British Geological Survey

Mineral Reconnaissance Programme

# Mineral Exploration in the Cockermouth area, Cumbria.

## Part 1: Regional surveys

Department of Trade and Industry

MRP Report 118

Technical Report WF/91/4

# Mineral exploration in the Cockermouth area, Cumbria. Part 1: regional surveys

D C Cooper, D G Cameron, B Young, J D Cornwell
and D J Bland

BRITISH GEOLOGICAL SURVEY

Technical Report WF/91/4

Mineral Reconnaissance Programme Report 118

# Mineral exploration in the Cockermouth area, Cumbria. Part 1: regional surveys

D C Cooper, D G Cameron, B Young, J D Cornwell
and D J Bland

*Authors*
*Compilation*
D C Cooper, BSc, PhD
*Geochemistry*
D G Cameron, BSc
D C Cooper, BSc, PhD
*Geology*
B Young, BSc
*Geophysics*
J D Cornwell, MSc, PhD
*Mineralogy*
D J Bland, BSc
*BGS Keyworth*

This report was prepared for the Department of Trade and Industry

Maps and diagrams in this report use topography based on Ordnance Survey mapping

*Bibliographical reference*
**Cooper, D C, et al.** 1991. Mineral exploration in the Cockermouth area, Cumbria. Part 1: regional surveys. *British Geological Survey Technical Report* WF/91/4 (*BGS Mineral Reconnaissance Programme Report* 118).

Keyworth, Nottingham 1991

## BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth, Murchison House, Edinburgh, and at the BGS London Information Office in the Natural History Museum, Earth Galleries. The adjacent bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue, and can be bought from Ordnance Survey agents as well as from BGS.

*The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.*

*The British Geological Survey is a component body of the Natural Environment Research Council.*

Keyworth, Nottingham NG12 5GG
☎ Plumtree (06077) 6111 Telex 378173 BGSKEY G
Fax 06077-6602

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 031-667 1000 Telex 727343 SEISED G
Fax 031-668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE
☎ 071-589 4090 Fax 071-584 8270
☎ 071-938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF
☎ 031-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ Exeter (0392) 78312 Fax 0392-437505

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY
☎ Aberystwyth (0970) 611038 Fax 0970-624822

Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB
☎ 091-281 7088 Fax 091-281 9016

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ Belfast (0232) 666595 Fax 0232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ Wallingford (0491) 38800 Telex 849365 HYDROL G
Fax 0491-25338

*Parent Body*
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ Swindon (0793) 411500 Telex 444293 ENVRE G
Fax 0793-411501

This report relates to work carried out by the British Geological Survey on behalf of the Department of Trade and Industry. The information contained herein must not be published without reference to the Director, British Geological Survey.

Dr D Slater
Minerals Group
British Geological Survey
Keyworth
Nottingham NG12 5GG

Printed in England for the British Geological Survey by
Saxon Printing Limited, Derby

CONTENTS

TABLES

FIGURES

# SUMMARY

The results of geochemical, geological and geophysical surveys over Carboniferous rocks along the northern margin of the English Lake District are given in two reports. This report (Part 1) describes broadscale surveys across an area bounded by Caldbeck in the east and the coast at Maryport in the west, and confined roughly by the boundary of Carboniferous rocks to the north and south. Part 2 contains details of orientation and follow-up surveys in the Ruthwaite, Tallentire and Whitrigg areas.

Revision geological mapping of the area discovered many new occurrences of baryte mineralisation, which is particularly common in the Dinantian and Namurian rocks of the Tallentire - Bothel area. The mineralisation usually comprises epigenetic fracture fillings of baryte, often accompanied by brown carbonate and minor chalcopyrite or malachite. Locally in the Tallentire area baryte also occurs in disseminated and veinlet form within the Hensingham Grit. Lead-zinc mineralisation is less common; it occurs as epigenetic fracture fillings and locally as syngenetic or diagenetic concentrations in mudstones and shales of the Coal Measures.

A geochemical drainage survey involving the analysis of water, stream sediment and panned concentrate samples revealed the presence of numerous metal anomalies. These required careful interpretation due to the presence of extensive contamination and glacial deposits derived from metalliferous source rocks in the Lake District and southern Scotland. The mineralogical examination of panned concentrates was used successfully to discriminate between anomalies caused by natural and artificial sources. In many cases evidence for both sources was found in a single sample. The data confirmed the widespread occurrence of baryte and suggested that hitherto undetected mineralisation may be present around Ruthwaite (Ba), Tallentire Hill (Ba, Cu), Broughton Moor (Ba, base-metals), near Binsey (polymetallic) and south of Stockdale (Zn, Pb).

Gold and cinnabar were reported for the first time from this area. Gold was observed in 21 panned concentrates, most collected over Upper Carboniferous rocks in the west of the area. It may have a local bedrock source, but comes probably from glacial deposits derived from mineralised Lower Palaeozoic rocks in southern Scotland and the north-east Lake District. Cinnabar was identified in 22 concentrates and is believed to be locally derived. Samples of mineral veins and altered wallrocks contain appreciable (up to 40 ppm) Hg, indicating that it is associated with the epigenetic mineralisation.

A re-appraisal of the existing regional magnetic and gravity data for the area suggested that a north-west-trending fracture, named the Bothel Fault, could be a more significant structure than was apparent from existing maps, and may have been active during the Carboniferous. The magnitude of the gravity anomaly over the Solway Basin suggests the presence of either a thickened Carboniferous sequence, perhaps across a concealed growth fault, or more low-density (acid volcanic) rocks in the Lower Palaeozoic basement than is indicated on existing maps. Satellite imagery proved useful for indicating the direction of ice movement from glacial features, as well as suggesting the possible location of major fractures along the southern edge of the Solway Basin.

It was concluded that the baryte mineralisation may be present locally in sufficient quantities to be of economic interest, but that base-metal mineralisation was weak. The epigenetic mineralisation is considered to be Upper Carboniferous to Lower Permian in age and to be the product of fluid flow through open fractures at the margin of the Solway Basin. The deposits have several features in common with Irish and Pennine-style ore deposits but there are also some clear differences, notably the paucity of Pb-Zn mineralisation.

## INTRODUCTION

This report describes broadscale geological, geochemical and geophysical surveys across Carboniferous rocks which crop out along the northern margin of the English Lake District (Figures 1 and 2). The results prompted brief follow-up investigations in the Ruthwaite, Tallentire and Whitrigg areas (Figure 1) which are described in Part 2. The work was carried out to aid a reassessment of the mineral potential of this area. The reassessment was prompted by the results of the BGS regional geochemical survey, recent geological mapping and the application of geological models, all of which suggested that mineralisation in this area was probably more extensive than suggested by published information.

The area investigated extends from near Caldbeck in the east, where rolling hills reach 373 m above OD at Sandale, across undulating mainly drift covered low ground forming the north-eastern portion of the Cumbrian Coalfield, to the coast at Maryport. Pasture covers much of the area though a little arable farming is practised and there are some areas of rough marginal grazing, particularly in the east. To the north the land is low-lying and underlain by the Permo-Triassic rocks of the Solway Basin. In the south the margin of the area is formed by the Lower Palaeozoic rocks of the Lake District massif. Here the land, which rises rapidly to 931 m on Skiddaw, is covered by rough grass and heather and is used mainly for grazing sheep. The south-eastern part of the area lies within the Lake District National Park, the boundary passing close to Ireby and Cockermouth (Figure 1). In stark contrast, the coastal belt is industrialised. Industrial activity, formerly based on the presence of coal and iron ore, is now heavily dependent on the British Nuclear Fuels reprocessing facility at Sellafield. Quarrying and opencast coal mining are also major employers.

Coal is currently worked opencast at two sites within the area and was formerly won from several sites which are now abandoned and restored. Two large modern quarries produce limestone, mainly as crushed rock aggregate and roadstone, and the area includes many abandoned limestone quarries. Sandstone was formerly worked for building stone and some clay ironstone and fireclay are known to have been extracted. Small quantities of baryte were mined near Gilcrux and Ruthwaite and trials were made last century on copper-bearing veins at Threapland, Papcastle and near Whitrigg.

The area is situated within Ordnance Survey 1:50,000 map sheets 85 (Carlisle) and 89 (West Cumbria), and British Geological Survey 1:50,000 map sheets 22 (Maryport), 23 (Cockermouth) and 28 (Whitehaven). Regional geochemical and geophysical survey data are also available. The regional geophysical data comprise the results of an airborne magnetic survey (Institute of Geological Sciences, 1978) and a gravity survey (Institute of Geological Sciences, 1977) published as 1:250,000 contour maps. Both datasets are now also available in digital form (Smith and Royles, 1989). The results of a rapid regional geochemical stream sediment survey of England and Wales carried out by the staff and students of Imperial College was published in 1978. The BGS stream sediment Geochemical Survey Programme has covered this area recently and the results are now available in digital form. The results of mineral exploration work carried out in this area under the MEIGA (Mineral Exploration and Investment Grants Act) scheme are held on open file by BGS.

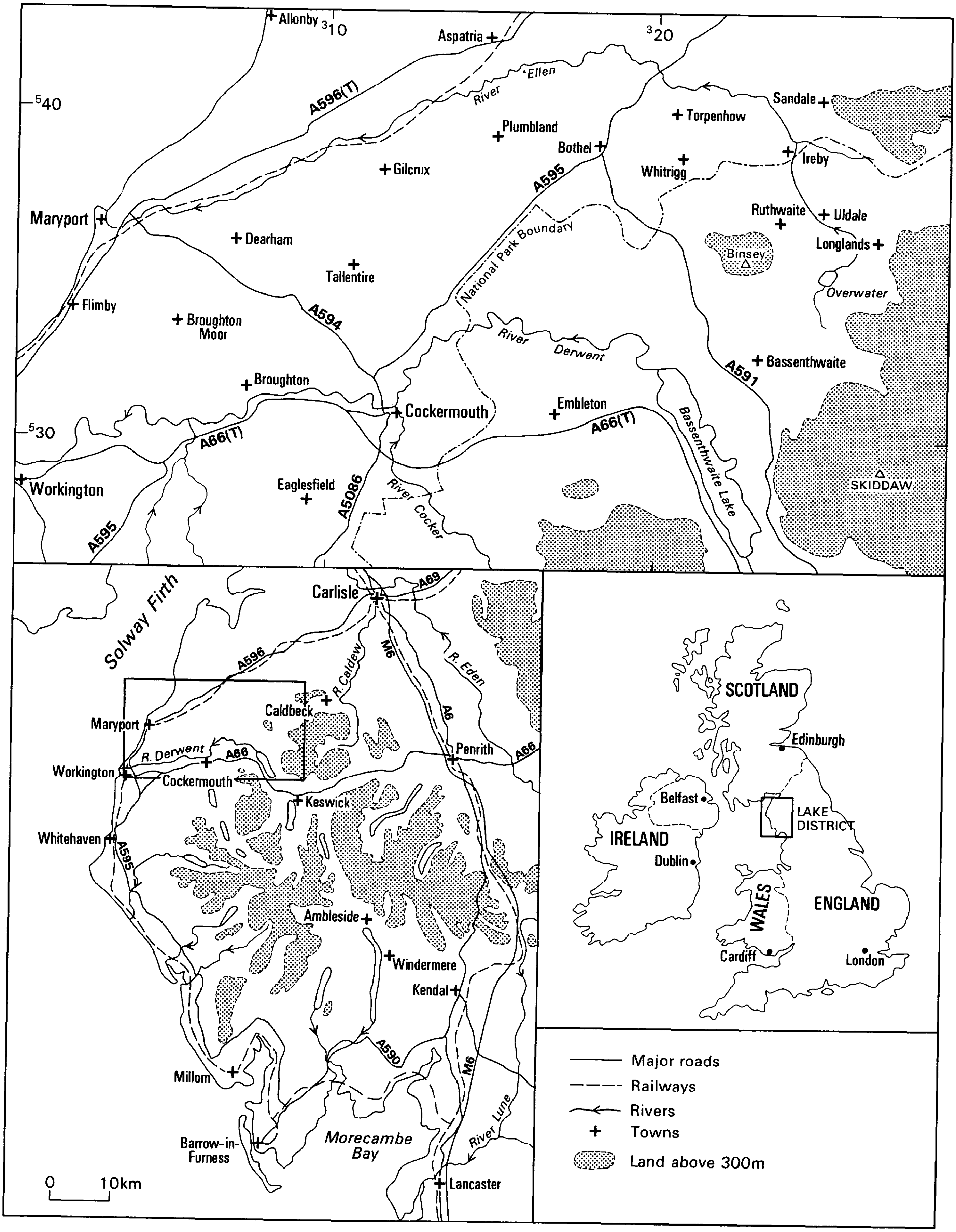


**Figure 1** Location of the survey area

**Previous research**

The area was originally geologically surveyed at the six-inch scale by T V Holmes, R Russell and J C Ward and published as one-inch maps in 1890 and 1892. Some revision by J G Goodchild and Sir A Strahan was undertaken in 1894 and published in 1895. Re-surveying on the six-inch scale was carried out by E E L Dixon, T Eastwood, S E Hollingworth, W C C Rose, B Smith, L H Tonks and F M Trotter between 1921 and 1932. Memoirs were published for each of the Geological Survey One-inch (now 1:50,000) sheets (Eastwood, 1930; Eastwood et al., 1931; Eastwood et al., 1968). Revision surveys of parts of the area have recently been undertaken by M Armstrong, R P Barnes, D V Frost and B Young as part of a study commissioned by the Department of Environment (Barnes, et al., 1988; Young and Armstrong, 1989).

Other studies concerned with the Carboniferous rocks of the area include those by Garwood (1913), Taylor (1961), Mitchell et al. (1978) and Ramsbottom (1973, 1977). The most detailed recent study of the Carboniferous Limestone is that by Stabbins (1969). The geochemistry of the Cockermouth lavas was described by McDonald and Walker (1985).

Little has been published on mineralisation within the Carboniferous rocks of the Cockermouth area except for descriptions of the Ruthwaite and Gilcrux baryte workings (Wilson et al., 1922; Dunham and Dines, 1945; Adams, 1988). Eastwood et al. (1968) discussed mineralisation at Threapland Hall and Whitrigg. Calvert (1854) reported finding small patches of gold in hard gossan in a mine near High Ireby, but no further details were given and as far as is known no gold has been found since. Firman (1978) made passing reference to trials for copper near Papcastle and to the common occurrence of baryte coating joints in the Carboniferous limestones near Cockermouth. Other brief notes on mineral occurrences within the area have been published by Young and Nancarrow (1988A, 1988B)

There have been few geochemical or geophysical studies in the area except for those related to mineral exploration or forming part of a regional survey. Geophysical studies forming part of a BGS Regional Geological Survey Project have provided data relevant to the regional and deep structure of the area (Lee, 1986; 1989) and assisted in mapping the Eycott Volcanic Group.

Metalliferous mineral exploration along the northern margin of the Lake District has been concentrated in three small areas. These are around Longlands [NY 267 360] and Woodhall [NY 341 372], which lies to the east of the area covered by this report, and Whitrigg near Bothel (Figure 1). During the first phase of the MRP, geological mapping accompanied by geochemical (stream sediment and soil) and geophysical (IP and EM) surveys were carried out across two areas, each of about 10 km$^2$, around Longlands and Woodhall. The two areas were selected on the basis of the known geology, both being drift covered areas where the projection of mineralised structures in the Lower Palaeozoic rocks of the Lake District massif intersected the Lower Carboniferous. Geochemical and geophysical anomalies were detected, but the geochemical anomalies were attributed to secondary concentrations arising from the redistribution of metals from old mines and the geophysical anomalies were assessed as not constituting viable drilling targets, so no further work was carried out (Wadge, Appleton and Evans, 1977).

Following reconnaissance sampling in the Cockermouth - Sandale area Consolidated Goldfields Ltd. carried out soil sampling, trenching and IP surveys in the area around Whitrigg, Stangerhill and Bird House under the provisions of the Mineral Exploration Investment Grants Act 1972

(MEIGA). Geochemical and geophysical anomalies were identified and six diamond drill holes sunk to investigate their cause. No potentially economic sulphide concentrations were located. IP anomalies were attributed to pyrite in both the Carboniferous and underlying altered volcanic rocks. The geochemical anomalies were not satisfactorily explained. A few years later BP Minerals International re-appraised these data and concluded that the area merited further investigation. Detailed geological mapping accompanied by further soil sampling and geophysical survey work was completed under another MEIGA project. A substantial Cu, Pb and Zn in soil anomaly with a coincident gravity anomaly was located and investigated by two bore-holes. These failed to provide an explanation for the gravity anomaly and no source of base-metals was intersected. It was considered that the geochemical anomalies might be caused by leakage along fractures or mineralised faults. Following drilling, deep overburden traversing and a VLF survey were carried out. The VLF data indicated the probable line of the boundary fault between the Lower Palaeozoic and Carboniferous rocks beneath the drift, while the presence of higher Pb and Zn anomalies in overburden at 1 m than at the bottom of the holes suggested that the soil anomalies were transported.

### Selection of the survey area

During a re-assessment of the mineral potential of the Lake District the Lower Carboniferous rocks along the northern margin were identified as potential hosts for base-metal mineralisation. The principal reasons for this conclusion were the apparent similarity of the geological setting of the Cockermouth area and that of Pennine and Irish-style ore deposits, and two new lines of evidence which were considered to enhance the mineral potential of the area. Firstly, revision geological mapping of the Carboniferous Limestone north of Cockermouth during 1986-7 revealed that baryte, locally accompanied by copper minerals, was very common in many exposures of limestone and locally sandstones, where in places it occurred in veinlet and disseminated form. A brief reconnaissance of the Lower Carboniferous outcrop indicated that such mineralisation was locally abundant between Cockermouth and Caldbeck. Secondly, the BGS regional stream sediment survey data showed the presence of a large area of very high barium values extending from the known mineralisation in the Caldbeck Fells northwards and westwards across Carboniferous rocks to the coast between Workington and Maryport. Prominent Cu and, locally, Zn, Sb, V and Pb highs were also evident well to the west and north of the mineral deposits on the Caldbeck Fells. Some of the high base-metal values in drainage were probably caused by contamination (from mining, industrial and domestic sources) but the new records of baryte and copper mineralisation clearly indicated that at least a proportion of the anomalies were related to hitherto undetected mineralisation. The work reported here was instigated to gain more information on the extent and magnitude of this mineralisation.

## GEOLOGY

The Carboniferous rocks of the Cockermouth area form part of an almost continuous outcrop which surrounds and unconformably overlies the Lower Palaeozoic rocks forming the central Lake District (Figure 2). The stratigraphical sequence is summarised in Table 1.

**Table 1** Stratigraphical succession

| | | |
|---|---|---|
| PERMO-TRIASSIC | | St Bees Sandstone |
| | | St Bees Shales |
| ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^unconformity^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ | | |
| CARBONIFEROUS | | |
| | Westphalian | Coal Measures |
| | Namurian | Hensingham Group |
| | | (Hensingham Grit at base) |
| | | First Limestone |
| | Dinantian | Second Limestone |
| | | Orebank Sandstone |
| | | Third Limestone |
| | | Fourth Limestone* |
| | | Fifth Limestone |
| | | Sixth Limestone |
| | | Seventh Limestone |
| | | Cockermouth Lavas |
| | | Basement Beds |
| ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^unconformity^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ | | |
| ORDOVICIAN | | Eycott Volcanic Group |
| | | Skiddaw Group |

*Detailed in Figure 3

## Lower Palaeozoic

In the neighbourhood of Cockermouth the Lower Palaeozoic rocks comprise a thick sequence of turbiditic sandstones, siltstones and mudstones forming part of the Skiddaw Group (Jackson, 1978), and basaltic to rhyolitic lavas and tuffs of the Eycott Volcanic Group (Moseley and Millward, 1982). The Skiddaw Group rocks range from Tremadoc to Llanvirn in age and their precise relationship to the Eycott lavas and tuffs is uncertain. Published work indicates that the volcanism is early Llanvirn in age and contemporaneous with part of the Skiddaw Group (Downie and Soper, 1972; Wadge, 1978). The succession is folded, faulted and affected by low-grade metamorphism which accompanied Caledonian tectonic events. To the south of the survey area the succession is cut and metamorphosed by the late Caledonian (395 Ma) Skiddaw Granite, a component of the Lake District granitic batholith (Firman and Lee, 1986), and the older Carrock Fell gabbro-granophyre complex, which is associated with the Eycott volcanic event. The Skiddaw Group is also cut by a range of variably altered ultrabasic, basic and lamprophyric minor intrusions attributable to a number of Caledonian igneous events.

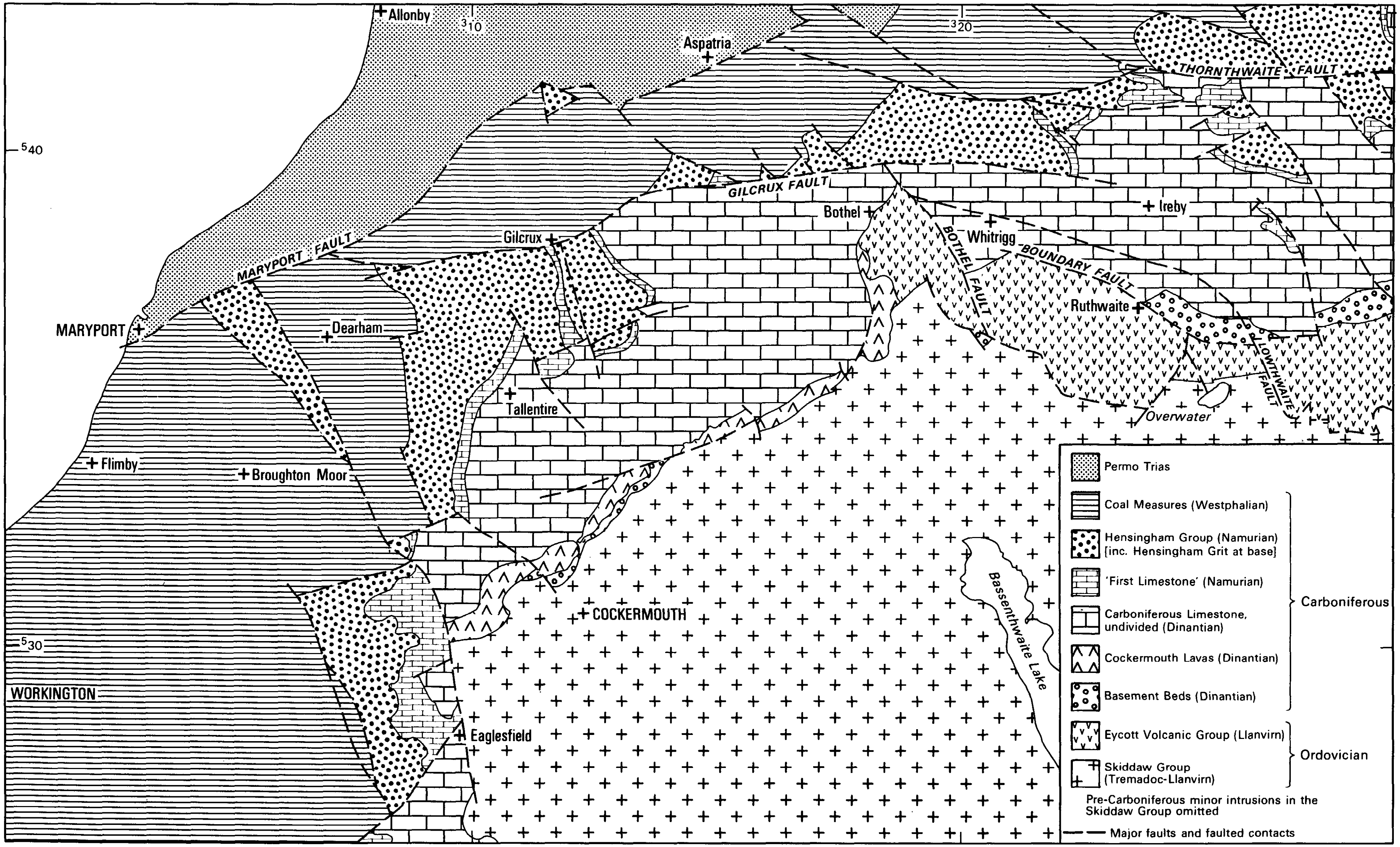


**Figure 2** Simplified geological map of the survey area

## Carboniferous

During early Carboniferous time the area lay adjacent to the northern margin of the much eroded Manx-Cumbrian-Alston ridge, the rocks of which had been folded and elevated during the Caledonian earth movements. To the north lay the Northumberland Trough and its westward extension the Solway Basin. Separating these two structural and depositional provinces was a major east-west fault belt along which considerable northward subsidence took place during Carboniferous sedimentation. This line corresponds to the present day Gilcrux-Stublick-Ninety Fathom fault systems of Cumbria and Northumberland. Evidence for contemporaneous Carboniferous movement along this fault belt is provided by the rapid increase in thickness of Carboniferous formations as they are traced northwards from the relatively stable shelf areas on the margins of the massif into the basin in which subsidence was comparatively rapid. Leeder (1982) proposed that basin subsidence was caused by lithospheric stretching resulting in regional tension, rift formation and volcanism along part of the remnant Iapetus suture. The presence of a series of tholeiitic basalts, the Cockermouth Lavas, locally at the base of the Cumbrian Carboniferous succession, records a volcanic episode associated with early movement along this fault-belt during the initiation of the basin (McDonald and Walker, 1985). Renewed movement along the fault belt in post-Carboniferous times produced the prominent *en echelon* system of east-west faults of which the Maryport and Gilcrux faults form part.

### *Dinantian*

The earliest Lower Carboniferous deposit in the area is the Basement Conglomerate. This comprises a group of conglomerates composed mainly of pebbles of locally derived rocks from the Skiddaw and Eycott Volcanic Groups. Thin beds of coarse-grained sandstone and mudstone are also present locally. Up to 30 m of Basement Conglomerate is present in the east near Ruthwaite, though the thickness is much less around Cockermouth, and near Bothel mapping suggests that these basal beds may be absent. Mitchell et al. (1978, pp 171) record the presence of a spore assemblage indicative of the Courceyian Stage at the base of the Dinantian near Bothel.

Between Cockermouth and Bothel the basal conglomerate is overlain by the Cockermouth Lavas; a group of tholeiitic basalts and minor andesites up to 100 m in thickness. McDonald and Walker (1985) noted that up to six individual flows may be present. The top and bottom of the flows are typically vesicular and commonly contain silica, calcite and chlorite amygdales. The tops of the flows commonly exhibit 'bole' horizons indicative of sub-aerial weathering. Macdonald and Walker (1985) concluded from a study of the geochemistry of the lavas that they were derived from the partial melting of homogeneous mantle source rocks followed by fractional crystallisation at a high crustal level. Intrusion was associated with crustal attenuation and initiation of the Northumberland Trough.

Overlying the Cockermouth Lavas, or where these are absent, the Basement Conglomerate or the Lower Palaeozoic rocks, the West Cumbrian Dinantian sequence is dominated by limestone (Table 1). Individual limestone units have long been recognised and named in descending order from the Second down to the Seventh Limestone (the First Limestone, is of Namurian age and is discussed briefly below). This nomenclature has its origins in the early days of west Cumbrian iron ore mining when successively lower limestones were encountered in shaft sinking and mine development. They have since been grouped into a number of lithostratigraphical and chronostratigraphical classifications summarised by Young and Armstrong (1989).

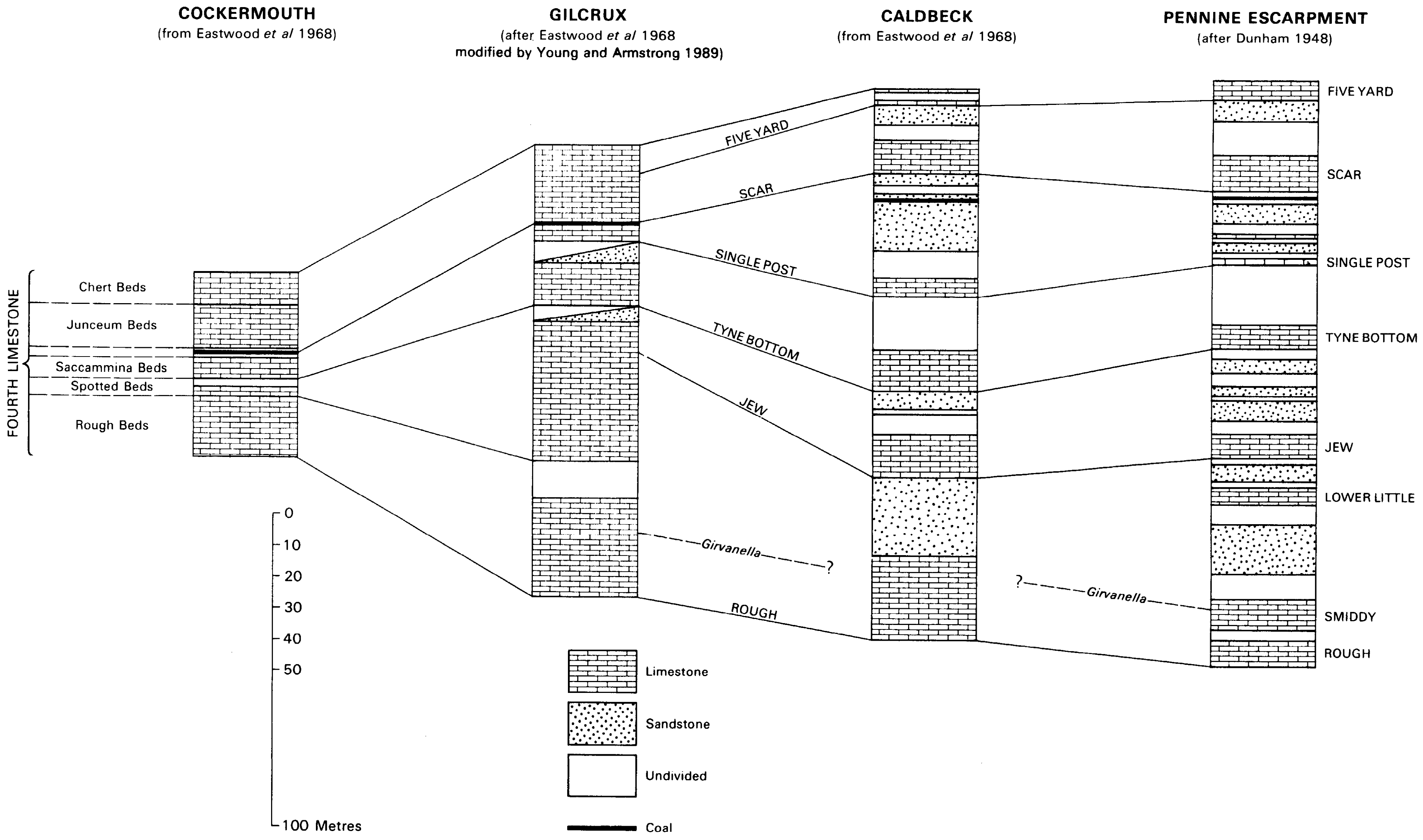


Figure 3 Lateral variation in the Fourth Limestone

A variety of limestone lithologies and textures is present within the area. Detailed descriptions of individual units and outcrops have been published by Eastwood et al. (1968), Stabbins (1969) and Young and Armstrong (1989) and only brief comments are given here. Most of the limestones are medium to pale grey wackestones and packestones as defined by Dunham (1962). Within certain limestone units, e.g. the Fourth Limestone, beds of fine grained porcellanous limestone, mudstone of Dunham's classification, occur. Many beds of nodular limestone are present especially in the Fourth Limestone and beds of limestone pseudobreccia, known in earlier literature as "spotted limestone", are also common. In places, e.g. Moota Quarry, massive limestones pass cyclically upwards into markedly nodular beds. The limestones are commonly thickly bedded and well-jointed rocks with individual beds or "posts" up to over 1 m thick. Thin beds or partings of calcareous mudstone up to 0.1 m thick are locally common. Many of the area's limestones are slightly bituminous and smell faintly "oily" when hammered. Slight recrystallisation has affected most of the limestones though fossils are generally still easily recognisable. Fossils are common and are most easily seen on weathered surfaces. Most common are crinoid fragments, brachiopods and large colonial corals with bryozoa, foraminifera and algae locally.

Between the limestones occur other lithologies, mainly mudstone and sandstone. The sandstone between the Second and Third Limestone is known as the Orebank Sandstone. This is a variable succession of terruginous sediments which in the south-east is dominated by sandstone, around Gilcrux comprises shales and minor sandstone, and in the east is dominated by coarse feldspathic sandstones (Eastwood et al., 1968). Bentonitic characteristics noted in some of the mudstones of the west Cumbrian Dinantian by Walkden (personal communication in Mitchell et al., 1978, pp 175) have been interpreted as the products of accumulated air-borne volcanic ash which became weathered into soils during periods of emergence. Within the Lower Carboniferous rocks of the Cockermouth area the predominance of limestone, with only comparatively thin sandstone, mudstone and coal intercalations, indicate that non-marine influences were in general weak. However when traced eastwards from Cockermouth towards Caldbeck a progressive increase in the thickness of non-marine intervals marks the transition to the typical rhythmic "Yoredale facies" of the Northern Pennines. This is well illustrated within the Fourth Limestone (Figure 3).

### *Namurian*

The Namurian sequence is the least known part of the west Cumbrian Carboniferous succession. In this area it comprises the Hensingham Group as described by Young and Armstrong (1989). The basal unit is the First Limestone, a generally medium grey thickly-bedded wackestone with scattered crinoid and shell debris which closely resembles many of the underlying Dinantian limestones. The First Limestone represents the last major period of limestone deposition in west Cumbria. It is overlain by a sequence of clastic sediments which reflect increasingly important deltaic influences with only comparatively minor marine incursions. Except in the extreme east of the area the First Limestone is overlain by the Hensingham Grit. This is typically a coarse to very coarse-grained, thickly bedded massive sandstone in which kaolinised feldspar grains are common. Pellets of earthy hematite or hematite-rich shale up to 2 cm across are present locally. The Hensingham Grit has not been recognised in the extreme east of the area (Eastwood et al., 1968, pp 181-2). Above the Hensingham Grit the sequence is very poorly known but appears to consist predominantly of non-marine sandstones and mudstones in places with clay-ironstone nodules. Thin marine mudstones may be present and thin marine limestones are known locally. The sediments of the Hensingham Group appear to exhibit a passage from the dominantly marine environments of the Dinantian to the essentially non-marine fluvial and deltaic environments of the uppermost Carboniferous, the Westphalian.

*Westphalian*

The base of the Westphalian Coal Measures of Cumbria is taken at the inferred horizon of the Subcrenatum Marine Band. Much of the Coal Measures sequence comprises a cyclical succession of mudstones, sandstones, seatearths and coals. Marine bands, thin beds of mainly dark grey mudstone with marine fossils such as brachiopods, bivalves and goniatites, record comparatively rare and short-lived incursions of marine conditions within the otherwise freshwater environment of the Coal Measures. These marine bands provide excellent correlative horizons with other coalfields. Much of the coal production from the Cumbrian coalfield has been obtained from about 15 main seams, some of which are up to 3 m thick. Other, generally thinner and poorer quality seams also occur and many of these have been worked locally. Iron ore which occurs as "clay ironstone" (siderite mudstone) nodules in some mudstones has been mined in places. Fireclay has also been worked and production continues intermittently as a by-product of opencast coal mining: all coal won from the coalfield today is obtained by opencast mining. In West Cumbria, as in many parts of Britain, the higher parts of the Coal Measures succession commonly exhibits strong red colouration due to intense oxidation beneath the sub-Permian unconformity. This oxidation is believed to have developed under arid conditions when the water table was considerably depressed.

## Permo-Triassic

The Permian rocks of the area, the St Bees Shales, are known only in boreholes from the area north of Maryport. They are overlain by the Triassic St Bees Sandstone, a thick formation of fine-grained red to reddish-brown sandstones which crop out on the coast at Maryport. At outcrop in the area described here, the Permo-Triassic rocks are everywhere faulted against the Carboniferous rocks.

## Structure

The Carboniferous rocks of the Cockermouth area dip westwards and north-westwards away from the Lower Palaeozoic basement of the Lake District. The general regional dip is considerably interrupted by a number of gentle folds and by many normal faults in which two principal trends may be recognised. One trend is north-west - south-east the other varies between east-west and east-north-east - west-south-west. Members of both sets of faults truncate fold structures although it is likely that both faults and folds developed simultaneously. The north-west-trending faults throw down both to the south-west and north-east whereas the complimentary east-west or east-north-east - west-south-west set throw down mostly, but not exclusively, to the north. Throws of over 200 m are common and the Gilcrux Fault can locally be shown to have a northerly displacement of approximately 400 m. The fault pattern can be traced in greatest detail in the varied sequence of Carboniferous rocks. Less detailed interpretations can be made within much of the underlying Lower Palaeozoic basement. However there are good grounds for believing that re-activation of fractures within the Lower Palaeozoic in post Carboniferous times may have been responsible, at least in part, for the present structural pattern of the Carboniferous cover.

