



Natural Environment Research Council  
Institute of Geological Sciences

# Mineral Reconnaissance Programme Report



*A report prepared for the Department of Industry*

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No. 55

**Mineral exploration in the  
area of the Fore Burn igneous  
complex, south-western  
Scotland**

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western Scotland**

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- 11 A study of the space form of the Cornubian granite batholith and its application to detailed gravity surveys in Cornwall
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## SUMMARY

The Fore Burn igneous complex consists mainly of quartz-microdiorite, tonalite and feldspar porphyry forming semiconcordant or concordant bodies within early Devonian volcanic and sedimentary rocks, just north of the Southern Upland Fault, some 24 km east of Girvan. There is evidence that the complex has been folded. Several small bodies of intrusion breccia occur within both the complex and the country rock and there is a zone of monolithologic breccias along a fault followed by the Fore Burn itself.

The mineral composition of rocks throughout the area has been modified by alteration to sericite, carbonate and chlorite. Tourmaline is also widely distributed, but it is most abundant within the zone of breccias along the Fore Burn. The rocks in this zone are the most intensely altered in the area. They contain locally abundant disseminated sulphides and are cut by veins rich in sulphides. The rocks in this zone also contain secondary apatite.

A drainage survey revealed high levels of B and As in stream sediment samples within an area of about 4 km<sup>2</sup>, and suggested the presence of Cu-As-B-Au-Mo mineralisation concentrated along the Fore Burn breccia zone. Ba values are locally high, but it appears that they represent a totally separate episode of barite mineralisation.

Rock geochemistry and detailed mineralogical examinations confirmed the general findings of the drainage survey. Arsenopyrite, pyrite and chalcopyrite are the main sulphide phases in the breccia zone. Smaller quantities of tennantite, tetrahedrite, cobaltite and native gold were also noted. Cu, As, Mo, Au, Sb, Bi, Co, Ni, Pb and Zn were all enriched in analysed samples of mineralised rock. An examination of the so-called stable elements in the igneous rocks showed that in the highly altered rocks they had undergone remobilisation, probably under the influence of Na metasomatism.

Geophysical surveys located three small areas of low resistivity, one of which is in the breccia zone, which contain concentrations of massive sulphides in veins at surface. The IP chargeability levels do not indicate any widespread, significant, near-surface disseminated sulphide mineralisation. Comparison with similar examples from western Canada suggest that the mineralisation exposed at Fore Burn may represent the upper and outer parts of a Cu-Mo-Au porphyry system.

## INTRODUCTION

The area, about 7 km south-east of Straiton (Figure 1), is situated on the south side of the Water of Girvan between Knockdon Farm and Tairlaw Burn.

The Fore Burn complex, described by Eyles and others (1929, 1949), consists mainly of intrusive rocks of intermediate composition emplaced within lavas and sedimentary rocks of Old Red Sandstone age. Both the complex and the country rock are tourmalinised and there are records of veins of pyrite, arsenopyrite and tourmaline with traces of topaz and cassiterite. The area was investigated by Riofinex in 1970/71 when three boreholes were drilled, but their results are not available. During a stream sediment survey across the Doon-Glenkens area (Dawson and others, 1977) some samples collected from around Fore Burn yielded interesting Cu and B values.

Tourmaline has been recorded in association with Canadian porphyry copper deposits (Drummond and Godwin, 1976) and it is commonly present in breccia pipes which have been mined for copper in Chile (Sillitoe and Sawkins, 1971). Thus, there was a possibility of disseminated copper mineralisation in the Fore Burn area. An alternative explanation, that the tourmaline was indicative of copper-tin-tungsten mineralisation, similar to that of south-west England, was not ruled out.

## GEOLOGY

### PREVIOUS WORK

The Fore Burn complex lies in a graben-like structure between two north-east-trending faults: the Southern Upland Fault to the south and an unnamed fault to the north, which separates the early Devonian rocks in the graben from the mainly conglomeratic Ordovician rocks of the Big Hill of the Baing (Figure 1). Northwards these are unconformably overlain by Lower Devonian conglomerates, sandstones, basic and intermediate lavas and tuffaceous sedimentary rocks. The sedimentary rocks are of lacustrine or fluvial origin and demonstrate folding about north-easterly axes. South of the Southern Upland Fault the Ordovician succession consists mainly of greywacke and shale.

Eyles and others (1929) described the Fore

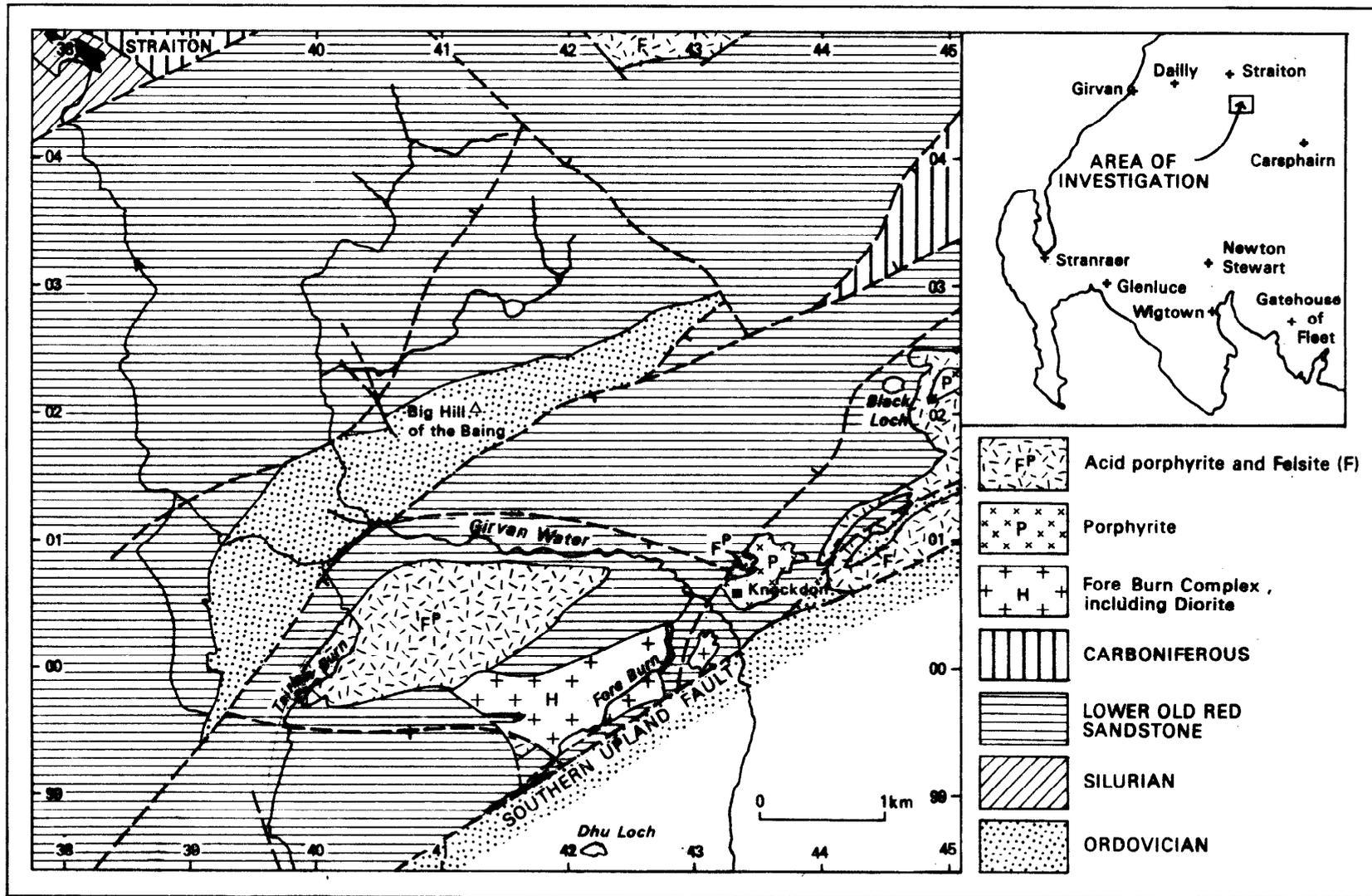


Fig 1: Geology of the area south east of Straiton. Geological lines taken from the Scottish 1:50,000 sheets 8W, 8E, 14W, 14E.

