep.). The complex is a composite of a) intersecting porphyritic microgranodiorite (porphyrite) dyke swarms of at least three different ages, b) granodiorite sheet intrusions, c) small granodiorite stocks with steeply-dipping contacts, d) breccia pipes, e) vent agglomerates with plugs of basic igneous rock, and f) basic dykes. The granodiorite sheets outcrop within an arcuate belt about 4 km long (Fig. 3) but appear to be located in discrete centres in the form of cedar-tree laccoliths. Three phases of igneous activity have been recognised and features of each component are summarised in Table I and described briefly below. Partial chemical analyses of the various igneous and sedimentary rocks encountered in the boreholes are given in Appendix I.

First intrusive phase

a) Dykes

First phase porphyrite dykes (D1) follow approximately the strike of the Lower Palaeozoic turbidites throughout the area and are concentrated in distinct swarms of which the most obvious occur near Jordieland and north of Lochdougan (Fig.3). In most swarms individual dykes are less than 10 m wide but near Jordieland they reach about 40 m in width. The dilation associated with the intense swarm north of Lochdougan has been calculated at 45% over a width of 320 m. Most of the thicker dykes appear to be near vertical but several thinner dykes dip at 60° - 75° to the west or north-west. Fractures are usually conspicuous within D1 dykes, orientated both parallel and oblique to their margins. The petrography of D1 porphyrites is summarised in Table I. The phenocryst-poor varieties are relatively thin (< 2 m) and have been encountered most frequently in the boreholes. Oligoclase/andesine is always the predominant phenocryst mineral and often shows oscillatory compositional zonation. A small number of D1 dykes contain conspicuous ovoid amygdales filled with calcite, chlorite, actinolite, quartz and opaque minerals.

b) Sheet intrusions

Granodioritic sheets outcrop along a zone up to 800 m wide which follows the regional strike of the sedimentary rocks from Culdoach Moor in the south through Black Stockarton Moor to Lochdougan Moor in the north but exposure is very limited, particularly around Culdoach Moor. The sheet-like form of these intrusions can be demonstrated by low angle contacts with sedimentary rocks in exposures and the borehole sections (Figs. 25 and 26). Many individual sheets have been recognised in the borehole sections as separate intrusions into the sedimentary rocks and as components of thicker bodies. Several adjacent sheets can be distinguished by textural differences based on the presence or absence of phenocrysts and variations in matrix grain size. There is generally good correlation between abrupt textural variations within the multiple sheet intrusions and significant changes in chemical composition (Appendix I). Recognisably different sheets vary in thickness from a few centimetres to at least 110 m of texturally and chemically homogeneous rock.

Within the zone of sheet intrusions there are at least three emanative centres which produced cedar-tree laccoliths, but at its northern end outcrop evidence suggests that the granodiorite is a linear stock with steeply dipping contacts rather than a sheet. Also within this zone there are roughly circular exposures of porphyritic granodiorite at Lochdougan Moor and north of Culdoach Moor, similar in textures to D1 porphyrite dykes, but with a probably pipe-like form.

Though boreholes within the sheet complexes show that some north-trending first phase porphyrite dykes cut the granodiorite sheets, these dykes are much less abundant than in the extensions of the fissure zone beyond the sheet complexes. At Lochdougan Moor there is also outcrop evidence to suggest that the linear granodiorite is intrusive into the dyke swarm.

The thinner granodiorite sheets, up to a maximum of about 10 m thick, are always markedly porphyritic, as are the peripheral parts of some of the thicker sheets. Several sheets in boreholes and outcrop from Black Stockarton Moor, including one equigranular granodiorite at least 110 m thick, contain conspicuous miarolitic cavities up to 5 mm in diameter. These are filled with various combinations of quartz,

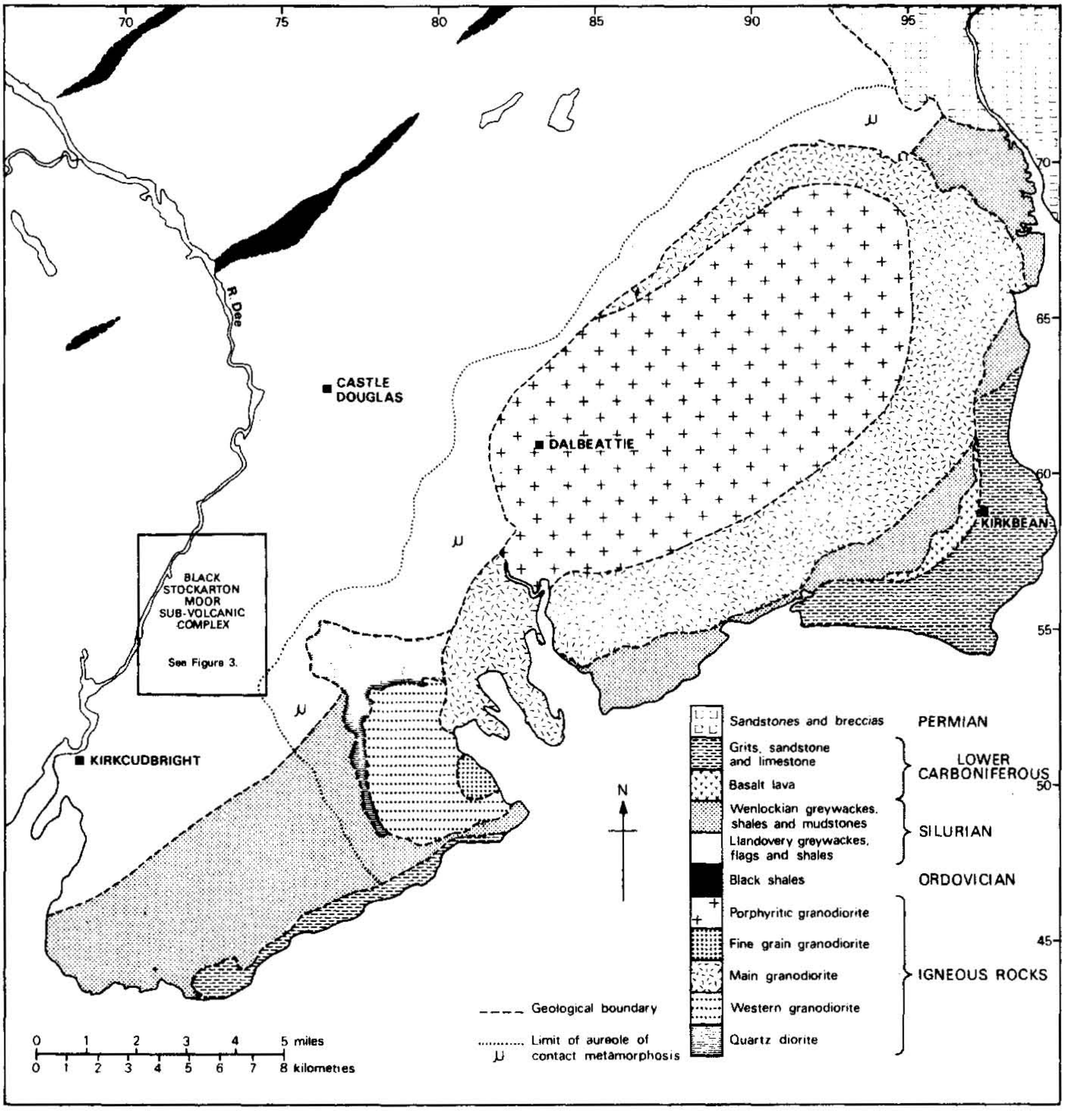


Figure 2 Geology of surrounding area

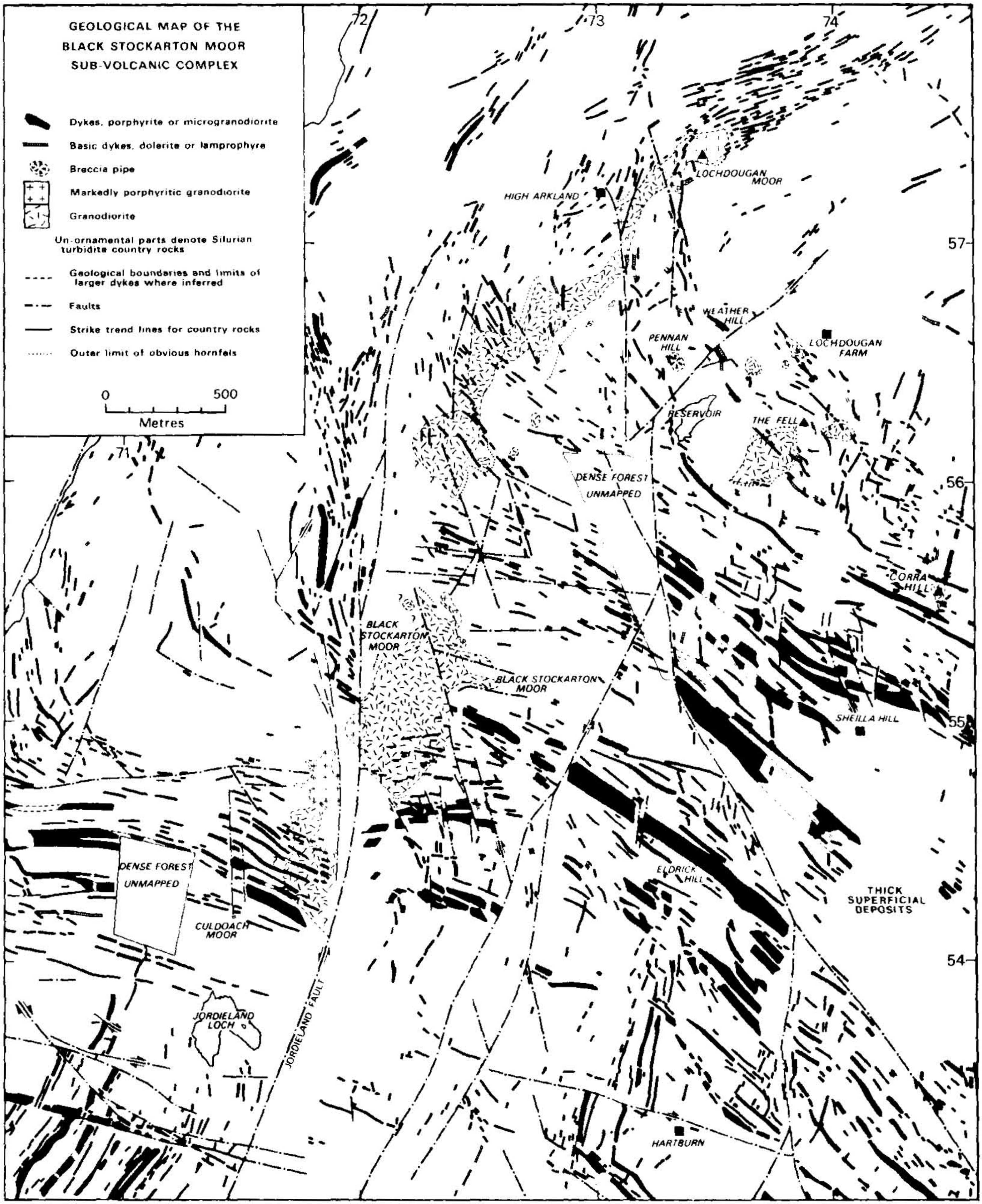


Figure 3 Detailed geology of the area

TABLE I   Components of the Black Stockarton Moor subvolcanic complex

Phase	Rock Unit	Composition	Mineralogy
1	Porphyrite dykes (D1)	1. 40-60% phenocryst porphyritic microgranodiorite. 2. minor 5-25% phenocryst porphyritic microgranodiorite	Phenocrysts: oligoclase/andesine, green hornblende ± chlorite ± quartz Matrix: feldspar, quartz ± chlorite ± biotite, opaques, apatite
	Basic dykes	1. Spessartite 2. Ophitic dolerite	Brown hornblende, plagioclase ± biotite, opaques. Plagioclase, brown hornblende/pyroxene ± olivine?
	Cedar-tree laccoliths	1. Granodiorite 2. Minor diorite	60-70% oligoclase/andesine, 10-15% quartz, 10-15% hornblende + biotite, 5% opaques, minor myrmekite, apatite. Andesine, hornblende, biotite, opaques
	Stocks	Granodiorite	60-70% plagioclase, 15-25% hornblende, quartz, biotite opaques ± graphic quartz-feldspar intergrowth
	Breccia pipes	Turbidite fragments	Matrix silica, actinolite, epidote ± carbonate ± opaques
2	Porphyrite dykes (D2)	40-60% phenocryst porphyritic microgranodiorite	Phenocrysts: oligoclase/andesine, green hornblende, chlorite, biotite ± quartz, Matrix: feldspar, quartz, Hornblende, opaques, apatite
	Basic dykes	1. Spessartite 2. Ophitic dolerite	As above As above
3	Porphyrite dykes (D3)	As D2	As D2

chlorite, muscovite, calcite, dolomite, pyrite, chalcopyrite and hematite and often have a conspicuous pink rim. The proportion of cavities varies considerably within and between the various sheets but in some sections they form as much as 5% by volume. No granodiorite sheets with miarolitic cavities have been noted either in outcrop or borehole sections from the sheet complex to the north of Culdoach Moor. A few sheets are noticeably rich in xenoliths of sedimentary rock, forming up to 10% by volume, while in others there are conspicuous clots of mafic minerals. The petrography of the sheet intrusions is summarised in Table 1.

In the borehole cores there is evidence of magmatic pressure during sheet intrusion as brecciation and abundant tension gashes can be seen in the sedimentary rocks immediately above many of the sheets. In borehole 7 (Fig. 22) there are thin sheets of porphyritic granodiorite in the turbidites above a 12 m thick sheet, which become thinner and more widely spaced with vertical distance above this sheet, being replaced finally by a brecciated zone containing granodiorite fragments and then several thin brecciated zones containing only sedimentary rock fragments. The turbidites also show a great deal of tensional fracturing, immediately above the 12 m thick sheet. Abundant brecciation and intense tensional fractures or pull-apart structures are also found in the sediments immediately above the main thickness of sheet intrusions lower down the borehole. In contrast, brecciation and intense tensional fracturing is inconspicuous in the turbidites immediately below sheet intrusions.

c) Granodiorite stocks

In the western part of the area, around the Fell and at Corra Hill (Fig. 3), there is a group of lenticular granodiorite intrusions, several of which show evidence of vertical or steeply dipping contacts. No first phase dykes have been observed cutting these intrusions but there are several cross-cutting second phase dykes. Both porphyritic and equigranular varieties of granodiorite occur but the latter are more common. Compared with the mineralogy of rocks from the sheet complexes, hornblende in the stocks tends to be more conspicuous, in relatively large brown prismatic crystals, and zonation in plagioclase is much less apparent. Since the preparation of the geological map of the area (Fig. 3) similar lenticular granodiorite outcrops have also been found to the north-west of Sheillahill.

d) Breccia pipes

The breccia pipe at Pennan Hill (Fig. 3) has a roughly ovoid outcrop but with a linear western boundary and measures 75 m and 40 m north by east. It is situated within sub-vertical turbidites and is composed of irregular angular fragments of silicified mudstone and greywacke ranging in size from less than 1 cm to about 1 m. Fragment orientation is generally irregular and the margins of most of the fragments are silicified. The matrix of the breccia consists of jasperoid silica with small crystals of actinolite and epidote. Vuggy cavities are frequent and contain crystals of quartz, calcite, dolomite, pyrite and chalcopyrite. Two prominent fracture sets roughly at right angles cut the breccia as do a series of porphyrite dykes. Some of the dykes are linear, trending either east-north-east or north-north-west, but others are curved or irregular and bifurcating. The age relations of the dykes within the pipe to the rest of the complex are uncertain as none can be traced unbroken into the surrounding country rocks due to lack of exposure, but the presence of dykes suggests that the pipe was formed during a relatively early stage of the evolution of the complex. Other breccia pipes have been found in the east of the area (since the map was produced), one of which is clearly associated with the top of a granodiorite stock.

Second intrusive phase

The D2 dykes are grouped into a series of sigmoidal en-echelon swarms with the thickest dykes, reaching 140 m in outcrop width, occurring in the south-central part of the area. Towards the west the dykes become thinner and swing northwards. The thicker dykes are composite intrusions containing porphyrites with varying proportions of phenocrysts and showing marginal flow banding, often bifurcating and including lenses of sedimentary rocks. Dilation within the zone of the thicker dykes has been calculated to be 55% over a width of 700 m in the area around Sheillahill. Most of the dykes appear to be vertical though a few dip steeply to the south or south-south-west. The contacts are often irregular on a small scale but linear on a large scale and everywhere sharply discordant to the strike of the turbidites and the trend of the first phase intrusions. The cross fractures prominent in the first phase dykes are absent but jointing is present. Xenoliths of sedimentary rocks and particularly granodiorite have been observed at a number of sites. The vast majority of the second phase dykes are porphyritic microgranodiorites (porphyrites) and in general they show less hydrothermal alteration than first phase intrusions. The petrography of the D2 porphyrites is summarised in Table I.

Third intrusive phase

A few dykes in the extreme south of the area cut dykes of the first and second phases and are assigned to a third phase of igneous activity. Unlike dykes of the two earlier phases they are linear and closely associated with roughly east-west faulting. Texturally and compositionally they appear similar to the second phase porphyrite dykes.

Basic dykes

A small number of dykes of basic composition occur in the two main swarms and range in thickness from a few centimetres to about 10 m. The majority are spessartites consisting of prismatic brown hornblende and plagioclase laths and are similar to those described in detail by Phillips (1955). Other dykes have a more doleritic texture with ophitic plagioclase and phenocrysts of brown hornblende and some partly altered pyroxene set in a fine aggregate of feldspar laths and in some cases with possible olivine ghosts. Amygdales are frequently present ranging up to 5 mm in diameter and containing chlorite, epidote, quartz, carbonate and pyrite. Both field and borehole sections show some thin basic dykes in close spatial association with porphyrite dykes.

Faulting

Three major fault trends can be recognised which, because of their homogeneity, possibly represent distinct episodes of deformation. The first group trend north-north-west and, where strike slip movement has been observed, they are dextral. The fault traces are linear but can only be traced for a few hundred metres. The second group of faults trend roughly west-north-west and are concentrated in the southern part of the area. Like the first phase they have linear traces but show sinistral strike-slip movement. The third group of faults are more persistent with sinuous traces trending between north and north-north-east and where horizontal movement can be determined are dextral.

In the borehole sections (Figs. 25 and 26) fault planes possibly belonging to the first or an earlier group can be recognised by abrupt changes in the dip of the turbidites, the occurrence of clay gouge material and several adjacent fracture planes showing slickensides. Adjacent to these planes the turbidites are flexured and folded with some sections showing overturned bedding. Within the granodiorites, particularly in borehole 8, fault zones appear to be marked by rocks showing intense argillic alteration although the actual planes cannot be recognised in the core.

Relationship between the subvolcanic and plutonic igneous activity

The Black Stockarton Moor subvolcanic complex outcrops largely to the west of the multiphase Criffel granodioritic plutonic complex (Phillips, 1956). The Bengairn quartz diorite (Fig. 2), the earliest and most westerly phase of the plutonic complex, is in faulted contact with the Bentudor granodiorite (Leake and Cooper, in prep.), an irregular-shaped stock similar to but larger than those stocks at the Fell and elsewhere described above. D2 porphyrite dykes cut the Bengairn quartz diorite but no D1 dykes have been observed within this pluton. D2 porphyrites also cut the later Western Granodiorite and the southern peripheral facies of the Main Criffel Granodiorite (Phillips, 1956). Thus the successive phases of plutonic rocks which form the Criffel complex were emplaced largely if not completely between the first and second phases of the subvolcanic complex (Table I). Examination of the spatial distribution of non-dyke intrusions eastwards from the Black Stockarton Moor area suggests that there may have been a progressive shift in both the centre and intensity of magmatism eastwards with time. Such a shift would have been responsible for the preservation of the early phase of subvolcanic activity in the west but its partial obliteration further to the east.

Tectonic evolution of the igneous complex

The sigmoidal disruption of the regional strike of the Lower Palaeozoic sedimentary rocks within the Black Stockarton Moor area (Leake and Cooper, in prep.) may have developed by a process of updoming as a consequence of magmatic pressure from below. D1 dykes were intruded into a sigmoidal tension fracture system taking advantage of the inherent structural weakness provided by the steeply dipping sedimentary layering. Subsequently the style of magmatic activity changed with the emplacement along a D1 fissure zone of nests of laccolithic sheets. Further east a series of small granodioritic stocks were intruded, possibly with satellite roof stopes, which after magma degassing and collapse were left as breccia pipes. Magmatic intensity then increased with the intrusion of the successive phases of the Criffel plutonic complex further to the east. A renewal of fissure-controlled intrusive activity then followed, possibly before the final products of the main Criffel Granodiorite had solidified. This took place within an entirely different stress field to that during D1 dyke emplacement. Maximum dilation was roughly at right angles to that of the D1 phase and intrusion was confined to a narrower belt with dykes in sigmoidal swarms arranged en-echelon. Magmatic intensity was greater with the repeated intrusion of dykes producing composite bodies up to 140 m thick. Finally the D3 dykes were intruded along lines of dextral shear faulting.

Age of igneous activity

Both subvolcanic and plutonic igneous rocks are intrusive into Silurian turbidites, the more precise age of which is uncertain. South-east of the Criffel granodiorite there are Upper Old Red Sandstone sediments containing fragments of granodiorite and porphyrite dyke rocks (Leeder, 1971). Fragments of igneous rock similar to those exposed within the Black Stockarton Moor area are abundant in the downfaulted Lower Carboniferous sediments along the Solway coast to the south. No age dates are available yet for rocks from the Black Stockarton Moor complex but the main Criffel granodiorite has given potassium-argon dates of 397 ± 8 m.y. and 391 ± 8 m.y. (Brown et al, 1968) and a zircon age of 406 ± 15 m.y. (Pidgeon and Aftalion, 1978). It seems likely therefore that igneous activity in the area spans a period within the end Silurian to Lower Devonian.

GEOPHYSICAL SURVEYS

Introduction

The geophysical investigations at Black Stockarton Moor and its environs have been divided into 1) attempts to define the gross structure of the area by a gravity survey and by reference to aeromagnetic data, and 2) the use of induced polarisation, resistivity and magnetic methods for more detailed studies to define the extent and nature of metalliferous mineralisation. The methods used and results obtained can be found described in detail in Appendix II.

Structural geophysical investigations

Gravity surveys

The gravity survey was carried out to investigate the form and extent of granodiorite bodies found outcropping in the area. In all, 163 observations were made over an area of 40 km^2. Some readings were taken at ordnance survey bench marks, but most were taken at intervals of about 150 m along tachyometrically levelled traverses across Stockarton and Culdoach Moors.

Fig. 4 shows the Black Stockarton Moor area in the context of the Bouguer anomaly pattern of south-west Scotland. The area is surrounded by three major gravitational disturbances: two lows due to the granodiorites of the Criffel-Dalbeattie and Fleet intrusive complexes, and a high, of unknown origin, centred on Kirkcudbright Bay. The effects of these disturbances as well as the linear regional gravity gradient were subtracted from the gravity field in the Black Stockarton Moor area, leaving the residual Bouguer anomaly pattern shown in Fig. 5.

A weak low, about 4 km long, and arcuate in form, can be seen to follow the line of outcropping granodiorites from Culdoach Hill to Loch Dougan Moor and beyond. This is clearly related to the intrusions and in particular to the granodiorite having a density lower than the surrounding sediments, by 0.06 gcm (see Appendix II).

The gravity survey evidence suggests that the granodiorites are laminar bodies of varying thickness, probably connected at depth. They dip and probably thin to the east, but are cut off more sharply to the south and west. A limb of the Bouguer low which extends east-south-east from Milnthird Hill reflects the intense injection of dykes along this line. Locally these dykes occupy over half the ground by volume. The small, steep-sided granodiorites in the east, such as that at the Fell, are not reflected by the Bouguer anomaly pattern and are probably of limited extent.

Aeromagnetic data

The 1000 ft (mean terrain clearance) aeromagnetic survey (Fig. 6) shows an approximately rectangular high centred over Black Stockarton Moor. Both dyke and sheet intrusions are apparently responsible for features in the contour pattern following both Phase 1 and Phase 2 dyke swarms. Attempts to interpret the shapes of the granodiorite bodies using these data and surface traverse data were hindered not only by the effects of these dykes, but also by variations of magnetic susceptibility within the larger intrusions.

However, the indications are again that the granodiorite occurs as a single sheet or series of sheets. In agreement with the interpretation of the gravity survey there seem to be sharp boundaries to the south and west of the intrusion, while a dip to the east, and thinning to the north are indicated. Estimates of thickness are difficult, because of the uncertainty of the susceptibility, but range from 150 m to 500 m.

Detailed geophysical investigations

Induced polarisation and resistivity

These surveys were undertaken to locate sulphide mineralisation within the area. Three techniques were used: gradient array surveys in the frequency domain, variable separation dipole-dipole surveys in the time domain and constant separation dipole-dipole profiling, also in the time domain.

The induced polarisation (IP) survey reveals an anomaly almost 6 km long with values typically from two to five times background stretching from south of Jordieland Farm to High Arkland in the north (Fig. 7). No comparable feature is encountered elsewhere in the area surveyed. The anomaly approximately follows the strike of the greywackes and over much of its length it lies over the sheet intrusives of granodiorite. It is arcuate rather than linear, with its bearing changing by 60° over its length. The highest IP effects were measured in the south, where they coincide with high resistivities. The anomaly is cut off just north of Jordieland Farm, apparently by an east-west fault. It is also apparently faulted out against the north-south Netherthird fault. Its northern limit is also quite abrupt, but there is no evidence of faulting in the vicinity.

The resistivity data (Fig. 8) reveal the major faults as bands of low resistivities and show certain dykes as linear highs. The possible existence of extensions of major fracture zones identified from satellite photographs crossing southern Scotland from north-west to south-east, have no expression in the resistivity results. There is no correspondence between IP and resistivity anomalies, except in the south, where high IP values accompany high resistivities.

