British Geological Survey

Mineral Reconnaissance Programme

Mineral exploration in the Lower Palaeozoic rocks of south-west Cumbria. Part 1: regional surveys

Department of Trade and Industry

MRP Report 128
Technical Report WF/93/4

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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

Cameron, D G, Cooper, D C, Johnson, E W, Roberts, P D, Cornwell, J D, Bland, D J, and Nancarrow, P H A. 1993. Mineral exploration in the Lower Palaeozoic rocks of south-west Cumbria. Part 1: Regional surveys. *British Geological Survey Technical Report* WF/93/4 (*BGS Mineral Reconnaissance Programme Report* 128).

Keyworth, Nottingham 1993

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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 The information contained herein must not be published without reference to the Director, British Geological Survey.

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

CONTENTS

FIGURES

TABLES

SUMMARY

The results of geochemical, geological and geophysical surveys over Lower Palaeozoic rocks in the south-western part of Cumbria are given in two reports. This report (Part 1) describes the results of a geochemical drainage survey and an examination of mineralised sites, and relates them to information from new geological mapping and an assessment of regional geophysical data. Part 2 contains details of follow-up surveys in the Black Combe inlier.

The geochemical drainage survey, involving the collection and analysis of heavy mineral concentrates and stream sediment samples from 119 sites, found substantial antimony, arsenic, barium, bismuth, copper, iron, lead, tin, tungsten and zinc anomalies. Gold was reported for the first time from this part of the Lake District: small amounts were noted in panned concentrates from five sites. Other minerals identified in panned concentrates included arsenopyrite, baryte, bismutite, bismuthinite, cassiterite, chalcopyrite, cerussite, pyrite, pyromorphite, scheelite, sphalerite, stolzite and wolframite.

The examination of old workings and outcrops revealed many undocumented occurrences of quartz-sulphide vein-style mineralisation. The chemical analysis of samples taken from old workings and other occurrences confirmed field observations that locally, particularly in the Black Combe area, this mineralisation is polymetallic with variable amounts of arsenic, gold, bismuth, copper, lead, zinc and in a few cases antimony, barium, cobalt, nickel, tungsten and tin. Iron mineralisation occurs both as oxide (hematite) and sulphide deposits. Mercury was present in appreciable amounts in samples from the High Brow pyrite mine.

The distribution of panned concentrate anomalies suggests that the vein-style mineralisation is polyphase and that individual phases may be zoned. Highest zinc anomalies occur near Torver and the highest lead on the west side of Black Combe. Tin and tungsten are restricted largely to the central part of Black Combe, and the most prominent arsenic and bismuth anomalies are found in the same area. Copper anomalies are widespread over the Skiddaw Group and the Borrowdale Volcanic Group. Barium anomalies indicate that baryte mineralisation is weak and localised, occurring principally within the Black Combe area and close to the Windermere Supergroup basal unconformity. Iron oxides from host rocks and hematite mineralisation are responsible for local enrichments of iron, antimony, arsenic and molybdenum in panned concentrates.

The results indicate the presence of a hitherto undetected episode of tin-tungsten mineralisation in Black Combe, where it is associated with tourmalinites and bleached (metasomatised) rocks of the Skiddaw Group. Gold, associated with arsenic ± bismuth ± copper ± cobalt mineralisation, is also present in Black Combe and to the north-west in the Borrowdale Volcanic Group. This mineralisation is believed to be Devonian in age and associated closely with a putative buried, evolved end-Caledonian granitic intrusion on the southern margin of the Lake District batholith. Lead-zinc mineralisation may either accompany this event or form a separate episode of mineralisation. Baryte occurrences may be related to later Carboniferous to Mesozoic events, including hematite mineralisation. The regional controls on the location of mineralisation include the Lake District batholith, the Ulpha basin, the Westmorland Monocline/Southern Borrowdales Lineament and host rock lithology.

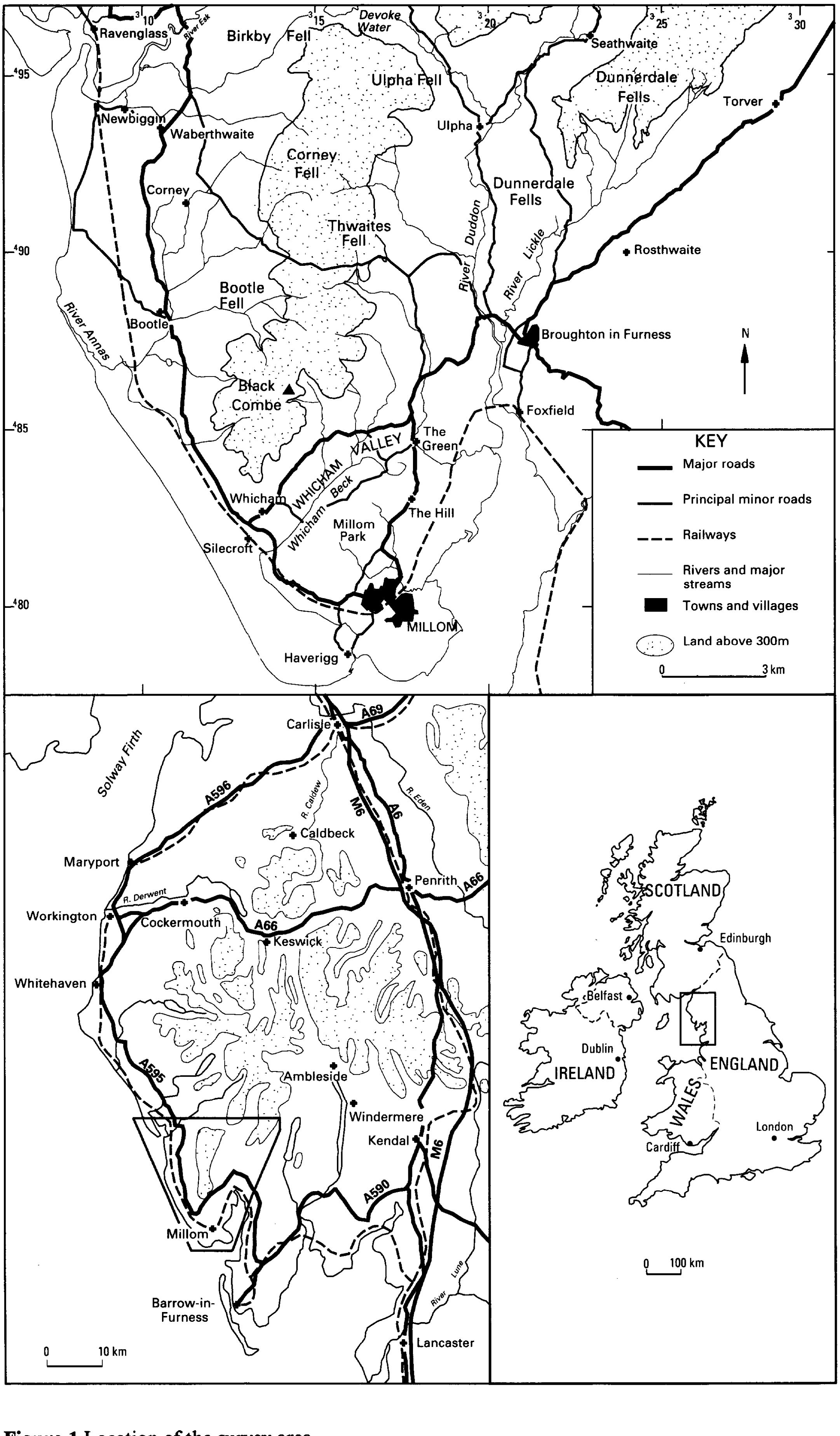

Figure 1 Location of the survey area

INTRODUCTION

This report describes a reconnaissance geochemical survey in the south-western part of Cumbria carried out by the Mineral Reconnaissance Programme and summarises the results of recent BGS geological and geophysical surveys across the same area. Integration and interpretation of these data led to follow-up surveys in the Black Combe area which are reported in Part 2.

The area was selected for investigation following an appraisal of the mineral potential of the Lake District, which suggested that the ground adjacent to the southern margin of the Lake District batholith was favourable for gold and possibly tungsten mineralisation.

A roughly triangular area was selected for the reconnaissance drainage survey, covering mainly the massif which takes its name from Black Combe, its highest peak, and part of the neighbouring Dunnerdale Fells. The northern boundary follows a line between the Esk estuary, Devoke Water, Seathwaite and Torver, south-west of Coniston. The western side is bounded by the Irish Sea and the south-eastern boundary follows the Duddon estuary and the road from Broughton in Furness to Torver (Figure 1).

The coastal strip and Duddon estuary area are low-lying, but the land rises steeply to 600 m on the Black Combe massif and the undulating upland to the south of Eskdale. In the east, rough hills to the east of Dunnerdale rise to over 800 m towards Coniston Old Man. Most of the upland is used for sheep grazing, but in the lower ground some arable farming is practised. Most of the area lies within the boundary of the Lake District National Park.

Superficial deposits, associated mainly with the Pleistocene glacial episode, cover much of the northern part of the area and the coastal strip, where till, moraine and fluvio-glacial sediments related to both Lake District and Irish Sea ice are found. Glacial erosion has stripped much of the higher ground to bedrock.

The area is composed largely of sedimentary and volcanic rocks of Ordovician age cut by several minor intrusions and underlain to the north by the Lake District batholith. Small quantities of base metals were extracted from a number of small mines in the area and at one site pyrite was extracted for use in sulphuric acid manufacture. Hematite mines were sited on the fringes of the area, some of which operated until after the Second World War. Quarrying for slate has taken place at several sites in the area, notably in the Borrowdale Volcanic Group near Ulpha, but extraction is now restricted to one quarry at Broughton Moor. A roadstone quarry is operating at Ghyll Scar, Millom Park, also in the Borrowdale Volcanic Group outcrop.

The area is covered by Ordnance Survey 1:50 000 sheet 96, Barrow-in-Furness and South Lakeland area. British Geological Survey (BGS) coverage is available at 1:50 000 scale for parts of the area, combined sheet 37 and 47 covers Gosforth and Bootle, and sheet 38, Ambleside, will be available shortly. Old Series 1:10 560 sheets 98NW, 99SE and 99SW cover the remainder of the area. In addition, the area north of Ulpha is covered by a new 1:25 000 scale geological sheet, SD 19, Devoke Water and Ulpha.

Regional geochemical and geophysical survey data are available. The regional geophysical data comprise the results of a gravity survey (Institute of Geological Sciences, 1977) revised in 1984 (Lee, 1984), and an airborne magnetic survey (Institute of Geological Sciences, 1978). Both datasets are available in digital form (Smith and Royles, 1989). The results of a rapid regional geochemical stream survey of England and Wales, carried out by staff and students of Imperial College, were published in 1978 (Webb, 1978). The BGS Geochemical Survey Programme subsequently covered the area in more detail and the results are now available in an atlas with accompanying explanation and in digital form from BGS (British Geological Survey, 1992).

Previous research

In 1871-2, the area was surveyed at six-inch scale by W T Aveline and A G Cameron and the results published at one inch scale in 1882. A partial revision was made by W C C Rose in 1932. New mapping at 1:10 000 scale of the Lake District is now in progress and the Ulpha-Coniston area has been completed. The first results have been published at 1:25 000 scale (British Geological Survey, 1991) and the derived 1:50 000 scale Ambleside sheet (British Geological Survey, in press) will be available shortly.

An overview of the geology of the Lake District was provided by Moseley (1978). Within this compilation are chapters summarising information on intrusions (Firman, 1978), the Skiddaw Group (Jackson, 1978), the Eycott and Borrowdale volcanic rocks (Millward, Moseley and Soper, 1978), the Windermere Supergroup (Ingham and others, 1978) and the deep structure (Bott, 1978). Since this summary there have been many new contributions to our knowledge of Lake District geology, some including data for the survey area. These contributions, many of which arise from the BGS mapping programme, include information on the structure and stratigraphy of the Skiddaw Group (Webb and Cooper, 1988; Hughes and others, 1993), the volcanism represented by the Borrowdale Volcanic Group (Branney, 1988; Petterson and others, 1992), the age, geochemistry and form of the granitic intrusions (Rundle, 1981; O'Brien and others, 1985; Firman and Lee, 1986), the tectonic setting of the Windermere Supergroup (Kneller, 1991), the metamorphism (Fortey and others, 1993), the deep structure as deduced from geophysical modelling (Lee, 1986; 1989) and the tectonic setting (Soper and others, 1987; 1992; Kneller and Bell, 1993; Cooper and others, 1993; Kneller and others, 1993).

Only Helm (1965; 1969), who remapped the area, and Rushton and Molyneux (1989), who presented fossil evidence for the age of the rocks, have presented geological data specifically on the Black Combe inlier.

McAllister (1979) conducted a geochemical survey of the south-western part of Lake District which primarily involved the collection and analysis of stream sediments samples. The results led to the more detailed examination of metal anomalies in three catchments: Goat Tarn Beck [27 96]* (As, Bi, Cu, Mo, Pb), Whillan Beck [18 02] (U) and Crookley Beck [12 88] (As, Co, Pb). In all three cases it was concluded that drainage anomalies might be caused by appreciable mineralisation. The results from Whillan Beck were summarised in a short paper (McAllister, 1980).

With the exception of alteration and mineralisation within the Eskdale Granite and Granodiorite (Young, 1985a; 1985b; Young and others, 1986; 1991), little has been published on specific mineral occurrences within the survey area. Old mines in the area were inexplicably omitted from special reports on the mineral resources of Britain published in the 1920s (e.g. Dewey and Eastwood, 1925). Young (1987) published a glossary of the minerals of the Lake District in which several localities within the survey area are mentioned under individual minerals, and Adams (1988) provides a useful

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* National Grid Reference, all sites lie within 100 km square SD (34)

but incomplete list of mine workings with some details of each. Stanley and Vaughan (1982) discussed the metallogenesis of all Lake District mineral deposits and classified them on the basis of mineralogy and age. The only deposit mentioned in the survey area, the copper mine at Ulpha, was believed on the basis of its mineral paragenesis to have formed during an early Devonian mineralising event. The BGS Geochemical Survey Programme data for As, Sb and Bi in the Lake District were examined using image processing methods by Plant and others (1991) who concluded that gold mineralisation in the Lake District was associated with the Lower Devonian mineralising event, and inferred that there was a strong possibility of finding gold mineralisation within the survey area.

The hematite mining on the periphery of the survey area has received much attention. Smith (1924) and Rose and Dunham (1977) provide detailed descriptions.

Selection of the survey area

As part of a re-assessment of the mineral potential of the Lake District, the Skiddaw and Borrowdale Volcanic groups were identified as potential hosts for base and precious metal mineralisation and the southern margin of the Lake District as a particularly favourable area for vein-style fracture-controlled mineralisation. The reasons for this conclusion included (i) geophysical, geochemical and mineralogical work which suggested that widespread alteration in the Skiddaw Group was associated with fluid movement probably driven by heat from granitic intrusions; (ii) the presence of a major geophysical lineament, possibly related to a deep seated fracture; (iii) unexplained metalliferous enrichments in reconnaissance stream sediment survey data; (iv) indications from old maps and other sources that mineral working had been more extensive in the area than was indicated from most publications; (v) geological parallels with south-east Ireland; and (vi) a geological setting favourable for "slate belt" turbidite-hosted gold mineralisation.

GEOLOGY

Lower Palaeozoic rocks occupy most of the survey area (Figure 2). West of the Haverigg Fault, sandstones and shales of Permo-Triassic age are preserved, but this outcrop is mostly drift covered and is excluded from this survey.

The three main lithostratigraphic divisions of the Lake District Lower Palaeozoic Inlier - the Skiddaw Group, Borrowdale Volcanic Group and Windermere Supergroup - are represented in the area. The oldest rocks, part of the Skiddaw Group, comprise mainly mudstones and siltstones of Arenig age. Their outcrop is commonly referred to as the Black Combe inlier. The Skiddaw Group is overlain by a thick succession of volcanic rocks, the Borrowdale Volcanic Group, which outcrops in the north and east of the area and is separated by an unconformity from the upper Ordovician and Silurian sedimentary rocks of the Windermere Supergroup which form the south-eastern margin of the area (Figure 2). The Lower Palaeozoic succession is intruded by a composite granitic batholith (Lee, 1989). Some of the component intrusions are seen at outcrop and one of these, the Eskdale Granodiorite, is exposed in the north-west of the survey area. Much of the batholith is concealed beneath the Borrowdale Volcanic Group, although geophysical data shows that its south-eastern margin runs through the survey area at depth in an east-north-east–west-south-west direction, close to the line of the sub-Windermere Supergroup unconformity.

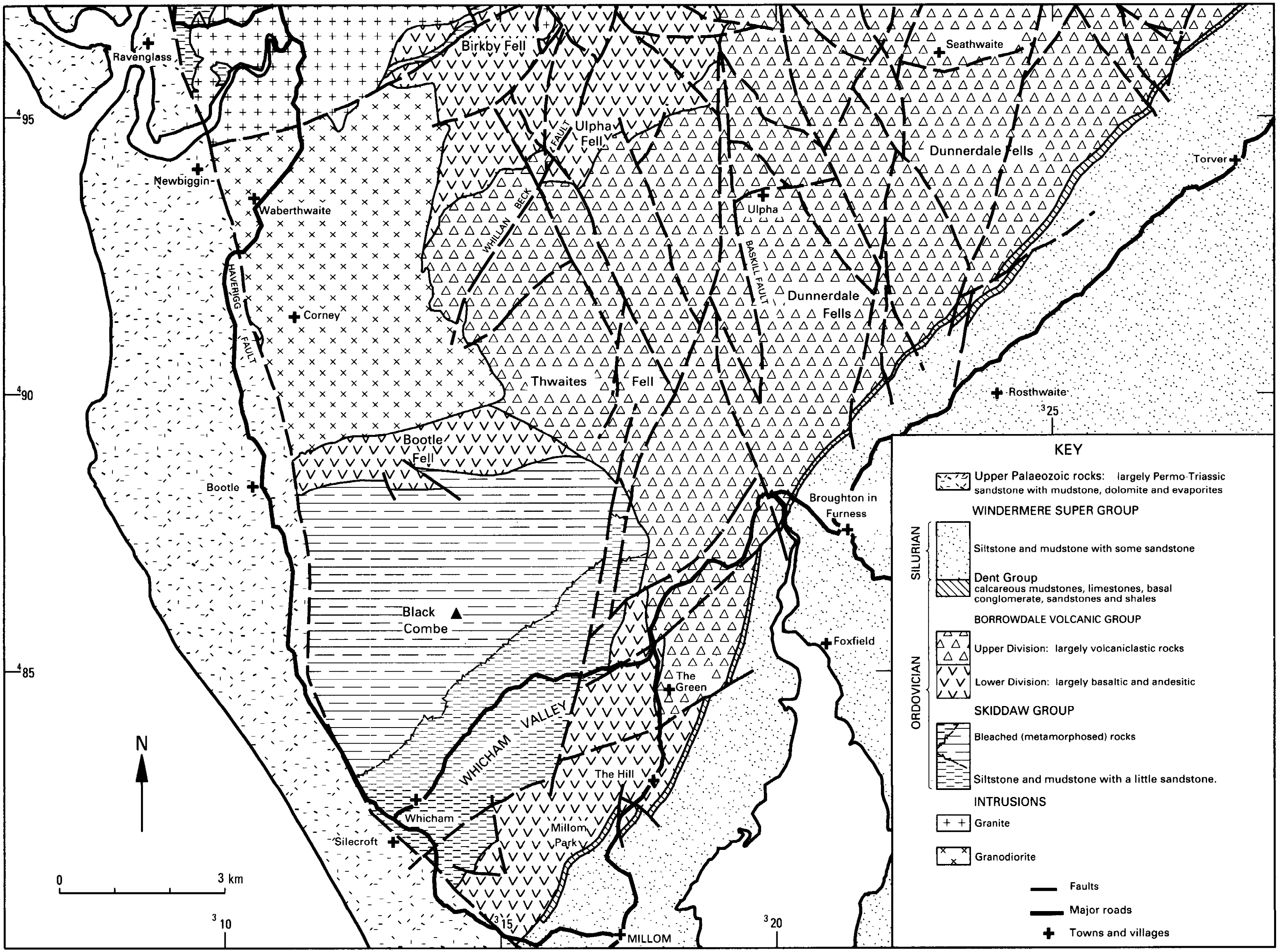

Figure 2 Simplified geological map of the survey area

Tectonic setting and evolution of the Lower Palaeozoic rocks

The Lake District Lower Palaeozoic inlier lies immediately south of the Iapetus suture and, along with other inliers in northern England and Ireland, the rocks of the area record the early Palaeozoic history of the northern margin of a microcontinent known as Eastern Avalonia. This terrane, rifting away from Gondwana, migrated northward during the Ordovician as intervening Iapetus oceanic crust was consumed. Eventually it accreted to Laurentia and was deformed in the early Devonian during the Acadian orogeny (Soper and others, 1992).

The Lower Palaeozoic rocks of the Lake District can be divided into three distinct stratigraphical belts separated by long-lived east-north-east-trending crustal fractures (A H Cooper and others, 1992). Division between the northern and central belt is along the Crummock Water line (Cooper and others, 1988; Cooper and Molyneux, 1990). The central and southern belts are separated by the Southern Borrowdales Lineament (Lee, 1989). This structural feature is largely coincident with the sub-Windermere Supergroup unconformity, running close to the south-east margin of the survey area, along the Whicham valley and through Broughton in Furness and Torver (A H Cooper and others, 1992). To the north of the Southern Borrowdales Lineament, the Skiddaw Group is overlain by a thick succession of the Borrowdale Volcanic Group, whereas to the south either an attenuated volcanic succession is present, or the Skiddaw Group is overlain directly by the Windermere Supergroup.

The Skiddaw Group rocks were deposited in a deep clastic marine environment on the continental margin of Eastern Avalonia, during the Tremadoc, Arenig and Llanvirn epochs, in a southern palaeolatitude (McKerrow and others, 1991).

The change to sub-aerial calc-alkaline volcanism (Borrowdale Volcanic Group) in the mid-Ordovician represents a fundamental change in tectonic setting to one of probable southerly dipping subduction associated with the northward migration of Eastern Avalonia. Widespread uplift of the Skiddaw Group occurred while the descending buoyant, oceanic lithosphere extended the overlying continental crust, caused partial melting and produced the calc-alkaline magmas. Increasing rates of crustal extension allowed the segregated magmas to rise and eruptions occurred on the irregular surface of an emergent arc on the continental margin of Eastern Avalonia. Volcano-tectonic collapse and emplacement of a sub-volcanic batholith followed. The remnants of the multi-centred volcanic field, represented by the Borrowdale Volcanic Group, are now preserved in a regional rift zone. Slowing rates of subduction and reducing extension caused volcanism to wane. The ensuing regional subsidence is marked by a marine transgression that defines the base of the overlying Windermere Supergroup.

The unconformity at the base of the Windermere Supergroup is a product of regional subsidence and marine planation rather than an orogenic feature (Branney and Soper, 1988). The rocks record a transition from shore-face, through a mixed carbonate/clastic shelf and deep shelf to a deep clastic depositional environment. Basin analysis indicates that the rocks were deposited in a foreland basin that lay ahead of a southward prograding thrust belt initiated during the collision of Avalonia and Laurentia and the subduction of Avalonian continental crust beneath Laurentia (Kneller, 1991).

By the close of the Silurian, the effects of continental collision began to influence deposition in the foreland basin. Subsidence rates declined and sedimentation occurred within a progressively shallowing basin. Penecontemporaneous deformation of the sedimentary succession occurred during basin inversion as the deformation front continued to prograde southwards, marking the onset of the late Caledonian (Acadian) orogeny. Marine conditions then gave way to a terrestrial environment during regional uplift. Deformation produced typical slate belt structures, folds, cleavage and minor thrusts that indicate regional sinistral transpression (Soper and others, 1987).

The most intense deformation occurs in a 10 km wide zone of steeply dipping rocks that form the south-eastward facing limb of a regional north-east-trending fold structure, the Westmorland Monocline (Kneller and Bell, 1993). These authors consider the monocline to have formed early in the local Acadian deformation sequence and to accommodate at least 8 km (the thickness of the Windermere Supergroup) of uplift. It coincides with the steep south-east margin of the Lake District batholith and the Southern Borrowdales Lineament. Kneller and Bell (1993) illustrate the structure in terms of a south-dipping back thrust and consider that the monocline is characteristic of a mountain front that formed in response to south-eastward vergent thrusting. The model shows displacement taking place on a gently north-westwards dipping ramp that remains mostly concealed beneath the central Lake District and in a flat detachment beneath the Windermere Supergroup. The deepest levels of the monocline now exposed occur in the Skiddaw Group rocks of the Black Combe inlier.

Components of the batholith were emplaced in at least two phases, of which the earlier is pre-Wenlock (c. 430 Ma) in age and may be associated with subduction. The later phase occurred at the close of the Silurian or early in the Devonian period, associated with the Acadian orogeny. Kneller and Bell (1993) argue that the Shap Granite, one of the later group, was emplaced after monocline formation and close to the time of cleavage formation.

Lithostratigraphy

Skiddaw Group

A lithologically uniform succession of siltstones and mudstones comprises most of the Skiddaw Group in the Black Combe Inlier (Figure 2). Colour variations offer the only practical method for subdivision, but in the most recent survey (Johnson, 1992) the tripartite division of Helm (1965; 1969) could not be substantiated and a bipartite division into dark and pale types was made. The boundary between the two is gradational and it was established that this colour variation was not related to lithological variation, but was caused by metasomatic alteration similar to that described at Crummock Water (Cooper and others, 1988). This conclusion explains why the earlier stratigraphic classification based on colour and lithology (Helm, 1965; 1969) produced complicated outcrop patterns that appeared to have no stratigraphic order. Bedding is generally poorly defined and obscured by penetrative cleavage. Where clearly discernible, such as on Seaness, north of Whicham, it reveals that the strata are deformed in small to medium scale folds and that there is no significant consistency in the direction and amount of dip. This, in conjunction with possible strike faulting and thrusting, makes any estimate of the true stratigraphic thickness of the Skiddaw Group in the Black Combe inlier speculative, but it is probably in excess of 500 m. Fossil evidence (Rushton and Molyneux, 1989) indicates a late Arenig age.

Borrowdale Volcanic Group

This group comprises a dominantly sub-aerial, calc-alkaline, basalt to rhyolite volcanic sequence at least 6000 m thick. The stratigraphy of the group is extremely complex, and a detailed description of the formations present in the multi-centred volcanic field is beyond the scope of this report. A broader view reveals that the succession is divisible into lower and upper divisions (Moseley and Millward, 1982). These represent pre-caldera effusive and caldera-forming explosive stages in the evolution of the volcanic field (Petterson and others, 1992).

Lower division. This consists essentially of basaltic and andesitic sheets that formed numerous low-relief shield cones in the volcanic field. The succession, up to 3 km thick, crops out in the north and south of the area. The northern crop lies within the inferred regional rift zone and the southern one to the south of the Southern Borrowdales Lineament.

In the northern outcrop the strata, bounded to the north-west by granitic intrusions, strike north-east and dip southwards, generally at angles between 50° and 70°. The contact with the Eskdale Granite in the north is broadly concordant, while the contact with the Eskdale Granodiorite in the west is markedly discordant.

In the southern outcrop, on the south side of the Whicham Valley, the rocks of the Lower Division also strike north-east. The dip varies from 30° to 60° to the south-east. At the base of the succession, the volcanic rocks are intercalated with silty mudstones overlying the Skiddaw Group. These silty mudstones are not as strongly deformed as similar lithologies in the Skiddaw Group and the deformation style is similar to that found in younger strata.

Upper division. The upper part of the Borrowdale Volcanic Group consists of a succession of andesitic, dacitic and rhyolitic pyroclastic rocks with interbedded remains of volcanogenic sedimentary rocks. In this area it is of above average thickness, and is the most complete succession found so far in the current mapping of the Lake District. Up to 6 km are preserved in a caldera basin on the hanging wall side of the inferred regional rift zone adjacent to the Southern Borrowdales Lineament; this structure is also known as the Ulpha or Duddon Basin. The enhanced rates of subsidence in the basin are illustrated by the presence of the only proven marine intercalation in the subaerial Borrowdale Volcanic Group succession. This is the Holehouse Gill Formation, a sequence of up to 450 m of dark grey mudstone, siltstone and sandstone of probable Caradoc age (Molyneux, 1988). A much thinner succession of volcaniclastic rocks is present to the south of the Southern Borrowdales Lineament.

Windermere Supergroup

The lithostratigraphy of the marine sedimentary rocks formerly referred to as the Windermere Group (Moseley, 1984; Cocks and others, 1992) has recently been revised and given Supergroup status (Kneller and others, in press). The mixed carbonate and clastic rocks of Upper Ordovician age at the base of the succession form the Dent Group, the distinctive anoxic and oxic mudstones of Llandovery age, the Stockdale Group, and the thick succession of turbiditic sandstones of Ludlow age, the Coniston Group. Most of the remainder of the 8 km thick Supergroup consists predominantly of laminated hemipelagic siltstones in which other lithologies are recognised as formations.

The lower part of the group outcrops in the south-east of the area, where the strike is north-east and the strata dip to the south-east at 60° to 80°. The basal beds rest unconformably on the Borrowdale Volcanic Group, the discordance being greatest in parts of the Ulpha Basin where the strikes of the two groups are at 90°. The Dent Group succession within the study area is of Ashgill age and consists of fossiliferous, calcareous siltstone and limestone with interbedded conglomerate, sandstone, dark siltstone and pyroclastic rocks; several non-sequences are present and indicate periods of marine regression. The group records the transition from a shoreface situation through a storm-dominated, mixed carbonate clastic, shallow shelf into a deep shelf environment (Kneller, 1991). Graptolite faunas and lithologies in the overlying Silurian strata signify virtually continuous deposition in a deep clastic marine environment.

Intrusive igneous rocks

Granitic plutons

Two component intrusions of the Lake District granitic batholith are exposed in the area, the Eskdale Granite and, along the northern margin of the survey area, the Eskdale Granodiorite (Firman, 1978; O'Brien and others, 1985). Field (Johnson, 1992) and geophysical (Lee, 1989) evidence indicate that further intrusions may be present at shallow depth beneath the Skiddaw Group in Black Combe.

The Eskdale Granite is lithologically variable. Medium to coarse grained perthitic granites predominate, but there are also large areas of aphyric and porphyritic microgranite. Contacts between lithologies are complex. Most commonly they are diffuse but sharp and chilled contacts are present locally. The less well exposed Eskdale Granodiorite appears to be lithologically more uniform. It is typically medium grained, with abundant biotite and amphibole as well as mafic xenoliths. The relationships between the granite and granodiorite are unclear because no contacts between them are exposed and they yield isotopic ages that are identical within error (429 ± 4 Ma; Rundle, 1979). There is a broad thermal metamorphic aureole associated with both intrusions, with the biotite zone extending up to 2 km into the country rocks. The outer amphibole zone has diffuse, ill-defined limits. Slivers of hornfelsed Skiddaw Group and the width of the metamorphic aureole suggest that the granite penetrated as far as the base of the volcanic succession.

Both the granite and granodiorite are pervasively altered and, locally, the granite carries a spaced cleavage related to the Acadian deformation. Besides almost universal chloritisation of biotite and saussuritisation of plagioclase, there are areas of strong argillic alteration of uncertain origin within the granodiorite (Young and others, 1986). These may be associated with late-stage hydrothermal processes or represent areas of deep Mesozoic or Tertiary weathering. The granite is affected widely by sericitisation of feldspar and chloritisation of biotite, and locally by hematisation and tourmalinisation. Greisens containing topaz and mica (Young and others, 1988) are present near the margins of the granite.

In the northern part of the Black Combe inlier, field evidence from BGS mapping and MRP work reported below suggest that there is a buried, evolved granitic intrusion in the vicinity. This evidence includes the bleaching and induration of the Skiddaw Group rocks, the outcrop locally of quartz-tourmaline veins and minor granitic intrusions, and the presence of quartz veins with minerals typical of high temperature granite-related mineralisation.