Over much of the area faults of north-west - south-east-trend are dominant. However a belt of country up to about 5 km wide which runs roughly east-north-east - west-south-west from Maryport to north of Caldbeck is characterised by prominent groups of *en echelon* faults of generally east-west-trend. This belt corresponds closely to the inferred position of the marginal zone of Carboniferous deposition on the northern fringe of the Lake District massif. Contemporaneous faulting on east-north-east - west-south-west lines, perhaps accompanied by some deformation in the marginal zone, may have affected deposition of Lower Carboniferous sediments. Re-activation of such deep-seated faults in late or post-Carboniferous times may have given rise to the present fault pattern.

There is no direct evidence of contemporaneous faulting of Carboniferous age. However Eastwood (1930) concluded that an anticline in the Allerby area was initiated following deposition of the Namurian First Limestone, thus accounting for the known thickness variations in the Hensingham Group in the Crosby and Bankend areas (see also Young and Armstrong, 1989).

All faults in the area displace various horizons within the Carboniferous sequence. The latest movements are therefore no earlier than late Carboniferous. In places the Gilcrux Fault throws reddened Coal Measures against rocks of the Hensingham Group. As the reddening does not appear to cross the fault final movements must post-date the reddening and are therefore probably of Permian or later age. Final movement along the Maryport Fault, which brings Coal Measures against St Bees Sandstone, is clearly no earlier than mid-Triassic although some early or pre-Triassic dislocation may have taken place.

### Drift deposits

Glaciation during Pleistocene times produced extensive but discontinuous spreads of boulder clay. Erratic boulders within the boulder clay indicate derivation from both south-west Scotland and the Lake District. Ice directions, deduced in part from trains of erratics and drumlins, show that during the main glaciation ice moved northwards from the highlands of the Lake District and then westwards across the Solway Basin into the Irish Sea (Figure 4). The course of the ice across low ground in the north of the area is marked by numerous drumlins which are particularly well marked on low-angle sun satellite imagery. Comparatively small areas of glacial sand and gravel, mainly deposited during the glacial retreat, are present locally. Post-glacial deposits include alluvium, river terrace sediments and peat.

## MINERALISATION

### Introduction

There are few published references to mineralisation in the Carboniferous rocks of the Cockermouth area. Those which have appeared are mainly brief and confined to descriptions of individual mine workings (e.g. Wilson et al., 1922; Dunham and Dines, 1945; Eastwood et al., 1968). Mineralisation in the Lower Palaeozoic rocks to the south is better documented and will not be described here. Published descriptions include those of Dewey and Eastwood (1925), Eastwood (1921), Firman (1978), Postlethwaite (1913), Rastall (1942), Cooper and Stanley (1990), Fortey (1978) and Fortey et al. (1984). Young (1987) has listed mineral occurrences in the Lake District and around its margins. Stanley and Vaughan (1982) have discussed the metallogenesis of the Lake District ore deposits and classified them on the basis of mineralogy and age.

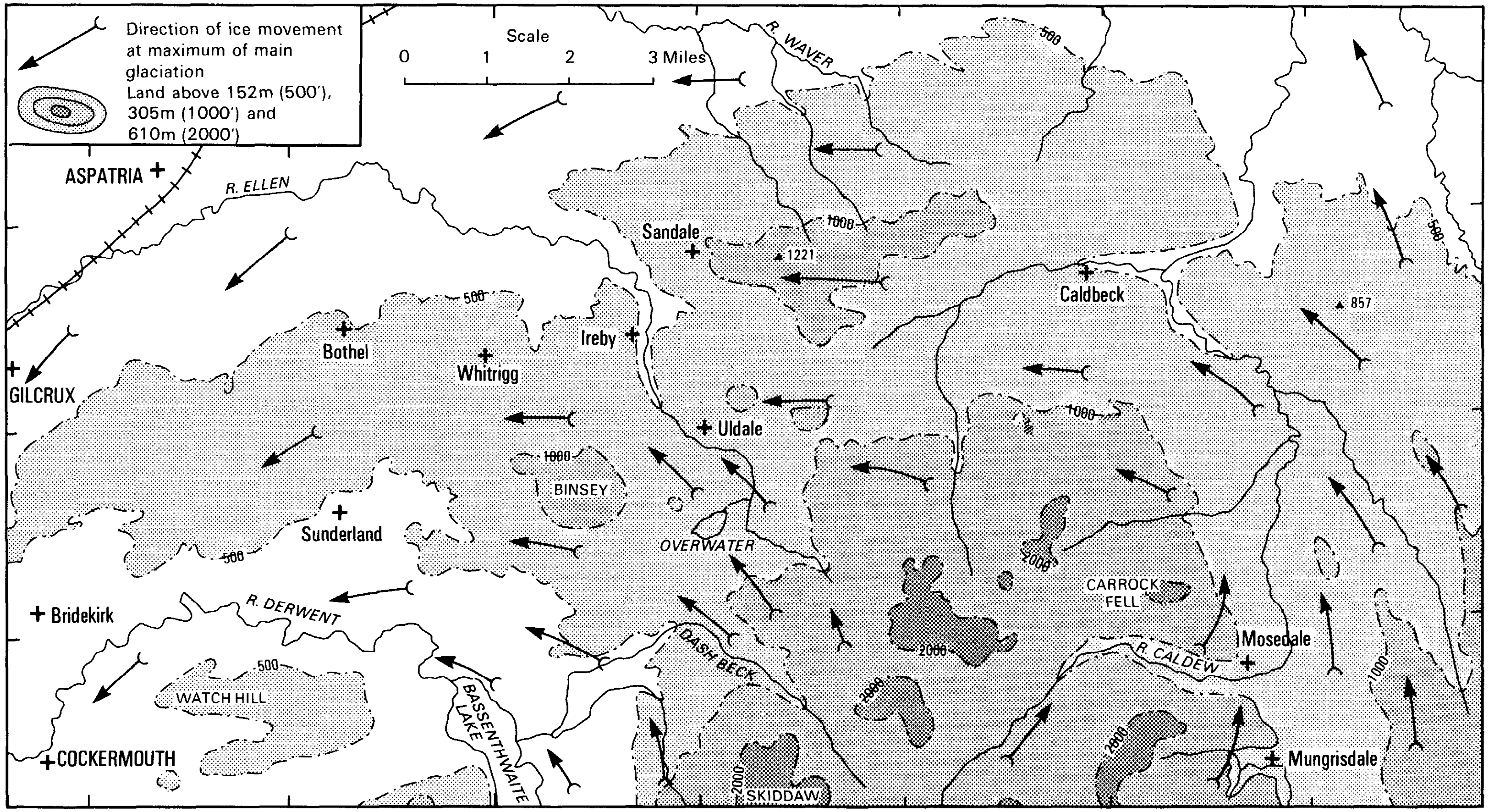


**Figure 4** Direction of ice movement deduced from glacial features and deposits (after Eastwood et al., 1968)

As a result of revision geological mapping of the Lower Carboniferous outcrop north of Cockermouth, a reconnaissance of the Lower Carboniferous outcrop along the northern flank of the Lake District, and the work reported here, many new mineral occurrences have been found. All known mineral occurrences in the Upper Palaeozoic rocks are shown in Figure 5 and listed in Appendix 2. Details of individual occurrences in the Tallentire, Ruthwaite and Whitrigg areas will be given in Part 2.

## Mineral occurrences

Most of the mineralisation seen within the area (Figure 5) is clearly of epigenetic origin and occurs mostly as fillings, generally up to 2 cm thick, of joints in limestones and locally sandstones. No evidence has been found for any preferred joint direction for mineralisation. In many localities the dominant joint direction at that site hosts most of the mineralisation. At several places all joints carry minerals. In places wider mineralised bodies occupy faults. A very small number of such deposits have been worked on a small scale or trials made on them. Vein widths of up to 4.9 m of baryte were recorded at Ruthwaite Mine. In the Tallentire area the Hensingham Grit contains patchy impregnations of baryte considered here to be related to mineralisation along nearby faults.

Mineralisation of diagenetic origin is also present within the area. Pyrite is found generally in small amounts, disseminated through many of the Carboniferous shales. Boreholes near Whitrigg revealed pyrite as disseminations and small nodules in Lower Carboniferous shales. Pyrite is common in many of the Coal Measures shales and is abundant in certain coal seams, most notably the aptly named "Brassy" and the Ten Quarters. Diagenetic siderite, both in the form of "clay ironstone" and as the spherulitic variety sphaerosiderite is widespread in mudstones, especially seatearth mudstones, in both the Hensingham Group and Coal Measures. One bed of clay ironstone nodules (between the Rattler and Ten Quarters seam) in the Oughterside opencast coal site was notable for the presence of relatively abundant millerite, sphalerite and chalcopyrite, all considered to be of diagenetic origin (Young and Nancarrow, 1988A). Coarsely crystalline baryte within a septarian clay ironstone nodule in the Coal Measures near Gilcrux is also most probably of diagenetic origin.

A small number of altered and mineralised rocks were analysed for a wide range of elements by X-Ray Fluorescence Spectrometry to look for significant metal concentrations not evident in hand specimens. The results are listed in Table 2.

### *Barium*

Baryte is the most widespread introduced mineral throughout the area. In most exposures it occurs as medium to coarsely crystalline fillings of joints up to 2 cm thick. In most instances the joints are entirely filled, though locally open vugs are lined with terminated crystals typically forming "cockscomb" aggregates. Good examples may be seen in Wardhall Quarries [NY 1347 3832] near Gilcrux and in Clints Quarries, Bothel [NY 1620 3630] and [NY 1610 3570]. Much of the baryte is salmon pink in colour, especially adjacent to the limestone wall-rock, though it commonly becomes white or colourless towards the centre of wider joint or fault fillings. A crude colour banding parallel to the walls may be observed at Wardhall Quarries. Imperfectly developed tabular white crystals up to 15 cm across are conspicuous on joints in the First Limestone on Wardhall Common [NY 1365 3718].

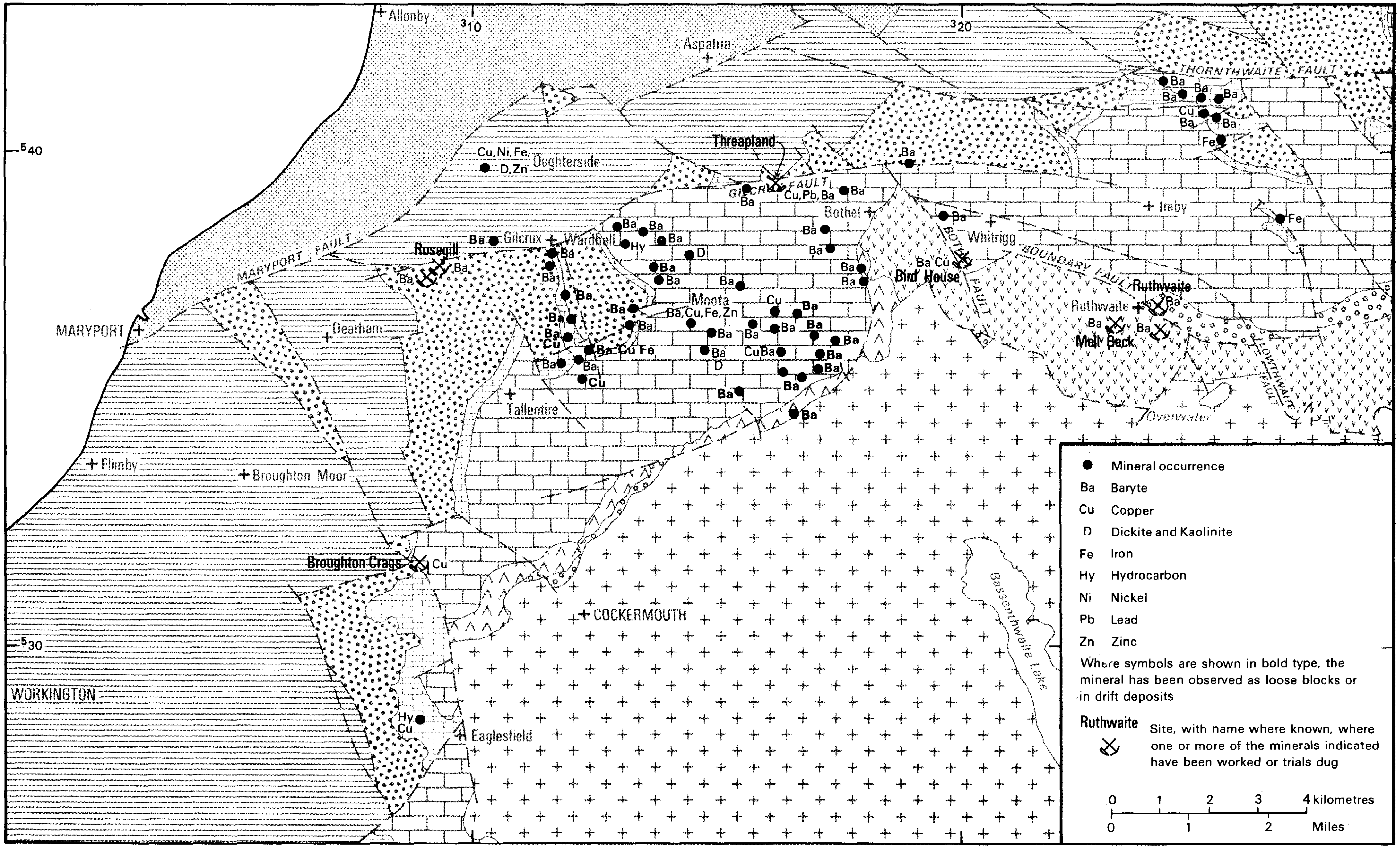


**Figure 5** Location of mineral occurrences

Thick veins of baryte, described in Part 2, have been worked at Ruthwaite, Mell Beck and Birdhouse. Elsewhere, widths of baryte greater than a few centimetres are known from a few sites. Probably the most spectacular exposure of baryte mineralisation is in the abandoned central quarry [NY 1620 3624] at Clints near Bothel. Here coarsely crystalline tabular white baryte occurs as abundant bands and lenses up to 30 cm wide within two parallel vertical north-east - south-west-trending bands of brown altered limestone, interpreted as the Fifth Limestone. No displacement can be demonstrated along the mineralised bands which appear to be unusually wide mineralised joints. The dark brown and locally earthy-textured altered limestone appears to consist simply of calcite with a small but conspicuous content of ferric oxide. Infra-red spectroscopy indicated that no dolomite, ankerite or siderite was present in the samples analysed. The brown carbonate alteration appears to predate the baryte. Similar wall-rock alteration, though usually on a millimetre scale, is present at many of the baryte occurrences. A little fine-grained quartz is present in the brown altered rock at Clints Quarry. Goethite pseudomorphs after chalcopyrite were noted encrusting "cockscomb" baryte in a few vugs here.

West of Gilcrux, trials were made on two vertical north-north-west - south-south-east fault veins of baryte in sandstones and shales of the Hensingham Group in Rosegill [NY 0912 3741] and Green Gill [NY 0928 3752]. Brief descriptions of the workings were given by Wilson et al. (1922, pp 27-28). The western vein, formerly exposed in Rosegill [NY 0912 3741] was up to 0.61 m wide over a strike length of only a few metres. A trial below stream level to a depth of 5.5 m revealed good quality baryte but further exploration was prevented by flooding. The eastern vein showed a similar width of baryte in a trial pit 8.8 m deep on the north side of Green Gill but here also flooding prevented deeper exploration. Attempts to locate the vein on the south side of the stream were unsuccessful. The date of these operations is unknown but was probably late last century. Wilson et al. (op. cit.) report a total production of only 25 tons of baryte. Blocks near the western trial suggest that the mineral in both veins varied from white to pale pink and was coarsely crystalline. No other introduced mineral has been observed, although an analysed sample of tip material (Table 2) contained significant amounts of Cu (310 ppm) accompanied by relatively high levels of V (345 ppm) and Mo (11 ppm).

A distinctive form of baryte mineralisation consists of the white to pink patchy impregnations of baryte found in coarse-grained Hensingham Grit at Top Wood south-east of Gilcrux ([NY 1329 3659] and [NY 1325 3640]). Similar impregnations are present on Wardhall Common [NY 1395 3729] in the sandstone beneath the Third Limestone. Analyses of two samples (Table 2, nos. 1253 and 1254) indicated that, apart from Sr and traces of Hg, no significant enrichment of other metals accompanied the baryte mineralisation.

### *Copper*

Small amounts of chalcopyrite, or more rarely malachite, are found with baryte at many localities but it rarely forms a major constituent of the mineralisation. The largest known concentrations of copper ore are at Threapland, near Bothel, and Broughton Crags, near Cockermouth. Trials have been made on both of these deposits.

At Threapland [NY 1620 3942] the remains of an adit and its associated dump could be seen until recently when the site was reclaimed by the landowner. No plans or other records of the mine or trial have been traced and the date of working is unknown. Eastwood et al. (1968, pp 168) concluded that the adit was driven on a mineralised section of a north-north-west - south-south-east fault with a large downthrow to the east though there is no direct field evidence that this was the mineralised structure. The dump contained fine-grained white sandstone together with abundant compact grey limestone. Mapping suggests that the beds penetrated belonged to the Fourth to Fifth Limestones. Mineralised material on the dump included limestone, veined with pale fawn dolomite, pure white baryte, in pieces up to 5 cm across free of any matrix lithology, and abundant chalcopyrite in masses up to 3 cm across, usually with colourless quartz veining sandstone. The chalcopyrite locally was associated with galena. Sphalerite was also present. Supergene minerals associated with, and commonly encrusting chalcopyrite were malachite, azurite and rarely a little compact red cuprite. Analyses of tip material (Table 2) indicate that, besides the visible Cu, Zn, Ba and Pb mineralisation, Hg and As are also present in small amounts. The vein mineralisation here shows a wider range of metal enrichments than elsewhere within the Lower Carboniferous of this area and may be polyphase: in some specimens coarsely crystalline baryte can be seen overgrowing and filling the central parts of quartz-sulphide veins. The tip material suggests a wallrock control on mineralisation with most sulphides associated with quartz gangue in sandstone whilst the limestone host rocks are dominated by carbonate veins.

Firman's mention (1978, pp 237) of a copper trial at Papcastle near Cockermouth refers to a small trial adit formerly visible near the entrance to Broughton Crags Quarry [NY 091 317]. The quarry has long been abandoned and used as a rubbish dump: no sign of the adit or of mineralisation in situ can now be found. According to J A D Dickson (personal communication) the adit, still visible in the late 1950's, was driven along a fault adjacent to strongly dolomitised limestone. Chalcopyrite was apparently the ore mineral though nothing is known of its abundance or of any associated minerals. The fault seems to trend roughly north-west - south-east and chalcopyrite is believed to have been visible at one time a short distance to the south-east in the banks of the River Derwent, along what was presumed to be the same fault.

Other occurrences are small. Chalcopyrite and malachite are comparatively common in soil brash on parts of Tallentire Hill and 1.8% Cu was recorded in a sample of mineralised clasts from here (Table 2, no. 1296). Chalcopyrite, locally in masses up to several centimetres across, occurs in joints and fault veins in Moota Quarry. Traces of chalcopyrite and rare stains of malachite accompany baryte in the Clints Quarry area near Bothel and on the tips of the Birdhouse trial. A little malachite has been observed in the Sandale area and at the Ruthwaite baryte mine. Rare disseminated chalcopyrite associated with pyrite, was recorded in dolomite fracture fillings in boreholes through the Lower Carboniferous succession at Whitrigg and crystals of chalcopyrite of syngenetic/diagenetic origin are recorded from the Coal Measures (Young and Nancarrow, 1988B).

### *Lead*

Lead minerals occur only in very small amounts at a few localities. Galena has been found only at the Threapland trial [NY 1620 3942] where it occurs in small amounts associated with chalcopyrite. Cerussite was also found here in a partially oxidised block of galena-rich veinstone. Analysed samples of altered volcanic rocks from the tips of the Birdhouse trial were found to be enriched in Pb (Table 2) but no Pb-minerals were seen.

### *Zinc*

Zinc mineralisation is also rare. A little brown sphalerite was found in debris from the Threapland trial and a few small specimens of pale brown sphalerite have been obtained from a dolomite vein in Moota Quarry [NY 1430 3625]. Large amounts of Zn were recorded in an analysed sample of

**Table 2** Chemical data (in ppm) of rocks collected in the Cockermouth area

| Number | Grid Ref. (NY) | Description | Ti | V | Cr | Mn | Fe |
|---|---|---|---|---|---|---|---|
| Birdhouse trial | | | | | | | |
| 1201 | 2012 3764 | Birdhouse mine tip debris | 1880 | 229 | <2 | 210 | 2700 |
| 1203 | 2001 3760 | Altered andesitic tuff | 5970 | 20 | <2 | 1260 | 67500 |
| 1204 | 2001 3760 | Brecciated andesitic tuff | 6190 | 62 | 3 | 1210 | 47300 |
| 1205 | 2001 3760 | Brecciated, altered tuff | 6130 | 26 | 6 | 170 | 8400 |
| 1206 | 2012 3764 | Birdhouse mine tip debris | 740 | 407 | nr | 50 | 800 |
| 1207 | 1996 3789 | Brecciated, altered? tuff | 7340 | 89 | 8 | 50 | 1210 |
| Ruthwaite area | | | | | | | |
| 1210 | 2386 3683 | Baryte vein from mine tip | 860 | 369 | <2 | 20 | 400 |
| 1263 | 2381 3684 | Ruthwaite mine tip debris | 2000 | 125 | 134 | 3480 | 20700 |
| 1265 | 2340 3668 | Mell Beck vein material | 4200 | 108 | 79 | 6100 | 27100 |
| 1283 | 2399 3678 | Baryte, Ruthwaite | 1220 | nd | nd | 510 | 3600 |
| 1284 | 2341 3667 | Alt. volcanic rock, Mell Beck | 7580 | nd | nd | 1210 | 70700 |
| 1285 | 2340 3667 | Baryte from Mell Beck tip | 770 | nd | nd | 50 | 300 |
| Threapland and Rosegill | | | | | | | |
| 1202 | 1620 3942 | Threapland mine tip debris | 540 | 44 | 22 | 2150 | 27900 |
| 1208 | 1620 3942 | Threapland mine tip debris | 1190 | 18 | 29 | 90 | 30700 |
| 1209 | 0912 3745 | Rosegill mine debris | 720 | 345 | nr | 2560 | 33000 |
| Embleton | | | | | | | |
| 1234 | 1517 3046 | Altered diorite | 4710 | 134 | 25 | 1810 | 55500 |
| 1235 | 1460 3045 | Pyritic sericitised diorite | 6580 | 25 | <2 | 200 | 62200 |
| 1241 | 1670 3050 | Pyritiferous diorite | 11690 | 283 | 25 | 1510 | 85800 |
| 1244 | 1748 3088 | Brecciated diorite | 4430 | 101 | <2 | 14280 | 96400 |
| 1245 | 1748 3088 | Gossaneous breccia | 6900 | 129 | <2 | 8220 | 82900 |
| 1247 | 1670 3050 | Brecc. sandstone + qtz. vein | 8730 | 164 | 24 | 490 | 51500 |
| Tallentire area | | | | | | | |
| 1253 | 1400 3724 | Sandstone with baryte | 670 | 138 | 3 | 80 | 1100 |
| 1254 | 1329 3659 | Sandstone with baryte | 610 | 193 | <2 | 10 | 400 |
| 1262 | 1232 3570 | Mineralised float | 230 | 22 | 280 | 1200 | 35200 |
| 1296 | 1231 3572 | Mineralised float | 7790 | nd | nd | 270 | 97000 |
| Coal Measures | | | | | | | |
| 1237 | 0445 2732 | Spherulitic siderite | 2030 | 77 | 20 | 13710 | 429000 |
| 1238 | 0445 2732 | Ironstone nodule with baryte | 1050 | 99 | nd | 19710 | 347700 |
| 1239 | 0398 2672 | Sandstone | 4140 | 49 | 59 | 360 | 25800 |
| 1242 | 0392 3094 | Sandstone | 2100 | 30 | 40 | 1270 | 23100 |
| 1243 | 0392 3094 | Limestone with sulphide | 2390 | 31 | 71 | 4120 | 172100 |
| 1246 | 0445 2732 | Seatearth (siltstone) | 7660 | 128 | 155 | 110 | 13600 |
| 1255 | 0770 3330 | Pyrite from Coal Measures | 400 | 14 | <2 | 30 | 236400 |

nd not detected

nr not recorded (interference)

| Number | Co | Ni | Cu | Zn | As | Mo | Sn | Sb | Ba | Hg | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Birdhouse trial | | | | | | | | | | | |
| 1201 | 2 | 2 | 68 | 2 | 3 | 4 | <2 | <2 | 183200 | 7.10 | <3 |
| 1203 | 13 | <2 | 4 | 95 | 3 | <1 | <2 | <2 | 2014 | nd | 4 |
| 1204 | 24 | <2 | 34 | 65 | 19 | <1 | <2 | 4 | 1225 | nd | 357 |
| 1205 | 32 | 9 | 29 | 8 | 41 | 1 | <2 | 3 | 594 | nd | 264 |
| 1206 | <2 | 4 | 255 | <1 | <2 | 9 | 7 | <2 | 508960 | 6.50 | <3 |
| 1207 | 36 | 25 | 393 | 2 | 400 | 1 | <2 | 2 | 3827 | 40.0 | 25 |
| Ruthwaite area | | | | | | | | | | | |
| 1210 | <2 | 5 | 93 | 3 | <2 | 8 | 5 | <2 | 423846 | 0.02 | 78 |
| 1263 | 4 | 10 | 26 | 25 | 4 | 7 | <2 | nd | 68234 | 0.10 | 5 |
| 1265 | 23 | 41 | 79 | 8191 | 35 | 10 | <2 | 3 | 38317 | 1.10 | 54 |
| 1283 | <2 | 10 | 203 | 7 | 11 | 18 | 5 | <2 | 364000 | nd | 24 |
| 1284 | 18 | 16 | 33 | 98 | 7 | 5 | <2 | 2 | 640 | nd | 19 |
| 1285 | <2 | 15 | 61 | 34 | 2 | 18 | 11 | <2 | 593920 | nd | 47 |
| Threapland and Rosegill | | | | | | | | | | | |
| 1202 | 20 | 46 | 9509 | 145 | 263 | 5 | <2 | 30 | 35177 | 0.73 | 4789 |
| 1208 | 27 | 36 | 18053 | 534 | 330 | 2 | 2 | 35 | 1681 | 3.90 | 4000 |
| 1209 | 6 | 21 | 310 | 7 | 20 | 11 | 8 | <2 | 438180 | 0.04 | 5 |
| Embleton | | | | | | | | | | | |
| 1234 | 20 | 7 | 13 | 68 | 316 | <1 | <2 | 4 | 111 | 0.02 | 114 |
| 1235 | 12 | <2 | 10 | 57 | 328 | 1 | <2 | <2 | 405 | nd | 70 |
| 1241 | 31 | 14 | 20 | 140 | 8 | 1 | 4 | 2 | 268 | nd | 15 |
| 1244 | 10 | <2 | 68 | 21 | 5 | 2 | 4 | 10 | 64 | nd | <3 |
| 1245 | 13 | <2 | 9 | 41 | 5 | <1 | <2 | <2 | 94 | 0.01 | <3 |
| 1247 | 15 | 10 | 147 | 40 | 106 | 1 | <2 | <2 | 71 | nd | 9 |
| Tallentire area | | | | | | | | | | | |
| 1253 | 3 | 8 | 13 | <1 | <2 | 3 | <2 | nr | 105180 | 0.42 | <3 |
| 1254 | <2 | <2 | 25 | <1 | <2 | 2 | <2 | <2 | 162600 | 0.12 | <3 |
| 1262 | 20 | 15 | 3056 | 54 | 54 | 9 | <2 | 11 | 414 | 1.60 | 72 |
| 1296 | 15 | 20 | 17969 | nr | 495 | 10 | 30 | 28 | 85 | nd | 61 |
| Coal Measures | | | | | | | | | | | |
| 1237 | 58 | 12 | 10 | 85 | <2 | 3 | 5 | 7 | 210. | 0.08 | 11 |
| 1238 | 13 | <2 | 99 | 9 | <2 | 4 | 6 | 6 | 60655 | 0.04 | <3 |
| 1239 | 20 | 17 | 7 | 80 | 15 | <1 | <2 | <2 | 402 | nd | 24 |
| 1242 | 30 | 51 | <2 | 3 | 88 | <1 | <2 | 3 | 128 | nd | 4 |
| 1243 | 7 | 7 | 9 | 5 | 33 | 2 | <2 | 10 | 75 | nd | 4 |
| 1246 | 15 | 33 | 15 | 19 | 2 | <1 | <2 | <2 | 242 | nd | 7 |
| 1255 | 247 | 93 | 1087 | 14 | 986 | 34 | 11 | 45 | 275 | nd | 374 |

Au was determined on 12 samples, 10 (1201, 1202, 1207-1210, 1283-1285, 1296) gave results less than the detection limit of 10 ppb and 2 from Embleton values of 46 ppb (1234) and 71 ppb (1235). Ag was determined but the highest values (maximum 27 ppm) were caused by analytical interference from very high levels of Ba in the samples concerned. W, all results <6 ppm, and Bi, all results <4 ppm, were also determined.

vein material from Mell Beck (Table 2) but no zinc minerals were recognised in hand specimens. Small dark brown crystals of sphalerite, which accompany millerite and other minerals in septarious nodules at Oughterside, are of diagenetic origin.

*Nickel*

Millerite, no doubt of diagenetic origin (Young and Nancarrow, 1988A) was found in some abundance as capillary crystals within clay ironstone septarian nodules at Oughterside Opencast Coal Site [NY 110 398]. Numerous evenly spaced bands of apparently similar ironstone nodules occurred in the mudstone between the Rattler and Ten Quarters seams here though the millerite was confined to only one bed. The significance of its common presence in only one bed is not understood.

*Gold*

The only record of in situ gold mineralisation within Upper Palaeozoic rocks is from High Ireby (Calvert, 1854). The absence of confirmatory reports makes this occurrence of doubtful significance. Samples of Upper Palaeozoic rocks analysed for gold all yielded results less than the detection limit of 10 ppb (Table 2).

Gold grains were identified in several panned concentrates collected during the geochemical drainage survey. Although these could have a local source it is considered more likely that they are derived from the Lake District massif or southern Scotland. Their occurrence is described in more detail in the drainage geochemistry section.

*Mercury*

No mercury minerals have been recorded previously from this area and none were found in situ during this investigation. However, cinnabar was found in heavy mineral concentrates from several catchments during the geochemical drainage survey (see below) and relatively large amounts of Hg were recorded in some analysed rocks. The rock containing the greatest quantity of Hg (40 ppm) is an altered volcanic rock from the Birdhouse baryte working (Table 2). Significant amounts of Hg (> 1 ppm) were also recorded in bulk samples of mine tip debris from Threapland and Mell Beck, and mineralised float from Tallentire Hill. There is no significant statistical correlation between Hg and any other element analysed, but all samples containing > 1 ppm Hg also contain either Cu or Ba mineralisation.

*Arsenic*

No arsenopyrite was identified in the field but chemical analyses of mineralised float from Tallentire Hill and tip samples from Threapland and Birdhouse (Table 2) suggest that it may be present in small amounts at these localities.

*Iron*

Diagenetic pyrite and siderite are widespread and small amounts of iron occur in the earthy "limonite" associated with many of the baryte occurrences. Dark brown botryoidal goethite occurs within the copper-rich assemblage in soil brash on Tallentire Hill. Red earthy hematite is present in one of the mineralised faults at Tallentire and is also present in a wide calcite vein in Moota Quarry. In the Sandale area, patchy replacements of crinoidal limestone by purplish-red earthy hematite within the Second or Four Fathom Limestone in an old quarry at [NY 2518 4039] recall the distinctive hematite replacement mineralisation of west and south Cumbria. No other sign of mineralisation occurs here and there is no obvious associated fracture. Similar reddish-purple hematite occurs as a network of veinlets up to 5 mm wide in the First Limestone in old quarries [NY 2651 3846] north of Aughertree Fell.

*Non-metallic minerals*

Dickite is present as small pockets apparently coating small fractures up to a few millimetres across in limestone east of Wardhall Common [NY 1461 3748] and south of Moota Hill [NY 1468 3561]. At the latter locality the limestone contains joint coatings of baryte. The dickite may be the result of metasomatism or a product of diagenesis.

Diagenetic kaolinite is present in clay ironstone nodules at Oughterside Opencast Site.

Hydrocarbons have been seen at two sites within the area. Small pockets of solid black brittle bitumen unaccompanied by any other minerals were collected from an outcrop [NY 1335 3800] of Third Limestone near Eweclose Farm, Plumbland. This bitumen closely resembles bitumen found recently in a mineralised fault in the First Limestone at Park Head Quarry, Caldbeck [NY 340 407], a short distance east of the present area. At Tendley Hill Quarry, Eaglesfield [NY 088 288] solid black brittle and sticky brownish-black bitumen is present lining and partly filling vugs in dolomite veins in the First Limestone. These hydrocarbons may have been introduced during a mineralising episode.

## SATELLITE IMAGERY

Two images covering the Northern Lake District were examined: (i) band 7 of a LANDSAT image taken in June 1975 printed at 1:250,000 scale and (ii) a 1:100,000 scale edge-enhanced combination of bands 4, 5 and 7 from a Thematic Mapper scene aquired in February 1984. The low resolution of the LANDSAT image coupled with the high sun angle results in only major large-scale features being visible. The higher resolution of the Thematic Mapper image coupled with a low sun angle from the south produced a much more useful image for geological purposes. It was not found possible to discriminate between rock types on either image but some limestones and glacial features are prominent on the Thematic Mappper image. Both images display linear features; those on the LANDSAT image are mainly the most prominent large-scale features whilst on the Thematic Mapper image small features which can be related to cleavage, bedding and jointing are also evident locally.

The more prominent features noted are shown on Figure 6 and summarised below.

1. Glacial features, mainly drumlins, indicating ice-movement northwards off the Lake District massif and then westwards over the low ground occupied by Carboniferous rocks.

2. Large-scale lineaments. Seven significant features were distinguished in this area: (i) a well-defined north-east-trending line extending from the coast south of Whitehaven to the northern end of Bassenthwaite Lake, and possibly extending in weaker form through Overwater to the Vale of Eden. (ii) A weak east-west feature extending from Workington through Cockermouth to Bassenthwaite. (iii) A weak feature corresponding in part to the line of the Gilcrux fault. (iv) Another east-west feature to the north of the Gilcrux Fault, extending from Allonby through Aspatria towards the Vale of Eden. Both (iii) and (iv) may be reflecting the presence of major faults on the south side of the Solway Basin. (v) A weak north-north-west-trending feature

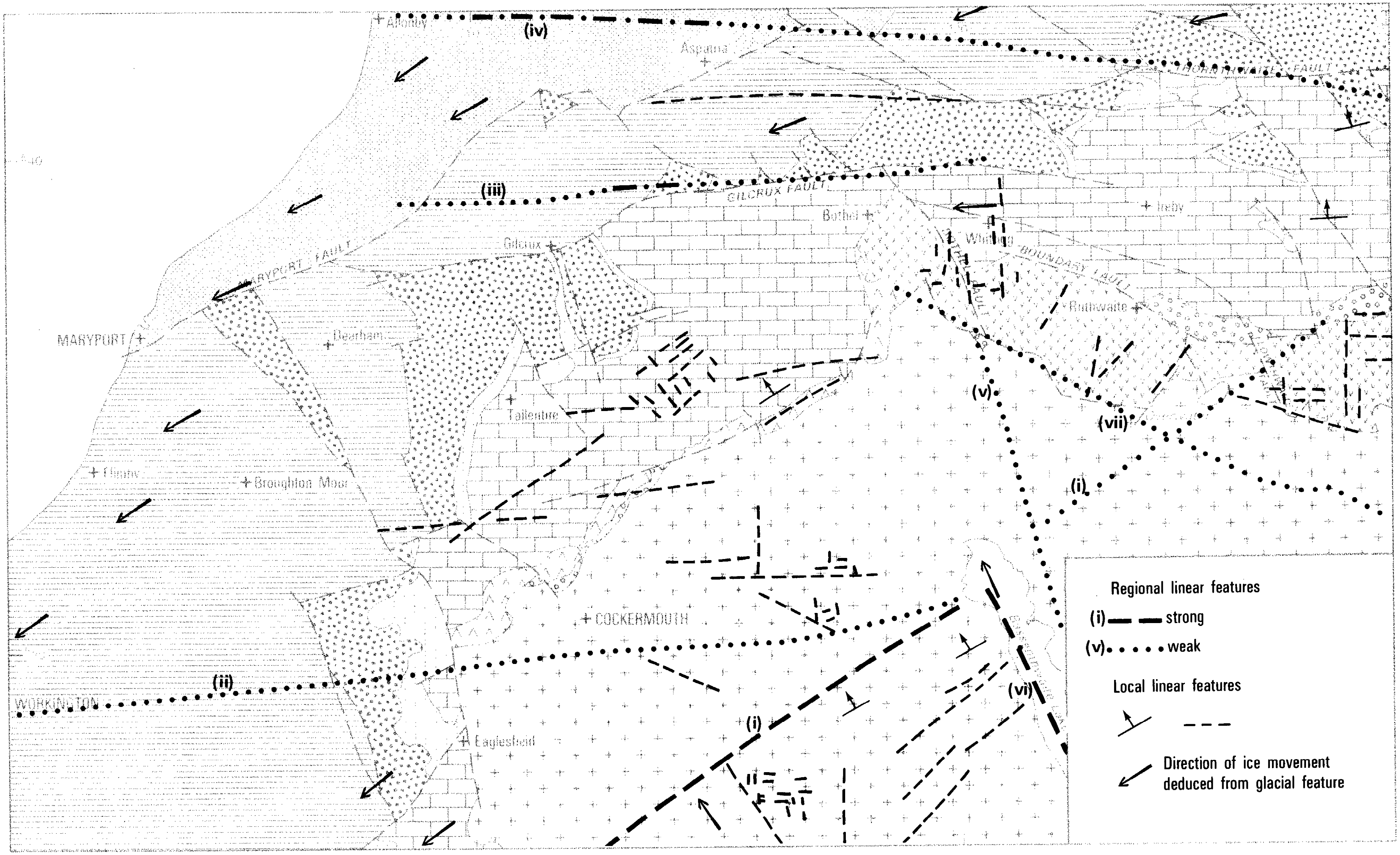


**Figure 6** Linear features extracted from satellite imagery

coincident with the Bothel Fault but extending much further south, suggesting that this fault is a more significant feature than is apparent from the geological map. (vi) A prominent north-north-west-trending feature running down the western side of Bassenthwaite Lake and extending south-south-eastwards towards the western side of Derwentwater. (vii) A tenuous north-west-trending feature extending from just south of Bothel, through Orthwaite [NY 253 340] and Mungrisdale Common [NY 31 30], where it appears to be displaced, to near Matterdale End [NY 396 235].