Magnetic data

Magnetic field measurements (Fig. 9) taken on a grid show clearly the pattern of

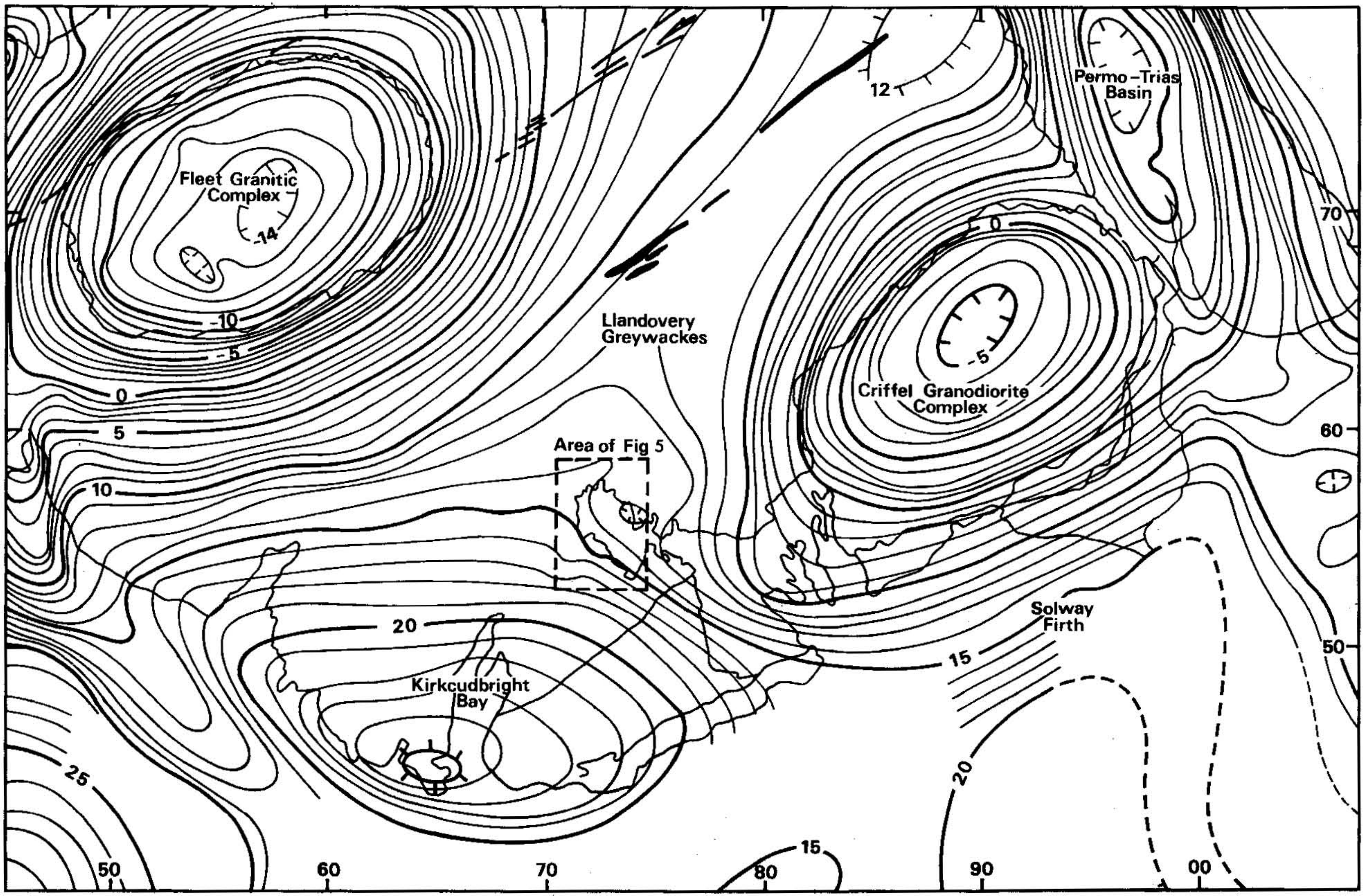


Figure 4 Gravity map of the Fleet and Criffel plutonic complexes

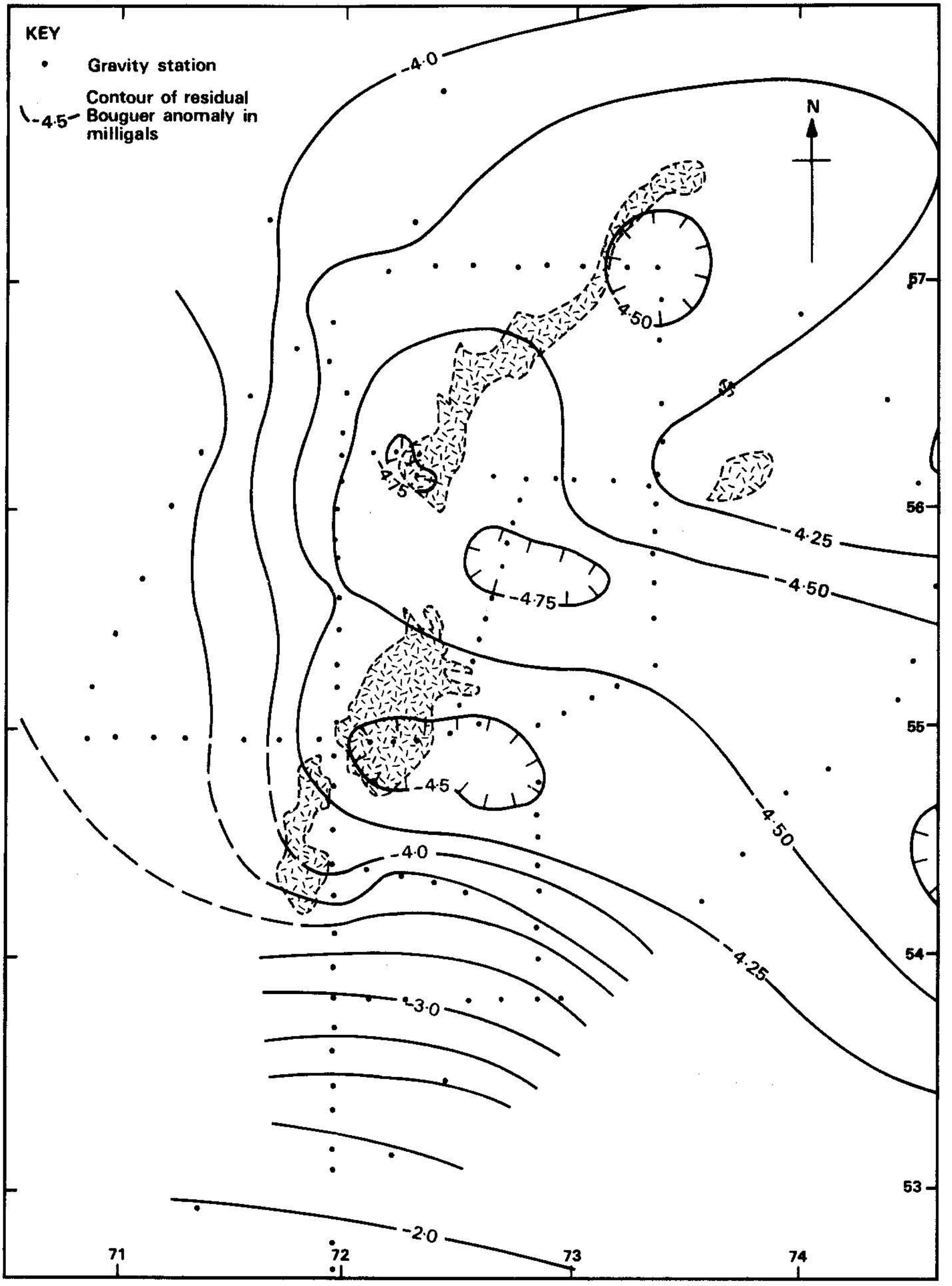


Figure 5 Gravity of the Black Stockarton Moor area

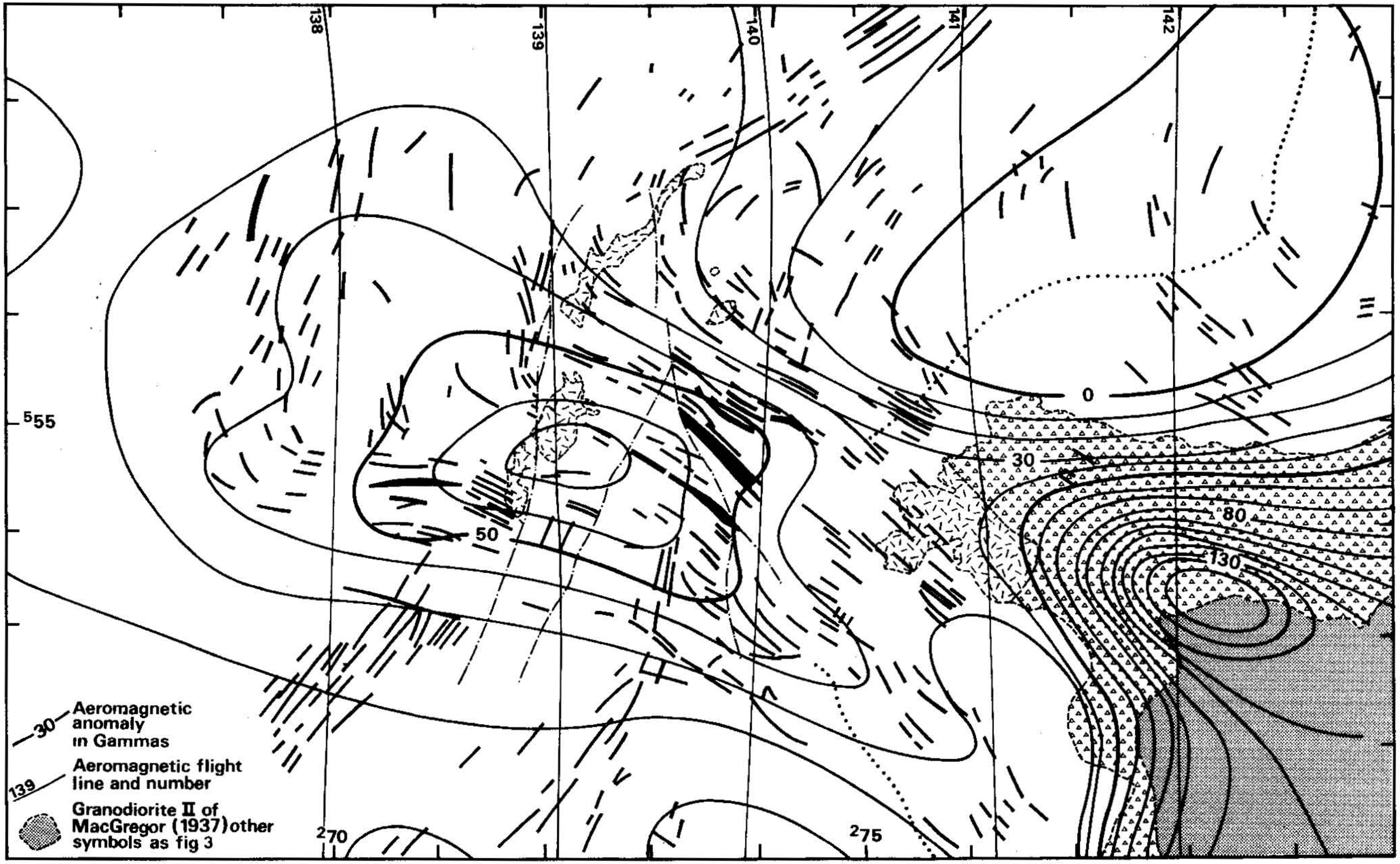


Figure 6 Aeromagnetic map

magnetic dykes intruded into both the greywackes and the more northerly granodiorites. With the exception of a single very magnetic north-south dyke near Weather Hill, the phase 2 dykes are the most magnetic. There are apparently variations in the magnetic susceptibility of the granodiorites near Jordieland Loch. An intense magnetic anomaly occurs on part of the IP anomaly: the source of this is at present unknown.

GEOCHEMICAL SURVEYS

Introduction

The geochemical drainage reconnaissance survey of the Criffel-Dalbeattie area (Leake et al, 1978) indicated anomalous levels of copper in stream sediment and panned concentrate samples in several streams draining into the River Dee from the Black Stockarton Moor and Weather Hill areas.

Using these data, follow-up investigations were undertaken to locate the source of the copper. Initial investigations involved the collection of closely spaced drainage samples and the collection of soil samples over two reconnaissance lines. These were laid out at right angles to each other across an uncultivated part of Black Stockarton Moor in an attempt to obtain reliable results without interference from contamination and recent soil movement due to cultivation and the addition of fertilisers.

Favourable values of copper in soil over the reconnaissance lines led to an initial soil grid of 0.7 km^2 being sampled. Further geological information and results from the IP survey outlined targets for soil sampling. In areas of deep overburden and in areas where copper values in soil were high the sampling was supplemented by the collection of basal till samples by means of a mechanical auger.

Drainage sampling

A total of 31 water samples, 73 stream sediments and 41 heavy mineral concentrates were collected over an area of 35 km^2 during the reconnaissance and follow-up stages of the investigation. The methods of collection and analysis employed are given in Appendix III.

The drainage of the area is impeded by a large number of bogs over the moorland. Drainage ditches have been cut over a large part of the area.

Initial follow-up investigations located structure-controlled mineralisation, containing chalcopyrite or malachite with calcite, barite and traces of lead and zinc minerals, exposed in Milnthird Burn about 0.5 km above Milnthird (NGR 720 562). The level of Cu in each sample type was plotted by the method of class interval representation described by Leake et al (1978).

Examination of the drainage maps (Figs. 11 and 12) shows the levels of Cu in most samples to be of low tenor (maximum stream sediment value 65 ppm Cu and maximum panned concentrate value 616 ppm Cu), showing no distinct distribution patterns. In one of the main mineralised areas (NGR 726 552) results do not reflect the levels of copper in the adjacent rocks. Sediment and panned concentrate samples from a small burn near BH 8 (NGR 7235 5520) gave values of 20 ppm and 69 ppm Cu respectively draining an area where rock outcrops were known to contain up to 0.13% Cu. The samples collected downstream of the anomalous area gave rise to higher concentrations i.e. 65 ppm Cu in stream sediment near Milnthird and 616 ppm Cu in panned concentrate near Mayfield.

As the distribution of Cu in stream sediments and panned concentrates was difficult to interpret in relation to known mineralisation, a limited programme of water sampling was undertaken to determine the amount of Cu in solution. These samples were mainly taken from seepages and the sources of small streams. From Fig. 10 it can be seen that the levels of Cu are variable, this in part being due to a range of pH values.

Soil sampling

Soil sampling was undertaken to supplement geological and geophysical work. (For details of sampling and data processing see Appendix III). Results have been plotted by the method of class interval representation (Lepeltier 1969).

Over most of the area sampled soils are poorly developed, consisting of a thin top peaty layer below which is a poorly developed podzol derived from a clay-rich water saturated till. The development of a recognisable B horizon is rare, this being seen in some profiles by the eluviation of iron below the top layer. Samples collected with a hand auger at depths between 0.5 and 0.8 m mainly represent C-horizon material. Most soil grids were laid out using 100 by 25 or 100 by 50 m spacings, this being the optimum size in order to identify anomalous areas based on orientation work using a closely spaced grid (10 by 50 m). The distribution of Cu in soil shows a lognormal pattern with the lowest class plotted marking the upper limit of the first population as shown by the break in slope of the cumulative frequency diagram (see Appendix III). The other class limits are based on arbitrary limits above the mean of the upper population.

Anomalous levels of Cu in soil, when plotted (Fig. 13), delineate a zone measuring approximately 2 x 0.5 km forming a lensoid feature trending 040°. This zone coincides with the mapped outcrop of the Black Stockarton Moor and Culdoach Moor granodiorite sheets, the intervening greywackes and the porphyrite dykes and greywackes to the south-west. In contrast the soils collected over the granodiorite sheet to the north (Milnthird/High Arkland) exhibit a low Cu content with a few minor exceptions which form no distinctive pattern. To the south of Jordieland Loch over an area of greywackes cut by two sets of intersecting dykes Cu values are relatively low when compared to the central area. The zone of high copper tends to lie to the east of the IP anomaly (see Fig. 20) with some overlap in the central area.

The distribution of Pb and Zn shows no direct association with Cu. Pb values show a

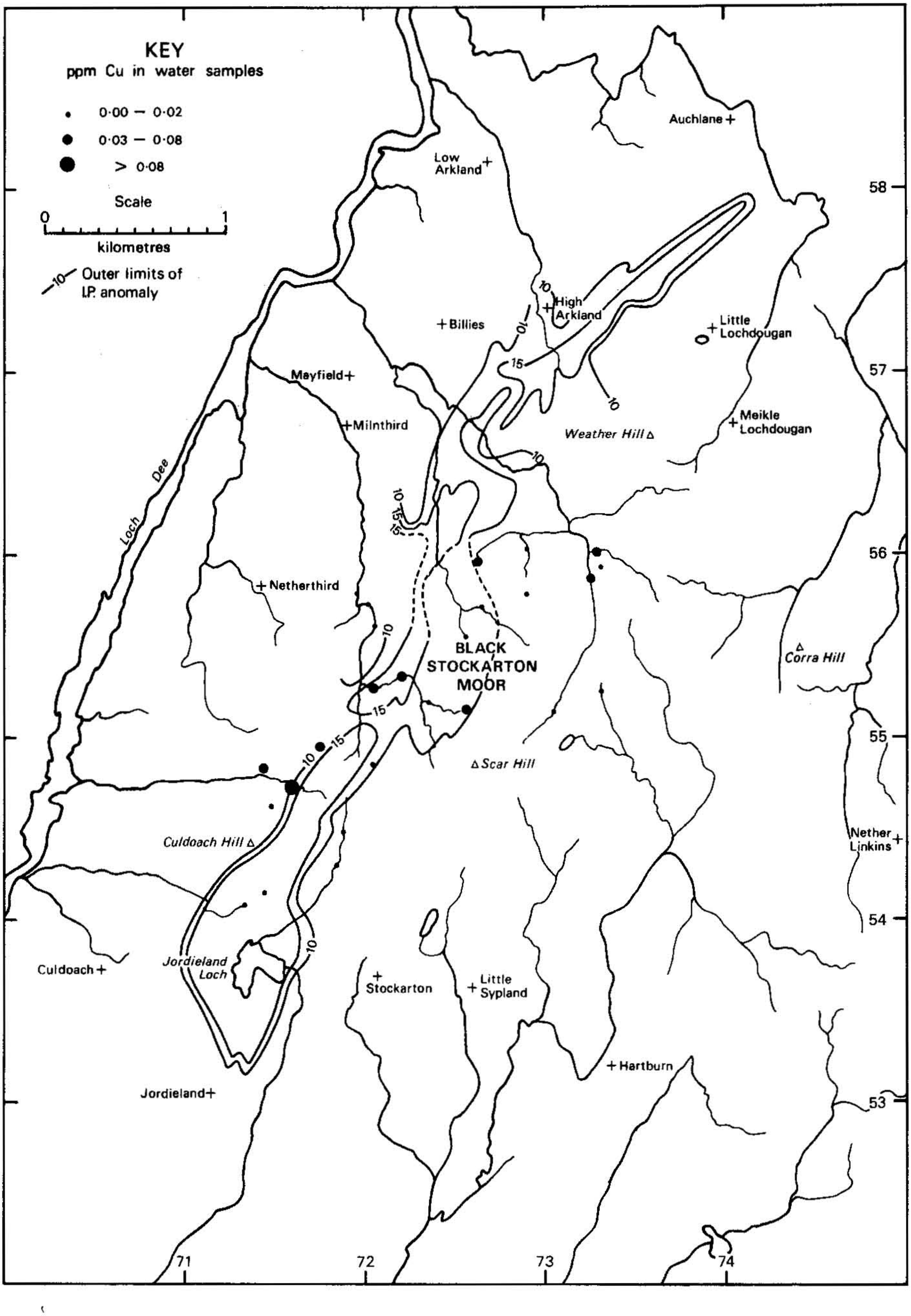


Figure 10 Copper in water

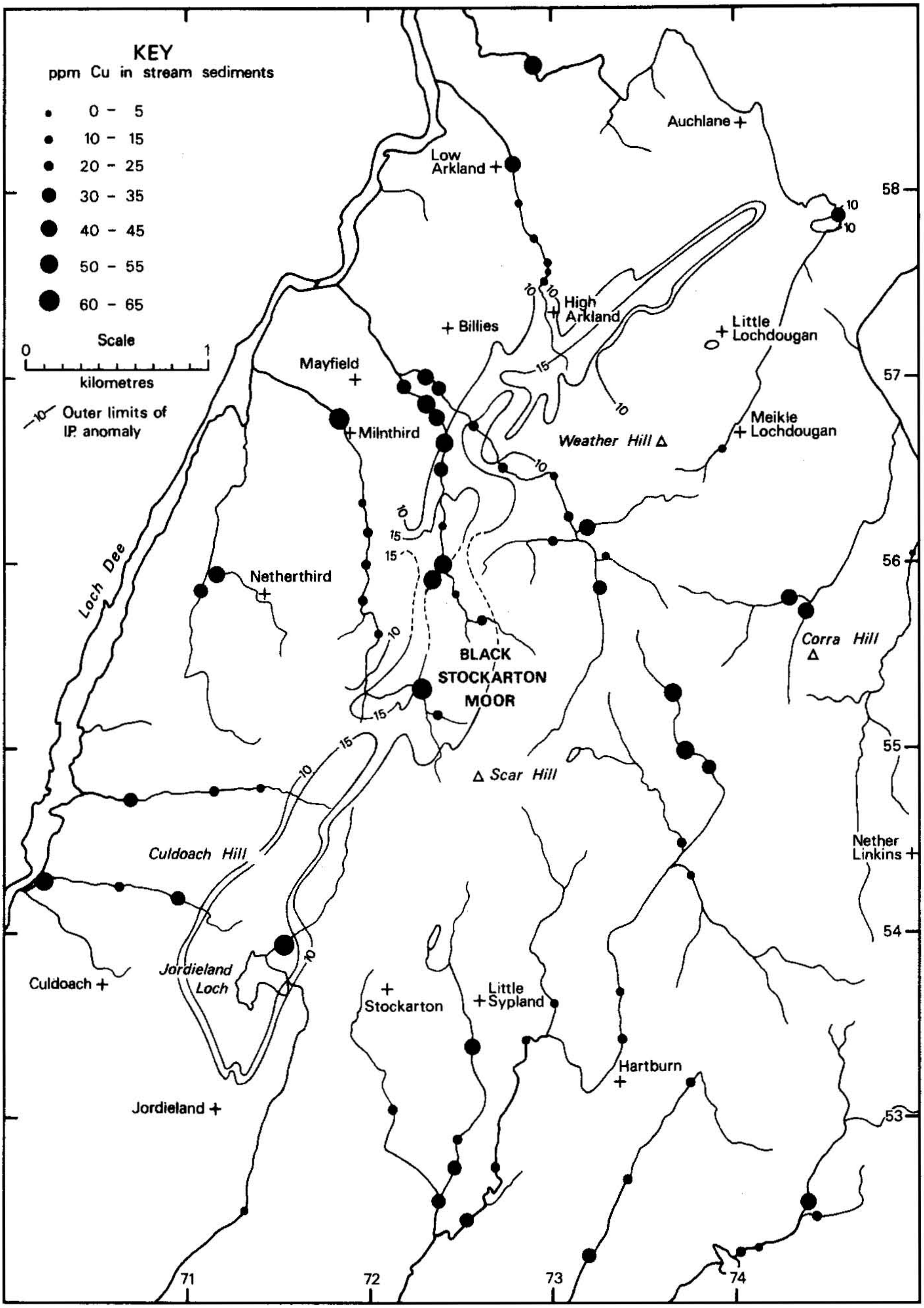


Figure 11 Copper in stream sediments

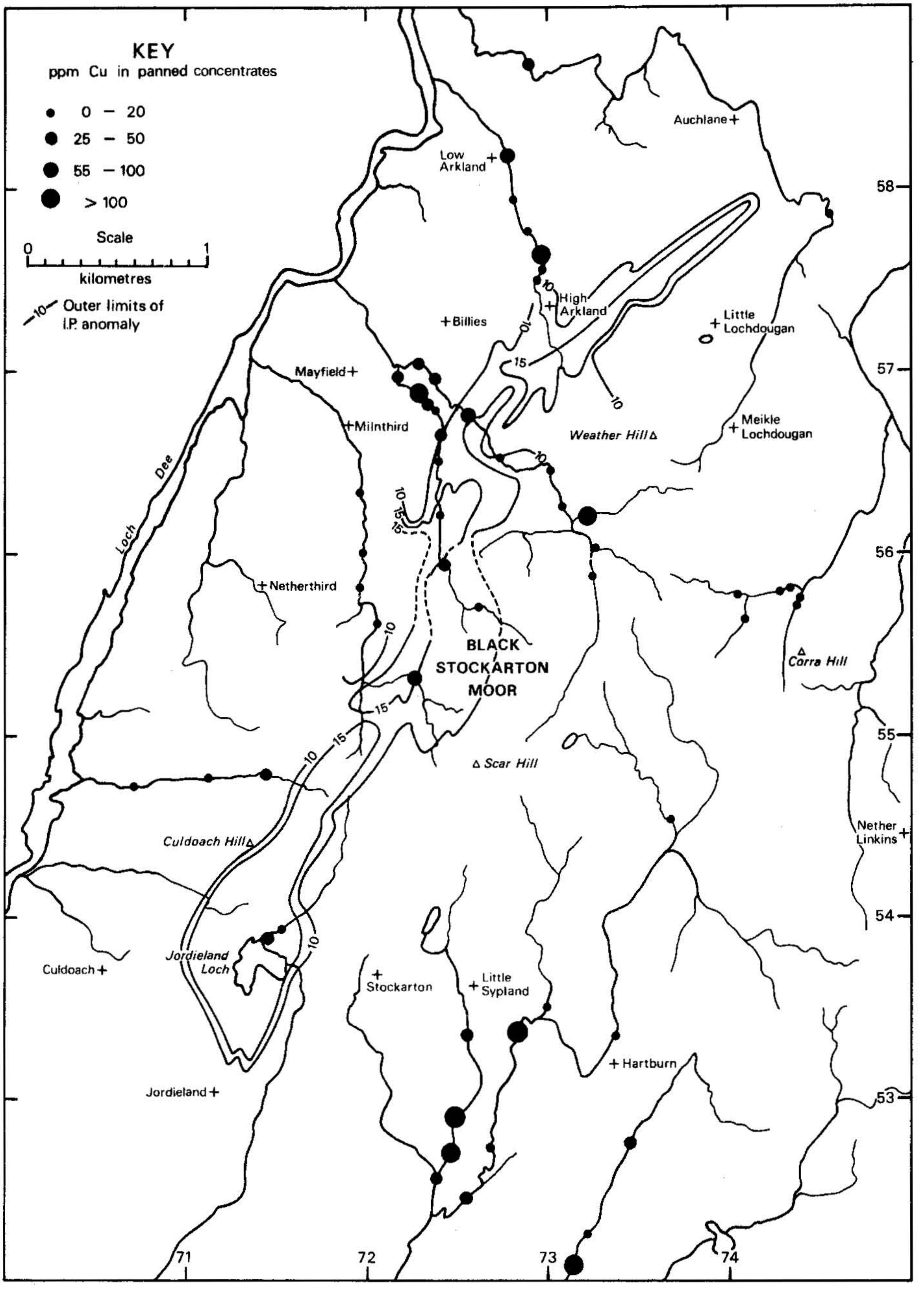


Figure 12 Copper in panned concentrates

lognormal distribution and have been plotted in a similar manner to Cu (see Appendix III). A study of the distribution of Pb (Fig. 14) shows that most of the anomalous samples fall outside the zone of high Cu, and are generally associated with the greywackes and porphyrite dykes rather than the granodiorite sheets. These anomalies may be indicative of weak Pb and Zn mineralisation in rock outside the zone of copper.

Zn shows a near arithmetic normal distribution (see Appendix III). As only a few samples contained anomalous levels of Zn the element has not been plotted in map form.

Till sampling

In order to confirm the copper anomalies shown by the soil survey and to investigate areas of deep overburden, a programme of till sampling was undertaken over an area of 5 km^2. A portable mechanical auger was used for the sampling of tills and also, at a few sites, for the collection of shallow rock samples by replacing the auger flights by a diamond bit and drill rods. Details of the method of sampling are given in Appendix III.

Samples were collected at all sites from the bedrock/till interface and in deeper holes representative samples of the till profile were taken to investigate the dispersion of Cu, Pb and Zn with depth. Part of the material collected from the basal till section was panned at site to give an immediate visual indication of the metalliferous minerals present. The larger rock fragments from the till were also collected for examination.

A total of 235 holes were sunk in the area ranging in depth from 0.1 to 7.3 m giving an average till depth of 1.66 m. Sampling was undertaken on a north-south grid, in most cases at 50 m intervals between east-west lines and 50 m between samples (Figs. 15, 16 and 17).

Examination of the rock fragments from the tills in the field laboratory showed that in most cases the fragments were consistently of the same type (greywacke, porphyrite or granodiorite) making it reasonable to assume that the material was directly derived from the bedrock. This information was also useful as an aid to geological mapping in areas of poor exposure. At the sites where the fragments were mineralised, or where a large amount of sulphide was apparent in the heavy mineral concentrates of the basal till, a sample of the bedrock was taken by converting the auger to a small drilling rig (see Appendix III).

Till samples collected varied greatly in colour mainly due to the variable eluviation of iron and a fluctuating water table. In deep holes (up to 7.3 m) in boggy ground a yellow/orange to white water-saturated clay was common. Clay rich tills dominate the area with varying amounts of silt though some profiles show very sandy layers.

Till profile sampling and geochemistry

Where a reasonable section of till was encountered samples were taken down profile based on changes in colour and texture. In the case of uniform till, sampling was carried out at intervals of 0.5 m.

In a large proportion of the profiled holes there is an increase of Cu with depth (Fig. 18) which in many cases is indicative of bedrock mineralisation. Other profiles show complex distributions which may be due to several separate or interacting factors such as changes in the level of the water table, the variation in the eluviation of iron or transported overburden. From two sample lines which were profiled (Fig. 19) it is clear that the distribution of Cu is not influenced to any great extent by the topography through downslope movement of overburden.

In most holes Pb shows the highest concentration near surface, the remainder of the profile showing an even distribution (Fig. 18). Zn tends to show an irregular distribution down profile (Fig. 18) probably due to hydromorphic dispersion related to a fluctuating water table.

Anomaly patterns in basal till

In general the Cu anomalies located by basal till sampling are higher than those in sub-surface soils. The log mean value for Cu in 235 basal till samples was calculated as 50 ppm whereas the log mean value for soils within the same area was 20 ppm (see Appendix III). Based on 38 sites the log mean value for Cu in basal till is nearly twice the log mean value for near surface soils collected from the same profile but Pb and Zn do not show such a marked increase with depth (see Appendix III).

Maps showing the distribution of Cu, Pb and Zn in basal till (Figs. 15, 16 and 17) are based on class interval presentation as described for the soil maps. Cu and Pb show a lognormal distribution whereas Zn shows a near arithmetic normal distribution where class limits are based on arbitrary limits (see Appendix III).

The plot of Cu in basal till confirms the occurrence of an anomalous lensoid feature (Fig. 15) exhibited by the results of the soil sampling programme. As with the soils, Pb and Zn anomalies in basal till lie outside the anomalous copper zone (Figs. 16 and 17).