Minor intrusions

Several suites of minor intrusions, predominantly dykes, are present in the Lower Palaeozoic rocks. Four groups were distinguished in the Skiddaw Group by Johnson (1992) during mapping in the Stoupdale area: basic, intermediate, granodioritic and altered intermediate-basic types. The basic and intermediate types are highly altered rocks, in which all the mafic minerals are replaced by chlorite and feldspar by sericite. They are more strongly deformed than the other two groups and are possibly related to, or pre-date, the uplift of the Skiddaw Group. The petrography of the altered intermediate-basic type suggests an affinity with the Borrowdale Volcanic Group. The variably altered granodiorite type are mostly cleaved and therefore pre-date the main Acadian cleavage; some are probably associated with the emplacement of the granite batholith.

Tholeiitic basalt and dolerite dykes are present in the Borrowdale Volcanic Group, some pre-date and others post-date the Eskdale Granite (Macdonald and others, 1988). Andesitic and basaltic sills as well as rhyolitic dykes, representing intrusive components of the volcanism, are also present.

Microgranite dykes, related to the end-Caledonian episode of granitic emplacement, occur in the Borrowdale Volcanic Group as well as the Skiddaw Group. In the classification of minor intrusions adopted in the Stoupdale area these formed part of the granodiorite suite. A few lamprophyre dykes of uncertain affinity are also found intruded into the Lower Palaeozoic strata.

Superficial deposits

There is an extensive cover of Pleistocene and Recent superficial deposits, most of which are the products of subaerial erosional processes that operated during and after the Devensian glacial period. Older superficial deposits may be present beneath this cover, particularly over those parts of the Borrowdale Volcanic Group and Eskdale Granite that form the interfluve between the Duddon and Esk rivers; an area which appears to have escaped glacial erosion. However, there is no positive evidence of multiple glaciation and no more than one lodgement till appears to be present.

Glacial till (Boulder clay)

Glacial till of varying thickness covers much of the area. The silty matrix of the till supports abundant pebbles, cobbles and boulders and irregular bodies of gravel may be present locally. The till was deposited from ice sheets that emanated from two different centres, the Central Lake District and the Irish Sea. The boundary between the two ice sheets was approximately along the watershed between Devoke Water and Black Combe. The till in the former area is wholly local in origin, whilst in the latter, erratics whose source is in southern Scotland are also present. There was probably little ice movement at the boundary of the two sheets and this may, in part at least, explain the subdued topography and more extensive superficial deposits on the high ground in the Duddon-Esk interfluve.

Moraine

Areas of moraine, ill-sorted and generally clast-supported mixtures of angular to subrounded pebbles and cobbles in a sandy matrix, are distinguished by their moundy surface topography. The deposits represent accumulations of debris, some of which may have been reworked by water, from the decaying ice sheet. The most extensive deposits occur to the west of the watershed between Devoke Water and Black Combe, north of Crookley Beck.

Head

Regoliths of rock fragments that are present at the rockhead surface are classified as head. These develop in-situ, but on steeper slopes may move slowly down hill under the influence of gravity. The deposits are thin, rarely exceeding 5 m in thickness, and have been produced by weathering in glacial and post-glacial times.

Alluvial deposits

These sediments consist of gravel, sand, silt and clay and are present adjacent to rivers and streams. Coarser material, sometimes being reworked, is present locally in small terraces adjacent to upland streams. The most extensive deposits occur in the lower reaches of the larger rivers.

Peat

This organic deposit occurs as an extensive blanket on high ground throughout the area. Elsewhere patches are present in hollows and on benches. Generally it overlies till, but locally it occurs on other superficial deposits or rests directly on the rockhead.

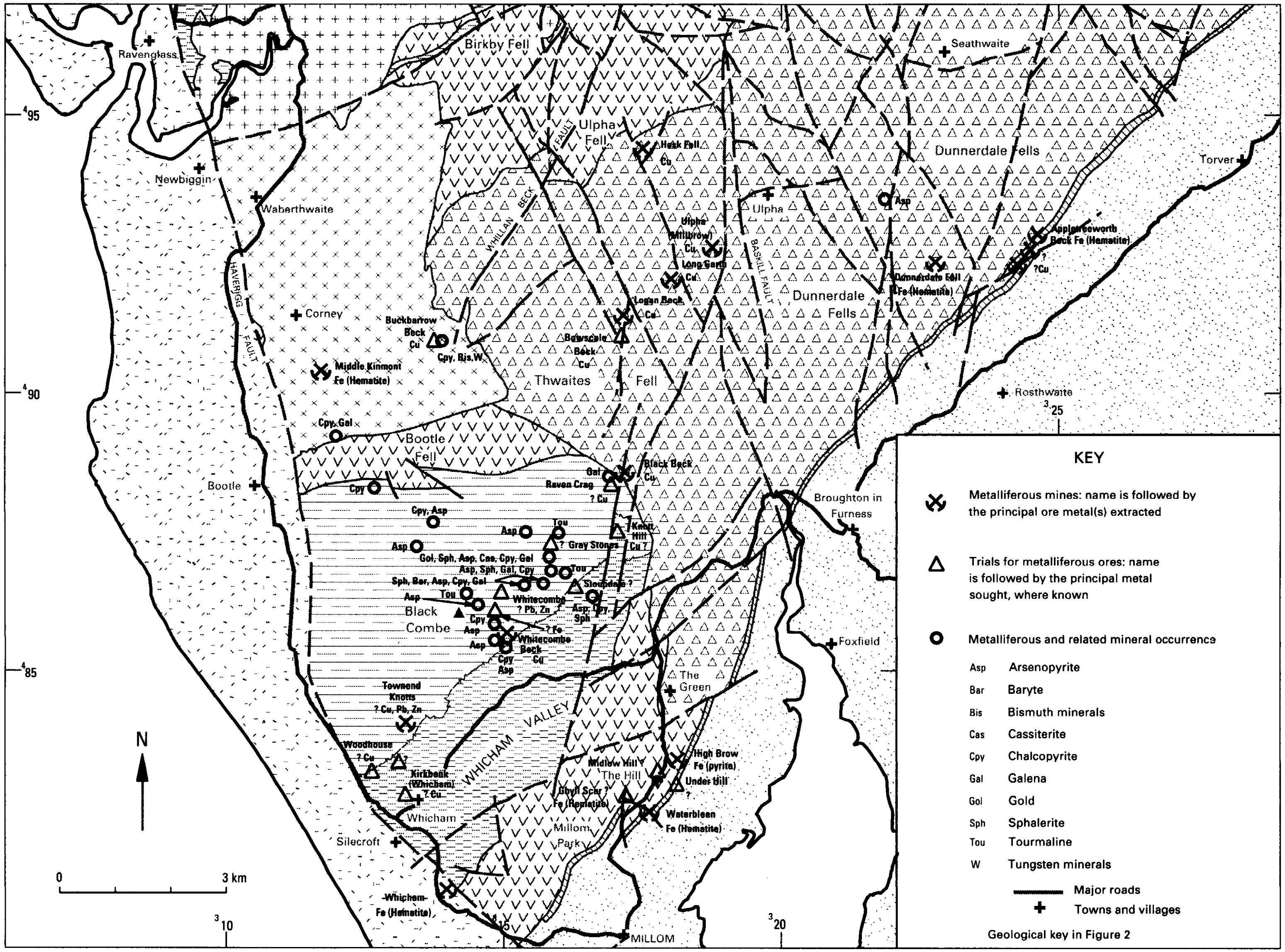

Figure 3 Location of metalliferous mines, trials and other metalliferous mineral occurrences

Lacustrine deposits

The floor of the Whicham valley is covered by clay and silt deposited in a Devensian glacial lake. Fans and other glaciofluvial deposits are also found in the valley (Boardman, 1985).

MINERALISATION

Very little has been written about the mineralisation of the survey area (see Previous Research) and little is known about metalliferous mining that took place in the Ulpha and Black Combe areas. Sites of former trials and workings are shown on Ordnance Survey and Old Series Geological Survey maps as shafts, quarries and adits. These were visited during the course of the geological mapping and the geochemical drainage survey to gather information on the extent of the workings, the structures tried and the metals sought. During this work, several unrecorded metalliferous mineral occurrences and old workings were found. Samples from tips and mineralised structures were collected and most were analysed for a wide range of elements to confirm visual identification of the principal minerals and to determine any associated metalliferous enrichments. Listings of all the mineral workings and metalliferous mineral occurrences located during this survey are contained in Appendices 1 and 2 with summary details of the metal anomalies and minerals recorded during the drainage survey in Appendix 3. Additional information on an element-by-element basis is given below. Details of the lithogeochemical sampling from the follow-up survey and the mineralogical examination of these rocks will be given in Part 2.

Hematite workings, forming part of the South Cumberland iron ore Mining Field which lie within the survey area are shown on Figure 3 and briefly described and listed in the Appendices, but were not investigated in detail.

Mineral workings

Most of the workings and trials appear to have been made for copper in quartz-vein structures, probably stimulated by the exploitation of the copper mineralisation at Coniston. In most cases the veins tried are polymetallic and it is possible that the miners did not know that, for example, tungsten minerals occur in the Buckbarrow Beck occurrence (Young and others, 1986). At High Brow, pyrite was extracted in the last century and used as a source of sulphur in sulphuric acid manufacture. Other, small, diggings where pyrite appears to be the only mineral present could represent exploration for further deposits of this type, e.g. Horse Back [149 860].

One name, Leadmine Breast, in Stoupdale, could not be related to any trace of working. A round excavation, resembling a bell pit, discovered in the valley below may have been a trial but there was no evidence of any mineralisation in the excavated material. A number of other excavations were found where the reason for the working was uncertain. Notable amongst these were small excavations in weakly mineralised rock near paths which may either have been small trials or road metal quarries, for example on Gray Stones [160 871]. The presence locally of slate quarries with adit levels, e.g. in Hentoe Beck or Stainton Ground has caused some confusion on maps and in manuscripts. In one case, on The Pike, Ulpha, such an adit is marked as 'Copper Mines (dis)' on Ordnance Survey maps.

Where seen, the worked or tried veins appear to be relatively narrow, usually 1 to 2 m wide. Veins commonly occupy northerly to east-north-east (Caledonian) trending fractures and in Black Combe most follow the northerly dipping cleavage of the Skiddaw Group host rocks.

There are few production records for mines in the survey area, but most if not all are believed to have been small, each producing no more than a few hundred tons of ore.

Mineral occurrences

Appendix 2 lists the principal mineral occurrences discovered or verified during the reconnaissance drainage survey. Minor pyrite occurrences, typically weak disseminations in sedimentary and igneous rocks or quartz veins carrying small amounts of pyrite, have been omitted from Appendix 2. Appendix 3 lists rock samples collected for verification purposes. With the exception of disseminated pyrite and replacive hematite in limestone, all the mineralisation recorded in the survey area is vein-style. Mined, tried and other mineral occurrences are reviewed below on an element-by-element basis.

Antimony
No antimony minerals were recognised during this survey and none have been recorded previously. However, high levels of antimony (>500 ppm) were recorded in a few mineralised rock samples, notably from Stoupdale in a gossan [157 866] and a carbonate-quartz-sulphide vein [161 867] (WCR 992 and 986, Appendix 3).

Arsenic
Arsenopyrite occurs commonly in quartz veins throughout the survey area and arsenic shows enrichment in a greater number of analysed rock samples than copper, lead or zinc. Arsenopyrite is found with pyrite in small vein structures in the Black Combe massif, for example in Hentoe Beck [133 873], Grassgill Beck [136 876] and Stoupdale Crags [154 871], and at an isolated occurrence in the Borrowdale Volcanic Group at Stainton Ground [220 934]. More commonly, it is found with pyrite in polymetallic, sometimes polyphase, quartz-sulphide veins with one or more of chalcopyrite (e.g. Whitecombe [151 855]), galena (e.g. Stoupdale [157 866]), sphalerite (e.g. Townend Knotts Mine [132 840], cassiterite (Stoupdale [159 868], tungsten minerals (Buckbarrow Beck Trial [137 910]), bismuth minerals (e.g. Ulpha Mine [184 922]), erythrite (Hesk Fell Mine [175 941]) and fluorite (Whitecombe Trial [148 863]).

Barium
Baryte was only recorded at two localities. At Waterblean Mine [176 825], it occurs in association with hematite in altered Dent Group limestone, and at an outcrop in Stoupdale [159 868] it occurs associated with galena in a polyphase, polymetallic vein structure in altered Skiddaw Group silty mudstones. Baryte was also identified in a few mineralised float blocks in the Stoupdale area, where textural evidence suggests that baryte it is a late fracture infill.

Bismuth
Bismuth minerals have been reported previously from two mineralised structures in the survey area. In Buckbarrow Beck [137 910; 136 909], Young (1985b) notes the presence of argillic alteration in the Eskdale Granodiorite and the presence of quartz veining which carries copper and tungsten minerals as well as the supergene bismuth minerals, russellite and bismutoferrite. The area is largely drift covered and these deposits may hide further veins in the vicinity. Bismuth minerals were also noted on the tips at Ulpha (Millbrow) Mine [186 924] in association with chalcopyrite and arsenopyrite (British Geological Survey, 1991).

Minor amounts of unidentified secondary bismuth minerals were found in tip samples from the workings on Townend Knotts [132 840]. Pyrite, arsenopyrite, chalcopyrite, galena and sphalerite also occur in the tips from these workings. Bismuth was also recorded in relatively large amounts

(>500 ppm) in quartz-sulphide veins from Whitecombe, Whicham and Stoupdale Beck within the Skiddaw Group outcrop and from Hesk Fell within the Borrowdale Volcanic Group (Appendix 3).

Cobalt

Erythrite has been found in small amounts on the tips at the Hesk Fell mine [175 941] (Young, 1987) and at Wood House Trial [125 831]. In addition, during mineralogical studies minute grains of a Co-S mineral in a 1 mm wide fracture in a quartz-sulphide veined mudstone were recorded from the tips of the Townend Knotts workings. At all three localities high (>500 ppm) levels of Co were reported in analysed samples and cobalt is associated with quartz-pyrite-arsenopyrite-chalcopyrite mineralisation (Appendix 3).

Copper

Vein-style copper sulphide mineralisation is widespread in the survey area and most of the mines and trials appear to have been started for copper. Chalcopyrite is the dominant copper mineral and other copper-rich phases are rare.

Judged by the size of the tips and number of shafts or adits it appears that the larger copper workings were Black Beck, Hesk Fell, Logan Beck, Ulpha (Millbrow), Townend Knotts and Whitecombe Beck (Appendix 1). In some places, for example Black Beck, chalcopyrite occurs with quartz and only minor amounts of other sulphides except pyrite, whereas in others, such as Townend Knotts, chalcopyrite is accompanied by equal or greater amounts of a number of other sulphide minerals, typically arsenopyrite, galena and sphalerite with traces of bismuth, tungsten or cobalt minerals (Appendix 3). The reasons for this variation are uncertain, but may be related to polyphase mineralisation. The differences appear unrelated to host rock and there is no clear spatial control. In Appletreeworth Beck, north-east-trending thrust faults intersect the sub-Windermere Supergroup unconformity and a short trial adit [242 922] has been driven into the fault zone. No sign of copper mineralisation is seen here, although the mudstones contain disseminated pyrite and some texts suggest that the trial was for copper.

Fluorine

Fluorite has been reported previously (Young, 1987) from the tip of a trial into a quartz-sulphide (galena, sphalerite, pyrite, chalcopyrite, arsenopyrite) vein in the catchment of Whitecombe Beck [148 863]. During this survey fluorite was found in a quartz-sulphide float block in Stoupdale Beck. This block, in addition to quartz and fluorite, contained pyrite, arsenopyrite, chalcopyrite, sphalerite and, probably, baryte. This block is probably not far removed from source, showing the typical bladed pyrite rimmed by arsenopyrite common in this area. In both cases, the textures and mineral assemblage suggest the presence of two episodes of mineralisation.

Gold

No gold occurrences were known in this area prior to the survey, the nearest being reports of small amounts in the Coniston mines, associated with cobaltite, silver and bismuth telluride (Young, 1987), but chemical analyses revealed that some polymetallic quartz-sulphide veins sampled during this survey contained gold. A diligent search of polished sections made from quartz-sulphide veins from the Black Combe area in which chemical analysis reported appreciable gold (>1 ppm) failed to reveal any grains of free gold, suggesting that most if not all is held within sulphide minerals. This work will be reported in more detail in Part 2.

Iron

Iron, in the form of pyrite, is widespread in the survey area. It occurs (i) sparsely disseminated and locally forming pods, aggregates and bands in the volcanic and sedimentary rocks, (ii) in quartz - chlorite veins, (iii) in quartz-polymetallic sulphide veins, and (iv) in a massive pyrite-quartz vein structure cutting highly altered Borrowdale Volcanic Group rocks at High Brow. Chemical analysis of a massive pyrite sample from the adit revealed the highest level of mercury (66 ppm) in any of the analysed rocks and appreciable amounts of arsenic, but only low levels of other metals were determined (WCR 758, Appendix 3).

Hematite was worked at five sites in the survey area, Dunnerdale, Appletreeworth Beck, Waterblean, Whicham and High Kinmont (Figure 3) but only Waterblean was sampled during this work. This deposit is formed in Upper Ordovician age limestones of the Dent Group and may be an extension of the mineralisation worked at Hodbarrow, Millom, once the largest hematite mine in Britain. The deposit is a flat with some veining in the limestone host (Smith, 1924). Analysis of Waterblean ore showed high levels of molybdenum (>50 ppm), arsenic (300–1000 ppm) and antimony (100–500 ppm; WCR 760, Appendix 3). In addition, there is baryte veining and some small trials along strike in the vicinity may have been for this mineral or hematite. Waterblean and Appletreeworth Beck are the only South Cumbria hematite occurrences hosted by the Upper Ordovician Dent Group.

Lead

Galena is distributed widely in quartz veins (Appendix 3). Other lead minerals were recorded rarely, but at Damkirk Beck [121 891], within the Eskdale Granodiorite, galena occurs in a quartz vein with chalcopyrite and supergene pyromorphite (Young, 1985b). With the exception of Townend Knotts [132 840] and the trial in Whitecombe Beck [148 863], worked or tried vein mineralisation contains less lead (as galena) than copper (as chalcopyrite) and some worked veins contain no galena. However, the polymetallic vein mineralisation found in Stoupdale Beck normally contains galena in association with pyrite, arsenopyrite, chalcopyrite and sphalerite, and analyses indicate that commonly the metal concentration in these veins follows the order Cu < Pb < Zn < As. A few weakly mineralised rocks are enriched in lead without copper or zinc, for example a quartz vein on Little Fell [121 866] and a quartz-veined rock at Swinside [168 884] carrying pyrite and galena (WCR 959 and 315, Appendix 3), but typically lead and zinc enrichment occur together in varying proportions.

Mercury

No cinnabar was seen during the survey and only a selection (38) of the rock samples collected during reconnaissance and follow-up surveys were analysed for mercury. Of these only WCR 757 and 758, both from the High Brow Mine [182 834], contained high (>500 ppb) levels of mercury (Appendix 3). One sample, containing 860 ppb Hg, consisted of quartz veined, pyritic altered host rock and the second, containing 66 ppm Hg, was massive pyrite with subordinate quartz and carbonate. All other rocks analysed contained <220 ppb Hg, mostly <100 ppb.

Molybdenum

No molybdenite has been reported from this area and molybdenum levels in analysed rock samples were low. The highest result was 61 ppm in weathered kidney ore from the Waterblean hematite working [176 825] (WCR 760, Appendix 3).

Nickel

No nickel minerals have been reported from the survey area and none were recognised during this investigation. However, a high (600 ppm) nickel content in the tip sample from the Woodhouse Trial

[125 831] (WCR 456, Appendix 3), associated with high cobalt, copper and arsenic, suggests the possible presence of cobalt-nickel sulpharsenide minerals, particularly as smaltite and niccolite have been reported from the Coniston mines (Russell, 1925).

Tin

Tin mineralisation has not been reported from this area previously, but cassiterite was found in panned concentrates collected in the Black Combe area during the drainage survey (see below) and, in the course of follow-up investigations, an in-situ occurrence, described in Part 2, was found in Stoupdale Beck [159 868] (WCR 954, Appendix 3).

Tungsten

Substantial tungsten anomalies, caused by the presence of wolframite and scheelite, were recorded in panned concentrates from Black Combe during the drainage survey (see below). These were investigated by follow-up surveys reported in Part 2. Wolframite and scheelite have been reported from Buckbarrow Beck, in quartz veins with copper and bismuth minerals [136 909, 138 912] (Young and others, 1986), but no new in-situ occurrences were found during this survey. Analysed rocks all contained moderate to low levels of tungsten (maximum 73 ppm).

Vanadium

At Buckbarrow Beck, russellite was found to contain trace amounts of vanadium, and additionally, the copper vanadate namibite has been recorded here (Neall and others, in press).

Zinc

Sphalerite is common in the survey area but no other zinc minerals were found (Appendix 3). Sphalerite always occurs with other sulphide minerals, most commonly galena. In the polymetallic quartz veins both are accompanied by arsenopyrite, pyrite and chalcopyrite with metal enrichment commonly in the order Cu < Pb < Zn < As. With the exception of Townend Knotts [132 840] and the trial in Whitecombe Beck [148 863], worked or tried vein mineralisation contains less zinc than copper and some of these veins contain little or no sphalerite. (e.g. Whitecombe Beck Mine [151 857]).

LINEAMENT ANALYSIS OF SATELLITE IMAGERY

The results from two independent studies of lineaments on satellite images covering the survey area were available for inclusion in this report. Both studies employed imagery in the form of hardcopy photographic prints produced after geometric correction, edge enhancement and contrast stretching of the digital satellite data. The first study, by the MRP, was based on the examination of a band 7 LANDSAT image recorded in June 1975 printed in black and white at 1:250 000 scale, and a 1:100 000 scale false-colour combination of bands 4, 5 and 7 from a Thematic Mapper scene obtained on 15 February 1984. The second study (Berrangé, 1991) also used the 1:100 000 February 1984 false colour image, together with a band 5 black and white print at the same scale and a later winter scene captured on 25 November 1989. Glacial features, which are very well displayed on the TM imagery, were omitted from both studies.

Comparison of the results from the two studies showed very good agreement on the location of lineaments that might be attributable to fractures and consequently the results have been combined to produce Figure 4. Discrepancies between the studies only occurred in the smaller features and could be attributed to: (i) faintness of linear feature, (ii) linear feature only visible on one image, (iii) linear

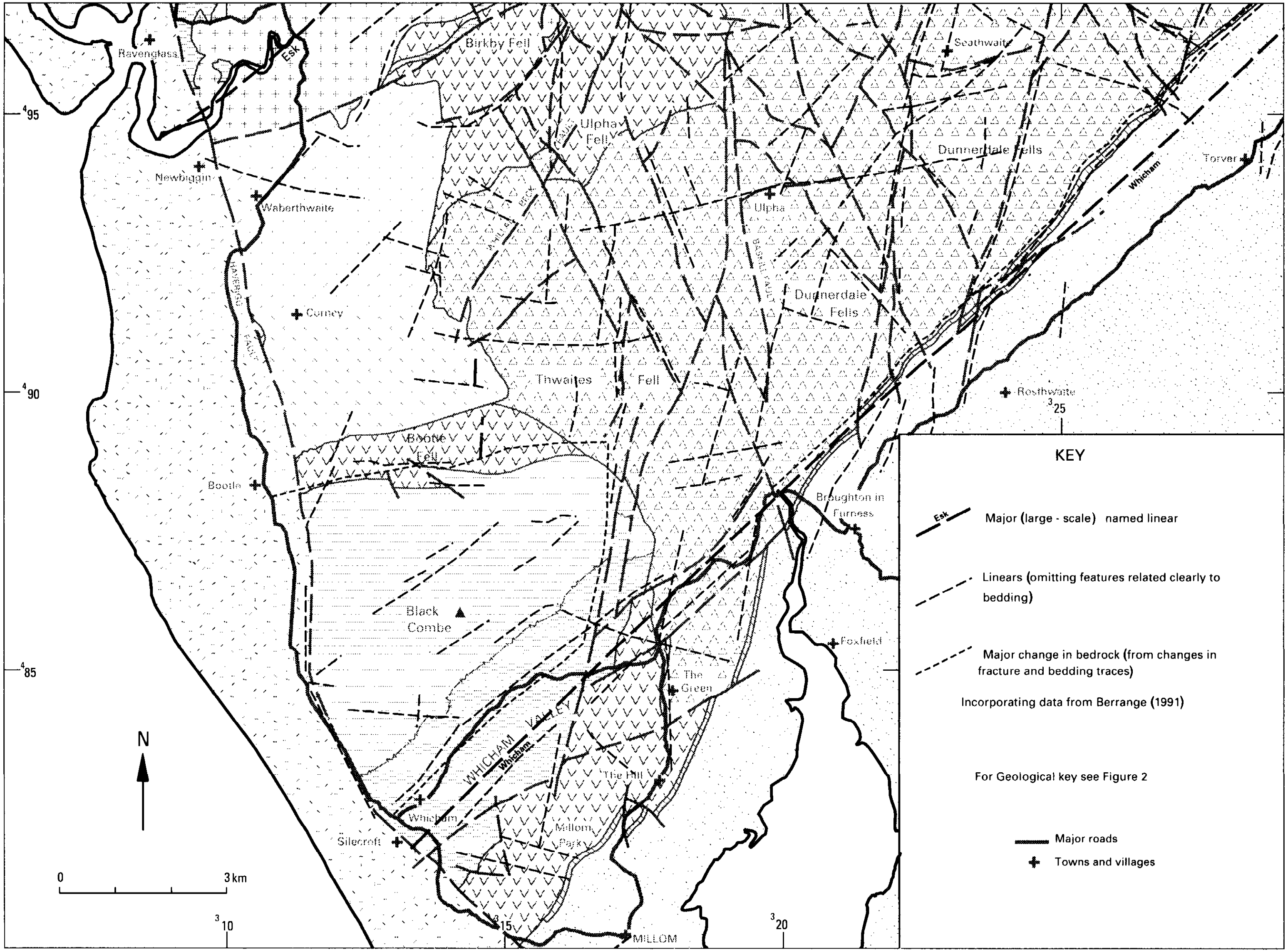

Figure 4 Linear features extracted from satellite imagery

feature believed to be enhanced or generated by human activity (e.g. road, edge of forest), and (iv) differences in interpretation of lineaments as fracture or bedding traces.

Major lineaments

Two major north-east (Caledonide) trending lineaments were identified crossing the survey area by both studies. These were named the Esk and the Whicham by Berrangé (1991). The Esk lineament, which only enters the survey area in the north-west where it runs along the Esk valley (Figure 4), is coincident with a ground mapped fault and a geophysical lineament derived from gravity data (Lineament 7 of Lee, 1989; Figure 5). Regional assessment of geological and geophysical data (Lee, 1989) suggests that other major north-east-trending lineaments, including the Whicham lineament, are probably of more profound geological significance in the development of the area.

There is no mapped fault coincident with the Whicham lineament but it is coincident within the survey area (Whicham Valley) with a regional geophysical lineament evident on images derived from both magnetic and gravity data (Lineament 9 of Lee, 1989; Figure 5). At its north-eastern end, to the east of the survey area, the Whicham lineament follows a major gravity feature called the Southern Borrowdales Lineament by Lee (1989). This feature, which shows clearly on Bouguer anomaly, residual gravity field and Bouguer anomaly second vertical derivative colour shaded images, is attributed to the density contrast between the Borrowdale Volcanic Group and Windermere Supergroup and is concordanr with the Westmorland Monocline. The Whicham satellite lineament and a sub-parallel offshoot to the north are coincident with the boundary between the Borrowdale Volcanic Group and Windermere Supergroup from near Broughton in Furness to north of Torver. It is probable that this line is the product of a major deep-seated fracture which developed early in the geological history of the region and, due to periodic reactivation, has had a profound influence on the geological history of the area (Lee, 1989). A H Cooper and others (1992), in a recent summary of the geology of the Lake District, supported this view and drew the western end of the boundary between the central and southern stratigraphical belts of Lower Palaeozoic rocks along the line of the Whicham lineament.

Other lineaments

There is good agreement between lineaments and mapped faults (Figure 4). As the lineaments were identified without reference to geological maps, it suggests that some of the lineaments that are not coincident with mapped faults may be related to fractures, particularly in poorly exposed ground. Three main directions are evident, north-east (Caledonian), north-north-east and north-north-west. A substantial number of east to north-east-trending lineaments were also observed which, generally, are not coincident with mapped faults. Several of these are coincident with the strike and are no doubt picking up prominent bedding or cleavage partings, perhaps accentuated by strike faulting. A few, for example near Great Worm Crag [195 961], are coincident with mapped boundaries between formations, in this case between the Airy's Bridge and Whorney Side formations of the Borrowdale Volcanic Group. Others cut across mapped geological boundaries, for example the 4 km long near east-west feature through Buckbarrow [152 910], which intersects north-north-east-trending mineralised structures in Buckbarrow Beck and at Bowscale.

Comparison of the lineament plot (Figure 4) with the location of metalliferous mines and trials (Figure 3) shows that nearly all the sulphide metal workings lie on or close to (within 100 m) linear features. Some, for example those at Hesk Fell and Logan Beck, lie close to the termination of lineaments. In contrast, the locations of most of the hematite workings (Middle Kinmont, Dunnerdale

Fell, Whicham and Waterblean) are not coincident with lineaments. However, four out of the five are in fractured rocks within about 2 km of major lineaments. This differing relationship to linear features may be coincidence (as only five cases are involved in one group), but it could also reflect different metallogeny. A feature of the sulphide mineralisation emphasised by the lineament analysis is the general spatial coincidence between northerly trending lineaments and worked mineralisation, particularly in a zone extending from Stoupdale [164 866], through Black Beck, Bowscale Beck and Logan Beck to Hesk Fell [175 942] (Figures 3 and 4).

Lithological variation

Although individual lithologies could not be distinguished by colour variation or vegetation changes in the images examined, differences in competence resulting in contrasting fracture patterns and the change from massive to well bedded rocks could be distinguished in areas of good exposure on the Thematic Mapper images. Particularly clear locally are the boundaries between the well bedded rocks of the Windermere Supergroup and the more massive lithologies of the Borrowdale Volcanic Group, and between the Skiddaw Group and the Borrowdale Volcanic Group.

REGIONAL GEOPHYSICS

The significance of Bouguer gravity data for the Lake District was first discussed by Bott (1974), mainly in terms of a concealed granitic batholith. The Lake District was subsequently resurveyed with an increased number of gravity stations and Lee (1986; 1989) made use of the improved data set to carry out a comprehensive reinterpretation of the regional gravity and magnetic data using a combination of image processing techniques and detailed modelling. This study resolved a number of regional geophysical features, including residual gravity lows and lineaments which had not been recognised by the earlier work. Interpretation of the geophysical data in conjunction with improved geological information arising from current mapping enabled conclusions to be drawn on the most likely structure and composition of the upper crust.

A brief summary of the principal regional geophysical features revealed by the image processing and the results of the crustal modelling exercise that have a direct bearing on this investigation are given below. Most of the work is based on the gravity data as there are few significant aeromagnetic features in the survey area; further details are contained in Lee (1989). Details of the gravity data for the survey area are briefly discussed below.