Burn complex as being composed of '... coarse-grained rocks allied to quartz diorite together with acid porphyrites and fine-grained reddish types, which closely resemble the plagiophyre and quartz-plagiophyre intrusions of the Maybole district'. In their later publication (1949) they proposed that the intrusive rocks were older than the last major movement of the Southern Upland Fault.

#### SEDIMENTARY AND VOLCANIC ROCKS

The area of open heathland along the northern side of the complex (Figure 2) is underlain by lavas, conglomerates and sandstones. The lavas are mostly grey, massive, locally autobrecciated andesite and purplish amygdaloidal basalt with a few flows of black iron-rich basalt. Porphyritic andesite is restricted to a small area between the two main quartz-microdiorite intrusions [NX 4162 9983]. Conglomerate, exposed in two broad strips, forms units over 50 m thick. The rock contains well-rounded pebbles and cobbles, up to 15 cm long, and generally of low sphericity. In contrast the matrix consists of poorly sorted subangular grains, mostly of quartz. Greywacke, quartzose sandstone and muddy siltstone are the most common pebbles, but there are some of igneous rocks from the underlying volcanic succession. Rusty sandstone occurs beneath the northern belt of conglomerate around NX 4182 0039.

Within the forest in the south-western part of the area and in the upper and middle reaches of the Fore Burn, the volcanic succession consists of volcanic breccia, agglomerate and tuff, some well bedded, in addition to lavas. The lavas tend to be lighter coloured, mainly because of the more intense alteration here than in the north, but the compositional range is probably the same.

#### INTRUSIVE ROCKS

The two main rock types in the Fore Burn complex are feldspar porphyry and quartz microdiorite (Figure 2). A small body of tonalite is present in the lower reaches of the Fore Burn and various other rocks occur in small dykes. There are several broadly concordant intrusions of feldspar porphyry, and it is likely that in the main area of exposure, which is along the Fore Burn itself, there are several small intrusions. At intervals along the burn small areas of volcanic rock appear to be slices of country rock caught between intrusions. Relations between the feldspar porphyry and the quartz-microdiorite suggest that the porphyry is the older of the two. Xenoliths of porphyry occur within quartz-microdiorite at NX 4204 9993 and a 2 m dyke of quartz-microdiorite cuts porphyry at NX 4175 9985.

The form of the two main quartz-microdiorite intrusions is not clearly defined, but geophysical evidence (see later) suggests that the eastern body may be sill-like. There are internal variations in

colour, grain size and abundance of phenocrysts. The main rock type is quartz-microdiorite but the composition ranges from microdiorite to microtonalite. There is a suggestion of polyphase intrusion in the presence of xenoliths of quartz microdiorite in a similar rock type at one locality [NX 4204 9993].

Coarse-grained tonalite occurs in two small bodies at the north-eastern margin of the complex. On the north-eastern side of the larger of the two, exposed in a stream at NS 4278 0032, highly altered and mineralised microtonalite with unusual textural characteristics (p. 5) may represent a marginal phase of the intrusion. On the western side of the same body, at NS 4266 0023, the tonalite becomes finer-grained towards the contact with feldspar porphyry. The porphyry (S67307\*) is highly altered, sparsely porphyritic and possibly quartz-microdiorite in composition. It is unlike the more common variety of feldspar porphyry in the area and for this reason it is not certain that the tonalite is younger than the main phase of porphyry intrusion. The age relations between the quartz-microdiorite and tonalite cannot therefore be established on this basis.

Sparsely porphyritic microdiorite forms a dyke 2 m thick in basalt lava at NS 4277 0013 and a dyke of porphyritic hypersthene microdiorite occurs at NS 4278 0012.

#### BRECCIAS

Intrusion breccias have been identified in four different outcrops. They comprise small bodies the form of which can be determined with any certainty in only one outcrop [NX 4210 9987]. Here the breccia forms a thin dyke cutting quartz-microdiorite. The breccia consists of subangular to subrounded fragments of microdiorite and quartz-microdiorite in a matrix of sand-size particles of rock, feldspar crystals and fine-grained feldspar, chlorite and quartz probably representing recrystallised rock flour. Another small body of intrusion breccia occurs at the margin of a feldspar porphyry intrusion in porphyritic andesite at NX 4162 9983, where fragments of basalt and sandstone are present as well as these two rock types. The matrix consists largely of recrystallised quartz, feldspar and chlorite, and contains tourmaline. The host rock here has suffered *in situ* brecciation and is tourmalinised and mineralised.

A somewhat larger mass of intrusion breccia occurs within feldspar porphyry adjacent to the larger of the two tonalite intrusions [NS 4264 0020]. It consists of fragments of the adjacent porphyritic quartz-microdiorite together with texturally different varieties of feldspar porphyry, in a matrix of rock debris, feldspar crystals, quartz, sericite and carbonate. Tourmaline and pyrite are also present. Polymict breccias also occur in the

\*Number of specimen held in IGS collection.