DRILLING

Drilling targets

The sites of the 12 boreholes drilled within the Black Stockarton Moor area are shown in Fig. 20. Boreholes 1, 2 and 3 were put down at an early stage of the investigations in order to confirm the existence of granodiorite which was suspected from occurrences of boulders and small exposures to underly the western part of Black Stockarton Moor. In addition, samples probably derived from outcrop near the site of borehole 1 contained disseminated pyrite and chalcopyrite, two of which assayed 1350 ppm and 970 ppm Cu. Boreholes 4 to 6 and 10 and 11 were drilled principally to investigate copper anomalies in soil and

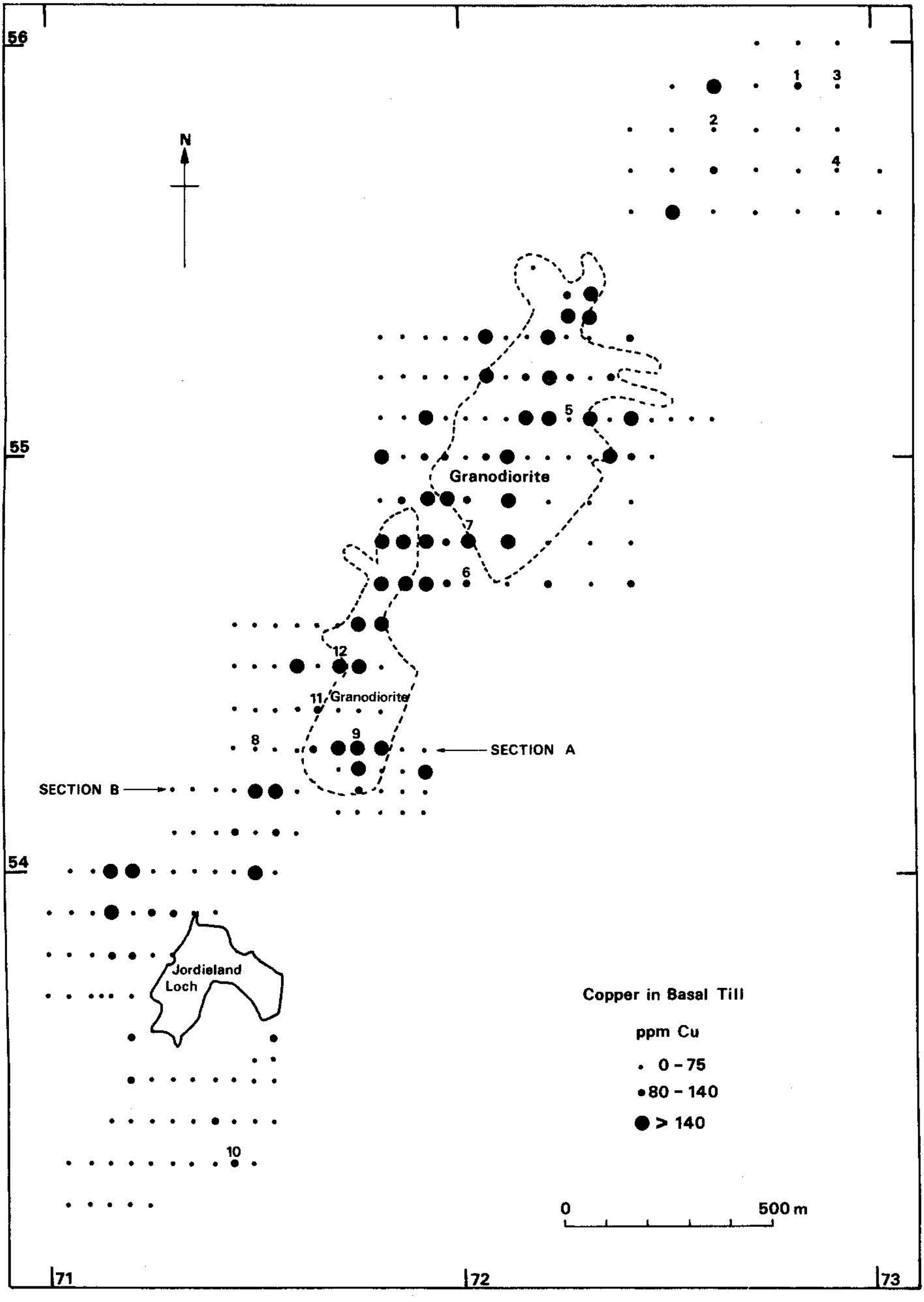


Figure 15 Copper in basal till

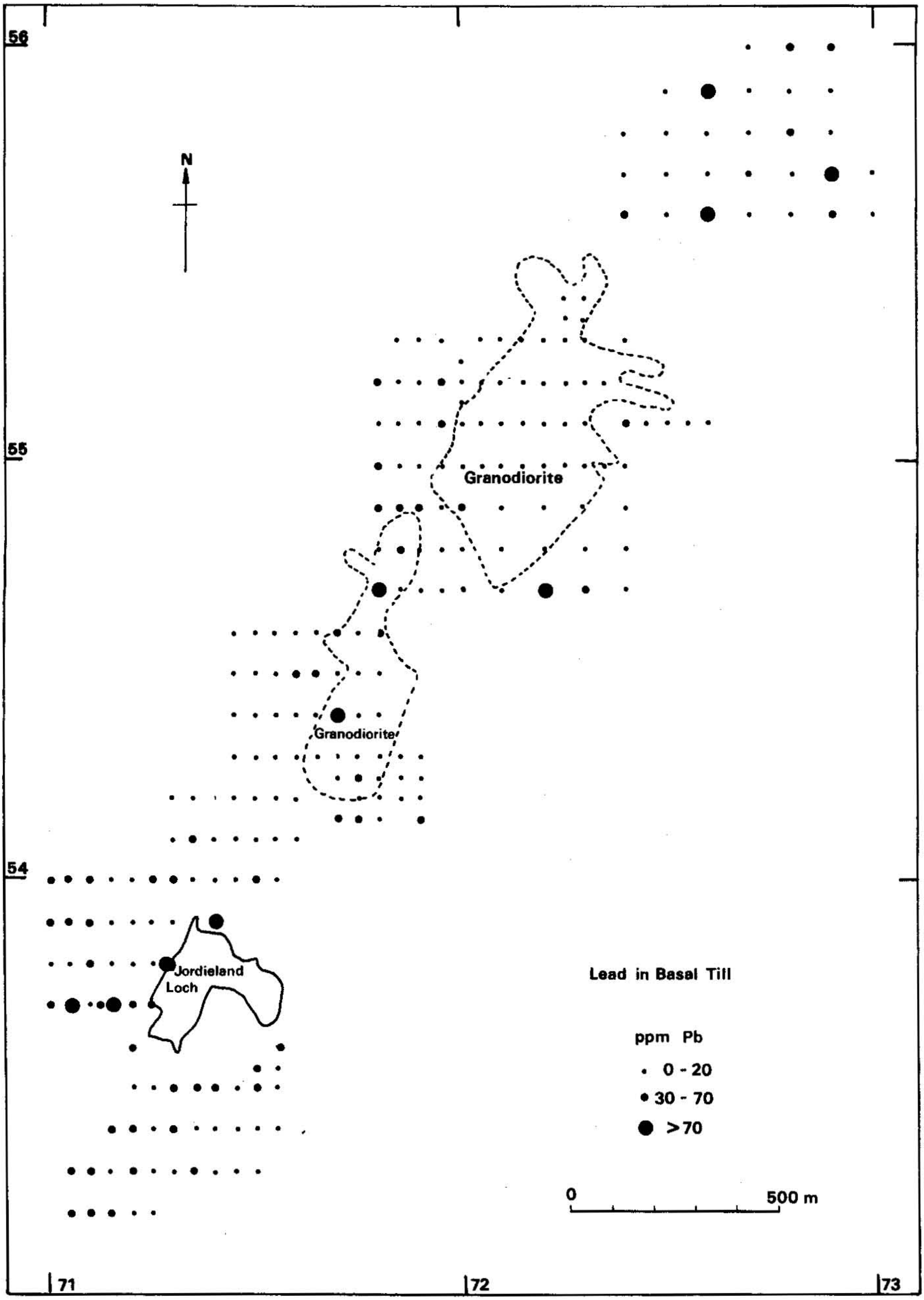


Figure 16 Lead in basal till

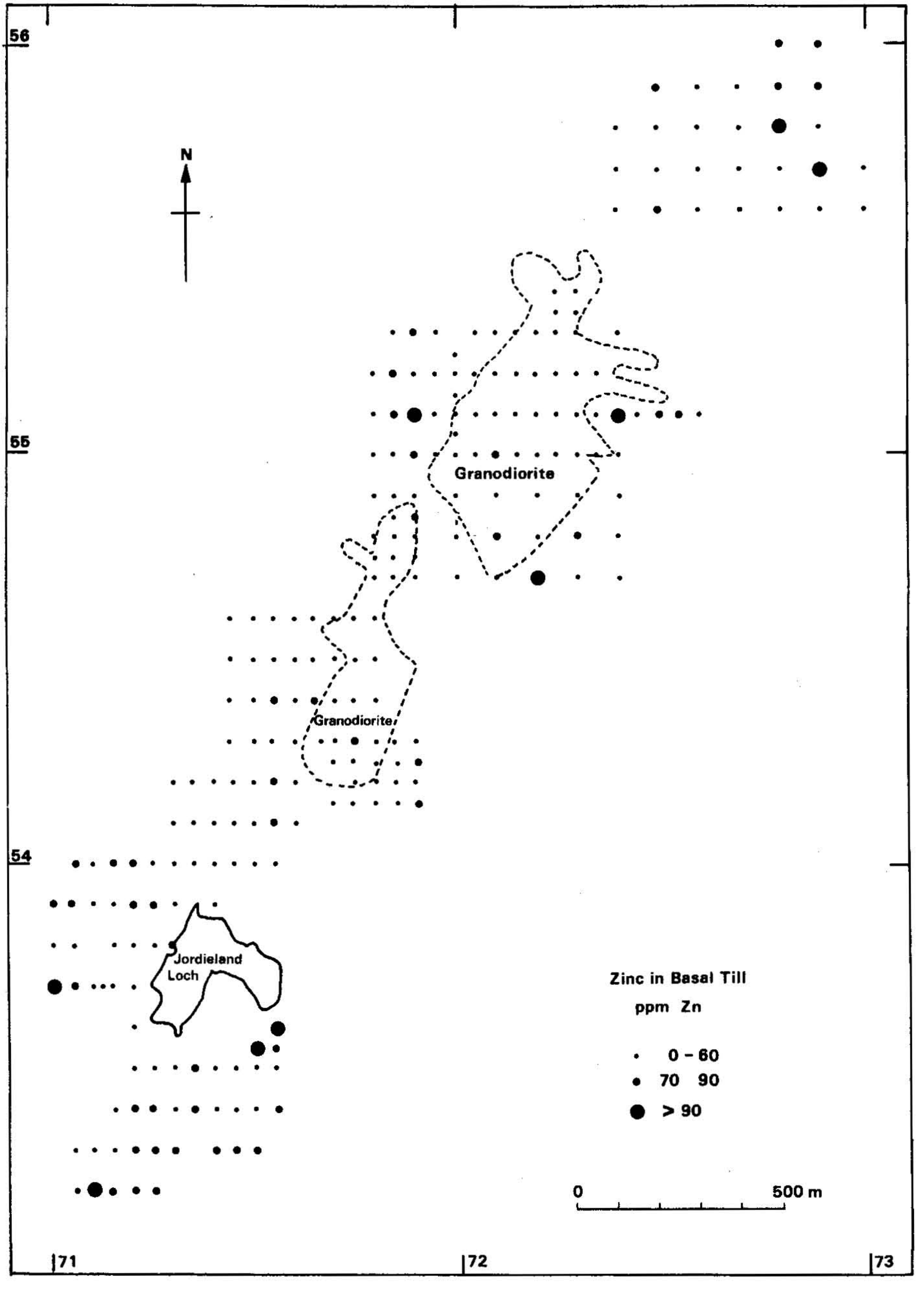


Figure 17 Zinc in basal till

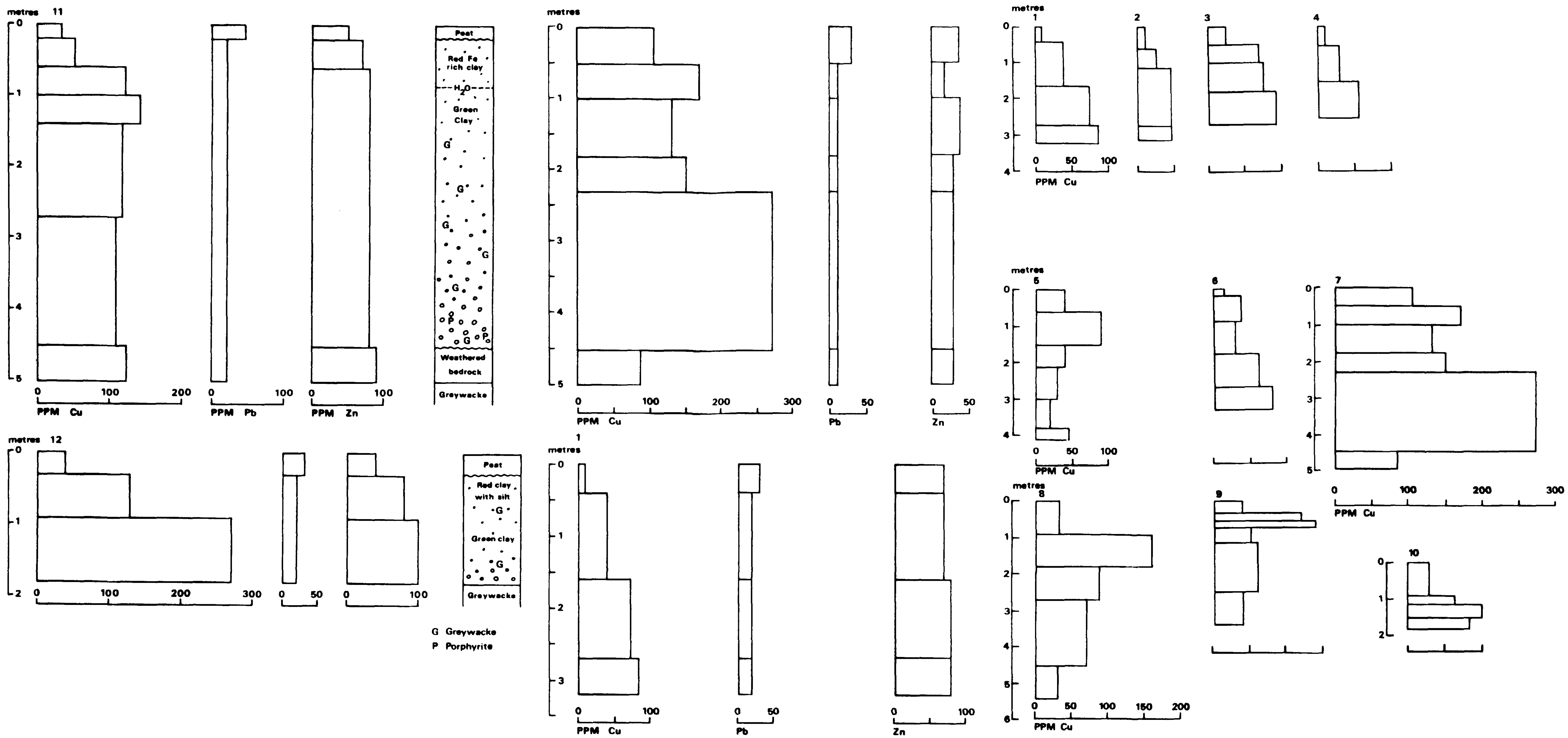


Figure 18 Copper, lead and zinc distribution in till profiles

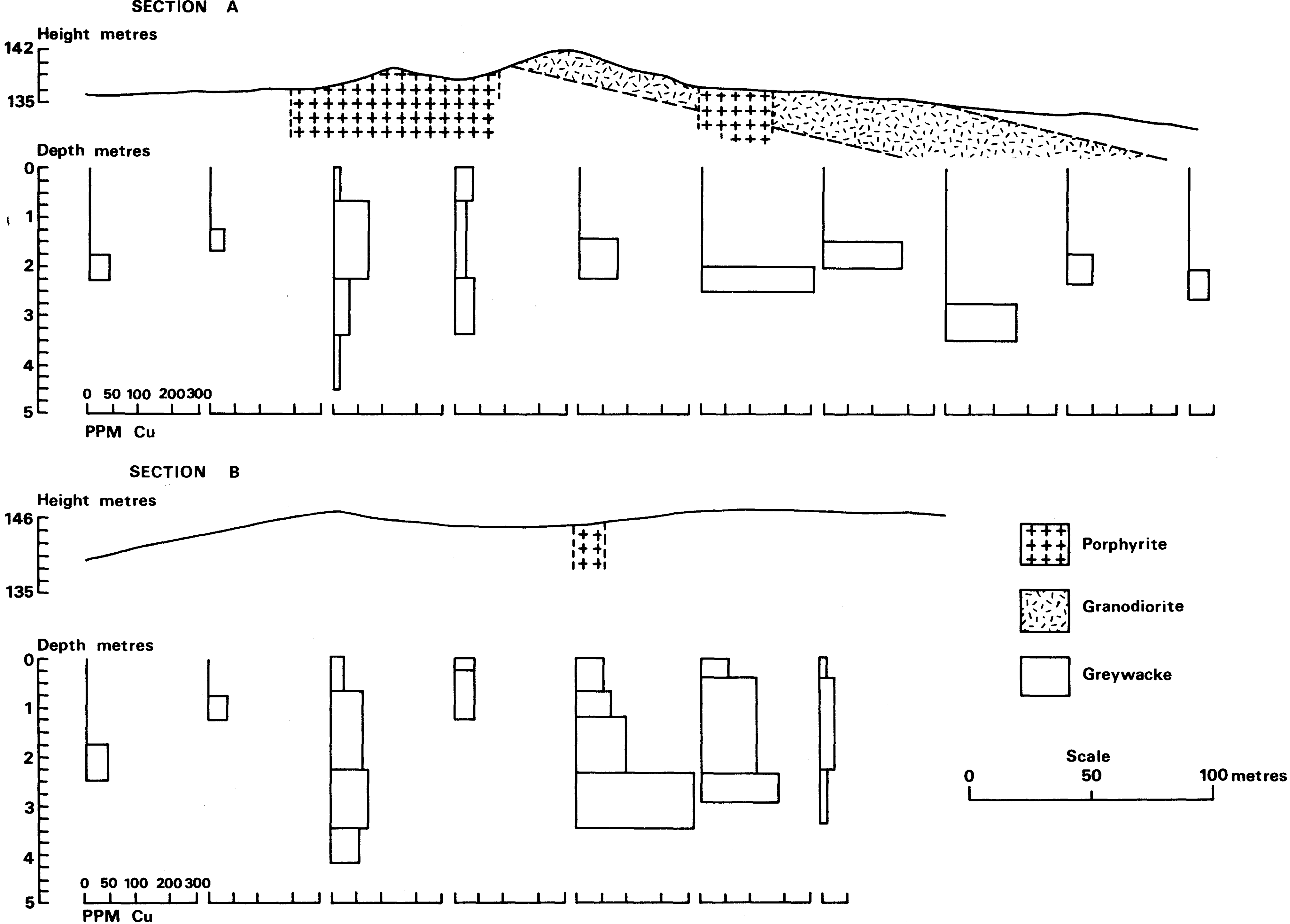


Figure 19 Copper in till along sections A and B

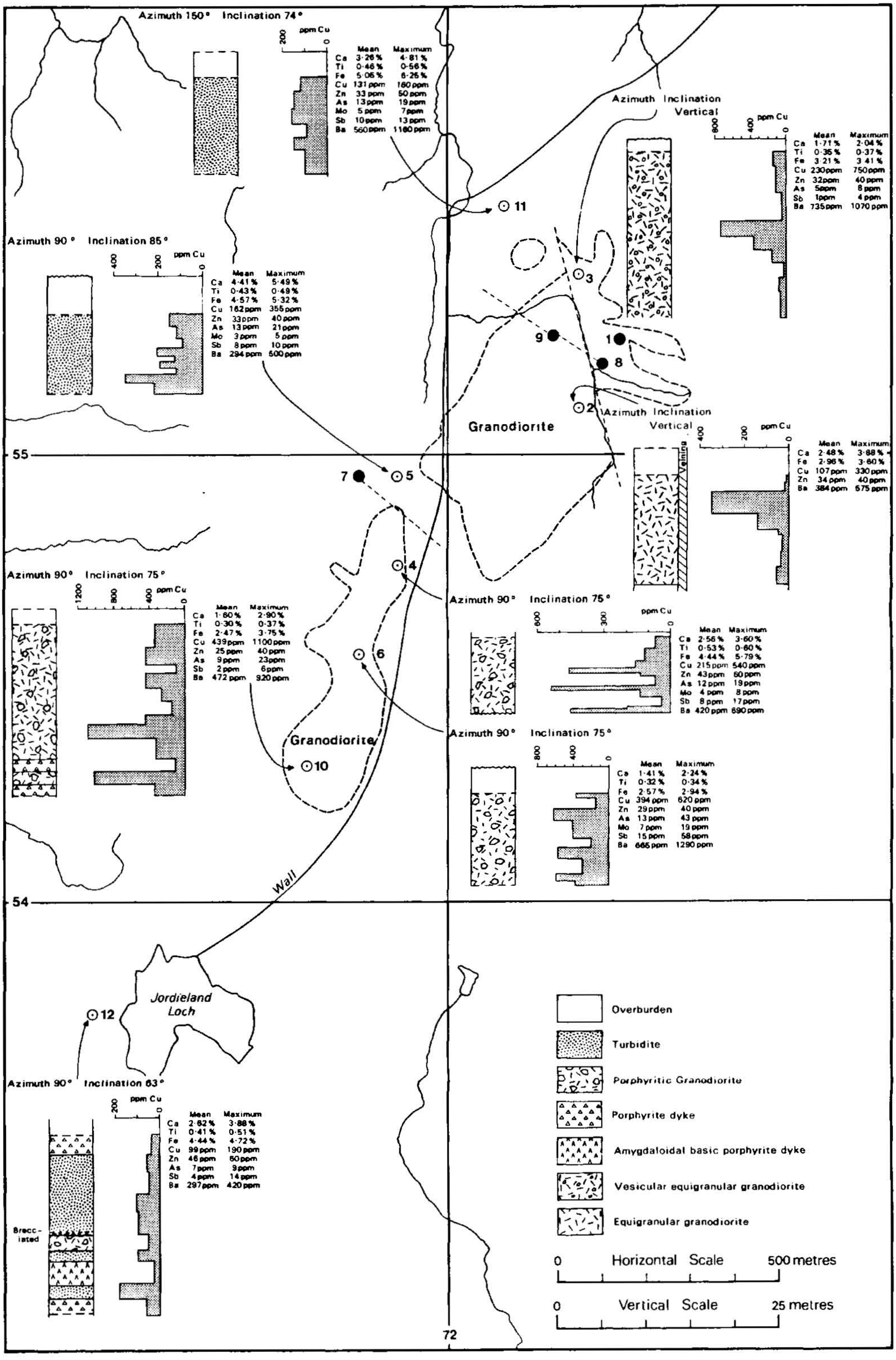


Figure 20 Borehole location map and graphical logs of BHs 2, 3, 4, 5, 6, 10, 11 and 12

basal till, and borehole 12 was put down in the vicinity of the maximum IP anomaly in order to investigate a possible relationship between the intensity of IP response and sulphide mineralisation.

The three deeper angled boreholes, 7, 8 and 9, were orientated so as to pass through the IP anomalies and beneath surface copper anomalies to investigate possible zonation of the mineralisation. At the time that these boreholes were sited existing results suggested that the geochemical anomalies formed an annulus centred on the western edge of Black Stockarton Moor after allowance had been made for possible lateral movement along the Jordieland fault. The boreholes were therefore inclined towards the presumed centre of the zone from each side.

Geological interpretation of boreholes

Geological sections of the boreholes drilled within the area are shown in Figs. 21 to 24. Borehole 1 which was drilled vertically showed that contacts between granodiorite intrusions and the turbidites were relatively low angle. Structural sections through boreholes 7 to 9 (Figs. 25 and 26) were assembled using evidence of contact angles and turbidite bedding angles with the assumption that the strike of the turbidites is overall the same as that seen at surface, since it is constant over a wide area. Some uncertainty exists in the interpretation of borehole 9 below the depth of 150 m down the hole because of the similarity in texture between some porphyritic granodiorite sheets and the thicker porphyrite dykes.

Three near-vertical faults were recognised in borehole 7, marked by abrupt changes in the attitude of the turbidite bedding, by several adjacent small fractures and slickensides and in one case by a clay gouge. The fault intersected at about 196 m can probably be correlated with the approximately north-trending fault mapped as a satellite of the main Jordieland fault. There is no evidence from the borehole that the main Jordieland fault was intersected though the line of the hole passed beneath its presumed surface expression, which also coincides with a band of low resistivity. It is therefore concluded that the fault hades at a significant angle towards the east.

In borehole 8 there is no recognisable plane which can be correlated with the north-north-west trending fault mapped at surface, though there are several zones within the upper part of the core which are marked by intense red goethitic and clay-rich alterations. Two faults were recognised from the lower part of this borehole, the upper being marked by a clay gouge with adjacent slickensides at the contact between granodiorite and turbidite and the lower by an abrupt discordance in the attitude of the turbidites.

Detailed correlation between boreholes 8 and 9 proved impossible even though the start of borehole 9 was vertically above the end of borehole 8. Though two turbidite rafts occur in each borehole there is a marked dissimilarity in texture and composition between the granodiorites in the upper part of each hole. In borehole 8 the granodiorite down to 125 m in the hole is non-porphyritic and markedly less basic than the porphyritic granodiorite in the upper 67 m of borehole 9, though both contain miarolitic cavities in parts. Furthermore the composition and texture of the upper granodiorite from borehole 8 is remarkably constant whereas in borehole 9 within the same length of core five texturally and compositionally different intrusions have been recognised. These relationships may be indicative of great heterogeneity and complexity in the individual member intrusions of the complex or, alternatively, they may suggest that the faulting seen in the lower part of borehole 8 is of major significance. Granodiorite intersected in borehole 3 is similar in texture and composition to that occurring in the upper part of borehole 8.

No direct correlation between borehole 7 and borehole 9 is possible because they are separated by the major Jordieland fault and also because the granodiorite in each probably originated from different centres of igneous activity. No trace of miarolitic cavities in granodiorite has been found in any of the boreholes from the western side of the Jordieland fault though in other textural and compositional features close similarity exists. Granodiorites from boreholes 6 and 10 are markedly similar in texture and composition but are quite different from the highly porphyritic relatively basic rock intersected in borehole 4. Furthermore no trace of a rock similar to that from borehole 4 was intersected in borehole 7.

MINERALOGY OF DEEP BOREHOLES

Introduction

Mineralogical examination of drill core from boreholes 7, 8 and 9 was carried out to provide a detailed account of the alteration and mineralisation present in depth at Black Stockarton Moor. For the three main boreholes the numbers of specimens examined in thin section are as follows: Borehole 7 - 69 specimens; Borehole 8 - 50 specimens; Borehole 9 - 28 specimens. The descriptions of these specimens are summarised in Appendix IV, (Tables X, XI and XII). These are based upon Mineralogy Unit Reports 186 (Fortey, 1976a), 189 (Fortey, 1976b), 207 (Easterbrook and Fortey, 1977) and 208 (Fortey, 1977). Graphical logs of these boreholes incorporating mineralogical information obtained both from thin sections and from a complete binocular microscope examination of the core are shown in Figs. 22, 23 and 24. The geographical distribution of ore minerals in the boreholes is also shown in Fig. 27.

In the following account each of the principal boreholes is described in turn, and then a general discussion is given.

