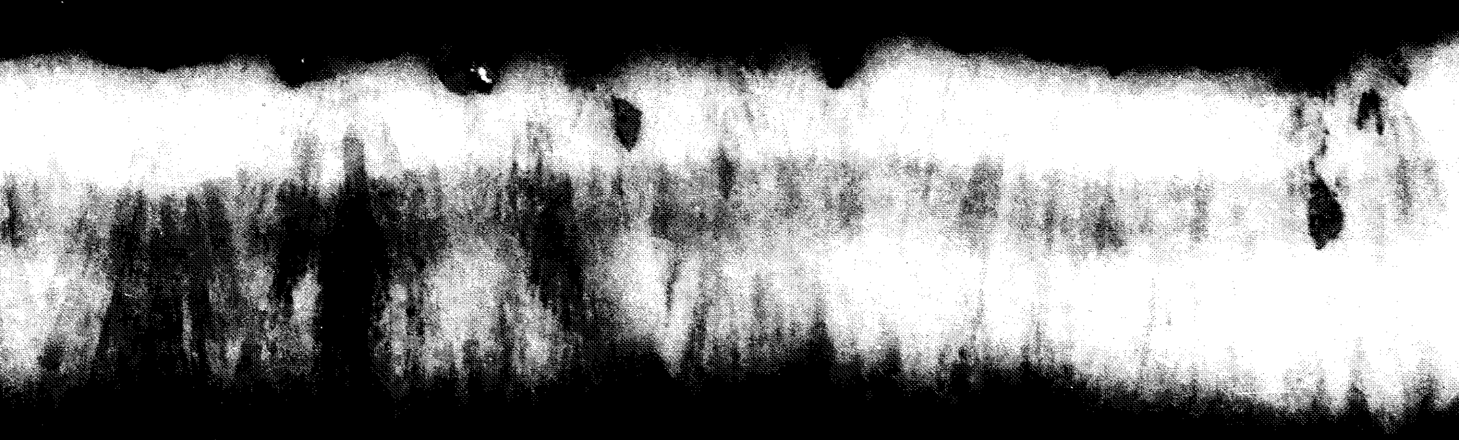
British Geological Survey

MINERAL RECONNAISSANCE PROGRAMME

No. 91

A geochemical survey of part of the Cheviot Hills and investigations of drainage anomalies in the Kingsseat area



Department of Trade and Industry

Cover illustration
A banded carbonate/sphalerite vein from the Gwynfynedd Gold Mine, near Dolgellau in North Wales. The photograph shows banded carbonate, sphalerite and marcasite.

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 The information contained herein must not be published without reference to the Director, British Geological Survey.

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BRITISH GEOLOGICAL SURVEY

Mineral Reconnaissance Programme

Report No. 91

A geochemical survey of part of the Cheviot Hills and investigations of drainage anomalies in the Kingsseat area

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A report prepared for the Department of Trade and Industry

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BRITISH GEOLOGICAL SURVEY

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DATA PACKAGE

This report contains a summary of geochemical surveys carried out in the western Cheviot Hills. A comprehensive data package is available at a current (1988) cost of £1000 sterling. This includes:

A—Consultation with available British Geological Survey staff who carried out the surveys.

B—Examination of thin sections and rock samples collected during the surveys.

C—A detailed data package containing the items listed below. The analytical data are available in digital form if required:

1 Be, B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Zr, Mo, Sn, Ba, Pb and LoI analyses for 708 stream sediment samples collected during the reconnaissance survey.

2 Ti, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Mo, Sn, Sb, Ba, Ce and Pb analyses for 708 panned concentrate samples collected during the reconnaissance survey.

3 Cu, Zn and Pb analyses for 710 streamwater samples collected during the reconnaissance survey.

4 Fiche containing the analytical data for the 708 stream sediments and panned concentrates collected during the reconnaissance survey.

5 Notes on the determination and distribution of metal anomalies in stream sediments and panned concentrates.

6 Notes on the mineralogical examination of panned concentrates from the Kingsseat area.

7 Cumulative frequency plots for elements determined in the reconnaissance drainage survey samples.

8 1:100 000-scale maps showing the location of anomalies for Be, B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Zr, Mo, Sn, Ba and Pb in stream sediments; Ti, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Mo, Sn, Sb, Ba, Ce, Pb, Bi and U in panned concentrates and Cu, Zn and Pb in streamwaters.

9 Notes on regional geochemical variation.

10 1: 200 000 scale moving-average figure-field plots for Be, B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Zr, Mo, Sn, Ba and Pb in stream sediment and Ti, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Mo, Sn, Sb, Ba, Ce and Pb in panned concentrates.

11 Report of investigations in the Kingsseat area. This includes:

i Maps of the geology and alteration assemblages in the Kingsseat area.

ii Be, B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr, Mo, Ag, Sn, Ba, Pb and LoI analyses for 93 additional stream sediment samples collected from the Kingsseat area.

iii Ca, Ti, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Mo, Sn, Sb, Ba, Ce, W, Pb, Bi, Th and U analyses for 93 additional panned concentrates collected from the Kingsseat area.

iv Ca, Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, Sn, Sb, Ba, Ce, W, Pb, Bi, Th and U analyses for 82 rock samples collected from the Kingsseat area. Au analyses for 29 of these samples.

v List of thin sections.

vi Petrographic notes on major lithologies, based on 48 thin sections.

vii Geochemical maps of the Kingsseat area showing the location of stream sediment and panned concentrate anomalies.

Enquiries regarding the data package should be made to Dr D J Fettes, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, or Mr J H Bateson, British Geological Survey, Keyworth, Nottingham NG12 5GG.

SUMMARY

The results of a reconnaissance geochemical drainage survey across an area of 850 km^2 in the Cheviot Hills are reported. At each of the 708 sample sites, the − 0.15 mm fraction of the stream sediment, a panned heavy mineral concentrate derived from the − 2 mm fraction of the stream sediment and a water sample were collected. Be, B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Zr, Mo, Sn, Ba, Pb and LoI were determined in stream sediment samples; Ti, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Mo, Sn, Sb, Ba, Ce, Pb, Bi and U in panned concentrate samples and Cu, Zn and Pb in water samples.

The survey area is composed largely of andesitic volcanic rocks of Lower Devonian age. Underlying Silurian greywackes and shales and overlying Devonian and Carboniferous sedimentary rocks and basaltic lavas are exposed around the periphery of the volcanic complex. The Cheviot granite crops out on the eastern margin of the area.

Anomalous concentrations of metals recorded in the drainage samples are, in general, related to (i) known mineral occurrences, (ii) hydrous oxide precipitation and scavenging processes, (iii) the relatively widespread occurrence of baryte, (iv) contamination, (v) tourmalinisation and other hydrothermal activity and (vi) high background levels in unmineralised rocks. At several localities, however, the source of an anomaly is uncertain and some of these may reflect hitherto unknown mineralisation. Anomaly groupings and regional variation patterns in the data are influenced by major structures such as the Gyle-Harthope fracture zone.

Follow-up investigations into a wide range of metal anomalies in the the Kingsseat area involved more detailed drainage sampling, geological mapping at 1:10 000 scale and petrographic, mineralogical and lithogeochemical studies. Rocks, previously mapped as extrusive mica felsites, are reinterpreted as a high level intrusion complex, named the Cock Law Complex, which contains five distinct types of porphyry. Many of the intrusive and extrusive rocks are highly altered and seven alteration assemblages are identified, arising from sericitisation, kaolinisation, silicification, tourmalinisation, haematisation and carbonate alterations. All except haematisation are related to Lower Devonian igneous activity. Metal enrichments were recorded in many of the analysed rocks. The greatest enrichments, for the widest range of elements, occur in samples taken from a gossanous structure, where the mineralisation has features in common with the epithermal precious-metal style of mineralisation associated with sub-aerial volcanism.

RECONNAISSANCE DRAINAGE SURVEY

Introduction

A geochemical drainage survey was carried out across the outcrop of the Lower Devonian volcanic rocks of the Cheviot Hills in Roxburghshire and Northumberland (Figure 1). It was designed to complement similar surveys of the Cheviot Granite and the adjacent Silurian-Devonian contact zone (Haslam, 1975; Leake and Haslam, 1978). A geochemical survey of the Lower Carboniferous outcrop south of the present survey area has also been reported (Bateson and others, 1983).

The area is covered by O.S. 1:50 000 topographic sheets 74, 75, 80 and 81; Geological Survey of Scotland 1:50 000 or 1:63 360 sheets 11, 17, 18 and 25: Geological Survey of England and Wales 1:50 000 sheets 3, 4, 5, 6 and 7.