3. Shorter lineaments. These may indicate faults, bedding, cleavage and fracture/joint patterns in the rocks. Only a selection of these features are illustrated on Figure 6. They include: (i) north-south and east-west-trending fractures in the Caldbeck Fells, where there appears to be some coincidence between the north-south fractures and the location of mine workings. (ii) well developed north-west and north-east-trending fractures in the Carboniferous rocks around Tallentire Hill. (iii) A north-south and east-west-trending pattern of probable fractures near Whitrigg. (iv) The direction and dip of bedding locally within the Carboniferous and bedding/cleavage in the Skiddaw Group.

## REGIONAL GEOPHYSICS

The area covered by this report includes significant Bouguer gravity and aeromagnetic anomalies. Although these are largely associated with pre-Carboniferous rocks, the anomalies indicate the presence of structures which are relevant to this investigation. To the north of the Cockermouth district commercial seismic reflection surveys have been carried out to investigate the structure of the Solway Basin.

### Physical properties

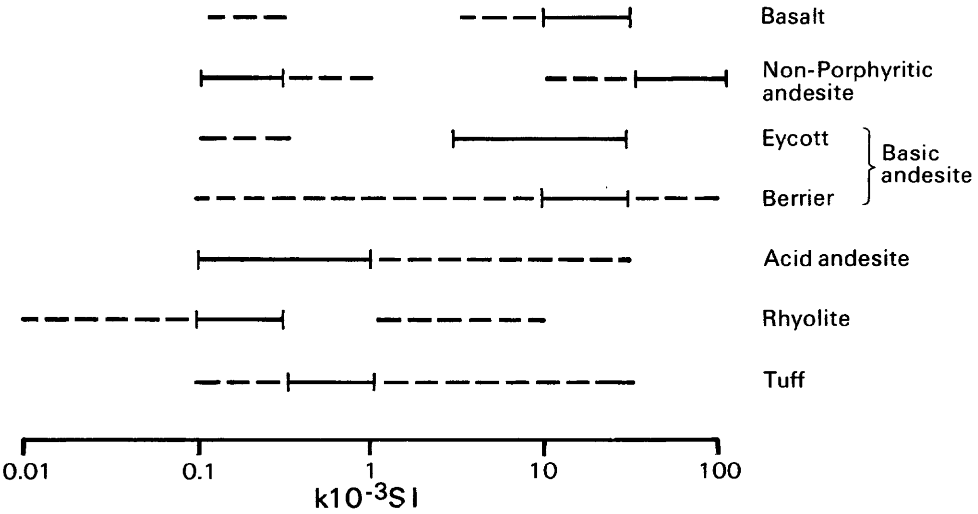
Physical property information for the main rock units relevant to the interpretation of the regional geophysical data has been summarised by Bott (1974, 1978) and Lee (1986, 1988, 1989). The density values used in the gravity interpretation shown in Figure 12 are those adopted by Lee (1989).

More detailed information has been obtained on the magnetic susceptibility of members of the Eycott Volcanic Group as this is particularly relevant to the interpretation of the pronounced aeromagnetic anomalies. The measurements were made mainly on samples in the BGS Petrology collection and described in Eastwood et al. (1968) using a Kappameter model KT-5 (Geofyzika Brno). Although the collection allowed easy access to a wide range of rock types and the relative values should be representative, the small size of some of the samples reduced the accuracy of measurements.

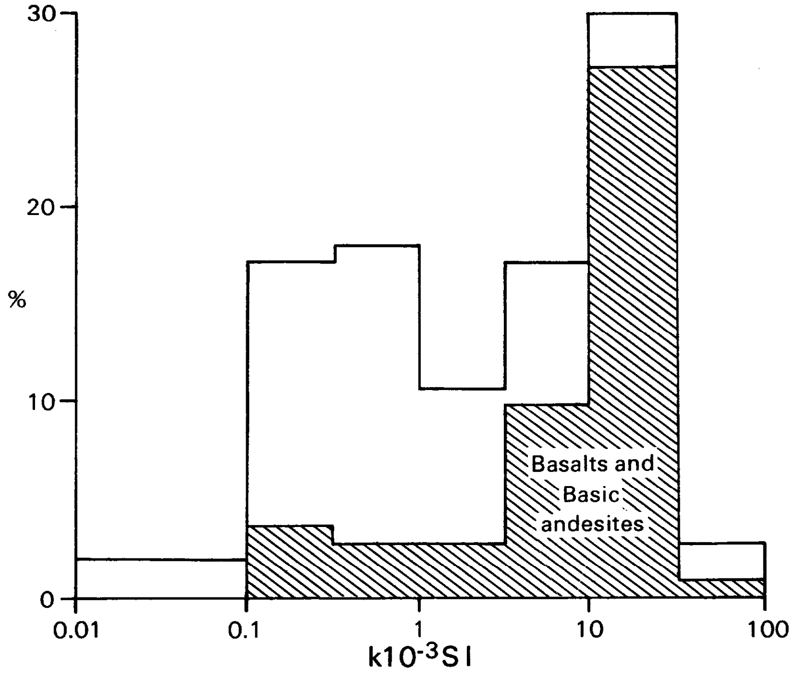
The susceptibility values are shown in Figure 7a for the main rock types described by Eastwood et al. (1968). The mean values are listed in Table 3.

The results indicate that the basic andesites (both the Berrier and Eycott types) and the basalts (both the olivine-bearing and olivine-free types) are sufficiently magnetic (i.e. with susceptibilities greater than about 10 x $10^{-3}$ SI) to give rise to significant magnetic anomalies. The non-porphyritic andesites were not sampled intensively but a few samples of this lithology have high susceptibilities. The acid andesites, rhyolites and tuffs are not likely to be associated with magnetic anomalies. Briden and Morris (1973) reported the results of a palaeomagnetic study of the Eycott Volcanic

a) Summary of measurements on samples in the BGS Petrology collection. The full range is indicated by a pecked line. Lines between ticks contain at least 25% of the values



b)Histogram of magnetic susceptibility measurements on specimens in the BGS Petrology collection



c)Summary of field measurements on Binsey; letters a to m refer to horizons identified by Eastwood et al. (1968 p63-64).

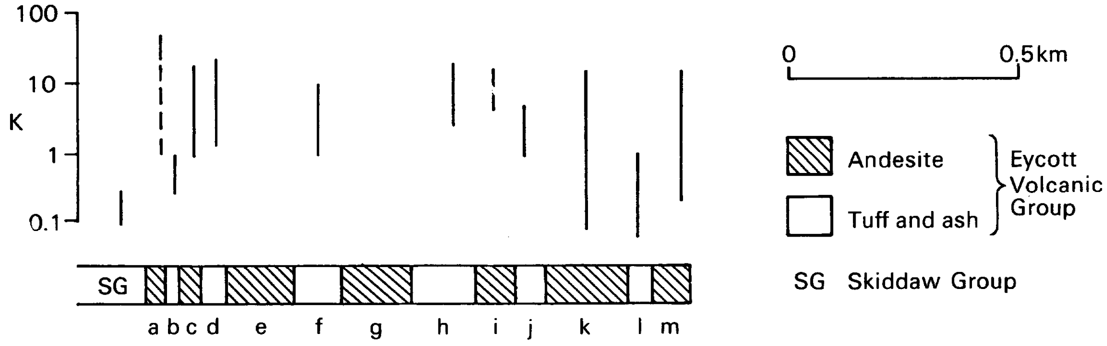


Figure 7 Magnetic susceptibilities for the Eycott Volcanic Group (k in SI Units x $10^{-3}$)

Group, including some information on the intensities of the remnant and induced magnetisations. This information was used subsequently by Collar and Pattrick (1978) to derive a total magnetisation for aeromagnetic anomaly interpretation.

**Table 3** Summary of magnetic susceptibility measurements on rock samples from the Eycott Volcanic Group

| Lithology | No. of samples | Susceptibility x $10^{-3}$SI | |
|---|---|---|---|
| | | Mean | Standard Deviation |
| Basalt | 1 | 15.5 | 7.8 |
| Non-porphyritic andesite | 7 | 12.5 | 15.8 |
| Basic andesite | 46 | 10.9 | 9.1 |
| Acid andesite | 19 | 1.8 | 3.3 |
| Rhyolite | 13 | 1.4 | 2.6 |
| Tuff | 24 | 1.9 | 4.1 |

Susceptibility measurements taken across the lower part of the Eycott Volcanic Group succession exposed on the slopes of Binsey (Figure 7c) indicated that individual lavas and tuffs have very variable susceptibility. Consequently it is unlikely that a horizon with distinctive susceptibility exists which can be used as a marker, but there would appear to be potential for correlating magnetic anomaly patterns characteristic of a sequence of lavas and tuffs.

The Eycott Volcanic Group contrasts magnetically with the Borrowdale Volcanic Group in the southern part of the Lake District, which is characterised by low susceptibilities (about 0.8 x $10^{-3}$ SI; Lee, 1989) and weak aeromagnetic anomalies.

Susceptibility measurements at one site in the Cockermouth Lavas [NY 133 335] indicated that the rocks here are weakly to moderately magnetic with maximum values of about 5 x $10^{-3}$ SI.

### Regional gravity survey

The deeper structure of the Lake District has been investigated through the interpretation of the main gravity anomalies by Bott (1974, 1978) and Lee (1986, 1989). These studies indicated that the main gravity features (a series of connected gravity lows extending in a east-north-east direction across the Lake District) were due to the granite intrusions. These form part of a large batholith extending to depths of 9-10 km (Figure 8). Lee (1989) has also undertaken detailed comprehensive interpretations of the gravity and aeromagnetic data and presented the results in part as a series of profiles. A compilation of these results is shown in Figure 9.

The gravity data for the Lake District also provide evidence for the existence of a series of lineaments, several of which have been shown to have geological significance (e.g. Cooper et al., 1988). Lineaments recognised by Lee (1989) are shown in Figure 8 with an additional possible lineament (LL') suggested by the aeromagnetic evidence.

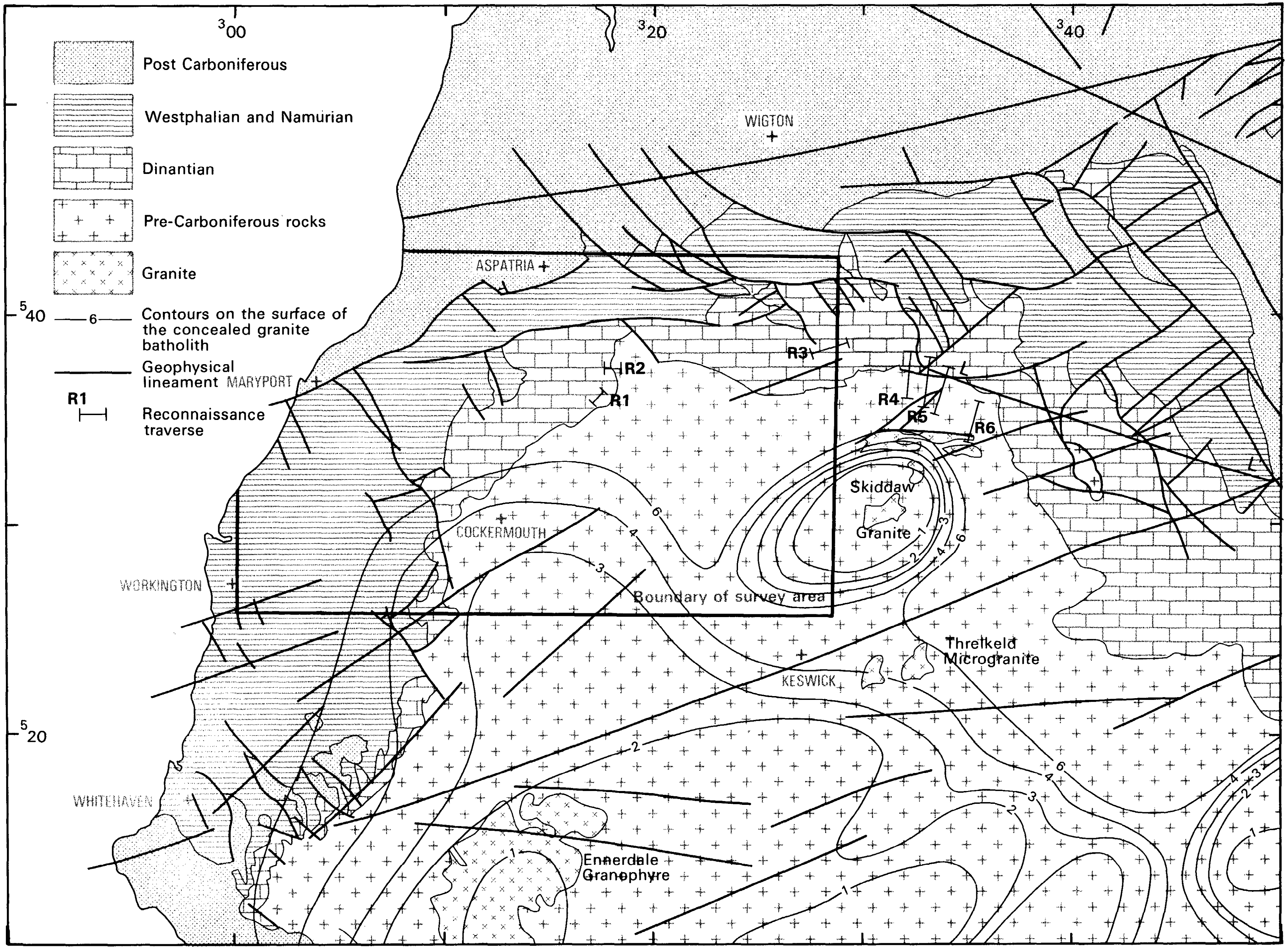


**Figure 8** Geophysical compilation map for the northern Lake District showing simplified geology, contours on the surface of a model for the concealed granitic batholith (Lee, 1989), geophysical lineaments from Lee (1989), and this study, (L-L') and the location of ground traverses detailed in Figure 13

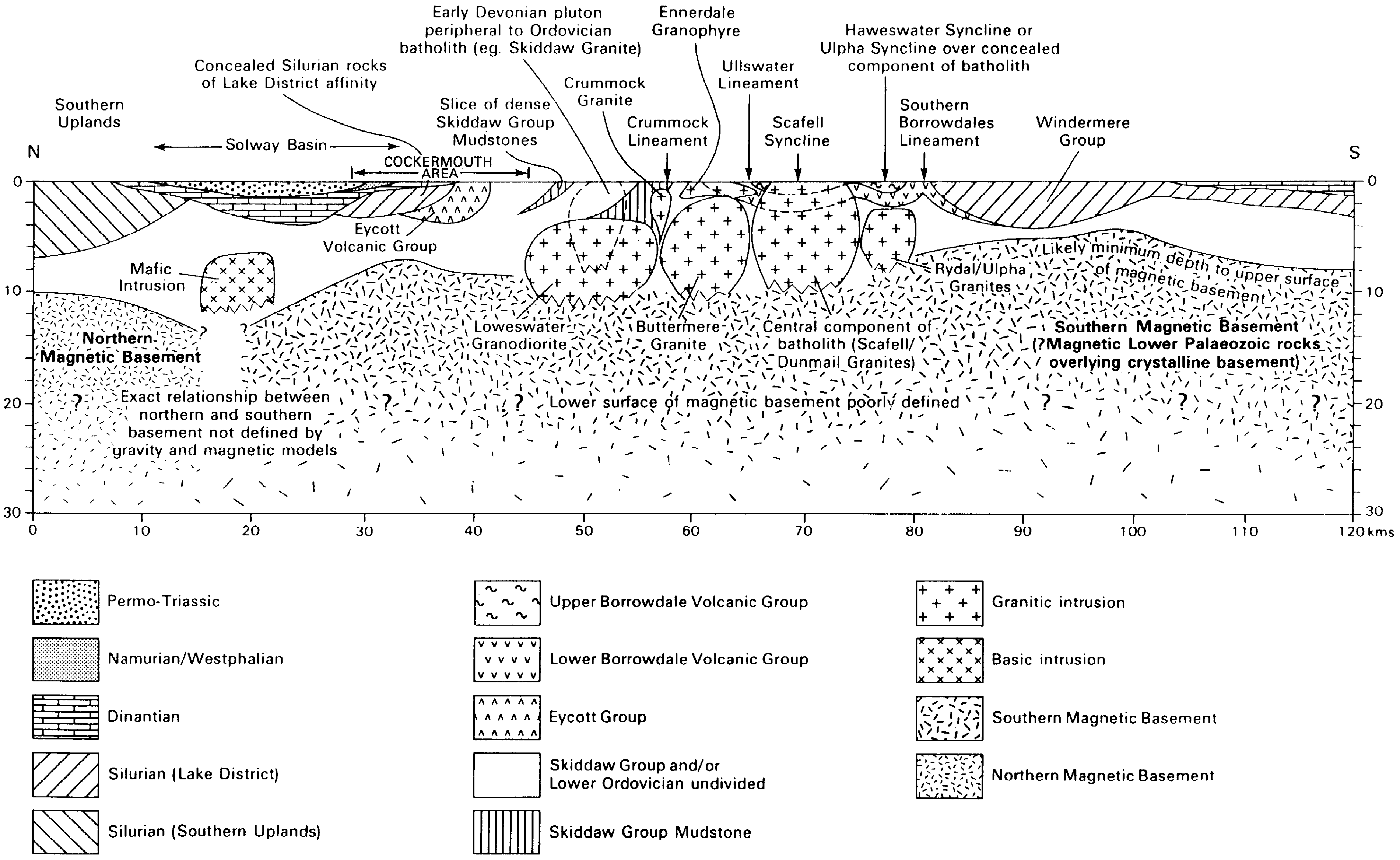


**Figure 9** Schematic cross-section of the Lake District (from Lee, 1989)

Bouguer anomaly data in the Cockermouth area are characterised by low values in the north over the Permo-Trias of the Solway Basin and an east-west high in the western part (Figure 10). The high was interpreted by Lee (1989) as a small segment of the 'background' field remaining over the Skiddaw Slates between gravity lows due largely to a concealed portion of the batholith to the south and sedimentary rocks in the Solway Basin to the north (Figure 9). The thickness of Permo-Triassic rocks in the Solway Basin is insufficient to explain the amplitude of the northern low and Lee (1989) suggested that there were additional contributions to the anomaly by the Eycott Volcanic Group, and possibly by concealed Silurian sedimentary rocks and a thickened Lower Carboniferous sequence (Figure 9).

### Aeromagnetic survey

The aeromagnetic map of the area (Figure 11) is dominated by an east-west anomaly with an amplitude of more than 500 nT (c.f. Collar and Patrick, 1978; Collar in Arthurton and Wadge, 1981; Drury and Walker, 1987; Lee, 1989). The anomaly is clearly related to the Eycott Volcanic Group at outcrop and indicates an extension of these rocks westwards beneath the Carboniferous. However, the detailed interpretation of the main anomaly is not straightforward and Collar and Patrick (1978) proposed three alternative models to explain its form. The models included a wedge of lavas dipping steeply southwards and a wedge dipping northwards at a small angle. Lee (1989) suggested that the interpretation is further complicated by the presence beneath the lavas of a deep-seated magnetic basement and preferred a model in which the lavas extend northwards at depth, although not necessarily immediately beneath the Carboniferous sequence. Lee also points out the difficulties and uncertainties associated with the interpretation of both the aeromagnetic and the gravity anomalies in the area.

North of the Cockermouth area, a well-defined aeromagnetic anomaly over the Solway Basin provides the main evidence for the deep-seated mafic intrusion shown in Figure 9.

### The Cockermouth area

An examination of the regional geophysical data for the Cockermouth area (Figures 10 and 11) suggest several aspects relevant to more detailed interpretation. Notable amongst these is the significance of a north-west-trending fault, here termed the Bothel Fault, which is shown on the published geological map as extending from near Bothel, where it abuts the Gilcrux Fault [NY 184 397], to Whittas Park [NY 205 363]. This and other features were examined in part by interpreting two profiles across the area (Figures 10 and 12) using information from Lee (1989), particularly concerning the background field and physical properties of the rocks. Exceptions to this approach are that the Eycott Volcanic Group is assumed to be magnetised in the direction of the present geomagnetic field and the effect of remnant magnetisation is neglected. The reasons for this are the lack of detailed information on the intensity of the remnant magnetisation and the uncertainty in compensating for the variable dip of the lavas.

Although the aeromagnetic anomaly (Figure 11) is continuous across the area, it changes in character from a single longer wavelength high in the west to two more sharply defined highs to the east of the Bothel Fault. The double highs are indicated on two flight lines only (along grid lines 22E and 24E) but their existence has been confirmed by ground magnetic measurements

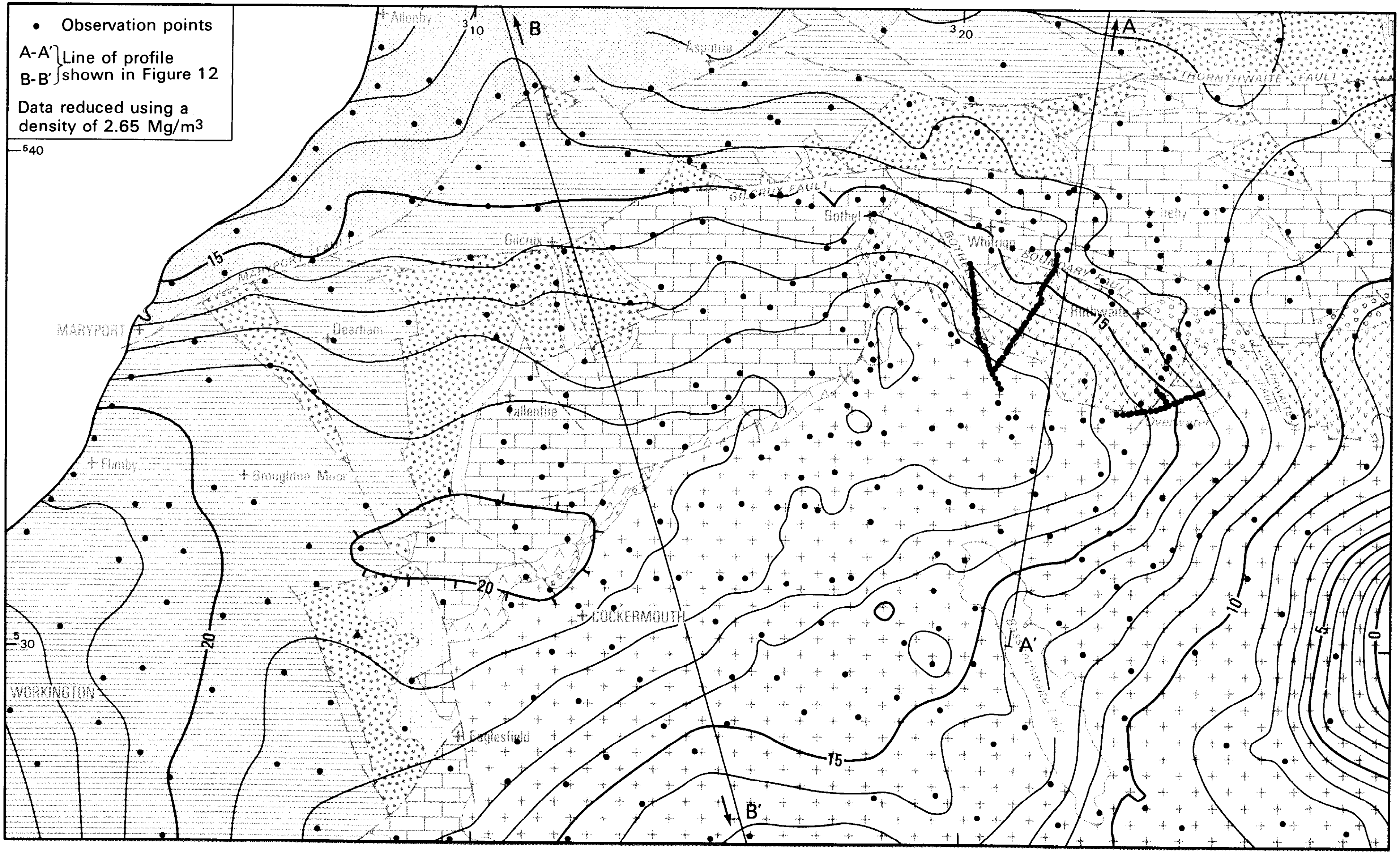


**Figure 10** Bouguer gravity anomaly map (contours at 1 mGal intervals) and location of profiles shown in Figure 12

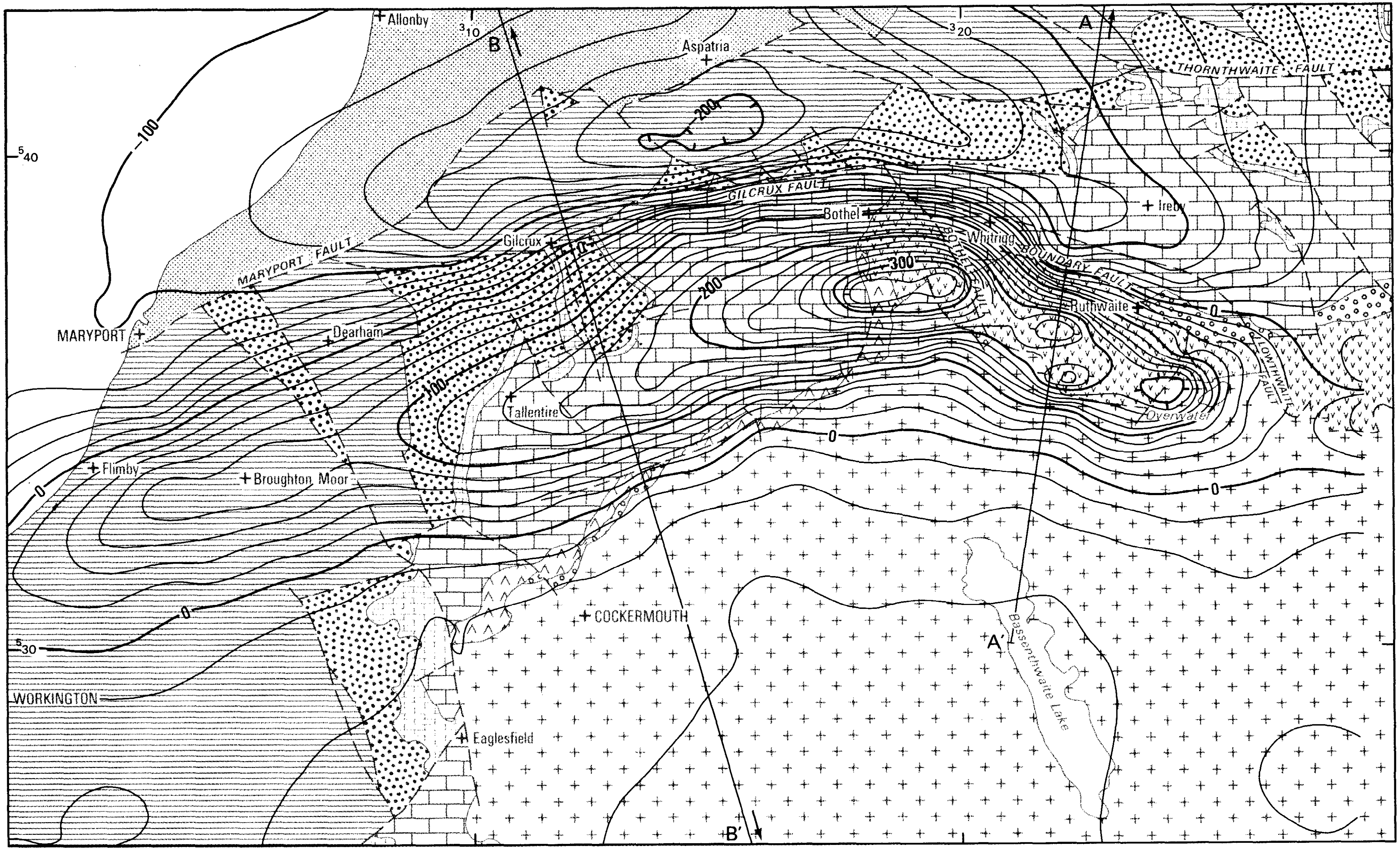


**Figure 11** Aeromagnetic anomaly map (contours at 20 nT intervals)

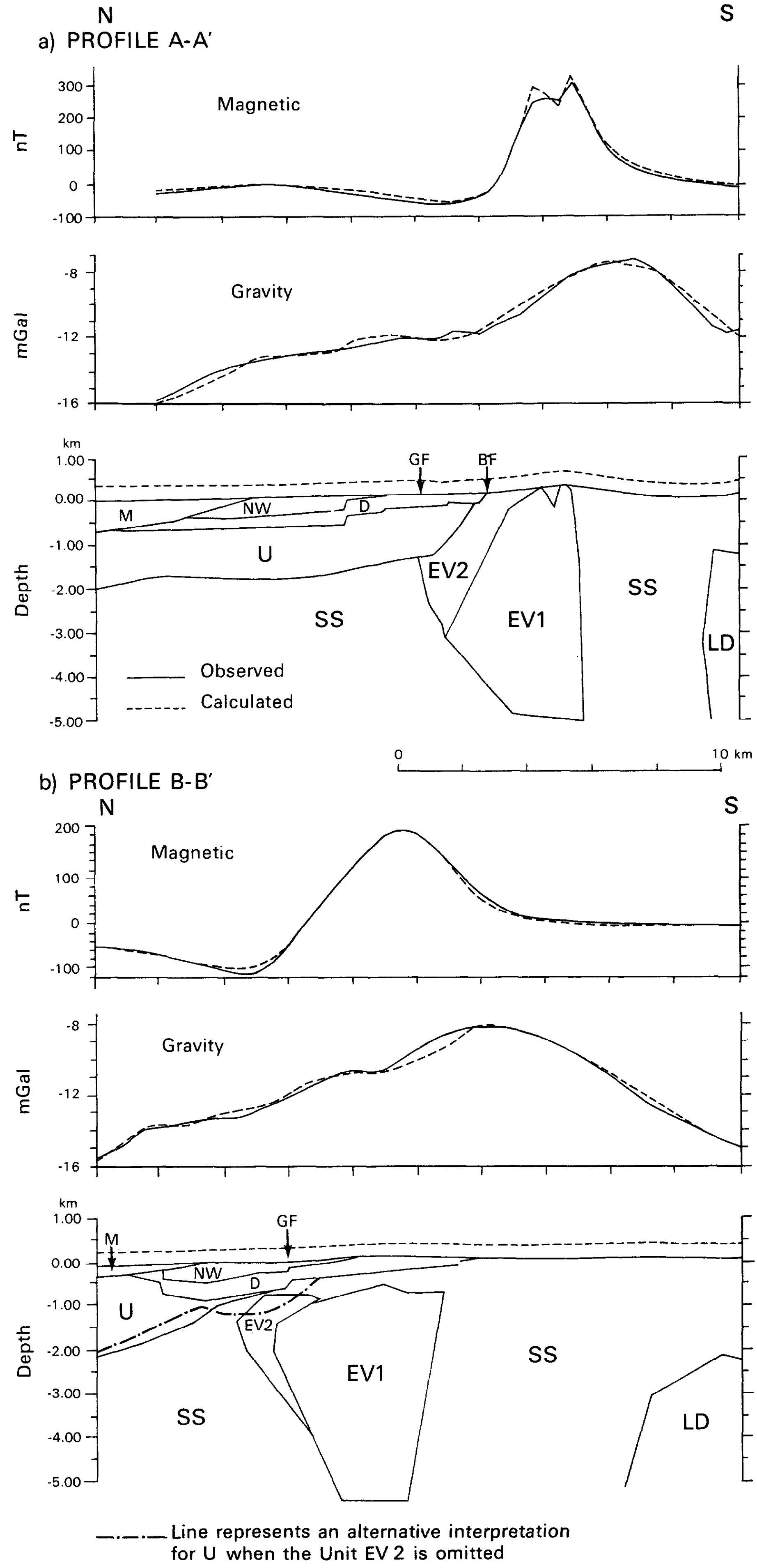
(R M Carruthers, personal communication 1989). The more southerly high coincides with the sequence of lavas and tuffs exposed on Binsey, while the second high occurs over lavas of the High Ireby Formation. Ground magnetic survey results to the west suggests that as the Bothel Fault is approached the strike of the magnetic anomalies diverges from that of the lavas but further evidence is required to resolve this inconsistency. The magnetic profile in this area (Figure 12a) has been interpreted as a single homogeneous body, although it is more likely that several discrete bodies exist, probably corresponding with the basic andesites and basalts in the volcanic pile. Similarly a single density has been assumed for the main block of the Eycott Volcanic Group (EV1), although a lower density, non-magnetic unit (EV2) has been introduced in the models to represent an acid component.

West of the Bothel Fault the form of the magnetic anomaly is indicative of a more deep-seated source, lying at a depth of up to about 1 km (0.7 km below the surface). In this area the Eycott Volcanic Group is concealed by Lower Carboniferous rocks but the thickness of these (0.3 km maximum) is inadequate to explain the apparent change in depth to the magnetic rocks unless these form a single, broad homogeneous body. The top of the model for EV1 shown in Figure 12b lies at a depth of about 0.7 - 0.8 km but the observed profile can be reproduced by models with greater and smaller depths. The form of the model is the inverse of that for profile AA' with the widest part occurring nearest the surface. In geological terms the irregular forms for EV1 on both profiles could represent a steeply dipping pile of lavas with variable thicknesses, a folded sequence of lavas, or fault-defined blocks. Some of the uncertainties could be resolved from ground magnetic survey data. It is also noted that the susceptibilities used in the models are greater than all except a few of the observed values (Table 3). It is suggested that the Bothel Fault (and possibly the Binsey Boundary Fault) had a significant vertical component of movement, dropping the magnetic component of the Eycott Volcanic Group beneath a cover of non-magnetic members of the High Ireby Formation. There is also a change in the strike direction of the anomaly approximately along the line of the Bothel Fault and a 1-2 km displacement of the anomaly peaks (Figure 11), suggesting some horizontal component of movement.

The maximum amplitude of the aeromagnetic anomaly, about 550 nT, occurs just to the west of the Bothel Fault (this value would be even greater if the source rocks occurred at the ground surface). The most simple interpretation of this is that the Eycott Volcanic Group reaches its maximum development at about grid line $^{3}$18E, a suggestion supported by the conclusion reached by Eastwood et al. (1968, pp 50-51) that the group had a source to the west or north-west of Binsey. The magnetic anomaly continues westwards with diminishing amplitude as far as $^{2}$98E where it is truncated along the line of the off-shore Mesozoic Basin.

Further interpretation of the gravity data confirms that the estimated thicknesses of the Carboniferous and younger rocks in the Solway Basin are insufficient to explain the amplitude of the low. As Lee (1989) points out, this could be explained by either a thickened Lower Carboniferous sequence, perhaps along a concealed growth fault running parallel with the strike, or by older rocks with a density lower than that of the Skiddaw Group. The first alternative is supported by the MEIGA project drilling at Whitrigg where the depth to basement was found to be most difficult to predict because of faulting. This alternative has been assumed for the unit U in Figure 12 but the form and position of its southern margin is dependent upon the form of the model chosen for unit EV2 (Figure 12). Other sources of evidence are required to resolve the uncertainties in interpretation.