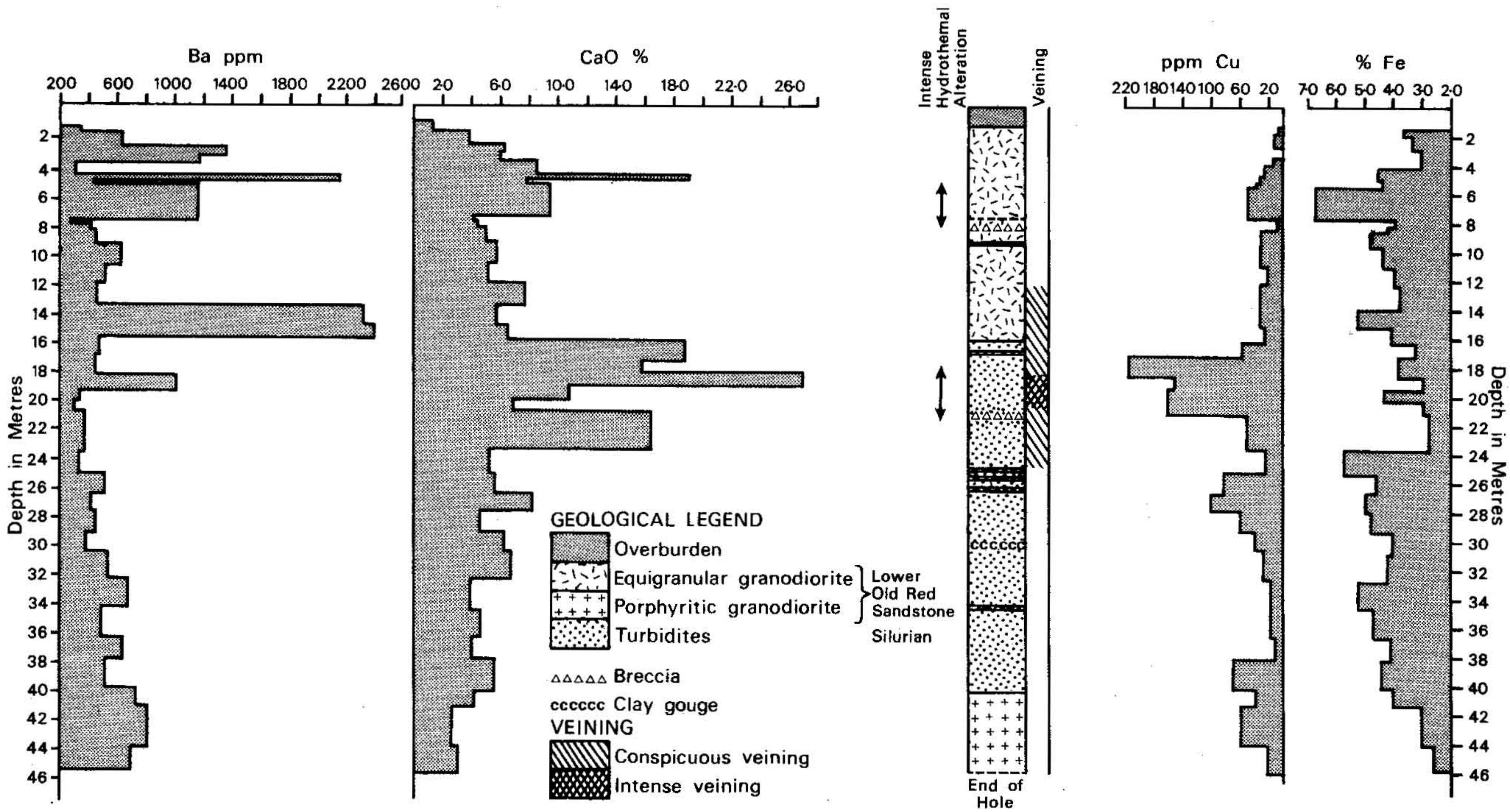


Figure 21 Graphical log of BH 1

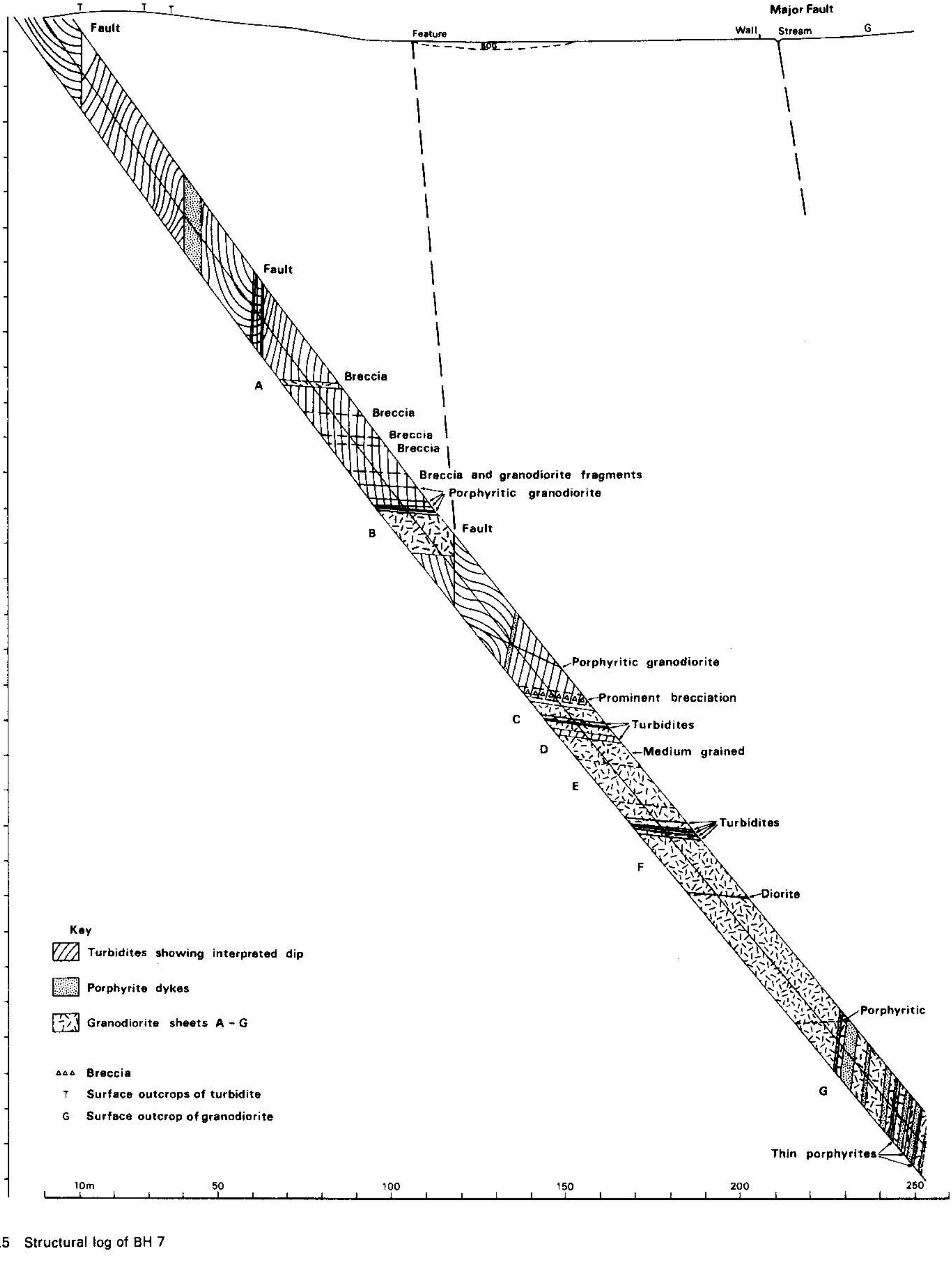


Figure 25 Structural log of BH 7

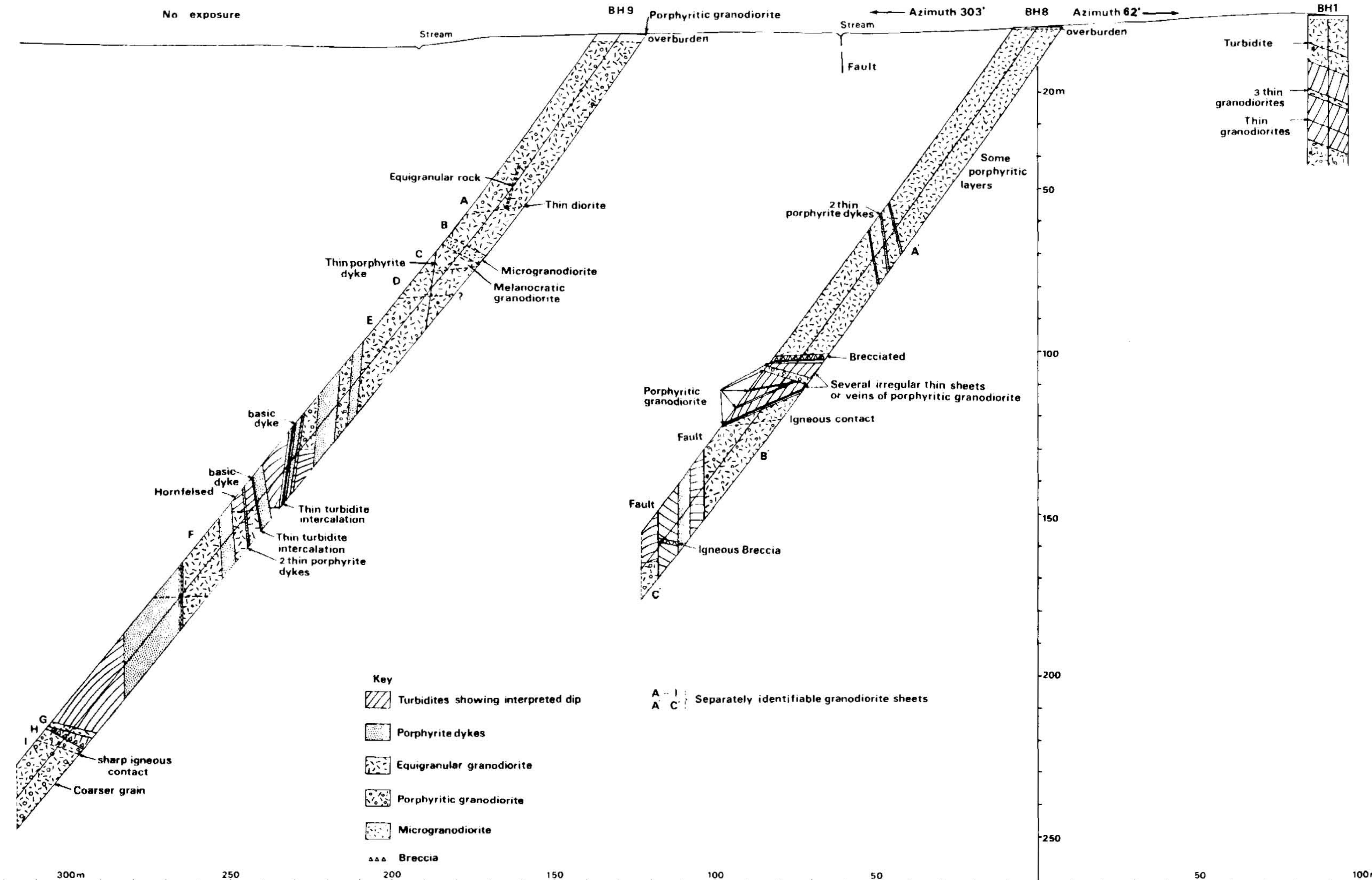


Figure 26 Structural log of BHs 8 and 9

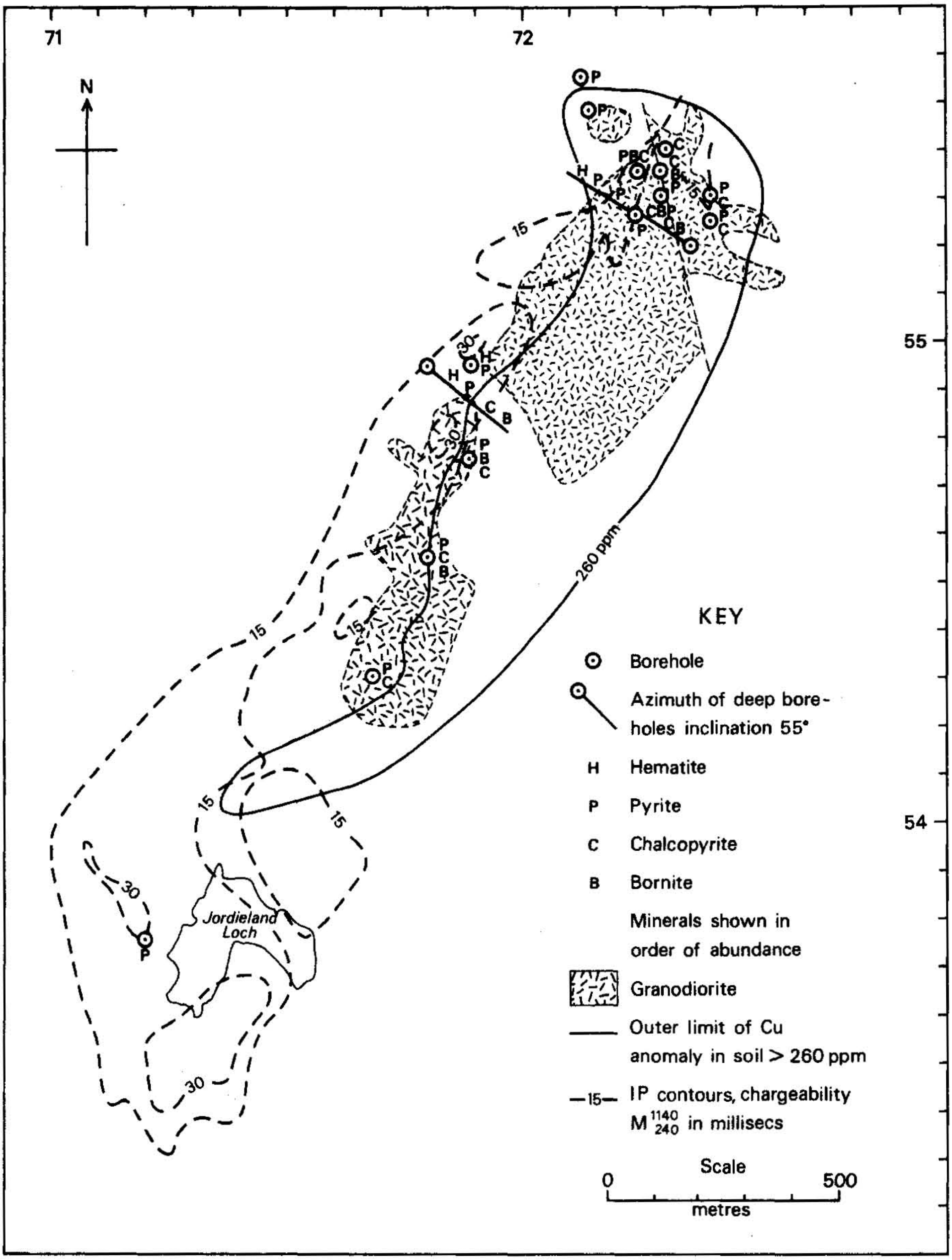


Figure 27 Distribution of minerals in boreholes

Borehole 7

General description

Veins are found in all parts of the drill core, and most appear to have formed during pervasive hydrothermal alteration before the formation of the Jordieland fault. This alteration is extremely variable, and is frequently zoned symmetrically about veinlets. The zonation provides an optical criterion whereby veins developed before, during and after the zoned alteration may be distinguished. In Appendix IV these are denoted by the symbols V0, V1 and V2 respectively. Contemporaneous (V1) veins form the great majority of the veins observed. Post-alteration (V2) veins are widespread but only locally well developed. Pre-alteration (V0) veins appear to be rare. The mineralogy of the veins reflects the overall changes of rock-type and alteration in the core. Where present V0 'veins' are quartz hair veinlets. V1 veins contain a variety of minerals as described below. V2 veins have a more limited mineralogy, but still reflect to some extent the nature of the host rocks.

Despite their frequent occurrence, veins account for only a small proportion by volume of the drill core. Their host rocks consist principally of sediment, porphyritic granodiorite and granodiorite. In the upper 240 m of core, sediments are dominant (Fig. 22) and contain bodies of feldspar-porphyry and some sheets of granodiorite. Below 240 m the core consists of granodiorite containing porphyrite dykes and occasional xenolithic masses of sediment.

The alteration varies from a propylitic type rich in chlorite, amphibole, epidote and calcite in the upper part of the core, to a sericitic type rich in muscovite, dolomite and quartz in the lower parts (Fig. 22). Three other alteration types occur. One is a red calcareous, limonitic type occurring in a zone from 130 m to 165 m down the hole, probably originating by the action of late stage groundwaters moving through brecciated rock. The second is an argillaceous alteration in which kaolinite and dolomite are developed. The third is a propylitic type of alteration rich in chlorite, found in certain dykes of a distinctive phenocryst-poor type of porphyrite encountered in the deepest part of the borehole.

Mineralisation reflects the types of alteration developed (Fig. 22). In the upper propylitic section of the core, pyrite accompanied by minor amounts of chalcopyrite, is developed sporadically. In the lower parts of the core propylitic alteration gives way to sericitic alteration. Pyrite becomes more common and chalcopyrite is still present as a minor constituent, with trace amounts of bornite and molybdenite, and the rock contains minor amounts of arsenic as tennantite as well as arsenopyrite. Between 230 m and 250 m is a zone in which pyrite frequently exceeds 2% by volume, the highest level recorded being about 9%. Below this sulphide levels fall for a short distance to trace amounts. At about 280 m pyrite becomes a minor constituent, but chalcopyrite, bornite and molybdenite become more common.

Sediments

Greywackes and mudstones account for almost all of the sediments. The greywackes are dark grey, medium to coarse-grained rocks in which graded bedding occurs. The mudstones are compact, massive black rocks which in some cases contain bands of lighter coloured material.

Thin (generally 0.5 cm thick) cherty laminae are present in the mudstones, and appear to have acted as impermeable barriers modifying the flow of percolating fluids and so causing localised propylitic alteration.

All the sediments appear to have undergone a low degree of thermal metamorphism prior to alteration. The greywackes are notably hard, and the mudstones are flinty where little altered. Thermal metamorphic minerals are not well developed except for fine-grained biotite in the fresher greywackes and minute white spots of what may be retrogressively sericitised andalusite noted in one specimen.

Granodiorite

The granodiorite is a coarse-grained hypidiomorphic rock in which plagioclase, orthoclase, quartz, apatite, biotite, likely hornblende, and composite magnetite-ilmenite oxide grains are the principal constituents. The mafic silicate constituents tend to be altered, so that the former presence of magmatic hornblende can only be inferred. Primary biotite is preserved in a few specimens. The plagioclase is an intermediate (oligoclase/andesine) type occurring as subhedral laths often displaying simple or complex patterns of growth zoning. Orthoclase is confined to an interstitial and mantling role with respect to the plagioclase. The quartz occurs as irregular interstitial grains whose content varies from less than 2% by volume to about 30%.

Feldspar microgranodiorite (porphyrite)

This rock constitutes almost all the dykes found in the area. In Borehole 7 it is a hypabyssal rock in which phenocrysts of intermediate plagioclase (euhedral laths displaying growth zoning) and a mafic silicate (now replaced) occur in a fine grained rhydo-acitic groundmass. Phenocryst contents vary considerably, but are generally between 20% and 40% by volume. Quartz phenocrysts occur as very minor constituents of some specimens.

In the lowest part of the core (380 m to 408 m) the host granodiorite contains sheets of a porphyry unusually poor in phenocrysts (less than 10% by volume) and it is possible that these represent a distinct phase of intrusion from the more common, phenocryst-rich type.

Propylitic alteration

Where developed in the igneous rocks the propylitic alteration is expressed by chloritisation of primary mafic silicates, alteration of primary oxides to hematite, formation of disseminations of epidote and minor sericitic alteration of plagioclase.

The alteration is however principally seen in the sediments. Here the rocks tend to be chloritised and crossed by veinlets containing calcite and quartz. The alteration is intensified in certain zones, notably those in which lithological irregularities have created local chemical gradients. Such irregularities are often spatially related to cherty layers. Close to these, intense alteration has often produced replacement, metasomatic veins (Fig. 28) containing secondary hornblende, actinolite, epidote, calcite and albite, while the chert layers themselves tend to be slightly recrystallised and given a pink colouration, but not replaced to a significant degree. Dilational veinlets in these zones contain a similarly diverse mineralogy, and have in addition yielded specimens of illitic clay and, in one specimen, tourmaline.

Mineralisation in these rocks occurs in the intensely altered replacement veins and is somewhat more widespread in dilational veinlets. Pyrite and a small amount of chalcopyrite are the sulphide phases. Hematite and other ferric oxide minerals are also common.

Sericitic alteration

Fine grained sericitic alteration is responsible for the bleaching of the sediments and producing a pink colouration in accompanying igneous rocks in the lowest part of the core where sedimentary rocks predominate (170 m to 240 m). Below this the igneous rocks generally possess sericitic alteration in which quartz, dolomite, muscovite and hematite have developed. Locally, zones of an orange rock in which this alteration is intense occur, often centred about dilational quartz-dolomite veins (Fig. 29). More generally, the rocks tend to consist of patches of less altered, sometimes chlorite-bearing greenish rock enclosed in more thoroughly sericitic alteration. Dilational veinlets are common throughout these rocks, and contain quartz accompanied by dolomite or calcite, and in some cases, chlorite, sericite or feldspar.

Mineralisation in these rocks occurs both as disseminations and as developments in veinlets. In general most of the copper-bearing phases occur in the latter situation, while most of the pyrite occurs in disseminations. Molybdenite is confined to minor developments on the margins of veinlets. In the lower parts of the core (below 280 m), in which pyrite is a very minor constituent, chalcopyrite and bornite occur both in veinlets and as disseminations, and a trace of chalcocite was observed.

Argillaceous alteration

Local developments of kaolinitic rock were encountered. Petrographically these appear to be sericitic rocks in which kaolinitic plagioclase alteration has developed. No coherent zone of this alteration is present. It is possible that this "argillic" alteration developed at a later stage than the sericitic and propylitic types.

Paragenesis

Mineralisation developed during pervasive hydrothermal alteration later than the emplacement of the igneous rocks encountered in the borehole. Essential to the alteration was a general fracturing of the host rocks which allowed hot aqueous fluids to permeate the whole mass. Rocks close to these fractures tend to be highly altered, while more remote areas show less developed alteration, in some cases of a lower temperature kind.

The alteration shows an overall zoning, with propylitic assemblages in the upper parts of the core and sericitic in the lower parts (Fig. 22). It is considered that these broad zones developed during one phase of hydrothermal activity and that they reflect variations in wall-rock chemistry, fluid chemistry, and temperature similar to the model for porphyry copper deposits discussed by Hemley and Jones (1964). During this activity virtually all the sulphide minerals and the hematite formed.

Later phases of alteration are represented by minor developments of argillaceous alteration, calcareous limonitic alteration, and possibly by the chloritic (?retrogressive) alteration seen in phenocryst-poor porphyry dykes in the lowermost part of the core. None of these produced significant sulphide mineralisation.

Borehole 8

General description

Most of the rocks encountered in Borehole 8 are granodioritic igneous rocks with rafts of sediment in the lower part.

Veining and hydrothermal alteration occur along the entire length of the core. In the upper 120 m sericitic alteration is dominant, but below this point a chloritic type becomes important and below 180 m is dominant (Fig. 23). Local zones of argillaceous alteration also occur and reddened, limonitic rocks are seen in a few sections. The development of propylitic alteration appears to reflect the change from the rather massive granodiorite of the upper parts of the core (0 to 125 m) to the mixed lithologies including porphyritic microgranodiorite, baked sediments and a body of granodiorite somewhat distinct from that in the upper part (Fig. 23).

As in Borehole 7, the veining can in many cases be divided into sets predating, contemporaneous with and post-dating the alteration: V0, V1 and V2 respectively. V0 veins are usually quartz veinlets, though in one specimen calcareous early veinlets were observed. V1 (contemporaneous with alteration) veinlets contain quartz, calcite and dolomite in the sericitic parts of the core, and in addition contain chlorite in the lower chloritic zone.

Figure 28 Diagrammatic portrayal of propylitic alteration "vein" in Borehole 7

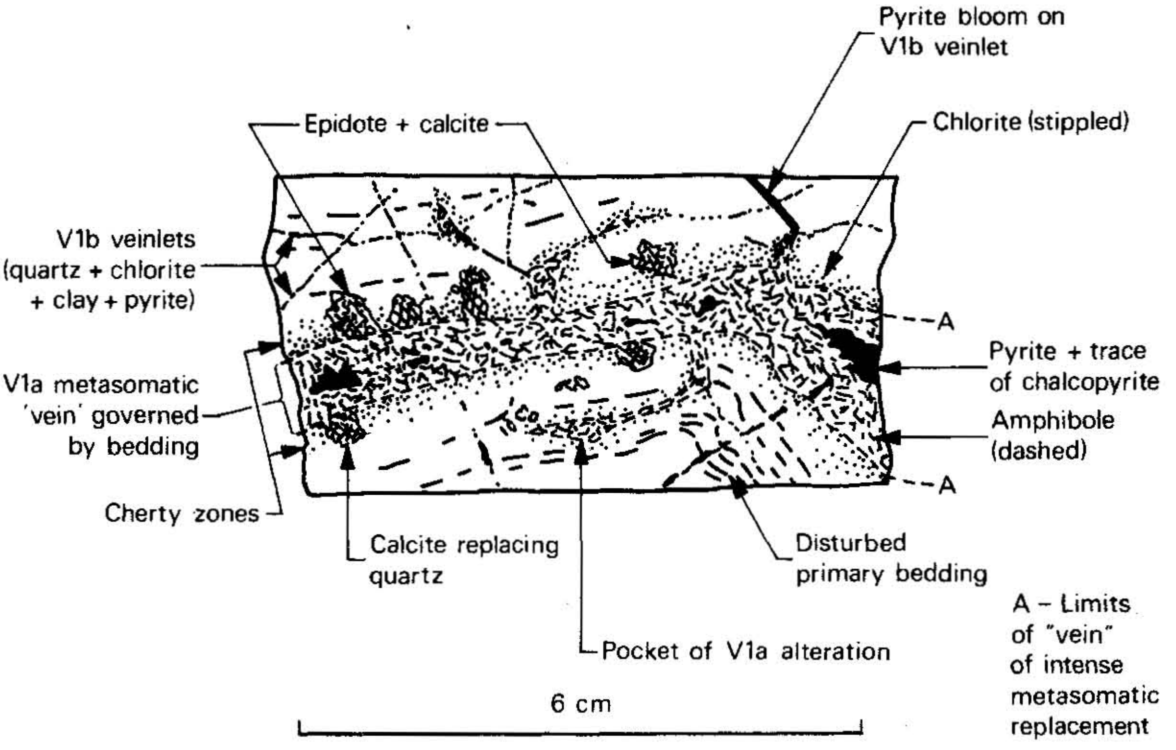
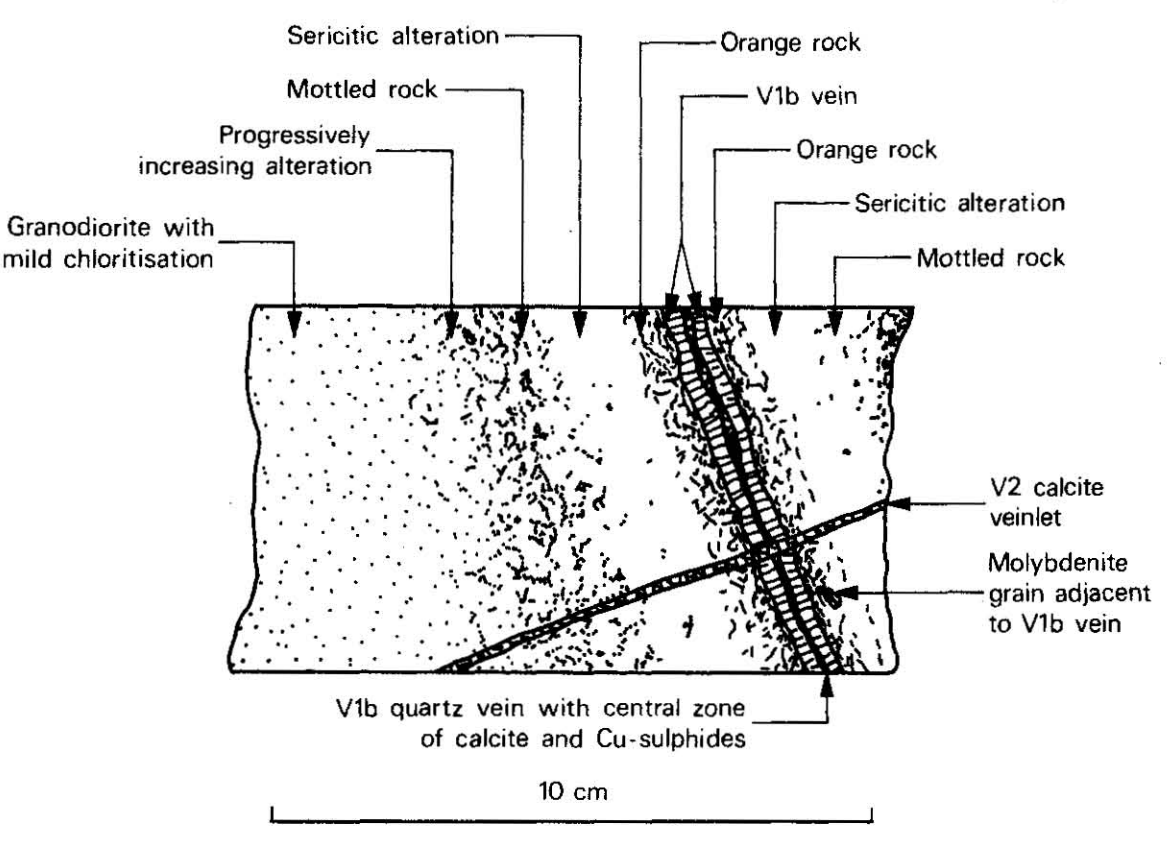


Figure 29 Diagrammatic portrayal of zoned sericitic alteration in Borehole 7



Sulphide mineralisation is developed both in veinlets and as disseminations. The principal minerals involved are pyrite, chalcopyrite and bornite. Other phases reported include chalcocite, enargite, covellite and sphalerite, but not molybdenite. In the sericitic granodiorite of the upper core, levels of mineralisation are very low. Almost all the sulphides occur in the lower parts. The reason for this distribution may be related to the presence of locally marked chemical gradients during alteration of this part of the core, as indicated by the rapid alternation in it of propylitic and sericitic alteration.

Sericitic alteration

In this alteration zone sericite, dolomite, muscovite and hematite have formed and the rocks have a pink colour. In the lower parts of the core this alteration is associated with sulphide mineralisation in which pyrite is accompanied by chalcopyrite and bornite, and in some cases other copper sulphide minerals.

As observed in Borehole 7, sericite alteration tends to be dominant in narrow, discrete zones centred about veinlets. The intervening rocks show lower degrees of alteration and are sometimes chloritic.

Argillaceous alteration

Sporadic developments of argillaceous alteration similar to that described from Borehole 7 occur. Such alteration is well developed in a 6 m zone at about 130 m, where it is enriched in disseminated Cu sulphides (up to 10% by volume). No comparable phenomenon was observed in Borehole 7, but it may be noted that an association between Cu and Mo enrichment and discrete argillaceous zones was reported in drill core from broadly similar mineralisation at Kilmelford, Argyllshire (Ellis et al., 1977).

Propylitic alteration

Propylitic alteration is common in the lower parts of the core, possibly related in part to the presence of country-rocks (as may well be the case in Borehole 7). The minerals formed are chlorite, hornblende, calcite, epidote, albite, sphene and hematite. Altered material is often concentrated into vein-like bands bounded by layers of bleached, welded, cherty rock.

In the propylitic material disseminated pyrite occurs and is accompanied by minor chalcopyrite in veinlets. No other sulphides have been reported.

Borehole 9

General description

This borehole was started approximately above the base of Borehole 8, and was drilled on the same azimuth. It penetrated a varied series of granodioritic, porphyritic-microgranodioritic and dacitic rocks before entering a zone in which masses of sediment are common. Alteration and veining occur in all specimens. The principal types of alteration observed are sericitic, argillaceous and propylitic, but little broad zonal separation of these types was observed, save for a weak tendency for sericitic alteration to be prevalent in the upper parts of the core (Fig. 24).

Pre-alteration (V0) veins were observed in four specimens, and contain quartz, calcite and dolomite. Veins developed with the alteration (V1) are common and contain quartz, calcite and dolomite, together with sericite, kaolinite and chlorite in different parts of the core. Post-alteration (V2) veins are infrequent and tend to contain calcite.

In the upper parts of the core pyrite is frequently developed and is sometimes accompanied by chalcopyrite and bornite and in one specimen arsenopyrite. In the lower parts of the core copper-sulphides are less common and pyrite is frequently the only sulphide observed. In all of the core sulphide developments are sporadic, contents varying from nil to an estimated 4% by volume.

MINERALISATION

Geochemical zonation of mineralisation

Four zones can be recognised in Borehole 7 on the basis of the nature and abundance of the opaque minerals. These are 1) hematite plus minor pyrite, 2) pyrite and hematite plus trace of copper minerals, 3) pyrite plus minor copper mineralisation, and 4) minor pyrite plus several copper minerals. Examination of material from the other boreholes indicates that these zones can be recognised throughout the area in both sedimentary and igneous rocks. The distribution of ore minerals in the Black Stockarton Moor area in order of relative abundance is shown in Fig. 27. The distributions of As, Sb, Cu and Ba, which are shown graphically adjacent to the borehole logs in Figs. 22, 23 and 24, are considered below.

a) Zone 1

The only section of this zone sampled is in the upper 80 m of borehole 7. Copper and molybdenum levels are low, of the order of 40 ppm and 5 ppm respectively. In contrast, arsenic levels are relatively high, around 50 ppm but decreasing to about 30 ppm at the base of the zone. The antimony levels are relatively low, within the range 10-15 ppm except for a few samples. Lead levels of 230 ppm and 270 ppm in two samples suggest the presence of minor galena mineralisation within this zone. The concentration of barium is relatively uniform at around the 400 ppm level.

b) Zone 2

This zone, which can be correlated with

the outer part of the pyrite halo of typical porphyry copper deposits, extends from a depth of about 80 m to about 206 m in borehole 7. Copper mineralisation occurs in the form of minor amounts of chalcopyrite with copper levels usually within the range 80 ppm to 200 ppm though there are isolated sections, where brecciation and tensional fracturing is intense, which assay up to 1000 ppm Cu. Levels of molybdenum reach 35 ppm in the most fractured and brecciated parts of this zone. Arsenic levels are significantly lower than in Zone 1 but concentrations of antimony are broadly similar. Barium concentrations in the turbidites are similar to those in Zone 1 but can be significantly higher, up to 1700 ppm in the igneous rocks. Material with similar mineralogy and metal content was intersected in boreholes 5 and 12 and in much of borehole 9 though in this case amounts of pyrite tend to be lower than in borehole 7.

c) Zone 3

This zone, which has been recognised from a depth of 206 m to 300 m in borehole 7, is characterised by conspicuous pyrite sometimes in amounts up to 10% volume, and by frequent presence of chalcopyrite, in places accompanied by minor amounts of bornite. The amount of pyrite decreases significantly in the lowest 20 m of this zone however. In borehole 7 copper levels are usually within the range 150 ppm to 300 ppm but in isolated sections of highly brecciated rock they are much higher, reaching 3200 ppm. Levels of molybdenum are variable up to 40 ppm but reach 350 ppm in highly brecciated rock. Arsenic and antimony levels are highly variable from a few ppm to maxima of 300 ppm and 180 ppm respectively in highly brecciated rock. Concentrations of barium are highly variable, particularly within the igneous rocks where the maximum level within this zone of borehole 7 is 2300 ppm. Material with similar opaque mineralogy was intersected in boreholes 4, 3, 6 and 10 with average copper levels of 195 ppm, 185 ppm, 410 ppm and 470 ppm respectively and at the very top of borehole 9 and the lower 600 m of borehole 8 where the range in copper contents is similar to that in borehole 7. Molybdenum levels in all these other boreholes are relatively low and only in borehole 6 do arsenic and antimony levels reach 43 ppm and 58 ppm respectively.

d) Zone 4

This zone which is characterised by minor amounts of pyrite and significant amounts of chalcopyrite and bornite together with some chalcopyrite and rare covellite and enargite can be recognised from about 300 m to the base of borehole 7 and in the upper part of borehole 8. In borehole 7 copper levels commonly range from around 200 ppm to 800 ppm but molybdenum reaches only 25 ppm in a few sections. Both arsenic and antimony levels are low, reaching a maximum of 20 ppm and 35 ppm respectively. In borehole 8 copper levels are generally lower than in borehole 7 ranging from 100 ppm to 500 ppm except in one brecciated section containing 700 ppm Cu accompanied by 100 ppm As and 200 ppm Sb

Gold distribution

Although gold determinations were obtained from relatively few samples it is clear that no general positive correlation exists between gold and copper levels. There is some indication that gold shows a positive correlation with antimony and to a lesser extent arsenic as the highest concentration of gold, 0.06 ppm, is associated with relatively high levels of these elements.