Topographically, the survey area forms part of a deeply dissected plateau, with round-topped hills and steep sided valleys. The plateau stands some 400 m above the floodplains of the rivers Tweed, Till, Aln and Breamish. Rough grass covers the hills except over the highest ground where heather grows on peat. The high ground is mainly used for sheep grazing, with some softwood planting and a large tract used as a military firing range. Only in the north of the survey area, on the Tweed floodplain, is large scale arable farming possible.

The upland area is sparsely populated but the military ranges are a major source of artificial contamination. In the northern, more populated, lowland section of the survey area, artificial contamination of the streams from agricultural and domestic sources is widespread.

Thick glacial deposits and alluvium are mainly confined to the lowlands but rock exposure is relatively poor in the uplands, as head, scree and boulder clay cover the steep hillsides. Most rock exposure is found along stream courses where active erosion has cut to bedrock.

Geology

There are few accounts of the geology of the area and there has been no resurvey of the Scottish part since Geikie mapped it in 1883. The English side was resurveyed in the 1920's (Carruthers and others, 1932) and the descriptions given below are based largely on this work supplemented by the observations of Robson (1976, 1977).

Most of the survey area is composed of extrusive and intrusive volcanic rocks of Lower Devonian age which lie unconformably on Silurian shales and greywackes. The volcanics are unconformably overlain by Upper Devonian sandstones and Carboniferous conglomerates, sandstones, mudstones, cementstones, dolomitic limestones and basaltic lavas (Figure 2).

Sedimentary and volcanic rocks

Silurian The oldest rocks, exposed in the west and southwest of the area (Figure 2), form a folded and cleaved sequence of Wenlockian mudstones, siltstones and sandstones (greywackes). These rocks suffered deformation and low-grade metamorphism during the Caledonian (end-Silurian) tectonism.

Devonian The earliest Devonian rocks comprise the Cheviot Volcanic Group. These dominantly sub-aerial volcanics contain minor intercalations of grey and red

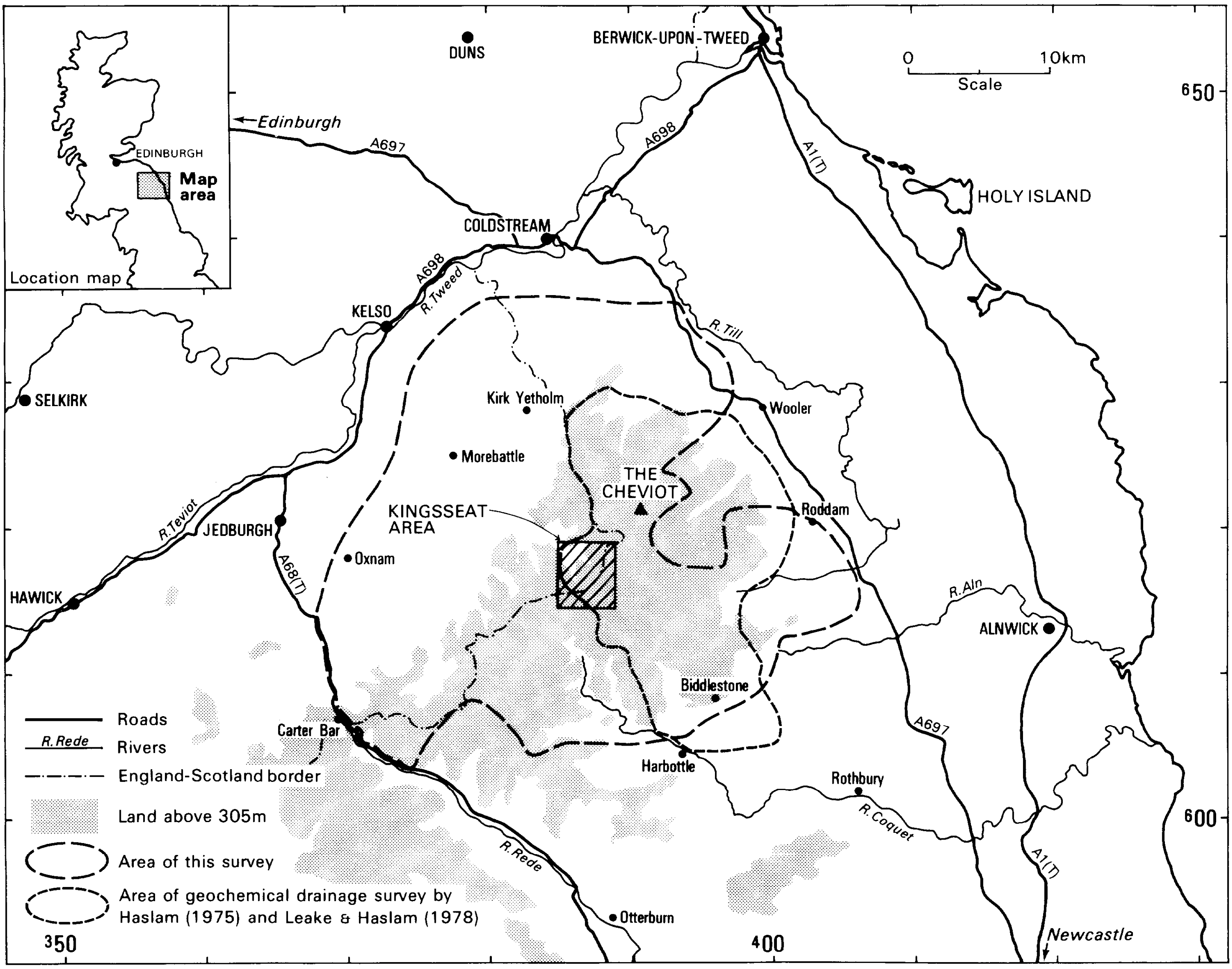

Figure 1 Location of the survey area

sandstones, marls and greenish mudstones. The group unconformably overlies the Silurian rocks and is in turn unconformably overlain by Upper Old Red Sandstone conglomerates (of Upper Devonian age). It is therefore presumed to be of Lower Devonian age. At Oxnam, near Jedburgh, red sandstones, shales and conglomerates unconformably overlying near-vertical Wenlockian strata, may have been deposited contemporaneously with the volcanism.

The lower part of the volcanic succession comprises a series of agglomerates, tuffs and ashes, probably erupted from a number of separate centres. These rocks are best exposed on the southwestern side of the Cheviot massif, where they directly overlie Silurian rocks and are estimated to be less than 60 m thick (Taylor and others, 1971). The agglomerate is described by Carruthers and others (1932) as a 'silicified breccia, the fragments of which are usually of a fine-grained purple mica-felsite'.

The remainder of the succession is comprised largely of variably altered, grey and purple, porphyritic, andesites, with minor amounts of pyroclastics. The lavas carry phenocrysts of andesine-labradorite feldspar and, invariably, altered orthopyroxene and clinopyroxene; they are commonly amygdaloidal, with small irregularly shaped vesicles, infilled with chalcedony or quartz and chlorite. Locally, flows of dark grey or black 'glassy andesite' are found cut by red veinlets of jasper and chalcedony. These lavas are unusually fresh and contain phenocrysts of hypersthene, augite and labradorite. Oligoclase trachytes are recorded in the upper part of the Alwin basin (Carruthers and others, 1932). They are fine-grained and consist of rare feldspar phenocrysts set in a matrix of oligoclase feldspar and altered pyroxene.

Near the base of the succession, at least in the western part of the area, the pyroclastic rocks are overlain by some 15 m of porphyritic acid volcanics, described as mica-