**Figure 12** Geophysical profiles and models along AA' and BB' (Figure 10). The model includes a deep-seated magnetic basement (c.f. Lee, 1989). SS = Skiddaw Group (density 2.78 Mg/m$^3$, susceptibility 0 x 10$^{-3}$SI), LD = Loweswater Granodiorite (2.70, 0), EV1 = Eycott Volcanic Group 1 (2.74, 0.02), EV2 = Eycott Volcanic Group 2 (2.86, 0), U = low density basement unit (2.65, 0), Dinantian (2.65, 0), NW = Namurian and Westphalian (2.65, 0), M = Mesozoic (2.4, 0), BF = Bothel Fault and GF = Gilcrux Fault



The southern margin of the gravity high is considered by Lee (1989) to have been determined by the position at depth of the concealed margin of the northern component of the batholith (the Loweswater Granodiorite c.f. Figure 9). In places however the steepness of the gravity gradient seems to be more consistent with a near-surface density contrast. To the east the high is terminated by the large gravity low due to the Skiddaw Granite but this explanation is inadequate for the observed decrease in values to the north-east. This decrease occurs partly over the Bothel Fault (Figure 10) and it is suggested that a low density unit within the Eycott Volcanic Group might be responsible. This unit is probably partly concealed by the Dinantian strata and could comprise the more acid, non-magnetic members of the volcanic group. Lee (1989) has also pointed out that density variations within the Skiddaw Group can give rise to gravity anomalies. The gravity evidence tends to support that obtained from the aeromagnetic data concerning the Bothel Fault, namely that it is probably a major structure active in Carboniferous and earlier times. Geological evidence for its effect on sedimentation in Dinantian times is sparse but it is noted that the structure coincides approximately with the eastern limit of the Cockermouth Lavas and the western thinning of the Basement Conglomerate. The results of geophysical and geochemical traversing across the fault at Whitrigg will be described in Part 2.

*Trial ground surveys*

Trial reconnaissance traverses were made at three localities in the Cockermouth area in order to assess if geophysical methods could be used to detect lithological boundaries and faults. Conductivity mapping (EM31 equipment) and VLF-EM methods were used, the former with EM 31 equipment (Genoics Ltd.) with an effective depth of exploration of about 5 m.

On profile R1 (Figure 13), which crosses only Dinantian rocks at surface, conductivity values increase markedly at the mapped location of a fault. The results are less clear cut on profile R2 (Figure 13), perhaps due to the presence of thicker drift (suggested by the absence of the low conductivity values expected from Dinantian bedrocks). On profile R3 (Figure 13) the variable nature of the conductivity profile and the high values are largely due to the variable drift cover and little relationship to mapped faults is evident. In a few places, such as near the south-west end, lower conductivity (limestone) bedrock, which underlies most of the traverse, appears to approach the surface. The VLF profile is also devoid of any distinctive anomalies, apart from that over a pipe near the north-east end.

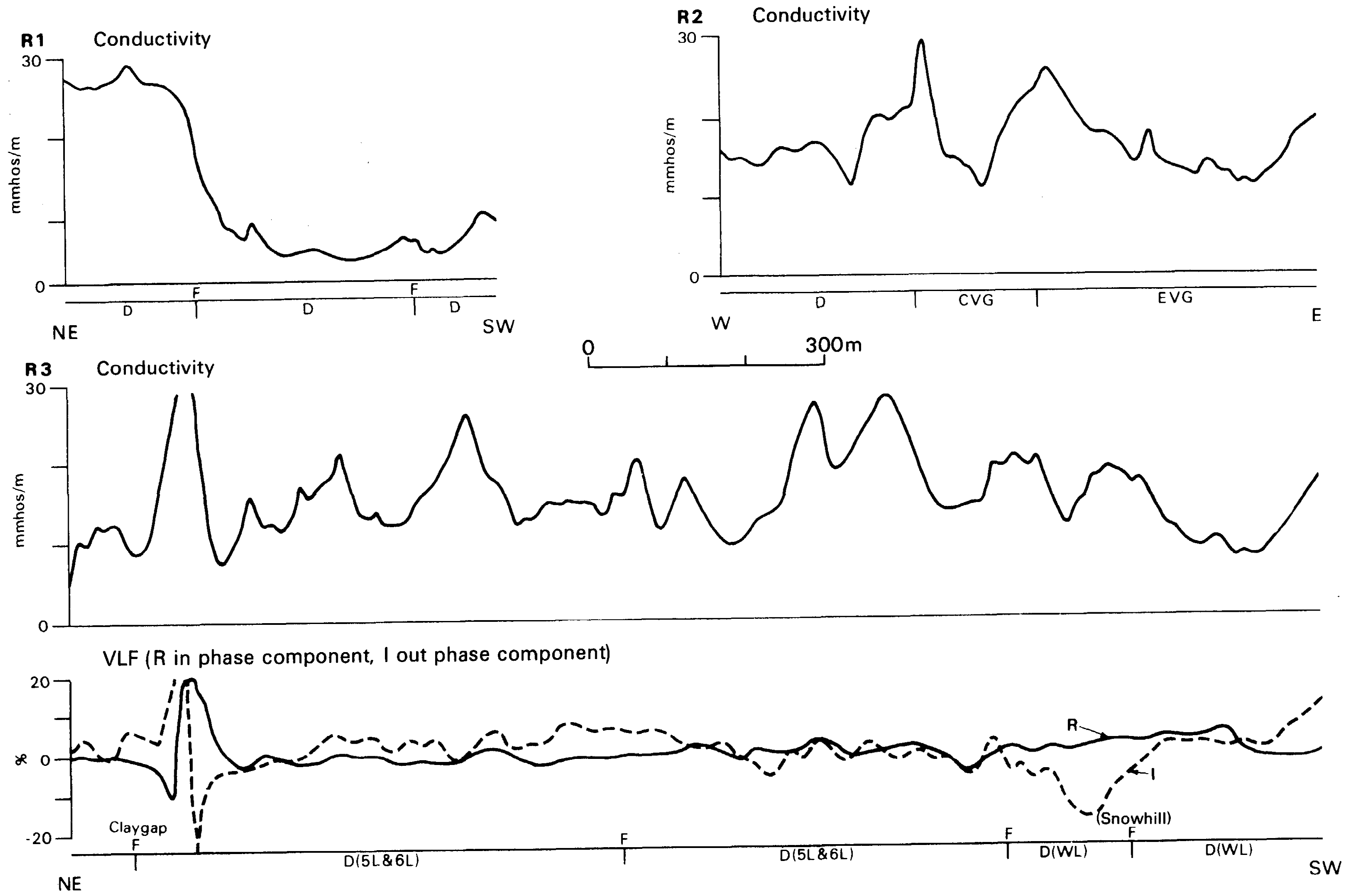
In addition three magnetic traverses were made to the east of the survey area to examine the relationship between anomalies and mineralisation in Lower Palaeozoic rocks (R4-R6; Figure 8). The traverses, largely across rocks of the Eycott Volcanic Group containing vein mineralisation, confirmed aeromagnetic evidence that the magnetic anomalies appear to occur further north than those near Binsey and are associated with parts of the High Ireby Formation.

## Conclusions

1. Gravity and magnetic data suggest that the Bothel Fault is a major structure which was active in the Carboniferous. It may not be coincidence that its position coincides with the eastern limit of the Cockermouth lavas and the western thinning of the Basement Conglomerate.

2. The magnitude of the gravity anomaly over the Solway Basin suggests the presence of either a thickened Lower Carboniferous sequence, perhaps along a concealed growth fault, or more low density rocks (acid volcanics?) in the Lower Palaeozoic basement.

3. Trial ground surveys indicated that VLF(EM) and conductivity surveys could be useful locally for mapping purposes, but variations in drift thickness also produces significant anomalies.



Location of traverses shown on Figure 8
EVG Eycott Volcanic Group  CVG Cockermouth Volcanic Group
D Dinantian (WL White; 5L Fifth Limestone; 6L Sixth Limestone)
F Fault

**Figure 13** VLF(EM) and conductivity profiles along traverses shown in Figure 8

## GEOCHEMICAL DRAINAGE SURVEY

### Sampling and analysis

To supplement the BGS regional geochemical survey data, panned heavy mineral concentrates were collected from 124 sites in an area of about 250 km$^2$. Sampling density was constrained by the poorly developed surface drainage across much of the area. At all except ten of the sites a sediment sample was also taken. The samples were collected using methods described in detail elsewhere (Plant, 1971; Leake and Smith, 1975). Briefly, stream sediment was wet sieved at site using a minimum of water (to retain the fine fractions) through nylon mesh and the -0.15 mm (100 mesh) fraction retained for analysis. Heavy mineral concentrate samples were made by panning about 4 kg of the -2 mm (8 mesh) fraction of the sediment down to a constant volume weighing about 50 g. Sites were inspected carefully for signs of contamination and mineralisation and the panned concentrates examined for metalliferous mineral grains. In the laboratory individual samples were dried, thoroughly mixed and a split milled. A wide range of elements (Table 4) were determined on the resulting powder by X-Ray Fluorescence Spectrometry. An additional split of the stream sediment was analysed for Hg by cold vapour atomic absorption spectrophotometry (AAS) following dissolution of 0.5 g of powder in a hot nitric and hydrochloric acid mixture for one hour. The fluorine content of 85 250 ml water samples collected from springs, wells and streams was also determined using a specific ion electrode.

### Results

Metalliferous minerals were seen in the heavy fraction of many panned concentrates. Most importantly, gold (maximum four grains) was noted in the concentrates from 21 sites and cinnabar in 22. Neither mineral had been recorded in the area previously and their occurrence is described in more detail below. Other minerals noted at site in the pans were baryte, pyrite, Fe/Ti oxides, chalcopyrite and galena.

Despite every effort to avoid contaminated sites, some evidence of contamination was observed close to or upstream of many sites. Brick, concrete, plastics, pottery and metallic fragments, such as copper wire, were the most common contaminants identified in the stream sediment. Roads, with associated fly-tips, domestic rubbish tips and coal workings were the most common sources noted.

The analytical results, summarised in Table 4, are available from BGS. Results for Mo (20%), Ag (60%), Sb (15%), Sn (51%), W (7%), Bi (100%) and U (2%) in stream sediments, Cr (1%), Co (1%), Mo (6%), Ag (17%), Sn (27%), Sb (28%), Ce (7%), W (15%), Bi (88%) and U (45%) in panned concentrates and F (50%) in water were truncated by a proportion of results, shown in brackets, below the detection limit. Plots of the concentration of selected elements in stream sediments and panned concentrates at each site are shown in Figures 14 to 24.

For conciseness in the text results for waters, stream sediments and panned concentrates are differentiated by the subscripts w, s and p respectively after the symbol of the element concerned. For example, copper in panned concentrate is shortened to $Cu_p$.

**Table 4** Summary statistics for stream sediment and panned concentrate analyses

| Element | Median | Mean | Std.Dev. | Minimum | Maximum | Threshold |
|---|---|---|---|---|---|---|
| Stream sediments n=114 | | | | | | |
| Ca | 6000 | 14383 | 18376 | 1400 | 107600 | 60000 |
| Ti | 4720 | 5002 | 1351 | 2380 | 9220 | 4801 |
| V | 88.5 | 93 | 33 | 37 | 191 | 150 |
| Cr | 90 | 89 | 15 | 57 | 117 | 113 |
| Mn | 3325 | 7774 | 16041 | 610 | >20000 | 7101 |
| Fe | 47300 | 49869 | 15972 | 20700 | 86000 | 78890 |
| Co | 25 | 28.2 | 15.1 | 10 | 143 | 55 |
| Ni | 31 | 35.1 | 21.6 | 14 | 222 | 60 |
| Cu | 32 | 35.3 | 13.4 | 10 | 90 | 45 |
| Zn | 93.5 | 115 | 87 | 32 | 714 | 161 |
| As | 24 | 29.1 | 19.6 | 10 | 156 | 71 |
| Rb | 88.5 | 91 | 24.9 | 44 | 144 | 132 |
| Sr | 112 | 114 | 27.2 | 69 | 209 | 180 |
| Zr | 441 | 485 | 255 | 169 | 1191 | 1000 |
| Mo | 1 | - | - | <1 | 6 | 4 |
| Ag | <2 | - | - | <2 | 3 | 3 |
| Sn | <2 | - | - | <2 | 25 | 16 |
| Sb | 4 | 3.9 | 2.3 | <2 | 11 | 9 |
| Ba | 735 | 1014 | 1126 | 260 | 6619 | 888 |
| Ce | 57.5 | 58 | 10.7 | 32 | 87 | 75 |
| W | 3 | 3.3 | 1.2 | <2 | 6 | 6 |
| Hg* | 80 | 117 | 210 | 20 | 2200 | 221 |
| Pb | 40.5 | 55 | 43 | 14 | 277 | 57 |
| Bi | <2 | - | - | <2 | <2 | - |
| U | 4 | 4.0 | 1.4 | <2 | 9 | 7 |
| | | | | | | |
| Panned concentrates n=122 | | | | | | |
| Ca | 3900 | 6458 | 7464 | 800 | 31800 | 5501 |
| Ti | 5050 | 9815 | 18356 | 1490 | 140390 | 6501 |
| V | 123 | 189 | 203 | 27 | 1402 | 179 |
| Cr | 95.5 | 125 | 120 | <1 | 654 | 130 |
| Mn | 1500 | 3349 | 9339 | 90 | >20000 | 2470 |
| Fe | 75700 | 80875 | 46700 | 6800 | 248100 | 107500 |
| Co | 18 | 20.9 | 11.9 | <1 | 75 | 51 |
| Ni | 26 | 33.3 | 27.3 | 5 | 202 | 101 |
| Cu | 73.5 | 144 | 252 | 6 | 1843 | 101 |
| Zn | 81.5 | 151 | 265 | 14 | 2431 | 111 |
| As | 40 | 45 | 37 | 2 | 265 | 135 |
| Sr | 231.5 | 541 | 684 | 26 | 3449 | 101 |
| Zr | 245 | 554 | 668 | 87 | 3934 | 2001 |
| Mo | 4 | 4.8 | 4.6 | <1 | 36 | 13 |
| Ag | 3.5 | 4.4 | 4.4 | <2 | 24 | 8 |
| Sn | 19 | - | - | <2 | 605 | 21 |
| Sb | 4 | - | - | <2 | 131 | 19 |
| Ba | 13674 | 44923 | 76742 | 164 | 519947 | 901 |
| Ce | 39.5 | 46 | 25.8 | <7 | 133 | 101 |
| W | 4 | 7.6 | 23.2 | <2 | 252 | 8 |
| Pb | 82 | 697 | 2156 | 8 | 15126 | 111 |
| Bi | <2 | - | - | <2 | 14 | 5 |
| U | 2 | - | - | <2 | 6 | 6 |

*Values in ppb. Other values in ppm.

## Data interpretation

Statistical treatment of the stream sediment and panned concentrate analyses was restricted by the bimodal to complex form of most element distributions. The complex sample populations could not be subdivided readily into simple forms on the basis of a single parameter, such as background geology, and it was clear that the complexity was the product of a number of factors. Consequently the data was interpreted in the following way.

A representative selection of panned concentrates with high metal contents were examined mineralogically to determine the mineral phases responsible for the high values. A detailed report on this work is included as Appendix 1. The mineralogical results were then assessed in conjunction with spatial distribution plots of the analytical data, field observations, the results of non-parametric inter-element correlation statistics and the known geology and mineralisation (Figure 5), to determine the major sources of geochemical variation in the area. This information was then applied to the interpretation of cumulative frequency plots (Parslow, 1974; Sinclair, 1976) which were used to set threshold levels and define anomalous results.

## Major sources of geochemical variation

From the work outlined above seven major sources of variation which influence element concentrations in stream sediments and panned concentrates from this area were identified. These are briefly described below.

1. Grain size of clastic sediments. This, the principal source of variation in the dataset, is caused by the compositional variation between sandstone and mudstone bedrocks and coarse and fine-grained surficial materials. It produces close positive correlations between Ti, V, Fe, Co, Ni and Rb in stream sediment (Table 5) and strong negative correlations between these variables and Zr, caused by the concentration of the former group of elements in fine-grained phases such as clay minerals, chlorite and hydrous oxide precipitates, and of Zr in coarser detrital/resistate minerals.

2. Baryte mineralisation. Ba variation in both sediments and concentrates is controlled by the amount of baryte in the samples. Mineralogical work showed that baryte is present in streams throughout the area and that even panned concentrates with low levels of Ba contained small amounts of baryte (e.g. 458 ppm Ba in WCP 1161, Appendix 1). $Sr_p$ variation is also related to the proportion of baryte in the sample.

3. Sulphides and oxides. The close positive correlations between Mn, Fe, Co, Ni, Zn and As levels in panned concentrates (Table 5) are attributed to the presence of sulphide and iron oxide minerals in most samples (Appendix 1).

4. Basic igneous rocks. The close correlation between Ti and V in panned concentrates is caused primarily by the presence of these elements in ilmenite derived from basic rocks within the Eycott Volcanic Group and the Carrock Fell Complex. The association is reinforced by the presence of both elements in chlorite in mudstones and Coal Measures.

5. Limestones. The presence of these rocks is responsible for the correlation of $Ca_s$ and $Ca_p$ and the lack of correlation of these variables with most others. The correlation of $Ca_s$ with $Hg_s$ (Table 5) suggests a relationship between mercury mineralisation and the Carboniferous Limestone succession. $Sr_s$ correlates because of the substitution of Sr for Ca in the calcium carbonate lattice.

**Table 5** Summary of significant positive inter-element Spearman-rank correlations derived from the stream sediment and panned concentrate analyses

| Element | | | Correlation coefficient | | |
|---|---|---|---|---|---|
| | 0.40 - 0.49 | 0.50 - 0.59 | 0.60 - 0.69 | 0.70 - 0.79 | >0.80 |
| Stream sediments n=114 | | | | | |
| Ca | $Zr_s$,$Hg_s$ | | $Sr_s$,$Ca_p$ | | |
| Ti | | $Cr_s$,$Cu_s$,$Ni_s$ | | $Co_s$,$Fe_s$,$Zn_s$ | $Rb_s$,$V_s$ |
| V | | $As_s$,$Cr_s$,$Mn_s$,$Zn_p$ | $Cu_s$,$Ni_s$ | $Zn_s$ | $Ti_s$,$Rb_s$ $Co_s$,$Fe_s$ |
| Cr | | $Co_s$,$Fe_s$,$Ti_s$ | $Ni_s$,$Rb_s$ | | |
| Mn | | $Rb_s$,$V_s$,$Zn_s$,$Mn_p$ | $As_s$,$Fe_s$,$Ni_s$ | $Co_s$ | |
| Fe | | $Cr_s$,$Co_p$ | $Cu_s$,$Mn_s$,$Zn_p$ | $As_s$,$Rb_s$,$Ni_s$, $Zn_s$,$Ti_s$ | $V_s$,$Co_s$ |
| Co | | $Cr_s$,$Co_p$,$Zn_p$ | $As_s$,$Cu_s$ | $Mn_s$,$Rb_s$,$Zn_s$ | $Fe_s$,$Ni_s$,$V_s$ |
| Ni | | $As_s$,$Cu_s$ | $Cr_s$,$Mn_s$,$V_s$,$Zn_s$, $Co_p$,$Ni_p$ | $Fe_s$,$Rb_s$ | $Co_s$ |
| Cu | | $As_s$,$Ni_s$,$Pb_s$,$Rb_s$, $Ti_s$ | $Co_s$,$Fe_s$,$V_s$,$Zn_s$ | | |
| Zn | | $As_s$,$Mn_s$,$Zn_p$ | $Cu_s$,$Ni_s$,$Rb_s$ | $Co_s$,$Fe_s$,$Pb_s$, $Ti_s$,$V_s$ | |
| As | | $Cu_s$,$Ni_s$,$Pb_s$,$Rb_s$, $V_s$,$Zn_s$,$Zn_p$,$Sb_p$ | $Co_s$,$Mn_s$ | $Fe_s$ | |
| Rb | | $As_s$,$Cu_s$,$Mn_s$ | $Cr_s$,$Zn_s$,$Zn_p$ | $Co_s$,$Fe_s$,$Ni_s$ | $Ti_s$,$V_s$ |
| Sr | | | $Ca_s$ | | |
| Zr | $Ca_s$ | | | $Zr_p$ | |
| Ba | | | | $Sr_p$,$Ba_p$ | |
| Ce | $Rb_s$,$Cr_s$,$Ni_s$ | | | | |
| Hg | $Ba_p$,$Ca_s$ | | | | |
| Pb | | $As_s$,$Cu_s$,$Pb_p$ | | $Zn_s$ | |
| Panned Concentrates n=122 | | | | | |
| Ca | | | $Ca_s$ | | |
| Ti | $Cr_p$,$Ce_p$,$W_p$ | | $V_p$ | | |
| V | | $Mo_p$ | $Ti_p$ | | |
| Cr | $Zr_p$,$Ti_p$ | | $Ce_p$ | | |
| Mn | | $Mn_s$,$Sb_p$,$Ce_p$ | $Co_p$,$Fe_p$,$Zn_p$,$As_p$ | | |
| Fe | | $Ni_p$,$Sb_p$ | $Mn_p$,$Co_p$ | $As_p$ | |
| Co | | $Co_s$,$Fe_s$,$As_p$ | $Ni_s$,$Mn_p$,$Fe_p$,$Zn_p$ | | $Ni_p$ |
| Ni | | $Fe_p$,$Cu_p$,$Zn_p$ | $Ni_s$ | | $Co_p$ |
| Cu | $Pb_p$,$Fe_p$ | $Ni_p$,$Zn_p$,$As_p$ | | | |
| Zn | | $As_s$,$Co_s$,$Ti_s$,$V_s$ $Zn_s$,$Cu_p$,$As_p$ | $Rb_s$,$Mn_p$,$Co_p$,$Ni_p$ | | |
| As | | $Co_p$,$Ni_p$,$Cu_p$,$Zn_p$, $Sb_p$ | $Mn_p$ | | |
| Sr | | | | $Ba_s$ | $Ba_p$ |
| Zr | $Cr_p$ | | | $Zr_s$ | |
| Mo | $Sn_p$ | $V_p$,$Ba_p$ | | | |
| Sn | $Mo_p$ | $Pb_p$ | | | |
| Sb | | $As_s$,$Mn_p$,$Fe_p$,$Pb_p$ | | | |
| Ba | $Hg_s$ | $Mo_p$ | | $Ba_s$ | $Sr_p$ |
| Ce | $W_p$ | $Mn_p$ | $Cr_p$ | | |
| W | $Ti_p$,$Mn_p$,$Ce_p$ | | | | |
| Pb | $As_p$,$Fe_p$ | $Pb_s$,$Sn_p$,$Sb_p$ | $Ti_s$ | | |

$Ag_s$, $Sn_s$, $Bi_s$, $Bi_p$ and $U_p$ omitted because of the high percentage (>45%) of results below the detection limits.

$Mo_s$, $Sb_s$, $W_s$, $U_s$ and $Ag_p$ show no highly significant correlations ($r > 0.4$) with other elements.

6. Contamination. The mineralogical examination of panned concentrates showed that virtually every stream in the area contains some form of contamination. Though contamination is strongest in the industrialised coastal strip in the west of the area, highly contaminated stream courses were also found in the rural uplands. The most common particulate contaminants recognised under the microscope were lead glass, slag (fly-ash) and fragments of lead, iron and copper (Appendix 1). These give rise to positive Sn, Pb and Sb correlations in the panned concentrate data. Mineralogical data indicates that all $Sn_p$ anomalies are generated by contamination but $Pb_p$ and $Sb_p$ anomalies may be caused by mineralisation or contamination. Site observations also recorded lighter materials, such as plastics and paint, and waste-water effluent, but these do not appear to have had a major effect on the stream sediment data.

7. Resistates. Some elements forming resistate mineral phases such as chromite, monazite and zircon show similar behaviour. This is demonstrated by the positive correlations between Ce, Cr, W, Zr and Ti in the panned concentrate. This variation is accounted for by the sorting of these minerals during weathering, transport and sedimentation.

## Definition of anomalies

Threshold levels were determined by cumulative frequency curve analysis (Parslow, 1974; Sinclair, 1976). The majority of elements have sample distributions suggesting the presence of two or more overlapping unimodal populations. In some cases these sub-populations can be related to a particular feature, such as the presence of baryte mineralisation or a bedrock lithology, but in other cases the origin is not obvious. Thresholds were set to separate higher populations which might be related to mineralisation or some other source of metal enrichment. This source of enrichment might simply be heavy mineral layers in sandstones (e.g. Zr, Ce), the presence of basic rocks (e.g. Co, Ni), or contamination (e.g. Sn, Sb). A few variables without distinctive bimodal or polymodal distributions display approximately normal ($Ce_s$) or lognormal ($Co_p$) distributions and in these cases thresholds were arbitrarily set at the 97 percentile level. Threshold levels are denoted by a pecked line in the key of Figures 14 to 24, which show the concentration of selected elements in stream sediments and panned concentrate samples across the area. Class intervals on these plots were chosen to distinguish populations discerned in the cumulative frequency plots or, in their absence, the top 3% of samples.

## Distribution of anomalies

### *Fluorine*

Interpretation of the F concentrations in over 1700 water samples from the North Pennines (Hunting Geology and Geophysics, 1983) showed that clusters of F results over 120 ppb accurately defined areas of F mineralisation and that levels over 200 ppb were good indicators of mineralisation. A similar threshold level was found in this geologically similar area (median = 23 ppb, minimum = < 20 ppb, maximum = 537 ppb, threshold = 115 ppb, n = 66) and it seems probable that the three results above this level (286, 493 and 537 ppb; Figure 14) are distinct anomalies reflecting the presence of mineralisation in the vicinity. There appears to be a regional trend in the F data, with a clustering of high values in the Dovenby-Dearham area.

### *Titanium and vanadium*

These two elements show very similar distribution patterns in stream sediments and panned concentrates. Highest levels of both elements in panned concentrates are located in the north-west of the area (at [NY 2832 3822], [NY 2528 3884] and [NY 2882 3703], Figure 15). They are caused

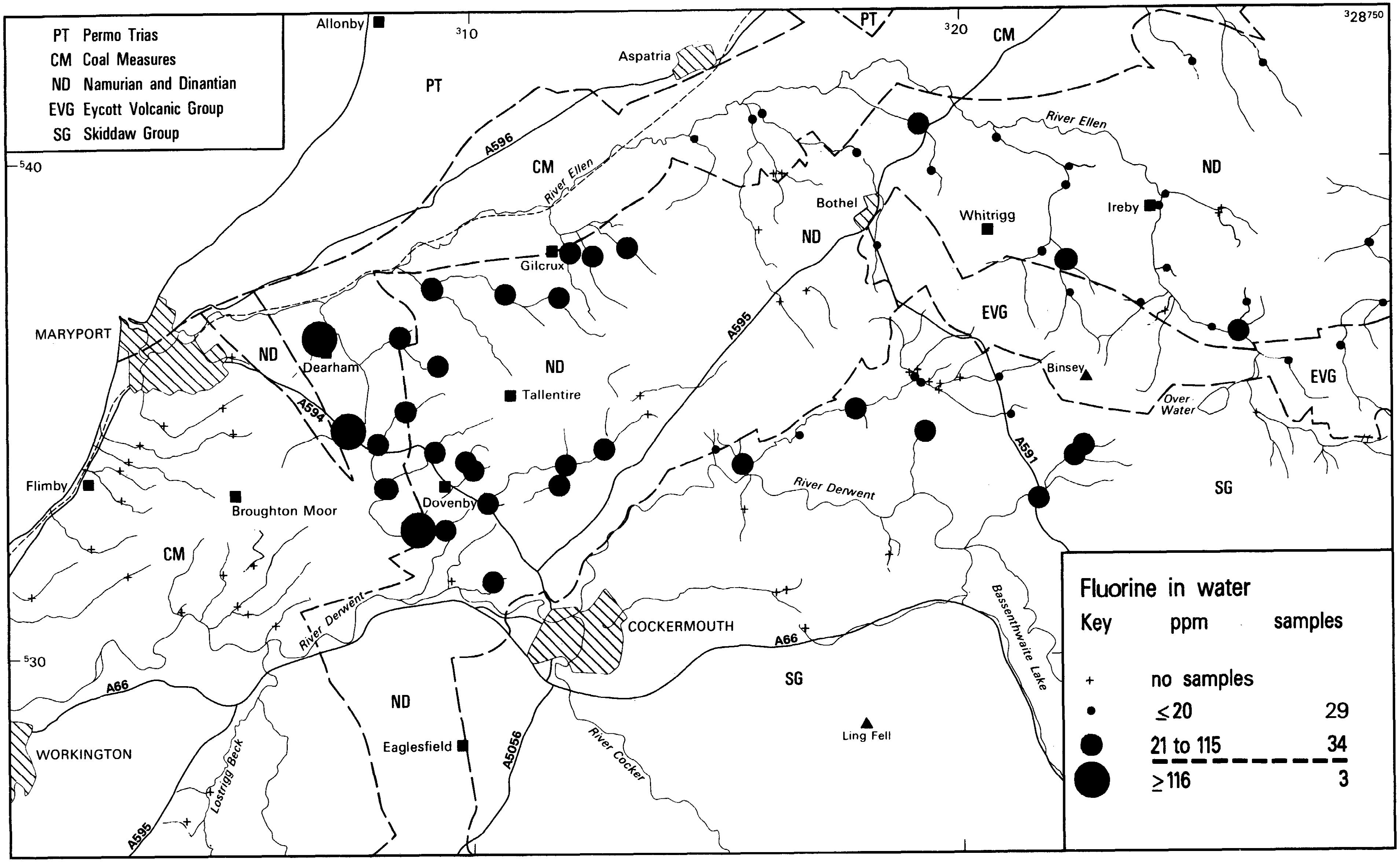


**Figure 14** Fluorine in water samples

by the presence of abundant ilmenite and magnetite in the samples (WCP 1085 and 1086, Appendix 1). The source of these minerals is believed to be glacio-fluvial concentrations derived from gabbroic rocks within the Carrock Fell Complex. Locally these gabbroic rocks, which outcrop on high ground up-ice of the sample sites (Figure 4), contain high concentrations of ilmenite and magnetite (Eastwood et al., 1968) and are compositionally so distinct (Table 6) that very high $Ti_p$ can be taken as an indicator of the glacial dispersion of this lithology. Weaker $Ti_p$ anomalies in the west of the area (Figure 15) are probably derived from the Coal Measures. The distribution of both elements in stream sediments shows some significant differences from the panned concentrates, highest values occurring around Ruthwaite (at [NY 2364 3704] and [NY 2214 3793]) and Longlands (at [NY 2782 3635]). The source is the Eycott Volcanic Group where the elements must be concentrated in a light phase, most probably chlorite.

**Table 6** Composition of major rock types in the Cockermouth area

| Element | Coal[1] (East Germany) | Skiddaw Group[2] (all lithologies) | Basaltic[3] Andesite | Ilmenite[4] Gabbro | Carboniferous[5] Limestone |
|---|---|---|---|---|---|
| $SiO_2$ | | 48.12 - 84.48 | 54.15 | 41.38 | 2.60 |
| $Al_2O_3$ | | 5.81 - 29.83 | 16.56 | 14.04 | 0.11 |
| $TiO_2$ | | 0.30 -1.51 | 1.24 | 5.05 | 0.02 |
| $Fe_2O_3$ | | 4.57 - 15.23 | 8.89 | 20.83 | 0.61 |
| MgO | | 0.79 -2.92 | 5.97 | 5.63 | 1.20 |
| CaO | | 0.02 -3.48 | 8.73 | 9.73 | 52.90 |
| $Na_2O$ | | <0.01 -2.17 | 1.99 | 1.56 | 0.02 |
| $K_2O$ | | 0.52 -7.27 | 2.06 | 0.72 | 0.07 |
| MnO | | 0.02 -1.44 | 0.15 | 0.37 | 0.04 |
| $P_2O_5$ | | 0.06 -1.72 | 0.23 | 0.14 | 0.02 |
| | | | | | |
| V | 1 - 48 | 33 - 185 | | | |
| Cr | | 25 - 167 | 141 | | |
| Co | 1 - 65 | 4 -61 | | | |
| Ni | 2 - 42 | 12 -75 | 80 | | 4.7 |
| Cu | 3 - 320 | 6 - 123 | | | 3.2 |
| Zn | 13 - 1600 | 25 - 331 | | | 7.6 |
| Sr | | 7 - 206 | 319 | | 600.0 |
| As | 5 - 400 | <2 - 117 | | | |
| Zr | | 79 - 312 | 175 | | |
| Mo | 1 - 16 | <1 - 7 | | | |
| Sn | 0.5 - 9 | | | | 0.9 |
| Ba | | 112 - 1220 | 273 | | 50.0 |
| Pb | 8 - 1600 | 3 - 192 | 80 | | 2.8 |
| U | | <2 - 8 | | | |

1. Range of 479 analyses of coals from East Germany (Rosler and Lange, 1972).
2. Range of 308 analyses of sandstones, siltstones and mudstones (D C Cooper, unpublished data)
3. From Moseley and Millward (1982).
4. From Eastwood, et al. (1968).
5. Shelf limestone, Northumbria: majors n=3, traces n=35 (J H Bateson personal communication).

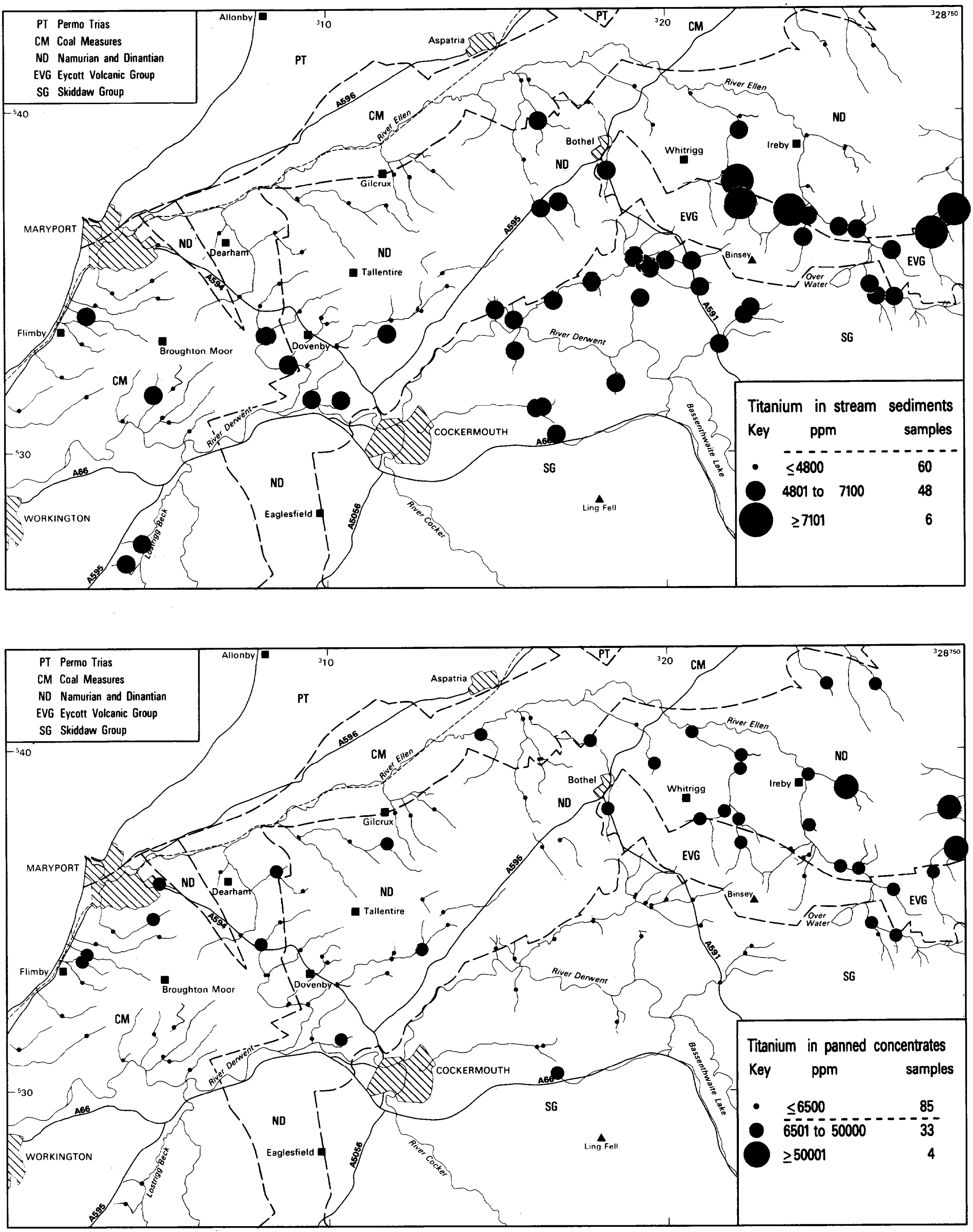


Figure 15 Titanium in stream sediment and panned concentrate samples

*Manganese and iron*

High levels of $Mn_s$ and $Fe_s$ show a general association with high ground and the Skiddaw Group outcrop, reflecting the high levels of these elements in the Skiddaw Group (Table 6) and the effects of hydrous oxide precipitation in streams draining uplands with acidic soil. The highest values (8.6% Fe at [NY 1995 3558], 8.5% Fe at [NY 2096 3480], 8.1% Fe at [NY 2618 3451] and >2% Mn at [NY 1611 3126], [NY 1904 3572] and [NY 1950 3534]) may be generated by other factors, such as contamination and mineralisation. $Mn_p$ results, highest in the south of the area, show a broadly similar pattern of variation to $Mn_s$ and $Fe_s$. Highest values (>1.5% at [NY 1778 3494], [NY 2599 3486] and [NY 2599 3484]) reflect the presence of Fe-Mn oxides and, possibly, contaminants. The distribution pattern of $Fe_p$ is quite different, showing similarities with $Co_p$ and $Ni_p$ in that some of the highest values are over Coal Measures in the west of the area (e.g. 24.8% Fe at [NY 0682 3643], 23.6% Fe at [NY 0502 3609] and 22.7% Fe at [NY 0288 3399]). These are probably caused by the presence of pyrite derived from the Coal Measures and clay ironstone. Other $Fe_p$ highs cluster south of Binsey (e.g. at [NY 2096 3480] and [NY 2245 3419]) in samples containing a wide spectrum of enriched metals and around Ireby (e.g. at [NY 2528 3884] and [NY 2096 3793]) due to Fe-Ti oxides derived from rocks of the Eycott Volcanic Group or Carrock Fell Complex.