Hydrothermal alteration

Three widespread zones of hydrothermal alteration have been recognised in boreholes throughout the area. These comprise 1) an outer propylitic zone characterised by the presence of jasperoid, epidote, chlorite, actinolite and calcite in the turbidites and chlorite and calcite in the igneous rocks, 2) an inner propylitic zone characterised by chlorite, calcite, minor epidote, dolomite and sericite and trace jasperoid and actinolite in the turbidites and chlorite and sericite in the igneous rocks, and 3) a sericitic zone dominated by sericite together with dolomite and calcite, minor chlorite and trace epidote in the turbidites and dolomite and minor chlorite in the igneous rocks. Alternations of different alteration types can occur over short distances but in general one type is dominant in each zone. There is overlap between the alteration and the ore mineral zones but it is apparent that copper minerals occur mainly in the sericitic zone. No trace of a potassic alteration zone has been found in the drill cores except for possible secondary biotite in borehole 10 and at an isolated point in the lower part of borehole 7. Variation in rock chemistry can only be related directly to differences in hydrothermal alteration within the turbidites as these rocks appear relatively uniform in composition on the basis of their titanium contents, which is an element considered relatively immobile during hydrothermal alteration. The composition of the various types of igneous rock is too variable for meaningful comparisons of alteration geochemistry (see Appendix I).

Calcium

Calcium distribution appears complex but there appears to be a tendency for levels to decrease outwards and upwards within the outer propylitic zone in borehole 7 and for concentrations to be generally lower than in sections from the other alteration zones.

Manganese

Manganese shows a clear tendency to increase upwards and outwards within the upper part of borehole 7. A similar relationship was found by Chaffee (1975) within the Kalamazoo porphyry copper deposit. Within the other two alteration zones manganese distribution is irregular but in some sections there is a significant positive correlation with relatively high calcium levels which suggests that minor amounts of manganese are associated with the carbonate minerals.

Iron

Iron distribution appears irregular but there is a tendency for levels to increase within borehole 7 outwards and upwards within the outer propylitic zone. The highest levels of iron encountered occur in sections from the uppermost part of borehole 7 and the lowest part of borehole 9.

Nickel

No association between concentrations of nickel and variations in the nature of the alteration assemblages is apparent from the borehole material.

Zinc

Within the outer propylitic zone intersected in borehole 7 zinc levels increase outwards and upwards. The concentration of zinc in turbidites from the uppermost part of borehole 7 is significantly greater than in all other turbidite samples while the lowest levels tend to occur in rocks from the sericitic alteration zone. This pattern of zinc distribution is similar to that found by Chaffee (op. cit.) within the Kalamazoo porphyry copper deposit.

GENESIS OF MINERALISATION

Introduction

A porphyry deposit has been defined by Lowell and Guilbert (1970) as a copper or molybdenum deposit consisting of disseminated and stockwork veinlet sulphide mineralisation emplaced in various host rocks that have been altered by hydrothermal solutions into roughly concentric zonal patterns. Sillitoe (1973) has also recognised that porphyry copper deposits are normally located in a subvolcanic environment beneath a comagmatic calc-alkaline volcanic pile. Consideration of the geology of the Black Stockarton Moor area indicates that the copper mineralisation was emplaced within a major subvolcanic complex of granodioritic rocks containing both porphyritic and non-porphyritic rock types with the former predominating. Zonation, expressed in terms of ore mineralogy and types of hydrothermal alteration, exists and appears to be roughly coaxial. The above features and other details of the mineralogy and mineralisation style indicates that the Black Stockarton Moor mineralisation can be classified as a porphyry copper style of deposit.

Extent of mineralisation

So far only one segment of the porphyry copper mineralisation has been located definitely, stretching in an arcuate zone for above 6 km from south of Jordieland Loch to south-east of Auchlane. In view of the regular zonal arrangement of alteration and mineralisation at Black Stockarton Moor, which indicates that the centre of magmatic hydrothermal activity lies to the east of the pyrite zone, it is reasonable to suppose that other segments of the mineralised complex probably exist further to the east and south-east of the segment located. Rocks containing disseminated pyrite and exhibiting signs of sericitic alteration have been found near Aireland and Kirkland of Gelston, respectively 1 km and 3 km east of the north-eastern part of the anomalous IP zone. South-east of Jordieland Loch no evidence of significant copper mineralisation was found in a reconnaissance soil traverse from near Little Sypland southwards as far as east of Bombie Glen, but several low-amplitude copper drainage anomalies exist in the area. A zone of anomalous IP response which occurs in the vicinity of White Hill some 15 km to the east of Black Stockarton Moor is clearly related to the pyrite mineralisation there and is the only anomaly so far found which could represent the eastern margin of the pyrite halo. This area, together with mineralisation encountered around Screel Burn and Over Linkins, will be described in a further report. The area potentially enclosed by a pyrite halo would therefore seem to be of the order of 15 km by 10 km, which are also the approximate dimensions of the most intense manifestation of subvolcanic igneous activity within the Black Stockarton Moor complex.

Origin of mineralisation

Detailed isotopic studies of porphyry copper deposits (Sheppard, 1977) have demonstrated that initial ore transportation and alteration processes take place within a magmatic hydrothermal regime by means of highly saline chloride-rich brines which produce low-sulphur sulphide mineralisation within a zone of potassic alteration surrounded by a broad propylitic zone. A convecting meteoric hydrothermal system develops in the surrounding country rocks driven by the magmatic heat energy and this collapses in on the magmatic hydrothermal system during its waning stages. Feldspar and biotite destructive alteration results from the activity of the low to moderate salinity fluids within the convective system. Pyrite is formed by reaction between the two systems and chalcopyrite tends to be concentrated about the interface. The magmatic hydrothermal fluid is thought to be released either by reduction in confining pressure due to ascent of the magma to near surface, producing vesiculation, or by the process of retrograde boiling (Phillips, 1973) due to rapid crystallisation within a restricted temperature range. If this process occurs within a largely consolidated rock, rapid brecciation and tensional fracturing occurs which opens up a large volume of rock for relatively easy penetration by the hydrothermal solutions. Within the Black Stockarton Moor area the presence of amygdaloidal sheet and dyke intrusions, and the occurrence of zones of brecciation and intense tensional fracturing in the country rocks immediately above some of the granodiorite sheet intrusions and the breccia pipes and dykes, provide widespread evidence of the rapid release of magmatic hydrothermal fluids. The distribution of copper in soil within the Black Stockarton Moor area indicates that the copper mineralisation is closely associated with the outcrops of the sheet complexes and therefore probably derived from these centres of magmatic activity.

Comparison with other porphyry copper deposits

The mineralisation at Black Stockarton Moor most nearly resembles deposits in British Columbia when compared with other important regions of porphyry copper mineralisation. These deposits are characterised by relatively low sulphur contents and narrow pyrite haloes and are considered by Guilbert and Lowell (1974) to reflect a comparatively deep environment of deposition. Carson and Jambor (1974) describe several deposits in the Babine Lake area of British Columbia which appear very similar in mineralogy to those at Black Stockarton Moor. Sulphide mineralisation is zoned from a core containing bornite with some chalcopyrite, outwards through a zone (in one deposit) containing chalcopyrite with little or no pyrite; through a zone containing chalcopyrite and pyrite, to a typical pyrite-rich zone; and finally to an outer propylitic zone containing magnetite and hematite. This zonation is identical to that encountered in borehole 7 at Black Stockarton Moor. The widespread occurrence of carbonate minerals, with calcite predominating in an outer zone and siderite and dolomite-ankerite becoming more important towards the ore zone, is a further parallel with the mineralisation at Black Stockarton Moor. Hydrothermal amphibole of the tremolite-actinolite series has also been found in some of the Babine Lake deposits though its distribution appears not to be directly related to that of copper. Actinolite also occurs in a zone outside the biotite zone in the Bingham deposit (Bray, 1969). In this instance it appears to be incompatible with abundant carbonate, which also appears to be the case at Black Stockarton Moor where actinolite is absent from the dolomite-bearing sericitic alteration zone.

Variation in intensity of mineralisation

Both soil and borehole analyses indicate variations in the intensity and extent of copper mineralisation within the Black Stockarton Moor area. The area to the west of the Jordieland fault appears to be more richly mineralised than the area to the east of the fault. Furthermore there is a tendency for mineralisation intensity to increase southwards on the west side of the fault towards the Jordieland fault where the IP anomaly is both wider and more intense than elsewhere within the area. North of Black Stockarton Moor the intensity of the IP anomaly is similar to that on the Moor itself but on the basis of the soil results the amount of copper mineralisation is significantly lower, in spite of the presence of similar sheet intrusions to those further to the south. The main factors which, according to Guilbert and Lowell (1974), influence the copper grade in porphyry copper deposits are the chemistry and volume of the mineralising solutions and variations in the depth of exposure of the complex. Evidence as to the depth of erosion of the Black Stockarton Moor complex relative to other porphyry copper deposits is ambiguous. The age of the mineralisation; the absence of lavas preserved in the area; the relatively thin pyrite halo enclosing a large area of the complex; the presence of bornite-rich mineralisation, and the abundance of detritus from the complex preserved in the Lower Carboniferous sedimentary rocks along the Solway Coast, suggest a relatively deep level of erosion of the complex. However, the presence of sheet intrusions with miarolitic cavities, breccia pipes and vent agglomerates; the rarity of stock-like intrusions, and the insignificant amount of potassic alteration that has been found may indicate that the present erosion surface cuts a relatively high level of the complex. It is also possible that the subvolcanic complex and its associated mineralisation is tilted significantly away from its original configuration. Geological deductions (Leake and Cooper, in prep.) from features such as the overstep of the Carboniferous rocks to the south of the area, the apparent dip of an exposed sheet contact, and the increase in width of D1 dykes in one swarm from north to south would suggest that higher levels of the complex are exposed in the south than in the north. As the intensity of mineralisation increases from north to south it could be argued that much of the mineralisation, particularly in the northern part of the area, has been removed by erosion.

CONCLUSIONS

Detailed geological, geophysical and geochemical investigations over the Black Stockarton Moor area have outlined a zone of disseminated pyrite adjacent to a zone of copper mineralisation. Based on a study of the zonation of the mineralisation and the hydrothermal alteration of rocks within the sub-volcanic complex, the occurrence has been shown to exhibit characteristics of a porphyry-copper deposit.

From the limited deep drilling undertaken, a detailed assessment of the extent and/or grade of the copper mineralisation cannot be made, but geophysical and geochemical investigations outside the area examined by deep drilling indicate that there are further anomalies worthy of investigation.

The main features of the results of the survey are summarised below:-

1. Detailed geological mapping has placed a new interpretation on a complex of minor intrusive rocks which has received little attention in the past. Mapping showed

the occurrence of several intersecting dyke swarms emplaced in three phases of igneous activity and the presence of a series of granodioritic sheet intrusions, granodiorite stocks and breccia pipes. The area is considered to be a sub-volcanic complex with its earliest stage of igneous activity pre-dating the adjacent Criffel-Dalbeattie plutonic magmatism.

2. The gravity survey of the area suggested the occurrence of laminar bodies of granodiorite which was later confirmed by geological mapping and drilling. Induced polarisation work indicated an anomaly around 6 km in length which subsequent drilling showed to be due to a zone of pyrite mineralisation. The highest IP effects have been recorded in the south of the area and correspond with high resistivity.

3. Closely spaced drainage sampling within the area failed to locate any specific source of the mineralisation. Results of the extensive soil sampling programme showed a zone of anomalous copper centred on the granodiorite sheets of Black Stockarton and Culdoach Moors. The anomaly for the most part lies to the east of the IP anomaly with overlap in some areas. Subsequent basal till sampling confirmed the dispersion pattern of copper shown by the soil samples and also indicated an overall increase in concentration levels with depth. The drilling of the three deep inclined boreholes was based on the data given by the IP survey and the results of the geochemical sampling.

4. The three deep boreholes proved zoned alteration and mineralisation reflected in the geochemical and geophysical anomalies. Four zones of metalliferous and three zones of hydrothermal alteration were recognised. These comprise two outer zones of propylitic alteration and an inner zone of sericitic alteration. The highest grades of copper encountered in boreholes, apart from isolated richly mineralised brecciated sections, were between 357 and 391 m in borehole 7 where the weighted mean is 540 ppm and in borehole 10 where it is 470 ppm over 16.7 m. The copper mineralisation in the form of chalcopyrite, with increasing amounts of bornite, covellite and chalcocite with depth, is associated with the sericitic type of alteration. Molybdenum, arsenic and antimony levels are generally low except in sections of highly brecciated rock. Limited determinations of gold content show no positive correlation with copper levels.

5. The observed zonation of propylitic and sericitic alteration within the area resembles many aspects of the classic porphyry-copper model as described by Lowell and Guilbert (1970), although at present only one segment of such porphyry-copper mineralisation has been located. Extensive pyrite mineralisation and isolated occurrences of copper mineralisation occur within the eastern part of the sub-volcanic complex and form the subject of a further report, but further work is necessary to prove whether this or other mineralisation forms a complementary segment to the mineralisation at Black Stockarton Moor.

6. The mineralisation at Black Stockarton Moor closely resembles copper porphyry deposits in British Columbia which are characterised by relatively low sulphur contents and narrow pyrite haloes; but compared with these and other deposits the volume of rock potentially enclosed within a pyrite halo is extensive. The geophysical, geological and surface geochemical evidence suggests that grades of copper higher than those encountered in the boreholes may occur around Jordieland Loch, to the east of the IP anomaly. Further work to establish whether the IP anomaly could be traced further to the south beyond its present limit would be advantageous in view of the tendency for mineralisation intensity to increase southwards in the area.

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APPENDIX I PARTIAL CHEMICAL ANALYSIS OF DRILL CORE AND ROCK

KEY FOR TABLES II-IV

x	-	analysis of 1 sample
$\bar{x}$	-	mean analysis of several samples
D1	-	first phase dykes
D2	-	second phase dykes
P	-	porphyrite
PG	-	porphyritic granodiorite
G	-	granodiorite
MG	-	microgranodiorite

APPENDIX I TABLE II PARTIAL CHEMICAL ANALYSIS OF TURBIDITES FROM BH7

Depth No. Samples	6.20m – 18.95m (6)		18.95m – 67.80m (18)		77.25m – 103.72m (9)		103.72m – 129.08 (11)		130.78m – 174.22m (14)		190.05m – 196.60m (2)		196.60m – 221.60m (10)		224.11m – 244.39m (9)		254.79 – 256.55 m
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	x
CaO%	3.68%	0.64	4.17	0.62	4.54	0.55	3.98	0.83	3.12	1.10	8.77	2.16	5.71	2.34	5.46	2.68	3.71
TiO_2%	0.76%	0.05	0.76	0.04	0.76	0.06	0.76	0.09	0.75	0.08	0.67	0.06	0.76	0.07	0.75	0.17	0.87
Mn ppm	492 ppm	48	475	38	449	37	368	55	283	32	530	155	392	115	569	308	370
Fe_2O_3%	8.64%	0.76	8.04	0.69	7.81	0.52	7.06	1.24	7.51	1.22	6.46	0.41	7.32	1.11	7.67	1.56	5.50
Ni ppm	65 ppm	8	49	12	58	16	55	19	61	11	55	13	65	13	49	11	38
Zn ppm	96 ppm	26	56	19	46	20	33	13	59	18	40	14	37	7	38	17	30
Pb ppm	18 ppm	4	46	75	27	13	19	6	15	5	25	7	14	5	26	19	10

APPENDIX I TABLE II PARTIAL CHEMICAL ANALYSIS OF TURBIDITES FROM BH8

Depth No. Samples	125.17 - 126.91	130.06 - 132.05	136.73 - 138.20	139.35 - 144.58 (2)		175.31 - 182.91 (3)		190.82 - 196.73 (2)		197.74 - 200.19 (2)	
	x	x	x	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
CaO%	4.93	7.11	7.60	7.00	0.69	5.38	0.44	5.35	1.23	5.96	1.35
TiO_2%	0.82	0.70	0.70	0.69	0.02	0.77	0.10	0.84	0.04	6.76	0.10
Mn ppm	380	440	530	490	57	376	46	327	35	330	29
Fe_2O_3%	8.07	6.53	6.04	5.64	0.64	6.75	1.72	7.92	0.78	7.93	1.24
Ni ppm	61	48	45	45	2	47	16	58	7	54	14
Zn ppm	50	40	40	35	7	60	12	57	6	63	15
Pb ppm	20	20	20	20	-	20	-	20	-	23	5

APPENDIX I TABLE II PARTIAL CHEMICAL ANALYSIS OF TURBIDITES FROM BHS 9, 1, 5, 11 AND 12

BH9

Depth No. Samples	169.51 – 173.65 (2)		248.84 – 273.22 (6)		274.62 – 276.92
	$\bar{x}$	σ	$\bar{x}$	σ	x
CaO%	6.06	0.90	5.71	3.03	5.75
TiO_2%	0.73	0.05	0.79	0.13	0.84
Mn ppm	436	38	452	113	350
Fe_2O_3%	7.28	1.85	8.45	1.00	8.09
Ni ppm	49	11	62	10	57
Zn ppm	52	13	70	11	60
Pb ppm	22	4	12	4	10

No. Samples	BHI (16)		BH5 (9)		BH11 (6)		BH12 (6)	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
CaO%	8.31	6.76	6.16	1.06	4.56	1.22	3.67	1.18
TiO_2%	–	–	0.72	0.07	0.77	0.08	0.68	0.07
Mn ppm	614	250	–	–	–	–	–	–
Fe_2O_3%	5.74	1.93	6.54	0.94	7.20	0.94	6.34	1.78
Ni ppm	54	21	56	9	68	9	61	13
Zn ppm	69	38	33	5	33	8	46	11
Pb ppm	12	21	19	3	25	12	–	–

APPENDIX I TABLE III PARTIAL CHEMICAL ANALYSIS OF DYKES BHS 7 AND 8

BH7

Depth m	D2 67.80 – 76.74		D1 101.48 – 103.46	D2 106.30 – 106.65	D1 221.60 – 222.72	D1 371.00 – 376.57	
	$\bar{x}$	σ	x	x	x	$\bar{x}$	σ
CaO%	2.74	0.17	1.95	3.19	2.73	3.72	0.30
TiO_2%	0.46	0.02	0.49	0.50	0.59	0.73	0.01
Mn ppm	243	13	270	310	120	317	23
Fe_2O_3%	4.07	0.14	4.67	4.72	3.73	5.50	0.03
Ni ppm	40	8	35	25	55	79	3
Zn ppm	43	5	30	20	10	43	6
Pb ppm	10	0	10	10	10	20	0

BH8

D1 182.91m – 190.82m	
$\bar{x}$	σ
4.11	0.37
0.67	0.02
293	31
5.25	0.36
26	5
70	10
23	6

APPENDIX I TABLE III PARTIAL CHEMICAL ANALYSIS OF DYKES BHS 9 AND 12

BH9

Depth m	D1 P 98.00 – 98.42	D2 P 149.97 – 154.25	
	x	$\bar{x}$	σ
CaO %	1.71	3.79	0.06
TiO_2 %	0.52	0.57	0.02
Mn ppm	160	320	0
Fe_2O_3 %	4.41	5.30	0.65
Ni	32	45	2
Zn	30	45	7
Pb	10	20	0

BH9

D2? P 162.56 – 166.47		D2 BASIC 166.47 – 167.46	D2? P 167.56 – 169.51	D2? P 178.65 – 182.61
$\bar{x}$	σ	x	x	x
3.77	0.90	9.39	3.07	3.60
0.50	0	1.00	0.49	0.50
270	71	740	240	270
4.29	0.20	8.29	4.10	4.50
23	8	192	16	26
35	7	80	40	30
20	0	30	20	20

BH12

D1 PORPHYRITE 1.75 – 4.02	BASIC	D1 PORPHYRITE 20.14 – 21.78
x	x	x
0.77	3.10	1.67
0.46	0.90	0.47
110	390	130
3.91	7.85	3.77
21	154	20
30	50	30
10	10	10

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF SHEET INTRUSIONS BH7

Depth m	PG 129.14 – 130.80	PG 174.22 – 190.05		PG 244.39 – 254.61		PG 256.70 – 263.76		PG 266.44 – 280.43		PG 280.43 – 292.83		G 292.93 – 307.58		G 307.58 – 359.86		G 362.86 – 370.00		G 376.07 – 379.66		G 382.63 – 388.13	
	x	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
CaO%	5.30	3.96	0.61	2.81	0.36	3.44	0.17	2.46	0.30	2.53	0.58	2.56	0.37	3.06	0.57	3.64	0.31	3.66	0.77	3.19	0.05
TiO_2%	0.46	0.46	0.02	0.57	0.02	0.71	0.01	0.49	0.02	0.60	0.06	0.61	0.03	0.58	0.04	0.62	0.02	0.59	0.02	0.60	0.01
Mn ppm	270	230	59	255	44	327	31	212	29	288	58	240	56	253	42	297	35	305	7	350	14
Fe_2O_3%	4.27	3.39	0.52	3.57	0.30	5.55	0.37	3.52	0.35	4.33	0.73	4.36	0.46	4.44	0.50	5.26	0.27	4.50	0.22	5.14	0.02
Ni ppm	35	20	0	24	1	56	9	13	0.6	28	10	33	4	33	3	46	3	40	4	43	1
Zn ppm	40	18	4	23	5	37	6	24	5	34	5	30	6	38	8	40	0	35	7	45	7
Pb ppm	10	15	6	15	6	13	6	12	4	18	4	20	0	19	4	20	0	20	0	25	7

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF SHEET INTRUSIONS BH8

Depth m	G 4.25 - 26.35		G 26.35 - 38.50		G 38.50 - 71.53		G 71.53 - 125.17		G 126.91 - 127.53	PG 132.05 - 133.92	PG 144.58 - 150.60		PG 152.84 - 175.31		PG 205.41 - 208.00
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	x	x	$\bar{x}$	σ	$\bar{x}$	σ	x
CaO%	3.64	0.34	3.25	0.26	3.50	0.36	3.72	0.81	1.74	3.94	5.47	0.74	3.75	0.87	3.66
TiO_2%	0.52	0.02	0.58	0.02	0.58	0.04	0.54	0.02	0.64	0.61	0.54	0.04	0.58	0.04	0.58
Mn ppm	258	33	225	34	268	29	254	45	200	280	297	59	222	50	140
Fe_2O_3%	4.50	0.40	4.10	0.13	4.46	0.35	4.48	0.40	7.16	4.31	4.29	0.71	4.30	0.21	3.85
Ni ppm	33	2	28	2	33	4	33	4	10	26	24	1	26	4	15
Zn ppm	24	5	30	0	27	5	27	5	40	30	57	38	31	5	30
Pb ppm	21	1	20	0	24	5	22	4	20	20	20	0	20	0	40

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF SHEET INTRUSIONS BH9

Depth m	PG 6.10 – 32.65		PG 42.49 – 57.77		PG 64.90 – 66.70	PG 73.50 – 76.85	MG 81.12 – 82.27	G 86.65 – 89.29	PG 94.70 – 98.00		PG 98.42 – 101.60	PG 101.60 – 126.30	
	x	σ	$\bar{x}$	σ	x	x	x	x	$\bar{x}$	σ	x	$\bar{x}$	σ
CaO%	2.82	0.33	2.85	0.43	3.66	2.42	4.16	3.73	1.67	0.56	1.84	2.37	0.29
TiO_2%	0.72	0.02	0.69	0.05	0.68	0.53	0.43	0.91	0.58	0.03	0.61	0.47	0.02
Mn ppm	277	31	295	61	340	210	300	340	185	35	170	182	40
Fe_2O_3%	5.07	0.31	4.90	0.31	5.52	3.95	4.42	6.80	4.52	0.12	4.36	3.85	0.47
Ni ppm	13	1	10	1	31	27	31	70	21	3	22	17	1
Zn ppm	44	5	43	5	40	40	40	60	35	7	40	23	5
Pb ppm	23	8	15	6	20	20	20	20	20	0	10	18	4

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF SHEET INTRUSIONS BH9

Depth m	PG 155.93 – 157.79	PG 188.90 – 195.00		PG 200.45 – 217.89		PG 220.10 – 220.85	PG 273.22 – 274.62	PG 276.96 – 279.30	PG 282.34 – 288.13	
	x	$\bar{x}$	σ	$\bar{x}$	σ	x	x	x	$\bar{x}$	σ
CaO%	3.13	2.61	0.65	2.60	0.27	3.27	2.89	4.96	3.90	1.56
TiO_2%	0.48	0.50	0.05	0.50	0.01	0.50	0.53	0.72	0.56	0.09
Mn ppm	260	148	23	130	14	130	200	300	250	14
Fe_2O_3%	3.71	3.79	0.29	4.20	0.41	4.06	4.57	5.50	4.12	1.16
Ni ppm	18	17	1	19	1	26	20	70	29	6
Zn ppm	30	22	4	20	0	30	40	50	30	14
Pb ppm	20	8	4	10	0	10	10	10	10	0

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF ROCKS FROM SHEET INTRUSIONS

	BH1						BH2		BH3		BH4		BH6	
Rock Type	Granodiorite		Granodiorite		Porphyritic Granodiorite		Granodiorite		Granodiorite		Porphyritic Granodiorite Pipe?		Porphyritic Granodiorite	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
CaO%	8.40	4.28	4.68	2.60	2.37	1.71	3.47	0.84	2.40	0.29	3.58	0.63	1.97	0.53
TiO_2%	-	-	-	-	-	-	-	-	0.38	0.02	0.88	0.07	0.53	0.02
Mn ppm	325	189	308	158	210	152	-	-	181	19	301	69	160	29
Fe_2O_3%	5.73	1.60	5.19	2.66	3.59	2.54	4.23	0.50	4.58	0.23	6.34	1.06	3.67	0.32
Ni ppm	38	17	41	23	27	18	36	7	42	3	95	20	26	3
Zn ppm	38	8	45	24	35	33	34	5	32	4	43	11	29	6
Pb ppm	3	7	5	5	0	0	15	8	16	5	14	9	11	3

APPENDIX I TABLE IV PARTIAL CHEMICAL ANALYSIS OF ROCKS FROM SHEET INTRUSIONS

Rock Type	Porphyritic Granodiorite		Porphyritic Granodiorite
	$\bar{x}$	σ	x
CaO%	2.24	1.02	2.13
TiO_2%	0.50	0.07	0.44
Mn ppm	140	86	190
Fe_2O_3%	3.53	0.90	4.31
Ni ppm	31	6	39
Zn ppm	25	10	30
Pb ppm	13	5	10
	BH10		BH11

APPENDIX II GEOPHYSICAL INVESTIGATIONS

Introduction

The geophysical investigations of the Black Stockarton Moor area carried out between 1974 and 1977 can be divided into two parts: the structural studies and the detailed investigations. The methods used and the results obtained are described below, with details of interpretation.

Structural geophysical investigations

Gravity survey

To investigate the forms and extent of the granodiorite bodies outcropping in the area, a gravity survey was carried out. In particular, it was hoped to decide on one of three possibilities: (1) that they were all separate, small-scale sheets; (2) that they were outcrops of a single approximately laminar body; or (3) that they were all part of the roof of a large body, perhaps related to the Criffel complex.

A total of 163 observations were made; the majority were along traverses across the Moor, and the remainder at Ordnance Survey benchmarks or spotheights along roads in the area, for regional control. Measurements were made at intervals of about 150 m along the traverses (the exact station positions being chosen to minimise local terrain effects), and the heights of the stations were determined to better than 0.2 m by tacheometric levelling between OS benchmarks. All readings were related to the 1973 National Gravity Reference Net by reference to Buittle FBM. Normal gravity for each station was obtained using the 1967 International Gravity Formula. Bouguer anomalies were calculated in the field, but subsequently checked by computer. Inner zone (A to H) terrain corrections were applied to each station.

For the purposes of elevation correction, a density of 2.73 g cm^{-3} was used for the Lower Palaeozoic sediments. This value was obtained from the literature (Bott and Masson Smith 1960; Kennett, 1960; McLean, 1961; Parslow and Randall, 1973) and agrees well with measurements made by A. Forster of the IGS Engineering Geology Unit on samples from the area (Table V).

From an assessment of the errors associated with the survey techniques and the data reduction, it is believed that the maximum possible error in the Bouguer anomaly is 0.3 mgal, with probable mean error about 0.1 mgal. The minimum significant contour interval was taken as 0.25 mgal.

The regional gravity field over south-west Scotland (Fig. 4) shows the Black Stockarton Moor area surrounded by three major gravitational disturbances. Two of these are lows, identified with the Fleet granite to the north-west (Parslow and Randall, 1973; Allsop, 1975) and the Criffel granodiorite complex to the east (Bott and Masson Smith, 1960; Kennett, 1960). The third feature is a gravity high, peaking over Kirkcudbright Bay, and has no known geological source.