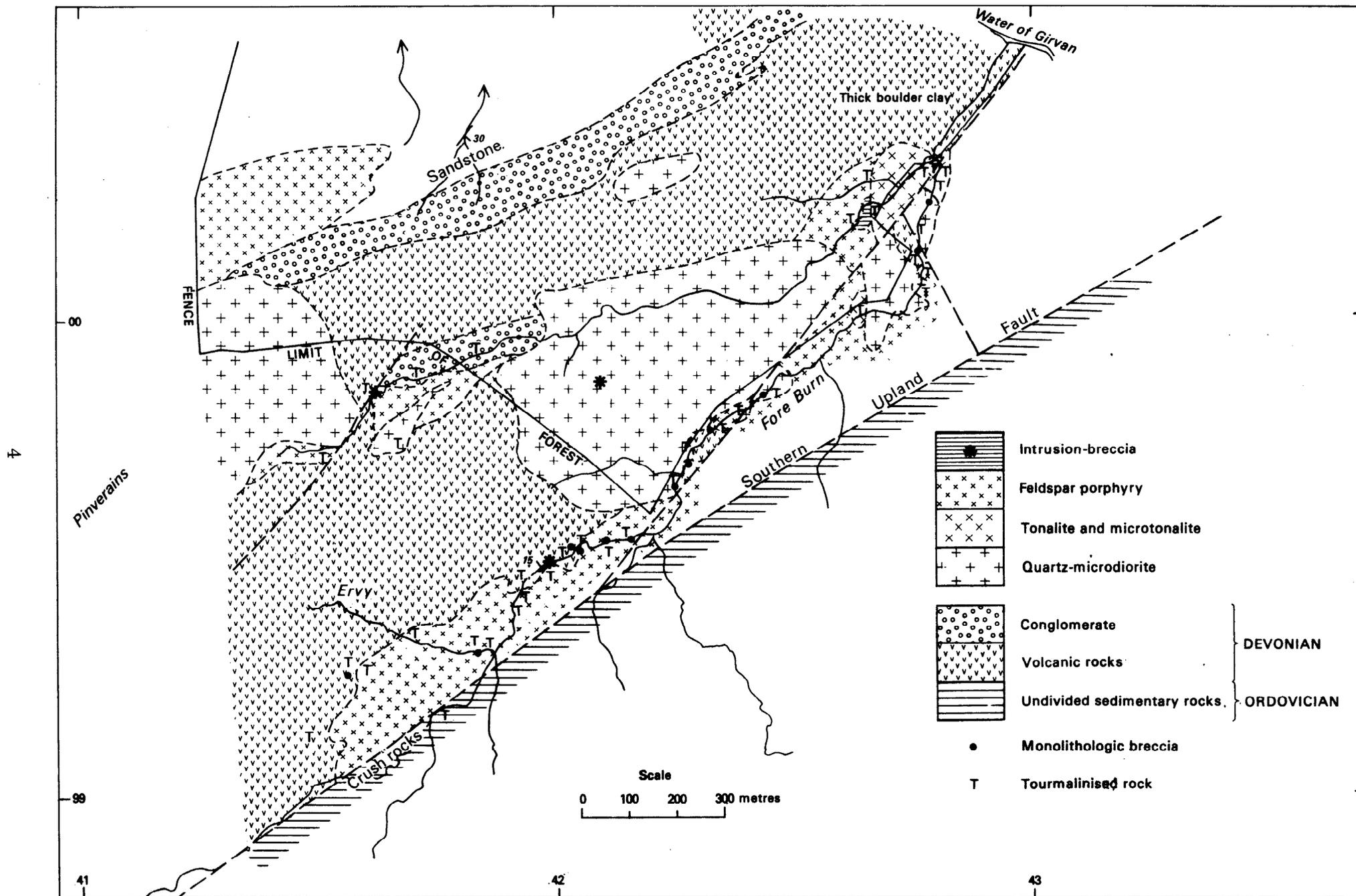


Fig 2: Geology of the Fore Burn area.

gorge along Fore Burn above the sheepfold at NX 4199 9945.

Monolithologic breccias, in which the fragments appear not to be abraded and there is an absence of any signs of transportation of the majority of the fragments, occur within a distinct linear zone at intervals along the Fore Burn and elsewhere within about 300 m of the Southern Upland Fault over a distance of about 2 km. The form of the breccias is not known, though they may comprise a string of pipe-like structures within a fault zone. Feldspar porphyry, quartz-microdiorite and adjacent volcanic rocks are all brecciated. The fragments are angular, close fitting and in most cases do not appear to have been rotated or transported. The space between them is commonly filled by carbonate and tourmaline. Thin veins composed of small, rotated and transported fragments set in crushed or pulverised rock do traverse these breccias.

Breccia pipes and dykes are commonly found in association with porphyry copper deposits and many of the pipes are mineralised. Mechanisms invoked to explain the origin of the pipes include hydrothermal stoping (Locke, 1926; Sillitoe and Sawkins, 1971), fluidisation (Reynolds, 1954; Gilmour, 1977) and phreatomagmatic explosion (Wolfe, 1980). In the last-named, fragmentation occurs when a rising body of magma encounters a voluminous supply of water, which instantly flashes to steam. After several repetitions of this process the resultant breccias, usually initiated along planes of weakness, may be sealed by crystallisation from hydrothermal fluids. Fluidisation may take place in size- and density-sorted material in fractures but this is uncommon, the main transportation process being essentially ballistic. The appeal of this mechanism is that it can explain the diversity of breccia type, the general absence of finely comminuted matrix material and the crystalline infilling between fragments. If it is accepted, then intrusion and 'crackle' breccias can only occur at shallow depths (<3 km) and usually above the intrusion which subsequently becomes the host to the porphyry copper body.

## PETROGRAPHY

### *Quartz-microdiorite*

In the two large bodies, this facies (S67296, 67298, 67301-2, 67309-10, 67320) is dark grey or, locally, pink and sparsely porphyritic with rare 4 mm phenocrysts of feldspar and pseudomorphs after ferromagnesian minerals. The rock consists of cloudy plagioclase crystals, mostly less than 0.75 mm long, which may show normal zoning from andesine/labradorite cores or be totally albitised. Alteration to sericite and calcite is usually incomplete. Interstitial areas are composed of quartz, potash feldspar and, rarely, chlorite. The quartz content varies between 8 and 17%, but is most commonly about 10-11%. Brown or green

biotite, which may be partly or totally altered to chlorite and minor actinolite, is the main mafic mineral but all rocks contain pseudomorphs of chlorite, chlorite and calcite, and fibrous green amphibole, presumably after amphibole or clinopyroxene. In the pink rocks the colour is due to reddish brown dust, probably hematite, impregnated in the margins of the feldspars. Accessory minerals include ilmenite, magnetite, hematite and apatite. Pyrite, arsenopyrite and chalcopyrite in association with carbonate and tourmaline are present in the altered rocks. Specimens from two small areas in the lower reaches of the Fore Burn (S64506, 67315-7) differ from the rocks in the main part of the complex in being finer-grained, poorer in quartz and free of potash feldspar. The rocks are also more intensely altered to carbonate.

### *Tonalite*

This rock (S64499, 64507, 67306) consists mainly of plagioclase, quartz and potash feldspar. The plagioclase, which is partly altered to sericite, carbonate and chlorite, may show normal zoning from calcic andesine cores, but some crystals are completely albitised. Quartz exceeds 18% of the rock. Both plagioclase and potash feldspar are resorbed by the quartz. Primary brown biotite has survived in only one rock (S64499). There is some tourmaline, ilmenite, magnetite, and sulphides including arsenopyrite, pyrite and chalcopyrite which are associated with patchy calcite and sericite alteration.

### *Feldspar porphyry*

The rock is pale brown, greenish-grey or pink. The main rock type (S64503-4) consists of euhedral to subhedral plagioclase phenocrysts up to 2.5 mm long, a few recrystallised small quartz phenocrysts, and chloritic pseudomorphs after biotite or amphibole, all set in a groundmass of plagioclase laths up to 0.1 mm long, anhedral quartz and minor potash feldspar. Accessory minerals include zircon, apatite and pyrite. Varieties occur in which phenocrysts are less common and in which the groundmass is a very fine-grained mass of anhedral feldspar and quartz, largely recrystallised (S67307, 67319, 67321-2). Most of these rocks are highly altered, with secondary quartz, carbonate, sericite and chlorite. Tourmaline, pyrite, apatite, arsenopyrite, chalcopyrite and tennantite-tetrahedrite have also been identified.