Lineaments

The image analysis exercise revealed a number of linear geophysical features, of which five cross part of the survey area (Figure 5). The northernmost, Lineament 7 in Figure 5, has a gravity expression at its western end which coincides with the Esk valley, a mapped fault and a major satellite imagery lineament. At its eastern end, outside the survey area, it has a magnetic expression which may be related to the presence of acid rocks of the Airy's Bridge Formation on the southern limb of the Scafell Syncline. It has an east-north-easterly, Caledonoid trend, as does Lineament 8, a combined magnetic and gravity feature on the southern side of Eskdale, close to the southern margin of the Eskdale Granite. In contrast Lineament 4 (Figure 5) has a north-easterly trend, cutting across the two previously described features at their eastern ends. The south-western end of this lineament lies close to the line of the Wrynose Anticline where it enters the survey area and lies along the north-western side of a residual gravity low. Lineament 9 has a similar north-easterly trend and runs close to the

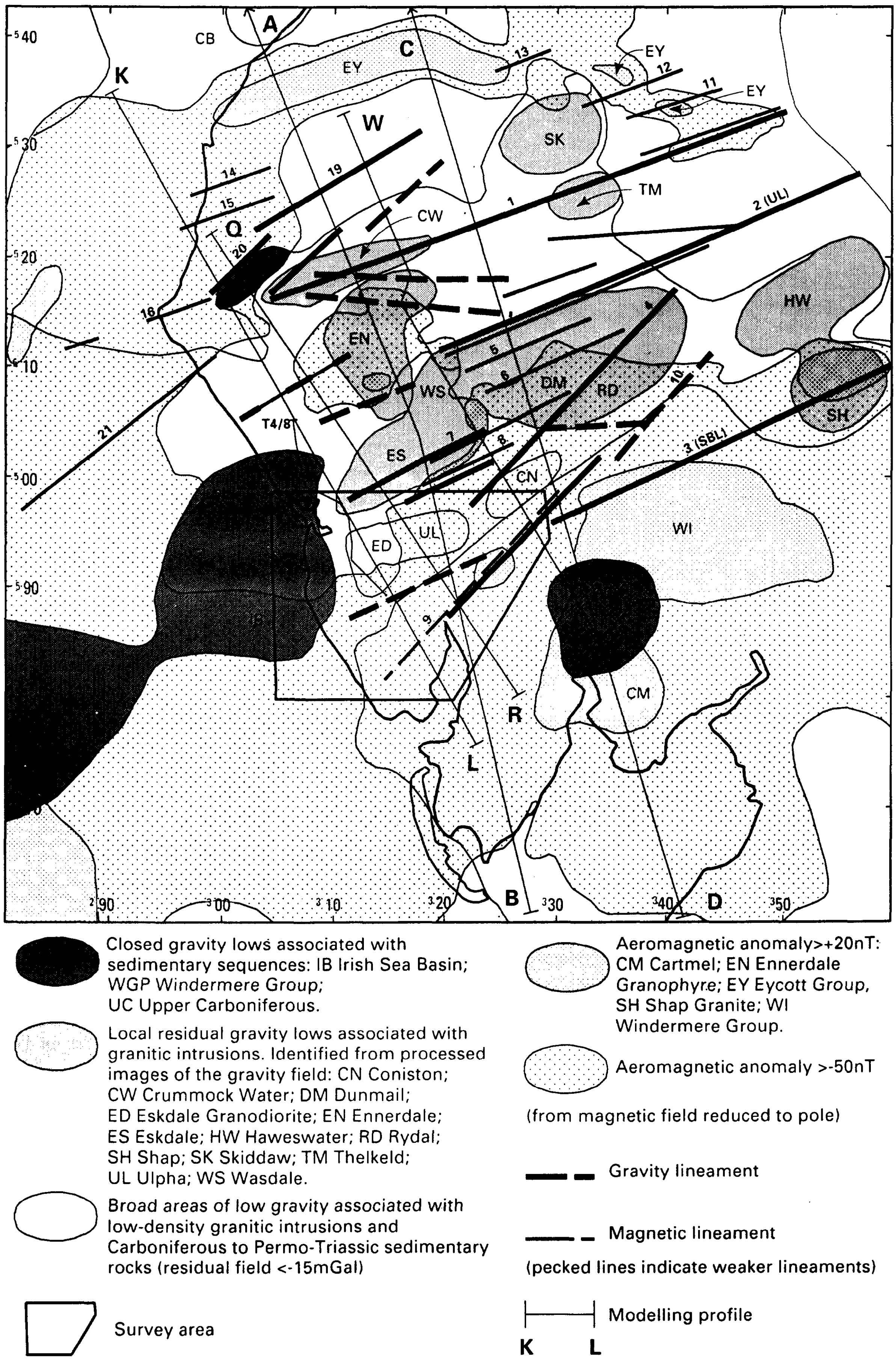

Figure 5 Regional gravity and magnetic features in west Cumbria and the location of the Black Combe survey area and modelling profiles (redrawn from Lee, 1989). Modelling profiles WX, OR and KL are included in this report (Figures 6, 7 and 8 respectively); AB and CD are shown in Lee (1989)

south-east boundary of the survey area, where it lies along the contact of the Borrowdale Volcanic Group and Windermere Supergroup. It is closely coincident over much of its length with a strong magnetic lineament and the Whicham satellite imagery lineament and its northern offshoot (Figure 4).

The other lineament crossing the area (3) is the weak western end of a major east-north-east-trending gravity feature called the Southern Borrowdales Lineament by Lee (1989). To the east, after crossing Lineament 9, this strong feature follows the boundary between the Borrowdale Volcanic Group and the Windermere Supergroup. Within the survey area, however, it is a relatively weak feature running across the Skiddaw Group rocks of Black Combe; there is no major corresponding feature evident on the satellite imagery.

Lee (1989) suggested that the location of these lineaments close to the margins of exposed granites, residual gravity lows and other geological boundaries was significant, and that these trends affected both the evolution of Borrowdale volcanicity and the intrusive form of the batholith components. It was also suggested that some, such as the Southern Borrowdales Lineament, reflected the presence of deep-seated fractures initiated early in the geological history of the Lake District and that their periodic reactivation had a profound effect on the geological history of the area. Certainly this lineament is coincident with a major monoclinal structure and shearing of the Skiddaw Group rocks in Black Combe may mark early activity along this line (A H Cooper and others, 1992).

Residual gravity lows

Lee (1989) identified three local residual gravity lows associated with granitic intrusions in the survey area (Figure 5). All three are situated on the north-easterly trending southern margin of a broad area of low gravity related to the southern margin of the Lake District batholith. The most westerly (ED in Figure 5) is spatially associated with the outcrop of the Eskdale Granodiorite and is attributed to a component of the batholith. Those to the east (UL and CN in Figure 5) are associated with outcrops of the Borrowdale Volcanic Group in the Ulpha Basin and Coniston areas and might be caused by thick sequences of acid volcanic rocks or acid intrusions. These alternatives were examined in more detail by 2.5D modelling along a series of profiles.

Detailed gravity and magnetic modelling

Modelling along the profiles shown in Figure 5 allowed Lee (1989) to investigate the crustal structure within the survey area, in particular the form of the southern margin of the batholith and the number and type of individual plutons comprising the batholith. In this area the resolution of the gravity data is increased by the existence of a detailed gravity profile (Figure 9). Starting in the north-east, modelling on profile WX (and CD) indicated that the residual gravity low in the Coniston–Torver area could be reasonably accounted for by (i) a small deep-seated acid intrusion or shoulder on the southern side of the concealed part of the Eskdale Granite (Figure 6A), (ii) a 2-3 km thick sequence of Borrowdale Volcanic Group rocks with a density of 2.70 Mg/m^3, implying a dominance of acid rocks and perhaps syn-volcanic faulting and subsidence (Figure 6B), or (iii) a small low density (2.62 Mg/m^3) high level intrusion (Figure 6C). The evidence is insufficient to choose between these interpretations, particularly as the Coniston low (CN in Figure 5) is defined by relatively few observations (Lee, 1989). A more detailed survey is merited.

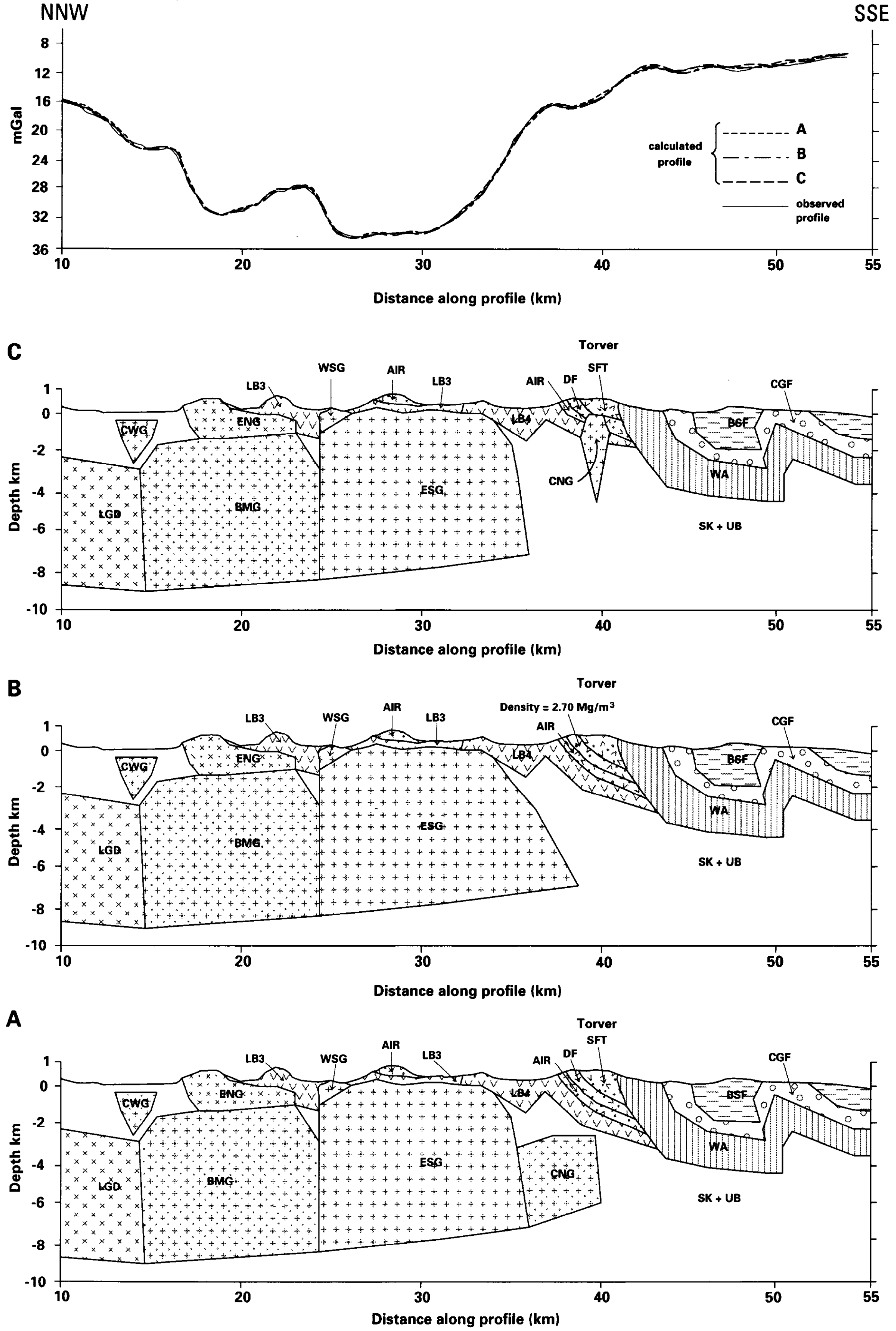

Figure 6 Alternative geophysical interpretations along part of profile WX (redrawn from Lee, 1989; for key to model see Figure 7)

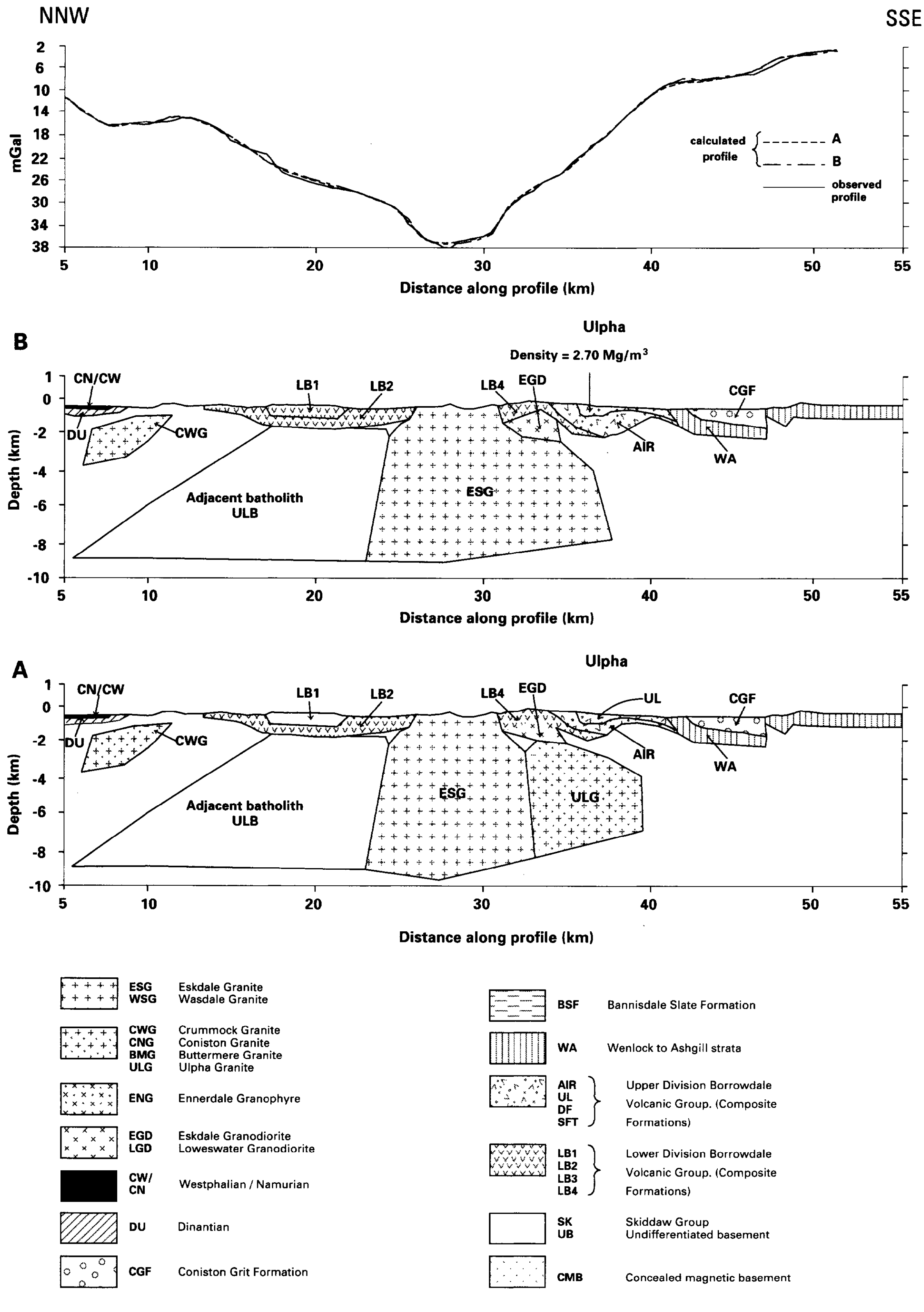

Figure 7 Alternative geophysical interpretations along part of traverse QR (redrawn from Lee, 1989; key to model also refers to Figures 6 and 8)

Modelling along QR (and AB) suggested that the residual gravity low over the Ulpha Basin was most likely to be caused by (i) a southward extension of the batholith at a depth of about 2 km, accompanied by a thickened sequence of low density (acid) volcanic rocks in the Ulpha Basin, perhaps caused by syn-volcanic faulting and subsidence of the volcanic pile (Figure 7B), or (ii) a separate concealed acid intrusion, the Ulpha Granite (Figure 7A). Various models between these extremes are also consistent with the data: for example, some thickening of the volcanic pile plus an intrusion.

In the south-west of the survey area, modelling along profile KL and detailed traverse T4/8 indicates that, as the Eskdale Granodiorite has too high a density to explain the observed anomaly, material of lower density must exist beneath the granodiorite outcrop and may extend south of it at shallow depth. The data suggest either that (i) the granodiorite persists in depth on the flank of the Eskdale Granite (Figure 8A), (ii) the granodiorite body is underlain by a southerly extension of the Eskdale Granite (Figure 8B), or (iii) a thin (laccolithic) granodiorite is underlain at less than 2 km depth by a low-density (acid) pluton which extends under the northern part of Black Combe (Figure 8C). This is the preferred model of Lee (1989), partly because of the evidence found during this investigation for high temperature granite-related (Sn-W) mineralisation in the Black Combe area. If the presence of an acid intrusion under the northern part of Black Combe is accepted, then weight is added to the model of the Ulpha Basin which includes the presence of a separate acid intrusion (Figure 7).

Bouguer anomaly and magnetic data of the survey area.

The Bouguer gravity anomaly map of the area around Black Combe and Ulpha (Figure 9) is dominated by the northward decrease of values towards the low over the Eskdale Granite and by the more sharply defined westward decrease across the Haverigg Fault. The evidence used by Lee (1989) for a concealed acid intrusion is apparent, at this scale, only as slight changes in the gradient associated with the Eskdale Granite anomaly. Linear feature 3 (Southern Borrowdales Lineament) and lineament 9 of Lee (1989) are seen as small-amplitude anomalies at the unconformable base of the Windermere Supergroup.

Another possible lineament is indicated by the north-south flexure in the contours approximately along grid line 315E in the northern part of the map. This runs parallel with the eastern margin of the Eskdale Granodiorite and is probably partly due to a small near-surface density contrast between this intrusion and its host rocks. The absence of a more pronounced anomaly over this intrusion is explained by Lee (1986; 1989) as being due to the Eskdale Granodiorite having a higher density than the granite and thus a lower density contrast with the host rocks.

In the west of the area the pronounced decrease in gravity values close to the Haverigg Fault is due to the rapid westward thickening of low density Permo-Triassic rocks. However, the linear nature of the northern part of this anomaly is interrupted at about 487N by an apparent displacement of the gradient zone to the west-south-west. This is interpreted as a previously unmapped cross fault, possibly a reactivated Caledonian structure. It could also represent an extension of the Whillan Beck Fault (Figure 2). There is a suggestion that a parallel structure exists to the south, but the gravity data are insufficient to demonstrate this clearly.

The magnetic data for the area are dominated by the effect of a deep magnetic basement (Lee, 1989), but a local anomaly between Broughton in Furness and Torver may have an igneous source.

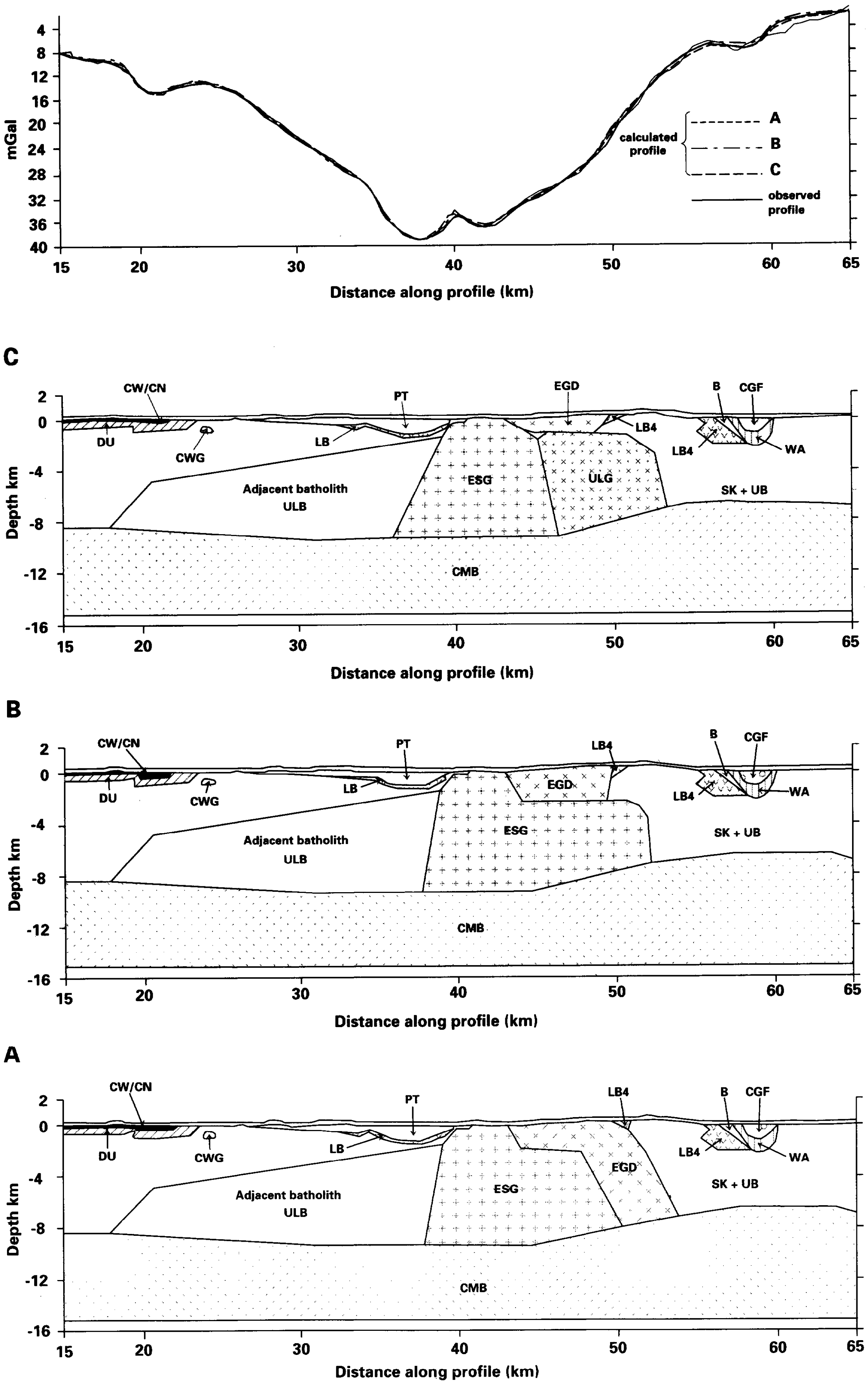

Figure 8 Alternative geophysical interpretations along part of traverse KL (redrawn from Lee, 1989; for key to model see Figure 7)

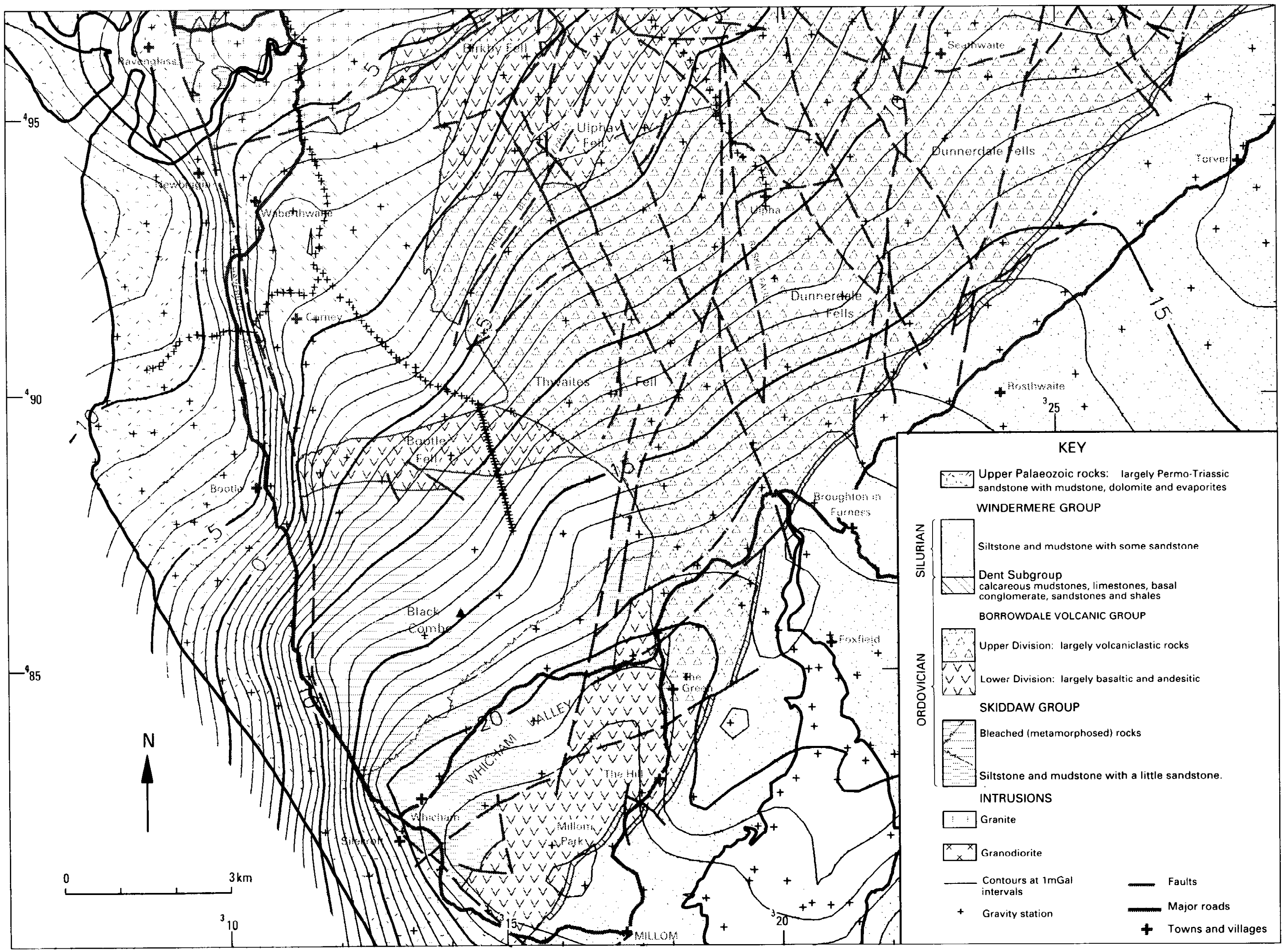

Figure 9 Bouguer gravity anomaly map of the survey area with contours at 1mGal intervals and locations of gravity stations. Density used for data reduction – 2.73 Mg/m^3

Relationship to mineralisation

On a regional scale there is a general relationship evident in the south-western Lake District between the steep southern margin of the batholith and the presence of sulphide mineralisation, particularly those deposits containing metals believed by Stanley and Vaughan (1982) to be characteristic of a relatively high temperature early Devonian phase of mineralisation. The discovery during the investigations reported here of tungsten and, particularly, tin mineralisation in Black Combe suggested the proximity of a highly evolved granitic intrusion. Tungsten mineralisation in the Lake District is only recorded close to or cutting Lower Devonian granite intrusions (Stanley and Vaughan, 1982; Young, 1987) and cassiterite mineralisation is typically found in association with granitic intrusions.

The presence of tourmaline veining, bleached rocks and As-Cu-Bi-Co-Ni sulphide vein mineralisation within the Skiddaw Group rocks of Black Combe also suggested the presence of an evolved granite in the vicinity (Stanley and Vaughan, 1982; Fortey and Cooper, 1986; Cooper and others, 1988). No such granite is exposed, which strongly favours geophysical models which include a hidden, evolved (low density) pluton (the Ulpha Granite) along the southern margin of the batholith in the south-western Lake District.

GEOCHEMICAL DRAINAGE SURVEY

Sampling and analysis

Stream sediment and panned concentrate samples were collected from 119 sites using methods described in detail elsewhere (Plant, 1971; Leake and Smith, 1975). Briefly, active stream sediment was wet sieved through 2 mm and 0.15 mm nylon mesh at site, using minimum water in order to retain the fine fractions, and the -0.15 mm (100 mesh) fraction bagged for analysis after settling. A heavy mineral concentrate was made by panning about 4 kg of the -2 mm (8 mesh) fraction down to a constant volume weighing approximately 50 g. Sites were inspected carefully for indications of mineralisation and contamination, and the concentrate was examined for metalliferous mineral grains. On return to the laboratory, the samples were dried and homogenised, and a 12 g subsample removed and pelletised for analysis by X-Ray Fluorescence Spectrometry (XRF). Fifteen elements were determined on the sediment samples and 17 elements in the concentrates (Table 1). Following chemical analysis, a few panned concentrates were examined mineralogically to determine the mineral phases responsible for high concentrations of one or more elements in the samples. The procedure employed and the results of these investigations are summarised in Appendix 4.

Results

Metalliferous minerals were seen commonly in the panned concentrates. Gold, which had not been reported from this area before, was reported visually at four sites. Subsequent laboratory work (Appendix 4) showed the presence in several samples of further minerals of metallogenetic significance not recorded previously from this area, notably cassiterite, wolframite and scheelite. Other metalliferous minerals noted in pans at site or found by mineralogical examination (Appendix 4) were anatase, arsenopyrite, baryte, bismutite, bismuthinite, chalcopyrite, cerussite, Fe/Ti oxides, galena, pyrite, pyromorphite, sphalerite and stolzite.

Little contamination was seen, as most sample sites are remote from habitation and roads, but lead shot, brick and pottery were recorded at a number of sites, and dumps of old mineral workings were present in a number of catchments. Following the identification of cassiterite, it was clear that the Sn content of a sample could not be used as a contamination guide in this area and that mineralogical examination was the most certain means of determining whether a metal anomaly had a natural or anthropogenic source (Cooper, Nutt and Morgan, 1982).

The analytical results are summarised in Table 1. The data for silver (79%), bismuth (52%), cobalt (2%), nickel (3%), molybdenum (25%), antimony (45%), tin (22%), tungsten (6%) and uranium (35%) in panned concentrate samples and molybdenum (45%), tin (29%) and uranium (47%) in sediment have a high percentage of results (shown in brackets) less than the analytical detection limit.

Table 1 Summary statistics for stream sediment and panned concentrate analyses

Element	**n**	**Median**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**	**Threshold**
Stream sediments							
As	119	89	127	183	6	1760	101
Ba	119	571	597	164	257	1196	800
Co	119	40	61	76	1	547	75
Cr	119	112	126	55	46	386	165
Cu	119	33	44	40	3	280	300
Fe	119	58300	60971	18312	11700	132400	110000
Mn	119	5280	8220	7554	70	>20000	20000
Mo	119	2	2	3	<2	17	6
Ni	119	36	39	20	9	116	90
Pb	119	100	226	547	16	5440	170
Sn	119	4	5	5	<3	28	8
U	119	3	3	2	<3	11	6
V	119	122	125	32	27	318	160
Zn	119	271	355	279	34	1248	251
Zr	119	212	241	98	128	649	450
Panned concentrates							
Ag	119	<3	-	-	<3	11	6
As	119	53	136	215	5	1491	71
Ba	119	515	1108	3248	167	31907	1000
Bi	118	<2	-	-	<2	1170	9
Co	118	18	20	13	<1	73	35
Cu	119	31	87	394	2	4319	45
Fe	119	66200	89395	66741	33700	470400	120000
Mn	119	1630	2000	1466	70	10100	5000
Mo	119	3	6	9	<2	79	6
Ni	117	27	35	25	<1	126	90
Pb	119	54	539	1943	8	165000	200
Sb	119	4	10	19	<4	154	7
Sn	119	11	54	126	<3	970	15
Ti	119	7870	9238	7819	960	48820	20000
U	119	4	4	3	<3	10	9
W	118	8	645	5427	<3	59016	20
Zn	119	140	207	335	34	3539	221

n = number of samples analysed

For conciseness in the text, results for stream sediments and panned concentrates are differentiated by the subscripts $_c$ and $_p$ respectively. For example, Fe_p represents iron in panned concentrate.

Table 2. Summary of Spearman-Rank inter-element correlation statistics derived from the stream sediment and panned concentrate analyses.