Before an interpretation of the Black Stockarton Moor data was possible, it was necessary to isolate those components of the anomaly which are believed to result from sources outside the area of interest, that is, the observed anomalies had to be resolved into regional and residual components. In the present context, the regional field over Black Stockarton Moor was regarded as a composite of the three major gravity disturbances mentioned above and a SW-NE linear gravity gradient of -0.26 mgal km^{-1} (obtained by examination of long regional profiles).

Existing documented three dimensional models for the Fleet granite (Allsop, 1975) and the Criffel granodiorite complex (Kennett, 1960) were used to calculate the effects of these bodies on the gravity field at Black Stockarton Moor. These components were combined with the linear regional field, and the result subtracted from the observed Bouguer anomalies over the Moor. The 'high' in Kirkcudbright Bay has not been modelled, so the effects of this remain as a NNE-SSW gradient on the residual Bouguer anomaly map (Fig. 5). Because of this, and the relatively small magnitude of the residual anomalies over the Black Stockarton area granodiorites, no quantitative conclusions are drawn, from the gravity data.

A weak low, about 4 km long, and arcuate in form, can be seen following the line of outcropping granodiorites from Culdoach Hill to Lochdongan Moor and beyond. This is clearly related to the intrusions along this line, and the granodiorites in particular. Density measurements given in Table V show that the granodiorites are on average 0.06 g cm^{-3} less dense than the surrounding sediments. A number of contour closures occur within this main low. They are barely significant, but could indicate thicker parts of the granodiorites.

To the south and west this low is bounded by relatively steep gravity gradients, indicating abrupt cut off of the intrusions at these margins, due to faulting or to steeply dipping contacts. There are indications that the low extends south between Culdoach Hill and Knockskelly Hill, which probably reflects the intrusions displaced sinistrally across the Jordieland fault. Alternatively, this could be due to the thicker overburden present in parts of this area - absence of data from the south-west corner precludes a more definite interpretation.

To the east, the gravity gradient away from the low is gentle, indicating that the granodiorites either dip gently away or thin gradually in this direction. Similar gentle gradients are seen in the north, but these are due in part at least to the decreasing influence of the Kirkcudbright Bay gravity high. A limb of the low extends almost unattenuated between Milnthird Hill and Ben Tudor, reflecting the east-west dykes of the second intrusive phase, which in places make up 55% by volume of the rock.

APPENDIX II TABLE V Density determinations

a. Determinations by Forster (1976) on rocks of the Black Stockarton area.

SAMPLE	ROCK	SATD. DENSITY $g\ cm^{-3}$	SAMPLE	ROCK	SATD. DENSITY $g\ cm^{-3}$
1	granodiorite	2.73	23	granodiorite	2.62
2	"	2.69	24	"	2.68
3	"	2.68	25	"	2.63
4	"	2.70	26	"	2.66
5	"	2.61	27	"	2.66
6	"	2.69	28	"	2.68
7	"	2.66	29	"	2.67
8	"	2.66	30	"	2.67
9	"	2.66	31	"	2.64
10	"	2.68	32	"	2.68
11	"	2.64	33	"	2.57
12	"	2.66	34	"	2.70
13	"	2.71	BH1/3	"	2.58
14	"	2.69	BH1/37	"	2.67
15	"	2.67	BH1/86	"	2.70
16	"	2.69	BH1/103	"	2.64
17	"	2.68	BH1/106	"	2.71
18	"	2.68	BH1/107	"	2.71
19	"	2.71	BH1/161	"	2.68
20	"	2.68	BH1/208	greywacke	2.74
21	"	2.59	BH1/210	"	2.70
22	"	2.66	BH1/231	granodiorite	2.70

Average value for granodiorite 2.67 $\pm$ 0.01 g cm^{-1} (range 2.57 - 2.74)
Average value for sediments 2.72 g cm^{-1}

b. Determinations by other authors of greywacke densities.

Bott and Masson Smith (1960) : 2.73 g cm^{-3}

McLean (1961) : 2.72 g cm^{-3}

Kennett (1960) : 2.73 g cm^{-3}

Parslow and Randall (1973) : 2.73 g cm^{-3}

The small granodiorite bodies in the east of the areas, such as those at The Fell and Weather Hill, are not reflected in the gravity pattern. They are slightly more basic than the western granodiorites, on petrographic evidence, and could have a similar density to the greywackes. Alternatively they might be so small that they are unresolved by the gravity survey.

Magnetic surveys

Two sources of magnetic data were available in the Black Stockarton area: the preexisting aeromagnetic survey, and surface measurements made along the 1975 gravity traverse lines. Interpretation of these data was attempted to complement the gravity work described above.

The 1000 ft (mean terrain clearance) aeromagnetic survey, flown in 1959 as part of the national aeromagnetic survey, shows an approximately rectangular high centred over southern Black Stockarton Moor (Fig. 6). Three flightlines cross the area of interest. Attempts to interpret the data were hindered by four main factors: the variability of magnetic susceptibility within the granodiorite (as indicated by the detailed magnetic surveys discussed below); the proximity of strongly magnetic parts of the Criffel complex; the possibility that the hydrothermal alteration may have introduced magnetic minerals into sediments and intrusions alike, and the presence in the area of numerous dykes of varying magnetic properties. The influence of these dykes can be clearly seen on the contour map: the anomaly is elongated along the main WNE-ESE dyke set, and bulges northwards in the west, where these dykes bend round to head NNE. The magnetic nature of these dykes is also seen from the surface measurements (both on the long traverses and on the detailed grid discussed below). However, the main part of the aeromagnetic anomaly occurs over granodiorite, so an interpretation was made assuming granodiorite to be its sole cause. An iterative computer program (Lee and Johnson, 1975) was used to give two-dimensional interpretations of flightline profiles 139 and 140. A susceptibility of 1.8×10^{-2} SI units was used, as being typical of similar rocks in other areas. Later direct measurements on samples from Black Stockarton Moor (using an ABEM Kappameter) show a considerable range of values. The bulk value probably lies between 0.6 and 1.8×10^{-2} SI units.

For FL139, a lensoid body, about 5 or 6 km from north to south was indicated, with its maximum thickness of about 0.3 km beneath the southern part of Black Stockarton Moor. To the south, the margin of the intrusion is steeply dipping, but to the north the body thins more gradually. A body of similar size or slightly smaller, but more deeply buried, is indicated by the profile of FL140. Certain of the assumptions made (absence of contributions from dykes and alteration of sediments) have probably resulted in this model being rather larger than the true intrusion; on the other hand, the use of a susceptibility which is probably too great would tend to counteract this. In either case, the interpreted shape is likely to be broadly correct, and is in agreement with the indications provided by the gravity survey.

Profiles of the total magnetic field measurements made along ground traverses show both short wavelength anomalies, usually corresponding to dykes, and broader features. On some profiles it was possible subjectively to remove effects thought to be due to dykes, and a quantitative interpretation was made of one such profile running east-west across southern Black Stockarton Moor. A non-iterative computer program (Lee and Johnson, 1975) was used, the shape of a polygonal model being adjusted by the operator. Again, the interpretation is not presented here in detail, because of the uncertainties discussed above. The body indicated is about 150 m thick, dipping at a low angle beneath the greywackes to the east. It thins towards the west, but on the west side of this fault it forms a wedge-shaped block, with maximum thickness about 150 m. The thicknesses assume a susceptibility of 1.8×10^{-2} SI units, but as explained above, this is at the upper limit of the likely range, so the true thickness could be greater than 150 m, up to about 400 m.

Thus, both gravity and magnetic structural investigations are in broad agreement, despite the difficulties of interpretation, showing the granodiorites to be in the form of a sheet, probably between 150 and 400 m average thickness, dipping away at a shallow angle to the east, but truncated quite sharply to the south and west.

Detailed geophysical investigations

Resistivity and induced polarisation (IP) surveys

The aims of these surveys were to find and trace sulphide mineralisation and to show its relationship with the geology. The surveys tended to proceed on an ad hoc basis, since the nature and scale of the target was at first unknown.

Three techniques were used: an initial reconnaissance survey in the frequency domain with the gradient array; variable separation dipole-dipole surveys in the time domain to investigate structures in areas of interest; and constant separation dipole-dipole array reconnaissance profiling, also in the time domain. The frequency effect measurements were made between 0.1 and 3 Hz, while in the time domain chargeabilities were calculated over the interval from 240 to 1140 ms after switchoff of a 2s primary pulse. All dipole-dipole array measurements were made using a dipole length of 30 m. Traverse lines were at 100 m separation, and certain lines were extended to investigate the ground to the east of the main survey area.

Fig. 8 is a contour map of apparent

resistivity, combining the gradient array results with those from the dipole-dipole survey obtained with a dipole centre to centre separation of 120 m.

The range of values measured is large, from 100 to 12000 ohm metres, although values are generally between 400 and 3000 ohm metres. The higher and better drained ground tends to show higher resistivities than the lower, often boggy areas. It is not generally possible to differentiate rock types from the resistivity map. Many of the clearest features are narrow linear lows, which almost all correspond to mapped faults. These depressed resistivities are likely to be due to permeable fractures and probable weathering along the fault zones, but low-lying boggy ground often occurs along faults in this area, and this undoubtedly contributes. There is no evidence from the IP results discussed below that sulphide mineralisation is developed along the faults.

Apart from the lows due to faulting, the following main features can be seen on the map, from north to south. In the northernmost part of the survey area, resistivities between 1000 and 5000 ohm metres correspond to an area of dense dyke intrusion. To the west, these dykes abut onto the eastern edge of the mapped granodiorite, and a pronounced band of high resistivities (5000 to 11000 ohm metres) occurs at the margin. From an examination of the point values, this band appears to run southwards past the volcanic vent at Penan Hill, where it is coincident with a dyke. However, in the south it is associated with a strong magnetic anomaly, whereas further north this is not the case, so it could be that the apparent continuity of the resistivity feature is merely fortuitous. Alternatively, intrusion of a dyke along this line could have been preceded or followed by intrusion of a more magnetic dyke along part of the line. Since the line marks the eastern end of the granodiorite at Lochdougan Moor, it is possibly of some structural importance.

From this high resistivity band, southwards and westwards to Jordieland Loch, the area is extensively crossed by the fault controlled linear lows discussed above, of which the main examples are along the Netherthird and associated faults. Outside these bands, values are generally in the range 700 - 2500, with no apparent contrast between the sediments and intrusions. There is no expression on the resistivity map of the discontinuity deduced from geochemical evidence to lie between Black Stockarton Moor and Milnthird Hill, or of the lineation seen on satellite photos which may be coincident with it.

In the area around Jordieland Loch, values of resistivity rise to over 10000 ohm metres, suggesting either a different rock type, or a different degree of hydrothermal alteration in this zone. Neither has been recognised during the geological mapping, however. In the extreme south of the survey area, values again fall within the range 700 to 2500 ohm metres, except along the line of the Netherthird fault, where lower values were obtained.

The chargeabilities measured in the Black Stockarton Moor area are almost all in the range 3 to 70 milliseconds. The majority lie between 4 and 25 ms, with a background of about 7 ms. The small number of values less than 3 ms or more than 70 ms all occur where artificial sources, such as rabbit fences, and a water pipeline, are the probable causes.

Fig. 7 is a contour map of induced polarisation (I.P.) effect, combining the chargeability measured in the time domain with the percent frequency effect measured in the frequency domain. The main feature is an IP high, almost 6 km long, with values typically from two to five times background. In form, the anomaly is slightly arcuate, with a change in bearing over its length of about 60°. The anomalous zone is irregular in both width and magnitude, the width varying from 100 m to about 700 m. Over its whole length, it lies approximately along the strike of the greywackes, suggesting a stratabound source. In evidence against this, however, the anomaly locally occurs over granodiorite. Borehole evidence also suggests that sediments and intrusions alike are mineralised, mainly with pyrite, along the line of the anomaly. For much of its length, the I.P. high occurs over one or other margin of the granodiorites. Offsets due to faulting can be seen. The axis of the anomaly is subparallel to, and 300 to 500 m west of, the geochemical copper anomaly, except around Jordieland Loch where the two coincide. It is in this area that the anomaly reaches its maximum amplitude and width, with a zone 700 m across containing chargeability values up to 70 ms. There is correspondence between high chargeability and high resistivity in this area.

The southern part of the anomaly is apparently faulted out, to the east by the Netherthird fault and to the south by an east-west fault. No offset continuation could be found nearby; if one exists it is expected on structural evidence to occur about 1 km south of Jordieland farm. The contours also close around the northern end of the anomaly, but here no fault has been mapped. Again, attempts to find a possible continuation revealed nothing.

From Black Stockarton Moor southwards to Jordieland Farm, some indications of the structure of the anomaly are available from the pseudosections plotted from expanding dipole-dipole array data. It would be unwise to use model studies to provide quantitative interpretations, since drilling has shown that the boundaries of the mineralisation are gradational. However, Table VI contains brief descriptions of the anomaly on each traverse, and any conclusions drawn.

Magnetic survey

To complement the IP survey, magnetic measurements were made on a rectangular grid between the IP traverse lines. Over most of the area the grid intervals were 30 m east to west, and 20 m north to south, but in some parts 25 x 25 m or 15 x 25 m intervals were used and in others readings were taken at 15 m intervals along the traverse lines only. All readings were corrected for diurnal variations, and reduced relative to a single datum.

APPENDIX II TABLE VI Induced polarisation anomalies on expanding dipole-dipole array pseudosections.

LINE	I.P. ANOMALY FORM AND INTERPRETATION (IF ANY)
300S	Minor high 375-210E.
400S	High 150-240E at depth. Probable overburden masking.
500S	Broad high 180E-90W, values increase with depth. Highest section centred on 15E; dip to W indicated, or cut off to E.
600S	Weak high at depth, 00-100W.
700S	High 60E-150W, centred on 60W. Steep dip to W indicated.
800S	Strong high, 60-240W, centred on ~140W. Complex form with strong surface effects.
900S	Strong high 120W-300W+, centred on 225W. Strong surface effects.
1000S	High 240-180W confused by very deep bog.
1100S	Diffuse high 210-400W, centre ~ 270W. Dip to W <u>or</u> cutoff to E indicated.
1200S	Weak high 420W-540W. Cutoff to E or dip to W.
1300S	Strong high 300-530W, probably at surface ~ 420W. No indication of dip etc.
1400S	Fairly strong high 570-680, probably outcrops ~ 630W. Dip to W or cutoff to E of anomalous area.
1500S	Broad high at depth, 480-750W, poorly defined in W due to plantation.
1600S	Broad high 500-700W+, undefined W margin due to plantation. Maximum near W. end, E. end diffuse.
1700S	Very broad high, 360-960W, maxima at 430-540W and 850-920W. May be cutoff to W.
1800S	Very broad high 360-960W, 2 maxima: 390-480W and 870-930W. Cutoff to W. not sharp. Outcrop probably 420-500W.
1900S	Very high, 780-960W. Undefined at E end due to Loch. Max value 69 ms here, possible dip to E?
2000S	Fairly strong anomaly 840-930W. Undefined to E due to Loch. No indications of shape.
2100S	Broad strong high, 540-810W but undefined to W due to woods. Max at 600W, cutoff to E indicated.
2200S	Strong high 600W-780W, undefined in W due to wood. Max at 675W, cutoff to E indicated.
2300S	Strong high, 600-850W, max at or near surface ~ 810. Confused picture.
2400S	Slight high ~ 750W.
2500S	Very slight feature ~ 650W.
2600S	No anomaly seen.
2700S	No anomaly seen.
2800S	Strong local feature at ~ 675W probably due to buildings etc.
2900S	No anomaly seen.
3000S	No anomaly seen.

Fig. 9 is the contour map of total magnetic field, plus 48000 nT. Most readings lay in the range 48700 to 49200 nT. Working from north to south the following major features can be seen.

In the far north of the survey area, a broad smooth high approximately follows the IP anomaly along the south-east edge of the granodiorite, with a peak along the margin of the intrusion. This suggests that the intrusion dips south-eastwards beneath the greywackes at a very low angle. South of Lochdougan Moor, the high broadens out and is crossed by large numbers of short wavelength linear anomalies, up to 500 nT in amplitude. Most of these can be attributed to the numerous NW-SE dykes in this area, but some anomalies have a different orientation, approximately parallel to the granodiorite suboutcrop, and could be due to susceptibility variations through the thickness of the granodiorite sheet. Running southwards from Lochdougan Moor, past the volcanic vent at Pennan Hill, a pronounced linear anomaly coincides with parts of the linear resistivity high described above. Possible causes of this feature have already been discussed.

The area immediately north of Black Stockarton Moor is crossed from ESE to WNW by strong linear anomalies corresponding to dykes. In the area of the Black Stockarton Moor granodiorite suboutcrop however, there are very few dyke-like anomalies, indicating that few, if any, dykes are intruded into the granodiorite. Along the southern margin of the granodiorite lies a pronounced but irregular high. Quantitative interpretation of this as part of the structural investigations described above has shown that the intrusion again dips away eastwards at a low angle.

Between Culdoach Hill and Jordieland Loch, the map is dominated by a dense swarm of ESE-WNW trending dyke anomalies. There is a distinct eastern limit to these, which coincides with the east limit of the IP anomaly in this area, and suggests the presence of a major north-south fault. The Netherthird fault as mapped lies about 100 m east of this however, and its position is confirmed by the position of the main linear resistivity low. It seems likely, therefore, that a splay or parallel fault exists. Such a fault has been recognised from geological borehole and resistivity evidence further north, and is indicated in the south by a linear resistivity low just east of Jordieland Farm.

At the south-west edge of Jordieland Loch is a large (600 nT) anomaly which does not have the same ESE-WNW orientation as the dykes in this vicinity. It is therefore possibly due to a geological body which has not yet been recognised. In the area south of Jordieland Loch, the magnetic field map is almost featureless, with only a few minor linear anomalies due to dykes.

Other detailed surveys

Two electromagnetic (EM) methods, Slingram and very low frequency (VLF-EM), were tried, but neither was used extensively. Neither method responded to the mineralisation shown by the IP survey, confirming that disseminated rather than massive mineralisation is responsible.

APPENDIX III GEOCHEMICAL INVESTIGATIONS

Drainage sampling, collection and analysis

Following the initial reconnaissance drainage sampling of the Criffel-Dalbeattie area further stream sediments, panned concentrates and a limited number of water samples were collected during follow-up investigations in an attempt to localise the source of copper.

Stream sediments

At all sites sediment samples were collected by the method described by Plant (1971) except that a minimum of water was used in the sieving process in order that the finer material was not lost. The wet sediments were then oven dried and sieved to minus 100 B.S.I. mesh (-150 μm) as this has been shown by Plant (op cit) to exhibit the best geochemical contrast in upland areas of Scotland. The sediments were analysed for a wide variety of elements by the Jarrell Ash. Mo and Sn were determined by optical emission spectroscopy (OES), Zn by atomic absorption spectrography (AAS) and U by delayed neutron activation (DNA). Only Cu has been plotted for the purpose of this report the distribution of the other elements in the area having previously been described (Leake et al., 1978).

Heavy mineral concentrates

Where enough material was available at site around 2-3 kgs of sediment was collected as described above and panned down by the classical gold panning technique to constant volume, producing on average 20-30 g. of concentrate. This material was prepared for analysis by the method described by Leake and Aucott (1973). As with the sediments only Cu has been plotted the others appearing on single element maps in the above mentioned report.

Water sampling

Seepages and a limited number of streams in the main mineralised area were sampled at a later stage in the programme in an attempt to explain the lack of Cu dispersion in the drainage samples. The water was collected in 30 ml bottles and later acidified with 0.5 g of ascorbic acid to prevent absorption of trace elements onto the bottle plastic. After pH and conductivity measurements were taken the samples were analysed for Cu only by AAS.

Soil sampling, collection and analysis

Soil samples were collected over and within the environs of the mapped exposures of granodiorite. The sample interval was based on a 50 m by 50 m grid closed to 50 m by 25 m over the granodiorites. The sampling interval was chosen after initial close spaced orientation soil collection over a selected part of undisturbed moorland. A total of 2267 soil samples were collected.

Samples were taken with a hand auger, after first digging a pit to remove the surface organic layer, to a depth of around 1 m. Over moorland the development of a B horizon was rarely observed hence most samples were recorded as being C horizon material. The colours of the soils were mainly dependant on the concentration of iron and the degree of saturation. The samples collected were mainly classified as clays with varying amounts of silt. All samples contained angular fragments of varying size which usually appeared to be locally derived.

The soils were collected in Kraft paper bags and then placed on racks in a field laboratory to dry. They were then crushed in a mortar and sieved to -80 mesh (BSI) a 15 g split being taken for despatch for analysis.

Analysis for copper, lead and zinc was carried out by atomic absorption spectrography after attack by hot nitric acid.

Basal till sampling

Samples of basal till were collected over areas of deep overburden and where high concentrations of copper in soil were delineated. Sampling was undertaken using a mechanical 'Minuteman' auger powered by a 7-hp motor driving 75 mm diameter flights attached to a tungsten-carbide mining bit. The machine can easily be converted to be used as a diamond drill to produce core from shallow depths by the addition of a pressurised water supply, drill rods and a diamond bit. The auger was mounted on the rear of a Land-Rover, or, where the ground was very soft, a Steyer-Puch Hafflinger cross-country vehicle. An average depth of 1.66 m with a range from 0.1 m to 7.3 m was achieved over the area sampled. Most of the work was undertaken by contract, the remainder by an IGS crew.

Notes of depth, colour and texture were recorded on site. The samples were oven dried then sieved and split with 15 g of the 100 mesh BSI fraction -150 μm being retained for analysis. The -150 μm fraction was chosen as this has been shown from previous experience to give the best contrast between mineralised and non-mineralised areas in an upland environment. The 15 g of sample was then ground and sub-sampled using a riffle splitter. Copper, lead and zinc were then determined by atomic absorption spectrography after extraction of the metals from 0.5 g of the sample by hot nitric acid.

Rock and drill core sampling and analysis

The core from all boreholes was split and either a quarter or half split sample taken, according to the diameter of core, at pre-determined intervals based on lithology. After passing through a jaw crusher the material was then ground to < 300 mesh BSI using a Tema mill with elvacite binder added to samples for XRF analysis.

Cu, Pb, Zn, Co, Ni and Ag were determined by Atomic Absorption spectrography. Ba, Sb, Ca, Ni, Fe, Mn, Ti, As and Mo were determined by XRF analysis. The few Au analyses that were carried out were by the neutron activation method.

Presentation of geochemical data

Data from drainage, soil and till surveys has been presented by the method of class interval representation for Cu, Pb and Zn (Figs. 10 - 12, 13 and 14 and 15 - 17). Class intervals are based on breaks in slope of the cumulative frequency plot and the mean plus standard deviation of the upper population using the graphical method described by Lepeltier (1969).

Cumulative frequency plots have been constructed for Cu in soil (Fig. 30), Pb in soil (Fig. 31), Cu in basal till (Fig. 32) and Pb in basal till (Fig. 33), all of which show a lognormal distribution. Zn (Fig. 34) shows a normal arithmetic distribution and a histogram has been plotted. In the case of the soil data the total data set has been divided into two based on geology and superficial cover, the results of which are shown in Table VII. Summary statistics for 235 basal till samples are shown in Table VIII and summary statistics comparing Cu, Pb and Zn levels in basal tills and sub-surface soils are shown in Table IX.

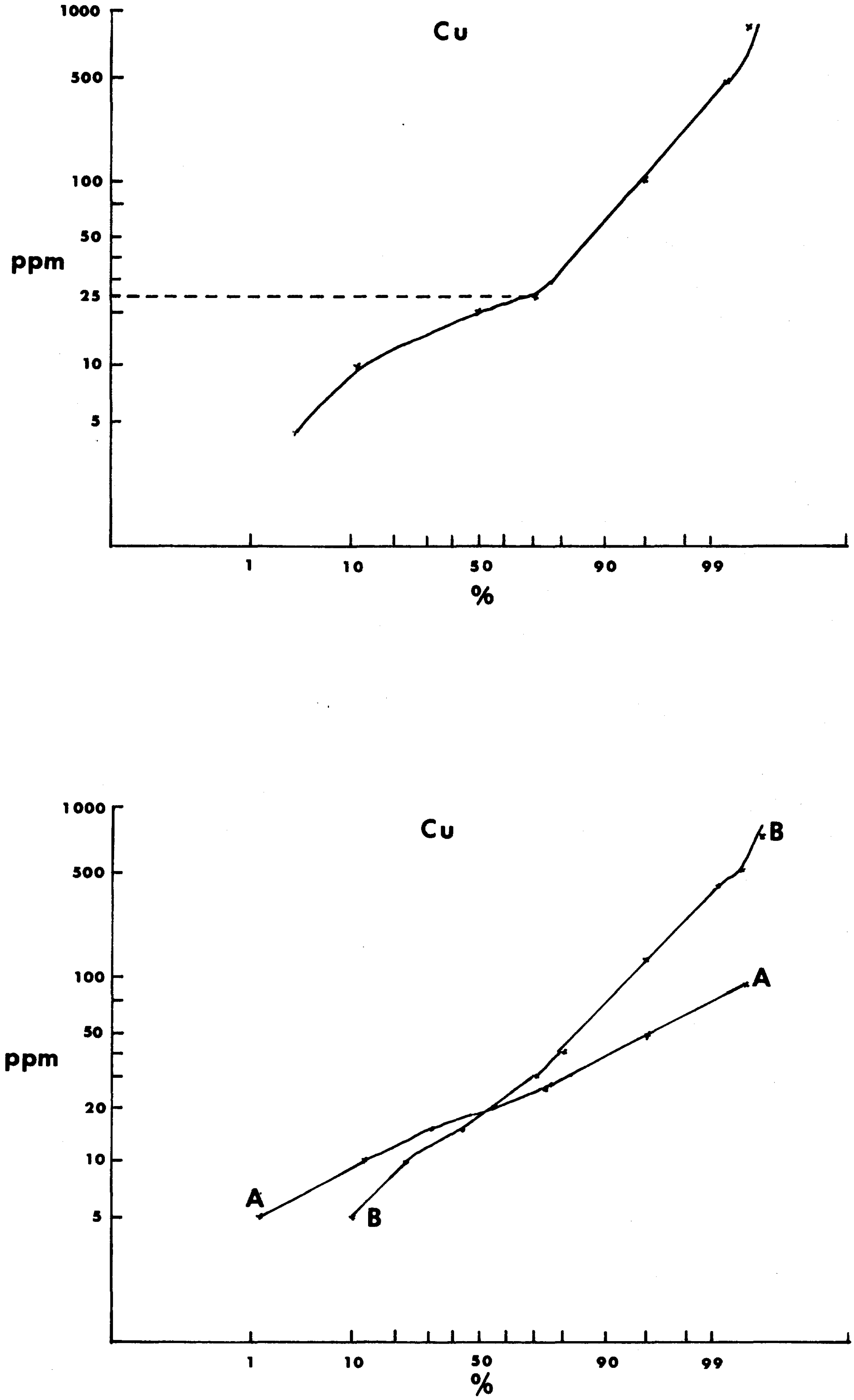


Figure 30 Cumulative frequency plot for copper in soil

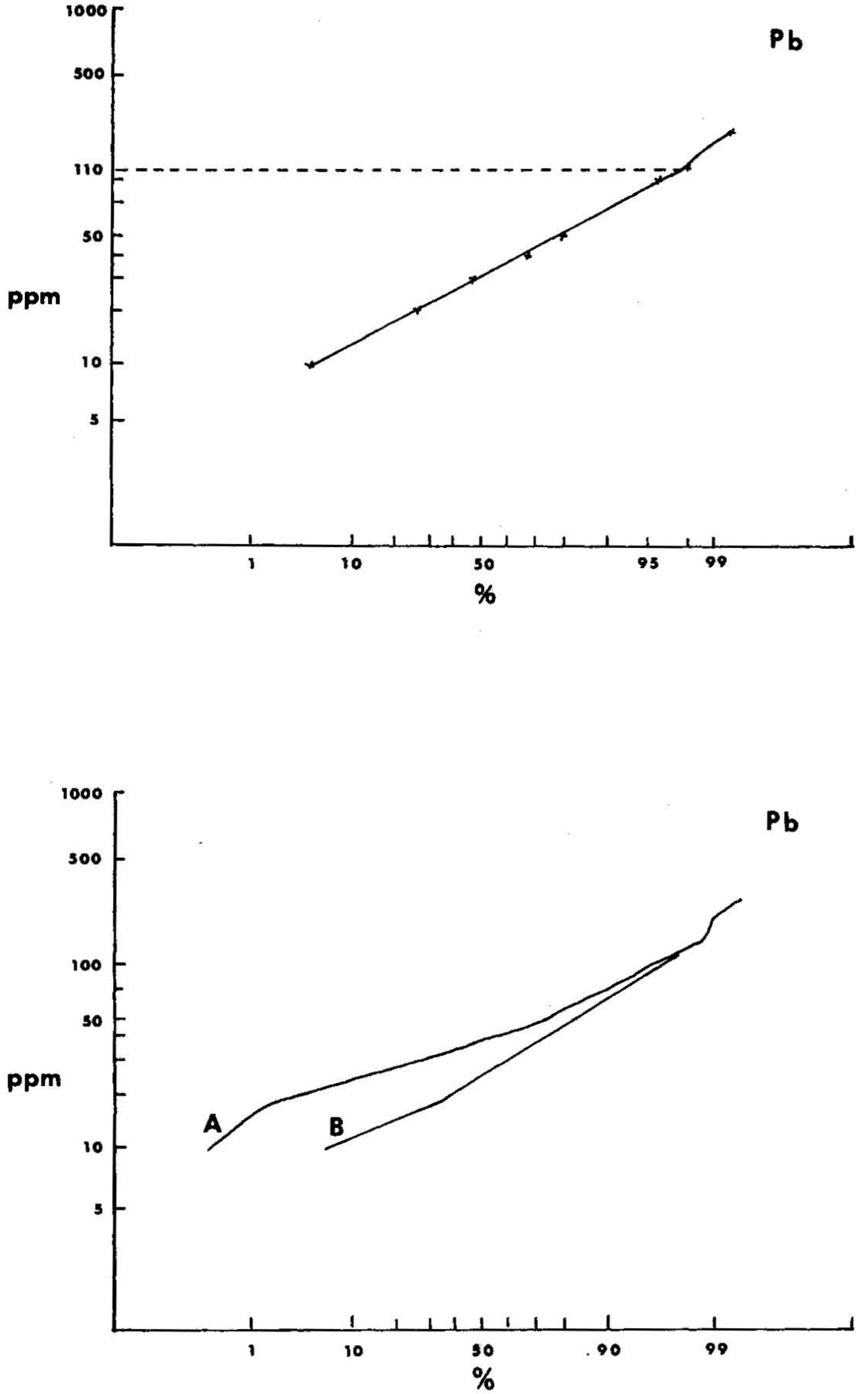
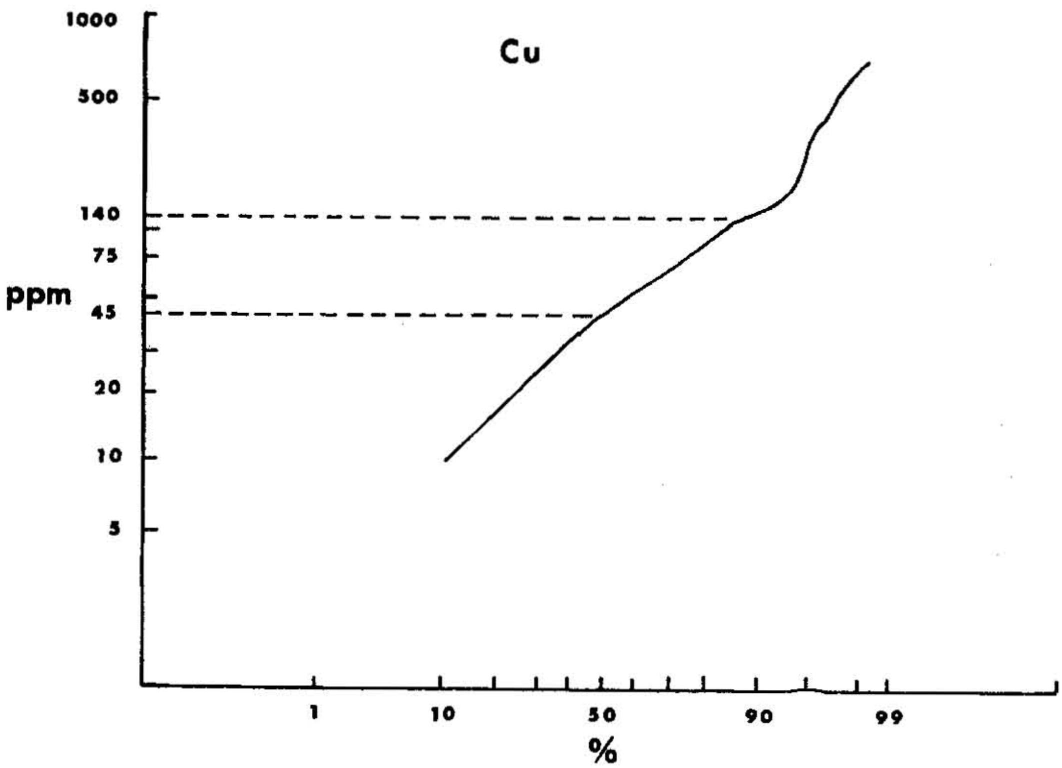