### *Porphyritic hypersthene microdiorite*

This rock (S64505) consists of crowded plagioclase crystals, ranging from 0.3 to 2.0 mm in length, showing normal zoning from labradorite to albite. Many crystals are subhedral, but albite in the outer zone may be intergrown with the groundmass. Some subhedral to anhedral clear hypersthene is present, but less commonly than sericite/calcite pseudomorphs after other ferromagnesian minerals and chlorite after biotite. The groundmass is

dominantly feldspathic, but with abundant ilmenite, some apatite, and tourmaline. Carbonate alteration is patchy.

#### *Microtonalite*

The highly altered, mineralised leucocratic microtonalite (S64498) exposed in the lower reaches of the Fore Burn has an unusual texture. In parts it consists of irregular poikilitic plates of quartz up to 0.2 mm diameter containing roughly orientated crystals of altered plagioclase, often in clumps. The quartz may be secondary. Tourmaline, calcite and pyrite are abundant with minor chalcopyrite and rare galena and sphalerite.

#### *Lavas*

Most of the rocks (DAR\* 5005-6, DAR 5012, 5014, S64496-7, 67312-3, 67318) are andesite or basaltic andesite. They are non-porphyrific, though occasional large plagioclase crystals and spongy chlorite pseudomorphs do occur. They consist of roughly orientated laths of feldspar about 0.3 mm long with interstitial areas of chlorite and ilmenite. The feldspar is commonly altered, but in some rocks multiple twinning remains in turgid, brownish albite/oligoclase. Many lavas contain amygdaloids of chlorite, calcite, pyrite, quartz and epidote in various combinations. One highly altered amygdaloidal rock (S67300) contains plentiful fibrous amphibole, leucoxene and small pseudomorphs of sericite and opaques after ?olivine.

One porphyritic specimen from the north side of the complex (S67303) consists of subhedral and euhedral plagioclase phenocrysts up to 2 mm long, now albitised, in a microcrystalline trachytic feldspathic groundmass. The rock is altered, veined and tourmalinised. A few small chlorite pseudomorphs survive.

#### **ALTERATION AND MINERALISATION**

All the rocks in the area have been altered to some degree: the feldspar is speckled with replacement sericite and carbonate, and the ferromagnesian minerals are partly or wholly replaced by chlorite, chlorite and carbonate, or actinolite. Tourmalinisation is also widespread, affecting all rock types including crush rocks in the Southern Upland Fault zone. Pyrite is present in small amounts, both as disseminations and in veinlets. There are, however, two areas of especially intense alteration and mineralisation affecting all rock types. Both follow approximately north-easterly lines, partly coincident with faults. The larger and more intensely altered zone along the Fore Burn coincides with the zone of breccias. The smaller zone to the west contains conglomerates.

Three main types of alteration and mineralisation are recognisable within these zones:

a. Pervasive replacement of feldspars and matrix by sericite or muscovite and carbonate associated with some chlorite and variable amounts of

disseminated sulphide. Pyrite may occur alone or with minor chalcopyrite and arsenopyrite. In some rocks arsenopyrite is dominant, while in others it mantles pyrite. Epidote is very rare. There may be large patches of carbonate containing pyrite with minor chalcopyrite and rare galena. The two sulphide assemblages that have been identified are pyrite-chalcopyrite-galena, detected only in the north-eastern part of the area, and arsenopyrite-pyrite-chalcopyrite.

b. Tourmalinisation. Tourmaline is the diagnostic metasomatic mineral in both zones. It is bluish-green or brown, zoned, and commonly forms radiating aggregates, sometimes spherulitic, though in some rocks the crystals are disseminated. The radiating aggregates tend to occur with carbonate, quartz and minor chlorite, but in some rocks they are associated only with large patches of secondary quartz replacing feldspar. Tourmaline preferentially replaces feldspar crystals. In rocks which are highly tourmalinised the accompanying alteration to carbonate and sericite is also commonly intense. In such rocks veinlets of carbonate may pre-date and post-date tourmaline veins and radiating aggregates. In the conglomerates and both types of breccia, tourmaline is largely confined to the matrix where it is fine grained and closely associated with abundant carbonate.

Twenty-two spots in tourmaline in DAR 5015B (No. 25 in Table 6) and twelve spots in DAR 5052 (No. 27 in Table 6) were analysed by electron microprobe for Mg and Fe. The results were corrected for background, dead time and drift only. The results for DAR 5015B were in the ranges 4.6-7.2% MgO and 9.7-20.1% FeO (throughout this report FeO means total Fe expressed as FeO), and for DAR 5052 3.4-9.0% MgO and 8.1-20.2% FeO. Zoning is common. In five grains Fe was found to decrease from core to margin while Mg generally, though not always, increased. In one grain in DAR 5015B, Fe increased while Mg decreased. In one grain in DAR 5052 a spot in the pale core of the crystal contained 8.3% MgO and 8.1% FeO and a spot at the pale margin 7.1% MgO and 11.7% FeO; a spot in a dark brown zone near the margin contained 3.4% MgO and 20.2% FeO.

With Mg:Fe atomic ratios varying from 65:35 to 23:77, the tourmalines in these rocks differ from the dravites which Slack (1981) suggested are characteristic of stratabound sulphide deposits.

Radiating aggregates commonly contain pyrite and, in places, minor amounts of chalcopyrite and rare galena and sphalerite, the last two forming blebs in pyrite. Small vugs or replacement patches contain coarse-grained quartz with tourmaline, arsenopyrite and chalcopyrite. Sulphides which have been recorded either disseminated or in veinlets and fractures, in places abundantly in tourmalinised rocks, include pyrite, arsenopyrite and chalcopyrite, the last two minerals partially replaced by tennantite-tetrahedrite. Apatite is also

\*Numbers of specimens held in the collection of Metalliferous Minerals and Applied Geochemistry Unit of IGS

present, locally abundantly.

c. Veins. Thin veins and veinlets of quartz and carbonate in places form a cross-cutting stockwork post-dating the hydrothermal brecciation and themselves may be cut by carbonate veinlets. Chlorite or quartz-chlorite veinlets are uncommon, but widely distributed. DAR 5013 (No. 1 in Table 6) contains barite in a quartz-carbonate vein. Veins and veinlets of quartz with carbonate, tourmaline and sulphides are common, but only rarely exceed 15 cm in thickness. They also may be cut by carbonate veins. Thick (>15 cm) veins of this type with arsenopyrite occur in the Fore Burn at NS 4278 0010. A little further upstream at NS 4265 0001 there is a group of several thick veins (e.g. DAR 5051-3, Nos 26-28 in Table 6). There is widespread carbonate in the country rock with minor tourmaline, abundant disseminated arsenopyrite and minor chalcopyrite. The main gangue minerals in the veins are quartz, tourmaline, chlorite, sericite and carbonate. Chalcopyrite is abundant; pyrite and arsenopyrite less so. Cobaltite occurs rarely (identified in DAR 5052) and may enclose chalcopyrite blebs. Minerals enclosed within the chalcopyrite in DAR 5052 were examined by electron microprobe energy-dispersive scan, and found to include relict pyrite, blebs of arsenopyrite, tennantite (which also forms veinlets) and native gold (which has a small silver content). A thick vein with abundant sulphide occurs at a third locality in the burn [NX 4226 9965].