Element	Correlation Coefficient				
	0.3-0.39	0.4-0.49	0.5-0.59	0.6-0.69	0.7-0.79
As_c	$Bi_p\ Ba_c\ -Ti_p$	$Ba_p\ Co_p\ W_p\ Fe_c\ Mo_c\ Ni_{cp}$	$Zn_p\ As_p\ Cu_c$	$Co_c\ Pb_c$	$-Zr_c$
Ba_c	$Co_p\ Cu_p\ Fe_p\ As_c\ Cu_c\ Mn_c\ Mo_c\ V_c\ Zn_c\ -Zr_c$	$Ni_p\ Zn_p\ As_p\ Bi_p\ Co_c\ Fe_c$	$Mn_p\ Ni_c$		
Co_c	W_p	$Ba_{cp}\ Bi_p\ Mo_c\ Zn_c$	$Co_p\ Zn_p\ Fe_c\ Mn_{cp}\ Ni_{cp}$	$As_c\ Cu_c\ Pb_c\ -Zr_c$	
Cr_c	Ba_p	Ni_p	Ni_c		
Cu_c	$Fe_p\ Mn_p\ W_p\ Ba_c\ Sn_c$	$Pb_p\ Mo_c\ -Ti_p$	$Ba_p\ Bi_p\ Co_p\ As_{cp}\ Ni_c\ Pb_c\ -Zr_c$	$Cu_p\ Ni_p\ Zn_p\ Co_c$	
Fe_c	$Co_p\ Fe_p\ Ni_c\ Zn_c$	$As_c\ Ba_c\ Co_c\ -Zr_c$		$Mn_{cp}\ V_c$	
Mn_c	$Ba_c\ Pb_c\ -Zr_c\ -Pb_p$		$Mn_p\ Co_c$	$Fe_c\ Zn_c$	
Mo_c	$Zn_p\ Ba_c\ Ni_c\ Pb_c$	$As_c\ Co_c\ Cu_c$			
Ni_c	$Cu_p\ Fe_c\ Mo_c\ Pb_c\ V_c$	$As_c\ -Zr_c\ -Ti_p$	$Zn_p\ Ba_{cp}\ Co_{cp}\ Cr_c\ Cu_c$		Ni_p
Pb_c	$Ba_p\ Co_p\ W_p\ Mn_c\ Mo_c\ Ni_{cp}\ Sn_c$	$Bi_p\ Zn_c\ -Zr_c$	$Zn_p\ Cu_c$	$As_c\ Co_c$	
Sn_c	$Sn_p\ Cu_c\ Pb_c$	$Bi_p\ W_p$			
U_c	$Ag_p\ Ti_p$		U_p		
V_c	$Mn_p\ Ba_c\ Ni_c\ -Zr_c$			Fe_c	
Zn_c	$Mn_p\ Zn_p\ Ba_c$	$Co_c\ Fe_c\ Pb_c$		$Mn_c\ Co_p$	
Zr_c	$-As_p\ -W_p\ -Ba_c\ -Mn_c\ -V_c$	$Ti_p\ -Bi_p\ -Cu_p\ -Mn_p\ -Fe_c\ -Ni_c\ -Pb_c$	$-Ba_p\ -Ni_p\ -Zn_p\ -Cu_c$	$-Co_c$	$-As_c$
Ag_p	$Fe_p\ U_{cp}$				
As_p	$Ba_p\ Co_p\ Mo_{cp}\ Ni_p\ -Zr_c\ Pb_c$	$Ba_c\ -Ti_p$	$Cu_{cp}\ W_p\ Zn_p\ As_c\ Ni_c\ -Zr_c$	$Bi_p\ Pb_p\ Sb_p$	Fe_p
Ba_p	$As_p\ Bi_p\ Pb_{cp}\ As_c\ Cr_c\ Mo_c$	$Cu_p\ Ba_c\ Co_c$	$Co_p\ Ni_{cp}\ Zn_p\ -Ti_p\ Cu_c\ -Zr_c$		
Bi_p	$Ba_p\ As_c$	$Co_p\ Cu_p\ Ni_p\ Zn_p\ Ba_c\ Co_c\ Pb_c\ Sn_c$	$Fe_p\ Mn_p\ Pb_p\ Cu_c$	$As_p\ W_p$	
Co_p	$As_p\ Pb_p\ W_p\ Ba_c\ Cr_c\ Fe_c\ Pb_c\ -Ti_p$	$Bi_p\ Cu_p\ As_c$	$Ba_p\ Mn_p\ Co_c\ Cu_c$	$Zn_c\ -Zr_c\ Ni_c$	Ni_p
Cu_p	$Fe_p\ Ba_c\ Ni_c$	$Ba_p\ Bi_p\ Co_p\ Ni_p\ -Ti_p\ -Zr_c$	$As_p\ Pb_p$	$Zn_p\ Cu_c$	
Fe_p	$Ag_p\ Cu_p\ Mn_p\ Sn_p\ W_p\ Zn_p\ Ba_c\ Cu_c\ Fe_c$	$Mo_p\ Pb_p$	Bi_p	Sb_p	As_p
Mn_p	$Fe_p\ Ni_p\ W_p\ As_c\ Cu_c\ V_c\ Zn_c$	$Bi_p\ Zn_p\ -Zr_c$	$Co_{cp}\ Ba_c\ Mn_c$	Fe_c	
Mo_p	As_p	Fe_p	Sb_p		
Ni_p	$As_p\ Mn_p\ Pb_{cp}\ W_p\ Ba_c\ -U_p$	$Bi_p\ Cu_p\ As_c\ Cr_c$	$Ba_p\ Co_c\ -Zr_c$	$Zn_p\ Cu_c\ -Ti_p$	$Co_p\ Ni_c$
Pb_p	$Ba_p\ Co_p\ Ni_p\ -Ti_p\ -Mn_c$	$Fe_p\ Sb_p\ Sn_p\ W_p\ Zn_p\ Cu_c$	$Bi_p\ Cu_p$	As_p	
Sb_p	Sn_p	Pb_p	Mo_p	$As_p\ Fe_p$	
Sn_p	$Fe_p\ Sb_p\ W_p\ Sn_c$	Pb_p			
Ti_p	$As_c\ U_c\ -Co_p\ -Pb_p$	$Zr_c\ -As_p\ -Cu_{cp}\ -Zn_p\ -Ni_c$	$U_p\ -Ba_p$	$-Ni_p$	
U_p	$Ag_p\ -Ni_p$		$Ti_p\ U_c$		
W_p	$Co_{cp}\ Fe_p\ Mn_p\ Ni_p\ Sn_p\ Cu_c\ Pb_c\ -Zr$	${}_cPb_p\ As_c\ Sn_c$	As_p	Bi_p	
Zn_p	$Fe_p\ Mo_c\ Zn_c$	$Bi_p\ Mn_p\ Pb_p\ -Ti_p\ Ba_c$	$As_{cp}\ Ba_p\ Co_c\ Ni_c\ Pb_c\ -Zr_c$	$Co_p\ Cu_{cp}\ Ni_p$	

Data interpretation

Evaluation of the drainage survey results using statistical techniques was restricted by the complex form of most of the element distributions. The complex sample populations could not be sub-divided into simple unimodal populations on single parameters such as background lithology, and it was clear that a number of factors were responsible for the complexity. In consequence, the results were evaluated by examination of spatial distribution plots of the analytical data in conjunction with field and mineralogical (Appendix 4) observations, the known geology and mineralisation and simple non-parametric statistics such as rank correlation data. The results were used to determine the main sources of variation in the dataset and were then applied to the interpretation of cumulative frequency plots (Parslow, 1974; Sinclair, 1976) from which threshold levels (Table 1) and class intervals (Figures 10-26) were set.

Major sources of geochemical variation

The principal sources of variation in the dataset are bedrock lithology and metalliferous mineralisation. Variation in most elements determined in sediment and Co, Ni and Mn in panned concentrate is primarily related to lithological variation, but concentrations of some of the elements determined in sediment (e.g. As and Mn) are also affected by redistribution in the surface environment due to the formation of hydrous oxide precipitates. The concentration of some elements in sediment, notably Cu, is also related to metalliferous mineralisation and this is reflected in close positive correlations (Table 2) with variables such as Bi_p and As_p.

Variation due to mineralisation is most evident in variables determined in panned concentrates, and most variation in As_p, Bi_p and W_p can be attributed to this source. Ba, Cu, Fe and Zn variation in panned concentrates appears to be partly the product of mineralisation and partly due to lithological variation. High Fe_p levels, for example, were generated principally by pyrite and Fe oxides. These minerals may also have carried some Mo and Sb, accounting for correlations between these elements. Sn in sediment and concentrate shows only weak correlations with other elements (Table 2) and it is probable that their variation is due to both mineralisation and contamination. The Sn_p-Pb_p correlation suggests that Pb_p variation is governed by the same two sources.

Variation in Ti_p, U_p and Zr_c is governed by the proportion of sandstone- and granite-related resistate mineral phases in the samples. As a result, these variables frequently show significant negative correlations with other elements determined.

Definition of anomalies

Threshold levels and class intervals for plotting purposes were determined by cumulative frequency curve analysis. Most variables showed a complex, multimodal distribution and the threshold was set to differentiate one or more upper populations attributable to mineralisation or other source of metal enrichment. Where doubt existed, the threshold was set to include as anomalous most samples likely to be reflecting the presence of mineralisation. Classes were set to reflect the presence of individual sample populations and outlying high values.

Distribution of anomalies

Antimony

A large proportion of Sb_p results are below the analytical detection limit. The distribution, correlation matrix (Table 2) and magnitude of the higher values reported suggests that weak enrichments in this area are related to iron oxides, sulphide mineralisation and contamination. Most values greater than 15 ppm are clustered in three areas: Millom Park, the upper part of the River Lickle catchment and Buckbarrow Beck (Figure 10). The maximum value was recorded in Millom Park (154 ppm in WCP 3021 [1727 8257]) in a sample also containing anomalous Fe_{cp}, Ba_{cp}, Ag_p and Mn_c. A nearby sample is also highly anomalous (60 ppm in WCP 3015 [1710 8238]) and trace amounts of Sb in Fe-oxides are the probable source of both anomalies. At The Green, anomalous Sb (64 ppm) occurs in a polymetallic anomaly (WCP 3041 [1804 8449]) which may have an anthropogenic source and a high value (35 ppm) was also recorded at High Brow Mine (WCP 3057 [1821 8347]).

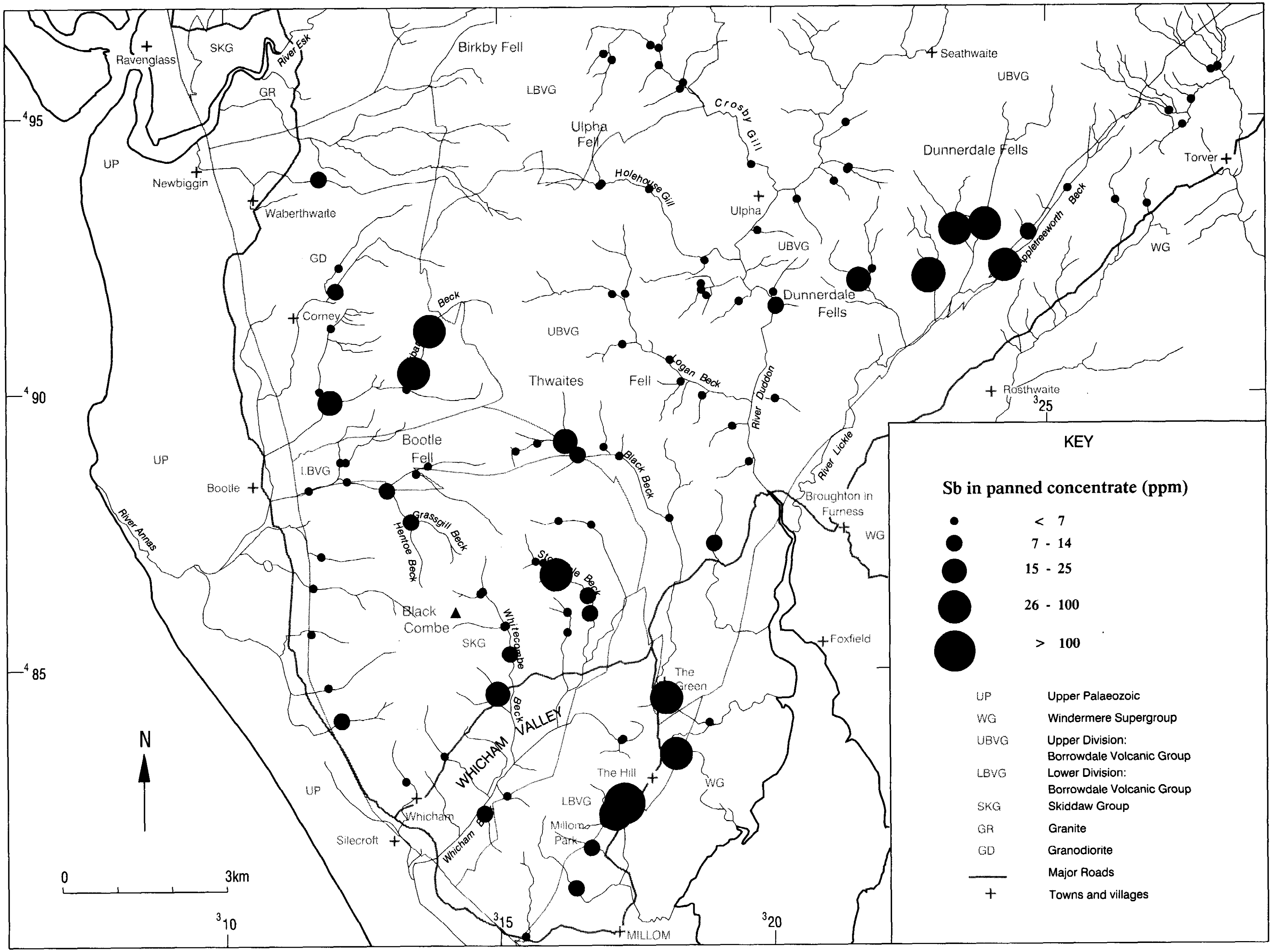

Figure 10 Antimony in panned concentrate samples

The second highest Sb_p value (69 ppm in WCP 3087 [2284 9210]) was recorded in the catchment of the River Lickle. Very high levels of Fe_p and weak enrichments of Ag_p, As_p and Mo_p were also recorded in this sample. There are hematite workings in the vicinity and abundant Fe-oxides and some pyrite were noted in the pan. Several similar anomalies recorded in this area are all thought to be caused by trace amounts of Sb in Fe-oxides.

Weak enrichments are recorded over the Eskdale Granodiorite, particularly in Buckbarrow Beck where the maximum value in this part of the area was recorded (41 ppm in WCP 3069 [1374 9114]). These elevated values are attributed to trace enrichment in sulphides or Fe-oxides associated with sulphide and hematite mineralisation recorded in this area. Weak enrichments ($\leq$27 ppm) occur in samples from the Black Combe inlier, probably reflecting trace amounts in the mineralisation found in that area. No antimony minerals were recorded in the panned concentrates subjected to laboratory examination.

Arsenic

As_p and As_c cumulative frequency plots are very similar, with closely comparable levels in both sample types. There is a strong positive correlation between As_c and As_p (Table 2). The As_c plot has a clearly defined inflexion point at 300 ppm separating a group of very high values from enriched samples which may also reflect the presence of mineralisation. In view of the presence of arsenopyrite in the pans, it is perhaps surprising that levels in concentrates are not higher than those in sediment. The reason is that much arsenopyrite has been destroyed and the As released has been concentrated into hydrous oxide phases, yielding some very high As_c values locally. As_c and, to a greater extent, As_p are relatively enriched in catchments draining Skiddaw Group rocks in the Black Combe area, suggesting the presence of widespread arsenic mineralisation in this area (Figures 11 and 12).

Catchments in the Borrowdale Volcanic Group of the Ulpha area also yield some high As_c results but As_p results are often low, despite the presence of old workings containing arsenic mineralisation. This suggests that the detrital As-bearing phases are often destroyed before reaching the streams in this area. Low As_c values, typically accompanied by higher As_p, are a feature of streams draining the Eskdale Granodiorite.

The highest As_c result is from Miller Gill, a stream draining the west side of the Skiddaw Group outcrop (1760 ppm in WCC 109 [1187 8468]). This site is also anomalous for As_p, Co_c, Cu_c, Pb_{cp}, and Zn_p, and was examined mineralogically (Appendix 4). The presence of arsenopyrite was suspected but not confirmed. Other As_c anomalies in the highest grouping are in the vicinity of old mines, notably near Hesk Fell, Ulpha (Millbrow), Whitecombe Beck and High Brow mines. The sites are anomalous for a wide range of metals, and anomalies are related to dispersion from worked mineralisation or extensions of it. Moderately high values (100–200 ppm) are common in the Black Combe inlier in association with anomalous As_p.

The majority of As_p anomalies are associated with the Skiddaw Group of the Black Combe inlier (Figure 12). The highest As_p concentration (1491 ppm) was recorded in a sample from below the old copper mine in Whitecombe Beck (WCP 119 [1519 8528]). This sample contains several other metal anomalies, and mineralogical examination showed the presence of arsenopyrite and bismuth and tungsten minerals (Appendix 4). Similar anomalies are recorded from elsewhere in Whitecombe Beck, Grassgill Beck, Stoupdale and small streams draining the west side of Black Combe. Follow-up work (Part 2) showed that these anomalies are related to vein-style mineralisation containing gold which has been tried locally. An As_p anomaly is associated with High Brow Mine, but not with the copper workings at Ulpha (Millbrow) and Logan Beck.

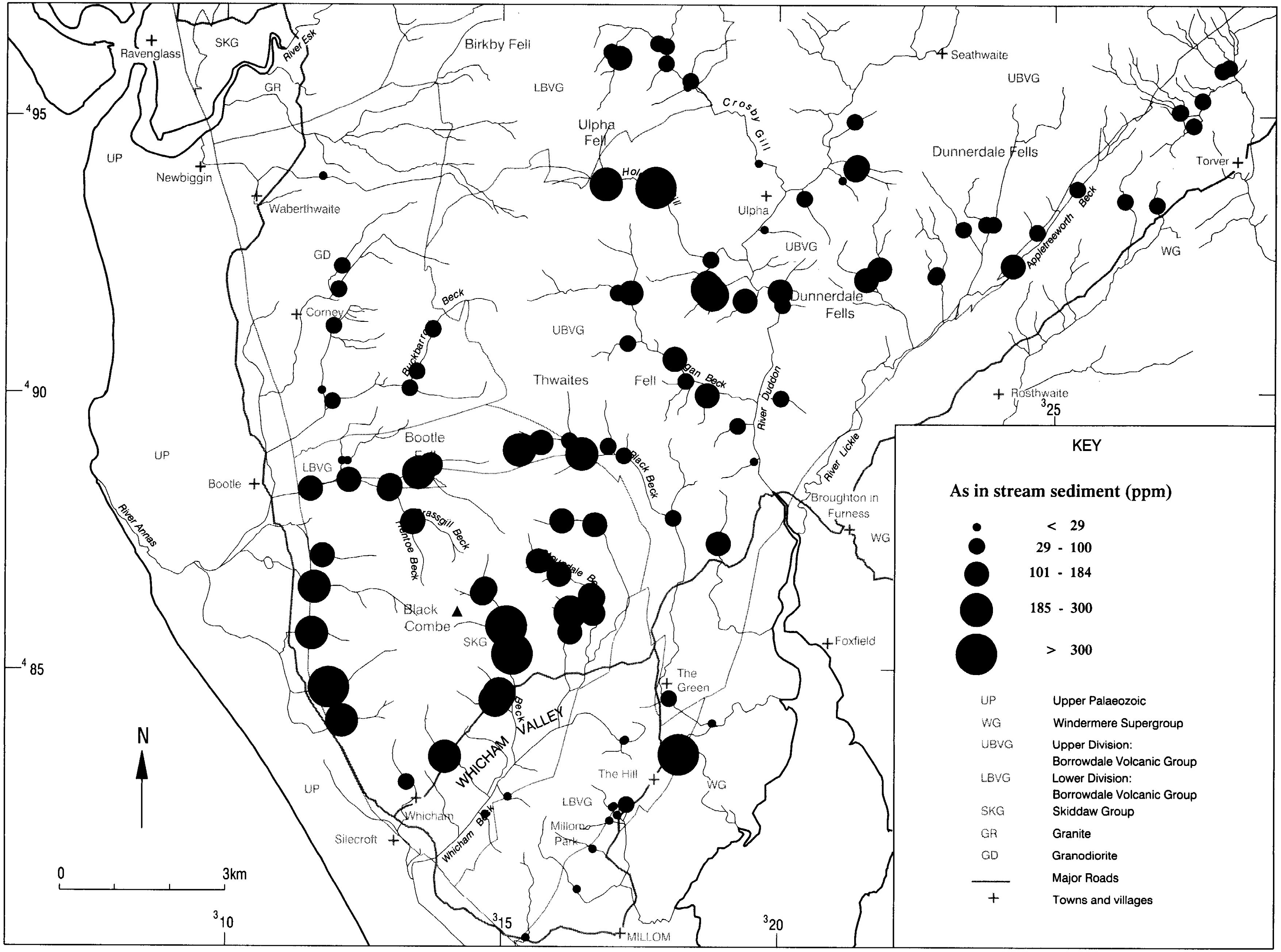

Figure 11 Arsenic in stream sediment samples

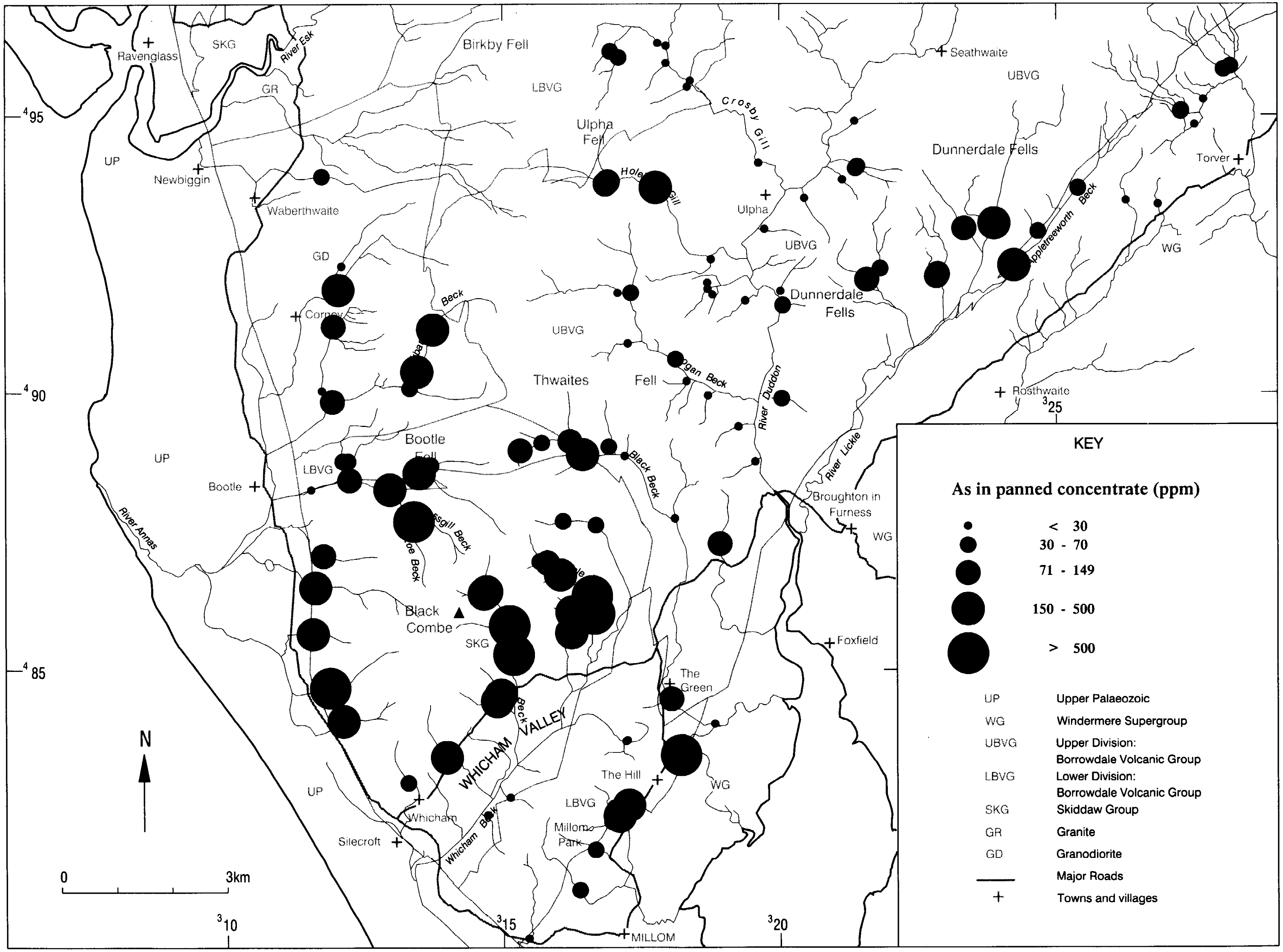

Figure 12 Arsenic in panned concentrate samples

Further As_p anomalies are associated with the Buckbarrow Beck mineralisation, and similar high values elsewhere over the Eskdale Granodiorite suggest that further mineralisation of this type may be present. Anomalies away from the Skiddaw Group outcrop are seen in Millom Park and in the upper reaches of the River Lickle catchment, where they are associated with Fe, Mo and Sb anomalies and related to trace-level enrichment of arsenic in iron oxides.

Barium

The Ba_p cumulative frequency plot indicates the presence of a distinct anomalous population (>1000 ppm) which can be related to the presence of baryte in the samples. The Ba_c distribution shows a more complex and less well defined grouping of samples enriched in barium, which has a number of sources. Consequently there is no significant positive correlation between Ba_c and Ba_p (Table 2). The largest Ba_c anomaly (1196 ppm) is in Holehouse Gill (WCC 3036 [1777 9370]). Other elements anomalous here are Mn, Mo, U and As in sediment. Another very high Ba_c result was collected upstream (WCC 3035 [1691 9380]). These and other very high (> 900 ppm) results within the Borrowdale Volcanic Group are accompanied by low Ba_p, indicating that the source is not baryte but perhaps caused by either a concentration of K-feldspar or co-precipitation with hydrous oxides. In contrast, two high Ba_c results from samples collected on the Windermere Supergroup near the Borrowdale Volcanic Group unconformity (WCC 3021 [1727 8257] and WCC 3070 [2626 9347]) are accompanied by high Ba_p and caused by baryte, most probably from vein mineralisation in the vicinity.

Panned concentrate sampling is particularly sensitive for baryte and the distribution of anomalous samples suggests that baryte mineralisation is restricted to parts of Black Combe and the area of the unconformity between the Borrowdale Volcanic Group and the Windermere Supergroup, where mineralisation may reflect the structure rather than the unconformity (Figure 13). The highest Ba_p value recorded (3.2%) is from a site draining the Windermere Supergroup outcrop, south-west of Torver (WCP 3070 [2626 9347]), This site is also anomalous for Ba_c, Cu_p, Ni_c and Zn_{pc}, and fine and coarse baryte was noted in the pan. It is probably derived from mineralisation in the Windermere Supergroup.

Baryte mineralisation most probably also accounts for the large Ba_p anomaly (13512 ppm) recorded over the Lower Division of the Borrowdale Volcanic Group in Millom Park (WCP 3010 [1696 8228]), three other anomalies near the Borrowdale Volcanic Group/Windermere Supergroup unconformity and an isolated anomaly on the south side of Whicham Valley (WCP 3006 [1471 8239]).

In the Skiddaw Group inlier of Black Combe Ba_p anomalies are also caused by baryte mineralisation. Baryte was identified in the pan collected from near Anna Crag in Whitecombe Beck (WCP 121 [1470 8645]), together with sphalerite and leucoxene. As well as other sites in Whitecombe Beck, Ba_p anomalies were also recorded within the inlier in samples from Stoupdale and Grassgill (Figure 13). A wide variety of other metals (W_p, Pb_{cp}, As_p, Zn_p, Sn_p and Ni_p) are anomalous at one or more of these sites, conforming to field observations that baryte occurs locally in the quartz-polymetallic sulphide veins found in this area.

Bismuth

A large number of Bi_p results are below the detection limit. The visible part of the cumulative frequency plot appears lognormal in form, but in detail is complex. It suggests that most values above 9 ppm are above background. The majority of high Bi results are in samples collected from the Skiddaw Group inlier of Black Combe and its periphery (Figure 14). Except for an anomaly (89 ppm

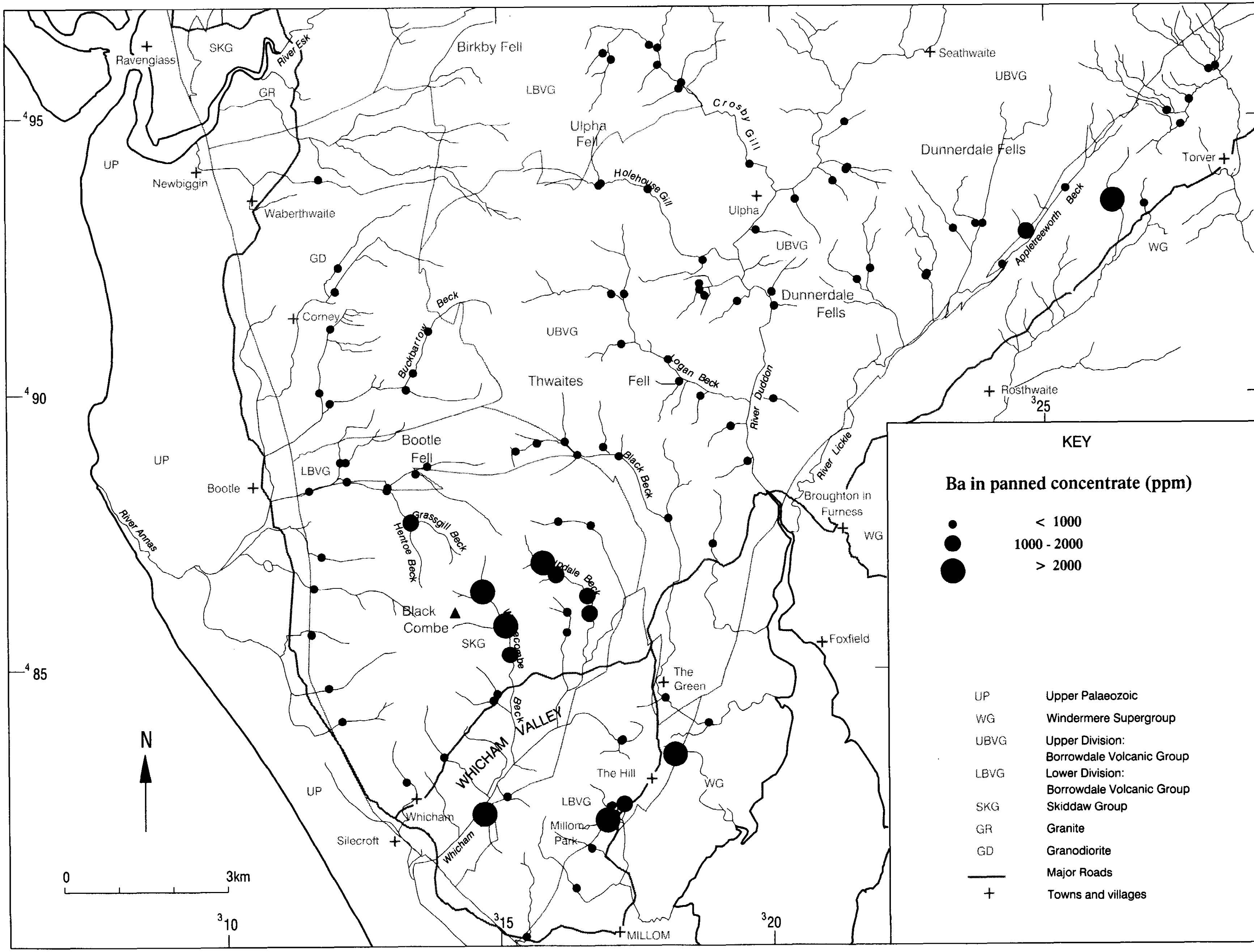

Figure 13 Barium in panned concentrate samples

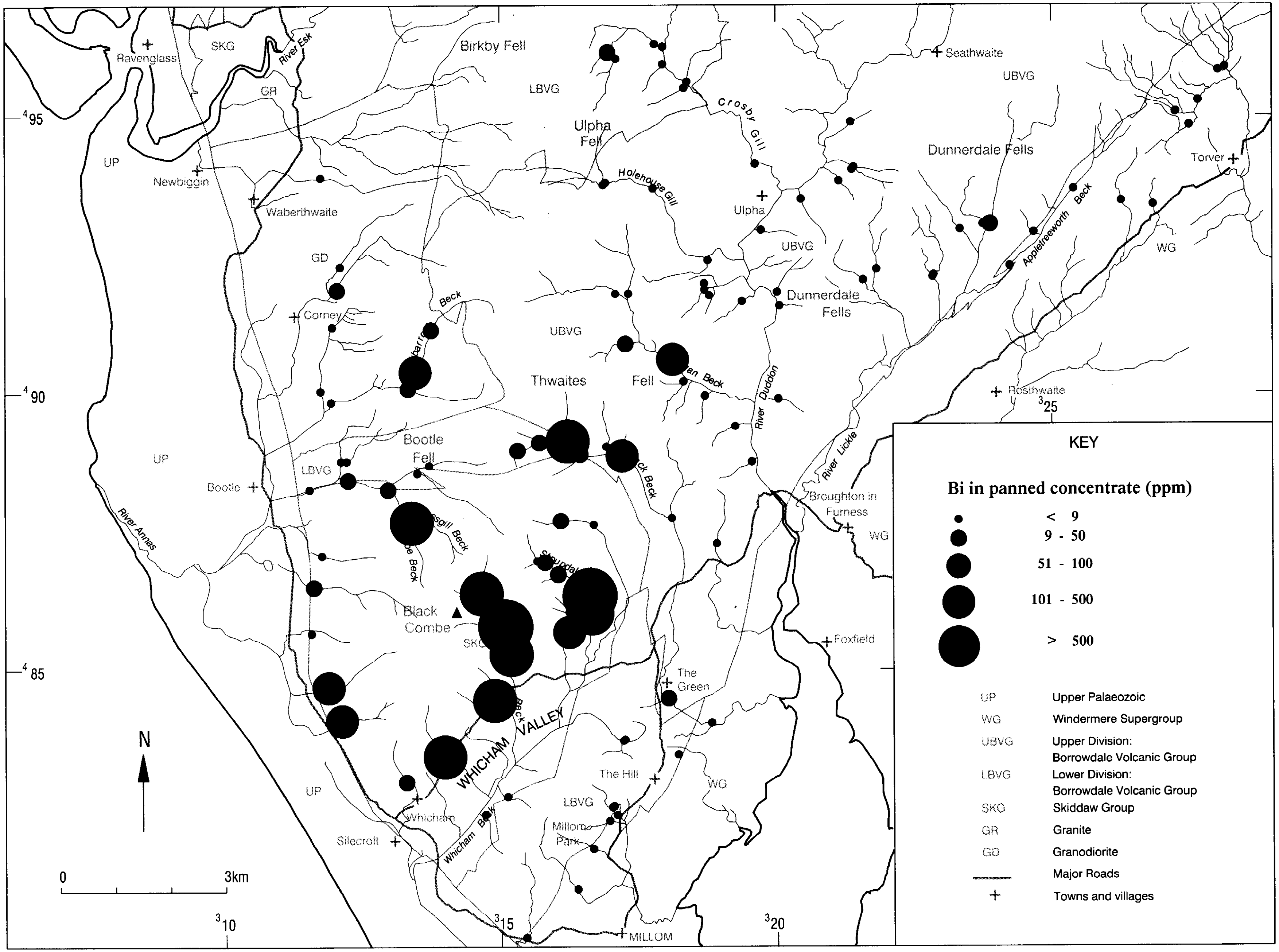

Figure 14 Bismuth in panned concentrate samples

in WCP 3032 [1812 9061]) in Logan Beck, related to worked mineralisation upstream, low Bi values characterise the Borrowdale Volcanic Group and Windermere Supergroup.