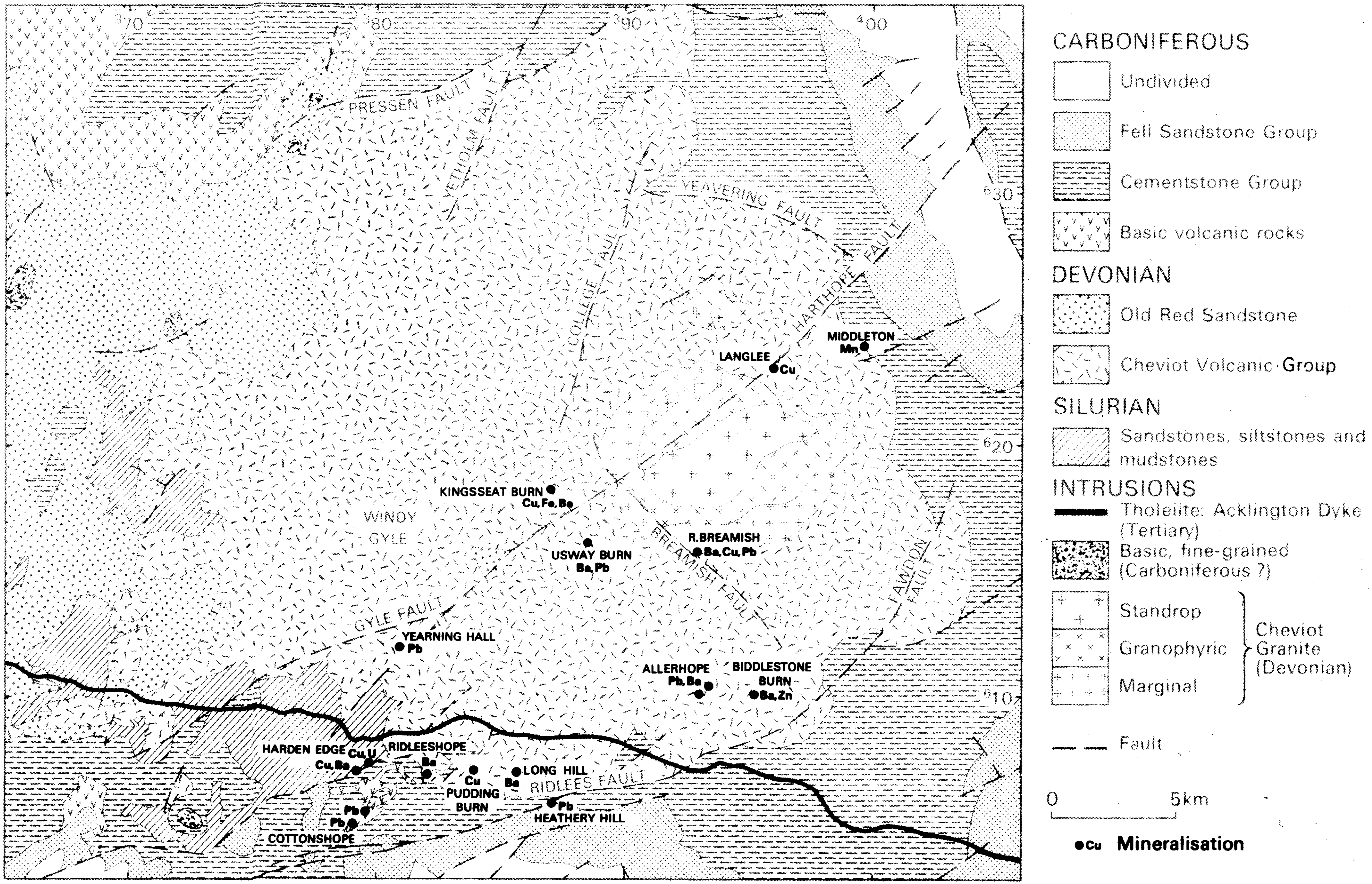

Figure 2 Simplified geological map of the Cheviot Hills area showing the location of documented metalliferous mineral occurrences (see Table 1)

felsites by Carruthers and others (1932) and rhyolites by Robson (1976). These rocks consist of a groundmass of quartz and feldspar, with prominent phenocrysts of biotite and, less commonly, alkali feldspar. A second group of rhyolitic rocks (Robson, 1976), which outcrop in the area between Cocklawfoot and the Border, have been reinterpreted during the present survey as part of a high level intrusive complex, in which the two main rock types are a biotite porphyry and a pyroxene-biotite porphyry. Volcanic breccias, probably indicating the sites of vents, have been noted at several localities, such as Fundhope Rig [NT 867 178]. The total thickness of the volcanic pile is uncertain. Robson (1976) estimates that 2000 m of lavas may have been erupted and that at least 500 m remain.

Sandstone, siltstones, marls and conglomerates of Upper Old Red Sandstone (Devonian) age unconformably overlie the andesites along most of their western outcrop. They are predominantly red in colour and contain cornstone bands.

Carboniferous In the north-west of the area the Upper Old Red Sandstone sequence is succeeded by basaltic lavas of the Birrenswark Volcanic Group (Kelso Traps) which form the base to the Carboniferous in this area. The lavas are succeeded by the Cementstone Group of the Dinantian, in which locally developed lavas of Puy-type represent the waning phases of the Lower Carboniferous volcanic episode. Small exposures of olivine-basalts (the Cottonshope Lavas) also lie near the base of the Cementstone Group in the south-west of the area (Figure 2).

In the east and south of the area, the Lower Palaeozoic rocks are unconformably overlain by the Cementstone Group. Here, this comprises a locally developed basal conglomerate, overlain by a cyclic sequence of mudstones, shales, cementstones, dolomitic limestones and sandstones. The basal conglomerate is exposed in Roddam Dene [c.NU 020 205], at Ramshope [NT 732 060] and Windy Gyle [NT 850 155]. At the first two localities pebbles are mainly andesitic, while at the third granite pebbles and boulders are predominant.

Small exposures of the overlying Fell Sandstone Group, which comprises up to 300 m of pink, coarse, false-bedded and massive sandstones, are found close to the margins of the area (Figure 2).

Intrusions

Cheviot Granite The Cheviot Granite cuts and bakes the Cheviot Volcanic Group and yields a Devonian isotopic age of 390 Ma (Halliday and others, 1979). It has been subdivided into three varieties (Jhingram, 1942), namely, a fine-grained marginal phase, termed either pyroxene-granodiorite (Haslam, 1975) or quartz-diorite (Lee, 1983) and a more acid phase split into the 'Standrop' and granophyric varieties (Jhingram, 1942). The Standrop variety is a light grey granodioritic rock containing diopside, whilst the granophyric type is pink, and contains little or no pyroxene.

A contact metamorphic aureole of baked andesites, about 1 km wide, surrounds the granite, except where the boundary is faulted. The unfaulted contact is locally complex, with ramifying veins of fine grained granite running into the andesitic host rocks. Rafts of metamorphosed lava, presumed to be part of the original roof, occur well within the granite boundary. These, together with the wide aureole, suggest that the present erosion level is near the top of a dome shaped intrusion and that the granite/lava contact is gently dipping (Robson, 1976). From geophysical data, Lee (1983) estimates that the granite has a diameter of 35 km at 9 km depth.

Minor Intrusions Most minor intrusions in the area are associated with Devonian and Carboniferous volcanicity. Dykes of Devonian age intrude both the Cheviot Volcanic Group and the granite. The dykes, trending NNW and NNE, appear to be concentrated in the southern part of the area (e.g. Robson, 1976, Figure 1) but it is uncertain how much this distribution is affected by the detail of the geological mapping. Four varieties of dyke were distinguished on the English side of the Border by Carruthers and others (1932); mica porphyrites, quartz porphyries, felsites and pyroxene porphyries. Their relationship to the granite is uncertain; only a few can be traced into it, suggesting that at least some may be earlier, but aplite veins cutting granite and lavas are in turn cut by dykes (Taylor and others, 1971; Mitchell, 1972). An intrusive complex comprised of at least five types of porphyry is located in the Cocklawfoot-Windy Gyle area. The complex, which the work reported here indicates is earlier than the granite and to have a laccolithic form, is described in more detail in the geology of the Kingsseat area. A laccolith of mica porphyrite is intruded into the andesite sequence at Biddlestone. Minor intrusions of basalt and dolerite, some marking vents, are associated with the Lower Carboniferous volcanism, while a dyke of fresh quartz dolerite outcropping at Windy Rigg is associated with the late Hercynian Whin Sill event (Robson, 1976). The Acklington Dyke of Tertiary age, composed of non-porphyritic tholeiitic basalt, crosses the southern part of the area (Figure 2).

Structure

The Cheviot igneous massif forms an easterly tilted block, whose structural history has been described by Robson (1977). The Lower Palaeozoic basement displays typical Caledonide structures, with major folds and faults striking NE–SW. Hercynian W–E compression generated NNE- and NNW-trending folds in sedimentary rocks adjacent to the massif as well as tear-faults, both in the sediments and in the block. These tear-faults, which include the major line of the Thieves-Gyle-Harthope fracture, all trend between 050° and 075°. In the central part of the area, the trend and disposition of the rocks on either side of the Gyle-Harthope fault zone is consistent with a dextral displacement. Conjugate sinistral movement may have taken place along the Breamish fault. The direction of faulting is probably controlled in part by the Lower Palaeozoic basement, which may also account for the weakly developed, sinistral, NW-trending conjugate set. Robson (1977) postulates that the anomalous trend of the College, Yetholm and Yeavering faults (Figure 2) is accounted for by rotation of the stress pattern in the northern part of the block adjacent to the less resistant and thick sedimentary succession of the Tweed floodplain. Further faulting, in response to N–S compression, occurred in the Tertiary, probably causing sinistral movement along the Gyle-Harthope fracture. The relative displacement of the Cheviot Granite suggests that this movement was less than the dextral Hercynian displacement. Final movements involved tilting and normal faulting along pre-existing fractures, with a southern downthrow on the Harthope, Ridlees and Ryle faults and a northern downthrow along the Gyle, Pressen, Flodden and Yeavering faults.