Veins up to 30 cm in thickness, composed mainly of tourmaline with arsenopyrite, pyrite and chalcopyrite in varying relative proportions, were found in the gorge above the sheepfold at NX 4204 9952 (DAR 5015, Nos 24 and 25 in Table 6). Some chalcopyrite occurs as veinlets in pyrite. Associated with the chalcopyrite and confirmed by electron microprobe energy-dispersive scans, is an intermediate member of the tennantite-tetrahedrite series, with As and Sb, as well as both end members. Minor cobaltite is also associated with chalcopyrite. Arsenopyrite is extensively altered to scorodite (ferric arsenate,  $\text{FeAsO}_4 \cdot \text{H}_2\text{O}$ ) which contains a little P substituting for As.

It is likely that the pervasive alteration to sericite and carbonate, the tourmalinisation and the mineralisation all took place during a single hydrothermal event in which tourmalinisation was more localised than alteration to sericite and carbonate.

Veins of quartz-pyrite, quartz-carbonate, chlorite and chlorite-carbonate all intersect tourmaline rosettes. Veins of carbonate post-date them whereas, in some rocks, thin veinlets of sericite cross-cut the carbonate veins.

### STRUCTURE

Only two bedding measurements were made (Figure 2). They and the general trend of outcrop indicate a north-east strike and suggest major

folding along north-east axes. Bedding dips do not exceed  $30^\circ$ .

The Fore Burn complex terminates at the Southern Upland Fault, which forms a conspicuous feature along which breccias have been located. Minor faults with a more northerly trend are more speculative, but are believed to follow the Fore Burn and a parallel tributary to the north-east.

### SUMMARY OF GEOLOGICAL EVENTS

The events listed below are considered in chronological order.

1 Eruption of basaltic and andesitic lavas and tuffs, probably mainly subaerial but in part probably laid in a lake.

Conglomerates containing debris derived mainly from the Ordovician-Silurian basement, but with some locally derived igneous material, were laid down during the volcanic episode.

2 Intrusion of the Fore Burn igneous complex. The feldspar porphyry was probably intruded before the quartz-microdiorite and tonalite.

3 ?Folding.

4 Brecciation and the emplacement of intrusion breccias in a zone along the Fore Burn. The distribution of the breccias in the Fore Burn zone in a linear fashion suggests that they may post-date or be contemporaneous with the parallel fault along the burn, which may have been a principal zone of weakness.

5 Mineralisation. The mineralisation took place within the Fore Burn breccia zone and in the conglomerates and fragmented rocks in a parallel zone to the west. The mineralisation sequence appears to have been:

i Pervasive alteration to sericite, carbonate and locally abundant tourmaline, apatite and secondary quartz, with minor chlorite and some disseminated sulphides. The latter include pyrite, chalcopyrite and rare galena and sphalerite in the north-eastern area and pyrite, arsenopyrite and chalcopyrite elsewhere.

ii Veins of quartz and pyrite; quartz-carbonate-tourmaline with sulphides and native gold; carbonate and chlorite, with sulphides.

iii Barren veins of quartz, with or without chlorite and carbonate.

iv Carbonate veins.

v Sericite veinlets.

There is some evidence that an early stage in the carbonate-sericite alteration may have preceded brecciation, but the main pervasive alteration either accompanied or post-dated brecciation firstly because alteration is most intense in the breccia zone and secondly because many of the breccias are cemented by fine-grained tourmaline and carbonate. All the veining post-dates brecciation.

Tourmalinised crush rocks in the upper reaches of the Fore Burn might indicate that mineralisation took place after the main movement along the Southern Upland Fault.

## GEOPHYSICS

### INTRODUCTION

Induced polarisation (IP), resistivity, and total magnetic force surveys were carried out over the Fore Burn Igneous Complex and adjacent country rocks. For the IP/resistivity measurements, the dipole-dipole array was used, with a dipole length of 60 m and a constant transmitter to receiver dipole separation of 120 m (centre to centre). The southern half of the survey area is covered by a dense forest, and several of the traverses were bent to run along fire-breaks.

### RESULTS

The chargeability, apparent resistivity, and magnetic anomaly results are presented as contour maps (Figures 3 to 5).

The resistivity map (Figure 3) shows generally low values in the west and north-west of the survey area, where two minima occur. One of these [approximately NX 4137 9990] lies close to a fence; the other, about 200 m to the south, coincides with a small feldspar-porphry body close to a fault. Over the central and northern parts of the survey area, resistivity is generally high, over intrusive and volcanic rocks alike, although a minor low runs approximately along the northern margin of the intrusions. Both bands of conglomerate in this area give comparatively high resistivities. Prominent low resistivity values over the eastern end of the complex (notably at NS 4270 0001) are coincident with sulphide mineralisation observed in the Fore Burn, but also lie close to a fence. The Fore Burn fault, particularly where it runs into the Southern Upland Fault, gives low resistivities. In the east a local minimum lies about 100 m south of the mapped fault line. This low, also near a fence, lies in an area of poor exposure, but nearby upstream intensive mineralisation is present at surface. There is no obvious low-resistivity zone along the Southern Upland Fault itself despite the extensive crushing seen. Finally, a band of high resistivity occurs in the east end of the survey area, unrelated to the known geology, and apparently crossing a minor north-south fault.

Chargeability values in the whole area (Figure 4) are low, rarely rising above 15 ms. There is little obvious correlation with the geology or known mineralisation although the conglomerates and the Southern Upland Fault both have rather low chargeability. The fault even gives some negative values. Four chargeability peaks can be seen. The most westerly [NX 4135 9989] is the strongest anomaly and coincides with the forest fence, a low resistivity feature and local disseminated and veinlet pyrite in quartz-microdiorite. Two moderately high chargeability zones occur to the south of this. The one around NX 4172 9974 is over a complicated area marginal to a small intrusion of quartz microdiorite in volcanic rocks. The intrusion contains locally moderate amounts

of disseminated pyrite. The other zone [NX 4168 9944], over volcanic rocks, is unexplained. The fourth peak, in the lower part of the Fore Burn [NS 4285 0029] coincides with locally intense tourmalinisation and sulphide mineralisation.

All the magnetic profiles show a relatively high noise level ( $\pm 50$  to 100 nT) except in the south, and they were smoothed by eye to give the contour map (Figure 5). Three major features can be seen. In the north-west corner of the survey area lies a zone of short-wavelength anomalies up to 200 nT. This 'noisy zone' is bounded to the south-east by a fault. Running approximately north-east through the centre of the survey area is a broad high, up to 700 nT, crossing volcanic and intrusive rocks alike, but parallel to the strike of the stratified Devonian rocks and displaying a greater amplitude over them. The anomaly is broader and smoother over the intrusion than over the volcanic rocks, showing perhaps that a magnetic horizon within the volcanic formation passes beneath a relatively thin sheet of the quartz-microdiorite. The high values obtained at the eastern end of this anomaly occur near an intrusion breccia, though no mineralogical explanation has been found for it. The third magnetic anomaly is a narrow high, up to 200 nT in the northern part of the survey area. It occurs over volcanic rocks immediately above the northern conglomerate. There are geochemical indications of high Ti, Cr and Fe in this area, but a specific magnetic rock type has not been identified.