The largest anomaly, 1170 ppm, is in a sample taken from Blackcombe Beck (WCP 117 [1509 8579]). As_c, Co_c, Cu_c, Pb_c and Mn_c are also anomalous in this sample and mineralogical examination revealed wolframite, scheelite, cassiterite, cerussite and stolzite in the concentrate. No mineralisation is recorded upstream but the site is close to, and may be contaminated by, the Whitecombe Beck Copper Mine. Although bismuth minerals were not reported in this sample, they were found in other anomalous samples from the Black Combe area: bismutite in WCP 135 [1665 8602], and bismutite and bismuthinite in WCP 119 [1519 8528]. A few of the Bi_p anomalies in the Black Combe area can be related directly to old mineral workings, for example in Whitecombe Beck and Black Beck, but later work (Part 2) indicated that most are probably derived from largely unworked quartz-sulphide polymetallic vein mineralisation.

A weak Bi_p anomaly (97 ppm) over the Eskdale Granodiorite in Buckbarrow Beck is related to the Cu-W-Bi mineralisation tried upstream (Young and others, 1986). Another weakly anomalous value (46 ppm) to the north may have a similar source, as may a larger anomaly (196 ppm) in a catchment draining the metamorphosed aureole of the granodiorite in the Thwaites Fell area.

Cobalt

Co_p levels are low throughout the area (maximum 73 ppm), but the cumulative frequency plot suggests the presence of an ill-defined sample population of relatively high values (>35 ppm). There is a strong positive Co_c-Co_p correlation (Table 2). Co_c values are greater than Co_p and, again, an ill-defined sample population of higher values (>75 ppm) is evident. All the highest (>120 ppm) Co_c results come from catchments draining the Skiddaw Group rocks of the Black Combe inlier. The largest Co_c value (547 ppm) is in a sample from Blackcombe Beck (WCC 117 [1509 8579]), where other metals anomalous in sediment are Mn, As, Pb and Cu. Similar relationships are noted at other sites with Co_c anomalies in the Black Combe area, and it is probable that the higher Co concentrations are derived from the weathering of polymetallic quartz-sulphide vein mineralisation found in this area. The four weak Co_c anomalies (>75 ppm) outside the Black Combe area are scattered, with catchments entirely or largely within the Borrowdale Volcanic Group outcrop. The highest of these values is in a sample from Torver Beck (WCC 3095 [2814 9588]) which also contains anomalous Ni_c and Zn_c.

All high (>35 ppm) Co_p concentrations are in samples from the Black Combe area. High values are concentrated in Stoupdale, where the maximum (73 ppm) was recorded (WCP 125 [1661 8634]). Wolframite, sphalerite, baryte and cassiterite were noted in the pan and As_p, Bi_p, Ni_p, Sn_p, W_p and Zn_p were also anomalous in this sample. The distribution of the higher values strongly suggests that they are caused by small amounts of Co in the lattice of arsenopyrite or other sulphides from the vein-style mineralisation. Higher values in sediment than concentrate are attributed to the breakdown of sulphides carrying cobalt and its subsequent concentration in hydrous oxide phases. There is no evidence for appreciable Co in Fe-oxides or other minerals within the Borrowdale Volcanic Group rocks of this area.

Chromium

Cr_c values form a broadly lognormal distribution with no well-defined anomalous population. Most of the higher values occur over Borrowdale Volcanic Group rocks on the north side of the Black Combe inlier (Crookley and Peathouse Becks), within the Skiddaw Group inlier and in the Millom Park area. Here the highest values recorded occur in streams draining the Lower Division of the Borrowdale

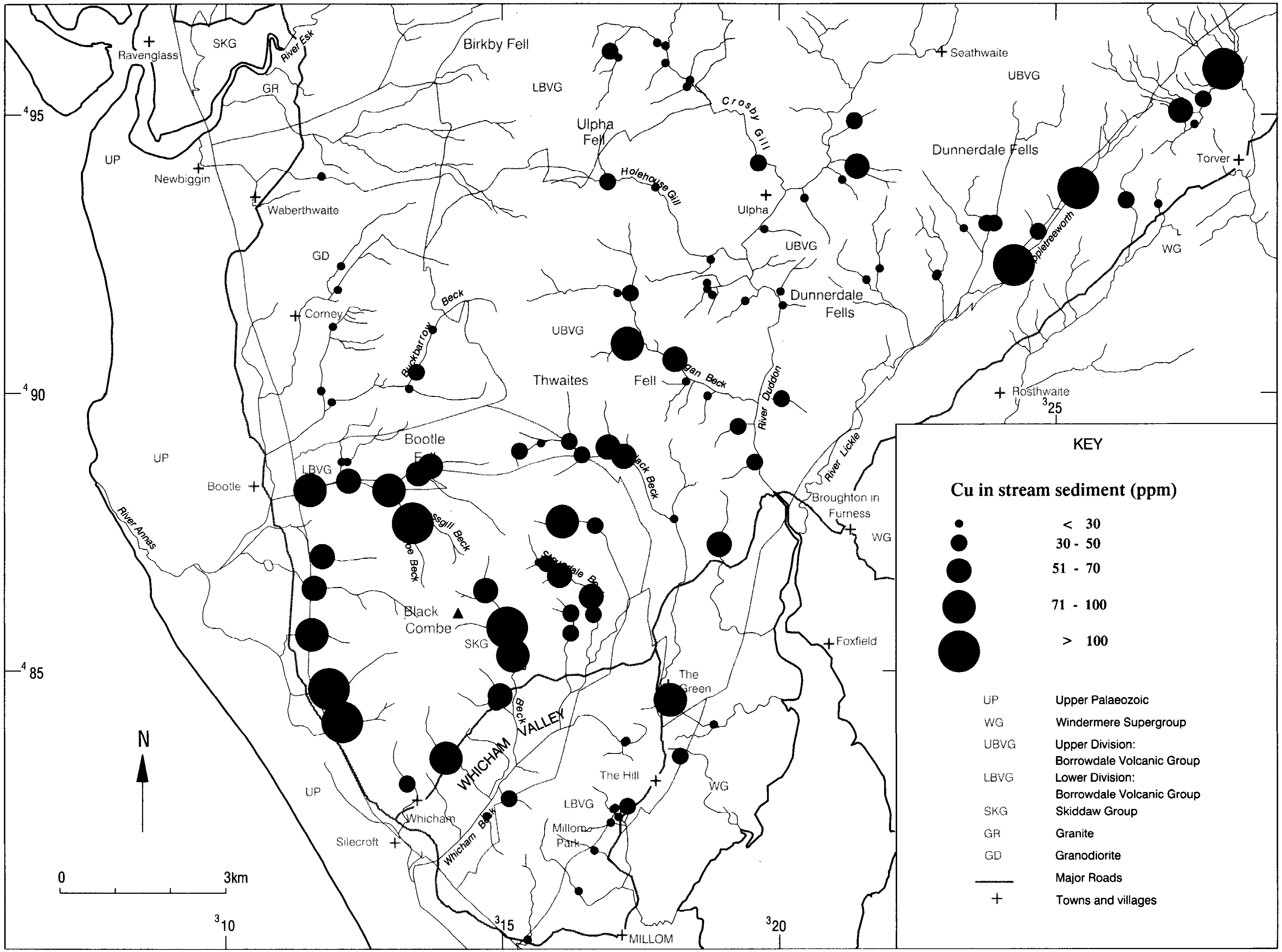

Figure 15 Copper in stream sediment samples

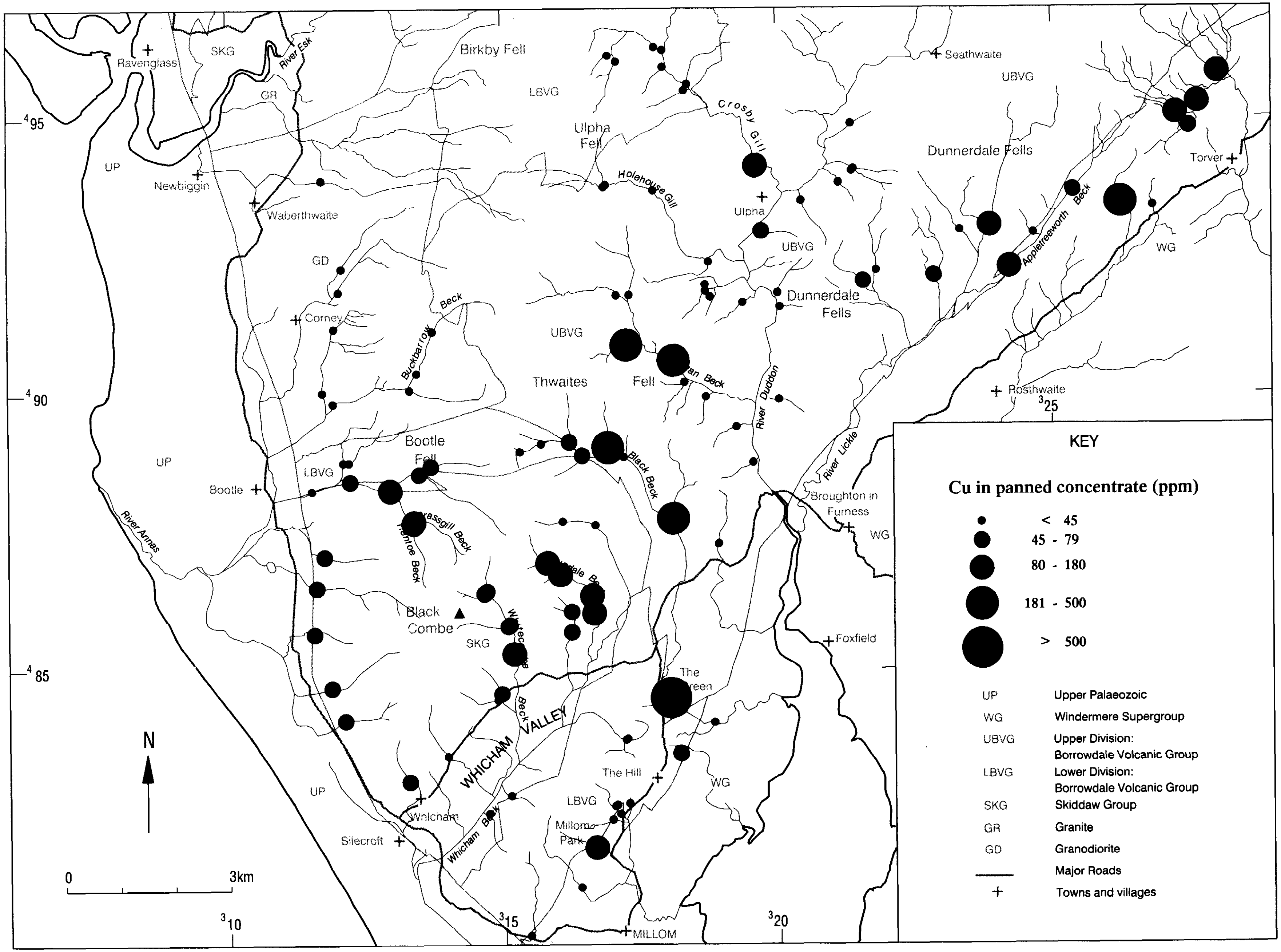

Figure 16 Copper in panned concentrate samples

Volcanic Group close to the sub-Windermere Supergroup unconformity. The outlying maximum value, 386 ppm, is in a sample from the Ghyll area (WCC 3056 [1704 8254]). The second highest value, 292 ppm, was collected from less than 1 km to the south-west (WCC 3010 [1696 8228]). It is probable that these, and other high values, reflect the andesitic to basaltic source rock lithology with a high proportion of Cr contained in minerals such as chlorite.

Copper

Cu_c and Cu_p have complex distributions with ill-defined high-value sample populations, possibly related to mineralisation. They show similar variation, and there is a very strong Cu_c-Cu_p correlation (Table 2). The highest Cu_c values are in samples collected from close to the sub-Windermere Supergroup unconformity, south-west of Torver and over the Skiddaw Group rocks of the Black Combe inlier (Figure 15). The maximum value (280 ppm) is from a site in Miller Gill (WCC 109 [1187 8468]) which drains altered Skiddaw Group rocks. A wide range of other metal anomalies are recorded at this site but Cu_p is only weakly anomalous (72 ppm) and copper minerals were not found in the concentrate (Appendix 4). It is probable that hydrous oxide precipitation processes contribute to the anomaly, but, although none is recorded in the catchment, mineralisation is the probable source. Large anomalies in Townend Gill (WCC 110 [1211 8408]), Grassgill Beck (WCC 116 [1338 8766]) and Blackcombe Beck (WCC 117 [1509 8579]) are very similar. With the exception of the sample from Torver Beck (WCC 3096 [2802 9583]) which contains high levels of Zn_p and Zn_c, the large Cu_c anomalies south-west of Torver are not greatly enriched in other base metals in sediment or panned concentrate. Also, Cu_p levels are lower or similar to those in the sediment, indicating an absence of heavy detrital copper minerals.

The principal Cu_p anomalies reflect the presence of detrital copper minerals, although the values are lower than might be expected. This may be due to the rapid dissolution of chalcopyrite under acid conditions. Some of the most anomalous values (>180 ppm) are found in streams which drain old mine workings, notably in the Logan Beck catchment (WCP 3031 [1726 9089] and WCP 3032 [1812 9061]). Other mines, e.g. the Whitecombe Beck Copper Mine (WCP 119 [1519 8528]) only generate weak Cu_p anomalies despite the presence of highly anomalous values of other metals.

The largest Cu_p anomaly (4319 ppm) is from The Green (WCP 3041 [1804 8449]) on the boundary between the Upper and Lower Divisions of the Borrowdale Volcanic Group. This outlying high value is an order of magnitude greater than the others and its source is uncertain. Ag_p, Pb_p, Sb_p and Sn_{pc} are also anomalous at this site, a grouping which suggests that contamination may be present. No contamination was noted at the site, although blue-grey metallic grains were seen in the pan.

Other highly anomalous Cu_p results may be related to undiscovered mineralisation. They include sites in tributaries of Black Beck, within the Borrowdale Volcanic Group outcrop (WCP 3027 [1691 8903] and WCP 3029 [1810 8774]) and a site south-west of Torver over the Windermere Supergroup where highly anomalous levels of Ba and Zn were also recorded in the sample (WCP 3070 [2626 9347]).

Moderate to weak Cu_p anomalies (45–180 ppm), also related to mineralisation, are concentrated in the Black Combe area, notably in Stoupdale, Grassgill and Whitecombe Beck. More isolated anomalies of similar magnitude in the Borrowdale Volcanic Group, such as those north of Ulpha (WCP 3100 [1962 9414]), in Torver Beck (accompanied by high Zn_p; WCP 3096 [2802 9583]) and in the Lickle catchment (WCP 3089 [2388 9305]) may also have mineralised sources.

Iron

Fe_c shows a near lognormal distribution, with a single outlying high value, but Fe_p, which reaches very high concentrations in some samples, has a complex distribution, indicating the presence of one or more anomalous populations. Consequently the Fe_p correlation with Fe_c is weak. The higher Fe_c values are scattered, but there is a correlation with the presence of Lower Division Borrowdale Volcanic Group rocks in the north of the area (WCC 3034 [1686 9376] and WCC 3043 [1710 9604]), pyrite-rich sulphide mineralisation in Stoupdale (WCC 3065 [1665 8630] and WCC 3003 [1566 8696]) and at High Brow Mine (WCC 3057 [1821 8347]), and hematite mineralisation in Millom Park (WCC 3021 [1727 8257]). The highest values are often a product of these factors and the effects of hydrous oxide precipitation, several high values occurring in the upper parts of catchments (WCC 3075 [1871 9187] and WCC 3076 [1879 9177]). The outlying highest value recorded (13.2% Fe in WCC 3034 [1686 9376]) is a further sample occurring in the upper reaches of Holehouse Gill draining the rocks of the Lower Division Borrowdale Volcanic Group. Mn_c, As_c and Ti_p are also anomalous here. High Fe_p values are also related to basic volcanic rocks and mineralisation. The highest value (47% Fe) is from Millom Park (WCP 3021 [1726 8257]) and the source of the anomaly is the abundant hematite and other Fe-oxides noted in the pan. Fe_c, Mn_c, Ba_{pc}, Ag_p and Sb_p are also anomalous in this sample. Other high values in the Millom Park area probably have a similar source (WCP 3015 [1710 8238] and WCP 3041 [1804 8449]) and the High Brow Mine also generates a significant anomaly (WCP 3057 [1821 8347]).

A cluster of highly anomalous (>20%) Fe_p values (WCP 3087 [2284 9210], WCP 3088 [2286 9214], WCP 3089 [2388 9305] and WCP 3064 [2334 296]) in the catchment of the River Lickle is associated with As_p, Ag_p, Cu_p, Mo_p and Sb_p enrichments at one or more sites. Both pyrite and iron oxides are recorded in the pans and the metal enrichments appear to be related to both sulphide mineralisation and trace concentrations of metals in the abundant Fe-oxides.

Two large (>20%) Fe_p anomalies in samples from Buckbarrow Beck (WCP 3051 [1345 9038] and WCP 3069 [1374 9114]) are accompanied by high levels of Ti_p, and enrichment in several other metals. The anomalies are related to Fe oxide, Fe-Ti oxide and sulphide minerals seen in the pans, derived in part from vein mineralisation recorded upstream (Young, 1985b) and in part from the host rocks. The Eskdale Granodiorite is locally highly altered and this may have promoted the release of heavy Fe/Ti rich phases. Minerals seen in the pans suggest that other high values recorded over the Eskdale Granodiorite (WCP 3052 [1203 9186] and WCP 3061 [1192 8984]) have a similar source. Anomalies (maximum 18.8 %) in Whitecombe Beck, Stoupdale and Black Beck are attributed to the presence of pyrite derived from the polymetallic vein-style sulphide mineralisation and pyrite in the host rocks.

Gold

The gold content of the drainage samples was not determined but small gold grains (maximum three) were seen in the panned concentrates collected at four sites. These were in Buckbarrow Beck (WCP 3051 [1345 9038]), the River Annas near Fold Gate (WCP 3052 [1203 9186]) and north of Low Kinmont (WCP 3062 [1173 9004]) draining the Eskdale Granodiorite, and in Langthwaite Beck, Millom Park (WCP 3005 [1545 8017]) draining rocks of the Borrowdale Volcanic Group. The source of the gold in these samples is uncertain, but a possible source for the Buckbarrow Beck grains is the upstream Cu-W vein mineralisation. Gold was not seen in the panned concentrates collected downstream of the polymetallic sulphide veining in the Black Combe area, suggesting that any gold in these veins is very fine or locked into other minerals.

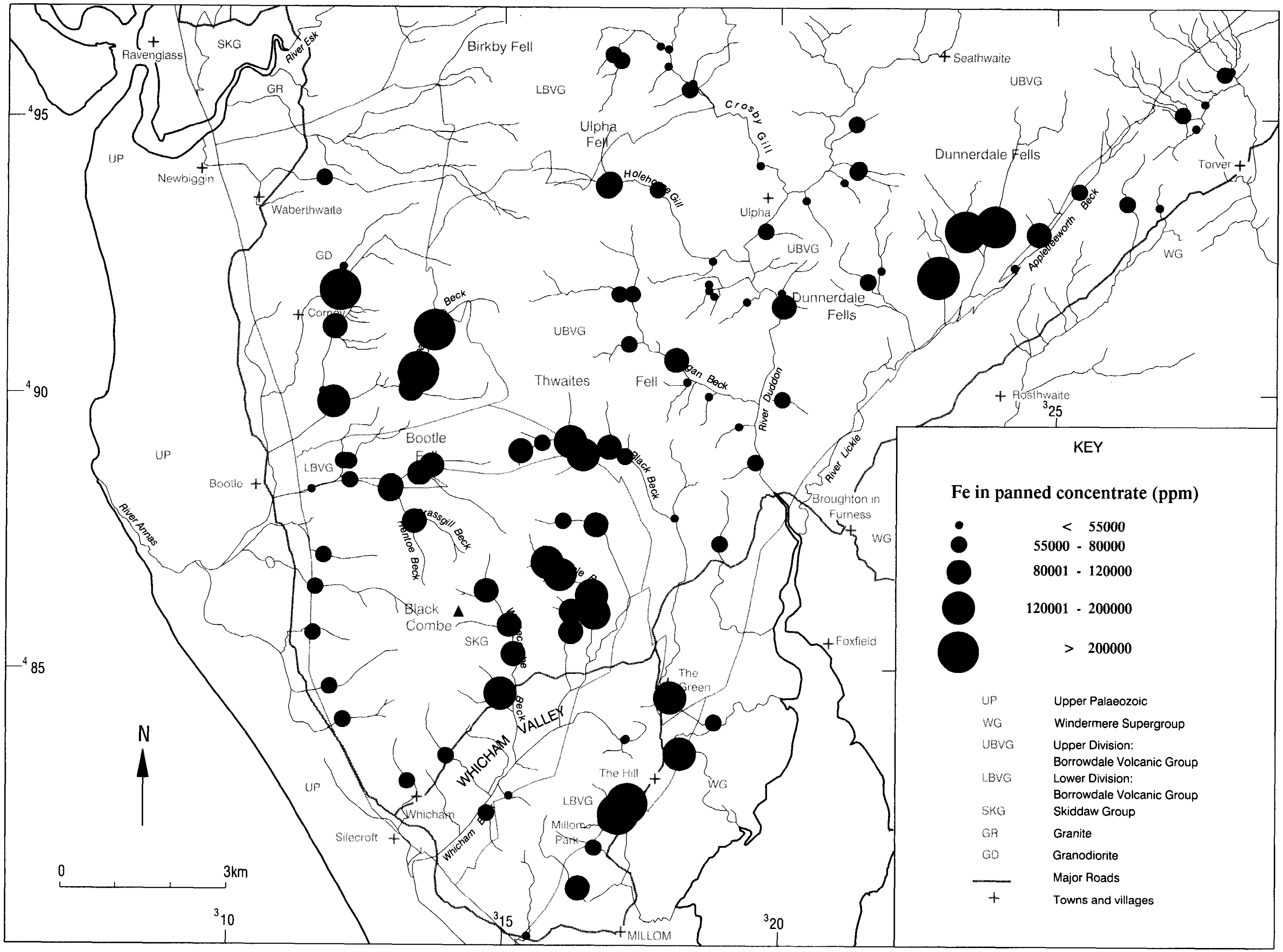

Figure 17 Iron in panned concentrate samples

Lead

Very high levels of lead were recorded in some samples and anomalous sample populations related to mineralisation can be identified on the complex cumulative frequency plots. The plots suggest more than one enrichment mechanism and thresholds were set to separate the reasonably well defined near-lognormal background populations from enriched samples. There is no positive Pb_p-Pb_c correlation (Table 2), indicating the presence of different enrichment processes in the two sample media. With one exception, all Pb_c results >300 ppm are in catchments draining Skiddaw Group rocks of the Black Combe inlier, with the most anomalous values in streams draining the western side (Figure 18). Only the highest value (5440 ppm in WCC 110 [1211 8408]) can be related directly to mineralisation - that worked on Townend Knotts, but the other anomalies suggest further mineralisation in the vicinity. Anomalous levels of Pb_p, Cu_c, Co_c and As_{cp} are also recorded at one or more of these sites. The highest Pb_c value recorded outside the Black Combe inlier (432 ppm) is in a sample draining the aureole of the Eskdale Granodiorite (WCC 130 [1570 8910]). The absence of any accompanying high values except for Ti_p and V_c suggests that this may be a secondary concentration in organic material. The same mechanism may account for the next highest value (295 ppm in WCC 3043 [1710 9604]) from a site draining Borrowdale Volcanic Group rocks in the north of the area. Most weak anomalies (170–250 ppm) are located in the Ulpha area, some downstream of known mineralisation in the Logan Beck catchment. Pb_c is low in streams draining the Eskdale Granodiorite and the Windermere Supergroup.

On a broad scale the distribution of Pb_p anomalies shows similarities to Pb_c with low levels over the Windermere Supergroup and Eskdale Granodiorite and a concentration of anomalies over the Black Combe inlier. The principal difference is the presence of Pb_p anomalies in the Millom Park area (Figure 19). All Pb_p anomalies, except two, are in samples from the Black Combe and Millom Park areas, with the largest anomalies in catchments on the north and west side of the Skiddaw Group inlier. The sample containing the maximum Pb_p value (1.65 % Pb in WCP 115 [1339 8768]) was collected from Grassgill Beck and the second highest from Hentoe Beck (1 % in WCP 116 [1338 8766]). Mineralogical examination of the latter sample revealed scheelite, stolzite and cerussite (Appendix 4). No mineral working has been recorded in this catchment and these data clearly suggest the presence of undiscovered mineralisation in the area. Further work in this area is described in Part 2. Anomalies on the west side of the inlier have large Pb_c anomalies associated with them and are also attributed to mineralisation. On the eastern side of the inlier (Stoupdale and Whicham Beck catchments) Pb_c and Pb_p values are lower, suggesting a regional change in the mineralisation.

In the Millom Park area a substantial Pb_p anomaly (798 ppm) is associated with the High Brow pyrite mine (WCP 3057 [1821 8347]). An anomalous sample near Po House (608 ppm in WCP 3006 [1471 8239]) also contains a high concentration of Ba_p, suggesting that mineralisation may be the source. The two other anomalous samples in this area are close to the road from The Green to Strands (1413 ppm in WCP 3041 [1804 8449] and 361 ppm in WCP 3018 [1882 8404]). Both contain high Sn_p and may have anthropogenic sources. Two weak Pb_p anomalies south-west of Torver (260 ppm in WCP 3080 [2540 9369] and 223 ppm in WCP 3058 [2375 9305]) are characterised by much higher Pb_p than Pb_c suggesting a detrital heavy Pb phase. However, few other metal enrichments are evident and at the latter site Sn_p levels are significant, suggesting an anthropogenic input.