Figure 31 Cumulative frequency plot for lead in soil



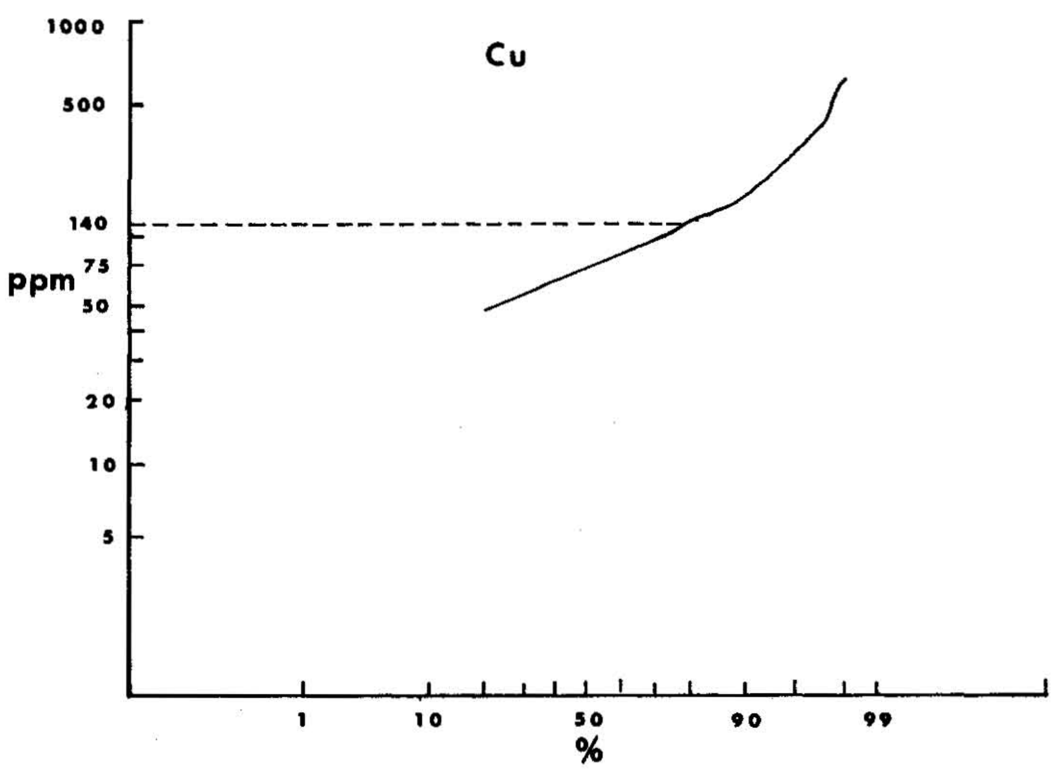


Figure 32 Cumulative frequency plot for copper in basal till

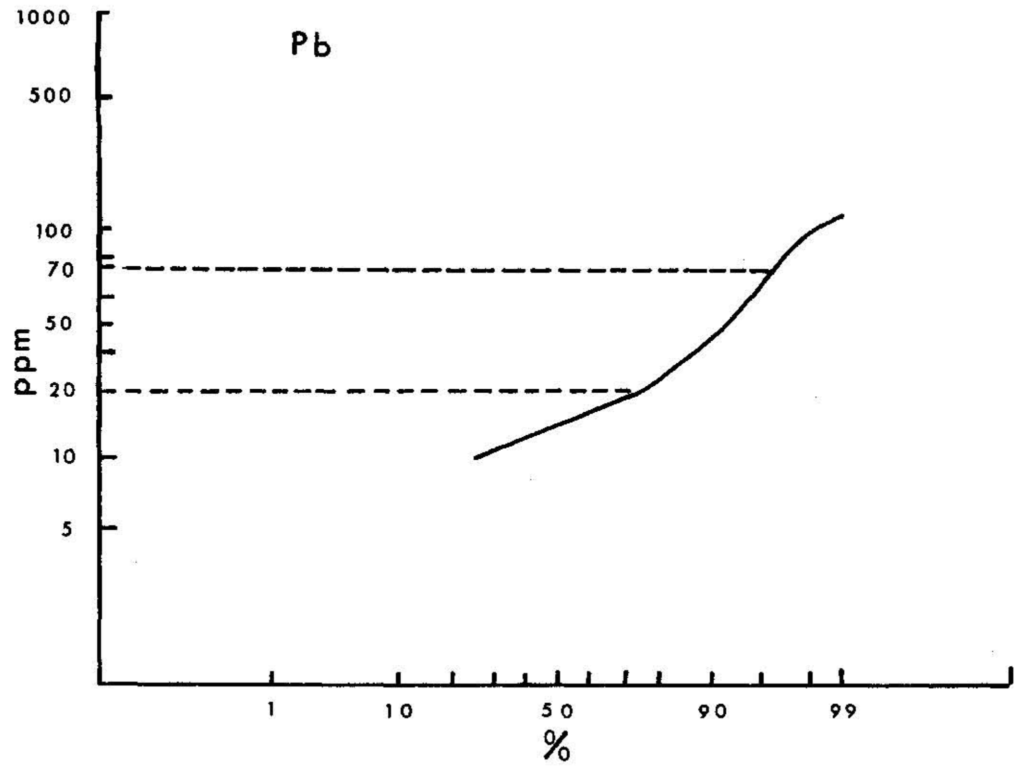


Figure 33 Cumulative frequency plot for lead in basal till

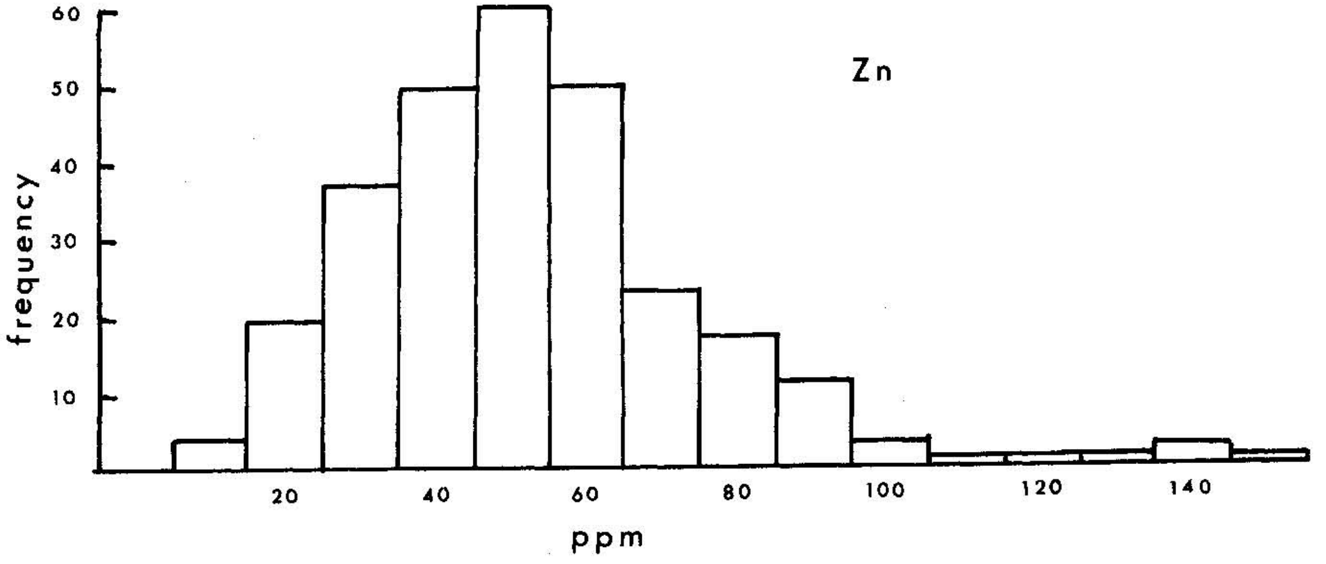


Figure 34 Distribution of zinc in basal till

APPENDIX III TABLE VII SUMMARY STATISTICS FOR SOIL DATA

Element	Total Data			Black Stockarton and Culdoach Moor Data			High Arkland and Milnthird Data ppm		
	$\log_{10}$ transformed			$\log_{10}$ transformed			$\log_{10}$ transformed		
	$\bar{x}$ (anti-log)	σ	range ppm	$\bar{x}$ (anti-log)	σ	range ppm	$\bar{x}$ (anti-log)	σ	range ppm
Cu	20	0.38	0-7750	20	0.42	0-7750	20	0.25	0-1350
Cu Upper population	50	0.25	30-7750	66	0.26	30-7750	43	0.21	30-1350
Pb	35	0.26	0-740	35	0.27	0-740	50	0.17	10-250
Zn Arithmetic data, normal distribution	50	-	0-600	50	-	0-600	65	-	10-250

APPENDIX III TABLE VIII SUMMARY STATISTICS FOR BASAL TILL DATA

Element Based on 235 samples	Mean $\log_{10}$ data (ppm) (antilog)	Standard deviation	Range ppm
Cu	50	0.46	5 - 5500
Cu upper population	110	0.29	50 - 5500
Pb	20	0.24	0 - 140
Zn (arithmetic data)	50	-	10 - 170

APPENDIX III TABLE IX SUMMARY STATISTICS FOR PROFILED TILL SECTIONS

	Basal tills 38 samples			Sub-surface tills 38 samples		
	mean $\log_{10}$ ppm (antilog)	σ	range ppm	mean $\log_{10}$ ppm (antilog)	σ	range ppm
Cu	57	0.34	0-480	34	0.34	0-200
Pb	20	0.21	10-140	27	0.23	10-140
	Arithmetic data for Zn.					
	$\bar{x}$	σ	range	$\bar{x}$	σ	range
Zn	62	30	10-870	53	24	10-120

APPENDIX IV MINERALOGICAL DATA FOR BLACK STOCKARTON MOOR DRILL CORE

Mineralogical investigations were conducted almost exclusively on small specimens of drill core from boreholes 7, 8 and 9. A small number of surface outcrop specimens and three small pieces of core from borehole 10 were also examined.

Investigations were carried out by examination of all hand specimens under a stereoscopic microscope, followed by examination of polished thin sections under a petrological microscope using incident and transmitted light. In addition, ad hoc mineral identifications were made by X-ray powder photography (D. Atkin) and the rocks were tested for calcite by the simple hydrochloric acid test. In a very small number of cases qualitative chemical data on specific minerals were obtained by electron microprobe scanning. Clay minerals and carbonates in four specimens from borehole 8 were identified by bulk-XRD (A. M. Shilston).

The object of this work was to build up a comprehensive picture of the petrographical phenomena encountered in the core sections. Only rocks examined in thin-section are reported on in the tables which refer to boreholes 7, 8 and 9. However, it should be borne in mind that these comprise only a small proportion of specimens examined from these boreholes, and that the general mineralogical interpretation given in the text of this report is based on consideration of all these specimens.

In the tables the mineralogical data has been considered by regarding the rocks as possessing three principal elements of composition, namely primary (pre-alteration/mineralisation) rock-type, alteration products and veining. Primary rock types are given as briefly as possible, usually by a single rock name. Alteration is described in terms of the type of alteration and its degree of development. Veins are divided according to their broad textural relationships, and four categories are recognised: veins of a replacement nature and associated with hydrothermal alteration - V1a; veins of a dilational nature and associated with the hydrothermal alteration - V1b; dilational veins which pre-date the alteration - V0; dilational veins which post-date the alteration - V2. In the few cases where full application of this system was not possible, the veins are distinguished simply as V1 and V2.

In the final column of the table a visual estimate of the total sulphide contents of the rocks is given.

Symbols used in the tables are as follows:

(a) Extent of mineralisation:

s - strong; d - moderate;
m - mild; w - weak to negligible.

(b) Types of alteration recognised:

P - chlorite prominent
S - sericite dominant, often accompanied by muscovite
R - disseminated limonitic oxide material
A - kaolinite and dolomite are prominent

(c) Secondary minerals observed:

Qz - quartz
Ch - chlorite
Se - sericite
Mu - muscovite
Ca - calcite
Do - dolomite
Ep - epidote
Ka - kaolinite
Il - illite
Mn - montmorillonite
Cy - clay (not specified)
Hb - hornblende
Tr - tremolite
Sp - sphene
Bi - biotite
Ru - rutile
Im - ilmenite
Fr - feldspar (not specified)
Mt - magnetite
Hm - hematite
Go - goethite
Ox - oxide (not specified)
Ba - baryte
To - tourmaline
Py - pyrite
Cp - chalcopyrite
Bo - bornite
Cc - chalcocite
Cv - covellite
Dg - neodigenite
Te - tennantite
En - enargite
Mo - molybdenite
Pr - proustite
Sl - sphalerite
Al - albite
Ad - adularia
Kr - potassic feldspar
Mi - microcline

(d) Volume % sulphides:

nil - none observed
tr - < 0.1%
NS - estimate unsatisfactory due to heterogeneous distribution of sulphide mineral grains

APPENDIX IV : TABLE X Summary mineralogy of core specimens examined as thin-sections and hand specimens from borehole 7, Black Stockarton Moor, S W Scotland

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
15.0m	Greywacke	d	P	Ca, hb, ch, go	V1b V2b	Ca, qz, hb Ca	nil
32.7m	Banded mudstone	s	P	Ca, hb, ep, ch, ru	V1a V1b	Ca, hb, ep Qz, ca, fr	nil
41.2m	Banded greywacke	s	P	Qz, hb, ep, ch, al	V1a V1b	Ca, hb, ep, ch Ca, qz	nil
47.8m	Banded mudstone	d	P	Ch	V1a V1b	Ep, ch Ca, ch	nil
57.9m	Greywacke	s	P	Hb, ch, mt, hm	V1a V1b	Ca, hb, ep cp Ca, qz cp	tr
71.6m	Porphyry in contact with tonalite xenolith	s	P	Ca, ep, ch, mt, sp, al	V1b	Ca	nil
84.8m	Black mudstone	w	P	Ch py	V1b	Kr, to	tr
87.6m	Greywacke	d	P	Ca, ep, ch, sp	V1a V1b V2	Ca, hb, ep py, cp Ca, ch, mt py, cp Ca	1.5
92.7m	Impure sandstone	d	P	Ca, hb, ep, ch, hm, sp, al	V1a V1b	Ca, hb, ep, py Ca, hb	tr
100.9m	Graded, banded impure sandstone	s	P	-	V1a V1b	Ca, hb, al py, cp Qz, ch	NS

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
101.9m	Porphyry	s	P	Ca, se, ch, mt, go, py	V1b	Ca, ch	tr
105.3m	Greywacke	d	P	Ch, mt, al py	V1a V1b	Hb, ep py Qz py	0.1
106.9m	Mudstone	s	P	Ch, mt, go	V1a V1b	Hb py Qz, hb	1.0
111.5m	Coarse impure sediment	s	P	Hb, ch, mt, go	V1a V1b	Hb py Qz, hb, ep, py, cp	1.5
119.0m	Hornfelsed mudstone	w	?S	-	V1b	Qz, ch, il, py	tr
127.4m	Laminated black mudstone	d	P	Ep, kr, cp	V1b	Ca, ep, ch, py, cp	0.2
131.9m	Brecciated siltstone	s	R/P	Ch, mt, hm, go, py	V1 V2	Ca, ch py, cp Ca	0.2
146.0m	Mudstone	d	R/P	Ch, mt, go	V1a V1b V2	Ca, ch, py, Qz, ca, kr, py, cp Ca	0.2
147.6m	Mudstone	d	R	Ca, go, ox, cp	V1a V1b	Ca, ch Qz, ca, hm, py	tr
148.7m	Greywacke	d	R/P	Ca, ep, ch, mt, go, py, cp	V1b V2	Ca, qz, ch, py Ca, qz	2.0

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
155.8m	Greywacke	d	R	Ca, hm, go, py	V1b V2	Ca, qz, ch, py Ch	0.1
163.8m	Porphyritic Granodiorite	d	P/S	Qz, hb, ch, se, hm, py mo	V1 V2	Ca, ch, py Ca, qz	tr
165.6m	Banded mudstone	s	P/S	Ca, ep, se, hm, go	V1b V2	Ca, ch py, cp Ca, ch	0.6
167.6m	Banded mudstone	d	P/S	Ep py, cp	V1a V1b	Qz, hb, go py, cp Qz, ca, ch py, cp	0.4
170.0m	Impure sandstone	s	P	Ca, hm, go	V1a V1b	Ca, ch py, cp Qz, ca py, cp	0.4
171.0m	Mudstone	w	?P	Ca py, cp	V1b V2	Qz, ch, fr py Ca	0.7
172.1m	Porphyritic Granodiorite	s	S	Do, se, mu, go	V0 V1b V2	Qz Do py, cp Ca	0.1
172.5m	Granodiorite in contact with impure siltstone	s	S/A	Do, se, mu, ka, py, cp	V1a V1b V2	Qz, do, ch, py, cp Qz Ca	0.1
173.1m	Adamellite	s	S	Ca, se, mu, go, py, cp	V2	Ca	tr
176.2m	Porphyritic Granodiorite	d	S	Ca, qz, se, py, cp	V1 V2	Ca, qz, py, cp, mo Ca, ox	tr

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
182.8m	Porphyritic granodiorite	s	S/A	Ca, se, mu, ka, mt, hm py, cp	V1a V1b	Qz, hm, ad, cp Ca, qz, ox, cp, mo	0.2
188.8m	Porphyry	s	S	Ca, se, mu, ch, hm, go, py, cp	V1b	Ca, qz, ch, py, cp	0.1
196.0m	Mudstone	s	S	Ca py	V1b V2	Ca, qz py Ca	0.2
205.4m	Fractured greywacke	s	P/S	Hb, ch, se, go, sp, py	V1a V1b	Hb, ch, py Ca, qz	tr
212.5m	Banded mudstone	d	P/S	Go, py	V1a V1b V2	Ca, ep, ch, py, cp, bo, Ca, ch mo Ca	3.5
222.9m	Mudstone	s	S	Ca, se, mu, py	V1b V2	Ca, qz, fr, py Ca, qz	3.0
239.2m	Mudstone	s	S	Do, se, py, cp	V1b V2	Do, qz, se, py Do	4.0
241.4m	Brecciated mudstone	s	S	Ca, py	V1a V2	Ca, py, te, mo Ca, qz	9.0
242.8m	Granodiorite	s	S	Ca, se, mu, go, py, cp	V1a V1b	Ch Ca, ch, cp, bo, mo	tr

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
247.1m	Porphyritic granodiorite	s	S	Do, qz, se, mu, py	V2	Ca, qz	4.0
248.5m	Porphyritic granodiorite	s	S	Do, se, mu, go, py	V1b V2	Qz py, mo Ca, qz	1.0
253.4m	Porphyritic granodiorite	s	S/A	do, se, mu, ka, go, py	V1b	Do, qz, mo	1.0
260.5m	Microgranodiorite	m	S	Do, ca, ch, se, hm	V2	Ca, qz	nil
287.2m	Granodiorite	s	S/A	Do, se, mu, ka, hm, py	V1b	Do, qz, ch, cp	tr
291.0m	Adamellite vein in banded mudstone	s	S	Do, se, mu, ka, go, py	V1b	Do, qz, py	1.0
298.7m	Granodiorite	d	S	Do, se, mu, go	V1b V2	Do, qz, ch, cp	tr
305.5m	Granodiorite	w	P/S	Ca, ch, se, hm	V0 V1b	Qz Qz, ca, ch	nil
315.6m	Diorite	d	S	Ca, se, mu, go, py, cp	V1b V2	Ca Ca	0.1
323.1m	Granodiorite	s	S	Do, se, mn, hm, go	V1b V2	Qz, ch Ca	nil
335.5m	Granite	d	S	Do, se, mu, ch	V1b V2	Qz, ka Ca	nil
337.4m	Granodiorite	s	P/S	Ca, se, ch	V1b	Ca, qz, ch	nil
342.9m	Granodiorite	s	P/A	Ca, se, ch, mt, im	V1b	Qz, do, ch	nil

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
348.4m	Granodiorite	s	S/A	Ca, se, mu, bi, ka, hm, im	V1a V1b	Se, mu Ca, se, bo, cc	0.1
355.8m	Granodiorite	d	S	Do, se, mu, go, im, cp, bo, cc	V1a V1b	Se Qz, do, ch	0.2
357.6m	Granodiorite	s	S	Do, se, mu, hm, go, al	V1b V2	Do, qz, cp, bo, cc, cv Do	NS
358.0m	Granodiorite with pocket of hydrothermal carbonate	s	S	Do, qz, se, mu, go, py	V1b V2	Qz, py Do	tr
361.0m	Granodiorite	s	S	Do, se, ck, bi, ka, mt, hm	V1b V2	Qz, cp, bo, cc, cv Ca, qz, ba	NS
364.5m	Granodiorite	s	S	Do, se, mu, hm, go, cp	V1b	Qz, ch, cp, bo, pr	1.5
366.0m	Granodiorite	s	S	Ca, se, mu, hm, go, cp, bo	V1b V2	Qz, ca, cp, bo, cc Qz, ca, ba	NS
369.0m	Granodiorite in contact with porphyry	d	S	Do, se, ch, go	V1b	Do, qz	nil
372.0m	Tonalitic porphyry	m	P/S	Ca, se, ch, mt, hm	V1b V2	Ca, qz, cp, mo Ca	NS
374.2m	Granodiorite	s	P/S	Do, qz, se, ch	V1b	Ca, qz, ch, cp, bo, mo	NS
374.9m	Tonalitic porphyry	d	S	Do, mu, ch, mt, hm	V1b V2	Ca, qz, se, ch Ca, qz	nil

APPENDIX IV : TABLE X cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
380.0m	Granodiorite	s	S	Do, se, mu, hm, cp, bo, cr	V1b V2	Ca, qz, ch, bo, cc Ca, ka	tr
380.9m	Granodiorite in contact with porphyry	s	S/R	Ca, qz, se, mu, hm	V2	Ca, do	nil
390.6m	Calcite veins in altered porphyry	s	P/R	Do, qz, hm, go	V1b V2	Qz Do, qz	nil
405.5m	Granodiorite	s	S	Do, se, mu, py, cp, bo	V1b V2	Qz, py Ca	tr
407.0m	Tonalitic porphyry	s	P	Do, qz, ch, go	V2	Do, qz	nil

APPENDIX IV : TABLE XI Summary mineralogy of core specimens examined as thin-sections and hand specimens from borehole 8, Black Stockarton Moor, S W Scotland

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
7.14m	Granodiorite	s	S	Do, se, mu, ox	V1	Do, qz	-
7.77m	Granodiorite	s	S	Do, se, mu, ox	? VO V1 V2	Do Do, qz Ca	-
14.78m	Granodiorite	s	S	Se, mu, do, py	VO V1	Ca, qz Ca, qz, se, py, hm	NS
17.37m	Granodiorite	s	S	Se, mu, do, py	V1 V2	Do, qz, py Do	NS
21.43m	Granodiorite	d	S	Se, ka, ch, do hm, cp, bo	V1 V2	Ca, ch, go Ca	tr
23.62m	Granodiorite	s	S	Do, se, mu, go, qz, py, cp, bo	V1 V2	Do, ca, py, cp, bo Ca	NS
23.70m	Granodiorite	s	S	Se, mu, il, do, bo	V1 V2	Qz, do, py bo Ca	NS
25.15m	Porphyritic granodiorite	s	A	Do, ka, ox	? V2	Do	-
25.75m	Porphyritic granodiorite	s	A	Il, mt, mu, do, ox	? V2	Do	-
30.33m	Granodiorite	d	S	Se, mu, do, ka	? V2	Qz, do	-
39.56m	Autobrecciated granodiorite	s	? A	Se, ka, do, ox, hm, cp, bo	V1a	Cp, bo	NS

APPENDIX IV : TABLE XI cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
48.69m	Granodiorite	d	S	Se, do, ox, py, cp	V1	Qz, ca, ox	tr
49.01m	Granodiorite	s	S	Se, do, ? ka, py, cp, bo	? V2	Qz, do, mu	tr
50.93m	Granodiorite	s	A	Do, il, mt, ka, py	V1	Do	tr
57.90m	Granodiorite	s	S	Se, do, mu, ox, ? ch	V1	Qz, do	-
58.27m	Granodiorite	s	? P	? Ch, se, do, ox, mu	V0 V1 V2	Qz Qz, do Ca	-
64.40m	Granodiorite	d	S	Se, mu, ch, do, ox	V0 V1 V2	Qz Do Do	-
71.67m	Tonalite	w	S	Se, ox, do	V0 V1 V2	Qz Ca Ca	-
76.20m	Porphyry chilled against granodiorite	s	A	Do, ka, il, mu, ch	V1	Do	-
81.00m	Granodiorite	s	S	Se, mu, do, py	V1	Do, py	0.2%
100.66m	Granodiorite	d	P	Se, ch, ox, do	V1	Qz, ca, ox	-
111.70m	Granodiorite	s	P	Se, ch, ox, ? ca	V1 ? V2	Qz Ox	-

APPENDIX IV : TABLE XI cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
123.32m	Granodiorite	d	P	Se, cho, do	V0 V1	Qz ? Do	-
125.00m	Granodiorite	s	P	Se, ch, do, py	V0 V1	Qz Do, ch, cy	tr
125.09	Altered quartz-rich rock	s	S	Se, do, mu, py	V1 V2	Qz, do, py, bo, cp, cv, cc, en, sl ca	NS
125.47m	Altered quartz-rich rock	s	S	Ca, mu, do, sp, ru, py, cp bo, cc	V1	Qz, do	0.1%
126.30m	Flow banded porphyritic granodiorite	s	S	Se, do, ox	V0 V1	Qz Ca, py	tr
128.80m	Altered quartz-rich rock	s	P	Ca, cy, ca, ox	V1	Qz, do, py, cp, sp	NS
129.13m	Impure quartzose sediment	s	S	Do, se, mu, cy, py, cp	V0 V1 V2	Qz Do, py, cp, bo Ca	NS
130.24m	Granodiorite	s	P	Se, ch, ca, mt, hm, cp	V1 V2	Qz, hm, cp Ca	0.2%
133.84m	Granodiorite	s	A	ka, ca, hm, cp, bo	V2	Ca	9%
136.60m	Granodiorite	s	S	Se, qz, ca, ox, cp	V0 V1 V2	Qz Ca Ca	tr

APPENDIX IV : TABLE XI cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
137.78m	Greywacke	s	S	Se, do, cp, cc, bo, cv, en	V0 V1 V2	Qz Do, ca Ca	1%
143.12m	Greywacke	s	A	Se, do, ka, py	V1 V2	Do, qz Do	tr
143.74m	Greywacke	s	? S	Se, do, ? ka, py	V1 V2	Qz, do Do	0.25%
144.69m	Granodiorite	s	S	Se, ox, mu, do, py	V2	Qz, do	0.5%
145.92m	Dacitic porphyry	d	S	Mu, do, se, py	V1 V2	Do, bo, cc, cp Ca	0.3%
160.00m	Porphyritic granodiorite	w	P	Ch, se, ca, py	V1 V2	Qz, py, cp Ca	1.5%
163.35m	Porphyritic granodiorite	d	S	Se, sp, ru, mu, do, ch py, cp	V1 V2	Qz, py Ca	2%
174.96m	Porphyritic granodiorite	d	? S	Do, ca, se, mu, qz, cp	V1	Qz, do, py, cp	NS
177.70m	Greywacke	s	S	Mu, ca, se, py	V1 V2	Qz, py, cp Ca	2.5%
179.35m	Greywacke	d	S	Se, do, py	V1	Qz, do	3%
180.00m	Biotite-hornfels	w	P	Ch, ca, py	V1	Ca, ch, cp	0.1%