*Chromium, cobalt and nickel*

Results for these high-value elements concentrated in basic rocks are related to lithological variation, with the higher levels occurring over the Eycott Volcanic Group (e.g. at [NY 2096 3480]), Coal Measures (e.g. [NY 0288 3399] and [NY 0682 3643]), and the Skiddaw Group (e.g. at [NY 2670 3448]). There is no evidence to suggest the presence of any economic concentrations of these elements, and maximum levels of Co and Ni are lower in panned concentrates than stream sediments. However, the discovery of small amounts of millerite in two panned concentrates containing sub-anomalous levels of Ni, collected on the west side of Binsey (samples WCP 1076 and 1077, Appendix 1), suggests the presence locally of low-temperature Ni-bearing vein mineralisation within the Eycott Volcanic Group. Some $Cr_p$ is held in a distinctive chromite which is probably derived from basic intrusions into the Skiddaw Group south of this area (Appendix 1). Co is locally enriched in pyrite in the Coal Measures (Table 2). Levels of all three elements in concentrates may be enhanced locally by contamination from steel, and high levels of $Co_s$ are in part due to hydrous oxide co-precipitation processes in upland streams.

*Copper*

Levels of $Cu_s$ are low. The highest levels (>65 ppm) reflect a relatively high background (Table 2) in Coal Measures (e.g. at [NY 0510 3103] and [NY 0682 3643], Figure 16) and basic volcanic rocks (e.g. at [NY 2782 3635] and [NY 2219 3725, Figure 16) enhanced by contamination or mineralisation. In contrast, relatively high levels are recorded in panned concentrates due to the presence of Cu in chalcopyrite and detrital contaminants, notably Cu wire. Consequently there is no significant correlation between $Cu_s$ and $Cu_p$ (Table 5). The largest (>700 ppm) $Cu_p$ anomalies, all of which contain chalcopyrite, are located near Binsey (at [NY 2245 3419] and [NY 2096 3480]) and Broughton Moor (at [NY 0510 3103]) and appear to be unrelated to known occurrences of Cu mineralisation. The occurrences near Binsey are accompanied by a wide range of metal anomalies including W. Mineralogical work showed that besides contaminants, sulphide minerals and wolframite were present, which either suggests glacial transportation from the Carrock Fell area or an unknown source of polymetallic mineralisation in the vicinity. With one exception, from near Flimby (at [NY 0274 3380]), all $Cu_p$ anomalies in the range 215-700 ppm subjected to mineralogical study were also found to contain chalcopyrite. Besides anomalies recorded near the known copper

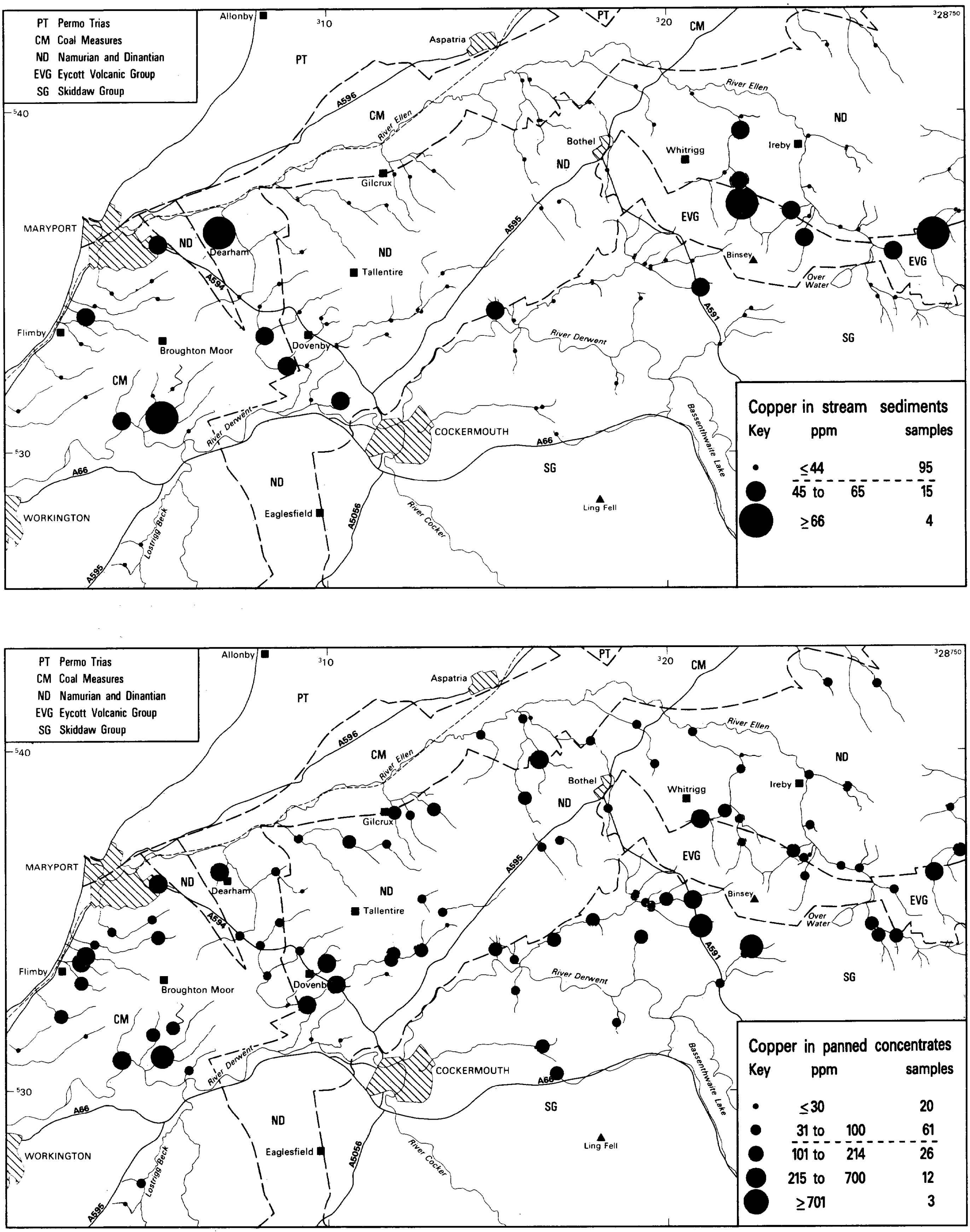


**Figure 16** Copper in stream sediment and panned concentrate samples

occurrences at Birdhouse, Threapland and down-ice of the Caldbeck Fells mineralisation, others suggest Cu mineralisation is present in the Eycott Volcanic Group west of Binsey (upstream of [NY 2073 3557]), in the Carboniferous Limestone of the Dovenby - Tallentire area, and locally in the Coal Measures in the west of the area. Here anomalies may be reflecting syngenetic or diagenetic metalliferous concentrations (e.g. WCR 1255, Table 2), but natural anomalies are frequently enhanced by contaminants, for example sample WCP 1150 from Flimby [NY 0288 3399] contains Cu wire (Appendix 1).

The number of copper anomalies in panned concentrates, the relatively low values in stream sediments and the widespread occurrence of small amounts of chalcopyrite suggest widespread mechanical dispersion, almost certainly by glacial action from a number of sources.

*Zinc*

Sphalerite was found to be present in many panned concentrate samples including some containing less than 100 ppm Zn (e.g. WCP 1047 and 1058, Appendix 1). Zn levels in most panned concentrates were not high, suggesting that, although widely dispersed, the amount of sphalerite present in streams is small. Sphalerite was recorded in all panned concentrates containing more than 270 ppm zinc except for one (from [NY 1547 3384]) which was not examined. $Zn_s$ background levels are higher than those of $Zn_p$ and $Zn_s$ does not show a very close positive correlation with $Zn_p$ (Table 5). This is due to the concentration of zinc in clay/chlorite and precipitate phases in the sediment samples. Highest $Zn_s$ values are found in streams draining the Eycott Volcanic Group (Figure 17) where, it is suspected, a high background from the basic rocks is enhanced either by hydrous oxide precipitation or the presence of zinc mineralisation. An exception is the highly anomalous sample from near Stockdale, south of Overwater, which has a catchment of Skiddaw Group rocks (Figure 17). Mineralogical work on the panned concentrate collected from an adjacent stream (WCP 1134, Appendix 1) suggests that in this case the cause of the anomaly is sphalerite mineralisation and contamination, perhaps enhanced by hydrous oxide precipitation.

Only two occurrences of Zn mineralisation are recorded in the area, which contrasts strongly with the widespread occurrence of sphalerite in panned concentrates. Although most of the sphalerite is dull and corroded, suggesting that it may transported by glacial and fluvial action from the Caldbeck Fells mineralisation, the presence of large isolated anomalies suggests that additional local sources may exist. Examples include the anomalies near Stockdale (e.g. [NY 2670 3448] and [NY 2599 3484]), Gilcrux [NY 1314 3823] and Binsey [NY 2073 3557] (Figure 17). Further large anomalies to the south-east of the latter site (Figure 17) may also have a local source but the presence of W anomalies in the samples suggest that they may be transported from the Carrock Fell area.

*Arsenic*

Arsenopyrite was only found in two of the panned concentrates examined mineralogically and this lack of arsenopyrite is reflected in the generally low levels of As found in sediments (maximum 156 ppm, nearest neighbour 101 ppm) and panned concentrates (maximum 265 ppm, nearest neighbour 160 ppm). Of the two samples containing arsenopyrite, one (from [NY 1670 3050]) came from close to a record of pyrite, arsenopyrite and gold mineralisation in Embleton quarry (Young, 1987). The second (from [NY 2858 3699]) is down-ice and probably derived from the Caldbeck Fells mineralisation. The sample containing the highest $As_p$ level (265 ppm from [NY 2096 3793]) was not examined mineralogically; it was collected south of Whitrigg (Figure 18) from a stream which contains the Birdhouse baryte mine in its catchment. A sample of brecciated altered tuff

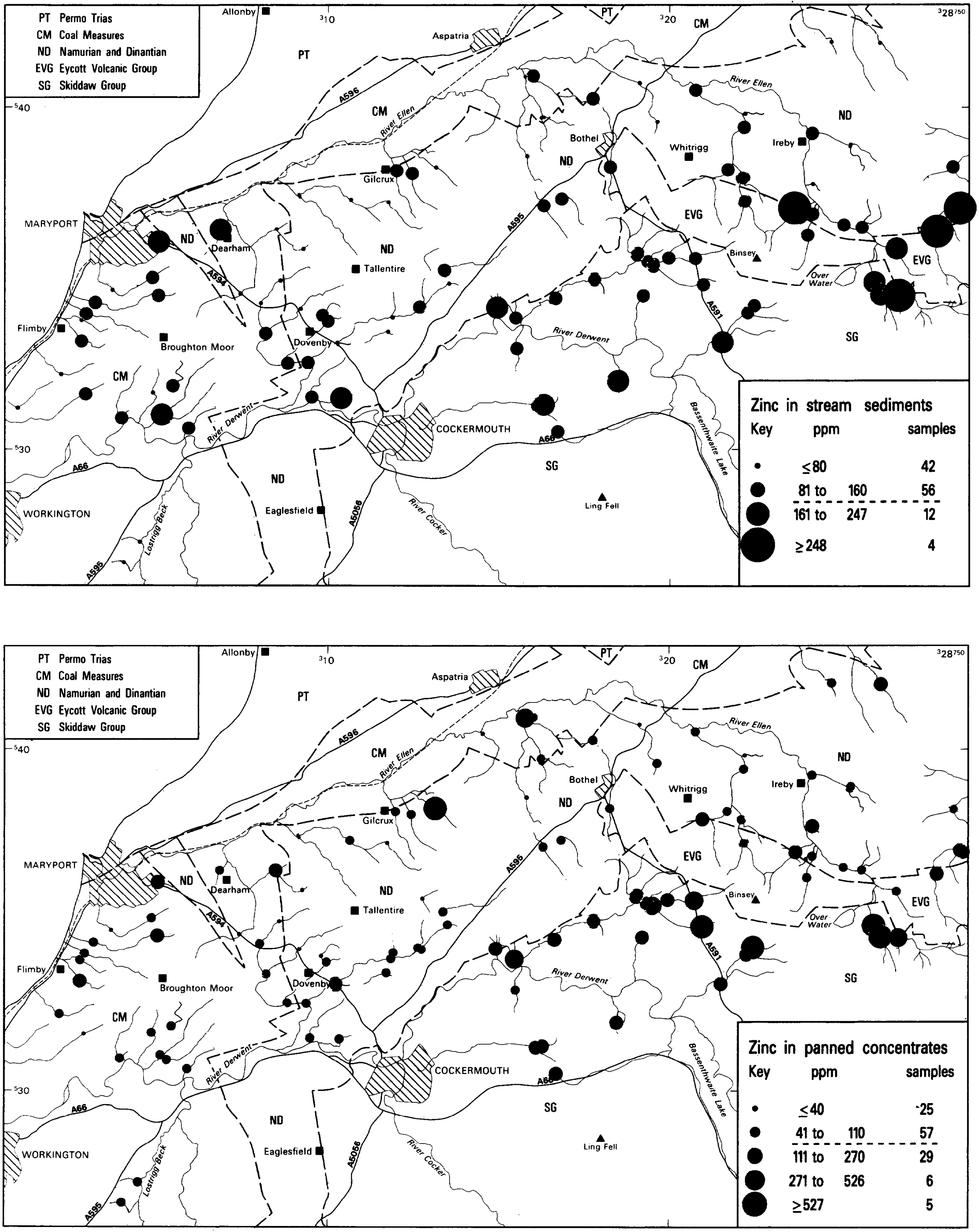


**Figure 17** Zinc in stream sediment and panned concentrate samples

collected from near the old working (Table 2, No. 1207) contains 400 ppm As, indicating local enrichment within the Eycott Volcanic Group in this area. Low levels of $As_s$ vary according to bedrock lithology with higher levels over mudstones and Coal Measures. The highest values reflect the presence of mineralisation, occurring in the samples from Embleton [NY 1670 3050], Stockdale [NY 2599 3486] and west of Caldbeck [NY 2858 3699] (Figure 18).

*Molybdenum*

Most anomalous values of $Mo_s$ (4-6 ppm) and $Mo_p$ (13-36 ppm) are located over the Coal Measures (e.g. 36 ppm $Mo_p$ and 6 ppm $Mo_s$ at [NY 0682 3643]) and reflect the concentration of this element in some coals and mudstones (Tables 2 and 6). There are a few anomalies in the east of the area whose cause is uncertain (e.g. 16 ppm $Mo_p$ at [NY 2400 3678] and [NY 2096 3793] and 5 ppm $Mo_s$ at [NY 2670 3448]). Maximum levels, however, are low and there is no evidence to suggest a concentration of any economic significance.

*Silver*

High $Ag_p$ results correlate with high $Ba_p$ and are caused by analytical interference, the presence of large amounts of Ba enhancing the Ag results. The low magnitude of the results (Table 4), despite this enhancement, suggests that no significant Ag mineralisation is present in this area.

*Tin*

No natural cassiterite or other Sn-bearing phase was found during the mineralogical examination of panned concentrates, but artificial sources were frequently reported from anomalous samples (e.g. WCP 1076 and 1119, Appendix 1), strongly suggesting that all $Sn_p$ anomalies in this area are the product of contamination. High $Sn_p$ values are scattered across the whole area (Figure 19), reflecting the presence of contamination in most streams. The association of Sn and Pb in artificial phases such as solder is believed to be the cause of the positive $Pb_p$ - $Sn_p$ correlation (Table 5). The presence of high $Sn_p$ is therefore a useful guide to the presence of substantial contamination in a sample from this area. However, not all forms of contamination are accompanied by high levels of Sn, so low $Sn_p$ is no guarantee of a contamination free sample. The few $Sn_s$ anomalies (25 ppm at [NY 0682 3643], 22 ppm at [NY 1492 3414], 20 ppm at [NY 0501 3608] and 19 ppm at [NY 0274 3319]) all occur at sites with high $Sn_p$ and all except one are in the more industrialised west of the area; they are all thought to be caused by pollution.

*Barium*

High levels of barium in both sediment and concentrate samples (Figure 20) are caused by the presence of baryte. Samples containing appreciable baryte were collected throughout the area and the distribution reflects the mechanical dispersion of baryte by glacial and fluvial action from a large number of sources. Because of the glacial dispersion it is difficult to distinguish anomalies derived from known occurrences of baryte from any which reflect undiscovered mineralisation. Large anomalies in the extreme east of the area (at [NY 2664 3584], [NY 2782 3635] and [NY 2858 3699]) are probably derived from the Caldbeck Fells mineralisation, whilst anomalies in the Whitrigg - Ruthwaite area are derived partly from known mineralisation (e.g. samples from [NY 2364 3704] and [NY 2417 3686]) and partly from hidden mineralisation of similar style in Eycott Volcanic Group or Lower Carboniferous rocks (e.g. samples from [NY 2402 3624], [NY 2219 3725] and [NY 2214 3793]). Many anomalies to the north and west of Tallentire (e.g. at [NY 1174 3723] and [NY 0857 3494] are probably derived from known occurrences in the area (Figure 5), but large anomalies over Upper Carboniferous rocks in the west (e.g. at [NY 0274 3319]) suggest that mineralisation may also be present in these rocks.

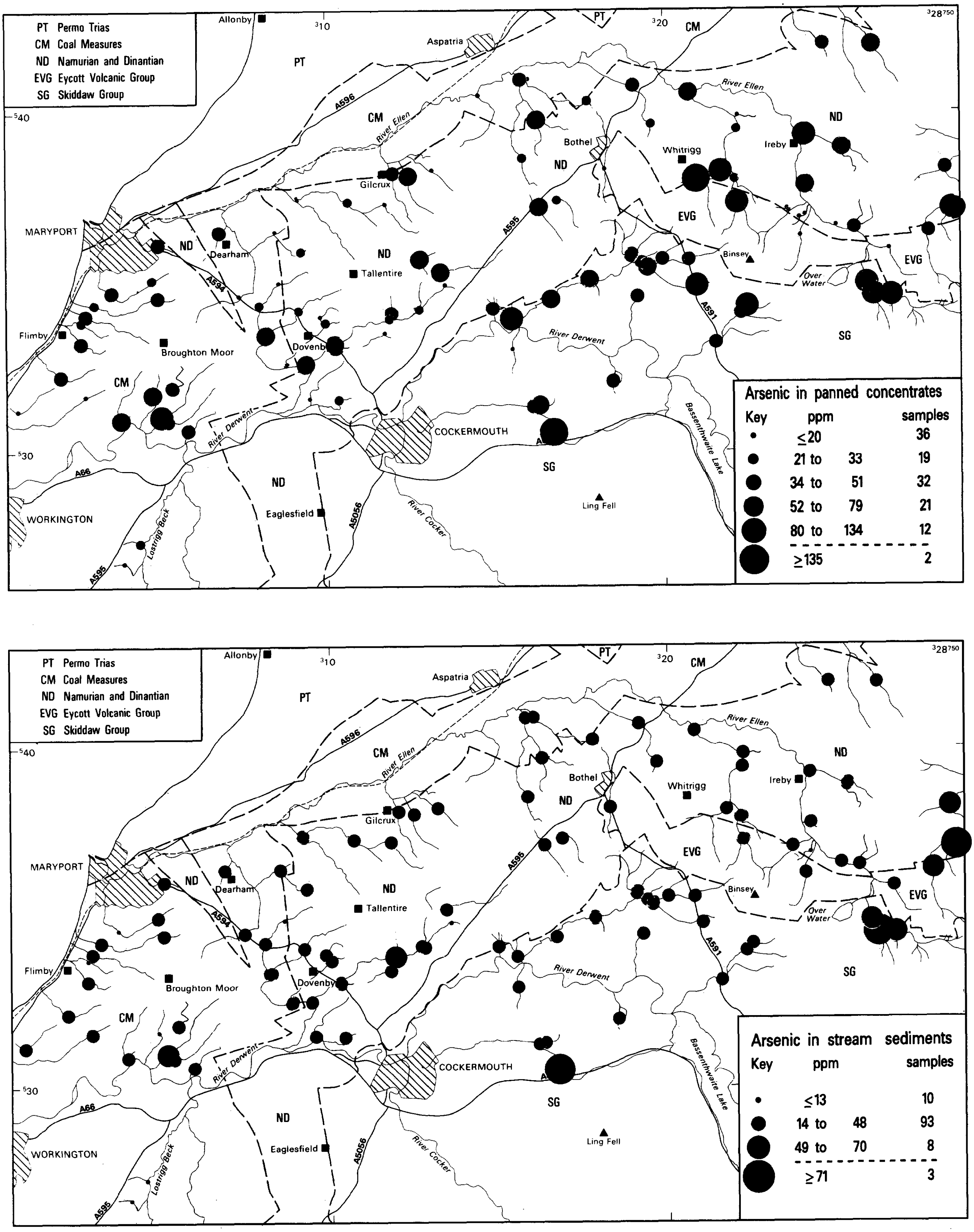


**Figure 18** Arsenic in stream sediment and panned concentrate samples

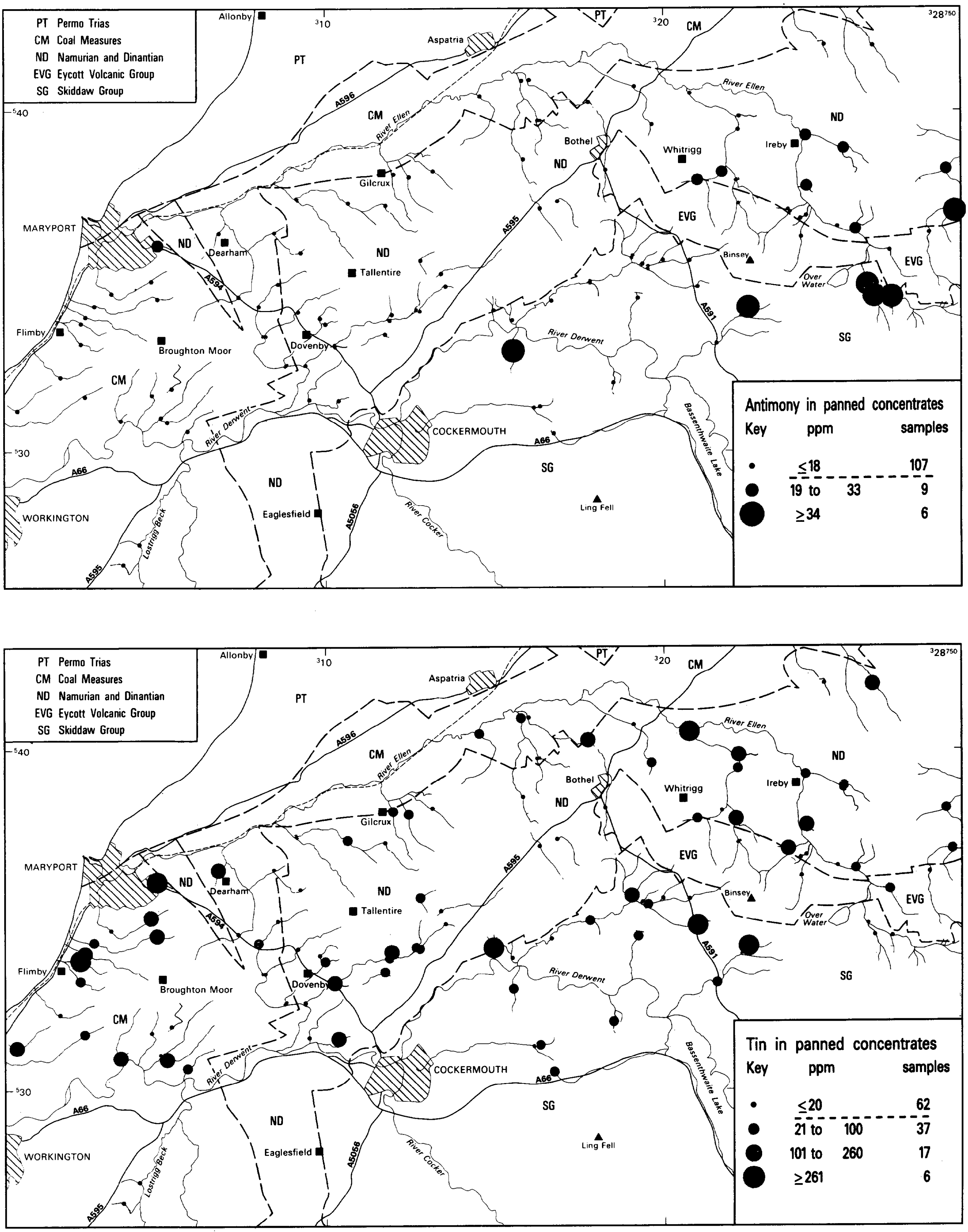


**Figure 19** Tin and antimony in panned concentrate samples

### *Antimony*

Most $Sb_p$ results are of low magnitude and no natural Sb-bearing phases were identified during the mineralogical study. Some high values are undoubtedly caused by contamination, notably from solder, which was identified in one anomalous sample (WCP 1119, Appendix 1). All anomalous $Sb_p$ sites (Figure 19) are in the eastern half of the area and the anomalous samples all contain > 3000 ppm $Pb_p$, a relationship which may be due to mineralisation or contamination. However, the Robin Hood Sb mine is situated within Skiddaw Group rocks about 2 km to the south of the sampled area (at [NY 228 330]) and four of the six $Sb_p$ anomalies lie where the southern boundary of the sampling area passes closest to the mine (Figure 19). $Sb_p$ also correlates with $Mn_p$ and $Fe_p$ (Table 5), which may be caused by the presence of small amounts of Sb in minerals such as magnetite. $Sb_s$ levels (Table 4) are generally low, the highest concentrations were recorded in samples from near Binsey [NY 2226 3398], Uldale ([NY 2563 3646] and [NY 2509 3654]) and Stockdale [NY 2599 3484]. They correlate with Sb results to the extent that the highest values are located in the south-east of the area, suggesting an association with mineralisation in the Skiddaw and Eycott Volcanic groups, transported by glacial action.

### *Tungsten*

$W_s$ levels are low. The highest values (6 ppm) show no correlation with high levels in panned concentrates and are scattered across the area; they are unlikely to be reflecting the presence of W mineralisation. Most anomalous $W_p$ sites are located east of Bothel (Figure 21) and can be divided into two groups. The first group, in the north-west of the area, around Aughertree Fell (at [NY 2832 3822], [NY 2528 3884] and [NY 2858 3699]) is associated with very high Ti and V due to the presence of abundant ilmenite and magnetite. The samples also contain baryte and sulphide minerals (Appendix 1) but no tungsten minerals were seen. The association of minerals and location of the sites suggests that these anomalies represent transported glacio-fluvial concentrations derived from the Carrock Fell area. The second group of anomalies, including the highest $W_p$ value (from [NY 2245 3419]) is located south of Binsey (Figure 21). Wolframite was identified in one of these samples (WCP 1076, Appendix 1). The samples also contain sulphide minerals and contaminants, but relatively low Ti and V levels, suggesting a different source from the first group. If not local, the direction of ice movement (Figure 4) suggests that the source most probably lies to the south-east.

### *Gold*

Small amounts (up to 4 grains) of gold were noted in panned concentrates from 21 sites, mostly in the centre and west of the area (Figure 22). One site is in the vicinity of the previously recorded gold occurrences on Slate Fell, near Cockermouth, and at Embleton (Young, 1987). Gold is also reported from several of the mines in the Roughton Gill area of the Caldbeck Fells and from Carrock Fell (Young, 1987). This area may be the source of the isolated gold occurrence on the eastern edge of the area at [NY 2832 3822] as the sample (WCP 1085, Appendix 1) contains a mineral assemblage suggesting derivation from the Carrock Fell Complex. There is no obvious correlation between samples containing gold and anomalous levels of elements concentrated in sulphides (Cu, Zn, Pb, Hg). Three gold grains from two panned concentrates (collected at [NY 1351 3484] and [NY 1629 3130]) were analysed by electron probe. The analyses showed the presence of small amounts of Cu in one grain and up to 13% Ag. The polished surfaces of the grains were uneven, perhaps due to fine-grained silicate inclusions (Appendix 1).

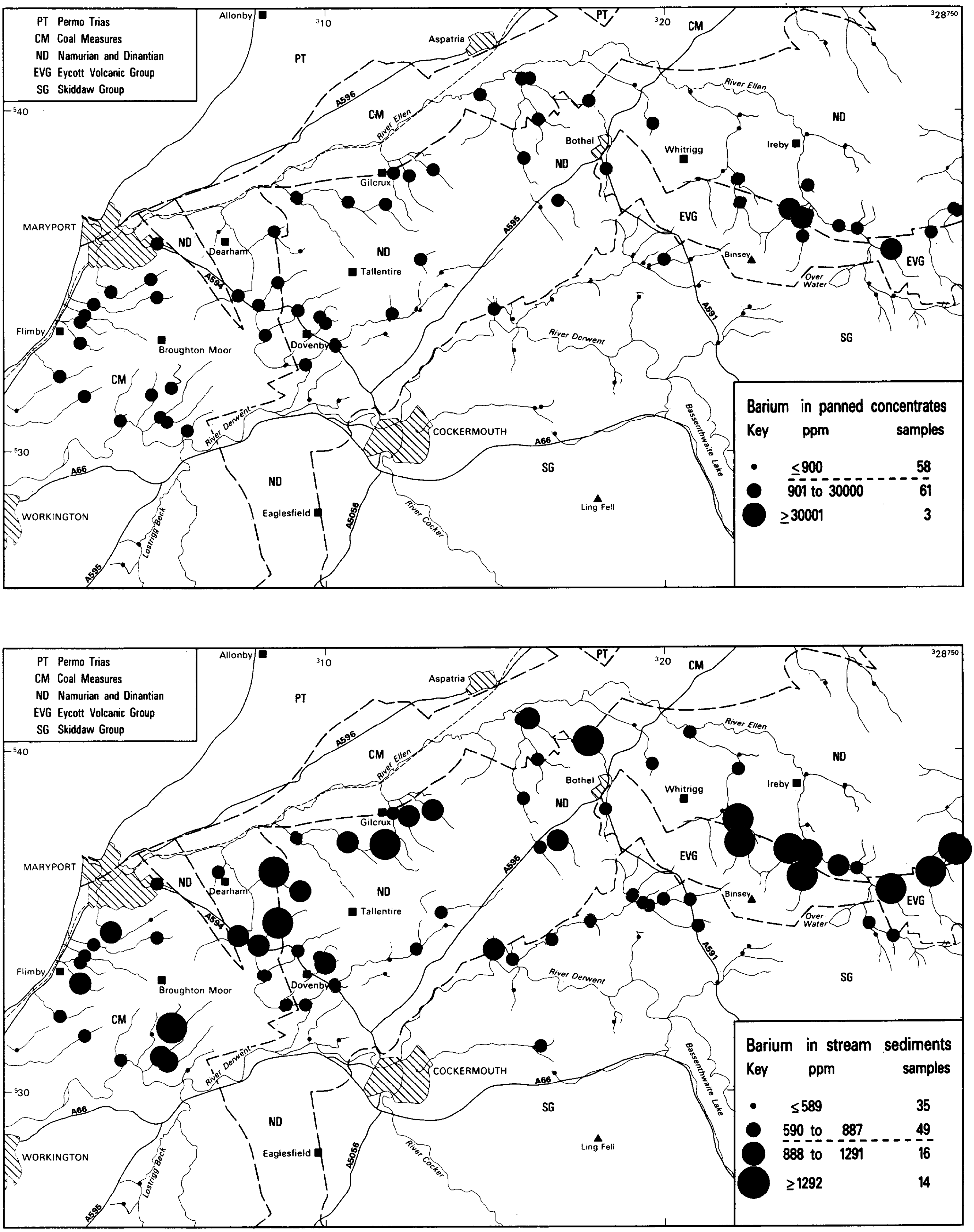


**Figure 20** Barium in stream sediment and panned concentrate samples

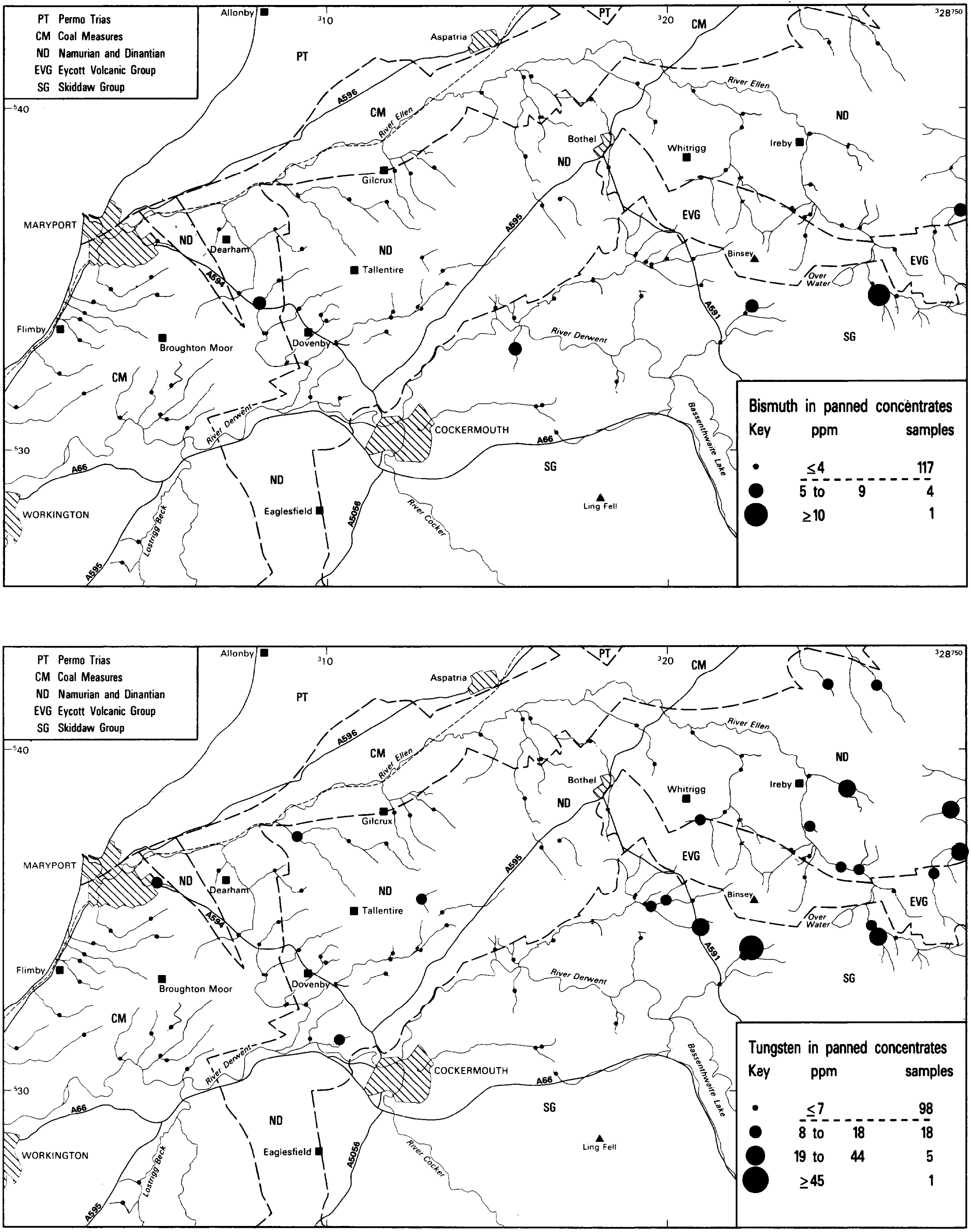


Figure 21 Tungsten and bismuth in panned concentrate samples

Gold was determined in a small number (16) of stream sediments to test for the presence of fine gold. All the results except two were less than the detection limit of 10 ppb. The highest value, 38 ppb, was in a sample collected near Dearham at [NY 0682 3643]; the panned concentrate from this site contained no visible gold though gold was recorded in samples collected in the general area (Figure 22).