Superficial Deposits

Most of these deposits date from the last (Weichselian) glaciation, when ice moving from the west bifurcated around the Cheviot massif, on which a small icecap had developed (Clapperton, 1971). Large deposits of boulder clay and glacio-fluvial sands and gravels formed on the eastern margin of the massif, where large meltwater features can be seen. In the Tweed valley, deposits are mainly of boulder clay in the form of drumlins. Elsewhere, boulder clay occurs in most valley bottoms and on the lower slopes of north and west facing hillsides. Deposits of head and scree, usually grassed over, conceal most of the bedrock on the hillsides. Ribbons of terraced alluvium in the main stream valleys are derived mainly from local glacial and periglacial deposits.

Mineralisation

Documented sulphide mineralisation in the survey area is essentially of vein style and localised (Table 1). However, in the report of their geochemical drainage survey, Leake and Haslam (1978) suggest that mineralisation may be more widespread than implied in Table 1. Three mineralised zones were identified in the volcanic rocks by this work (Leake and Haslam, 1978). The largest trends south-east from Kingsseat Burn [NT 869 182] to Allerhope [NT 920 100] and generates anomalous levels of Cu, Pb, Zn and Ba in drainage samples. The second is coincident with the Breamish Fault and it is also characterised by Cu, Pb, Zn and Ba anomalies. The third is an ill-defined area of Zn anomalies extending from the southern margin of the granite to the Biddlestone Burn [NT 950 100].

Two unsubstantiated gold occurrences are recorded. Firstly, Clough (1888) notes that 'the N and S quartz vein at the head of Lambden Burn (Goldscleugh) contains gold, but I could not learn of any satisfactory warrant for this belief'. Secondly, it is said in the area that gold has been panned from the stream above Cocklawfoot.

Siliceous veins, some with calcite, occur in vertical fractures within the Cheviot Volcanic Group and silicification extends for up to 20 m into the lavas, e.g. at Raker Crag [NT 857 098]. These siliceous zones pre-date Hercynian fractures but cut Devonian mica-porphyrite dykes (Robson, 1976). Tourmalinisation is also a relatively late-stage event, affecting dykes and crush zones which cut the Cheviot Granite (Carruthers and others, 1932). The granite contains tourmaline as an accessory mineral and the western part of it has been subjected to late hydrothermal alteration, with the crystallisation of 'pneumatolitic

Table 1 Documented metalliferous mineral occurrences in the Cheviot Hills

	Locality	Grid reference	Mineralisation
1	Heathery Hill	NT 870 060	Calcite with galena (Miller, 1887)
2	Allerhope	NT 930 103 NT 934 106	NW–SE trending calcite veins in andesite, with galena, pyrite and baryte (Clough, 1888)
3	Harden Edge	NT 792 068	Vein with chalcopyrite (Clough, 1888)
4	Langlee	NT 963 230	Veins with calcite, quartz and analcite (Clough, 1888)
5	Long Hill	NT 860 070	Baryte strings (Clough, 1888)
6	Pudding Burn Ridlees trib.	NT 840 070	Calcite vein with chalcopyrite (Clough, 1888)
7	Ridleeshope	NT 820 070	Baryte strings (Clough, 1888)
8	Yearning Hall	NT 810 120	Calcite vein with galena (Clough, 1888)
9	Harden Edge	NT 795 072	Cu/U occurrence (Haslam, 1975)
10	Biddlestone Burn	NT 950 100	Mineralised zone; baryte and sphalerite in panned concentrate (Leake and Haslam, 1978)
11	Kingsseat Burn	NT 869 182	Mineralised structure with malachite, haematite and baryte (Leake and Haslam, 1978)
12	R. Breamish	NT 930 155	Mineralised zone; baryte, chalcopyrite, malachite and pyromorphite recorded in panned concentrates (Leake and Haslam, 1978)
13	Usway Burn	NT 885 160	Baryte and secondary lead minerals in panned concentrate; pebbles of vein calcite (Leake and Haslam, 1978)
14	Cottonshope	NT 790 045 NT 803 058	Two E–W trending Pb veins (GSEW sheet 8)
15	Middleton	NT 990 240	Manganese oxide in crush (GSGB Northumberland (New Series) XXI NW)

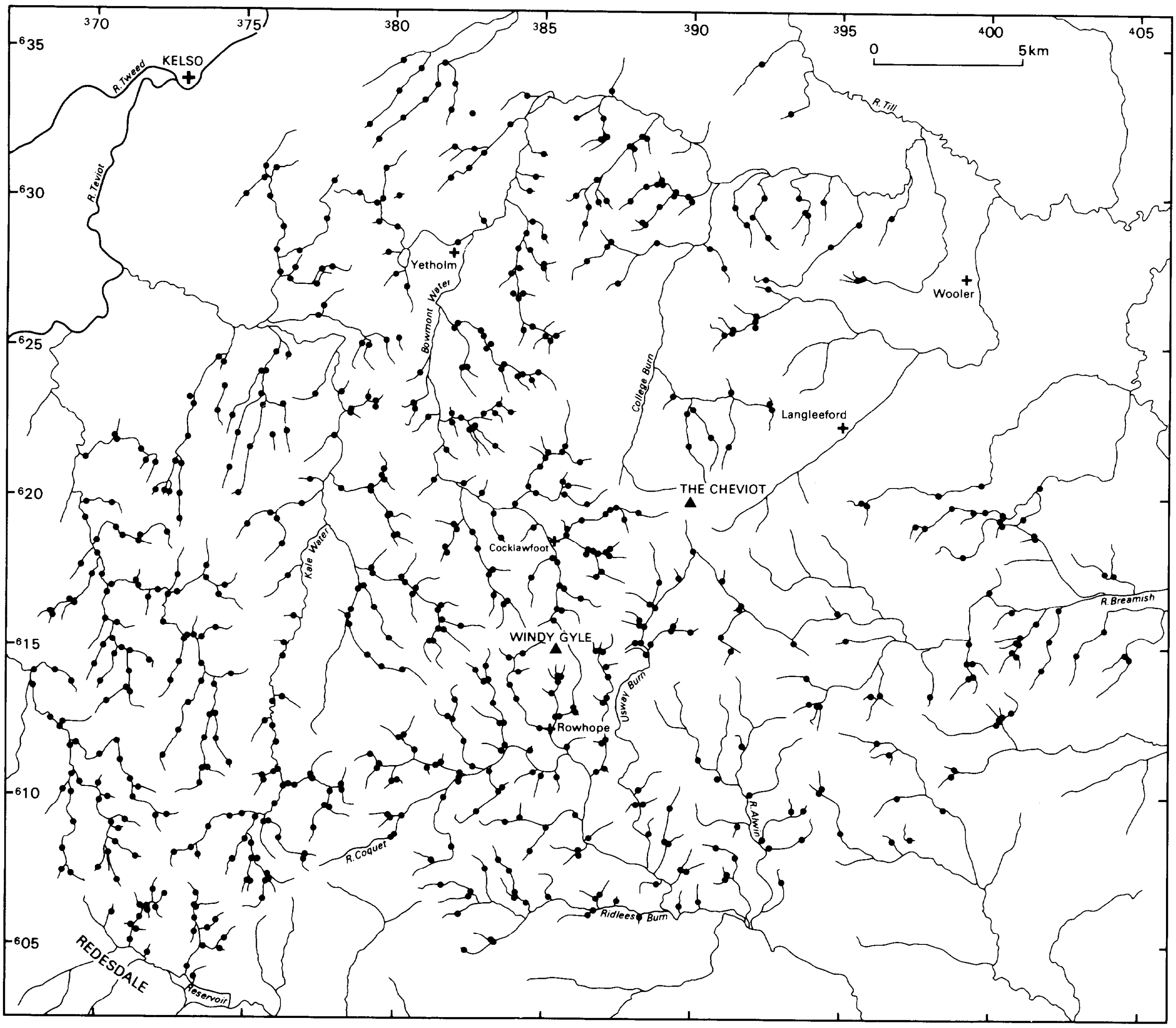

Figure 3 Location of reconnaissance drainage survey sample sites

micas' and tourmaline. Carruthers and others (1932) also note the presence of tourmalinised sedimentary rocks south of Score Head [NT 889 170], about half a mile from the granite contact.

Pervasive alteration has affected most of the Cheviot Volcanic Group. Robson (1976) records that most andesites are altered and that rhyolitic rocks, outcropping near the Border, are so altered that they crumble readily. A petrographic study of samples from the Kingsseat area (see below) enabled seven alteration assemblages to be identified resulting from sericitisation, kaolinisation, silicification, tourmalinisation, haematisation and carbonate alteration. Except for haematisation, all the alteration episodes are related to the Lower Devonian igneous activity.