Manganese

Mn_c and Mn_p show a strong positive correlation, but Mn_c shows a stronger correlation with Zn_c and Fe_c (Table 2). The distribution of Mn_c is controlled by bedrock lithology and hydrous oxide precipitation processes. All 16 results >2 % (the upper calibration limit) are in samples collected from

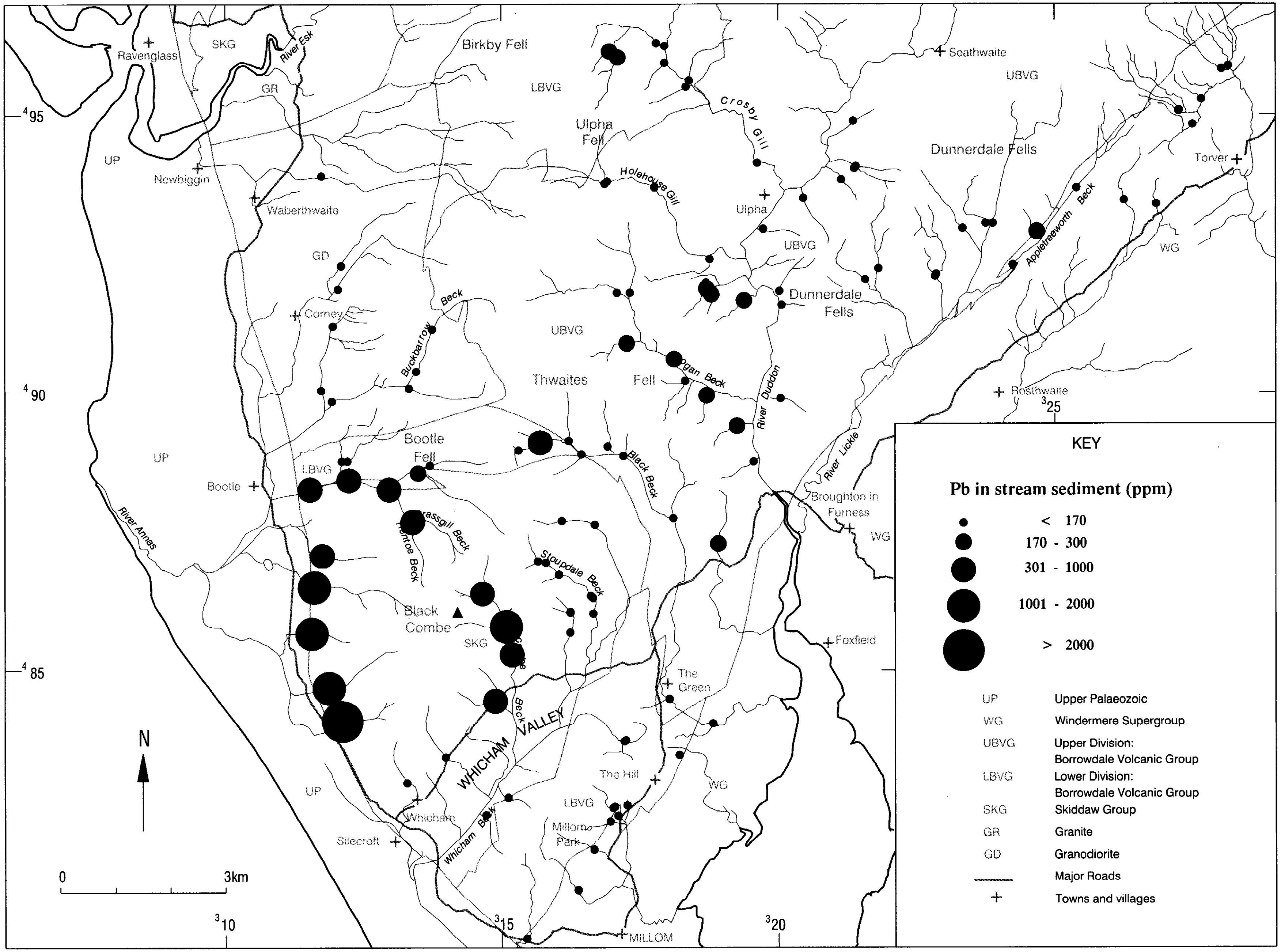

Figure 18 Lead in stream sediment samples

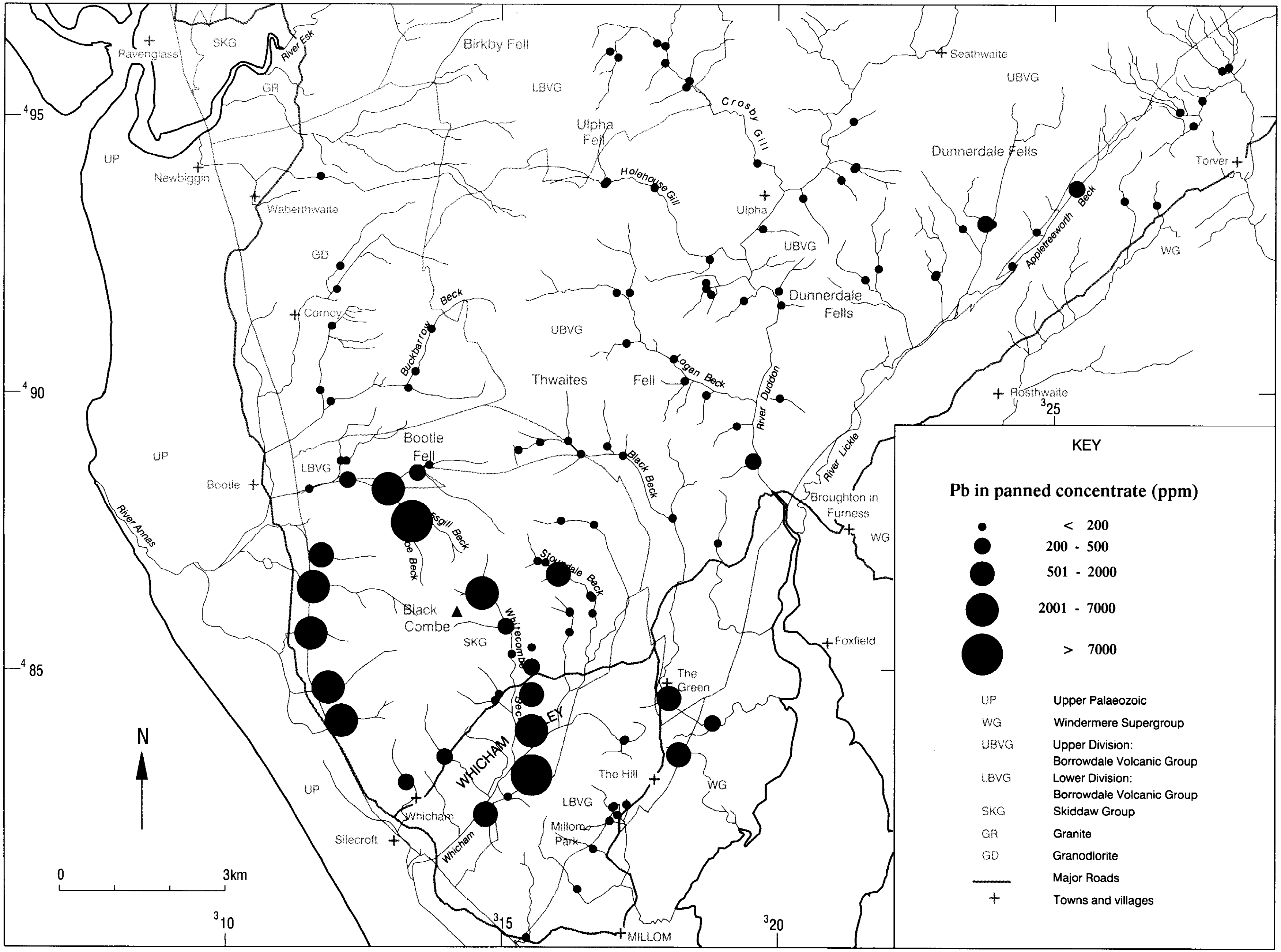

Figure 19 Lead in panned concentrate samples

catchments draining Borrowdale Volcanic Group rocks. One of these sites is in Millom Park (WCC 3021 [1727 8257]) but all the others are in the upper reaches of Crosby, Holehouse, Tongue, and Logan Gills and Bowscale and Black Becks, draining a peat-covered upland area. Concentrations of 1–2 % Mn_c are found over the upland parts of the Eskdale Granodiorite, catchments draining the Upper Division Borrowdale Volcanic Group and Windermere Supergroup in the north-east of the area, and Skiddaw Group in the north-east of the Black Combe inlier. Lowest values occur in the lower reaches of streams and those draining alluvial lowland, for example 200 ppm in WCC 3018 [1882 8404].

Mn_p values are generally lower than those in sediment, reflecting the impact of hydrous oxide precipitate phases on the sediment data. The cumulative frequency plot for Mn_p indicates the presence of an anomalous group of five samples containing >0.5 % Mn. Four of these were collected from Stoupdale Beck, the fifth and lowest (0.58 %) from a tributary to Black Beck draining Borrowdale Volcanic Group rocks (WCP 132 [1621 8913]). The highest value (1 %) was recorded in a sample from the upper part of Stoupdale Beck (WCP 124 [1580 8694]) also anomalous in Ba_p, Co_p and Ni_p. The manganese mineral cryptomelane and baryte were found during the mineralogical examination of this sample (Appendix 4). Mineralogical examination of the sample yielding the second highest result (0.74 % Mn in WCP 135 [1665 8602]) revealed wolframite, sphalerite, bismutite, sphalerite, arsenopyrite, baryte and cassiterite, as well as pyrite (Appendix 4). These results and field observations suggest that the anomalous Mn_p group is related to manganese minerals infilling mineralised structures.

Molybdenum

Some Mo_c and Mo_p results are below the analytical detection limit. This may in part account for the absence of any significant positive Mo_c-Mo_p correlation (Table 2). The cumulative frequency plots of both variables indicate the presence of anomalous populations, with greater enrichment in the panned concentrates than the sediments. Mo_c variation is related to bedrock lithology, mineralisation and re-distribution during surface processes. Anomalous levels of Mo_c (>6 ppm) and several other results close to the threshold (4–5 ppm) are in samples collected close to the unconformity between the Windermere Supergroup and the Borrowdale Volcanic Group, with the most anomalous results occurring in the vicinity of known mineralisation. In Appletreeworth Beck two high values (16 ppm in WCC 3079 [2424 9230], 15 ppm in WCC 3080 [2540 9369]) are in samples containing dark shales, which are as likely to be the source as the nearby mineralisation.

The maximum Mo_c value (17 ppm) was also collected from a catchment containing an old mine working, in this case the Hesk Fell Mine (WCC 3036 [1777 9370]). The sample with the next highest concentration came from High Brow pyrite mine (9 ppm in WCC 3057 [1821 8347]). The other above threshold result (8 ppm in WCC 3084 [2136 9490]) is from a small stream draining Borrowdale Volcanic Group rocks north-east of Ulpha. There is a general association of high values with first order streams, particularly where there are mineralised structures in the vicinity (e.g. 5 ppm in WCC 3076 [1879 9177] and WCC 3077 [1938 9166]) from the upper reaches of Blea Gill). This variation is probably caused by the release of Mo during weathering from source rocks and mineralised structures and its subsequent complexing with organic materials. All Mo_p values >21 ppm are in samples from the north side of Black Combe, in the Hentoe-Grassgill Beck system, and the upper reaches of the River Lickle (Figure 20). The associated anomalies differ in the two catchments. On the north side of Black Combe Mo_p-rich samples (27 ppm in WCP 105 [1296 8826] and 79 ppm in WCP 116 [1338 8766]) contain anomalous amounts of Bi, W and Pb. Bismutite, pyromorphite, stolzite, scheelite, sphalerite, wolframite and cerussite were reported in these samples (Appendix 4), suggesting that

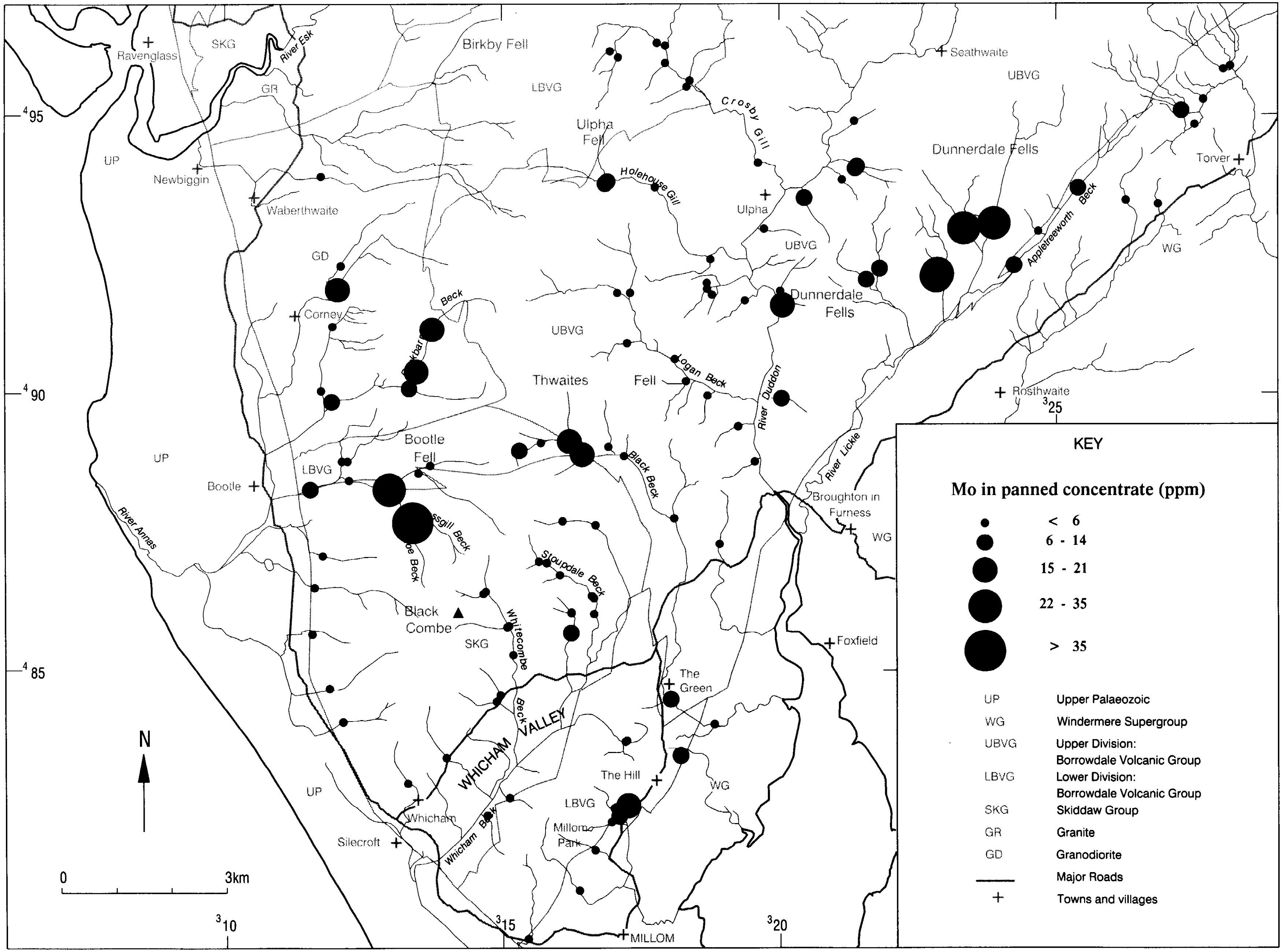

Figure 20 Molybdenum in panned concentrate samples

trace Mo is a component of the vein mineralisation here, perhaps partitioned into the tungsten minerals (Ure and Berrow, 1982). In contrast, anomalies in the upper reaches of the Lickle are associated with anomalous levels of Fe_p and Sb_p and some of the highest values are close to old hematite workings (27 ppm in WCP 3087 [2284 9210]), suggesting that Fe-oxides may be the source. A similar association is evident in samples containing 15-21 ppm Mo_p collected over the Eskdale Granodiorite, notably from Buckbarrow Beck (e.g. 20 ppm in WCP 3051 [1345 9038]), the upper reaches of Black Beck (17 ppm in WCP 132 [1621 8913]) and from Millom Park (20 ppm in WCP 3021 [1727 8257]).

Nickel

Ni concentrations are broadly similar in sediments and concentrates and there is a small anomalous group of samples (>90 ppm) discernible on both cumulative frequency plots. There is also a very strong positive correlation between Ni_p and Ni_c variation (Table 2). The three anomalous Ni_c results are in samples collected over Windermere Supergroup rocks south-west of Torver (116 ppm in WCC 3070 [2626 9347], 111 ppm in WCC 3095 [2814 9588] and 105 ppm in WCC 3080 [2540 9369]). The highest value is associated with anomalous Ba_{cp}, Cu_p, and Zn_{cp} believed to be derived from mineralisation. The other two anomalous samples contain high levels of several elements concentrated in mudstones (Co, Cr, Cu, Mo, Zn), some of which may be enhanced by hydrous oxide precipitation or mineralisation. Moderate Ni_c levels (28–80 ppm) characterise the Skiddaw Group rocks of the Black Combe inlier and low values (<25 ppm) are recorded from the Eskdale Granodiorite. Levels over the Borrowdale Volcanic Group are very variable, reflecting the acid to basic composition of the rocks.

Ni_p and Ni_c anomalies show no correlation. All four Ni_p anomalies (>90 ppm) are in samples collected from Stoupdale (125 ppm in WCP 125 [1661 8634], 120 ppm in WCP 135 [1665 8602], 115 ppm in WCP 3004 [1604 8672] and 105 ppm in WCP 124 [1580 8694]). Samples examined mineralogically (Appendix 4) revealed the presence of a wide range of minerals including pyrite, arsenopyrite, bismutite, wolframite, sphalerite, baryte and cassiterite. No Ni minerals were seen, and it is likely that Ni is distributed in trace amounts in more than one of the minerals named. There is a wider Ni_p enrichement in the Black Combe area attributable to the same source, with all results >62 ppm occurring in samples collected from catchments (Whicham, Crookley, Stoupdale and Whitecombe) in the centre and eastern part of the inlier. The highest Ni_p values outside the Black Combe inlier (c. 40-60 ppm) are recorded south-west of Torver, in part coincident with the Ni_c anomalies. The Eskdale Granodiorite is characterised by very low Ni_p values.

Silver

A high proportion (79 %) of Ag_p results are below the detection limit of 3 ppm, and the maximum value recorded, 11 ppm, suggests an absence of any appreciable Ag mineralisation. The visible part of the distribution indicates the presence of two populations and the threshold level was set at 6 ppm to distinguish the higher grouping. Most high values are in the Black Combe, Millom Park and Broughton Moor areas. The highest value is from a site on a tributary to the River Lickle (WCP 3087 [2284 9210]), draining Upper Division Borrowdale Volcanic Group rocks containing hematite mineralisation and also anomalous in Fe_p, Mo_p and Sb_p. Other anomalous Ag_p sites are WCP 3015 [1710 8238] and WCP 3021, [1726 8257] in Millom Park, WCP 3041 [1803 8448] near The Green, WCP 3057 [1821 8347] at High Brow, and WCP 3064 [2334 9296] in the River Lickle catchment. At only two of these are high levels of Pb recorded, suggesting that argentiferous galena is not the principal source of Ag_p anomalies. All the sites are characterised by relatively high levels of As_p (>100 ppm) and Fe_p (>18 %), and most show some enrichment of Sn_p, Sb_p and Mo_p.

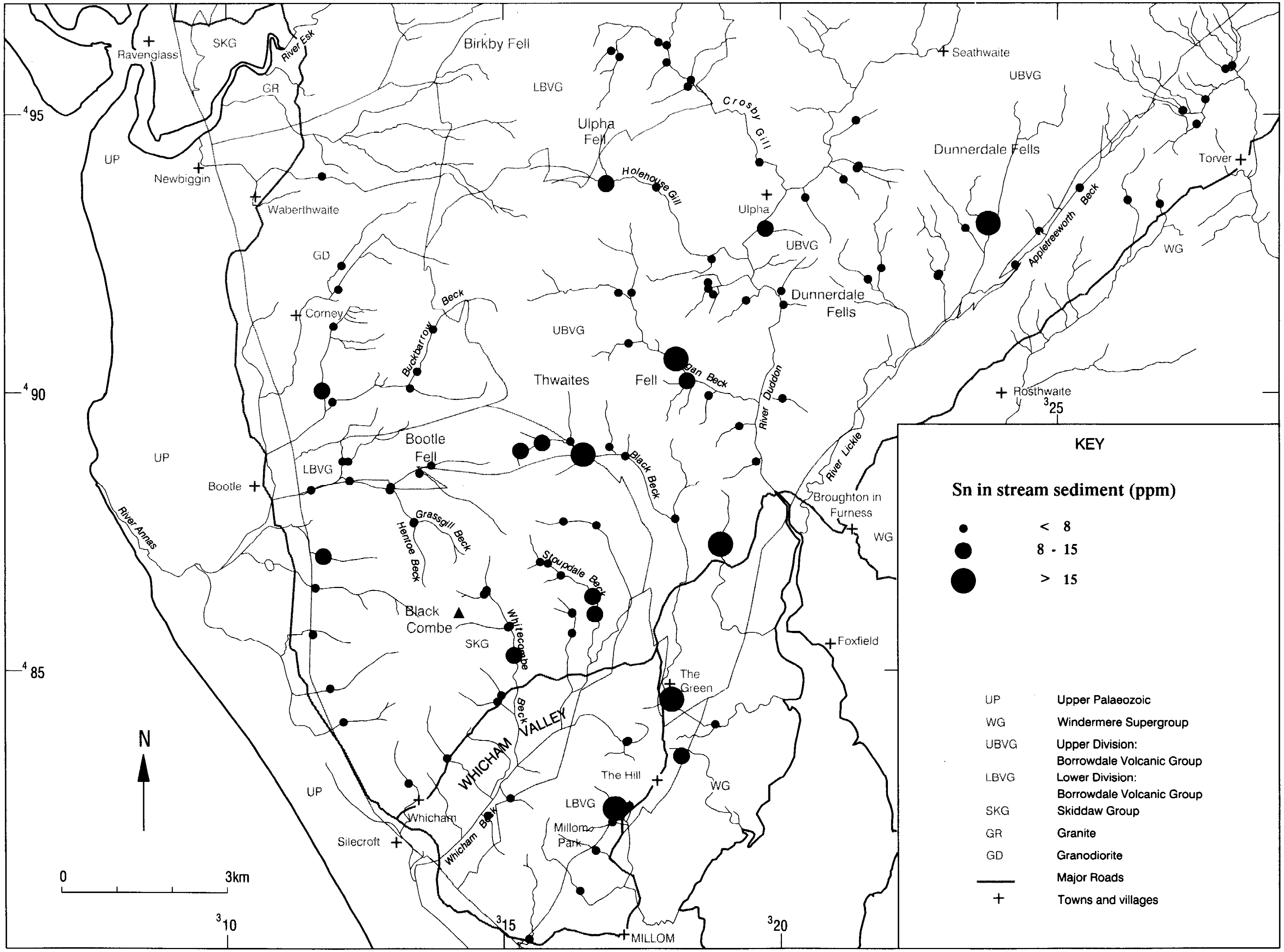

Figure 21 Tin in stream sediment samples

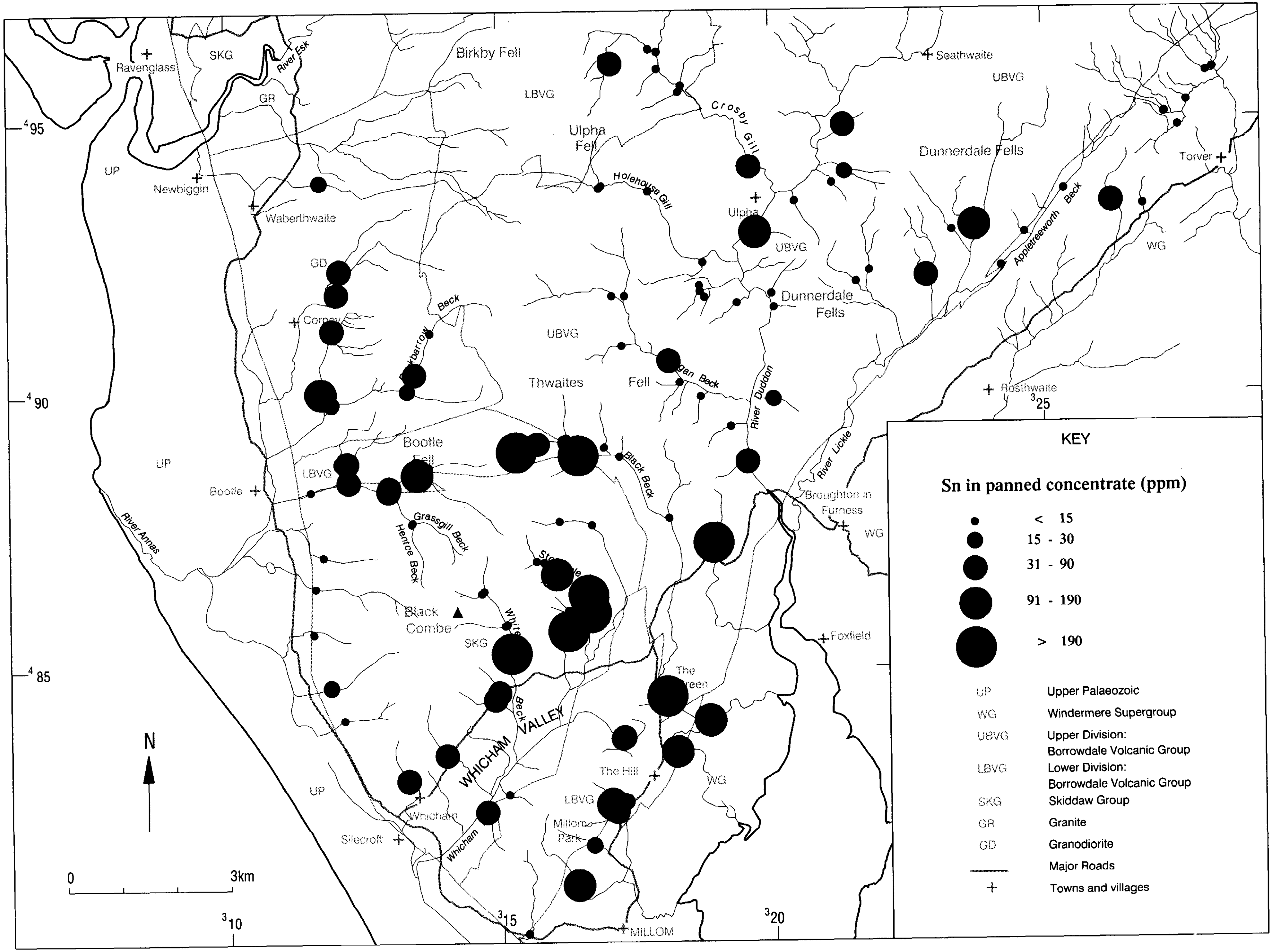

Figure 22 Tin in panned concentrate samples

Tin

Several Sn_c and Sn_p results are below the detection limit (3 ppm) but the higher levels recorded, particularly in panned concentrates, indicate the presence of detrital tin-bearing phases. Different enrichment mechanisms probably account for the poor Sn_c-Sn_p correlation (Table 2). Tin in sediment is generally low over the survey area (Figure 21) and no consistent pattern is evident, except that all the highest values (>15 ppm) are in samples collected over the Borrowdale Volcanic Group and all values over the Windermere Supergroup are low (<5 ppm). The maximum Sn_c value (28 ppm in WCC 3058 [2375 9305]) comes from the River Lickle catchment and contains relatively low levels of most metals except for anomalies in Sn_p and, weakly, Pb_p, suggesting that the cause may be contamination. The second highest value (27 ppm in WCC 3032 from Logan Beck [1812 9061]) represents the only sample containing >15 ppm Sn_c which does not show a substantial increase in Sn in the concentrate from the same site. Mn_c and Zn_c are very high at this site and Cu_p is also anomalous, reflecting upstream copper workings which are probably the source of the Sn anomaly, whether it is mineralisation or contamination. Several weak Sn_c anomalies (8–15 ppm) are in samples from sites where Sn_p is distinctly anomalous.

Sn_p values are often one or more orders of magnitude greater than those in sediment due to the presence of detrital tin-bearing minerals. These are related to Sn mineralisation, trace amounts of Sn in Fe-oxides and contamination. A group of samples containing highly anomalous levels of Sn_p (>190 ppm) occurs on the south-east side of the Black Combe inlier in Stoupdale, Foreslack and Whitecombe Becks (Figure 22) and the highest value recorded (970 ppm) was in a sample from Stoupdale (WCP 135 [1665 8602]). This pan contains bismutite, arsenopyrite, wolframite, sphalerite, baryte and cassiterite as well as pyrite. Cassiterite was also recorded in two other panned concentrates from the Black Combe inlier that were examined mineralogically (Appendix 4). Follow-up work (Part 2) subsequently found in-situ cassiterite mineralisation in Stoupdale.

Four other highly anomalous results (>190 ppm) were recorded, all from streams over Borrowdale Volcanic Group rocks. Two in the upper part of Black Beck (191 ppm in WCP 129 [1531 8896] and 385 ppm in WCP 131 [1644 8889]) drain the aureole of the Eskdale Granodiorite and may be related to mineralisation. Two others near The Green (483 ppm in WCP 3041 [1804 8449]) and Ash House (277 ppm in WCP 3030 [1892 8728]) may be, at least in part, derived from anthropogenic sources. Weaker anomalies may be related locally to traces of Sn in Fe-oxides (e.g. 34 ppm in WCP 3015 from Millom Park [1710 8238] and 57 ppm in WCP 3088 [2286 9214] from Lickledale). Others are associated with sulphide mineralisation such as at High Brow (148 ppm in WCP 3057 [1821 8347]) and in Buckbarrow Beck (59 ppm in WCP 3051 [1345 9038]), though contamination could also be a source of tin.

Titanium

Titanium variation is controlled by bedrock lithology and the concentration of detrital heavy minerals by surface processes. This accounts for the absence of positive correlations between Ti_p and other elements determined except for U_p and Zr_c. The log-scale cumulative frequency plot has a sinuous form reflecting the presence of several overlapping populations, but no well-defined anomalous group is evident and the highest values recorded do not suggest the presence of any rocks carrying abnormally high levels of Ti.

High (>2 %) Ti_p levels are recorded in three areas, the Lower Division of the Borrowdale Volcanic Group in the north of the area, the aureole of the Eskdale Granodiorite, and the Eskdale Granodiorite itself (Figure 23). The highest Ti_p value recorded (4.88 % in WCP 3034 [1686 9376]) is in a sample from a tributary to Holehouse Gill, draining Lower Division Borrowdale Volcanic Group. Leucoxene

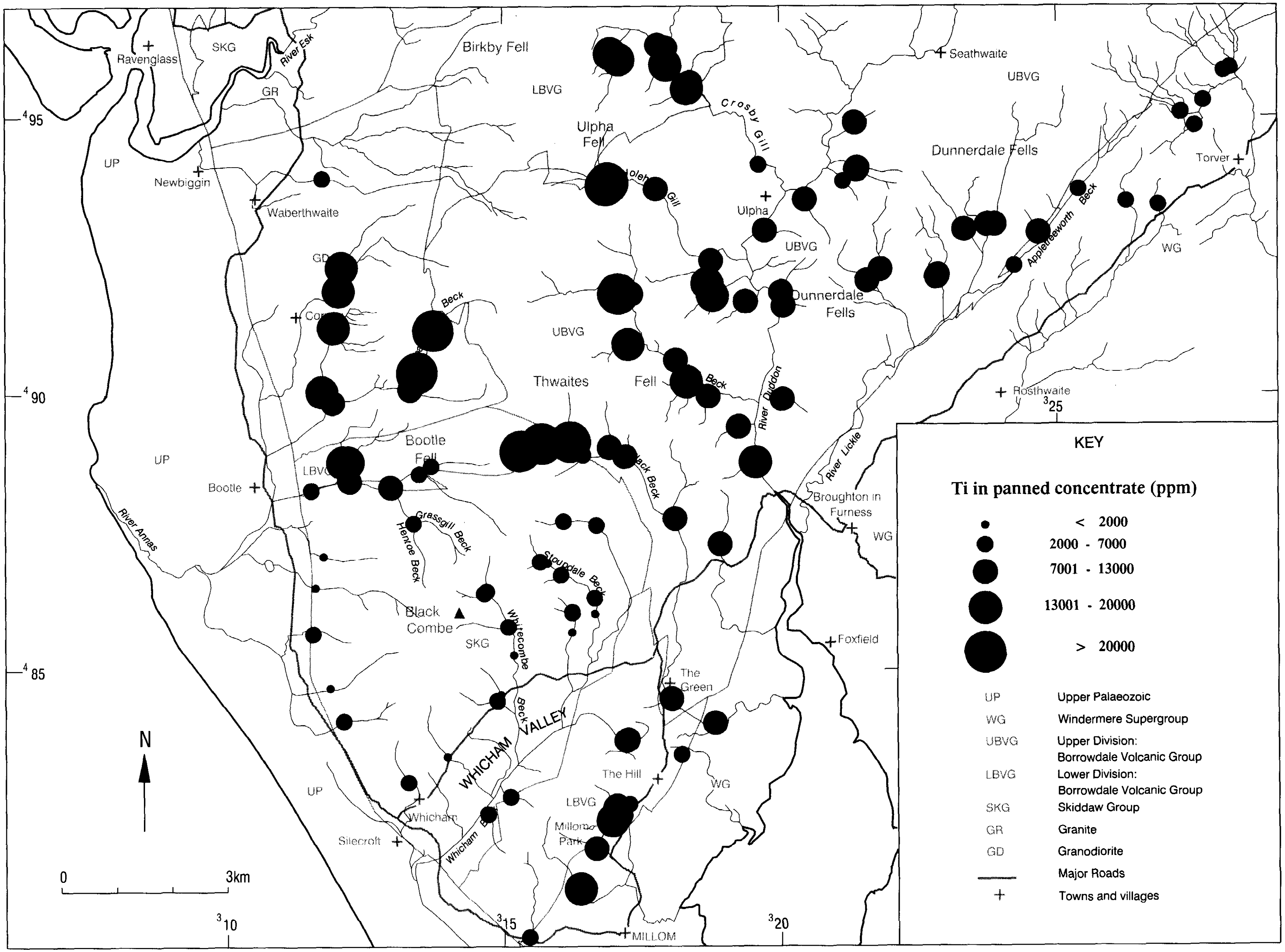

Figure 23 Titanium in panned concentrate samples

was seen during examination of the sample and it is likely, with ilmenite derived from the basic lavas, to be the cause of this anomaly and other high values recorded in the area (Figure 23).