Assuming that the presence of native gold is not caused by contamination, and this seems unlikely, its source must lie in the underlying bedrock or within the drift deposits. There is mineralogical evidence to suggest that the isolated occurrence in the east of the area is derived from the Carrock Fell area, but most occurrences lie over Carboniferous rocks. Possible sources in these rocks include: (a) fossil placers in channel sandstones or other clastic sediments, (b) small concentrations in sulphide minerals, mainly pyrite in the Coal Measures, (c) epigenetic mineralisation. Although far-travelled drift is a more likely source it is worth pointing out that the sample containing gold from Lostrigg Beck (at [NY 0445 2732]) has a catchment entirely within the Coal Measures and that the sediment contains a high proportion of locally derived material from outcrops and opencast coal operations.

There are two probable sources for drift-derived gold: the Lower Palaeozoic rocks of the Lake District and southern Scotland. There is good evidence to indicate that over much of the survey area tills of mixed origin are present, but that Scottish erratics become more numerous towards the coast, whilst those from the Lake District dominate in the east of the area. The distribution of gold grains (Figure 22) therefore suggests that, with the exception of the occurrence at the eastern margin of the area, a source in southern Scotland is probable.

*Mercury*

There is a general association of the higher $Hg_S$ results with Carboniferous rocks (Figure 23), and there is a positive correlation between $Ca_S$ and $Hg_S$ (Table 5). Samples containing high levels of $Hg_S$ do not form well-defined clusters which can be related to a particular geological feature, except that four of the six highest results occur within about a kilometre of the Gilcrux fault. Most anomalous values, except for one at Camerton [NY 0392 3094], occur within the Gilcrux - Dovenby - Dearham area (Figure 23). This pattern probably results from wide primary and secondary dispersion together with a number of sources in this general area. Only moderate levels of $Hg_S$ were recorded from the area around Birdhouse where the highest levels in rocks were recorded (Table 2).

Mercury was not determined in panned concentrates but cinnabar was noted in 22 samples whose distribution is broadly similar to that of the high values in sediment (Figure 23). Cinnabar was recorded at three of the six anomalous (>220 ppb) $Hg_S$ sites, but relatively large amounts of cinnabar were also found at sites returning quite low levels of $Hg_S$, for example nine grains of cinnabar from a site at [NY 0819 3340] where the $Hg_S$ content was 100 ppb (Figure 23). The presence of cinnabar suggests that high values of $Hg_S$ are not the product of contamination, although some are in highly contaminated samples (e.g. at [NY 0682 3643] and [NY 0392 3094]). There is no close correlation between high levels of $Hg_S$ and the presence of cinnabar or elements concentrated in sulphide minerals, but most anomalous $Hg_S$ sites contain high levels of Ba, reflected in the positive $Hg_S$ - $Ba_P$ correlation (Table 5).

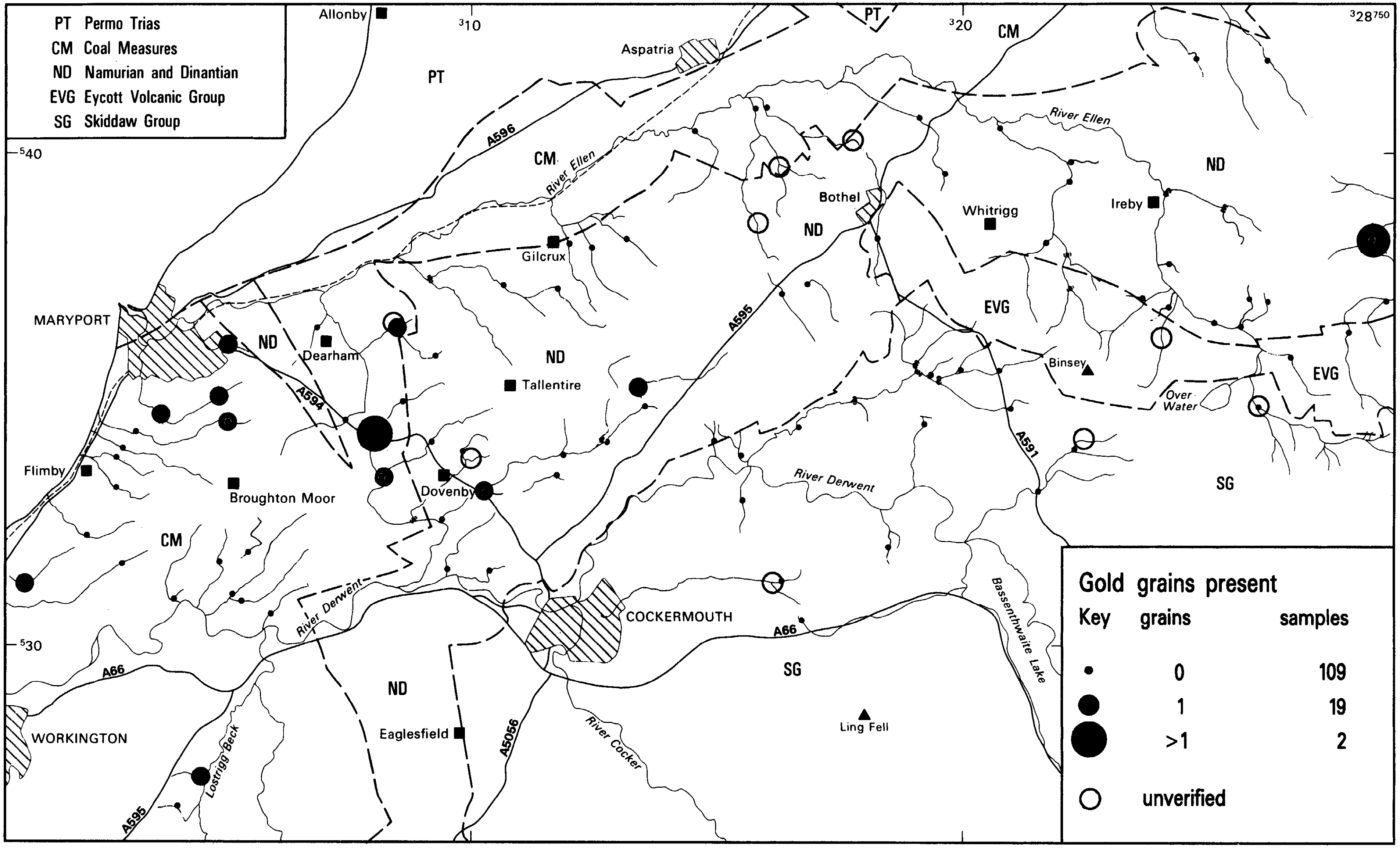


Figure 22 Location of gold occurrences in panned concentrates

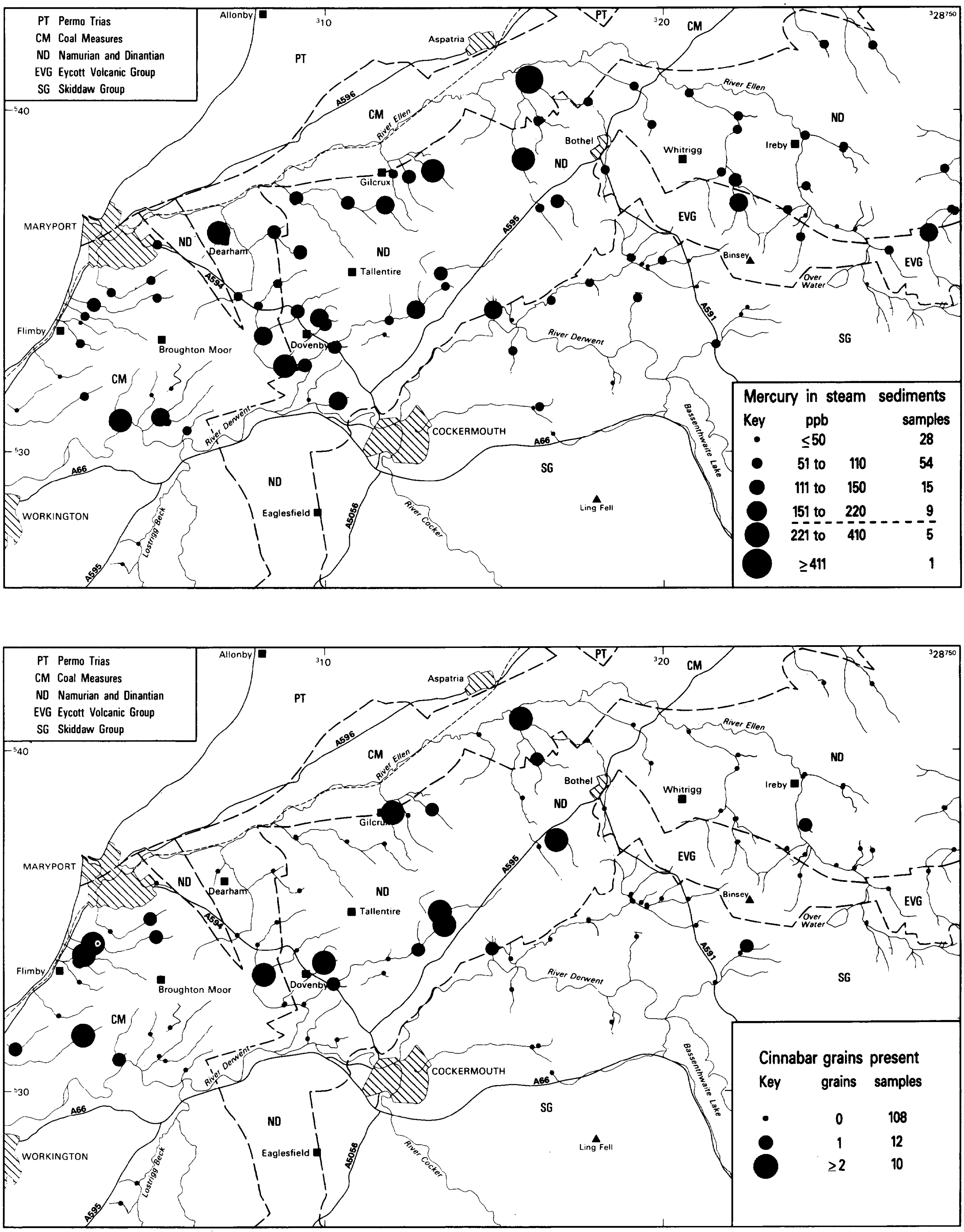


**Figure 23** Location of cinnabar occurrences in panned concentrates and mercury in stream sediment samples

element appears to show no geologically significant variation across the area, except for marginally higher $Ce_S$ values over the Lower Palaeozoic rocks.

### Assessment

Drainage anomalies in this area are particularly difficult to interpret and source correctly because of widespread contamination and the presence of far-travelled glacial material. Here the approach has been to establish first whether an anomaly is caused by contamination or naturally occurring minerals, and then to address the possible source of these minerals.

Element associations and the mineralogical examination of panned concentrates proved effective in discriminating natural anomalies and also provided some information on where the sources might lie. The mineralogical work supported the geological observations of Eastwood et al. (1968) who concluded that some of the drift was far-travelled and often from mixed sources. This is demonstrated by the presence of garnet in every panned concentrate examined, although it is not known to occur in any of the rocks that outcrop in this area[1]. Glaciation has deposited material derived from three principal areas, the south-east (Caldbeck and Carrock Fells), the south (Skiddaw and the central Lake District) and the north (southern Scotland). Predictably, evidence for material derived from the Carrock and Caldbeck Fells is strongest in the east of the area. In particular samples collected east of Ireby, around Aughertree Fell, carry a geochemical and mineralogical signature suggesting that they contain a large amount of material from the Carrock Fell area. Samples collected from the area between Bothel, Bassenthwaite and Overwater show less clear geochemical signatures but are probably dominated by material from the Skiddaw massif. In the central part of the area far-travelled material from the east and south is probably present, as suggested by the presence of chromite probably derived from intrusions into the Skiddaw Group to the south. Samples collected in low ground between Tallentire and the coast contain some relatively local material from the south and east, notably the Tallentire Hill area, but may be dominated by material from the north, deposited by the late Scottish readvance.

There is a marked contrast between the small number of known lead and zinc mineral occurrences in the area and the widespread occurrence of chalcopyrite, sphalerite and, to a lesser extent, galena in panned concentrates. It is not entirely clear if this is the result of glacial dispersion of mineralised material from the Caldbeck Fells, or if there is appreciable hidden base-metal mineralisation in the area. However, the mineralogical work, which found that most grains of galena, chalcopyrite and sphalerite were either pitted, tarnished, corroded or oxidised, suggests that the majority have been transported some distance in the weathering zone and may therefore be derived from known mineralisation to the south-east.

Bearing in mind these considerations , the following anomalies are considered the most likely to be indicative of undiscovered mineralisation in the vicinity:

1. Stockdale (Pb, Zn). High levels of base-metals occur in panned concentrates collected from the River Ellen and its tributary, Dale Gill, south-east of Stockdale Farm. Although mineralogical work on one of the samples shows that the Pb content is much enhanced by contaminants such as Pb glass, the presence of pyrite, chalcopyrite, galena and sphalerite indicates the presence of mineralisation. No mines or mineralisation are recorded in the catchments of these samples and

---

[1] Garnet may be present in some sandstones.

the magnitude of the anomalies increases upstream. Two sources appear most likely: (i) unknown mineralisation, most probably similar to that found on the Caldbeck Fells, in the stream catchment or (ii) mineralised glacial drift, derived from vein mineralisation to the east in the upper reaches of Roughton Gill. Evidence for at least some material coming from this general direction is provided by the presence in the anomalous sample examined mineralogically (WCP 1134, Appendix 1) of pale pink garnets, which are known to be present in the rocks exposed on Knott [NY 295 330]. However, the sample collected from the River Ellen below a gorge section (at [NY 2679 3448]) contains a high proportion of locally derived rock fragments and is highly anomalous, whilst a sample from a small stream which only cuts drift throughout its length contains only background levels.

2. Ruthwaite (Ba). Several panned concentrates collected in the Ruthwaite area carry large amounts of baryte although there is no baryte mineralisation recorded in their catchments. The most prominent of these were collected near The Marshalls (10.35% Ba at [NY 2402 3624]), Stanthwaite Bridge (3.1% Ba at [NY 2509 3654], and in Humble Jumble Gill (20% Ba at [NY 2214 3793] and 14% Ba at [NY 2219 3725]). The latter sample is below a gorge section cut into faulted and altered Eycott Volcanic Group rocks from which most of the sediment appears to be derived. For this reason, and bearing in mind the large size of the anomaly, it is considered that the most likely source of these anomalies is Ba mineralisation within the Eycott Volcanic Group, similar to that mined at Ruthwaite and Mell Beck. Soil sampling and geophysical orientation surveys were carried out in this area to look for extensions to the known mineralisation at Ruthwaite and the results of this work are reported in Part 2.

3. Binsey (polymetallic anomalies). Highly anomalous panned concentrates collected from streams south and west of Binsey suggest the presence of polymetallic mineralisation. The northernmost of these samples, collected from Scalegill Beck [NY 2073 3557], only contains anomalous levels of Cu and Zn but was found to contain pyrite, chalcopyrite, sphalerite, galena and millerite (WCP 1077, Appendix 1). Two streams sampled at High Bewaldeth [NY 2245 3419] and Bewaldeth [NY 2096 3480] both contain anomalous levels of a wide range of metals including Cu, Zn, As, Sn, W and Pb. The samples are highly contaminated but also contain sulphide minerals and wolframite. The only known source of this mineral suite is in the Carrock Fell area but: (i) it seems unlikely from the known directions of ice movement that material derived from the Carrock Fell area would be concentrated here, and (ii) the high Ti and V signature of the Carrock Fell gabbroic rocks is absent. It therefore appears possible that another source of W and base-metal mineralisation is present in the Eycott Volcanic or Skiddaw Group rocks of this area.

4. Tallentire Hill (Ba, Cu). Many of the panned concentrates collected from streams peripheral to the Tallentire Hill - Wardhall Common upland contain highly anomalous levels of Ba, usually accompanied by weaker Cu and other base-metal anomalies. Baryte mineralisation is reported from many localities in this area but shows of Cu mineralisation are relatively few (Figure 5). The largest anomalies are down-ice of Tallentire Hill, around Dovenby (e.g. at [NY 0857 3494] and [NY 0996 3375]). Anomalies which appear to contain more local material are present to the north, around Gilcrux (at [NY 1198 3814]), Wardhall Guards (at [NY 1314 3823]) and Plumbland (at [NY 1581 3856]). Reconnaissance soil sampling and geophysical traversing was carried out across the high ground, to seek for evidence of buried mineralisation and provide supplementary geochemical data across an area with little surface drainage. The results are described in Part 2.

5. Broughton Moor (Ba, base-metals). Samples collected around the periphery of Broughton Moor are all highly contaminated, but several also contain sulphide minerals (pyrite, chalcopyrite, galena, cinnabar), gold or large amounts of baryte. It was concluded above that the gold probably comes from southern Scotland and it is possible that some of the sulphides have the same or a similar distant source. However, sulphides of syngenetic/diagenetic origin are present in the Coal Measures, and some of the very high levels of Ba are unlikely to be derived from a distant source, unless there has been a local glacio-fluvial concentration.

### Conclusions

1. All streams in the area are contaminated and most anomalous results are caused either by contamination or by a combination of contamination and mineralisation.

2. It is very difficult to determine whether a natural anomaly is caused by undiscovered mineralisation or is transported from known deposits. The weathered nature of many sulphide grains suggest that they might have been transported from sources in the Caldbeck and Carrock Fells. There is a danger that transported anomalies may mask the geochemical signature from local hidden mineralisation.

3. There is some evidence to suggest the presence of hitherto undetected mineralisation south of Stockdale (Pb, Zn), south of Binsey (polymetallic), around Ruthwaite (Ba), in the Tallentire Hill area (Ba, Cu) and around Broughton Moor (Ba and base-metals). In the first two areas there is a possibility that at least some of the anomalies are transported whilst in the Broughton Moor area syngenetic/diagenetic mineralisation, similar to that commonly found in the Coal Measures, may be responsible for the base-metal enrichments.

4. Gold, reported for the first time from the streams of this area, may have a local source but it is more probably derived, via glacial till, from sources in southern Scotland and the Lake District massif.

5. Cinnabar, also reported for the first time from this area, was found to be widespread in panned concentrates. Some mineralised rocks were found to be enriched in Hg, suggesting that the cinnabar has a local source and is associated with the vein-style mineralisation.

6. High levels of Ti and V recorded in the east of the area are probably derived from the Carrock Fell Complex.

7. There was no evidence to suggest the presence of economically significant enrichments of any of the other high-value metals determined (Cr, Mn, Co, Ni, Mo, Ag, Sn, Sb, REE, Bi, U).

## DISCUSSION: THE EXTENT, AGE AND ORIGIN OF MINERALISATION

Most of the mineralisation seen in situ within the Cockermouth area is clearly epigenetic and belongs to Group 8 of Clarke's (1990) classification of baryte deposits. It occurs as fillings of joints and faults within sediments which were obviously well-lithified and subjected to brittle fracture before mineral emplacement. No evidence of syngenetic or diagenetic minerals other than those regarded elsewhere as normal for Carboniferous sedimentary rocks have been found. The most characteristic feature of the fracture-controlled epigenetic mineralisation is the abundance of baryte, commonly without any other mineral. Brown carbonate may accompany the baryte and small concentrations of copper and traces of zinc, arsenic, mercury and lead are present locally. The mineralisation occurs within rocks much affected by major *en echelon* faulting at the boundary between the Lower Palaeozoic rocks of the Lake District massif and the Upper Palaeozoic strata of the Solway Basin.

The Lower Palaeozoic rocks to the south contain locally abundant polymetallic vein mineralisation formerly of economic importance. Studies (e.g. Stanley and Vaughan 1982) indicate that several phases of mineralisation are present, each characterised by a distinctive suite of minerals and metals. Metals include copper, arsenic, antimony, bismuth, tungsten, lead, zinc, barium and small amounts of gold. According to Stanley and Vaughan (1982), the distinctive mineral suites found in the Lake District mineral deposits are related to their age of emplacement: the pyrite, chalcopyrite, arsenopyrite, bismuth and tungsten mineral veins were believed to be early Devonian; the galena, sphalerite and baryte dominated veins were assigned a Lower Carboniferous age, and baryte-dominant veins were identified as a later Upper Carboniferous to Lower Permian event.

The baryte-dominant mineralisation of the Caldbeck Fells is very similar to that observed in the Carboniferous and it is proposed here that the baryte mineralisation (± minor copper, lead, zinc and ?mercury) of the Cockermouth area is part of the same mineralising event. Reliable data for the age of this mineralisation are few. Ineson and Mitchell (1974) suggested an Upper Carboniferous - Lower Permian age from K-Ar determinations on clay minerals in altered Eycott Volcanic Group wallrocks to veins in the Caldbeck Fells, and these data were used by Stanley and Vaughan (1982) in reaching their conclusions. However, Ineson (1980) has advised that such ages should be treated with caution and should generally be interpreted as minimum ages for ore deposition. In the Cockermouth area the field evidence merely indicates that mineralisation post-dated lithification and fracture of Carboniferous sediments. This is consistent with the possibility of a very late Carboniferous (Stephanian) or Permian mineralising event. If so, these deposits are of very similar age to the majority of those of the Northern Pennine Orefield.

It is not known whether all the epigenetic mineralisation in the Cockermouth area forms part of this mineralising event. At most localities evidence of only one phase of mineralisation is seen, but at Threapland there is evidence to suggest that baryte post-dated base-metal mineralisation. The Threapland occurrence is unusual in the Cockermouth area in that it contains appreciable amounts of galena and chalcopyrite, but the age of the fractured host-rocks (Fourth Limestone) would appear to preclude the base-metal mineralisation belonging to the Lower Carboniferous episode of Stanley and Vaughan (1982).

The Cockermouth mineralisation occurs in a well-defined tectonic setting. Mineralisation was emplaced into Carboniferous (Dinantian and Namurian) and adjacent Lower Palaeozoic basement rocks at the southern margin of the Upper Palaeozoic Solway Basin. The east-west *en echelon* fault belt, of which the Maryport-Gilcrux faults form part, may be regarded as the present day surface expression of a major fault belt known to have been active as a hinge line or growth fault during much of the Carboniferous along the southern margin of this basin. The faultline extends eastwards into Northumberland and may represent a remnant of the Iapetus Suture. Faults oblique to this trend, such as the Bothel Fault, may also have moved at the time. The Carboniferous rocks include at their base tholeiitic basaltic lavas similar in composition to those of the South Pennine orefield

(McDonald and Walker, 1985). Their emplacement infers high heat flow conditions and is related by McDonald and Walker to lithospheric stretching, regional tension and the opening of the Northumberland (Solway) Basin. The southern margin of the Solway Basin is formed by the Lake District massif which is underpinned by a composite granitic batholith of Ordovician to Lower Devonian age (Lee, 1986, 1989). Intrusions forming this batholith have been linked to the formation of epigenetic mineral deposits within the Lower Palaeozoic rocks of the Lake District, both as sources of ore metals and as the instigators of convective hydrothermal cells from which ores were deposited (Shepherd et al., 1976; Firman, 1978; Moore, 1982; Cooper et al., 1988). However, whether the batholith influenced the formation of Upper Carboniferous - Permian mineral deposits, either as a source of radiogenic heat or by simply forming a buoyant relatively impermeable barrier, is open to question.

These stratigraphic, structural and igneous features highlight the similarity between the baryte mineralisation in the Cockermouth area and ore deposits referred to as Irish-style (e.g. Phillips and Sevastopulu, 1986) and the recently differentiated Pennine-style (Plant and Jones, 1989). Some of the attributes of these deposits are compared with Cockermouth mineralisation in Table 7, which is adapted from Table 8.1 of Plant and Jones (1989). Clearly, the Cockermouth mineralisation displays features in common with both these styles as defined by Plant and Jones (1989), and as might be expected there is more in common with the Pennine-style model. However, there are also distinct differences, the most obvious of which is the dominance of baryte and virtual absence of lead and zinc minerals and fluorite in the Cockermouth deposits. Whether this represents a fundamental difference, or more likely, a difference in the availability of metals in the source rocks or depositional environment is uncertain. One possibility is that the Cockermouth mineralisation represents a distal expression of Pennine or Irish-style mineralisation. For example, many of the Irish deposits are closely associated with contemporaneous Carboniferous faulting along the Navan-Silvermines fault, itself probably a remnant structure related to the Iapetus suture. The possibility must therefore be considered that deposits of base-metals and baryte of Irish-style may be present at depth within the Lower Carboniferous rocks of northern Cumbria and south Northumberland along the Gilcrux - Stublick line.

Mineralisation is found at intervals along the easterly extension of the Maryport-Gilcrux fault where it is known as the Stublick fault. Here the mineralisation carries base-metals. For example, baryte-galena mineralisation has been reported in the Brampton area (Trotter and Hollingworth, 1932), and the formerly important group of lead or zinc, baryte and witherite veins of the Haydon Bridge portion of the Northern Pennine Orefield (Dunham, 1948) also lie close to the Stublick line. In addition, Young et al. (1989) have recently described mercury mineralisation in association with copper, zinc and baryte from near the Stublick fault at Brampton, where it is believed to be a supergene product derived from primary sulphides within the Carboniferous-hosted mineralisation. This gives rise to the possibility, admittedly highly speculative, that the discordant and obviously epigenetic mineralisation in the Cockermouth and other areas could have been remobilised from stratiform Irish-type deposits at depth or earlier vein mineralisation within the Lower Palaeozoic rocks. Evidence for the latter source may come from the presence of pseudomorphs and epimorphs after baryte in Lake District veins assigned to the Lower Carboniferous mineralising event.

Though information is sparse, mercury levels may provide evidence relevant to the role of the Gilcrux - Stublick line. Levels of up to 3500 ppm were found by Bishara (1966) in sphalerites from the Haydon Bridge area, whilst elsewhere the mercury content of northern Pennine sphalerites is up to 110 ppm but is generally less than 50 ppm (Bishara, 1966). The occurrence of this otherwise rare element in higher than normal amounts along the Gilcrux-Stublick line may thus provide additional evidence in support of deep-seated mineralisation.

**Table 7** Comparison of some features of Irish and Pennine-style mineralisation with baryte mineralisation in the Cockermouth area

| Attribute | Pennine-style | Cockermouth | Irish-style |
|---|---|---|---|
| Style | epigenetic veins | dominantly epigenetic veins | dominantly syngenetic, stratiform |
| Host rocks | late Visean carbonates | Dinantian and Namurian carbonates, sandstones<br>L. Palaeozoic rocks | Tournaisian carbonates |
| Metals | F>Pb>Ba>Fe>Zn>?Hg | Ba>>Cu>?Hg | Fe>Pb>Zn |
| Salinity, wt.% NaCl | 18 - 25 | unknown | 10 - 15 |
| Ore - fluid | homogeneous | unknown | variable |
| Pb - isotopes | J-type | unknown | normal |
| Igneous activity | tholeiitic basalt intrusions pre-date mineralisation | tholeiitic basaltic volcanism pre-dates mineralisation | penecontemporaneous |
| Geothermal gradient | high (decreasing) | probably high (?decreasing) | high (increasing) |
| Tectonic setting | anorogenic, dextral transcurrent faults reactivating early Carboniferous growth faults | anorogenic, tensional, basin margin, possibly over reactivated deep faults | anorogenic, tensional, over reactivated deep faults |

In summary, it is believed that the baryte mineralisation in the Cockermouth area was formed by precipitation from fluids passing along tensional fractures at the margin of the Solway Basin in the Upper Carboniferous or Lower Permian. The precise source of fluids, the mechanism of transport and deposition and relationship to Pennine and Irish-style mineralisation models merit further investigation. The possibility exists that the Cockermouth mineralisation is a distal or remobilised expression of one of these styles of mineralisation which may be present at depth in the basin.

## CONCLUSIONS AND RECOMMENDATIONS

1. Baryte mineralisation is far more widespread than previously recognised and may locally be present in amounts sufficient to merit further investigation. Mineralisation largely comprises epigenetic fracture fillings of Dinantian and Namurian carbonates and sandstones and adjacent Lower Palaeozoic basement rocks, though locally disseminated and veinlet mineralisation has been found in Namurian sandstone. Mineralisation is believed to be Upper Carboniferous to Lower Permian in age and to be the product of fluid movement through tensional fractures at the southern margin of the Solway Basin.

2. Baryte is usually accompanied by brown carbonate and minor copper mineralisation. There is also evidence locally of epigenetic zinc, lead, arsenic and mercury mineralisation. Gold, only found in panned concentrates, is believed to have been transported by glacial action from source areas in southern Scotland and the Lake District. Syngenetic/diagenetic mineralisation is present within the Coal Measures, but there is no evidence to suggests that amounts exceed those normally found within these lithologies.

3. Satellite imagery proved useful for identifying glacial transport directions. One or more roughly east-west-trending linears may be related to deep fractures at the hinge of the Solway Basin and Lake District massif. Some smaller linears are related to joints and fractures which may locally have exercised a control on the site of mineralisation.

4. Geophysical surveys suggested that the north-west-trending Bothel Fault is a major feature which may have been active in the Carboniferous. Interpretation of gravity data suggested that either the Carboniferous succession was thickened across a concealed growth fault or the Lower Palaeozoic rocks were lighter, perhaps containing more acid volcanic rocks.

5. The geochemical data obtained from streams needed careful interpretation due to the presence of extensive contamination and far-travelled glacial deposits derived from metalliferous sources. The mineralogical examination of panned concentrates proved a time-consuming but most effective method of discriminating between anomalies caused by mineralisation and contamination.

6. From the geological and geochemical data it was concluded that undiscovered mineralisation might be present in the following areas: Ruthwaite-Whitrigg (Ba), Tallentire Hill (Ba, Cu), south of Stockdale (Zn, Pb), south of Binsey (polymetallic) and Broughton Moor (Ba, base-metals). In the latter area the mineralisation may largely comprise syngenetic or diagenetic concentrations in Coal Measures, whereas in the Binsey and Stockdale areas there is a distinct possibility that transported anomalies are present. In the first two areas further MRP work has been carried out which will be reported in Part 2.

7. The relationship between the baryte mineralisation of the Cockermouth area, mineralisation in the North Pennine Orefield, and Irish and Pennine-style mineralisation models merits further research.

## ACKNOWLEDGEMENTS

The geochemical samples were prepared and analysed by staff of the Analytical Geochemistry Group of BGS and all diagrams were prepared by staff of the BGS Drawing Office under the supervision of R J Parnaby. Sample collection was assisted by C R Hallsworth and T M Williams and M E Trease carried out text formatting and editing.

## REFERENCES

ADAMS, J. 1988. Mines of the Lake District Fells. *Dalesman Publishing Co., Clapham, Lancaster,* pp 160.

ARTHURTON, R S, and WADGE A J. 1981. Geology of the Country around Penrith. *Memoir of the Geological Survey of Great Britain.*

BARNES, R P, YOUNG, B, FROST, D V, and LAND, D H. 1988. Geology of Workington and Maryport. *British Geological Survey Technical Report,* No. WA/88/3.

BISHARA, W W. 1966. Studies of trace and minor elements in sphalerite and galena from the Northern Pennine orefield. *Unpublished PhD thesis, University of Leeds.*

BLAND, D J. 1989. Examination of some panned concentrates from the Cockermouth Area, Lake District. *British Geological Survey Technical Report,* No. WG/89/21C.

BOTT, M H P. 1974. The geological interpretation of a gravity survey of the English Lake District and the Vale of Eden. *Journal of the Geological Society, London,* Vol. 130, 309-331.

BOTT, M H P. 1978. Deep Structure. In: MOSELEY, F. (editor) The geology of the Lake District. *Yorkshire Geological Society Occasional Publication,* No. 3, 25-40.

BRIDEN, J C, and MORRIS, W A. 1973. Palaeozoic studies in the British Caledonides - III Igneous rocks of the Northern Lake District, England. *Geophysical Journal,* Vol. 34, 27-46.

CALVERT, J. 1854. The gold rocks of Great Britain and Ireland. *Chapman and Hall, London.*

CLARKE, S H B. 1990. A proposed classification of baryte deposits. In: Proceedings 8th symposium of the international association on the genesis of ore deposits, Ottawa 1990. *Geological Survey of Canada.*

COLLAR, F A, and PATRICK, D J. 1978. Aeromagnetic survey. In: MOSELEY, F. (editor). The geology of the Lake District. *Yorkshire Geological Society Occasional Publication,* No. 3, 41-44.

COOPER, D C, LEE, M K, FORTEY, N J, COOPER, A H, RUNDLE, C C, WEBB, B C, and ALLEN, P M. 1988. The Crummock Water aureole: a zone of metasomatism and source of ore metals in the English Lake District. *Journal of the Geological Society, London,* Vol. 145, 523-540.

COOPER, M P, and STANLEY, C J. 1990. Minerals of the English Lake District, Caldbeck Fells. *Natural History Museum, London.*

DEWEY, H, and EASTWOOD, T. 1925. Copper ores of the Midlands, Wales, the Lake District and the Isle of Man. Special Report on the Mineral Resources of Great Britain. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

DICK, H J B, and BULLEN, T. 1984. Chromian spinel as a petrographic indicator in abyssal and alpine type peridotites and spatially associated lavas. *Contributions to Mineralogy and Petrology,* Vol. 86, 54-76.

DOWNIE, C, and SOPER, N J. 1972. Age of the Eycott Volcanic Group and its conformable relationship to the Skiddaw slates in the English Lake District. *Geological Magazine*, Vol. 109, 259-268.

DRURY, S A, and WALKER, A S D. 1987. Display and enhancement of gridded aeromagnetic data of the Solway Basin. *International Journal of Remote Sensing,* Vol. 8, 1433-44.

DUNHAM, K C. 1948. The geology of the Northern Pennine orefield: Vol. 1. Tyne to Stainmore. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

DUNHAM, K C. 1962. Classification of carbonate rocks according to depositional texture. In: HAM, W E. (editor) Classification of carbonate rocks. *Memoir of the American Association of Petroleum Geologists*, Vol. 1, 108-121.

DUNHAM, K C, and DINES, H G. 1945. Barium minerals in England and Wales. *Wartime Pamphlet,* No. 46, *Geological Survey of Great Britain, HMSO, London.*

EASTWOOD, T. 1921. The lead and zinc ores of the Lake District. Special Report on the Mineral Resources of Great Britain. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

EASTWOOD, T. 1930. The geology of the Maryport district. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

EASTWOOD, T. 1959. The Lake District mining field. In: The future of non-ferrous mining in Great Britain and Ireland. *Institution of Mining and Metallurgy, London,* pp 149-174.

EASTWOOD, T, DIXON, E E L, HOLLINGWORTH, S E, and SMITH, B. 1931. The geology of the Whitehaven and Workington district. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

EASTWOOD, T E, HOLLINGWORTH, S E, ROSE, W C C. and TROTTER, F M. 1968. Geology of the country around Cockermouth and Caldbeck. *Memoir of the Geological Survey of Great Britain, HMSO, London.*

FIRMAN, R J. 1978. Epigenetic mineralisation In: MOSELEY, F. (editor) The geology of the Lake District. *Yorkshire Geological Society Occasional Publication* No. 3, 226-241.

FIRMAN, R J, and LEE, M K. 1986. The age and structure of the concealed English Lake District batholith and its probable influence on subsequent sedimentation, tectonics and mineralisation. In: NESBITT, R W, and NICHOL, I. (editors) Geology in the real world - the Kingsley Dunham volume. *Institution of Mining and Metallurgy, London,* pp 117-127.

FORTEY, N J. 1978. Mineral parageneses of the Harding Vein tungsten deposit, Carrock Fell Mine, Cumbria. *Institute of Geological Sciences Mineralogy Unit Report*, No. 228.

FORTEY, N J, INGHAM, J D, SKILTON, B R H, YOUNG, B, and SHEPHERD, T J. 1984. Antimony mineralisation at Wet Swine Gill, Caldbeck Fells, Cumbria. *Proceedings of the Yorkshire Geological Society*, Vol. 45, 59-65.

FORTEY, N J, and NANCARROW, P H A. 1990. Chromian minerals in microdiorite from the English Lake District. *Journal of the Russell Society*, Vol. 3, 15-22.

GARWOOD, E J. 1913. The Lower Carboniferous succession in the north-west of England. *Quarterly Journal of the Geological Society of London,* Vol. 68, 449-586.

HUNTING GEOLOGY and GEOPHYSICS LIMITED. 1983. Computer correlation of geological, geochemical and geophysical prospecting data with enhanced satellite imagery. *Hunting Geology and Geophysics Limited in association with the Institute of Geological Sciences, Keyworth, Nottingham.*

INESON, P R. 1980. Dating mineralisation; conference report. *Journal of the Geological Society of London*, Vol. 137, 101-102.