Sampling and Analysis

Seven hundred and eight sites were sampled in an area of 850 km^2, giving a sample density of 0.8/km^2 (Figure 3). Coverage was poorest on the Tweed floodplain and on the high plateau area, where sampling was constrained by a lack of streams. At each site, three samples were collected; a fine fraction of the stream sediment, a panned heavy mineral concentrate and a water sample. The samples were collected using methods described elsewhere in detail (Plant, 1971; Leake and Smith, 1975; Allen and others, 1979). Briefly, water samples were collected in 30 ml polyethylene bottles and acidified with 0.3 ml perchloric acid, to prevent sorption of metals onto the container, and analysed for Cu, Zn and Pb by Atomic Absorption Spectrophotometry (AAS). Stream sediment was wet seived to pass −100 mesh (0.15 mm) nylon, using a minimum of water to retain the clay and fine silt fractions. In the laboratory, samples were dried and finely ground before analysis. Cu, Zn and Pb were determined by AAS following digestion of a 0.5 g subsample in boiling concentrated nitric acid for one hour. Arsenic was determined by X-Ray Fluorescence Spectrometry (XRFS), on a pellet prepared by grinding a 12 g subsample with 3 g 'elvacite' binder before pressing. Other elements were determined by Optical Emission Spectrography (OES). Heavy mineral concentrates were collected by panning approximately 4 kg of the −8 mesh (2 mm) fraction of the stream sediment down to c.50 g. In the laboratory, the samples were dried and a 12 g subsample ground with 'elvacite' binder prior to pelletising and analysis by XRFS for the range of elements reported in Table 2.

Table 2 Summary of the analytical results for stream sediment, panned concentrate and streamwater samples collected during the reconnaissance survey

	Median	Mean	Maximum	Minimum	Standard Deviation	Detection Limit
Stream Sediments						
Be	2	3	12	<1	1.7	1
B	54	64	582	5	41	5
V	77	81	204	30	25	10
Cr	87	100	504	23	53	10
Mn	1290	2053	18800	59	2141	50
Fe	29200	30613	104000	5920	9673	5000
Co	15	17	59	<10	7.7	10
Ni	43	46	149	14	17	10
Cu	15	17	120	5	8.6	3
Zn	110	138	690	30	91	3
As	12	17	162	<2	11	2
Zr	435	656	4920	120	527	20
Mo*	<1	—	5	<1	—	1
Sn*	<5	—	139	<5	—	5
Ba	719	947	16000	237	1364	100
Pb	40	47	740	20	35	5
Panned Concentrates						
Ti	15740	19144	85400	910	13840	—
Mn	390	550	4190	30	485	—
Fe	49390	61634	309500	1680	46676	—
Ni	33	39	173	<1	27	1
Cu	11	22	1913	<2	77	2
Zn	81	107	2886	3	146	1
As	9	10	369	<2	33	2
Sr	110	153	2180	20	227	1
Zr	500	903	13720	110	1139	2
Mo	2	3	46	<2	4.0	2
Sn*	<7	—	1155	<7	—	7
Sb*	<8	—	1771	<8	—	8
Ba	739	8593	418400	115	37928	8
Ce	48	51	736	<17	41	17
Pb	43	90	10570	<4	436	4
Bi*	<2	—	220	<2	—	2
U*	<3	—	20	<3	—	3
Streamwater						
Cu*	<0.01	—	0.05	<0.01	—	0.01
Zn*	<0.01	—	0.30	<0.01	—	0.01
Pb*	<0.05	—	0.03	<0.02	—	0.02

All results in ppm.
Data compiled from the analyses of 708 stream sediment and panned concentrate samples and 710 streamwater samples.
Results less than the detection limit set at half the detection limit for statistical calculations.

* Elements with more than 50% of analytical results below the detection limit.

Results and interpretation

Introduction

Analytical results are summarised in Table 2. Elements which have reported concentrations below the detection limits, have those values set to half the detection limit for the purpose of statistical calculation. For conciseness in the text, results for sediments, concentrates and waters are differentiated by subscripts $_c$, $_p$ and $_w$. For example, copper in stream sediment is shortened to Cu_c. A high proportion of the analytical results for Cu_w, Zn_w, Pb_w, Bi_p, U_p, Mo_c and Sn_c were below detection limit and were excluded from statistical analysis.

Distribution analysis

The graphical analysis of cumulative frequency plots was used to determine population type, set thresholds and define anomalous populations (Lepeltier, 1969; Sinclair, 1976). Elements whose sample populations have near-lognormal distributions were log-transformed prior to parametric statistical analysis.

Sources of geochemical variation

Inter-element associations are illustrated by a summary of the most significant positive element correlations (Table 3) and a dendrogram constructed from a cluster analysis

Table 3 Summary of most highly significant inter-element correlations in the reconnaissance drainage sample data.

	Correlation coefficient 0.4–0.5	0.6–0.7	>0.7
Stream sediments			
V	$Ni_c Fe_c Co_c$		
Mn	Fe_c	$Co_c Zn_c$	
Fe	$Zn_c Mn_c Cu_c V_c Co_c$	Ni_c	
Co	$Ni_c Fe_c V_c Zn_c$	Mn_c	
Ni	$C_c Co_c$	Fe_c	
Cu	$Sn_p Pb_p Fe_c Ba_p$		
	$Ba_c Pb_c Sb_p Cu_p$		
Zn	$Fe_c Pb_c Co_c$	Mn_c	
Zr	Zr_p		
Sn	Sn_p		
Ba	Cu_c	$Sr_p Ba_p$	
Pb	$Cu_c Zn_c$	$Sn_p Sb_p Pb_p$	
Panned concentrates			
Ti	$Ce_p Mo_p$	$Mn_p Fe_p Ni_p$	
Mn	Ce_p	$Mo_p Ni_p Ti_p Fe_p$	
Fe	Ce_p	$Ti_p Mo_p Mn_p$	Ni_p
Ni	Ce_p	$Mo_p Mn_p$	$Ti_p Fe_p$
Cu	Cu_c	$Pb_c Sn_p$	$Pb_p Sb_p$
Sr		Ba_c	Ba_p
Zr	Zr_c		
Mo	Ti_p	$Mn_p Ni_p Fe_p$	
Sn	$Cu_c Sn_c$	$Pb_c Sb_p Pb_p Cu_p$	
Sb	Cu_c	$Pb_c Sn_p$	$Pb_p Cu_p$
Ba		Ba_c	Sr_p
Ce	$Mn_p Ni_p Ti_p Fe_p$		
Pb	Cu_c	$Pb_c Sn_p$	$Sb_p Cu_p$

based on the correlation matrix (Figure 4). From these and other statistical analyses, field observation and a study of the areal variation of element levels in relation to the geology and geography of the area, the following major controls on geochemical variation in the data were identified.

Heavy metallic minerals Factor analysis models indicate that this is the major source of variation in the dataset. It is caused by the upgrading of heavy minerals in the stream sediment (ilmenite, magnetite and locally sulphides and metallic contaminants) by the panning process. The widespread occurrence and locally high concentrations of ilmentite and magnetite in the panned samples generate the close Ti-Mn-Fe-Ni-Zn correlations whilst elements occurring in known mineralisation (Cu, Sb, Pb) correlate less closely (Figure 4) but form part of the same grouping. One interpretation of this grouping is that it reflects a relationship between ilmenite and magnetite and other metal enrichments.

Precipitates, clay minerals and organic matter Metals commonly concentrated in the fine and light fractions of the stream sediment (V, Mn, Fe, Co, Cu, Zn, Pb) form a well defined association (Figure 4). Many streams draining upland regions within the survey area contain hydrous Fe or Mn oxide precipitates. The precipitation of these elements and associated scavenging can concentrate many elements (Reedman, 1979). The statistical analyses and spatial distribution plots suggest that in the Cheviot Hills, Mn, Fe, Co, Ni and Zn are the elements most affected by this process. The presence of Pb in this group may be partially caused by its ability to form organometallic complexes, other elements in this group may be held in both hydrous oxide precipitates and clay minerals.

Baryte Ba and Sr form a close association, independent of other variables, due to the presence of baryte in many samples. The separation of these elements from the heavy metallic mineral group is due to differences in the spatial distribution of high and low values. This implies that at least one episode of baryte formation is unrelated to base-metal mineralisation and events associated with ilmenite-magnetite formation.

Sandstones The relatively large sandstone outcrops of Devonian and Lower Carboniferous ages are a major source of Zr variation, which is independent of other variables (Table 3). The more acid volcanic rocks within the Cheviot Volcanic Group and the Cheviot Granite are also sources of high Zr.