Catchments draining the Borrowdale Volcanic Group in the aureole of the Eskdale Granodiorite also generate high Ti_p, notably in the upper part of Black Beck (e.g. 3.9 % in WCP 130 [1570 8910]) and Logan Beck (3 % in WCP 3026 [1708 9180]). Moderate Ti_p values, typically 0.7–1.5 %, characterise the remainder of the Borrowdale Volcanic Group outcrop, including the Lower Division rocks of Millom Park (Figure 23). Values greater than 1 % Ti_p characterise the outcrop of the Eskdale Granodiorite with the highest levels recorded from Buckbarrow Beck (2.4 % in WCP 3051 [1345 9038] and 3.6 % in WCP 3069 [1374 9114]). These samples contain very high levels of Fe_p and are also enriched in several other metals. The granodiorite is highly altered locally and the Ti is held in anatase, rutile, leucoxene, sphene and ilmenite (Ansari, 1983; British Geological Survey, 1993). The alteration and subsequent decomposition of the rock has probably promoted the release of these minerals, partly accounting for the high values over the weathered granodiorite, typically 0.6 % Ti. Low Ti_p (<0.6 %) results are typical of samples collected over the Skiddaw Group rocks of the Black Combe inlier and the Windermere Supergroup outcrop, reflecting the lack of detrital Ti-rich minerals.

Tungsten

Very high levels of W_p were recorded in the area due to the presence in several samples of the tungsten minerals scheelite, wolframite and stolzite, not recorded previously from this area. The cumulative frequency plot shows the presence of a distinct anomalous population of samples containing more than 20 ppm W_p. W_p shows a very close positive correlation with Bi_p and a less strong correlation with As_p, suggesting an association with the polymetallic vein-style sulphide mineralisation. With the exception of a few weak anomalies (maximum 28 ppm) over the Eskdale Granodiorite, all anomalous W_p results are from sites draining Skiddaw Group rocks of the Black Combe inlier (Figure 24).

All the very high W_p values (>1000 ppm) are from sites in Whitecombe, Foreslack, Stoupdale, Hentoe and Grassgill Becks. The outlying highest result, 59016 ppm, was recorded in a sample from Foreslack Beck (WCP 126 [1624 8568]) which also contained anomalous amounts of As_p and Sn_p. The presence of wolframite and scheelite was confirmed by mineralogical examination, along with cassiterite, bismuthinite, pyrite, zircon and chalcopyrite (Appendix 4). The second highest value, 4540 ppm, is in a sample from Stoupdale Beck (WCP 125 [1661 8634]) which also contained anomalous levels of As_p, Ba_p, Bi_p, Cu_p, Ni_p, Sn_p and Zn_p. Wolframite, sphalerite, baryte and cassiterite were found in the pan (Appendix 4). Further very high results were in samples from Grassgill Beck (3180 ppm in WCP 115 [1339 8768] and 1030 ppm in WCP 105 [1296 8826]), Hentoe Beck (1920 ppm in WCP 116 [1338 8766]) and Whitecombe Beck (1100 ppm in WCP 119 [1519 8428]). Tungsten minerals associated with a wide range of sulphides and oxides were found in all the samples from this group subjected to mineralogical study (Appendix 4). These anomalies clearly indicate the presence of tungsten mineralisation within the area of these catchments.

Smaller anomalies (<1000 ppm) recorded elsewhere in the Black Combe inlier and its periphery may reflect further mineralisation or dispersion from the mineralisation causing the major anomalies. Only minor traces of tungsten were recorded in rock samples collected from quartz-sulphide veins (maximum 73 ppm, Appendix 3). The principal drainage anomalies were the subject of follow-up surveys reported in Part 2.

Two weak anomalies in Buckbarrow Beck (28 ppm in WCP 3051 [1345 9038] and 28 ppm in WCP 3069 [1374 9114]) reflect the presence of Cu-W vein mineralisation tried in this catchment

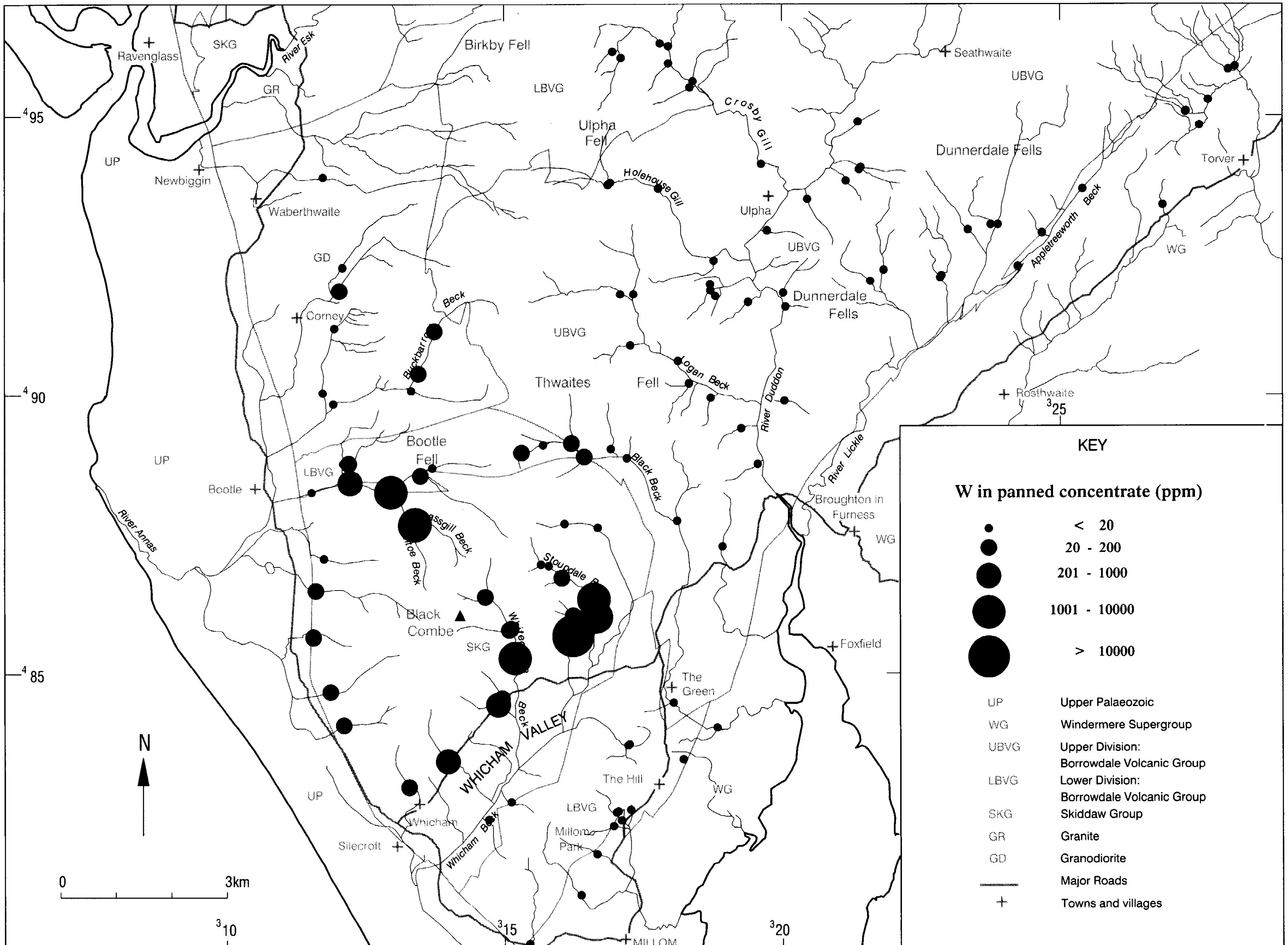

Figure 24 Tungsten in panned concentrate samples

(Appendix 1; Young and others, 1986). A further weak anomaly (22 ppm) over the Eskdale Granodiorite may indicate the presence of further similar vein mineralisation in the granodiorite. Samples collected elsewhere in the survey area all yielded W_p results below 20 ppm (Figure 24).

Uranium

A high proportion of U_c and U_p results are below the detection limit and the maximum values, which are similar (Table 1), suggest that there are no uraniferous concentrations within the survey area. The cumulative frequency plots do not define any distinct anomalous populations, but the maximum U_c value of 11 ppm is an outlier (nearest neighbour 8 ppm). U_c and U_p show a positive correlation and U_p is also correlated with Ti_p, which may be related to the sorting of heavy mineral phases.

Except for one value of 7 ppm in a sample from Stoupdale Beck (WCP 3004 [1604 8672]) all the higher (>5 ppm) U_c results come from sites over the Borrowdale Volcanic Group or the unconformity between the Borrowdale Volcanic Group and the Windermere Supergroup. Within the Borrowdale Volcanic Group outcrop most of these higher values are from sites over the Lower Division rocks in both the north and south of the survey area and the catchments between them, principally Logan Beck and Black Beck. The reason for this distribution is uncertain. Low U_c values (<5 ppm) characterise the Eskdale Granodiorite and the Skiddaw Group. The outlying highest U_c result is in a sample from close to the Borrowdale Volcanic Group/Windermere Supergroup unconformity in Appletreeworth Beck (WCC 3079 [2424 9230]) which could relate to a high percentage of dark shale clasts in the sample. Within the Borrowdale Volcanic Group samples containing 6–8 ppm U_c occur largely in small streams draining upland peaty areas and may be influenced by absorption and complexing of released U with organic material and hydrous iron oxides (e.g. 8 ppm in WCC 3045 [1795 9625]).

U_p shows similar variation to U_c across the survey area, except that much higher U_p values are present over the Eskdale Granodiorite. Consequently the U_p/U_c ratio which is close to one over much of the area is greatly increased over the Eskdale Granodiorite, suggesting the presence of small amounts of a heavy detrital uranium-bearing mineral. Descriptions of the granodiorite suggest that this might be allanite or zircon. The highest U_p values in this part of the survey area (9 ppm) are in samples from Buckbarrow Beck (WCP 3051 [1345 9038]) and the River Annas (WCP 3052 [1203 9186]). Within the Borrowdale Volcanic Group, the distribution of high values is similar to that in sediments with high (6-10 ppm) values all occurring over the Lower Division in Millom Park and the north of the area, in the catchments of Black Beck, Logan Beck and Holehouse Gill and Appletreeworth Beck. The highest U_p values recorded (10 ppm) are in samples from Logan Beck (WCP 3032 [1812 9061]) and Holehouse Gill (WCP 3036 [1777 9370]). U_p is low, typically less than 5 ppm, over the Skiddaw Group and Windermere Supergroup outcrops.

Vanadium

The cumulative frequency plot for V_c shows a large lognormally distributed background population with a distinct group of higher values (>160 ppm) and two outlying very high values. There is a correlation between high levels of V_c and U_c and it is probable that the high group of V_c results is caused in part by the affinity of V for organic sorption sites. The relative abundance of minerals containing V in the source rocks, typically Fe-oxides and Fe-Mg silicates, also exerts an influence on the distribution pattern and relatively low V_c levels (<125 ppm) are a feature of sites over the Eskdale Granodiorite. The only close positive correlation shown by V_c is with Fe_c, reflecting both a primary association with Fe^{3+} and redistribution during surface process into hydrous oxide phases, often associated with organic matter in upland streams. The two outlying high V_c values (318 ppm in WCC 3079 [2424 9230] and 254 ppm in WCC 3078 [2424 9230]) are from adjacent sites in Appletreeworth Beck. Weak enrichments of Cu_{cp}, U_{cp}, Mo_{cp}, As_{cp}, and Zn_c are present in one or both

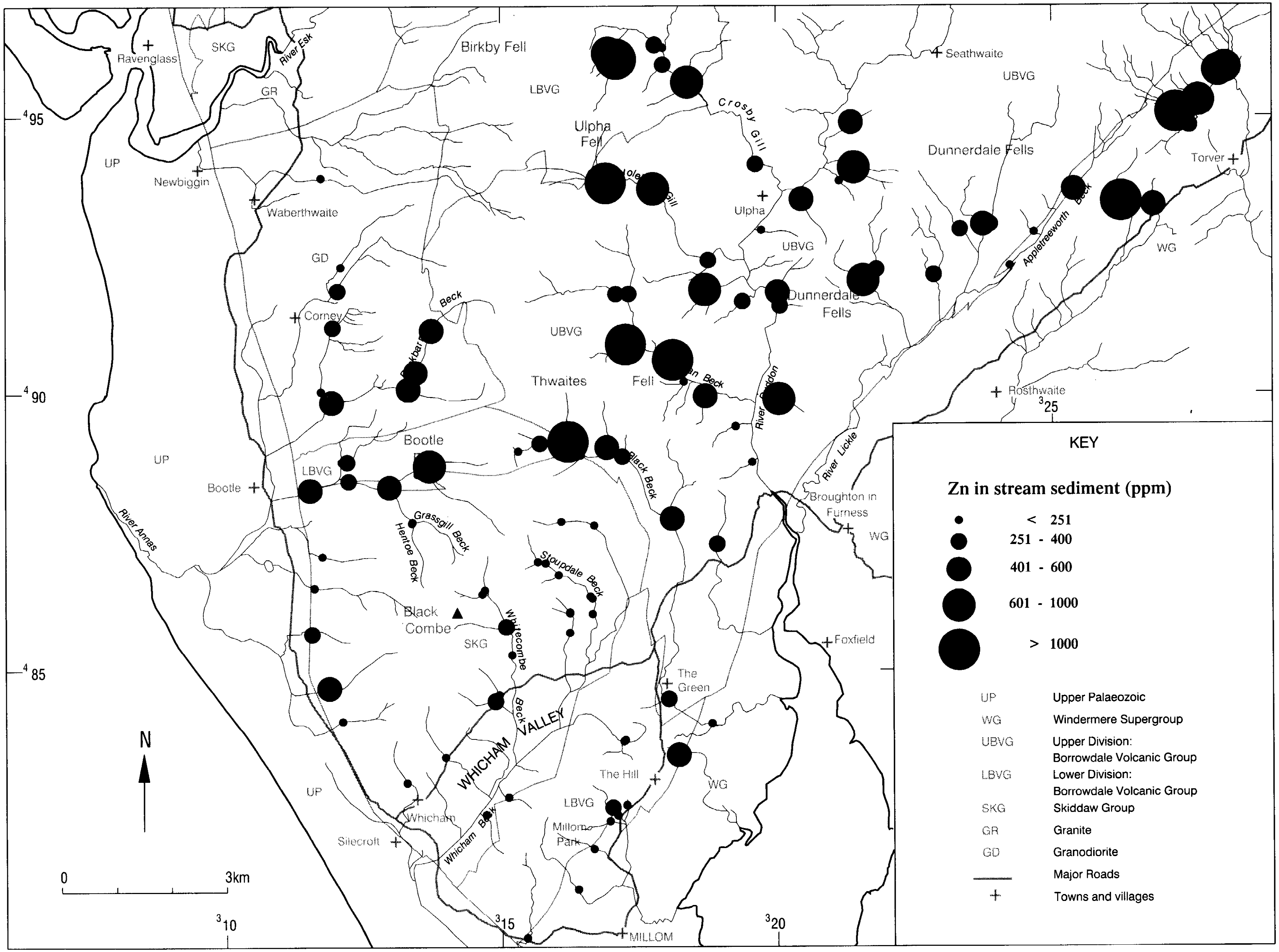

Figure 25 Zinc in stream sediment samples

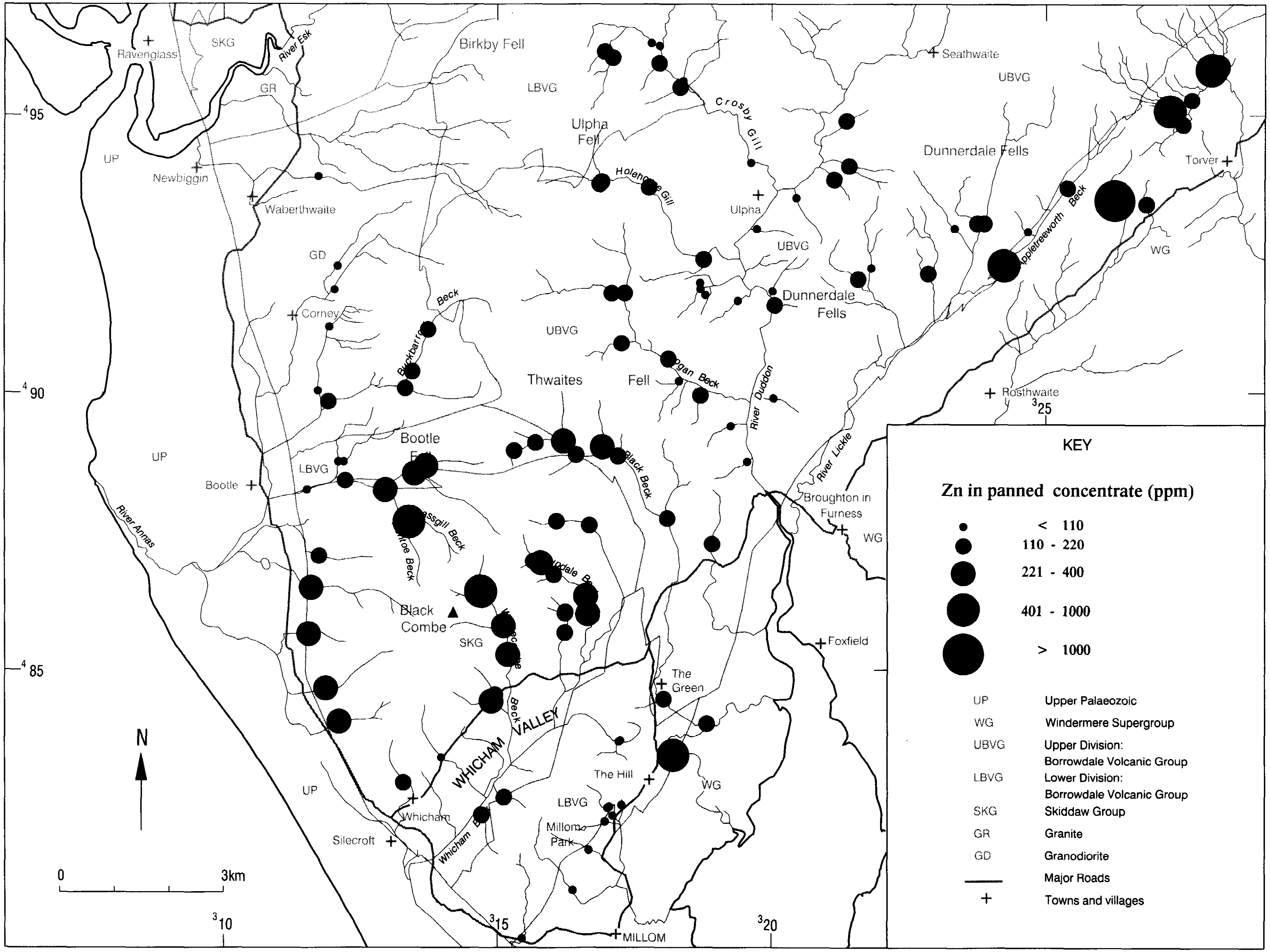

Figure 26 Zinc in panned concentrate samples

and the source of the anomalies is probably the dark shale clasts reported in the sediment. Two high V_c samples from the Appletreeworth/Lickle area, (174 ppm in WCC 3080 [2540 9369] and 165 ppm in WCC 3089 [2388 9305]), and one from High Brow Mine (182 ppm in WCC 3057 [1821 8347]) are thought to be caused by small amounts of V in pyrite. The remaining samples in the anomalous (>160 ppm) group all come from small streams draining peaty upland in Black Beck, Logan Beck and Crosby Gill (e.g. 173 ppm in WCC 132 [1621 8913], 167 ppm in WCC 3025 [1731 9180] and 172 ppm in WCC 3047 [1833 9551]).

Zinc

The Zn_c cumulative frequency plot is complex in detail, indicating the presence of several overlapping populations which include high groupings related to enrichment processes such as mineralisation and hydrous oxide precipitation. The Zn_p plot is simpler and an anomalous group of samples related to mineralisation can be discerned. These differences are reflected in the inter-element correlations (Table 2). There is only a weak correlation between Zn_c and Zn_p, but Zn_c is closely correlated with Mn_c reflecting its presence in hydrous oxide precipitates, whereas Zn_p is most closely correlated with Cu_{cp}, Ni_p and Co_p reflecting its presence in detrital oxides, sulphides and silicates.

In general, Zn_c is high over the main Borrowdale Volcanic Group outcrop, whilst moderate values are found over the Eskdale Granodiorite and low levels occur in the Millom Park area and most of the Skiddaw Group outcrop (Figure 25). In the group of high (>600 ppm) and very high values (>1000 ppm) south-west of Torver, in catchments of the Borrowdale Volcanic Group and Windermere Supergroup, at least one of the anomalies (1118 ppm in WCC 3070 [2626 9347]) is most probably related to mineralisation. High levels of Ba_{cp}, Cu_p, Ni_c and Zn_p also occur at this site (see below). Evidence from the Zn_p distribution suggests that other anomalies in this area may also be derived from mineralisation, although hydrous oxide precipitation has probably contributed to the high Zn_c results. Very high values occur in the north of the area in catchments draining the Lower Division of the Borrowdale Volcanic Group (e.g. 1248 ppm in WCC 3035 [1691 9380] and 1122 ppm in WCC 3043 [1710 9604]). Associated Mn_c and Ti_p enrichments and the location suggest the source of these and other high values recorded in the area is a combination of basic source rocks and hydrous oxide precipitation. High values downstream of mineralisation in Logan Beck (e.g. 1060 ppm in WCC 3032 [1812 9061]) appear to be largely the product of hydrous oxide precipitation rather than a detrital input from the upstream vein mineralisation. A number of other high Zn_c values occur in small streams over the Borrowdale Volcanic Group where Zn_c is much greater than Zn_p and Ti_p and Mn_c are high (e.g. 944 ppm in WCC 3090 [2004 8990] and 1080 ppm in WCC 132 [1621 8913]). These anomalies are also attributed principally to hydrous oxide precipitation processes, though the possibility of mineralisation in the catchment cannot be excluded.

Moderately high Zn_c values in Buckbarrow Beck (e.g. 590 ppm in WCC 3051 [1345 9038]) are probably related to the presence of iron rich minerals, alteration and vein mineralisation in the area. Only moderate to low Zn_c values, often less than 200 ppm, occur in samples downstream of polymetallic mineralisation containing sphalerite in the Black Combe area.

In contrast to Zn_c, Zn_p levels are generally low over much of the Borrowdale Volcanic Group and Eskdale Granodiorite. The highest values are close to the boundary between the Windermere Supergroup and the Borrowdale Volcanic Group in the north-east of the area near Torver and are most probably derived from mineralisation (Figure 26). The outlying highest value recorded (3539 ppm in WCP 3070 [2626 9347]) is in a sample taken from this area. The sample also contains anomalous Ba_{cp}, Cu_p, Ni_c and Zn_c, and tarnished pyrite and baryte were noted in the pan. Other high values in this area (e.g. 823 ppm in WCP 3096 [2802 9583]) are also probably derived from mineralisation in the catchments. The high value in neighbouring Appletreeworth Beck (868 ppm in WCP 3079 [2424 9230]) is probably derived from the mineralisation tried nearby (Appendix 1).

Other large anomalies can also be related to known mineralisation, notably the anomalies by the High Brow pyrite mine (526 ppm in WCP 3057 [1821 8347]) and from a site (578 ppm in WCP 121 [1470 8642]) downstream of a trial on a polymetallic vein in Whitecombe. Several weak anomalies (220–400 ppm) occur in catchments draining the Skiddaw Group rocks of the Black Combe inlier. These frequently contain high levels of other metals and on examination were found to contain sphalerite (e.g. 340 ppm in WCP 135 [1665 8602] and 376 ppm in WCP 105 [1296 8826]), derived from the polymetallic quartz-sulphide mineralisation found in the area. No Zn_p values >220 ppm were recorded in samples collected over the Borrowdale Volcanic Group or Eskdale Granodiorite.

Zirconium

Zr_c shows significant negative correlations with other elements determined in the sediment samples due to its presence in resistant detrital phases in streams, rather than clays, organic matter or hydrous oxide precipitates. This and possible substitution for Ti^{4+} in ilmenite and sphene probably accounts for part of the positive correlation with Ti_p (Wedepohl, 1978). High Zr_c values are characteristic of the outcrop of the Eskdale Granodiorite (281-624 ppm) and low levels (<200 ppm) occur over the Skiddaw Group. Samples from the Borrowdale Volcanic Group are typically in the range 160-300 ppm except in the extreme south-west of the area, north of Millom. Here, three of the five highest results, which form a distinct anomalous group (>450 ppm) on the cumulative frequency plot, are in samples from sites very close to the unconformity between the Lower Division of the Borrowdale Volcanic Group of Millom Park and the Windermere Supergroup (e.g. 649 ppm in WCC 3005 in Langthwaite Beck [1545 8017], 558 ppm in WCC 3008 [1638 8104] and 547 ppm in WCC 3009 [1666 8177]). Other high values, including one of the anomalous results, occur in samples collected to the north-east and it is probable that the source is either a sandy facies at the base of the Windermere Supergroup or tuffaceous units of dacitic composition within the Borrowdale Volcanic Group rocks of this area (Mathieson, 1986). The fifth of the anomalous results (624 ppm) is from a site draining the Eskdale Granodiorite (WCC 3062 [1173 9004]). The source of this and other high values from sites in this area is most probably zircon, or perhaps sphene, from the granodiorite.

ASSESSMENT

Drainage anomalies

Drainage anomalies, probably derived at least in part from previously unknown mineralisation, can be divided into seven areal groups as follows:

(i) sites associated with the Skiddaw Group rocks of the Black Combe inlier;
(ii) sites near Torver;
(iii) sites in the upper catchment of the River Lickle north-east of Broughton Mills;
(iv) sites around Ulpha;
(v) sites in the Millom Park area;
(vi) sites in the aureole of the Eskdale Granodiorite;
(vii) sites over the Eskdale Granodiorite.

Field observation and later follow-up work indicated that most of the mineralisation which gives rise to the substantial drainage anomalies in the Black Combe area is of vein-style. However, the distribution and range of metal anomalies, particularly in panned concentrates which contain detrital ore minerals, suggests the presence of several different phases of mineralisation, one or more of which may be zoned. The principal Sn_p anomalies, caused by the presence of cassiterite, are restricted to the Stoupdale, Foreslack and Whitecombe Beck catchments whilst all the large W_p anomalies (>1000 ppm), which reflect the presence of wolframite and scheelite, are located both in these streams and the northward flowing Hentoe and Grassgill Becks. The largest As_p and Bi_p anomalies, accompanied by substantial Fe and appreciable Cu, Zn, Sb, Co and Ni enrichments, also come from these north and south flowing streams in the central part of the inlier. A few barium anomalies are also present. The anomalies are related to the presence of arsenopyrite, baryte, bismuthinite, bismutite, chalcopyrite, pyrite and sphalerite in the samples, all of which are derived from polymetallic quartz-sulphide vein mineralisation discovered in the catchments. On the west side of Black Combe, in streams draining Townend Knotts, the western edge of the massif and, in part, the northward flowing streams, a different signature dominated by large Pb anomalies is evident. Substantial arsenic anomalies and, locally, moderate Bi, Co, Cu, Mo, Ni and Zn enrichments, accompany the lead anomalies, with high metal levels in sediment samples a feature of several sites. The location of the source of many of these anomalies is unknown, but one of the most prominent is related to a worked quartz-sulphide vein structure on Townend Knotts.

Anomalies near Torver, in the Millom Park area and in the upper catchment of the River Lickle north-east of Broughton Mills are all in catchments close to the unconformable junction of the Windermere Supergroup and Borrowdale Volcanic Group. In the Torver area, anomalies are recorded in Torver Beck and other southward flowing streams draining the Borrowdale Volcanic Group. The largest anomalies are recorded in sediment (Cu, Fe, Mn, Ni and Zn) but there are high levels of zinc in panned concentrate, accompanied by moderate nickel and titanium enrichments. Some of these anomalies are undoubtedly related to the bed rock lithology and hydrous oxide precipitates, but there is also a strong possibility of undiscovered base-metal mineralisation in the catchments. McAllister (1979), who undertook an earlier stream sediment survey, recorded anomalies (As, Bi, Cu, Mo and Pb) in this area which suggested the presence of mineralisation in the catchment of Goat Tarn Beck. To the south-west of Torver, there is a very pronounced anomaly at a site on the Windermere Supergroup, downstream of the unconformity at Hummer Bridge, which almost certainly reflects mineralisation in the catchment. The panned concentrate from here (WCP 3070 [2626 9347]) contains anomalous levels of Ba, Cu, Ni and Zn, and pyrite and baryte were seen in the pan.

Anomalies for a number of metals (As, Cu, Fe, Mo, Sb, Ti and V) dispersed at sites in tributaries to the River Lickle north-east of Broughton Mills may have a number of sources. Those in Appletreeworth Beck, close to the base of the Windermere Supergroup, are related to the sulphide mineralisation tried in the vicinity and dark shale clasts in the alluvium. Most other anomalies in this catchment are characterised by high levels of iron accompanied by some enrichment of antimony, arsenic, copper, molybdenum and titanium. The source of these enrichments is most probably an abundance of iron oxide minerals containing trace amounts of these metals. Some of the iron oxides are derived from rocks within the Borrowdale Volcanic Group, but at most of the anomalous sites it is probable that hematite mineralisation is the source, some of the highest results coming from sites close to the Dunnerdale Fell hematite working.

In the Ulpha area there are a number of anomalies which can be related to worked quartz-sulphide vein mineralisation at Hesk Fell and Ulpha (Millbrow) in the Holehouse Gill catchment, and at Logan Beck and Bowscale Beck in the Logan Beck catchment. Anomalies, particularly of base and transition metals in sediment, are common in the smaller tributaries of this area and the Duddon catchment to the north-east. These are in many cases the product of hydrous oxide scavenging or the complexing of lead with organic matter, but the source of the base metals may in some cases be further vein-style mineralisation.

The Millom Park area, composed of Borrowdale Volcanic Group rocks with Windermere Supergroup rocks to the south-east, generates a number of anomalies, attributable to various sources. A sample containing material from the High Brow pyrite mine contains a wide range of metal anomalies in panned concentrates (As, Ba, Fe, Mo, Sb, Sn and Zn). Sites to the south-west contain similar anomalies (Fe, As, Mo, Sb and Sn). Iron oxides and pyrite recorded in the pans suggest that iron mineralisation is the principal source. Enrichments of several elements in sediment samples (Cr, Fe, Mo, Sn and Zr) can be attributed largely to this source or to host rock lithology, but tin may have an anthropogenic origin. Barium anomalies here and to the north-west show a correlation with the line of the unconformity between the Borrowdale Volcanic Group and the Windermere Supergroup. A few of these, for example the anomaly north-west of Waterblean hematite mine, appear to be associated with iron anomalies and probably indicate the presence of baryte-hematite mineralisation. The evidence for appreciable sulphide mineralisation, except for pyrite, in this area is weak. The most prominent exception is a lead and barium in panned concentrate anomaly from the south side of Whicham valley (WCP 3006 [1471 8239]) which may be indicative of baryte - base-metal mineralisation in the catchment.

Few anomalies in the survey area have a signature which suggests an anthropogenic source but an exception may be the large anomaly at The Green. The panned concentrate from this site (WCP 3041 [1804 8448]) contained highly anomalous levels of copper, lead, antimony and tin as well as substantial amounts of iron. High tin levels in concentrates from a site at Ash House WCP 3030 [1892 8728], north-east of Millom Park, and others close to old mine workings, such as High Brow may also have an anthropogenic input.