INESON, P R, and MITCHELL, J G. 1974. K-Ar isotopic age determination from some Lake District mineral localities. *Geological Magazine*, Vol. 111, 521-537.

INSTITUTE of GEOLOGICAL SCIENCES. 1977. 1:250,000 series Bouguer gravity anomaly map, Lake District Sheet 54°N - 04°W. *Institute of Geological Sciences, Keyworth, Nottingham.*

INSTITUTE of GEOLOGICAL SCIENCES. 1978. 1:250,000 series Aeromagnetic anomaly map, Lake District Sheet 54°N - 04°W. *Institute of Geological Sciences, Keyworth, Nottingham.*

JACKSON, D E. 1978. The Skiddaw Group. In: MOSELEY, F. (editor) The geology of the Lake District. *Yorkshire Geological Society Occasional Publication*, No. 3, 79-98.

LEAKE, R C, and SMITH, R T. 1975. A comparison of stream sediment sampling methods in parts of Great Britain. In: ELLIOTT, I L, and FLETCHER, W K. (editors.) Geochemical Exploration 1974. *Elsevier, Amsterdam,* pp 79-94.

LEE, M K. 1986. A new gravity survey of the Lake District and three-dimensional model of the granite batholith. *Journal of the Geological Society, London*, Vol. 143, 425-435.

LEE, M K. 1988. Density variations within Lake District granites and Lower Palaeozoic rocks. *British Geological Survey Technical Report*, No. WK/88/9.

LEE, M K. 1989. Upper crustal structure of the Lake District from modelling and image processing of potential field data. *British Geological Survey Technical Report*, No. WK/89/1.

LEEDER, M R. 1982. Upper Palaeozoic basins in the British Isles - Caledonide inheritance verses Hercynian plate margin processes. *Journal of the Geological Society, London*, Vol. 139, 479-491.

MCDONALD, R, and WALKER, B H. 1985. Geochemistry and tectonic significance of the Lower Carboniferous Cockermouth Lavas, Cumbria. *Proceedings of the Yorkshire Geological Society,* Vol. 45, 141-146.

MOORE, J. McM. 1982. Mineral zonation near the granitic batholiths of south-west and northern England and some geothermal analogues. In: EVANS, A M. (editor) Metallisation Associated with Acid Magmatism. *Wiley, Chichester,* pp 229-241.

MITCHELL, M, TAYLOR, B J, and RAMSBOTTOM, W H C. 1978. Carboniferous. In: MOSELEY, F. (editor) The Geology of the Lake District. *Yorkshire Geological Society Occasional Publication,* No. 3, 168-188.

MOSELEY, F, and MILLWARD, D. 1982. Ordovician volcanicity in the English Lake District. In: SUTHERLAND, D S. (editor) Igneous rocks of the British Isles. *John Wiley and Sons Ltd.*, pp 93-111.

PARSLOW, G R. 1974. Determination of background and threshold in exploration geochemistry. *Journal of Geochemical Exploration,* Vol. 3, 319-336.

PLANT, J A. 1971. Orientation studies on stream sediment sampling for a regional geochemical survey in Northern Scotland. *Transactions of the Institution of Mining and Metallurgy,* (*Section B: Applied Earth Science),* Vol. 80, 324-345.

PLANT, J A, and JONES, D G. (editors) 1989. Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits - a multidisciplinary study in eastern England. *Institution of Mining and Metallurgy, London.*

PHILLIPS, W E A, and SEVASTOPULO, G D. 1986. The stratigraphic and structural setting of Irish mineral deposits. In: ANDREW, E J, CROWE, R W A, FINLAY, S, PENNELL, W M, and PYNE, J F. (editors) Geology and Genesis of Mineral Deposits in Ireland. *Irish Association for Economic Geology.*

POSTLETHWAITE, J. 1913. Mines and mining in the Lake District [3rd edition]. *W H Moss, Whitehaven. Reprinted 1975 by Michael Moon, Whitehaven.*

RAMSBOTTAM, W H C. 1973. Transgressions and regressions in the Dinantian: a new synthesis of British Dinantian stratigraphy. *Proceedings of the Yorkshire Geological Society,* Vol. 39, 567-607.

RAMSBOTTAM, W H C. 1977. Major cycles of transgression and regression in the Namurian. *Proceedings of the Yorkshire Geological Society,* Vol. 41, 261-291.

RASTALL, R H. 1942. The ore deposits of the Skiddaw district. *Proceedings of the Yorkshire Geological Society,* Vol. 24, 329-343.

ROSLER, H J, and LANGE, H. 1972. Geochemical tables. *Elsevier, Amsterdam.*

SHEPHERD, T J, BECKINSALE, R, RUNDLE, C C, and DURHAM, J. 1976. Genesis of the Carrock Fell tungsten deposits: fluid inclusion and isotopic study. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science),* Vol. 85, 63-73.

SINCLAIR, A J. 1976. Applications of probability graphs in mineral exploration. *Association of Exploration Geochemists Special Volume*, No. 4.

SMITH, I F, and ROYLES, C P. 1989. The digital aeromagnetic survey of the United Kingdom. *British Geological Survey Technical Report*, No. WK/89/5.

STABBINS, R. 1969. The depositional history of the Lower Carboniferous rocks of west Cumberland. *Unpublished PhD. thesis, University College, London*.

STANLEY, C J, and VAUGHAN, D J. 1982. Copper, lead, zinc and cobalt mineralisation in the English Lake District: classification, conditions of formation and genesis. *Journal of the Geological Society of London*, Vol. 139, 568-579.

TAYLOR, B J. 1961. The stratigraphy of exploratory boreholes in the west Cumberland coalfield. *Bulletin of the Geological Survey of Great Britain*, Vol. 17, 1-74.

TROTTER, F M, and HOLLINGWORTH, S E. 1932. The geology of the Brampton district. *Memoir of the Geological Survey of Great Britain, HMSO, London*.

WADGE, A J. 1978. Classification and stratigraphical relationships of the Lower Ordovician rocks. In: MOSELEY, F. (editor) The geology of the Lake District. *Yorkshire Geological Society Occasional Publication*, No. 3, 68-78.

WADGE, A J, APPLETON, J D, and EVANS, A D. 1977. Mineral investigations at Woodhall and Longlands in north Cumbria. *Mineral Reconnaissance Programme Report, Institute of Geological Sciences*, No. 14.

WILSON, G V, EASTWOOD, T, POCOCK, R W, WRAY, D A, and ROBERTSON, T. 1922. Baryte and witherite. Special reports on the mineral resources of Great Britain, *Memoir of the Geological Survey of Great Britain, HMSO, London*.

YOUNG, B. 1987. Glossary of the minerals of the Lake District and adjoining areas. *British Geological Survey, Keyworth, Nottingham*.

YOUNG, B, and NANCARROW, P H A. 1988A. Millerite from the Cumbrian coalfield. *Journal of the Russell Society*, Vol. 2, 5-7.

YOUNG, B, and NANCARROW, P H A. 1988B. Rozenite and other sulphate minerals from the Cumbrian coalfield. *Mineralogical Magazine*, Vol. 52, 551-552.

YOUNG, B, INESON, P R, BRIDGES, T F, and SMITH, M E. 1989. Cinnabar from the Northern Pennines, England. *Mineralogical Magazine*, Vol. 53, 388-390.

YOUNG, B, and ARMSTRONG, M. 1989. The applied geological mapping of the Dearham and Gilcrux area, Cumbria. *British Geological Survey Technical Report*, No. WA/89/70.

## APPENDIX 1 Mineralogical Examination of Panned Concentrates

Reproduced with minor amendments from the British Geological Survey Technical Report WG/89/21C (Bland, 1989)

### Introduction

Thirty panned concentrates, selected from over one hundred, collected in the Cockermouth area, have been examined in order to establish the causes of anomalous metal values. The samples were chosen on the basis of mineralogical observations made in the field and of bulk chemical data derived from the analysis of representative splits. Particular attention has been paid to the differentiation of anomalies due to natural minerals from those caused by artificial sources (contamination).

Also included in this report are the results of electron microprobe examination of three polished gold grains from this area.

This report is essentially a commentary on the detailed results, the majority of which are contained in the tables.

### Methods

The panned concentrate material remaining after removal of the split for chemical analysis was sieved through a 2 mm mesh before being separated into density fractions of greater and lesser than 3.33 g $cm^{-3}$ using methylene iodide. The 'sink' fraction was divided further by sieving through a 0.5 mm mesh and the oversize examined for the presence of artifacts under a binocular microscope. Results of this examination are given in Table 1A

The less than 0.5 mm fraction was separated into six fractions with the Frantz Isodynamic Magnetic Separator set as follows: 0.0-0.1 amps (10° slope), 0.1-0.3 amps (10°), 0.3-0.6 amps (10°), 0.6-max (1.7) amps (10°) and low side slope non-magnetic (3°).

These fractions were examined under a binocular microscope, the entire non-magnetic fractions being systematically examined grain by grain. The other fractions were generally much larger and more uniform and only a representative portion was examined in detail. During the examination two or three grains of each ore mineral recognised together with unidentified phases, were mounted on a microscope slide with double-sided tape for identification by the Electron Microprobe. This was done particularly to confirm possible sphalerite, galena which was found weathered and without bright cleavage faces, cerussite (easily mistaken for baryte) and chalcopyrite which has a blue or green iridescence similar to lightly oxidised pyrite. Possible pyromorphite, cinnabar, copper oxides and other unknown grains were also identified in this way.

*Electron microprobe examination*

Three slide - mounts were prepared of the grains selected for further study by electron microprobe using a Link Systems Energy Dispersive attachment. In order to correlate the analytical data with the sample numbers and the physical characteristics observed optically, a 'map' of each slide was prepared and each grain given a unique number. These numbers are used for reference in Tables 2A and 3A.

Examination was made first in a qualitative mode (Table 2A) in order to make an identification. Certain grains were then selected on the basis of interesting or unusual chemical composition for more precise analysis (Table 3A). It should be noted that these can be considered only as semi-quantitative in view of a number of factors, which include the uneven surface of a grain, the common presence of a clay layer screening the body of the grain and the likelihood of the grain surface being weathered and altered to varying degrees (the electron beam only penetrates about three microns).

*X-ray fluorescence (XRF) examination*

This technique was used only to check for the presence of an anomalous element in a fraction when no mineral containing that element had been identified optically or by the electron microprobe.

For instance, identification of tin in the most magnetic fraction would imply contamination by tin plate because the usual mineral containing tin (cassiterite) is generally non-magnetic. Vanadium in the magnetic fractions implies substitution in magnetite and/or ilmenite. Tungsten in a magnetic fraction suggests the presence of wolframite. Tin with antimony in weakly magnetic fractions implies solder. Copper in a large fraction of oxidised pyrite could be either inclusions in the pyrite or chalcopyrite masked by the pyrite.

*X-ray diffraction analysis (XRD)*

This was carried out on a few selected grains to resolve some identification problems.

### Results

Artifacts noted in the >30 mesh fractions are listed in Table 1A. Brief mineralogical descriptions of the -0.5 mm sink fractions of the samples are given in the supplement at the end of this appendix and the results of the microprobe analyses are summarised in Table 2A and 3A. Tables 4A and 5A contain the results of XRF and XRD identifications.

All the samples contained lead glass shards, fragments of lead glaze (often with traces of pottery on one surface) and occasionally also a lead glass slag. Lead metal and/or solder, in the form of various sized spheres and plates, was widespread, usually with a grey to white oxidised coat. Besides this contamination, galena, pyromorphite [$(Pb,Cl)Pb_4(PO_4)_3$], mimetite [$(Pb,Cl)Pb_4(AsO_4)_3$], cerussite [$PbCO_3$] and anglesite [$PbSO_4$] were found in many samples. Galena was usually weathered, fresh fragments were small and may be derived from the mechanical breakdown of larger grains.

Chalcopyrite was present in most samples. Although oxidised surfaces make recognition difficult, occasional fresh fracture surfaces aided identification.

The recognition of sphalerite was made difficult by the presence, often in large proportions, of baryte grains showing different hues. However the sphalerite often had a slightly etched or corroded surface. The colour of the sphalerite was generally medium to pale yellow with the darker reddish hues much rarer.

Cinnabar in general showed the typical scarlet colour. Some grains, however, showed a slightly deeper duller red and it is possible that, because of this colour variation, other grains could have been recorded as rutile. Also displaying this deeper duller red is a copper oxide (probably cuprite).

Some grains, thought initially to be cinnabar, showed only the presence of copper in the electron microprobe and therefore were probably cuprite. Most of the grains found were small to very small (0.1 mm to 0.01 mm) with only a few approaching 0.5 mm.

Rutile was found in all samples and varied in colour from black through red to pale yellow. The habit was generally slightly elongate though many were very rounded and a few were found as fine needles. Anatase occurred widely as striated octahedra. Leucoxene (oxidised ilmenite) occurred in most samples as grey tabular grains.

Chromite was found as octahedra in the two most magnetic fractions of several samples, where it was less weathered than the magnetite and ilmenite. Microprobe analysis showed it to have a distinctive chemical composition containing zinc at levels up to nearly 8%, with low magnesia (ranging from 0.5 to 8% with a median of 2.3%) and high ferric oxide (from 21 to 45% with a median of 35%).

Gold grains from WCP1145 and WCP1167 were polished prior to microprobe analysis. The appearance after polishing was somewhat uneven and not characteristically metallic. This is thought to be due to fine grained silicate inclusions which will have affected the probe results. Thus the composition figures given in Table 3A are normalised. The copper reported is only just significant at the 2 sigma level (so may not be real).

Spheroids of iron oxide were found in all samples, particularly in the more magnetic fractions. They were usually black and often very lustrous. In some samples larger spheroids were broken and could be seen to have a vesicular or cokey interior. A possible source of these is bonfires although similar forms commonly occur as emissions from coal-fired boilers (fly ash) in industrial plants, the iron coming from pyrite in the coal. Siderite was present as translucent brownish balls, occurring either singly or as fused groups of two to five or more.

The magnetic fractions showed a common pattern of mineralogical composition as follows :-

| | |
|---|---|
| 0.0-0.1 amps | Magnetite, ironscale, tramp iron, cokey material, chromite, wolframite |
| 0.1-0.3 amps | Garnet, ilmenite, siderite |
| 0.3-0.6 amps | Iron oxides, epidote |
| 0.6-1.7 amps | Chalcopyrite, oxidised pyrite, lead glass |
| non-mag (10°) | Leucoxene, rutile, millerite |
| non-mag (3°) | Baryte, zircon, anatase, fresh pyrite, cinnabar, lead metal, sphalerite, gold, copper oxide, malachite, galena, cerussite, arsenopyrite, pyromorphite, sphene |

*Sources of chromite*

The chromites found in the Cockermouth area are unusual in that they contain high zinc coupled with low magnesia and high iron contents. Indices ((Mg x 100/(Mg+Fe$^{2+}$) and (Cr x 100/(Cr+Al)) according to Dick and Bullen (1984) were calculated assuming a 50:50 division of iron between the ferrous and ferric states. This gives a reasonable correspondence to the 2:1 stoichiometry of $2^+$ and $3^+$ cation sites in spinel. Comparison with their diagrams showed little correspondence between these chromites and any of their clusters. However it must be emphasised that these analyses are on probably altered surfaces of detrital grains. Also low Mg and high Fe$^{3+}$

but not high zinc are typical of the so called ferrit chromite often found around the rims of chromite grains in serpentinised ultrabasic rocks.

The zinc rich, magnesia poor, high iron chromites have similarities with chromites reported by Fortey and Nancarrow (1990) from the Scawgill Bridge intrusion. Three of the analyses made by these authors are included in Table 3A for comparison, but it should be borne in mind that the analyses were obtained from polished specimens instead of the possibly altered surfaces of detrital grains analysed during this study. Their chromite is very similar to grain WCP1107/42, whilst grains WCP1063/38 and 47 (Table 3A) have affinities with their unnamed Cr-Ti mineral. The only other reference to chromites in the Lake District was in the Cockermouth and Caldbeck memoir (Eastwood et al., 1968 pp 95) where a slide from Carrock Fell was stated to contain chromite with rims of ilmenite. The section and polished block were recovered from the BGS reference collection (E15248) and XRF showed that the polished block contained between 500 and 600 ppm Cr with a few hundred ppm of V and about 2000 ppm Ti. Thus the abundant oxide mineral was of a titaniferous magnetite not chromite. The Ballantrae complex in Ayrshire contains chromite but all analyses show 10% or more magnesia. This leaves the provenance of the detrital chromites open but with a suggestion that minor intrusions a short distance to the south of the Cockermouth area are possible sources.

## Conclusions

1. Copper mineralisation in the form of chalcopyrite is present in most samples. Samples WCP1064, 1086, 1099, 1103, 119, 1150, 1161, 1166 and 1170 contain copper artifacts, even though not necessarily high in copper.

2. Galena is less common. Pyromorphite and/or mimetite are present in a few samples. Lead mineralisation was found as galena in samples WCP1056, 1070, 1076, 1077, 1079, 1099, 1106, 1119, 1132, 1134, 1153, 1160 and as pyromorphite or mimetite in WCP1079, 1085, 1107, 1111 and 1132. Cerussite or lead oxide were often found, but much of this could be a result of oxidation of metallic lead or solder, both of which are also common throughout the area.

3. Tin is often found together with lead in the same grain, all of which have been classed as artifacts. As well as tin in tin plate in the magnetic fraction some soft grains have been found containing romarchite (SnO) and cassiterite (normally a hard mineral). These are thought also to be oxidation products of artefacts. No naturally occurring Sb or Sn phases were identified.

4. High concentrations of lead and tin together in samples from this area are always due to contamination and are usually accompanied by high antimony.

5. Zinc, tungsten and arsenic anomalies are thought to be caused by mineralisation. Sphalerite was recorded in most samples, arsenopyrite in two (WCR1132 and 1161) and wolframite in two (WCP1076 and 1119).

6. Evidence of nickel mineralisation in the form of millerite was found in two samples (WCP1076 and 1077). Other nickel anomalies are thought to be due to contamination (? paratacamite and steel) or inclusions in magnetite and ilmenite.

7. High vanadium is attributed to the substitution of V in the magnetite and/or ilmenite lattice in these samples.

8. Some Cr anomalies are due to the presence of chromite with an unusual composition which suggests derivation from intrusions into the Skiddaw Group to the south of this area.

9. Small grains of gold, probably containing silicate inclusions and up to 13% Ag, are present in a few samples.

10. Baryte is abundant and widespread; cinnebar, in small amounts, is also widely distributed.

11. Most of the galena, sphalerite and chalcopyrite grains examined were weathered and/or corroded to a greater or lesser degree, perhaps suggesting glacial transport from source.

12. Some form of contamination was found in every sample. The principal contaminants, in approximate order of frequency, were lead glass, magnetic balls, solder and/or lead and iron scale/tramp iron.

**Table 1A** Contaminants found in the >30 mesh (oversize) fractions

| | |
|---|---|
| WCP1047 | cokey material, lead glass and lead shot |
| WCP1052 | lead sheet and lead glaze still attached to pottery |
| WCP1056 | iron oxide scale |
| WCP1058 | iron wire, slag balls and lead glass |
| WCP1063 | lead glass |
| WCP1064 | lead shot, iron sheets with attached ?malachite and lead glass |
| WCP1070 | lead glass, copper scale (with malachite) and iron oxide scale |
| WCP1076 | lead glass |
| WCP1077 | lead shot and iron oxide scale |
| WCP1079 | lead sheet |
| WCP1085 | lead glass |
| WCP1086 | no obvious contamination |
| WCP1099 | copper wire |
| WCP1103 | lead shot, lead glass, copper wire and cokey slag |
| WCP1107 | cokey slag |
| WCP1109 | lead sheet and lead glass |
| WCP1111 | cokey slag |
| WCP1112 | cokey slag and iron oxide slag |
| WCP1119 | paint, lead metal and lead glass |
| WCP1125 | cokey slag, iron scale and lead glass |
| WCP1132 | no obvious contamination |
| WCP1134 | glass slag and lead glass |
| WCP1140 | no obvious contamination |
| WCP1150 | copper wire, cokey slag, iron oxide slag and lead metal |
| WCP1152 | cokey slag, iron oxide scale and iron wire or nails |
| WCP1158 | iron oxide scale, lead glass, copper wire and nails |
| WCP1160 | iron oxide scale, copper wire, cokey slag and lead glass |
| WCP1161 | iron oxide scale |
| WCP1166 | copper wire, iron oxide scale, cokey slag and lead metal |
| WCP1170 | mainly glass slag with iron wire |

**Table 2A** Qualitative electron microprobe analyses.

The elements are listed in order of significance. A '+' indicates that the subsequent elements are probably an order of magnitude less important.

| Grain number | Elements detected | Likely phase |
|---|---|---|
| WCP1047 /1, 2, 3a, 4-6, 8-10 | Hg S | Cinnabar |
| /3, 15 | Ba S Si Ca Mg Al | Baryte + silicate |
| /7, 12 | Zn S | Sphalerite |
| /11 | Ti | Rutile |
| /13 | Sn Sn | Oxide |
| /14 | Sn Pb | Solder |
| /16 | Zr Si | Zircon |
| /17-19 | Cu Fe S | Chalcopyrite |
| /20 | Cu | Malachite |
| WCP1052 /1, 2 | Zn S | Sphalerite |
| /3 | Ba S | Baryte |
| /4 | Pb Sb Sn Ba | Solder |
| /5-7 | Cu Fe S | Chalcopyrite |
| WCP1056 /1-3 | Pb S | Galena |
| /4-6 | Fe S | Pyrite |
| /7-12 | Zn S | Sphalerite |
| /13-15 | Cu Fe S | Chalcopyrite |
| /16, 17 | Si Mg Ca Fe | probably Pyroxene |
| /18 | Ti Fe | Ilmenite |
| /19 | Hg S | Cinnabar |
| WCP1058 /1, 8, 9, 16, 17, 40, 41, 47 | Ba S | Baryte |
| /2, 12-14, 22-24, 48 | Ti | Rutile |
| /3, 10, 45 | Zn S | Sphalerite |
| /4, 5, 21 | Si Al K Ti Fe | probably Orthoclase |
| /6 | Sn Sn | Oxide |
| /7, 49 | Pb Sn | Solder |
| /11 | Si Al Ba | |
| /15 | Pb | Cerussite |
| /18-20 | Fe S | Pyrite |
| /25, 26 | Pb Si | Lead Glass/Glaze |
| /27 | Cu | Malachite |
| /28-31, 34, 39 | Si Al Mg Ca Fe | probably Epidote |
| /32, 33, 35, 37 | Si Ca Ti Fe | probably Sphene |
| /36, 50, 51 | Cu Fe S | Chalcopyrite |
| /38 | Fe | Iron Oxide |
| /42-44, 53 | Hg S | Cinnabar |
| /46 | Si Ca Al Mg | |
| /52 | Si Ca Al Cr Fe | |
| WCP1063/1, 5-7, 29-31 | Zn S | Sphalerite |
| /2-4, 26, 27, 32, 34, 37 | Ti | Rutile |
| /8, 18, 39 | Fe | Iron Oxide |
| /9-13, 15, 16, 19, 43-46, 48, 49, 51, 54-58 | Ti Fe Mn | Ilmenite |
| /14, 50 | Si Al Mg Ca Fe | |
| /17 | Si Al Ca Fe K | |
| /20 | Si Mg Ca Fe Al | |
| /21, 22, 35, 36 | Cu Fe S | Chalcopyrite |
| /23, 25 | Pb Si | Lead Glass/Glaze |
| /24 | Si Ca Ti Fe | probably Sphene |
| /28 | Hg S | Cinnabar |
| /33 | Si Al | |
| /38, 40-42, 47, 53 | Cr Fe Zn Si Al Mg Ti | Chromite |
| /52 | Fe + Ca Mn | Siderite |

**Table 2A** Continued

| | | |
|---|---|---|
| WCP1064 /1 | Pb | Lead Oxide/Carbonate |
| /2, 5, 9, 10, 12 | Zn S | Sphalerite |
| /3, 4 | Pb Sn Sb | Solder |
| /6, 25 | Cu | Copper Oxide |
| /7, 13-15, 19, 20, 26 | Ba S | Baryte |
| /8, 11, 26 | Ti | Rutile/Anatase |
| /16, 17 | Cu Fe S | Chalcopyrite |
| /18 | Si Mg Al Ca Fe | |
| /21 | Fe S | Pyrite |
| /22 | Cu | Malachite |
| /23 | Cu S+P Fe Ca/Cu S | Copper Sulphide |
| /24 | Ti Fe | Ilmenite |
| /27 | Hg S | Cinnabar |
| WCP1070 /1, 6, 11 | Pb S | Galena |
| /2-5 | Zn S | Sphalerite |
| /7 | Cu Fe S | Chalcopyrite |
| /9, 10 | Ni Cl Cu | |
| /8 | Cu P/inc Pb | |
| WCP1076 /1, 5 | Pb S | Galena |
| /2 | Cr Fe | Chromite |
| /3 | Pb | Cerussite |
| /4 | Al | Metal or Alumina |
| /6, 31-35 | Cu Fe S | Chalcopyrite |
| /7 | Pb S/Cu Fe S | Anglesite/Chalcopyrite |
| /8-13 | Zn S | Sphalerite |
| /12, 20 | Ti | Rutile |
| /15-19, 28, 30 | Ni S | Millerite |
| /21, 24 | W Fe | Wolframite |
| /22, 23 | Fe | Iron Oxide |
| /25-27 | Ni Cl Cu S | |
| /29 | Zn S/Cu Fe S | Sphalerite/Chalcopyrite |
| WCP1077 /1 | nothing | Plastic |
| /2 | Pb S | Galena |
| /3-7 | Zn S | Sphalerite |
| /8, 9 | Fe S | Pyrite |
| /10, 11 | Cu Fe S | Chalcopyrite |
| /12 | Ni S | Millerite |
| /13 | Si Al+Fe Mn | probably Topaz |
| WCP1079 /1-3 | Pb As | Mimetite |
| /3, 5, 6 | Zn S | Sphalerite |
| /4, 11-16, 27 | Ti | Rutile |
| /7 | Zn S/Si Al+Fe K | Sphalerite/Silicate |
| /9, 10 | Pb S | Galena |
| /17 | Cu/Cu | Cuprite/Melancolite |
| /18-22 | Fe S | Pyrite |
| /23 | Cu S | Copper Sulphide |
| /24 | Pb S | Anglesite |
| /25 | Cr Fe | Chromite |
| /26 | Ti Fe | Ilmenite |
| /28 | Ni Cl Cu S | |
| WCP1085 /1 | Pb P Cl | Pyromorphite |
| /2-4, 10-13 | Ti | Rutile (or Anatase) |
| /5 | Si Al+K Fe | probably Topaz |
| /6-8 | Fe S | Pyrite |
| /9, 14, 15, 18, 19 | Pb Si Al | Lead Glass/Glaze |
| /16 | Cu Fe S | Chalcopyrite |
| /17 | Si Al Ti Mn Fe K Ca | Silicate |
| /20-23 | Si Al+Fe Mn | Garnet |

**Table 2A** continued

| | | |
|---|---|---|
| WCP1086 /1-4, 6-8 | Ti | Rutile |
| /5 | Zr Si | Zircon |
| /9 | Si Ca Ti | Sphene |
| /10, 16 | Cu Fe S | Chalcopyrite |
| /11-14 | RE+P | Monazite |
| /15a | Al Zn Fe | |
| /15b | Si | Quartz or glass |
| /17, 18 | Si Al Ca Fe Mg | |
| /19 | Si Ca Fe | |
| /20, 21 | Ni Cl Cu | |
| WCP1099 /1-3 | Pb S | Galena |
| /4-6, 12 | Zn S | Sphalerite |
| /7-10, 14 | Fe S | Pyrite |
| /13 | Pb Si Al P | Lead Glass/Glaze |
| /15, 23 | Ni Cl Cu | |
| /16, 17, 19 | Si Al+Ca Fe | |
| /18 | Si Al+Fe+Mn Ca K | Garnet |
| /20-22 | Fe+Mn | Iron Oxide |
| WCP1103 /1, 5-7, 16 | Hg S | Cinnabar |
| /2, 4, 8, 14, 20-22 | Ba S | Baryte |
| /3 | Si Al+K Ca Ti Fe | |
| /9, 15 | Si Al | probably Topaz |
| /10 | Zn S | Sphalerite |
| /11 | Cu | Cuprite |
| /12, 13, 17, 18, 35, 36 | Ti | Rutile |
| /19 | Zr Si | Zircon |
| /23, 24, 27, 28, 34, 37 | Fe S | Pyrite |
| /25 | Fe | Iron Oxide |
| /26 | Ti Fe | Ilmenite |
| /29-31 | Cu Fe S | Chalcopyrite |
| /32, 33 | Cu | Malachite |
| /38, 39 | Fe | Siderite |
| /40 | Si Al | probably Topaz |
| /41 | Pb Si Al | Lead Glass/Glaze |
| WCP1107 /1-3 | Hg S | Cinnabar |
| /4 | Pb As P | Mimetite |
| /5, 9-13, 15, 18, 20, 33 | Ti | Rutile |
| /6, 21-23, 34, 53, 56-61 | Fe S | Pyrite |
| /7, 8, 40, 55 | Si Al Ca K Fe | |
| /14, 16, 17, 19, 31 | Ba S | Baryte |
| /24 | Pb P | Pyromorphite |
| /25-28, 32 | Cu | Cuprite |
| /29 | Pb | Cerussite |
| /35-38, 41, 43-45 | Ti Fe | Ilmenite |
| /39 | Fe | Iron Oxide |
| /42 | Cr Fe+Al Mg | Chromite |
| /46, 48-52, 54 | Cu Fe S | Chalcopyrite |
| /47 | Si Ca Ti | Sphene |
| WCP1109 /1 | Au+Ag | Gold |
| /2 | Hg S | Cinnabar |
| /3, 9, 13 | Zn S | Sphalerite |
| /4, 5 | Pb Cu S | |
| /6, 7, 11, 12, 18 | Pb S | Galena |
| /8 | Pb | Cerussite |
| /10 | Ba S | Baryte |
| /14 | Ti | Rutile |
| /15, 16 | Pb S | possibly Anglesite |
| /19, 20 | Cu Fe S | Chalcopyrite |
| /21, 22 | Cu | Malachite |

**Table 2A** continued

| | | |
|---|---|---|
| WCP1111 /1 | Sn Hg | |
| /2, 3 | Pb P | Pyromorphite |
| /4, 7, 16 | Ti | Rutile |
| /5, 11 | Cu | Cuprite |
| /6, 9 | Ba S | Baryte |
| /8 | Si | Quartz |
| /10 | Ag Hg S Sn | |
| /12 | Sn | Tin Oxide |
| /13 | Si Al K Fe | probably Orthoclase |
| /14, 15 | Si Ca Ti | probably Sphene |
| /17 | Si Al Mg Fe | |
| WCP1112 /1-3, 6, 9, 10 | Ba S | Baryte |
| /4, 5, 8, 15-17 | Fe S | Pyrite |
| /7 | Ti Fe | Ilmenite |
| /11 | Si Al | probably Topaz |
| /12 | Cu Fe S | Chalcopyrite |
| /13 | Si Ti | |
| /14 | Ni Cu Cl S | |
| WCP1119 /1 | Si Al K | probably Orthoclase |
| /2, 3 | Zn S | Sphalerite |
| /4 | Al + Si Fe | |
| /5, 6, 9 | Pb S | Galena |
| /7 | Zn + S | Zincite or Smithsonite |
| /8 | Pb | Cerussite |
| /10 | Hg S | Cinnabar |
| /14, 16-18, 21, 23 | Ti Fe + Mn | Ilmenite |
| /15, 19, 20, 22 | Fe | Iron Oxide |
| /24 | Cr Fe | Chromite |
| WCP1125 /1, 5, 8 | Pb Si | Lead Glass/Glaze |
| /2 | Pb + Si Al | Lead Oxide or Carbonate |
| /3, 7 | Si Al | probably Topaz |
| /4, 11 | Ti | Rutile |
| /6 | Si | Quartz |
| /9, 10 | Cu Fe S | Chalcopyrite |
| /12, 13 | Si Mg Al Ca Fe | probably Amphibole |
| WCP1132 /1 | Pb S | Galena |
| /2, 3, 5, 6, 17 | Pb As P | Mimetite |
| /4 | Zn S | Sphalerite |
| /7 | Pb | Cerussite |
| /8 | Sn | Tin Oxide |
| /9 | Si Ti + Al Mg Fe | |
| /10, 15 | As Fe S | Arsenopyrite |
| /11, 14, 16, 18, 19, 21, 23 | Ti | Rutile |
| /12 | nothing | probably Graphite |
| /13 | Fe S | Pyrite |
| /20 | Pb Si Al | Lead Glass/Glaze |
| /22 | Si Al Na K Ti Fe | |
| /24, 25 | Cu Fe S | Chalcopyrite |

**Table 2A** continued

| | | |
|---|---|---|
| WCP1134 /1, 5, 6 | Zn S | Sphalerite |
| /2 | Si Mg Al Fe | |
| /3 | Pb S | Galena |
| /4 | Pb | Cerussite |
| /7 | Mn + Ca Al Si | Manganese Oxide |
| /8-10 | Cu Fe S | Chalcopyrite |
| /11-13 | Si Al Mn Fe Ca | Garnet |
| /2 | Zn S | Sphalerite |
| /3, 4, 12 | Ti | Rutile |
| /5-11, 14-16 | Fe S | Pyrite |
| /13 | Pb | Cerussite |
| /17, 18 | Cu Fe S | Chalcopyrite |
| WCP1150 /1, 2 | Hg S | Cinnabar |
| /3 | Cu | Cuprite |
| /4, 8, 10 | Pb | Cerussite |
| /5 | Si + Fe | Quartz |
| /6 | Ba S | Baryte |
| /7 | Sn Pb | Solder |
| /9, 12-14 | Cu Fe S | Chalcopyrite |
| /11 | Fe S | Pyrite |
| WCP1153 /1 | Hg S | Cinnabar |
| /2, 5 | Pb S | Galena |
| /3 | Ba S | Baryte |
| /4, 7 | Ti | Rutile |
| /6, 10 | Fe S | Pyrite |
| /8, 9 | Cu S | Copper Sulphide |
| WCP1158 /1 | Hg S | Cinnabar |
| /2-4 | Ti | Rutile |
| /5, 8, 12 | Fe S | Pyrite |
| /6 | Mn + Ti Ca S Si Al | Manganese Oxide |
| /7, 10 | Ba S | Baryte |
| /9 | Zn S | Sphalerite |
| /11 | Si Al + Fe K Ti | probably Topaz |
| /13-16 | Cu Fe S | Chalcopyrite |
| WCP1160 /1 | Fe S | Pyrite |
| /2-4, 9 | Pb | Cerussite or Oxide |
| /5 | Pb + Sb | Lead Metal |
| /6 | Pb S | Galena |
| /7 | Cu | Copper Oxide |
| /8, 11 | Cu S | Copper Sulphide |
| /10 | Pb Ba Sn Sb | Solder |
| /12 | Ti | Rutile |
| /13, 14 | Cu Fe S | Chalcopyrite |
| /15 | Si Ca Ti | probably Sphene |
| /16 | Mg Si Fe | |
| WCP1161 /1, 5 | Pb S | Galena |
| /2 | Fe S | Pyrite |
| /3 | Zn S | Sphalerite |
| /4 | As Fe S | Arsenopyrite |
| /6 | Si Al K | probably Orthoclase |
| /7 | Si + Fe | Quartz |
| /8 | Cu Fe S | Chalcopyrite |
| /9 | Si Al K Ti Fe | |

**Table 2A** continued

| | | |
|---|---|---|
| WCP1166 /1 | Cu Sn | Artefact |
| /2 | Hg S | Cinnabar |
| /3-6 | Ti | Rutile |
| /7, 8, 10 | Ba S | Baryte |
| /9, 11 | Sn Pb | Solder |
| /12, 13, 19 | Pb | Cerussite or Oxide |
| /14 | Fe S | Pyrite |
| /15, 16 | Cu Fe S | Chalcopyrite |
| /17 | Ti Fe | Ilmenite |
| /18 | Si Ca Ti | probably Sphene |
| WCP1170 /1, 3b | Zn S | Sphalerite |
| /2 | Fe S | Pyrite |
| /3a | Cu Fe S | Pyrite |
| /3c | Pb | Cerussite or Oxide |
| /4-15 | Pb Si | Lead Glass/Glaze |

**Table 3A** Semiquantitative microprobe analyses

In the Table a "-" indicates that the element so marked was not analysed for on the probe. A blank means not detected.