APPENDIX IV : TABLE XI cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
183.20m	Flow-banded porphyritic granodiorite	d	P	Ch, ca, qz, se, cy, mu, ep py	V1	Ca, qz, ch	3.5%
193.25m	Dark shale boundary with greywacke	d	P	Ch, ca, py	V1 V2	Ca, ch, py, cp ca	1.5%
196.88m	Agglomeratic breccia	s	P	Ch, qz, ca, py	V1 V2	Qz, ca Ca	tr
197.52m	Agglomeratic breccia	m	P	Ch, ca	-	-	-
203.22m	Medium-grained greywacke	d	? P	Ch, ca, se, py	V1	Ca	0.2%
205.27m	Brecciated siltstone	d	P	Ch, ca	V1 V2	Ch, ca, py, cp Ca	NS
206.55m	Porphyritic granodiorite	d	P	Se, ch, qz, ca, py	? V2	Ca	3.5%
207.10m	Porphyritic granodiorite	d	P	Ch, se, qz, ca, py	? V2	Ca	3.5%

APPENDIX IV : TABLE XII Summary mineralogy of drill core specimens from borehole 9, Black Stockarton Moor, S. W. Scotland

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
7.81m	Porphyritic hornblende microtonalite	w	P	Hb, se	-	-	-
24.12m	Porphyritic microgranodiorite	m	P/S	Ch, ca, se, sp, cy, go	V1	Qz, ca, sp, ch, py	1.5%
30.98m	May be a sparsely porphyritic porphyry	s	S	Do, se, qz, mu, hm, go, py	V1	Qz, do, ca, py	NS
59.18m	Porphyritic microtonalite	d	P/S	Ca, se, ch, ru, ab, hm	V1	Ca, py	NS
68.37m	Altered porphyritic granodiorite	s	S	Do, se, mu, ch, hm, sp cp, py	V1 V2	Qz, do, py Ca	tr
83.09m	Porphyritic microgranodiorite	s	S	Do, se, mu, ox, sp	V1	Ca, qz, py	0.5%
94.50m	Porphyritic granodiorite	s	S/A	Do, se, ka, ch, mu, ox, py	V1	Do, qz, se, ka, py	2%
98.15m	Porphyry	s	S	Se, mu, ch, qz, sp, hm, go, py, cp	V1	Qz, ca, ka	4%
103.73m	May be porphyritic granodiorite	s	S	Do, qz, se, mu, sp, ap, py, cp, bo	-	-	2%
129.47m	Granodiorite	d	P/A	Do, se, ch, ka, sp, hm, py	-	-	tr

APPENDIX IV : TABLE XII cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
141.03m	Granodiorite	s	P/A	Ca, se, ka, ch, sp	-	-	-
156.70m	Porphyritic granodiorite	s	S	Do, se, mu, sp	V0 V1	Do Qz, do	-
164.53m	Porphyry	s	P/A	Ca, ka, ch, se, sp, ox	V1	Ca, se, py	tr
166.53m	Altered diabase-like rock	s	S	Do, se, ch, ka, ox	V1	Do	-
170.45m	Siltstone	s	S	Do, se, ch, qz, ox, py, cp	V0 V1	Qz Ca, py, cp	3.5%
202.95m	Intrusive contact of porphyry with granodiorite			Do, se, mu, ru, ox, py	V1	Do	2.5%
212.19m	Autobrecciated porphyry or granodiorite	s	P/A	Ca, ka, mu, ch, se, qz, Sp, ox, py, cp	V1	Ca	1.5%
215.25m	Altered granodiorite	s	S	Do, se, mu, qz, ox, sp, py, cp	V1 V2	Do, qz, py Do, ch	0.2%
220.30m	Granulitised porphyry	d	S	Ca, qz, se, mu, ka, ch, ep, ru, sp, ox	V1	Ca, ka, py	tr
237.64m	Porphyritic microgranodiorite	s	A	Ca, ka, ch, se, ox, qz	V1	Ca	-

APPENDIX IV : TABLE XII cont'd

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
248.92m	Brecciated siltstone with fragments of porphyritic granodiorite	s	S	Ca, qz, se, cy, sp, ox	V1	Ca, ch, py	tr
249.31m	Greywacke with silty bands	s	S	Ca, se, mu, ka, do	V1 V2	Ca, ch, py Ca	tr
252.00m	Finely banded mudstone	m	S/P	Ca, se, ch, im, ox, py, cp	V1	Ca, qz, ep, py, cp	0.1%
259.15m	Greywacke	s	P	Ca, ch, hm, py, cp	V1	Ca, py, ep	0.5%
273.41m	Porphyritic granodiorite	m	P	Ca, ch, se, sp, ab, mu, ox	V0 V1 V2	Qz Qz, se Ca	-
276.90m	Greywacke	s	S/A	Ca, se, ox	V1	Ka, ca, qz, se	-
279.52m	Porphyritic granodiorite	s	P	Ca, ch, se, ox, do	V0 V1	Ca, Ca, qz	
284.00m	Porphyritic micro-granodiorite	d	P	Ca, ch, sp, ox, hm	V1	Ca	

APPENDIX IV : TABLE XIII Summary petrography of three drill core specimens from borehole 10.

Specimen Position	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
4.15m	Porphyritic granodiorite	d	P	Ch, se, bi, hm, py	-	-	1.5
4.75m	Porphyritic granodiorite	d	P	Ch, se, py, cp, hm	P/S	Qz	1.2
6.70m	Porphyritic granodiorite	d	P	Ch, se, py			3.5

APPENDIX IV : TABLE XIV Summary petrography of four blocks of diorite collected from surface outcrop

Specimen Number	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
543	Quartz-diorite	d	P	Ch, se, ca, go, py, cp	-	-	0.1%
545	Quartz-diorite with cognate xenoliths	d	P	Ch, se, ca, go, py	-	-	1.5%
554	Quartz-diorite	d	P	Ch, se, ca, py, cp, go	-	-	0.15+%
563	Quartz-diorite	d	P	Ch, se, ca, py, go	-	-	0.6%

APPENDIX IV : TABLE XV   Summary petrography of small blocks collected from outcrop by Milnthird Burn

Specimen Number	Primary rock type	Alteration			Veining		Volume % Sulphide
		Extent	Type	Minerals	Type	Minerals	
104	Dacitic porphyry	s	S	Se, ch, qz, go, py, cp, bo cv	?V1	Ca	NS
105	Dacitic porphyry	s	S	Se, ch, qz, py, cv, dg	?V1	Ca (25% rock)	0.5
106	Dacitic porphyry	s	? S	Ca, qz, ox	?V1	Qz	-
107	Dacitic porphyry	s	S	Se, ch, ox, qz, ca	?V1	Qz, ca	-
108	Dacitic porphyry	s	P	Se, ch, ox	?V1	Ox	-
109	Dacitic porphyry	s	S	Se, qz, ox	?V1	Ca, qz	-
110	Dacitic porphyry	s	P	Ch, ox, qz	-	-	-
111	Dacitic porphyry	s	S	Se, ch, qz	-	-	-

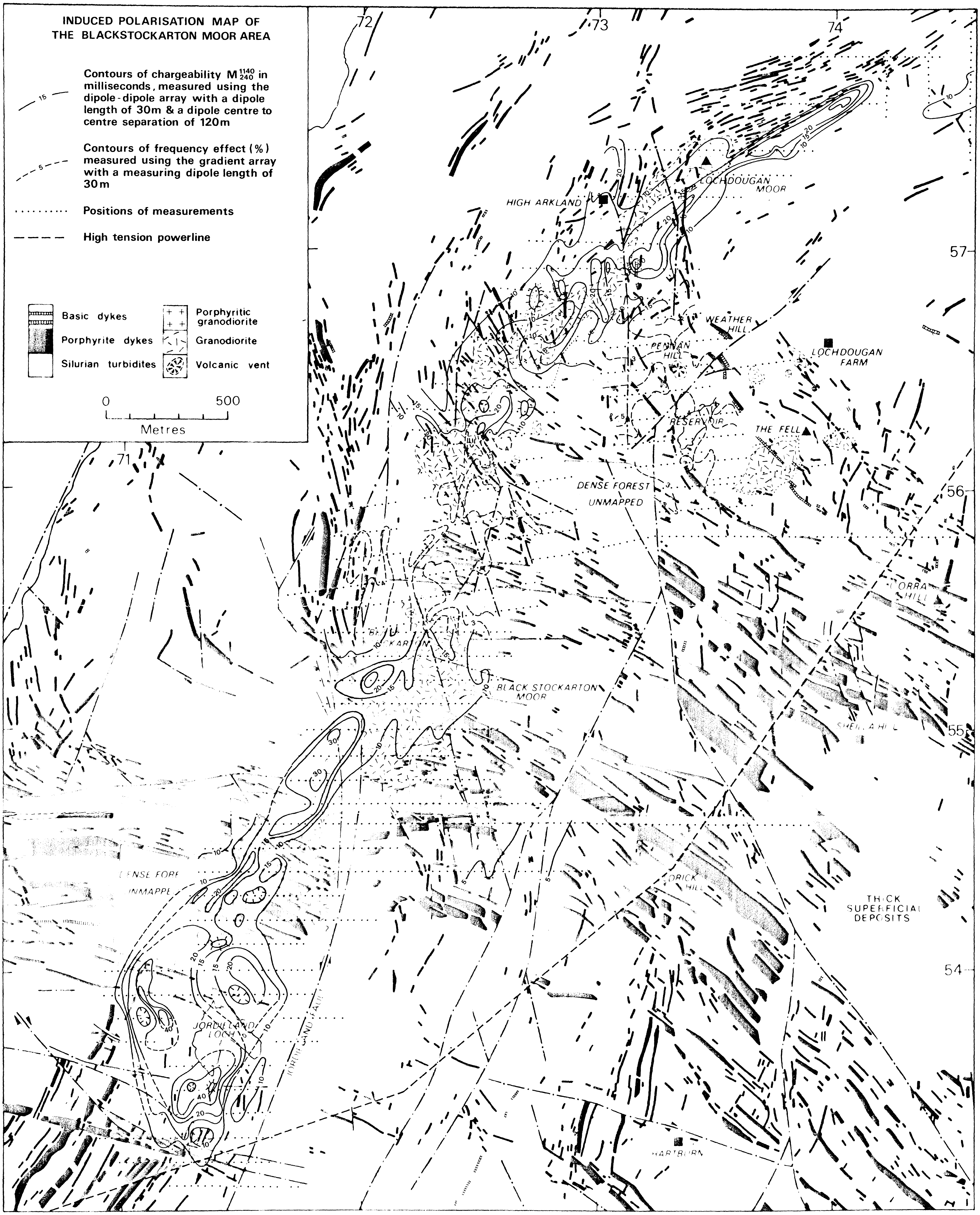


Figure 7 Induced polarisation

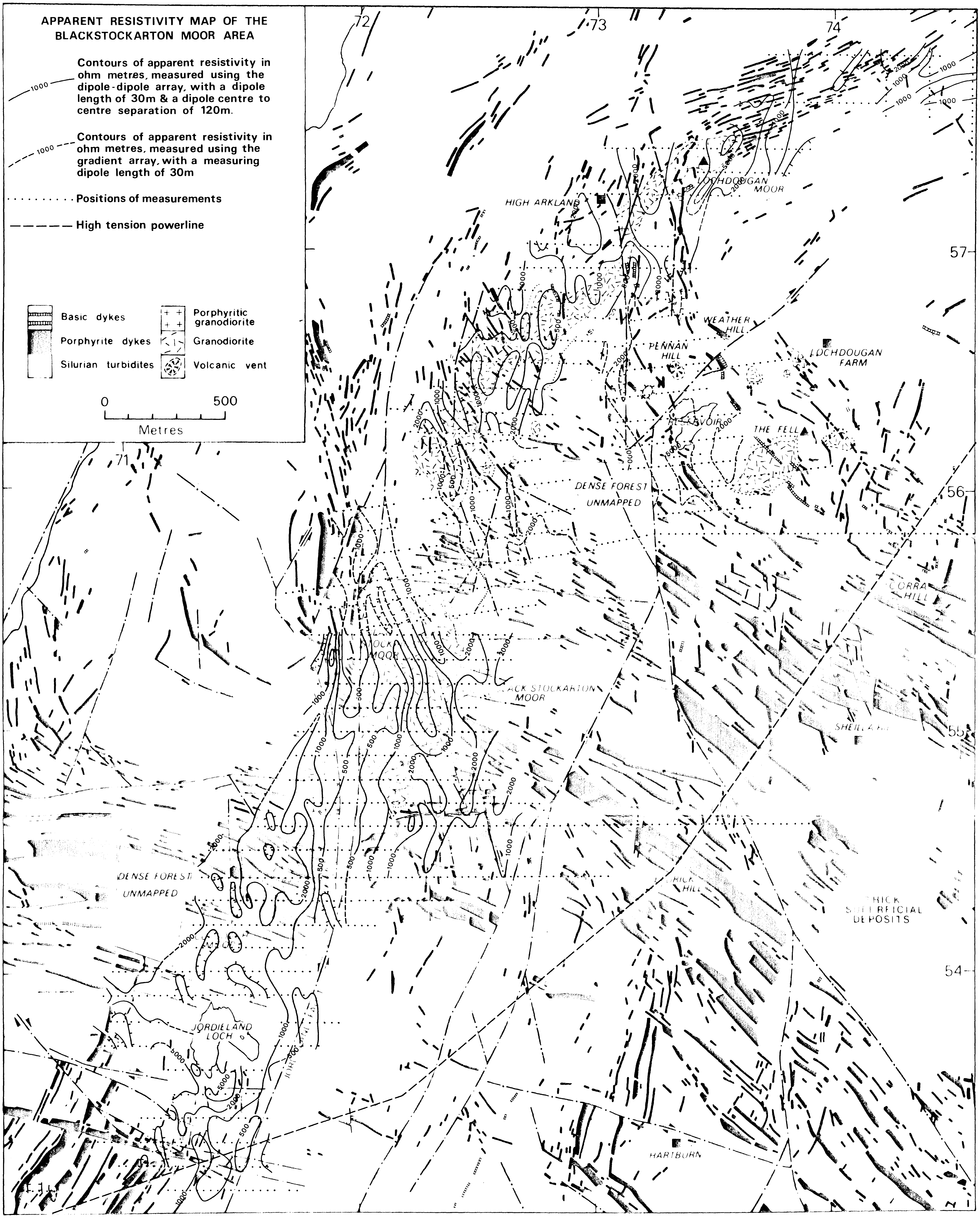


Figure 8 Apparent resistivity

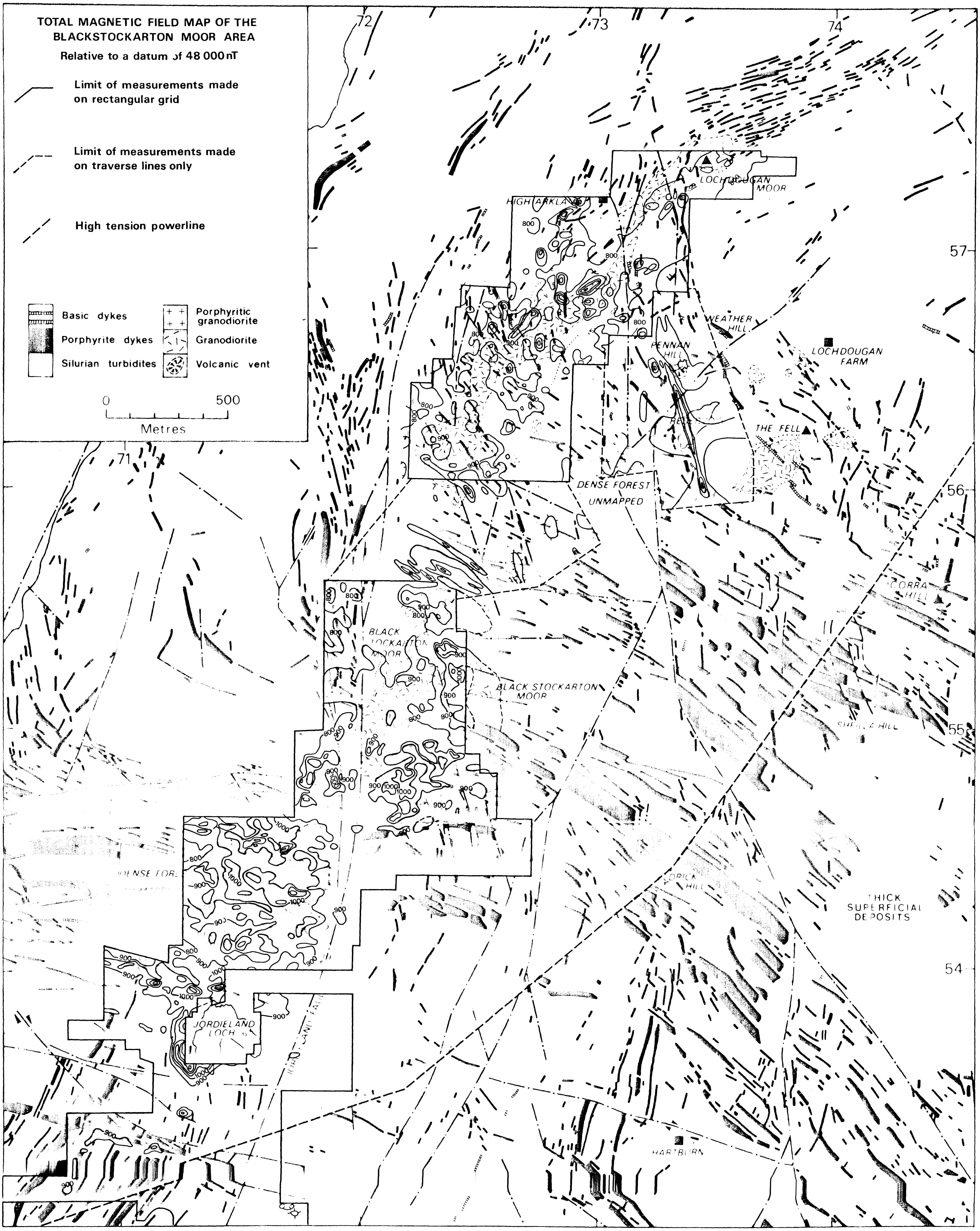


Figure 9 Total magnetic field

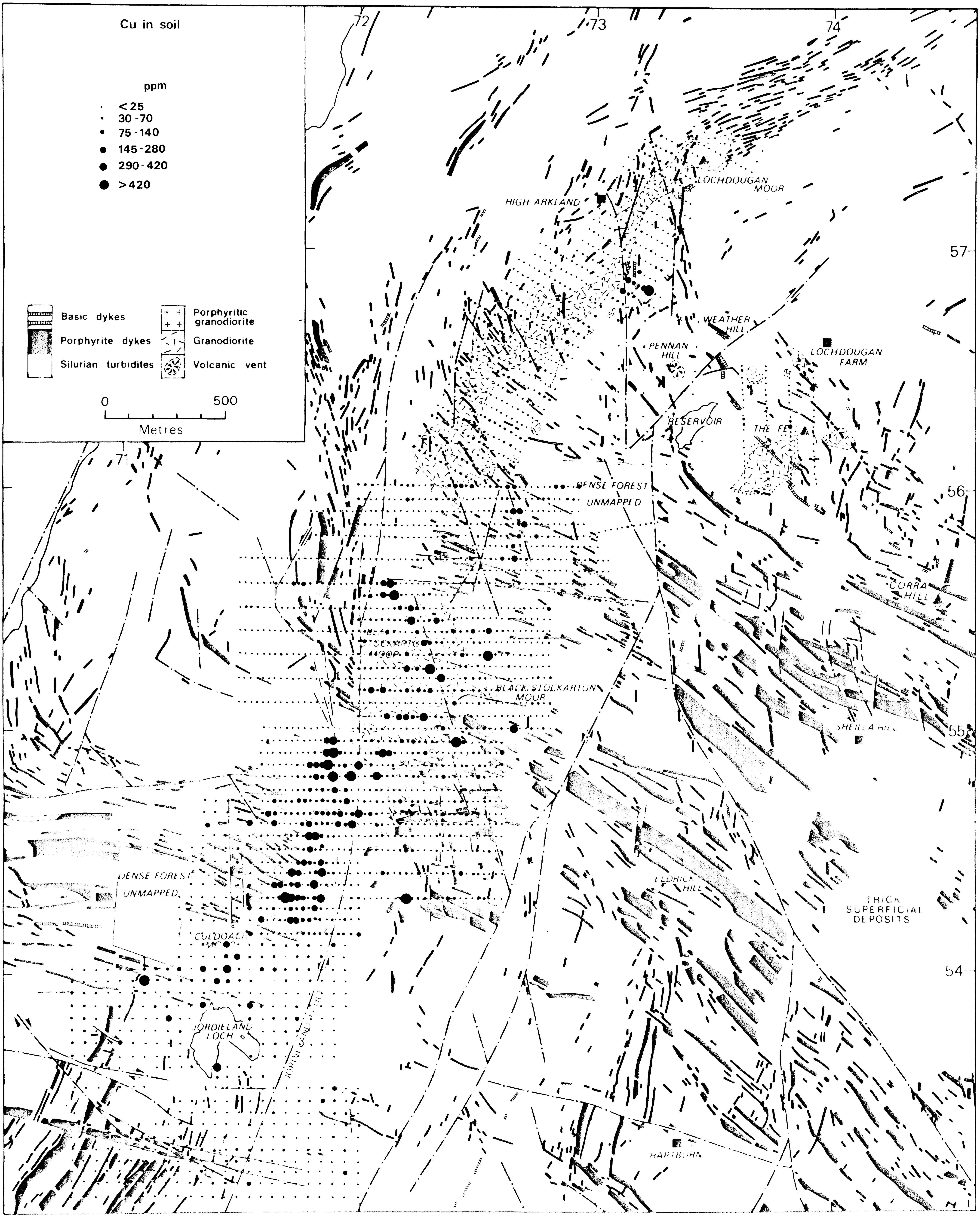


Figure 13 Copper in soil

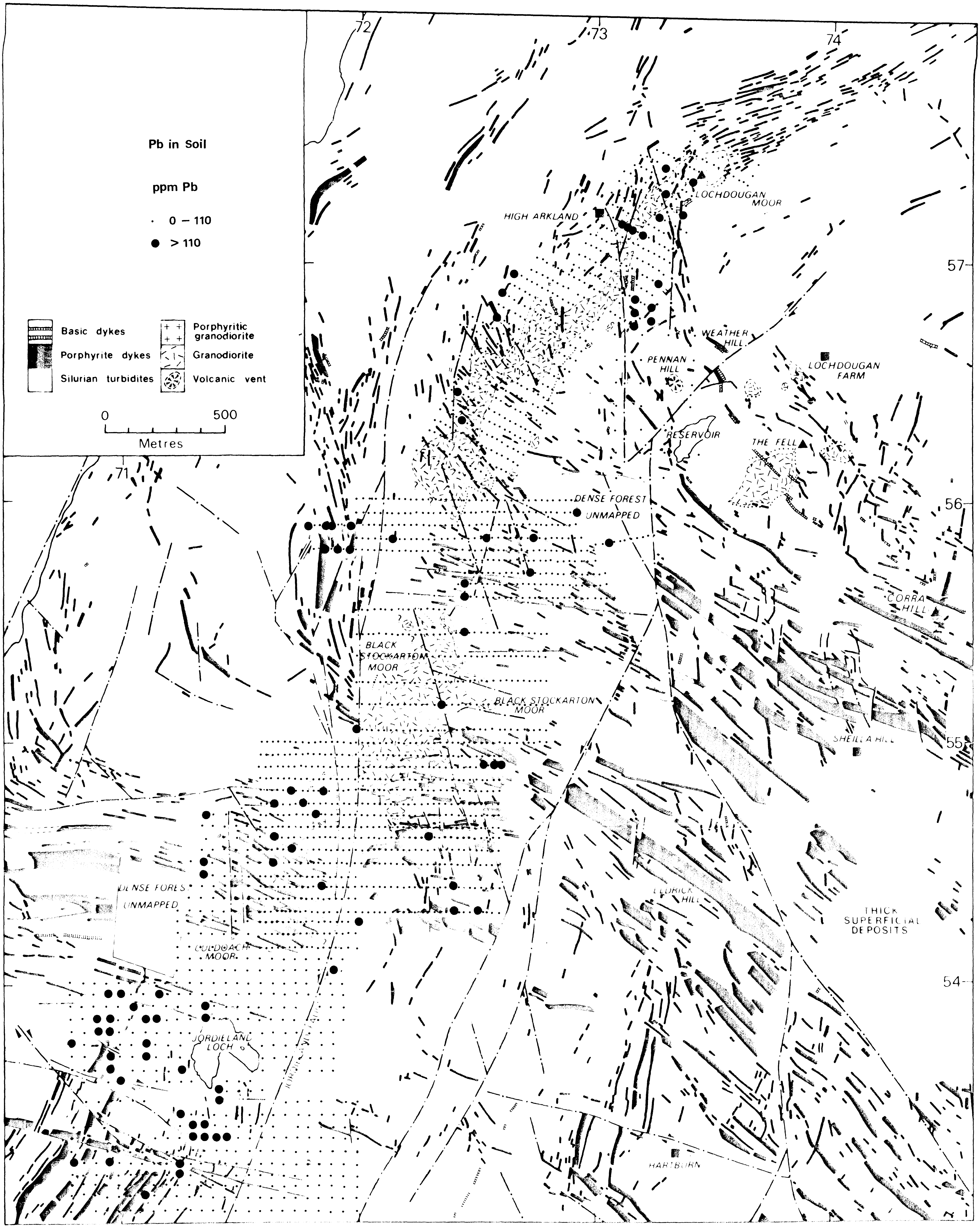


Figure 14 Lead in soil

Figure 22 GRAPHIC LOG BLACK STOCKARTON MOOR BH 7

Figure 23 Graphic Log Black Stockarton Moor BH8

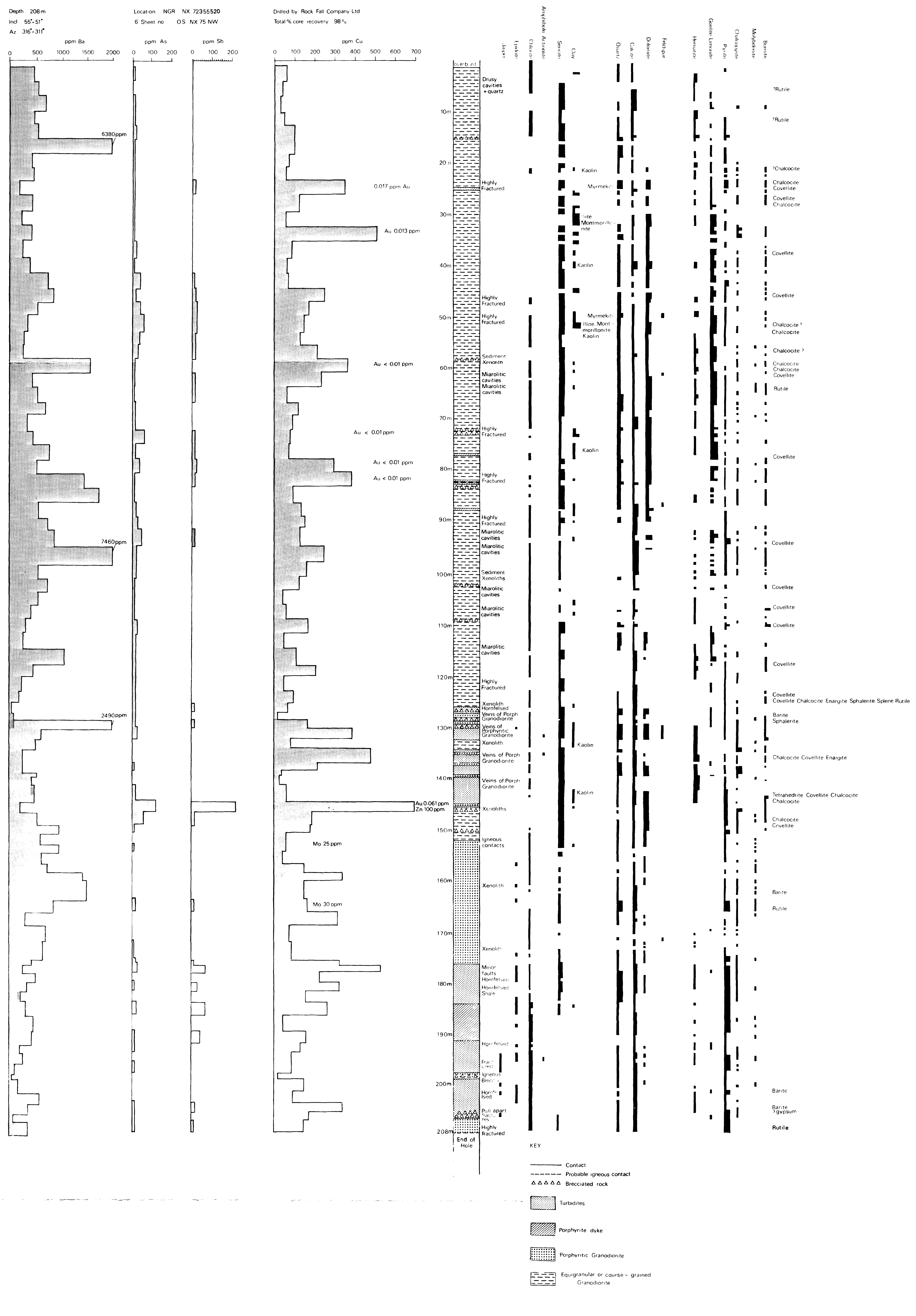


Figure 24 Graphic log Blackstockarton Moor BH9

Location NGR NX 7224 5527 drilled by Rock Fall Company Ltd

6" Sheet No NX 75 NW Total % core recovery 99 0%

Depth 303·3 m

Incl 55° - 51°

Az 316° - 311°