A cluster of anomalies for many elements in the upper reaches of Black Beck are in catchments draining the aureole of the Eskdale Granodiorite. The anomalies (Cu, Ba, Fe, Mn, Mo, Ni, Pb, Sn, Ti, V, Zn) are often stronger in sediment than concentrate and a combination of hydrous oxide scavenging and high background levels may account for several of the enrichments. However, quartz-sulphide and hematite vein-style mineralisation may also contribute.

The principal anomalies over the Eskdale Granodiorite occur in Buckbarrow Beck downstream of copper-tungsten-bismuth quartz vein mineralisation (Young and others, 1986). The anomalies (weak to moderate levels of As, Bi, Fe, Mo, Sn, W and Sb) appear to be derived from a combination of this mineralisation and iron oxides, principally from hematite mineralisation. Weaker anomalies with a similar signature elsewhere over the granodiorite suggest that further weak vein sulphide and hematite mineralisation may be present in the granodiorite, probably buried beneath the blanket drift cover.

Regional variation and controls on mineralisation

The distinctive spatial distribution patterns of anomalous levels of individual elements in drainage samples across the survey area reveals valuable information on mineralisation controls. Tin anomalies known to be caused by cassiterite mineralisation are restricted to the central part of the Skiddaw Group inlier. Here they occur in association with tungsten anomalies which extend into the northern part of Black Combe and occur again related to outcropping mineralisation in Buckbarrow Beck. In Black Combe, the tin and tungsten anomalies are associated with the presence of tourmalinites and bleached (metasomatised) Skiddaw Group rocks. Cassiterite is only found in the Lake District at one other locality, Carrock Fell Mine (Young, 1987), and all the tungsten minerals recorded here are also found associated with the late Caledonian intrusions at Skiddaw and Shap. There are no similar intrusions known in this area. The nearest exposed major intrusion, the Eskdale Granodiorite, is not highly evolved and has a Silurian age (Rundle, 1992), but one of the geophysical models suggests that an evolved granite may underlie the granodiorite and extend under the north side of the Skiddaw Group inlier (Figure 8). Such a model would provide a source of heat, fluids and metals to account for the tin-tungsten mineralisation, metasomatism and tourmalinisation found at surface. Parallels with the Skiddaw intrusion and associated mineralisation are strong and, by inference, an end-Caledonian age for this putative intrusion is likely. Minor acid intrusions poorly exposed in Hentoe and Grassgill Becks may be higher level expressions of this plutonic event.

Copper ± bismuth ± arsenic ± cobalt mineralisation is more widespread throughout the area than recognised previously and, according to Stanley and Vaughan (1982), forms (with tungsten mineralisation) part of a major Lower Devonian mineralising event in the Lower Palaeozoic rocks of the Lake District. If this is so, zonation is suggested with the highest temperature mineral suites restricted to the central part of Black Combe and with the copper ± bismuth ± arsenic ± cobalt association showing a more general relationship to the southern margin of the batholith. From the data presented here it is not clear if the large lead anomalies on the west side of Black Combe represent a further zone of this event, or are derived from a separate mineralisation event. Fracturing, perhaps related to the formation of the major volcano-sedimentary depression of the Ulpha Basin or formation of the Westmorland monocline, as well as the location of the granitic intrusions and lithology may have influenced the sites of vein-style ore deposition.

Evidence from the distribution of anomalies and mineralised rock samples suggests that baryte deposition formed part of one or more later mineralisation events, in which it may be associated with hematite or base-metal mineralisation, or may have been deposited alone. There is a general association of barium in panned concentrates anomalies with both the central part of the Black Combe inlier (sulphide associated) and the base of the Windermere Supergroup (hematite and sulphide associated). The precise nature of the controls on the location of baryte mineralisation is uncertain and may differ for each association. In the latter instance, the Southern Borrowdales Lineament coincides with the base of the Windermere Supergroup, which lies within the steep belt of the Westmorland monocline. Re-activation along this structure, controlled by deep-seated fractures, may have opened channelways for mineralising fluids and voids filled by this mineralisation.

Anomalies related to hematite mineralisation suggest that there is a tendency for this mineralisation to be concentrated in faults/fractures in the vicinity of major lineaments. There is a noticeable absence of anomalies related to iron oxides in the Skiddaw Group rocks of the Black Combe area, perhaps due to these argillaceous rocks acting as an effective seal to the passage of fluids at the time of hematite mineralisation.

Age of mineralisation and source of fluids

Stanley and Vaughan (1982) indicated that there are several episodes of vein mineralisation in the Lake District, each characterised by a distinctive mineral assemblage. Deposits containing pyrite, arsenopyrite, chalcopyrite, bismuth and tungsten minerals were believed to be the earliest and to be Lower Devonian (c. 390–370 Ma) in age. Geothermometric studies indicated that minerals in this suite had formed in the range 300–400° C. Veins dominated by galena, sphalerite and baryte veins were assigned a Lower Carboniferous (360–330 Ma) age, and baryte dominant veins were associated with an Upper Carboniferous to Lower Permian event (290–260 Ma). However, there is also some evidence to suggest the presence of an Upper Carboniferous or Mesozoic base-metal event (e.g. Naden, 1992), and some mineral parageneses could not be assigned readily to any of these events (e.g. quartz-stibnite veins).

At least some of the veins assigned to the Lower Devonian event are associated spatially with the last phase (c. 395 Ma) of Caledonian granitic pluton emplacement and there is evidence to suggest that fluids and metals may have been derived from both the granites and the host rocks (e.g. Ball and others, 1985; Cooper and others, 1988; Lowry and others, 1991). By contrast, there is increasing evidence to suggest that the Carboniferous and Mesozoic mineralisation is basin-related (Lowry and others, 1991; D C Cooper and others, 1992; Young and others, 1992).

The copper mineralisation at Ulpha and Coniston was assigned to the Lower Devonian event by Stanley and Vaughan (1982) but no mention was made of any other mineralisation in the survey area. The mineral suite in many of the veins recorded in the survey area (pyrite-arsenopyrite-chalcopyrite ± cobalt, tungsten and bismuth minerals) suggests that they were emplaced during the Devonian mineralising event. Gold and tin mineralisation recorded from this area for the first time and described in more detail in Part 2 is also associated with this Devonian event. The paucity of lead-zinc-barium mineralisation indicates that the later Carboniferous–Mesozoic mineralisation, which forms major deposits in the north of the Lake District, is poorly represented in this area, unless the lead anomalies on the west side of Black Combe are related to undiscovered mineralisation of this event. There is little evidence to indicate which, if any, of the major events described by Stanley and Vaughan (1982) the pyrite mineralisation at High Brow should be assigned.

CONCLUSIONS AND RECOMMENDATIONS

1. The results of the geochemical drainage survey revealed substantial tin, tungsten, copper, bismuth, arsenic, antimony, zinc, lead, cobalt and nickel anomalies which suggested the presence of polymetallic mineralisation in the Black Combe area. Large polymetallic anomalies were recorded in the Stoupdale, Foreslack, Whitecombe, Grassgill and Hentoe catchments, with lead anomalies dominant in the streams draining to the west of Black Combe.

2. Concurrent examination of rock outcrops supported the drainage data in indicating that quartz-sulphide vein-style mineralisation was more widespread and contained a greater range of metals than had been indicated by the brief published descriptions of mineralisation and mineral working in the area.

3. Chemical analysis of rock samples from old workings and other mineralised structures confirmed field observations that locally, particularly in the Black Combe area, the vein-style mineralisation is polymetallic with variable amounts of arsenic, gold, bismuth, copper, lead, zinc and in a few localities antimony, barium, cobalt, nickel, tungsten and tin. Iron mineralisation occurs as oxide (hematite) and sulphide deposits. Mercury was present in appreciable amounts in samples from the High Brow pyrite mine.

4. Assessment of drainage and lithogeochemistry data suggests that the vein-style mineralisation is polyphase and that individual phases may be zoned. Small-scale tin (cassiterite) mineralisation, concentrated in the central part of the Black Combe Skiddaw Group inlier, is probably the earliest and highest-temperature mineralising event. Drainage data indicate that tungsten mineralisation is present in this area as well as in the Eskdale Granodiorite. Arsenic ± copper ± bismuth ± gold and, locally,

cobalt mineralisation is more widespread, occurring in the Skiddaw Group in Black Combe and the Borrowdale Volcanic Group to the north-west. Lead - zinc mineralisation may accompany this event and/or form a separate episode of mineralisation. Baryte occurrences are most probably associated with later mineralising events, including hematite mineralisation.

5. The high-temperature (tin - tungsten - arsenic - copper - gold - bismuth - cobalt) mineralisation is related to the tourmalinisation and metasomatism of the Skiddaw Group in Black Combe and to the end-Caledonian (Acadian) granitic magmatism, mineralisation taking place in the Devonian (c. 370–400 Ma). Lead, zinc and barium mineralisation may be younger, Carboniferous or Mesozoic in age. The age of the massive pyrite mineralisation at High Brow is uncertain.

6. These discoveries support geophysical models which indicate a buried, evolved granitic intrusion underlying the northern margin of Black Combe on the southern side of the Lake District batholith. Other, structural, controls on mineralisation may include the Ulpha Basin, a major volcano-tectonic depression; the Acadian, south-east facing, Westmorland Monocline and any deep seated structure reflected in the Southern Borrowdales Lineament. In addition, lithology, particularly the differences in competence and composition between the volcanic succession, underlying Skiddaw Group mudstones and overlying Windermere Supergroup sandstones, shales and limestones, may also act as a control on deposition.

7. Other drainage sample anomalies are attributable to iron oxides, derived from the weathering of most rock types, and from hematite mineralisation. High levels of iron are accompanied locally by antimony, arsenic, molybdenum, cobalt, chromium, and nickel enrichments. Dark shales also produce enrichments in some of these elements in stream sediment samples locally.

8. Anthropogenic sources are responsible for very few of the drainage anomalies.

9. The principal drainage anomalies that merit further investigation are those in the Skiddaw Group inlier of Black Combe. First-stage follow-up of the drainage anomalies in this area, involving further drainage sampling, bank sampling, traverse-based soil and soil-gas sampling, and rock sampling has been carried out and will be reported in Part 2.

10. A second area which merits first stage follow-up to ascertain the source of drainage anomalies lies north and west of Torver.

ACKNOWLEDGEMENTS

Landowners and tenants in the survey area are thanked for their co-operation with access to land for sampling purposes. Sample collection was assisted by W J Chant, A Danson, N M Fraser, G E Hewson, R Knight, C J A McEwan, M H Strutt, and M N Ingham. Sample preparation and XRF analyses were carried out by BGS staff under the supervision of M A Allen and A S Robertson. Gold analyses were carried out by Analabs, Caleb Brett International Ltd, St Helens. Diagrams were prepared by C Simpson and other members of the BGS Drawing Office under the supervision of R J Parnaby.

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APPENDIX 1 Location of mineral workings (metalliferous minerals and slate) in the survey area.

Name	Grid reference SD		Workings	Worked or tried for
Appletreeworth Beck	242	922	adit	?copper
	245	926	adit	?slate
	246	926	adit	iron (hematite)
Birks	203	932	adit	slate
Black Beck	172	888	adit	copper
	173	887	adits, shaft	copper
	174	886	adit	copper
Bowscale Beck	172	908	adit	copper
Buckbarrow Beck	137	910	adit	copper
	136	908	open work	copper
Cotehaw	198	945	adit	slate
Dunnerdale Fell	227	924	adit	iron (hematite)
Hesk Fell	175	942	adit	copper
	175	942	adit	copper
	176	941	adit	copper
High Brow	181	834	adit	sulphur (pyrite)
	181	835	shaft	sulphur (pyrite)
	181	835	?shaft	sulphur (pyrite)
Kirkbank (Whicham)	130	829	adit	?copper
Knott Hill	169	875	adit	?copper
Logan Beck	172	916	shaft	copper
	173	915	adit	copper
	173	915	adit	copper
Long Garth	181	920	?adit and shaft	copper
Middle Kinmont	117	905	adit	iron (hematite)
Raven Crag	167	883	adit	?copper
Stainton Ground	220	934	quarry	slate
	217	932	quarry	?
The Pike	189	936	adit	slate
Townend Knotts	132	840	open cut	?copper, lead and zinc
	131	840	adit	?copper, lead and zinc
	132	840	open cut	?copper, lead and zinc
Ulpha (Millbrow)	187	923	shaft	copper
	186	924	adit	copper

Continued...

APPENDIX 1, continued

Name	Grid reference SD		Workings	Worked or tried for
Uncertain (Ghyll Scar)	172	828	adit	?iron(hematite)
Uncertain (?Gray Stones)	160	871	?collapsed adit	?
Uncertain (?Guinea Bridge)	149	862	adit	?
Uncertain (?Hentoe)	134	871	adit	slate
	132	868	adit	slate
Uncertain (?Horseback)	149	860	open cut	?pyrite
Uncertain (?Midlow Hill)	179	833	adit	?
Uncertain (?Seaness)	128	831	pits	?
Uncertain (?Stoupdale)	163	865	bell pit	?
Uncertain (?Tarn Dimples)	119	862	adit	slate
	118	863	quarry and adit	slate
Uncertain (?Under Hill)	180	830	adit	?
Waterblean	176	825	open cast	iron (hematite)
Whicham	139	809	open cast	iron (hematite)
Whitecombe	148	863	adit	?lead, zinc and copper
Whitecombe Beck	151	857	adits	copper
Woodhouse	125	831	adit	?copper

Note; names given in the form - ?Seaness - are applied by the authors of the current work, as no original name has been traced.

APPENDIX 2 Metalliferous mineral occurrences found and verified during the reconnaissance survey.

Locality name	Grid reference SD		Sample numbers	Mineralisation noted
Old workings				
Appletreeworth Beck adit	245	926	766	pyrite
Appletreeworth Beck	242	923	768	pyrite, arsenopyrite
Black Beck Mine tip	173	887	316, 971	pyrite
Black Beck Mine tip	171	888	317	pyrite, chalcopyrite, sphalerite,
Black Beck Mine tip	172	888	303, 304	chalcopyrite, pyrite, sphalerite,
Bowscale Beck Mine	172	908		chalcopyrite
Buckbarrow Beck tip	137	910	762	chalcopyrite, arsenopyrite, bismuth minerals
Buckbarrow Beck vein	136	909		chalcopyrite, bismuth minerals, scheelite, wolframite
Buckbarrow Beck vein	136	909		chalcopyrite, scheelite
Buckbarrow Beck vein	138	912		scheelite
Ghyll Scar Quarry	171	829	764	hematite
?Gray Stones	160	871	652	pyrite
Hesk Fell Mine tip	175	942	461	pyrite, chalcopyrite, arsenopyrite, sphalerite, galena
Hesk Fell Mine tip	175	941	462	pyrite, chalcopyrite, arsenopyrite, galena, sphalerite, erythrite
Hesk Fell Mine tip	175	942	968	pyrite, chalcopyrite, arsenopyrite, galena, sphalerite
High Brow	181	831	757	pyrite
High Brow Mine	182	834	758	pyrite
?Horse Back	149	860	301	pyrite
Kirkbank Trial tip	130	829	610, 612	pyrite, chalcopyrite, arsenopyrite
Logan Beck Mine tip	173	915	967	pyrite, chalcopyrite
Raven Crag Trial tip	168	883	314	pyrite, chalcopyrite
?Seaness	128	831	999	pyrite
Stainton Ground	220	934	658	pyrite, arsenopyrite
Townend Knotts tip	132	840	956	pyrite, arsenopyrite, bismuth minerals
Townend Knotts tip	132	840	963	arsenopyrite, pyrite, chalcopyrite, galena, sphalerite, bismuth minerals
Ulpha Mine tip	184	922		chalcopyrite, arsenopyrite, bismuth minerals
Ulpha Mine adit	186	924	772	chalcopyrite
Ulpha Mine tip	187	923	444	arsenopyrite, chalcopyrite
Ulpha Mine tip	186	923	969	pyrite, arsenopyrite, sphalerite
Waterblean Mine	176	825	760	hematite
Waterblean Mine	176	825	761	baryte

Continued...

APPENDIX 2, continued

Locality name	**Grid Reference SD**		**Sample numbers**	**Mineralisation noted**
Whitecombe	148	863	302, 409	galena, sphalerite, pyrite, arsenopyrite, chalcopyrite, fluorite
Whitecombe Beck	151	856	300, 406, 407	pyrite, arsenopyrite, chalcopyrite
Wood House	125	831	456	pyrite, chalcopyrite, arsenopyrite, erythrite
Unworked occurrences				
Anna Crag	145	865		tourmaline
Buckbarrow Beck	136	909		scheelite, chalcopyrite
Buckbarrow Beck	137	912		scheelite
Crookley Beck	127	883	507	pyrite, chalcopyrite
Damkirk Beck	121	891		chalcopyrite, galena
Grassgill Beck	136	876	427, 713, 714	pyrite, arsenopyrite
Gray Stones	161	873	651	tourmaline
Hentoe Beck	133	873	776, 777	pyrite, arsenopyrite
Stoupdale Crags	154	871		pyrite, arsenopyrite
Stoupdale	159	868	952, 953, 954 988, 989	pyrite, arsenopyrite chalcopyrite, cassiterite galena, sphalerite, baryte
Stoupdale Beck	159	868	654	pyrite, arsenopyrite, galena, sphalerite, chalcopyrite
Stoupdale	160	868	987	tourmaline
Stoupdale	161	867	986	pyrite, arsenopyrite, galena sphalerite, chalcopyrite
Stoupdale	157	866	990, 992	pyrite, arsenopyrite, galena sphalerite, baryte
Stoupdale	159	867	995 996	pyrite, arsenopyrite, galena, chalcopyrite, sphalerite
Stoupdale	166	863	783	pyrite, sphalerite, arsenopyrite, chalcopyrite,
Stoupdale	166	863	997, 998	pyrite, arsenopyrite
Swinside	168	884	315	pyrite, galena
Whitecombe Screes	147	868		pyrite, arsenopyrite
Whitecombe	147	862		pyrite, arsenopyrite
Whitecombe	151	855	405	pyrite, chalcopyrite, arsenopyrite
Whitecombe	150	854	449	pyrite, arsenopyrite
Whitecombe	150	858	451	pyrite, arsenopyrite

Unworked pyrite occurrences omitted.

APPENDIX 3 Summary of chemical and mineralogical analyses of rocks collected for verification of mineralisation in south western Cumbria

WCR	NGR SD		Location	Metalliferous Minerals	Metal enrichment
300	1516	8569	Whitecombe Beck, copper mine tip	cpy, pyr, asp	Au, As, Cu, (Fe), (Sb), (Pb)
301	1496	8605	Horse Back trial, by track	pyr	Fe, (As), Ti, (W)
302	1486	8638	Whitecombe, trial tip	gal, sph, pyr, asp, cpy	Ag, As, (Bi), Cu, Pb, Zn
303	1725	8883	Black Beck, mine tip on south-west bank	cpy, pyr, bornite	(Bi), Cu
304	1728	8880	Black Beck, mine tip on south-west bank	cpy, pyr	(Bi), Cu, Pb, Zn, (Ag), (As)
314	1680	8831	Swinside, trial tip, below Raven Crag	pyr, cpy	(Fe), (Pb), (Cu)
315	1687	8842	Swinside quarry by path north of farm	pyr, gal	(Fe), Pb
316	1731	8876	Black Beck Mine tip	pyr	not analysed
317	1714	8889	Black Beck, stream side mine tip	pyr, cpy, sph	not analysed
405	1518	8558	Whitecombe Beck	pyr, cpy, asp	not analysed
406	1517	8568	Whitecombe Beck Cu Mine tip; wallrock	pyr	(Au)
407	1517	8568	Whitecombe Beck, adit entrance	pyr, asp, cpy	not analysed
409	1486	8638	Whitecombe Beck trial tip	gal, sph, pyr, asp, cpy	not analysed
427	1360	8768	Upper Grassgill Beck, outcrop by stream	pyr, ?asp	As
443	1180	8632	Tarn Dimples, outcrop by slate trial	-	(Pb)
444	1875	9237	Ulpha (Millbrow) Mine, tip	asp, cpy	As, (Bi), Cu, (Fe), (Co)
449	1500	8547	Whitecombe Beck, trial tip east of Sty Knotts	pyr, asp	As, (Fe), (Au)
451	1503	8583	Whitecombe Beck, north of Blackcombe Beck	pyr, asp, ?cpy	Fe, (Cu), As, (Co)
456	1255	8310	Wood House, tip from trial	pyr, cpy, asp, erythrite	Co, Cu, Ni, As
461	1756	9426	Hesk Fell Mine, upper tip	pyr, ?sph, ?gal, asp, cpy	(Fe), Pb, Zn, As, (Co), Cu, (Sb)
462	1755	9419	Hesk Fell Mine, central tip	pyr, asp, ?gal, ?sph, cpy erythrite	Bi, Co, (Fe), Pb, Zn, As, Cu, (Ag)
507	1270	8830	Crookley Beck, outcrop by stream	pyr, cpy	not analysed
610	1302	8290	Kirkbank (Whicham), trial tip	pyr. cpy, asp	As, Bi, Cu, (Pb)
612	1302	8290	Kirkbank (Whicham), outcrop above level	pyr	-
651	1610	8730	Greystones summit	(tourmaline)	-
652	1600	8710	Greystones, by footpath, trial tip?	pyr	(Fe), (Mo)
654	1598	8680	Stoupdale, outcrop in stream bed	pyr, asp, gal, sph, cpy	As, (Cu), Pb, Zn
658	2202	9348	Stainton Ground, quarry, middle level	pyr, asp	As, (Sb)
713	1361	8766	Grassgill Beck, outcrop by stream	asp, pyr, ?cpy, sph	As, Au
714	1361	8767	Grassgill Beck, outcrop by stream	pyr, asp	As
757	1810	8310	High Brow, outcrop north-east of farm	pyr	Hg
758	1821	8346	High Brow Sulphur Mine; block	pyr	As, (Fe), (Sb), Hg, (Mo)
759	1821	8347	High Brow Sulphur Mine, adit entrance	-	(Fe), (As)
760	1760	8252	Waterblean Mine, north of farm	-	(As), (Ba), Fe, (Sb), Mo
761	1764	8254	Waterblean Mine, tip north-east of farm	hematite	Ba, Ca
762	1371	9101	Buckbarrow Beck Trial, tip north of stream	cpy, asp, bis	(As), Bi, Cu, (Fe), (W)
763	1717	8303	Ghyll Bank Quarry	-	Ca
764	1717	8299	Ghyll Bank Quarry	hematite	Ca
765	1821	8346	High Brow Sulphur Mine, entrance; block	pyr	(Ca)
766	2452	9260	Appletreeworth Beck, adit	pyr	-

Continued...

APPENDIX 3, continued

WCR	NGR SD		Location	Metalliferous Minerals	Metal enrichments
767	2424	9228	Appletreeworth, roadside adit	pyr	-
768	2423	9230	Appletreeworth, 15m north-east of adit	pyr, asp	(Fe), (As), (Mo)
769	2423	9230	Appletreeworth, 10m north-east of adit	pyr	-
770	2424	9228	Appletreeworth, adit entrance	-	-
771	2424	9228	Appletreeworth, adit	pyr	-
772	1862	9244	Ulpha (Millbrow), adit entrance north of road	cpy	(Bi), Cu, (Zn)
776	1338	8734	Hentoe Beck, outcrop on west side	pyr, asp	(As), (Fe)
777	1338	8734	Hentoe Beck, outcrop on west side	pyr, asp	As
778	1717	8306	Ghyll Bank Quarry	-	-
779	1717	8306	Ghyll Bank Quarry	-	(As), (Fe)
783	1661	8633	Stoupdale, west bank, base of waterfall	pyr, sph, asp, cpy	As
952	1591	8684	Stoupdale Beck, outcrop in west bank	pyr, asp, cas	As, Bi, Pb, Sn, (W), (Sb)
953	1591	8684	Stoupdale Beck, outcrop in west bank	sph	As, Bi, Pb, Sn, (W), (Sb)
954	1591	8684	Stoupdale Beck, outcrop in west bank	pyr, asp, cpy, gal, sph bar	As, Ba, Cu, Pb, (Sb), (Sn), Zn, Au
956	1322	8404	Townend Knotts, tip 10m below track	pyr, asp, ?bis	As, Bi, (Fe), (Pb), (Au), (Mo)
959	1218	8669	Little Fell, outcrop on crags	-	Pb
963	1322	8404	Townend Knotts, tip 100m below path	asp, pyr, cpy, gal, sph, bis, ?pyh	As, Bi, Co, Cu, (Fe), Pb, Zn, Au, (Ag)
967	1730	9157	Logan Beck Mine; tips	pyr, cpy	Cu, (Bi)
968	1750	9422	Hesk Fell Mine; tips	pyr, asp, cpy, gal, sph	As, Cu, (Fe), (Pb), Zn
969	1866	9237	Ulpha (Millbrow) mine tips south of road	pyr, asp, sph	As, (Cu), Zn, (Au)
970	1715	8888	Black Beck, mine tip	cpy	Cu
971	1730	8876	Black Beck, mine tip	pyr	(Mn)
986	1615	8673	Stoupdale, on hillside north-east of stream; block	pyr, asp, sph, gal, cpy	As, (Bi), Cu, Sb, Zn, (Pb), Au, Ag, (Ca)
987	1601	8685	Stoupdale, on hillside north-east of stream	(tourmaline)	-
988	1590	8684	Stoupdale, outcrop in stream bed	pyr	(Ba)
989	1591	8683	Stoupdale, outcrop in west bank	pyr, asp	As, (Ba), (Bi), Pb, (Sb), Hg, Sn, Au
990	1577	8661	Stoupdale, outcrop north of Windy Knott	pyr, asp, ?sph, ?gal	As, (Ba), (Bi), Pb, (Sb), Sn, Au
992	1577	8661	Stoupdale, outcrop north of Windy Knott	?asp, ?pyr, ?sph, ?gal	As, (Ba), (Bi), (Fe), Pb, Sb, Zn, (Au)
995	1597	8670	Stoupdale, north of Leadmine Breast	pyr, asp, gal, sph	As, (Fe), Pb, Zn
996	1597	8670	Stoupdale, north of Leadmine Breast	pyr, asp, gal, cpy, sph	As, (Bi), Cu, Pb, Zn, Au, (Ag)
997	1662	8633	Stoupdale, outcrop, east side of waterfall	pyr, asp	As
998	1662	8633	Stoupdale, outcrop, east side of waterfall	pyr, asp	As
999	1287	8314	Whicham, outcrop on Seaness hilltop	pyr	U

Continued...

APPENDIX 3, continued

Key

Mineralogical abbreviations		**Metal enrichments** values in ppm			
		Ca > 20%	(Ca) 10%-20%	Ni > 500	(Ni) 200-500
asp	arsenopyrite	Cu > 1000	(Cu) 300-1000	Pb > 1000	(Pb) 300-1000
bar	baryte	Bi > 500	(Bi) 100-500	Sb > 500	(Sb) 100-500
bis	bismuth mineral(s)	Fe > 20%	(Fe) 10%-20%	Sn > 500	(Sn) 100-500
cas	cassiterite	Mn > 5%	(Mn) 1%-5%	Ti >1%	
cpy	chalcopyrite	Ag > 50	(Ag) 30-50	U >10	
gal	galena	As > 1000	(As) 300-1000	V > 300	
pyh	pyrrhotite	Ba > 2000	(Ba) 1000-2000	W > 50	(W) 30-50
pyr	pyrite	Co > 500	(Co) 200-500	Zn > 1000	(Zn) 300-1000
sph	sphalerite	Cr >800	(Cr) 500-800	Hg > 500 ppb	(Hg) 100-500 ppb
-	no metalliferous mineral	Mo > 50	(Mo) 30-50	Au > 1 ppm	(Au) 500-1000 ppb
	noted in hand specimen	-	no anomalous element		

Analytical data is available from the Mineral Reconnaissance Programme Database.

APPENDIX 4 Mineralogical examination of panned concentrates

Adapted from: BLAND, D J and NANCARROW, P H A. 1988. Panned concentrates from Black Combe, Lake District. *British Geological Survey, Mineral Sciences Research Group Interim report.*

Introduction

Eleven panned concentrates collected in the Black Combe area of the English Lake District were examined to establish the source of high metal concentrations in the samples.

Method

The entire sample remaining after removal of a 12 g split for chemical analysis, was separated in methylene iodide (SG 3.33) and the sink fraction scanned by XRF.

After separation with the Frantz Isodynamic Magnetic Separator, the heavy mineral sink fractions were examined briefly under the binocular microscope using white and ultra-violet light. Ultra-violet light, used primarily to look for scheelite, also showed a mineral with a yellow fluorescence which was later shown to be stolzite. Selected grains were subject to XRF scanning (to confirm the presence of one or more of the anomalous elements) prior to XRD identification.

Results

The brief optical examination, combined with the XRF scanning of individual grains, suggested the presence of the following phases:-

WCP 105	wolframite, cerussite, scheelite, cassiterite, sphalerite (pale), pyromorphite.
WCP 109	cerussite, scheelite, cassiterite, (no wolframite)
WCP 116	scheelite, cerussite
WCP 117	wolframite, scheelite, cassiterite, cerussite, W + Pb mineral fluorescing yellow
WCP 119	oxidised pyrite, baryte, sphalerite, scheelite
WCP 121	baryte, sphalerite, leucoxene
WCP 124	baryte
WCP 125	wolframite, sphalerite, baryte, cassiterite
WCP 126	wolframite, pyrite (fresh to very oxidised), zircon, little scheelite, chalcopyrite, rare garnet, cassiterite
WCP 132	cerussite, leucoxene, anatase, no fresh pyrite
WCP 135	wolframite, sphalerite, baryte, cassiterite, pyrite

Arsenic is highly anomalous in several of these samples, but has not been allocated to any mineral as arsenopyrite or other arsenic-rich phases could not be identified visually. It was later found that this was because arsenopyrite is heavily altered on the surface, being black or reddish, which made its recognition with the binocular microscope highly unlikely.

Table 1 Results of XRF scans

Sample No.	Much	Some	Trace
WCP 105	Pb, As, W	Zn, Zr, Ba	Sn, Sb, Cu, Bi, Sr
WCP 109	Pb	Zn, As, W, Bi, Zr	
WCP 116	Pb, As	Zn, Bi, Zr	Ba, Cu, Sr, Ce
WCP 117	W, Pb, Bi, As	Zn	Sn, Ce, Ba, Sr, Zr
WCP 119	As, Ba	Pb, Bi, Zn, W	Sn, Sr, Zr
WCP 121	Ba, As	Zn, Sr, Pb, Zr	Zn, Bi, W, Y
WCP 124	Ba	Zn, Pb, Sr	As, Y, Zr, Ce
WCP 125	As	Bi, Pb, Sn, Ba, W	Ce, Sr, Y, Zr
WCP 126	W	Cu, As, Sn	Zn, Ba, Bi, Y, Sr
WCP 132	-	Zn, Sr, Y, Zr, Ba, Pb, As	Sb, Bi, W
WCP 135	W, As, Bi, Ba	Pb, Zn	Sn

Table 2 Results of XRD of selected grains

Sample No.	Description	Major element	XRD identification
WCP 105	greyish-brown vitreous	Bi	Bismutite $Bi_2(CO_3)O_2$+ Quartz
	yellow-green vitreous	Pb	Pyromorphite $Pb_5(PO_4)_3Cl$
WCP 116	colourless/yellow,	Pb + W	
	UV fluorescent yellow		Stolzite ($PbWO_4$)
WCP 119	brown vitreous	Bi	Bismutite $Bi_2(CO_3)O_2$
	soft flaky grey metallic	Bi	Bismuthinite Bi_2S_3
	brittle grey metallic with black tarnish	As	Arsenopyrite FeAsS
WCP 121	blue vitreous	Ba	Baryte $BaSO_4$
WCP 124	dark brown	Mn	prob. Cryptomelane KMn_8O_{16}
	dark brown	Fe	Goethite FeO(OH) + others
WCP 126	brown resinous, square prismatic	Sn	Cassiterite SnO_2
	brown resinous	Bi	Bismuthinite Bi_2S_3
WCP 135	brown resinous with yellow coating	Bi	Bismutite $Bi_2(CO_3)O_2$
	dark brown with rusty coating	As	Arsenopyrite FeAsS