Unconformities High Cr levels are associated with the top and bottom of the Cheviot Volcanic Group.

Tourmalinisation and other hydrothermal activity B displays independent variation which is greatly influenced by tour-

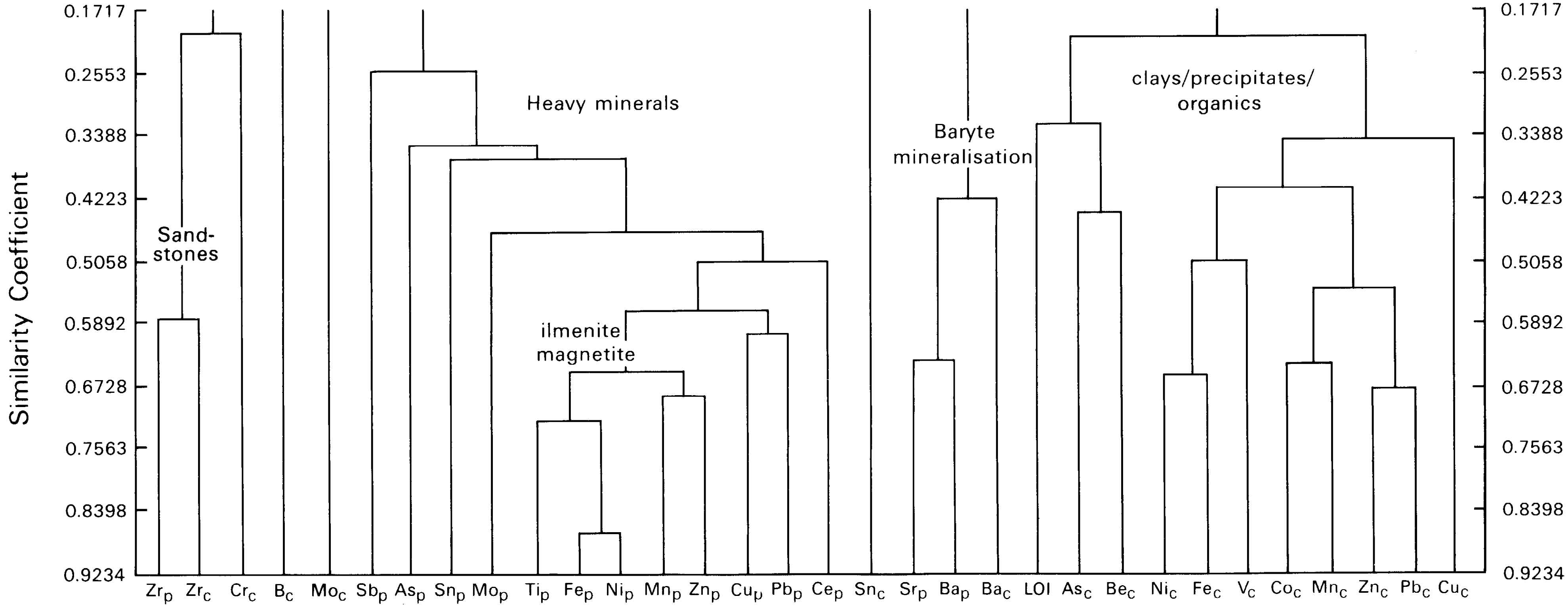

Figure 4 Dendrogram based on R-mode cluster analysis of analytical results from the reconnaissance drainage survey

maline derived from the Cheviot Granite and related veins. Relatively high levels of several variables, including Be_c, As_c and Pb_c, which form an association in factor analysis models, are found in the vicinity of the Gyle-Harthope fault zone and may be directly or indirectly the product of hydrothermal alteration related to this fracture.

Contamination This is a weak, ill-defined and relatively unimportant source of variation in the dataset. Elements normally used as contamination indicators (Sn_c, Sn_p and, to a lesser extent associated Sb_p and Pb_p) are largely derived from natural sources in this area. For example, high Sn_p and Sb_p levels are associated with the presence of abundant Fe-Ti oxides in uncontaminated streams of the Kingsseat area. The Cu_p-Sn_p-Sb_p-Pb_p correlation (Table 3), which indicates an association of Cu with elements often concentrated in contaminant phases, is misleading and greatly influenced by one contaminated sample containing the highest level of Cu_p recorded in the area.

Distribution of anomalies

Ba anomalies in both stream sediment and panned concentrate are widespread. At most anomalous sites $Ba_p > Ba_c$, suggesting that the cause is baryte and that baryte mineralisation is far more widespread than is indicated by the list of documented occurrences (Table 1). Cu, Zn, As, Sb and Pb anomalies are multisource, some being related to both documented and unrecorded mineralisation, alteration and contamination. Most Bi results were below the detection limit but several of the higher values are associated with Zn_p and Pb_p anomalies and are probably derived from mineralised rocks. Locally, grains of galena, sphalerite, baryte and, rarely, gold were identified in the panned concentrates in the field.

Sn anomalies show no close relationship to the geology or to tourmalinisation, as indicated by the presence of high concentrations of B_c. Several Sn anomalies can be attributed to contamination, although a grain of cassiterite was identified in a panned concentrate from the Kingsseat area.

There is evidence to suggest that the distribution of several elements, including those which are the most important indicators of mineralisation and hydrothermal alteration, has been strongly influenced by major structures such as the Gyle-Harthope and Breamish fractures. For example, on computer-generated, moving-average spatial distribution (figure-field) plots, the foci of highs and lows and changes in average metal concentration on a regional scale often correlate with the position of major fractures. Some of these patterns may have been generated by fluid movements along the fractures as suggested by Bateson (1985), others by lithological changes across fault lines.

One such structure-related geochemical feature is located in the Kingsseat-Windy Gyle area. It is prominent because of the exceptionally wide range of metals recorded in anomalous concentrations in both stream sediment and panned concentrate samples. In an attempt to clarify the sources of these anomalies additional work was carried out in the area.

INVESTIGATIONS IN THE KINGSSEAT AREA

Introduction

Follow-up work in the Kingsseat area (Figure 5) comprised geological mapping at 1:10 000 scale, a more detailed stream sediment survey and mineralogical, petrographic and lithogeochemical studies. The results of this work are detailed in a report contained in the data package.

Geology

The rocks of the area belong almost entirely to the Cheviot Volcanic Group and related intrusions. The eastern half is composed of lavas with minor intercalations of pyroclastic and sedimentary rocks, two main vent breccias and a number of small bodies of volcanic breccia (Figure 5). The lavas are dominantly andesitic with a small proportion of oligoclase trachyte. A unit of tuff, lapillistone, sandstone, siltstone and laharic breccia about 10 m thick overlies andesite at the foot of Randy's Gap. The underlying andesite is locally reddened, supporting the conclusion of Carruthers and others (1932) that the sedimentary intercalations are fluviatile or lacustrine. The volcanic breccia on Fundhope Rig [NT 867 178] consists of angular to round fragments of andesitic lithologies set in a matrix of coarse sand or lapillistone. The intergranular spaces are filled locally with concentric layers of chlorite and quartz. Narrow zones of green-veined, locally polymict breccia are not uncommon and may be intrusive.

Rocks covering the western half of the area previously mapped as mica-felsites (Carruthers and others, 1932) are reinterpreted as a tonalitic intrusive complex, named the Cock Law Complex. It comprises five distinct lithologies: biotite porphyry, pyroxene-biotite porphyry, pyroxene porphyry, biotite-quartz porphyry and granodiorite porphyry. The two main components are biotite porphyry and pyroxene-biotite porphyry. Evidence that the rocks are intrusive comes from several sources: (i) in thin section they show a recrystallisation fabric characteristic of intrusive rocks and there is no essential difference between them and and the dyke-like minor intrusions; (ii) alteration to kaolinite, which elsewhere appears to be a feature of minor intrusions, is confined to the rocks of the complex and immediately adjacent country rock; (iii) within the complex the contact between the biotite porphyry and the pyroxene-biotite porphyry components near Kelsocleuch Farm is unequivocably intrusive; and, at the foot of Randy's Gap, brecciated quartz-veined biotite porphyry shows a sharp contact against 2–3 m underlying flow banded biotite-quartz porphyry; (iv) in the same area biotite-quartz porphyry rests on pyroxene porphyry veined by intrusive breccia, but elsewhere it rests on a bedded succession of tuffs and sedimentary rocks. At the one locality where the contact is visible it is concordant, but the general disposition between the porphyry and the bedded rocks is discordant.

The overall form of the complex is difficult to determine from the part mapped but the available evidence suggests that it is laccolithic. Several kaolinised minor intrusions of stock or dyke-like form were also mapped in the area. At the head of Cheviot Burn exposures of pink biotite microgranite are possibly part of the Cheviot Granite complex.