### DISCUSSION

The three most distinct resistivity lows are probably due to genuine geological features even though they all lie close to fences. (These and other fences crossed elsewhere do not produce anomalies.) Sulphide mineralisation is exposed in all three low resistivity zones, but only the western one, where the sulphide is disseminated, also coincides with an IP high. Moderate IP effects are seen at the southern anomaly, but at the third locality chargeability does not rise significantly. At both these localities mineralisation takes the form of small lenses of massive sulphides in veins. Although two of the low resistivity zones occur on or close to the Fore Burn fault, there are also parts of the fault which are not conductive, and the Southern Upland Fault gives no significant resistivity low in spite of its extensive crushed and fractured zone. From these observations it may be concluded that low resistivities accompanying faults are probably a result of alteration due to hydrothermal fluids moving in the fault zone, and perhaps in part to small lenses of massive sulphide deposited by the fluids; that chargeability anomalies occur where disseminated sulphides are also present; and that the Southern Upland Fault has been active since the mineralising episodes at Fore Burn.

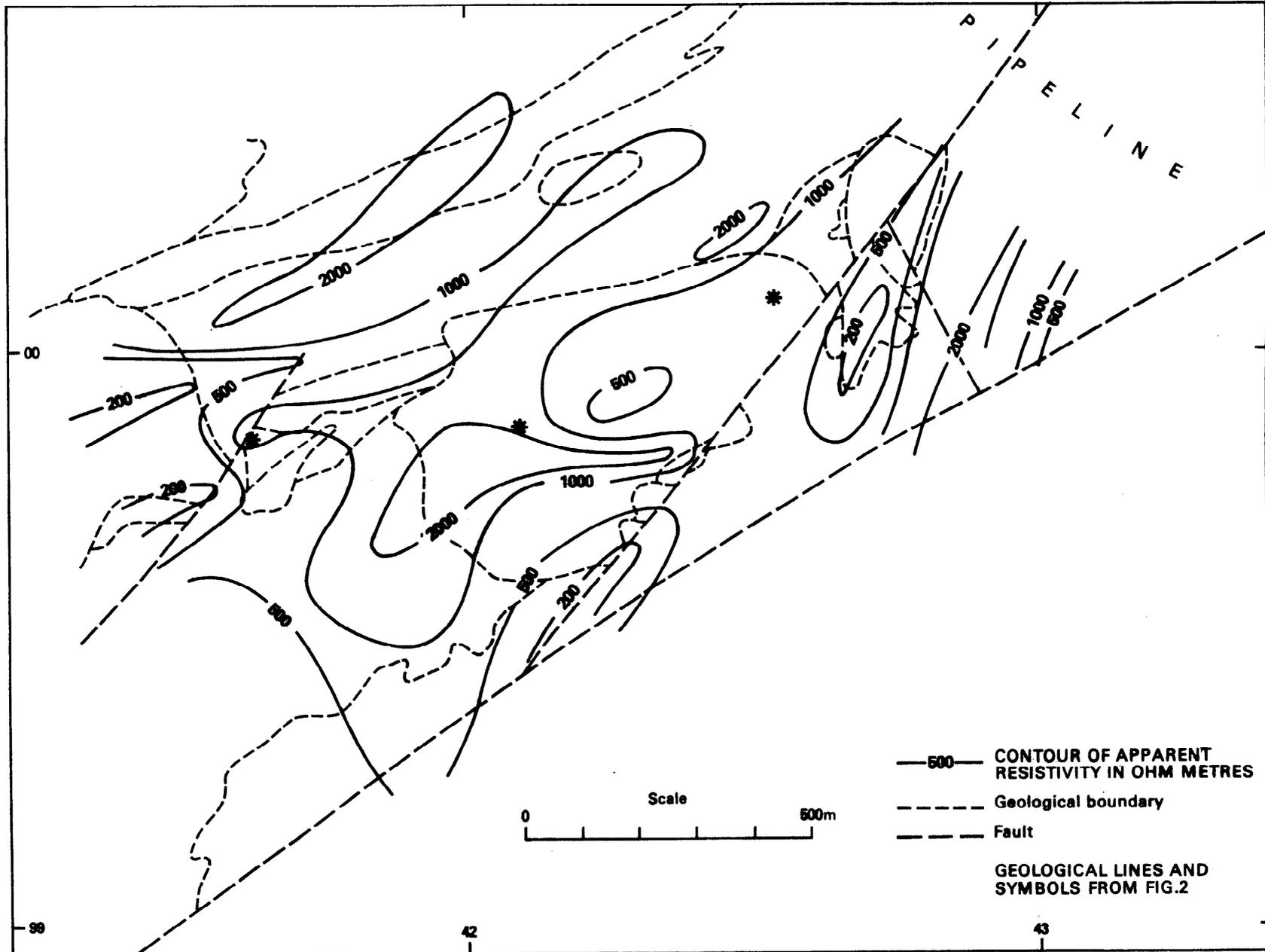


Fig. 3 Contoured plot of apparent resistivity results (n = 2, a = 60m.).