**Cinnabar**

| Grain No. | Hg | S |
|---|---|---|
| WCP1047 /1 | 78.0 | 15.9 |
| /2 | 81.6 | 15.0 |
| /3a | 74.8 | 14.6 |
| /4 | 73.7 | 14.4 |
| /5 | 78.6 | 15.4 |
| /6 | 82.6 | 17.1 |
| WCP1056 /1 | 72.9 | 14.3 |
| WCP1058 /1 | 79.1 | 15.9 |
| WCP1064 /2 | 80.1 | 16.6 |
| WCP1079 /1 | 83.3 | 16.4 |
| WCP1103 /5 | 84.4 | 17.1 |
| /6 | 79.7 | 15.3 |
| /7 | 78.7 | 15.3 |
| /16 | 80.6 | 15.7 |
| WCP1107 /1 | 84.8 | 15.3 |
| /2 | 77.1 | 15.3 |
| /3 | 80.7 | 15.2 |
| WCP1119 /10 | 79.4 | 15.5 |
| WCP1187 /1 | 82.3 | 18.1 |
| /2 | 81.6 | 18.3 |
| /3 | 70.8 | 16.2 |
| WCP1194 | 81.2 | 18.3 |
| WCP1195 /1 | 81.6 | 17.6 |
| /3 | 78.9 | 17.9 |
| /7 | 77.1 | 17.6 |
| /11 | 79.0 | 16.4 |
| /18 | 74.4 | 16.2 |
| /20 | 80.9 | 18.6 |
| WCP1196 /4 | 75.1 | 16.4 |

**Gold**

| Grain No | | Au | Ag | Cu |
|---|---|---|---|---|
| WCP1109/1 | Scratch | 90.9 | 8.22 | |
| | Surface | | 91.0 | 4.2 |

**Polished Gold**

| | | | | |
|---|---|---|---|---|
| Grain 'A' | top centre | 87.0 | 12.0 | 0.98 |
| " | " | 88.5 | 11.5 | |
| " | low centre | 87.7 | 11.5 | 0.84 |
| Grain 'B' | left centre | 91.6 | 8.41 | |
| " | " | 91.2 | 8.83 | |
| " | left edge | 84.5 | 5.41 | |
| " | " | 91.0 | 8.06 | |
| Grain 'C' | deep left end | 90.5 | 9.45 | |
| " | centre | 89.0 | 11.0 | |
| " | right end | 92.1 | 7.90 | |
| " | centre left | 86.7 | 13.3 | |

**Table 3A** continued

**Galena**

| Grain No | Pb | S |
|---|---|---|
| WCP1056 /1 | 89.6 | 12.4 |
| /2 | 87.4 | 11.9 |
| /3 | 79.8 | 10.0 |
| WCP1070 /1 | 80.1 | 10.0 |
| /6 | 88.9 | 11.2 |
| /11 | 90.2 | 12.7 |
| WCP1076 /1 | 89.7 | 12.4 |
| /5 | 83.8 | 11.5 |
| /7 | 79.4 | 11.3 |
| WCP1077 /2 | 85.4 | 11.3 |
| /10 | 85.4 | 11.6 |
| WCP1079 /9 | 85.1 | 11.2 |
| WCP1099 /1 | 99.0 | 12.3 |
| /2 | 88.0 | 12.3 |
| /3 | 82.9 | 10.0 |
| WCP1109 /6 | 85.9 | 11.4 |
| /7 | 93.7 | 11.3 |
| WCP1134 /3 | 81.9 | 11.5 |
| WCP1153 /2 | 86.1 | 12.9 |
| /5 | 88.2 | 12.7 |
| WCP1160 /6 | 77.2 | 10.5 |
| WCP1161 /1 | 81.2 | 11.7 |
| /5 | 83.1 | 11.9 |

**Cerussite/Minium/Litharge/Massicot/Hydrocerussite**

| Grain No | Pb | S | Ca |
|---|---|---|---|
| WCP1058 /15 | 81.8 | | |
| WCP1064 /1 | 81.4 | 0.49 | |
| WCP1076 /3 | 79.6 | 0.29 | |
| WCP1079 /24 | 77.8 | 3.03 | |
| WCP1109 /15 | 71.2 | | |
| WCP1134 /4 | 54.6 | 0.81 | 0.46 |
| WCP1140 /13 | 63.2 | 2.24 | |
| WCP1150 /4 | 73.7 | | |
| /8 | 59.8 | | 3.52 |
| /10 | 45.3 | 0.45 | 4.66 |
| WCP1160 /2 | 60.2 | 0.49 | |
| /3 | 59.4 | | |
| /4 | 62.8 | | |
| /9 | 53.1 | 1.09 | 0.29 |
| WCP1166 /12 | 60.1 | 0.44 | 0.48 |
| /13 | 64.0 | 0.93 | 0.47 |
| /19 | 53.2 | | 6.63 |
| WCP1170 /3c | 62.9 | | |

**Table 3A** continued

**Millerite**

| Grain No | Ni | S | Fe | Cl | Co | Cu |
|---|---|---|---|---|---|---|
| WCP1076 /15 | 55.3 | 30.5 | 0.56 | 0.21 | | |
| /30 | 55.3 | 30.0 | 1.13 | | 2.45 | |
| " | 63.1 | 34.3 | 0.48 | | 1.93 | |
| /35 nodule | 41.3 | 32.1 | 2.22 | | | 24.7 |
| body | 1.58 | 26.5 | 3.22 | | | 61.5 |

**Pyromorphite/Mimetite**

| Grain No | Pb | P | As | Cl | S |
|---|---|---|---|---|---|
| WCP1079 /1 | 71.0 | 0.74 | 9.90 | 2.34 | |
| /2 | 65.9 | 0.47 | 9.00 | 2.11 | |
| /8 | 76.1 | 3.11 | 5.21 | 2.56 | 0.74 |
| WCP1085 /1 | 74.0 | 4.96 | | 2.47 | |
| WCP1107 /4 | 65.1 | 3.51 | 3.71 | - | |
| /24 | 63.6 | 2.82 | | - | |
| WCP1111 /3 | 61.7 | 4.49 | | - | 1.36 |
| WCP1132 /2 | 60.1 | 1.09 | 8.22 | - | |
| /3 | 60.0 | 0.78 | 8.42 | - | 0.87 |
| /5 | 59.6 | 1.24 | 7.49 | - | 0.90 |
| /6 | 64.5 | 1.50 | 7.71 | - | |
| /17 | 61.7 | | 11.4 | - | |

| Grain No | PbO | $As_2O_5$ | $SO_3$ | $P_2O_5$ |
|---|---|---|---|---|
| WCP1111 /3 | 81.0 | | 2.13 | 11.7 |
| WCP1132 /6 | 75.1 | 11.0 | 2.40 | 4.74 |
| /17 | 80.4 | 20.6 | 1.87 | |

**Arsenopyrite**

| Grain No | As | Fe | S |
|---|---|---|---|
| WCP1132 /10 | 41.4 | 33.5 | 18.6 |
| /15 | 39.7 | 31.9 | 18.0 |

**Cuprite/Melancolite**

| Grain No | Cu | Fe | S |
|---|---|---|---|
| WCP1079 /1 red | 86.4 | 0.53 | 0.46 |
| black | 57.2 | 3.76 | 3.63 |

**Table 3A** continued

**Possible paratacamite**

| Grain No | Ni | Cu | Zn | Cl | S | Fe |
|---|---|---|---|---|---|---|
| WCP1079 /9 | 29.5 | 2.60 | 3.08 | 9.27 | 1.53 | 0.47 |
| /10 | 37.4 | | | 0.63 | 9.26 | |
| WCP1076 /25 | 30.5 | 14.1 | 3.09 | 16.6 | 0.92 | |
| /26 | 25.7 | 16.0 | 2.44 | 16.4 | 1.86 | 1.10 |
| /27 | 38.6 | 2.93 | 3.01 | 10.8 | 1.68 | |
| WCP1079 /28 | 29.9 | 12.4 | 1.98 | 10.1 | 1.48 | |
| WCP1086 /20 | 26.9 | 17.4 | 5.68 | 17.5 | 1.45 | |
| /21 | 27.0 | 15.0 | 6.08 | 16.9 | 1.63 | 0.35 |
| WCP1099 /15 | 15.3 | 11.4 | 2.75 | 10.7 | 0.31 | 0.71 |
| /23 | 20.1 | 23.7 | 4.07 | 14.1 | 1.02 | 0.58 |

**Chromite/Ilmenite**

| Grain No | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | FeO | MnO | MgO | ZnO | $K_2O$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| WCP1079 /25 | | | 12.1 | 57.3 | 21.6 | 8.47 | | | | 99.5 |
| WCP1076 /2 | 0.49 | | 9.08 | 50.1 | 25.4 | 2.01 | 1.49 | 7.56 | | 96.2 |
| WCP1119 /24 | | 0.59 | 9.42 | 50.0 | 31.0 | | 3.58 | 2.96 | | 97.6 |
| WCP1063 /40 | 0.35 | 0.39 | 4.29 | 49.7 | 37.0 | 1.79 | 0.99 | 0.94 | | 95.5 |
| WCP1107 /42 | | 0.49 | 11.8 | 47.9 | 34.9 | | 2.49 | | | 97.4 |
| WCP1063 /42 | | 0.90 | 9.25 | 42.9 | 40.1 | 1.43 | 2.14 | 1.40 | | 98.1 |
| /38 | 5.89 | 1.84 | 13.0 | 34.1 | 30.2 | | 3.19 | 3.29 | 0.55 | 92.5 |
| /53 | | 2.06 | 9.81 | 33.8 | 44.7 | 1.13 | 0.53 | 2.07 | | 94.1 |
| /47 | 0.42 | 1.69 | 17.1 | 33.6 | 35.1 | 0.92 | 3.87 | 4.52 | 0.17 | 97.4 |
| /41 | 0.65 | 1.58 | 10.7 | 32.6 | 43.4 | 1.21 | 1.15 | 1.85 | | 93.3 |
| /48 | 2.05 | 24.3 | 4.27 | 0.78 | 56.3 | | | | | 88.0 |
| /49 | 14.7 | 11.2 | 9.30 | 0.74 | 46.2 | | 2.32 | | 1.51 | 89.3 |
| Cr-Ti mineral 1* | 2.54 | 12.4 | 12.7 | 33.3 | 24.8 | | 0.72 | 5.85 | 0.47 | 92.8 |
| Cr-Ti mineral 5* | 1.30 | 3.51 | 16.6 | 35.4 | 29.4 | | | 6.01 | 0.40 | 92.6 |
| Chromite 1* | 0.50 | 0.83 | 11.3 | 42.2 | 39.0 | 0.87 | 3.50 | | | 98.2 |

* From Fortey and Nancarrow (1990)

**Unknowns**

| Grain No | Zn | Fe | Al | Sn | Hg |
|---|---|---|---|---|---|
| WCP1086 /15a | 27.7 | 6.49 | 32.3 | - | - |
| WCP1111 /1 | - | - | - | 62.4 | 32.8 |

**Table 3A** continued

**Artefacts**

| Grain No | Pb | Sn | Ba | Sb | Ag | P |
|---|---|---|---|---|---|---|
| WCP1047/6 | | 70.2 | | | | |
| /7 | 6.38 | 43.1 | | | | |
| /49 | 5.23 | 43.7 | | | | |
| WCP1058/6 | | 56.0 | 3.70 | | | |
| /7 | 74.7 | * | | | | |
| WCP1064/3 | 50.9 | | - | 23.7 | 0.43 | |
| /4 | 57.8 | 14.2 | - | | | |
| /28 | 23.2 | | | 15.1 | | |
| /29 | 40.9 | 5.22 | | 22.3 | | |
| WCP1107/24 | 63.6 | 0.90 | - | - | - | 2.82 |
| WCP1140/1 | 12.2 | 34.3 | | | | |
| WCP1150/7 | 7.27 | 54.1 | | | | |
| WCP1160/5 | 56.8 | | | 0.74 | | |
| WCP1166/9 | 1.96 | 65.1 | | | | |
| /11 | 38.3 | 21.1 | | 11.9 | | |

| Grain No | Pb | Sn | Cd | As | Zn | Cu |
|---|---|---|---|---|---|---|
| WCP1109/4 | 38.8 | 0.83 | - | - | 2.03 | 17.5 |
| /5 | 62.6 | | | | | 4.12 |
| /17 | 9.08 | 41.1 | 3.30 | 1.44 | 8.16 | |

* Sn present in the spectrum but not quantified.

**Table 4A** The results of X-ray fluorescence examination of selected fractions

When an element is underlined this indicates more is present than in other fractions of the same sample. Only the anomalous elements mentioned were looked for.

| Sample No | Fraction | Element detected | Probable host material |
|---|---|---|---|
| WCP1064 | 0.0-0.1 | Sn | with tramp iron |
| WCP1076 | 0.0-0.1 | Sn, ?Co, no Ni | iron scale |
| WCP1085 | 0.0-0.1 | V, ?Cr | V in magnetite |
| | 0.1-0.3 | V,no Cr | V in ilmenite |
| WCP1086 | 0.0-0.1 | V, Cr | V in magnetite, chromite |
| | 0.1-0.3 | Cr, V | Chromite, V in ilmenite |
| WCP1119 | 0.0-0.1 | Sn, Ni | with iron scale |
| | 0.1-0.3 | W | ? Wolframite |
| | 0.3-0.6 | Sn, Sb | Solder |
| | 0.6-non | Sn, Sb | Solder |
| WCP1132 | 0.0-0.1 | V | V in magnetite |
| | 0.1-0.3 | V | V in ilmenite |
| WCP1140 | 0.6-non+non(10°) | Cu | Chalcopyrite with oxidised pyrite |
| WCP1160 | 0.0-0.1 | much Cr | Chromite |
| | 0.1-0.3 | Cr | Chromite |

**Table 5A** X-ray diffraction identifications

| | | |
|---|---|---|
| WCP1076/19 | elongate sulphide | Millerite |

WCP1076/27 and WCP1099/15 brittle vitreous transparent green grains. On film No. Ph 7525, three very weak broad lines at about 5.5, 2.7-2.8, and 2.27A. On film No. Ph 7526, stronger broader lines at 5.45, 2.75 and 2.27A with additional very weak lines at 1.8 and 1.7A. These spacings are similar to paratacamite, but due to the poor quality of the diffraction patterns, a more precise identification was not possible.

| | | |
|---|---|---|
| WCP1058/6 | soft resinous brown grain | Romarchite(SnO) with lesser cassiterite |
| WCP1109/15 | pink scale | Litharge (PbO) with probable hydrocerussite ($Pb_3(CO_3)_2(OH)_2$) |
| WCP1150/4 | bright orange waxy grain | Minium ($Pb_3O_4$) |
| WCP1150/8 | very soft white grain | Hydrocerussite + probable trace calcite |
| WCP1160/10 | very soft white grain | Hydrocerussite, cerussite + probable trace of baryte |
| WCP1052/4 | soft white grain | Cerussite with baryte |
| WCP1047/13 | soft reddish brown grain | Cassiterite |

**Supplement: brief description of < 30 mesh (undersize) methylene iodide sink fractions**

The lists of minerals are given in the order from most to least abundant in the non-magnetic ($3^o$) fractions followed by the remaining magnetic fractions in order of increasing magnetic susceptibility. Analyses of selected anomalous elements are listed for each sample (in ppm, unless otherwise stated).

WCP1047 Dovenby - [NY 0819 3340]
Cu 382, Ba 1.5%

The sample contained 9 cinnabar grains. The ore minerals chalcopyrite and sphalerite were found. The other constituents recognised were baryte, zircon, rutile, anatase, pyrite (both fresh and oxidised), leucoxene, epidote, garnet, ilmenite and magnetite. The cokey magnetic material and black spheres are thought to be contamination, possibly from bonfires. The sample also contained lead metal fragments and particles of lead glass (or glaze).

WCP1052 Dovenby - [NY 0937 3254]
Cu 243, Ba 2.7%, Pb 401

The magnetic fraction contained cokey material and balls, both probably contamination. Baryte, rutile, zircon, pyrite (oxidised), epidote, garnet, ilmenite, leucoxene and iron oxide were recognised. The other contaminants were lead metal and lead glass or lead glaze. Oxidised chalcopyrite was also present.

WCP1056 Wardhall - [NY 1314 3823]
Zn 604, Cu 124, Ba 5%,

The phases recognised were baryte, zircon, rutile, galena, sphalerite, oxidised pyrite, oxidised chalcopyrite, epidote, garnet, ilmenite and the usual cokey magnetic material, balls, lead glass/glaze and iron oxides. One grain of cinnabar was found.

WCP1058 Gilcrux - [NY 1198 3814]
Cu 132, Sn 97, Sb 11, Pb 903, Ba 4.6%

Four cinnabar grains were found along with baryte, rutile, pyrite (both fresh, oxidised and framboidal), chalcopyrite, leucoxene, malachite, sphene, epidote, garnet, siderite dumbells, ilmenite and magnetite. The contaminants were iron wire or nails, magnetic spheres, lead glass or glaze and lead or solder fragments.

WCP1063 Tallentire - [NY 1274 3412]
Cr 276, Ce 133, Cu 101, Ba 783

One grain of cinnabar was found. The contaminants were lead metal fragments, lead glass/glaze and many small shiny magnetic black balls. The other minerals observed were zircon, rutile, baryte, anatase, leucoxene, oxidised pyrite, chalcopyrite, iron oxides, epidote, garnet, siderite dumbells, ilmenite and magnetite.

WCP1064 Blindcrake - [NY 1492 3414]
Cu 121, Zn 251, Sn 578, Sb 11, Ba 3.4%, Pb 1159

The minerals observed were one grain of cinnabar, baryte, zircon, rutile, sphalerite, oxidised pyrite (some framboidal), leucoxene, chalcopyrite, epidote, garnet, ilmenite, iron oxides and magnetite. Also present were lead fragments, copper wire, lead glass, tramp iron and magnetic spheres. The most magnetic fraction was checked with the XRF and Sn found, presumably some of the tramp iron was tin plate.

WCP1070 Binsey West - [NY 1950 3540]
Zn 319, Cu 72

This was a small sample and contained baryte, sphalerite, rutile, galena, anatase, pyrite, leucoxene, chalcopyrite, iron oxides, epidote, 'copper scale', garnet, ilmenite and magnetite. It was contaminated with lead glass, iron scale and magnetic spheres.

WCP1076 Binsey West - [NY 2096 3480]
Ni 75, Cu 805, Zn 1106, Sn 485, Ba 3111, Pb 938, As 102, W 44, Cr 200

This small sample contained corroded sphalerite, baryte, zircon, weathered galena, rutile, leucoxene, millerite, chalcopyrite, oxidised pyrite, 'copper scale', iron oxides, epidote, garnet, ilmenite, and magnetite. The contaminants were lead glass/glaze, lead sheet, lead turnings, iron scale and magnetic spheres. The most magnetic fraction showed the presence of tin in the XRF which suggests the presence of tin plate.

WCP1077 Binsey West - [NY 2073 3557]
Zn 521, Cu 234

A small sample containing baryte, sphalerite, galena, zircon, rutile, anatase, pyrite, millerite, leucoxene, chalcopyrite, iron oxides, epidote, garnet, ilmenite, goethite, and magnetite. The contaminants were lead glass, tramp iron and magnetic spheres.

WCP1079 Uldale - [NY 2418 3773]
V 341, Cu 96, Zn 120, Sn 111, Sb 26, Ba 1.6%, Pb 473

One grain of cinnabar was found. Other minerals were baryte, zircon, rutile, sphalerite, galena, mimetite, anatase, leucoxene, pyrite, chalcopyrite, iron oxides, epidote, garnet, ilmenite and magnetite. A two phase grain, black and bright red turned out to be copper oxide in both halves. The contamination was lead glass/glaze, iron scale and magnetic spheres.

WCP1085 Clay Gap -[NY 2832 3822]
Ti 14.0%, V 1402, Cr 216, Cu 86, Zr 2966

Minerals found were baryte, zircon, rutile, anatase, pyrite, leucoxene, chalcopyrite, iron oxide or oxidised pyrite, epidote, fresh ilmenite, garnet, magnetite and two gold grains. The only artefact noted was lead glass/glaze. The two most magnetic fractions gave V and possibly Cr by XRF probably due to vanadium in magnetite and ilmenite and possibly some chromite was present.

WCP1086 Ireby - [NY 2528 3884]
Ti 11.5%, V 1315, Fe 16.3%

This sample contains zircon, rutile, anatase, pyrite, leucoxene, monazite, epidote, 'copper scale', fresh ilmenite, garnet, iron oxide and magnetite. Lead glass and weakly magnetic spheres were the only contaminants noted. The two most magnetic fractions showed the presence of Cr by XRF which indicates the likely presence of chromite.

WCP1099 Sunderland - [NY 1778 3499]
Cu 146, Zn 270, Ba 5797, Pb 271

The minerals found in this sample were baryte, weathered galena, sphalerite, zircon, rutile, fresh pyrite, oxidised pyrite, leucoxene, chalcopyrite, iron oxides, epidote, ilmenite, pink and colourless garnet and magnetite. The contaminants were lead glass, iron scale and magnetic spheres.

WCP1103 Plumbland - [NY 1576 4088]
Fe 21.6%, Zn 526, Cu 70, Sn 46, Sb 14, Ba 1.8%, Pb 114

Five grains of cinnabar were found. The sample was contaminated by lead glass, lead metal fragments and magnetic spheres. The minerals were baryte, zircon, rutile, copper oxide, anatase, sphalerite, leucoxene, oxidised pyrite, iron oxides, epidote, ilmenite, garnet, siderite balls and dumbells and magnetite.

WCP1107 Dovenby - [NY 0996 3375]
Cu 378, Sn 80, Ba 9.9%, Pb 106

Three grains of cinnabar were found. The sample also contained baryte, zircon, rutile, anatase, pyrite, chalcopyrite, leucoxene, oxidised pyrite, iron oxides, epidote, garnet, ilmenite, goethite and magnetite. Lead glass, magnetic spheres and cokey magnetic material were the contaminants.

WCP1109 Dovenby - [NY 1024 3312]
Ni 88, Cu 351, Sn 169, Ba 7.2%, Pb 7448

One grain of gold together with one grain of cinnabar were found amongst the baryte, fresh pyrite, zircon, rutile, anatase, sphalerite, leucoxene, oxidised pyrite, chalcopyrite, iron oxides, epidote, garnet, ilmenite and magnetite. The contaminants were lead metal, lead glass, iron slag and magnetic spheres.

WCP1111 Torpenhow - [NY 2074 4048]
Fe 18.3%, Sn 457, Ba 6434, Pb 390

This sample contained baryte, zircon, rutile, pyrite, leucoxene, epidote, garnet, ilmenite and magnetite. It was contaminated with cokey magnetic slag, magnetic spheres, lead glass and lead and/or solder.

WCP1112 Dearham - [NY 0682 3643]
Fe 24.8%, Ni 202, Cu 572, Sn 185, Ba 4618, Pb 205, Mo 36

Here the highly magnetic fraction was a large proportion of the sample and was mainly composed of a cokey slag, probably contamination. The remainder of the sample comprised iron oxides, garnet, oxidised pyrite, epidote, chalcopyrite, rutile, baryte, zircon and some lead glass contaminate.

WCP1119 High Bewaldeth - [NY 2245 3419]
Fe 18.5%, Ni 99, Cu 1843, Zn 2431, Sn 471, Sb 48, Ba 7663, Pb 9367, W 252

One grain of cinnabar was found. The contaminants were cokey slag, magnetic spheres, lead glass/glaze, lead and/or solder and copper wire. The minerals were baryte, zircon, rutile, sphalerite, galena, cerussite, chalcopyrite, iron oxides, epidote, garnet, ilmenite and magnetite.

WCP1125 Bridekirk - [NY 1172 3344]
Pb 1681

A small sample contaminated by lead glass, paint, cokey slag and magnetic spheres. The minerals were zircon, rutile, baryte, pyrite, leucoxene, chalcopyrite, epidote, garnet, ilmenite and magnetite.

WCP1132 Branthwaite - [NY 2858 3699]
Ti 3.5%, V 707, Cu 105, Zn 187, Ba 2.5%, Pb 3617, Sb 43, W 29

The XRF showed that the two most magnetic fractions contained vanadium which is probably hosted in magnetite and ilmenite. The contaminants were lead fragments, lead glass/glaze and lead glass slag. The minerals were baryte, rutile, anatase, mimetite, zircon, cerussite, freshish pyrite, sphalerite, leucoxene, oxidised pyrite, chalcopyrite, iron oxides, ilmenite, garnet and magnetite.

WCP1134 Stockdale - [NY 2599 3484]
Mn 1.57%, Cu 134, Zn 656, Ba 1073, Pb 9121, Sb 86, As 124

The minerals found in this small sample were zircon, rutile, anatase, leucoxene, sphalerite, pyrite, baryte, chalcopyrite, oxidised pyrite, iron oxides, epidote, pink garnet, ilmenite, colourless garnet and magnetite. The sample is heavily contaminated with a lead glass slag besides lead glass/glaze and iron scale.

WCP1140 Broughton Moor - [NY 0510 3103]
Fe 14.3%, Cu 1809, Ba 2.8%, As 125

This large sample mostly went into the 0.6-1.7 amp fraction. The two non-magnetic fractions were also large. The 0.6-1.7 and non-mag($10^0$) which consisted essentially of oxidised pyrite with lead glass and rutile were combined; the combined sample was positive for Cu in the XRF. The other minerals found were baryte, zircon, pyrite, iron oxides (some cubic pseudomorphs of pyrite), epidote, garnet, ilmenite and magnetite. The sample contained lead glass, magnetic spheres and iron scale contaminants.

WCP1150 Flimby - [NY 0288 3399]
Fe 22.7%, Cr 561, Ni 183, Cu 448, Zn 80, Mo 19, Sn 116, Ba 5.9%, Pb 197

Two grains of cinnabar were found. The sample was contaminated with copper wire, lead balls, copper scale, lead glass, cokey magnetic slag and magnetic spheres. Minerals seen were baryte, zircon, rutile, anatase, pyrite, leucoxene, oxidised pyrite, iron oxide, chalcopyrite, epidote, garnet, ilmenite and magnetite.

WCP1153 Flimby - [NY 0274 3380]
Cr 586, Cu 467, Zr 2696, Sn 405, Ba 2.8%, Pb 520

One grain of cinnabar was found. The minerals seen were baryte, zircon, rutile, pyrite, anatase, galena, leucoxene, oxidised pyrite, iron oxides, epidote, garnet, ilmenite and magnetite. The contaminants were lead metal, lead glaze, cokey magnetic slag and magnetic spheres.

WCP1158 Maryport - [NY 0500 3451]
Fe 14.9%, Cu 176, Zn 122, Sn 76, Ba 1.4%, Pb 239

One grain of cinnabar was found. The contaminants were lead glaze, cokey magnetic slag and magnetic spheres. The minerals seen were zircon, rutile, baryte, pyrite, anatase, leucoxene, oxidised pyrite, chalcopyrite, iron oxide, epidote, ilmenite, garnet, siderite and magnetite.

WCP1160 Maryport - [NY 0502 3609]
Fe 23.6%, Cr 654, Ni 83, Cu 273, Mo 17, Sn 605, Sb 26, Ba 2.3%, Pb 1346

XRF checks on the two most magnetic fractions were positive for Cr. The minerals found were baryte, pyrite, zircon, rutile, copper oxide, a yellow earthy mineral which probe examination suggested was a lead oxide (perhaps oxidation of lead or solder), galena, sphene, leucoxene, iron oxide, chalcopyrite, epidote, garnet, ilmenite and one grain of gold. The contaminants lead metal (or solder), lead glass, cokey magnetic slag, iron scale and magnetic spheres were found.

WCP1161 Embleton - [NY 1670 3050]
Cu 139, Zn 189, Sn 52, Pb 178, As 160

In this small sample the minerals found were pyrite, baryte, zircon, rutile, galena, sphalerite, oxidised pyrite, leucoxene, chalcopyrite, iron oxides, epidote, garnet and ilmenite. It was contaminated with lead metal, copper wire, lead glass and iron scale.

WCP1166 Camerton - [NY 0392 3094]
Cu 501, Sn 130, Ba 5.0%, Pb 675

One grain of cinnabar was found. The contaminants were lead metal, copper wire growing malachite, copper oxide scale, lead glass, iron scale, cokey magnetic slag and magnetic spheres.

WCP1170 Hewthwaite - [NY 1550 3293]
Cu 87, Sn 69, Sb 40, Pb 7968

This was a small sample contaminated with much lead glass/glaze of various colours, copper wire, iron scale, cokey magnetic slag and magnetic spheres. Minerals seen were leucoxene, zircon, pyrite, sphalerite, baryte, iron oxide, chalcopyrite, epidote, garnet, ilmenite and magnetite.

## APPENDIX 2 List of Mineral Occurrences

The sites of mineral occurrences are shown on Figure 5. The minerals identified at each site are listed together with bibliographic references.

For most sites eight figure grid references are given: for a few large quarries six figure references for the approximate centre of the workings are given.

Chemical formulae are quoted for the first reference to each mineral.

At sites marked with an asterisk the mineral was not observed in situ but in loose blocks or in dry stone walls.

**OUGHTERSIDE OPENCAST COAL SITE, NEAR ASPATRIA [NY 110 398]**
(workings backfilled and site restored) chalcopyrite ($CuFeS_2$),
copiapite ($Fe^{2+}Fe_4^{3+}(SO_4)_6(OH)_2.20H_20$), epsomite ($MgSO_4.7H_2O$), gypsum ($CaSO_4.2H_2O$),
jarosite ($KFe_3^{3+}(SO_4)_2(OH)_6$), kaolinite ($Al_2Si_2O_5(OH)_4$), millerite ($NiS$),
pickeringite ($MgAl_2(SO_4)_4.22H_2O$), pyrite ($FeS_2$), rozenite ($FeSO_4.4H_2O$), siderite ($FeCO_3$),
sphalerite ($(Zn,Fe)S$).
Young and Nancarrow, 1988A, 1988B.

**ROSEGILL, GILCRUX [NY 0928 3752 and NY 0912 3741]**
baryte ($BaSO_4$)
Eastwood, 1930; 1959; Young and Armstrong, 1989.

**FRETCHVILLE COAL PIT, GILCRUX [NY 1045 3807]**
baryte
Young and Armstrong, 1989.

**BROUGHTON CRAGS LIMESTONE QUARRY, GREAT BROUGHTON [NY 090 318]**
dolomite ($CaMg(CO_3)_2$), chalcopyrite

**TENDLEY HILL LIMESTONE QUARRY, EAGLESFIELD [NY 088 288]**
calcite ($CaCO_3$), chalcopyrite, dolomite, solid and sticky hydrocarbons,
malachite ($Cu_2(CO_3)(OH)_2$), sphalerite

**OLD LIMESTONE QUARRY SOUTH OF GILCRUX [NY 1175 3769]**
baryte
Young and Armstrong, 1989.

**OLD SANDSTONE QUARRY, SOUTH OF GILCRUX [NY 1167 3763]**
baryte
Young and Armstrong, 1989.

**STREAM NORTH OF TALLENTIREHILL FARM [NY 1201 3695]**
* baryte in sandstone boulders
Young and Armstrong, 1989.

**OLD LIMESTONE QUARRY AT TALLENTIREHILL FARM [NY 1200 3640]**
* baryte in limestone boulders
Young and Armstrong, 1989.

**DRY STONE WALL SOUTH OF TALLENTIREHILL FARM [NY 1207 3600]**
* goethite and malachite in sandstone blocks
Young and Armstrong, 1989.

**OLD LIMESTONE QUARRY ON SOUTH WEST SIDE OF TALLENTIRE HILL [NY 1185 3559]**
baryte

**OLD LIMESTONE QUARRY ON SOUTH SIDE OF TALLENTIRE HILL [NY 1217 3571]**
baryte
Young and Armstrong, 1989.

**DRY STONE WALL SOUTH OF TALLENTIRE HILL [NY 1221 3535]**
* chalcopyrite and malachite in limestone block
Young and Armstrong, 1989.

**DRY STONE WALL AND FIELD ON EAST SIDE OF TALLENTIRE HILL**
**[between NY 1234 3592 and NY 1233 3567]**
* aragonite ($CaCO_3$), baryte, calcite, chalcopyrite, dolomite, goethite ( $Fe^{+3}O(OH)$),
hematite ($Fe_2O_3$), malachite, quartz in sandstone blocks.
Young and Armstrong, 1989.

**STREAM BANKS SOUTH OF WARDHALL COTTAGES, PLUMBLAND [NY 1296 3832]**
baryte
Young and Armstrong, 1989.

**WARDHALL LIMESTONE QUARRIES, PLUMBLAND [NY 1348 3832 and NY 1390 3816]**
baryte
Young and Armstrong, 1989.

**LIMESTONE OUTCROP NORTH WEST OF EWECLOSE FARM, PLUMBLAND**
**[NY 1335 3800]**
solid hydrocarbon
Young and Armstrong, 1989.

**OLD SANDSTONE PITS ON WARDHALL COMMON [NY 1394 3729]**
* baryte veins in sandstone blocks
Young and Armstrong, 1989.

**OLD LIMESTONE QUARRY ON WARDHALL COMMON [NY 1365 3718]**
baryte
Young and Armstrong, 1989.

**OLD SANDSTONE PITS SOUTH OF GRANGE GRASSINGS FARM, PLUMBLAND [NY 1328 3662]**
baryte impregnating sandstone
Young and Armstrong, 1989.

**OLD SANDSTONE PITS IN TOP WOOD, PLUMBLAND [NY 1326 3645 and NY 1325 3635]**
baryte impregnating sandstone
Young and Armstrong, 1989.

**OLD LIMESTONE QUARRY EAST OF WARDHALL COMMON [NY 1461 3748]**
dickite ($Al_2Si_2O_5(OH)_4$)
Young and Armstrong, 1989.

**MOOTA LIMESTONE QUARRY [NY 143 363]**
baryte, calcite, chalcopyrite, dolomite, goethite, hematite, malachite, sphalerite
Young and Armstrong, 1989.

**LIMESTONE OUTCROP SOUTH OF MOOTA QUARRY [NY 1468 3561]**
baryte, dickite
Young and Armstrong, 1989.

**THRUSHGILL LIMESTONE QUARRIES, PLUMBLAND [NY 1558 3817]**
baryte

**OLD COPPER TRIAL ADIT EAST OF THREAPLAND HALL [NY 1620 3942]**
anglesite ($PbSO_4$), azurite ($Cu_3(CO_3)_2(OH)_2$), baryte, calcite, cerussite ($PbCO_3$), chalcopyrite, cuprite ($Cu_2O$), dolomite, galena (PbS), malachite, quartz, sphalerite
Eastwood et al., 1968.

**BOTHEL LIMESTONE QUARRY, BOTHEL [NY 1760 3900]**
baryte

**WHARRELS HILL QUARRY, BOTHEL [NY 1700 3817]**
baryte

**OLD LIMESTONE QUARRY WEST OF MOOTA MOTEL [NY 1559 3717]**
baryte

**LIMESTONE OUTCROP SOUTH OF WHARRELS HILL, BOTHEL [NY 1711 3782]**
baryte

**LIMESTONE OUTCROP EAST OF MOOTA MOTEL [NY 1642 3681]**
calcite, chalcopyrite, quartz

**CLINTS LIMESTONE QUARRIES, MOOTA [NY 1585 3645, NY 1620 3625 and NY 1610 3570]**
baryte

**LIMESTONE OUTCROP NORTH OF CLINTS CENTRAL QUARRY, MOOTA [NY 1615 3640]**
calcite, chalcopyrite, goethite

**OLD LIMESTONE QUARRIES SOUTH OF BOTHEL [NY 1791 3744 and NY 1800 3721]**
baryte

**CLINTS CRAGS, BLINDCRAKE [centred around NY 164 354]**
baryte

**PARK WOOD, ISEL [NY 1664 3470]**
* baryte

**OLD LIMESTONE QUARRY, EAST OF BOTHEL [NY 1873 3951]**
baryte

**BORROWSCALE LIMESTONE QUARRIES, TORPENHOW [NY 1970 3865]**
baryte

**BIRD HOUSE MINE, WHITRIGG [NY 2010 3763]**
baryte, chalcopyrite, malachite, quartz
Eastwood et al., 1968.

**MELL BECK, RUTHWAITE [NY 2340 3667]**
baryte, calcite

**RUTHWAITE MINE, RUTHWAITE [centred around NY 2385 3685]**
ankerite ($Ca(Fe^{+2},Mg,Mn)(CO_3)_2$), baryte, calcite, malachite, quartz
Adams, 1988; Dunham and Dines, 1945; Eastwood et al., 1968.

**ROSTHWAITE BECK, RUTHWAITE [NY 2402 3624]**
baryte

**HEADEND LIMESTONE QUARRY, SANDALE [NY 2493 4084]**
baryte, malachite

**OLD LIMESTONE QUARRIES EAST OF HEADEND QUARRY [NY 2517 4080 and NY 2510 4069]**
baryte

**OLD LIMESTONE QUARRY SOUTH SOUTH EAST OF HEADEND QUARRY [NY 2518 4039]**
hematite

**CATLANDS HILL LIMESTONE QUARRY, SANDALE [NY 2510 4110]**
baryte

**LIMESTONE OUTCROPS NORTH-WEST OF HEADEND QUARRY [centred around NY 2480 4100]**
baryte

**OLD LIMESTONE QUARRY EAST OF AUGHERTREE [NY 2651 3846]**
hematite