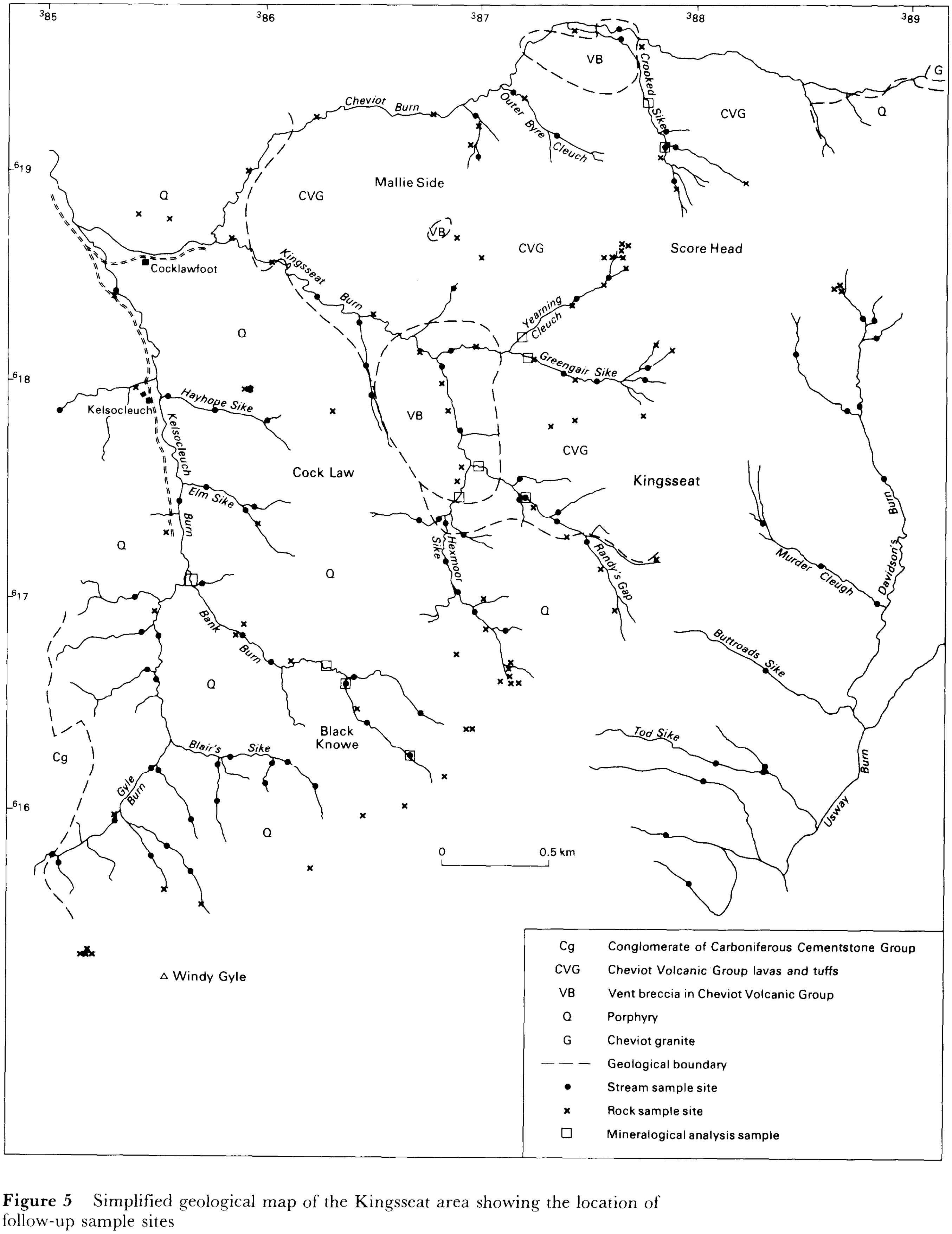

Figure 5 Simplified geological map of the Kingsseat area showing the location of follow-up sample sites

Alteration and Mineralisation

Mineralisation is recorded from the upper part of Kingsseat Burn, where Leake and Haslam (1978) found a mineralised structure containing malachite and baryte. The occurrence was linked to a mineralised zone defined by drainage anomalies, extending through Usway Burn to Allerhope Burn.

Minor quartz veins, quartz-filled tension gashes and quartz-cemented breccias with associated veins up to 30 cm thick are widespread in the lavas. Larger vein systems are also present. At one locality the country rock adjacent to a one metre thick quartz vein is silicified and penetrated by quartz veinlets, and at another, an anastomosing quartz vein complex with some late baryte veins crosscuts brecciated volcanic rocks.

All the rocks in this area have undergone some form of alteration, though it varies widely in type and intensity. Seven main assemblages of alteration minerals were recognised: (i) sericite ± amphibole ± chlorite ± epidote; (ii) sericite, quartz ± amphibole ± chlorite; (iii) kaolinite, quartz, sericite, haematite; (iv) kaolinite, quartz, chlorite; (v) carbonate; (vi) haematite and (vii) tourmaline. The sericite ± amphibole ± chlorite ± epidote assemblage occurs in five small areas within the Cock Law Complex and within large areas of the volcanic rocks. In most other volcanic rocks the predominant alteration assemblage is sericite, quartz ± amphibole ± chlorite. Kaolin-dominant alteration is ubiquitous in the porphyry intrusions and immediately adjacent wallrocks. It was not observed in the small exposed area of Cheviot Granite even though the adjacent porphyry was altered. The most widespread alteration assemblage is kaolinite, quartz, sericite and haematite. The consistent spatial association of kaolin-dominant alteration with the porphyry suggests that there may be a genetic relationship between them. Both the carbonate and haematite alterations are apparently late and imposed on other types. Carbonate is present only with sericite-dominant alteration assemblages and is closely associated with vent and other breccias. Haematite alteration is erratic and patchy but affects all the major lithologies; it is least common in the Cock Law Complex. It post-dates both kaolin and sericite dominant alteration assemblages, but locally predates quartz veining and brecciation. At the localities where haematisation is most intense, some of the rocks are limonitised, black manganese minerals and green copper secondaries are present and the rock has the appearance of a gossan. These late oxidising events are probably responsible for the absence of sulphide minerals. Tourmalinisation is localised; it is younger than the kaolinite alteration, and has long been attributed to a hydrothermal event associated with the intrusion of the Cheviot granite.

To summarise, the following sequence of events is proposed: (i) deuteric alteration of lavas and intrusive rocks to a sericite ± chlorite ± amphibole ± epidote assemblage; (ii) hydrothermal alteration of porphyry intrusions and country rock yielding kaolin-dominant and sericite-quartz assemblages; (iii) carbonate alteration and some epidotisation associated with volcanic breccias; (iv) tourmalinisation associated with granite intrusion and (v) late polyphase events including haematite alteration, quartz and calcite veining and gossan formation.

Stream sediment survey

Stream sediment and panned concentrate samples were collected from each of 93 stream sites to supplement the reconnaissance data. Identical methods of sample collection, preparation and analysis were employed but a slightly different range of elements was determined. The follow-up panned concentrates were analysed for Ca, W and Th by XRFS as well as all the elements determined on the reconnaissance samples. The same elements were determined in the follow-up stream sediments as in the reconnaissance samples except that Ag was determined (by OES) and As was omitted.

A summary of the analytical results for the follow-up stream sediment and panned concentrate samples is given in Table 4. Comparison with the data in Table 2 shows that the background levels of many elements in the Kingsseat area are substantially higher in both stream sediments (Be, Zn, Mn) and panned concentrates (Ti, Mn, Fe, Ni, Zn, As, Mo, Sb, U) than in the western Cheviot Hills region. The median levels and maximum concentrations suggest a wide range of metal enrichments in the area (Be, Ti, Cr, Mn, Fe, Co, Zn, Ni, As, Sr, Mo, Sb, W, Ba, Pb), and comparison of stream sediment and panned concentrate results indicate that with the exception of Mn and possibly Cr, Co and Zn, the enriched elements are contained in heavy minerals. Cumulative frequency analysis was used to set threshold levels and identify anomalous samples. The distribution of anomalous results indicated more than one source, a conclusion confirmed by the rock analyses.

Twelve anomalous panned concentrate samples were split into fractions on the basis of grain size and magnetic susceptibility, prior to mineralogical examination to determine the mineral phases responsible for the high metal content of the samples. The principal heavy minerals found were baryte, ilmentite, magnetite, haematite and zircon. Secondary lead minerals were identified in two samples, cassiterite in one and romanechite in another.