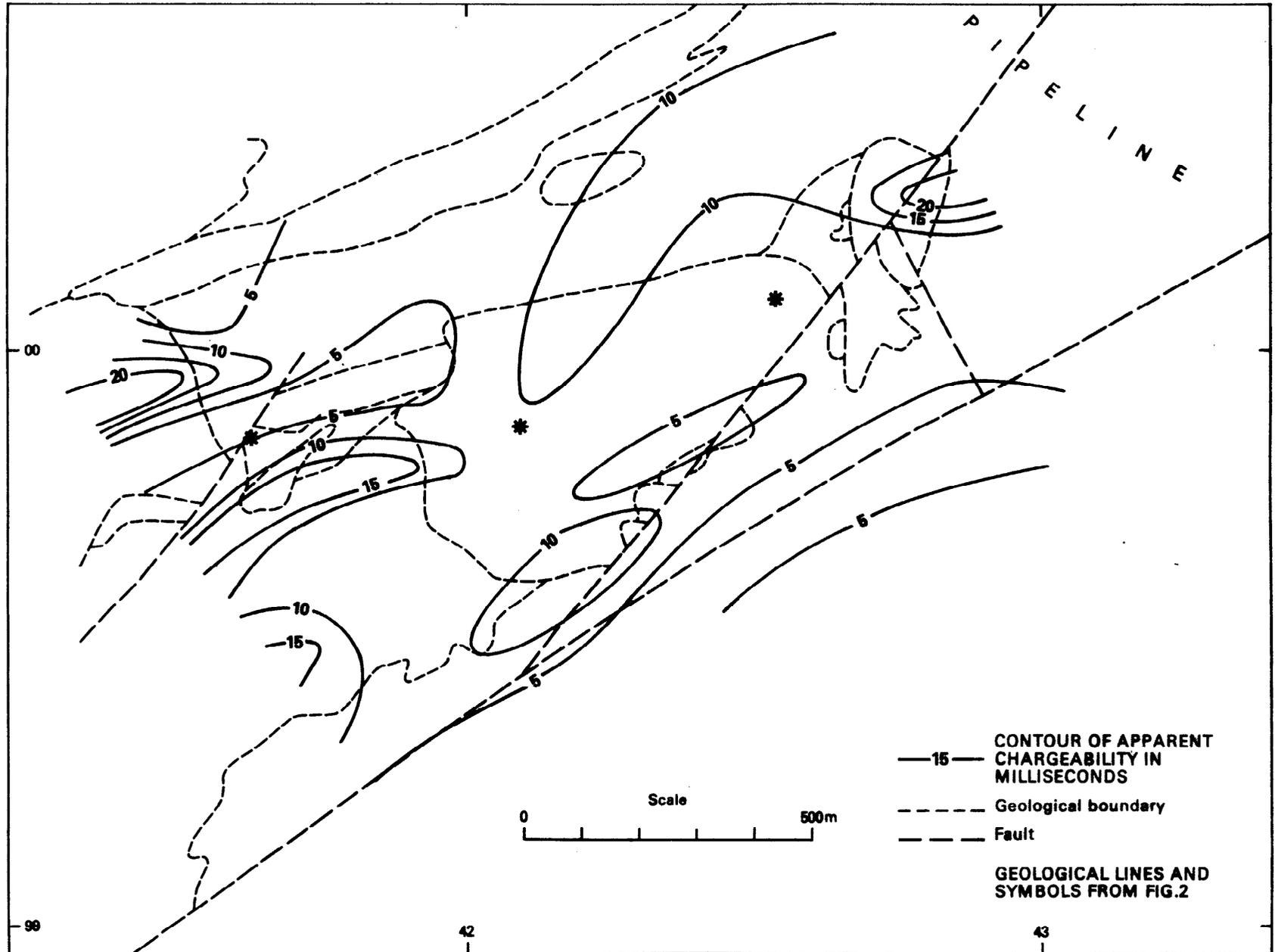


Fig. 4 Contoured plot of chargeability results (n=2, a=60m.).



There is a general trend to magnetic, resistivity and, to a lesser extent, chargeability features, parallel to strike. The magnetic anomalies in particular appear to be stratigraphically controlled. The evidence of the main magnetic anomaly suggests that the eastern body of quartz-microdiorite extends to no great depth above a horizon of magnetic rocks. Dip measurements are sparse in the stratified rocks, but this quartz-microdiorite may be a gently folded laccolith occupying a synform.

## GEOCHEMISTRY

### DRAINAGE SURVEY

#### *Sample collection, preparation and analysis*

Stream sediment, panned concentrate and water samples were collected from thirty-five sites at approximately 500 m intervals along stream courses at potential sites of heavy mineral accumulation (Figure 6). Water samples were also collected at six additional sites where no sediment was found. Two additional panned concentrates, made from three times the normal amount of sediment, were collected for gold analysis from near the site found to contain the largest metal anomalies [NX 4218 9955].

Stream sediment was wet-sieved at site to pass 100 mesh BSS (0.15 mm) using a minimum of water to retain the clay fraction. Samples were dried in the laboratory prior to grinding in a ball mill for 30 minutes. A 0.5 g split was analysed for Cu, Pb and Zn by AAS following digestion in hot concentrated nitric acid for one hour. As and W were determined by X-ray fluorescence spectrometry (XRF) following grinding of a 12 g subsample in a Tema mill with 'elvacite' binder and pelletising. A further range of elements was determined by optical emission spectroscopy (OES). Detection limits were approximately 1 ppm for Be and Mo; 2 ppm for As; 3 ppm for Cu and W; 5 ppm for Pb, Zn, B, Y and Sn; 10 ppm for V, Cr, Co and Ni; 20 ppm for Zr; 50 ppm for Mn; 100 ppm for Ba; and 0.5% for Fe.

Constant volume panned concentrates of about 50 g were made at site from about 4 kg of -8 mesh BSS (2 mm) stream sediment. Following drying, a 12 g subsample was ground in a Tema mill with 3 g of 'elvacite' binder for five minutes prior to pelletising and analysis by XRF for a range of elements. Detection limits were 2 ppm for Mo, Sr and As; 3 ppm for W, Zr and Zn; 5 ppm for Ni; 6 ppm for Mn and Cu; 9 ppm for Sn; 11 ppm for Sb; 13 ppm for Pb and 27 ppm for Ba. After drying, the two specially collected panned concentrates were combined prior to analysis for Au by an instrumental neutron activation method, detection limit 0.005 ppm (Plant and others, 1976).

At each site two water samples were collected

in 30 ml plastic bottles. One set of samples was acidified in the field with 0.3 ml perchloric acid and subsequently analysed for Cu and Zn by atomic absorption spectrophotometry (AAS) without further preparation. Detection limits were approximately 0.02 ppm. The second set was sealed, and uranium was determined on container and contents by a delayed neutron activation method (Ostle and others, 1972); detection limit 0.4 ppb.

#### *Presentation of results*

Analyses are listed in Table 1. The result of 3.69 ppm Au on the combined sample of two special panned concentrates is not included. Cu and Zn in water, Sb and Sn in panned concentrate and W in stream sediment are also omitted from the table as all except two of the results were close to or below the detection limits. The exceptions are 7 ppm W in sediment at NS 4190 0071 (No. 24) and 17 ppm Sb in panned concentrate at NX 4027 9994 (No. 33). These variables were also omitted from statistical calculations. For the remainder, results below the detection limit were set at half the detection limit prior to data processing. A summary of the results is given in Table 2.

#### *Population distributions*

The examination of element distributions on log-scale cumulative frequency plots indicated that in stream sediment all except Pb, Fe and Mn have approximately lognormal distributions. Pb has a binormal form (Parslow, 1974) with an inflexion point at 51 ppm (91% level); Fe and Mn have complex forms, possibly representing combined normal and lognormal populations (Sinclair, 1976).

Panned concentrates show a wider range of distribution types: Ca shows a normal distribution and Cu, Mo, Fe, Zr and Ni are lognormal, but Zn, As, Mn and Sr give weakly sigmoidal plots on logscale probability paper and Pb, Ti and Ba show binormal forms which suggest the presence of two sample populations.

The U in water distribution shows approximately normal form, but is distorted by the large proportion of results below the detection limit.

Most variables approximate to a lognormal form, so parametric statistical methods were used to examine the data after log-transformation of all variables except U and Ca.

#### *Determination of threshold levels*

Threshold levels proved difficult to determine. Though it was known that several elements were reflecting mineralisation, distribution analysis failed, for many elements, to distinguish more than one sample population. It is possible in this mineralised area that for some elements all samples came from a mineralised population. Using the mean plus two standard deviations as the threshold for elements with lognormal distributions was clearly inappropriate because