Rock geochemistry

Eighty six rock samples were collected for analysis from the principal lithologies exposed in the Kingsseat area (Figure 5) The c.2 kg samples were crushed, split and milled prior to pelleting and analysis for Ca, Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, Sn, Sb, Ba, Ce, W, Pb, Bi, Th and U by XRFS. In addition 29 of the more highly altered or mineralised samples were analysed for Au by AAS.

An approximation to the chemical composition of the porphyries and andesites was obtained by summarising the analyses of the samples classified as 'least altered' on the basis of field observation, petrography and chemistry (Table 5). The porphyries show a greater range of compositions than the lavas which are more basic in character, containing more Ca, Fe, Mn, Ni, Cu, Zn and Sr and less As, Y, Zr and Nb. Comparison of these analyses with data given for Cheviot Volcanic Group rocks by Thirlwall (1981) suggests that at least some of the lavas described in the field as andesites or basaltic andesites may be of dacitic composition. Too few relatively unaltered rocks of the Cock Law Complex were analysed for the chemical characteristics of the components to be defined, but the data allow the biotite and quartz-biotite porphyries to be readily distinguished from the pyroxene porphyry by their much lower Ni (<20 ppm), Fe($<3\%$), Mn (<100 ppm) and higher Th (>22 ppm) content.

Chemically the lavas show some characteristics of the calc-alkaline orogenic lavas of plate margins and other features suggesting the presence of thick crust. On tectonic setting discrimination plots (e.g. Pearce, 1982)

Table 4 Summary of the analytical results for 93 follow-up stream sediment and panned concentrate samples from the Kingsseat area

	Median	Mean	Maximum	Minimum	Standard Deviation
Stream Sediments					
Be	4	4.8	13	1	2.6
B	35	45	368	12	42
V	91	90	141	41	20
Cr	93	101	1080	<10	109
Mn	2460	3170	31800	144	3850
Fe	34800	37200	95800	11200	11800
Co	22	24	104	<10	12
Ni	47	48	79	15	14
Cu	15	17	90	<3	12
Zn	170	184	460	41	101
Zr	643	766	2570	236	490
Mo	1	—	3	<1	—
Sn	<5	—	10	<5	—
Ba	703	1060	12300	303	1430
Pb	60	57	140	20	22
Panned Concentrates					
Ca	2060	2240	11150	500	1350
Ti	25360	31300	94600	3410	19618
Mn	820	1080	4280	80	790
Fe	123140	133000	342600	13960	77800
Ni	52	63	177	12	35
Cu	18	24	101	4	18
Zn	146	177	474	24	106
As	24	55	612	<2	84
Sr	117	174	1530	24	251
Zr	770	943	4920	122	755
Mo	6	9	51	<2	9.4
Sn	9	19	99	<7	23
Sb	12	28	246	<8	46
Ba	671	12400	272600	213	41050
Ce	76	82	194	<17	40
W	9	13	116	<3	16
Pb	68	86	506	17	67
Th	20	22	43	5	8.5
U	6	6.6	16	<3	3.7

All results in ppm.
Results less than the detection limit set at half the detection limit for statistical calculations.
Ag in stream sediment and Bi in panned concentrate also determined, but all results were less than the detection limits (2 ppm).
Detection limits for other elements are given in Table 2.

based on relatively 'immobile' elements (e.g. Ti, Zr) the data produces ambiguous results, plotting close to the discrimination line between volcanic arc and within plate lava series. Examples are known of calc-alkaline volcanism persisting after subduction ceased, so the Cheviot Volcanic Group may represent such a transitional type between continental margin and within plate lavas, erupted after closure of the Iapetus Ocean. Thirlwall (1981) demonstrated that the Cheviot lavas differ chemically from others of Old Red Sandstone (Devonian) age in Scotland possibly reflecting a different tectonic setting.

The 'least altered' rock analyses were used as a baseline from which to calculate elemental enrichment and depletion in the more altered and mineralised samples of the same rock group. On this basis one or more samples collected were found to be enriched in Ca, Fe, Mn, Cu, As, Y, Mo, Ag, Sb, Ba, W, Pb and U, where enrichment was defined as a metal concentration more than twice the maximum recorded in the least altered rocks. Several rocks are enriched in a single element, for example two fresh-looking dark grey porphyritic andesites contain more than five times as much Cu as the maximum reported in their 'least altered' equivalents whilst other elements determined show no major differences. Other rocks are enriched only in Pb or As. The largest and greatest range of metal enrichments were recorded in samples collected from a gossanous structure. Here the mineralisation appears to have several features in common with the epithermal, precious-metal style of mineralisation associated with sub-aerial volcanism (Sillitoe, 1977), but the data is insufficient to verify these speculations.

Substantial element depletions were also evident in many altered rocks. Elements present in one or more samples in concentrations less than half that of the

Table 5 Composition of 'least altered' andesitic lava and porphyry samples collected in the Kingsseat area

	Porphyries n = 12					Andesitic lavas n = 15				
	Median	Mean	Maximum	Minimum	Standard Deviation	Median	Mean	Maximum	Minimum	Standard Deviation
Ca	1290	6479	23100	150	7320	15490	15711	24500	7330	3648
Ti	3860	3878	4710	2960	484	4870	4901	6030	4170	591
Fe	28430	30352	44000	17500	6963	41560	42164	51600	33500	5076
Mn	90	218	460	50	158	420	434	650	330	93
Ni	11	22	43	5	15	43	44	58	32	8.0
Cu	11	10	16	3	4.5	20	25	67	5	17
Zn	33	48	130	15	31	78	82	126	56	15
As	7	8	39	4	9.2	4	3.7	8	<2	1.7
Rb	207	192	287	11	85	191	189	227	156	22
Sr	117	163	344	26	106	367	377	495	198	81
Y	19	20	30	16	3.5	17	17	22	14	1.9
Zr	302	315	372	250	38	278	274	318	241	21
Nb	15	16	21	13	2.3	13	13	15	11	1.4
Mo	<2	—	3	<2	—	2	1.8	4	<2	0.8
Sn	2	2.7	4	2	0.9	2	2.1	4	2	0.5
Sb	<3	—	19	<3	—	<3	—	5	<3	—
Ba	671	588	988	147	261	746	749	912	542	104
Ce	76	75	87	63	8.4	75	74	92	55	9.1
W	6	6.5	9	3	1.7	4	4.5	8	<3	1.8
Pb	26	28	57	7	13	27	28	58	14	10
Th	22	23	29	20	2.9	20	20	25	14	2.4
U	5	4.8	7	2	1.7	5	4.7	7	3	1.3

Ag and Bi were also determined but all results were less than the detection limits (2 ppm).
All results in ppm

minimum recorded in the least altered rock group were Ca, Ti, Mn, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th and U. This suggests that during the alteration events that have affected this area, there has not only been movement of elements commonly affected by these processes such as alkalis but that, at least locally in the most altered rocks, so-called immobile elements such as Ti, Nb and Zr have also been affected. Within the porphyry group of least altered rocks, there is a marked contrast between the narrow compositional range shown by the more immobile elements (e.g. Ti, Y, Zr, Nb, Ce, Th) and the wide range of some other elements, suggesting that even in these rocks the concentration of, for example, Ca, Mn, Rb, Sr and Ba, has been affected by alteration processes. No attempt was made to detail chemical changes related to the different styles of alteration.

CONCLUSIONS

1 Barium mineralisation, in the form of baryte, is the most widespread mineralisation detected. Its prominence may in part be due to the sensitivity of panned concentrate sampling techniques to baryte. The lack of any close association between barium and any other metal enrichment except strontium suggests that it forms a distinct mineralising event.

2 A wide range of metals (Be, B, Ti, Fe, Mn, Cu, As, Mo, Sn, Sb, Ba, Pb, Bi and U) are locally enriched in the drainage samples. These enrichments are attributed to a variety of causes including documented mineralisation, contamination, hydrous oxide precipitation and scavenging processes, relatively high metal levels in bedrock typical of the lithology and of no economic interest, hydrothermal alteration and hitherto undiscovered mineralisation.

3 Element distribution patterns in drainage samples are influenced by major structures such as the Gyle-Harthope fracture zone. Such fractures may be deep seated and are believed to exert a major control on the distribution of alteration and mineralisation.

4 Work in the Cocklawfoot-Kingsseat area shows that the rocks of the area are affected by a complex sequence of alteration and mineralising events, some of which could be related to volcanism, associated porphyry intrusion and emplacement of the Cheviot Granite. These polyphase alteration and mineralisation events are the cause of the wide range of metal enrichments recorded in drainage samples collected from the Kingsseat area. Mineralisation associated with a gossanous structure appears to have features in common with the epithermal, precious-metal style of mineralisation associated with subaerial volcanism.

5 Further work is required to fully clarify the sequence, style and extent of alteration and mineralisation events in the Cheviot Hills.

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