**Table 1** Analyses of stream sediments, panned concentrate and water samples

Stream sediments																	
Grid																	
No.	Reference	Cu	Pb	Zn	As	Mo	Fe	Mn	Cr	Co	Ni	Y	Zr	Ba	B	Be	V
1	4164 9905	20	40	170	418	1.9	5.78	12500	158	84	104	30.1	293	769	165	2.7	116
2	4117 9881	15	40	210	339	1.7	5.08	7840	147	44	76	13.5	306	759	394	0.5	98
3	4185 9925	30	40	270	483	1.7	5.78	10200	233	71	148	35.1	309	1050	281	2.6	147
4	4188 9927	25	50	670	157	1.2	6.19	25600	198	114	172	39.8	236	553	79	4.2	163
5	4182 9930	30	30	190	1068	2.0	5.68	6500	215	68	152	30.2	359	531	2310	2.4	150
6	4219 9955	115	40	470	1420	3.9	5.97	11200	183	74	126	32.2	246	860	2200	3.4	119
7	4222 9952	30	30	180	112	2.3	4.91	1960	210	28	87	29.9	320	289	104	2.1	149
8	4218 9952	20	50	290	421	2.3	6.53	8470	257	59	147	37.8	277	429	1060	2.7	147
9	4216 9971	20	40	380	2293	2.5	5.81	7480	98	47	62	33.8	298	709	383	2.4	114
10	4226 9965	75	40	270	693	2.5	5.62	6730	162	57	118	31.8	256	413	1510	2.5	132
11	4238 9929	20	80	350	239	2.0	7.67	10400	166	88	109	36.8	216	422	58	2.8	168
12	4228 9975	15	30	150	210	2.6	4.77	1980	128	20	73	30.2	407	381	419	1.6	121
13	4254 9990	70	40	180	548	5.0	5.41	4120	194	32	123	32.9	304	411	1610	1.8	135
14	4257 9989	15	40	130	28	1.3	4.37	4120	152	35	86	28.1	320	513	59	2.7	102
15	4275 0004	60	40	210	546	3.4	5.84	5190	198	38	117	36.5	435	366	1420	2.5	153
16	4215 0001	30	40	370	247	1.7	6.95	11800	205	56	144	31.2	329	409	515	1.4	158
17	4183 9993	35	30	180	182	2.0	5.85	3830	220	41	160	26.4	250	396	982	2.1	126
18	4252 0009	20	90	350	160	1.5	5.91	10100	106	41	79	26.4	172	465	143	1.4	131
19	4264 0028	15	40	300	101	3.7	5.74	7370	138	27	65	27.7	238	519	233	1.4	122
20	4265 0023	25	100	430	242	2.8	6.87	13100	144	57	106	25.3	169	686	472	1.9	133
21	4281 0031	55	30	210	477	2.6	4.14	4110	185	35	110	29.8	272	566	1230	2.1	125
22	4290 0048	55	40	420	62	2.3	5.67	6000	171	47	116	35.8	281	709	1280	2.3	127
23	4302 0034	110	40	220	512	3.5	4.43	4600	145	89	87	27.5	451	453	393	2.6	128
24	4190 0071	10	30	180	609	1.6	4.50	6910	137	31	62	26.9	325	466	85	1.6	111
25	4135 0085	10	40	210	98	1.1	3.35	9080	74	24	47	22.6	319	468	247	3.0	74
26	4168 0083	15	20	80	102	0.5	3.56	1170	112	12	52	24.0	333	347	104	1.3	95
27	4161 9982	25	30	240	277	1.7	7.48	6900	218	62	110	23.7	203	357	626	1.5	191
28	4039 9827	40	30	170	99	1.6	5.06	3140	230	35	119	30.6	302	456	124	1.8	158
29	4069 9961	15	40	410	159	0.5	5.12	5130	257	40	114	29.6	228	368	396	2.3	145
30	4065 9953	15	50	300	208	1.0	5.23	8510	194	40	116	25.0	241	589	562	2.3	131
31	4056 0027	20	30	100	170	1.1	3.53	1670	137	15	56	24.3	288	366	294	1.4	91
32	4037 0000	10	30	140	58	0.5	3.10	2650	116	11	58	28.3	291	1220	208	2.1	86
33	4027 9994	10	30	250	96	0.5	3.91	5500	139	24	71	23.6	254	461	241	2.0	88
34	4000 9943	10	30	190	81	0.5	4.33	4970	176	23	91	24.7	401	486	89	0.5	113
35	3998 9870	10	30	180	79	1.4	4.30	10600	145	28	80	26.4	331	800	56	1.2	119

Panned concentrates																	Water	
Grid																		
No.	Reference	Cu	Pb	Zn	As	Mo	Fe	Mn	Ni	Ti	Ba	Sr	Zr	Ca	U			
1	4164 9905	3	20	49	30	2	3.10	470	21	5380	446	280	220	0.77	2.82			
2	4117 9881	3	14	59	58	2	4.10	560	28	4400	443	180	190	0.47	2.17			
3	4185 9925	17	28	150	336	3	4.55	1030	66	4590	21140	290	200	0.66	1.95			
4	4188 9927	3	18	190	18	1	4.60	1220	51	3860	471	210	130	0.54	1.51			
5	4182 9930	87	13	90	1107	3	5.83	890	71	5440	13070	240	170	0.56	1.95			
6	4219 9955	465	48	162	4815	8	6.09	1490	67	4610	19730	260	170	0.59	2.38			
7	4222 9952	12	28	127	59	1	4.52	430	55	4370	413	210	200	0.56	2.38			
8	4218 9952	7	16	79	46	1	4.54	510	41	4130	418	220	170	0.64	2.17			
9	4216 9971	6	18	70	146	1	3.54	360	20	4070	480	260	220	0.73	2.17			
10	4226 9965	220	18	144	2025	5	5.80	1090	57	4870	6955	240	190	0.56	3.68			
11	4238 9929	3	23	104	12	2	4.36	560	32	3670	473	240	140	0.67	0.64			
12	4228 9975	6	14	46	103	1	3.34	370	20	4820	510	320	170	0.79	0.20			
13	4254 9990	171	21	109	1309	3	5.80	870	53	4980	1933	240	210	0.61	1.30			
14	4257 9989	3	21	67	5	1	3.46	410	31	3820	506	260	210	0.73	0.64			
15	4275 0004	59	20	115	1308	3	5.99	920	54	4950	1139	250	220	0.61	1.95			
16	4215 0001	30	15	146	265	4	8.02	1220	72	11240	446	340	180	0.54	1.95			
17	4183 9993	17	21	130	87	2	7.53	1030	69	22100	498	320	200	0.57	0.86			
18	4252 0009	31	128	590	45	1	5.39	850	28	6220	1861	390	170	0.60	0.86			
19	4264 0028	3	20	122	54	3	7.43	750	27	11000	406	260	250	0.54	0.43			
20	4265 0023	7	50	150	75	2	5.44	1180	42	12390	3269	410	190	0.66	1.95			
21	4281 0031	172	38	120	829	1	5.62	950	52	4690	2596	250	160	0.59	2.17			
22	4290 0048	257	27	147	2510	5	6.30	1040	59	5390	13120	330	170	0.62	2.60			
23	4302 0034	102	6	75	217	2	3.80	540	35	4210	379	210	270	0.48	1.95			
24	4190 0071	3	13	70	24	1	4.28	540	30	4210	571	240	180	0.40	1.51			
25	4135 0085	6	17	93	30	3	3.81	910	21	4110	371	220	190	0.37	2.60			
26	4168 0083	3	334	62	20	2	5.86	490	35	5680	383	200	320	0.62	1.95			
27	4161 9982	33	27	177	128	2	7.71	1570	57	20900	493	420	170	0.62	3.47			
28	4039 9827	272	14	105	145	1	4.92	690	52	7480	4264	240	280	0.59	0.64			
29	4069 9961	12	16	118	31	2	4.04	510	42	4100	413	210	160	0.51	2.17			
30	4065 9953	28	18	141	68	3	5.44	1240	57	5620	604	210	170	0.51	0.64			
31	4056 0027	8	6	76	66	2	5.98	490	33	6030	323	220	230	0.52	2.17			
32	4037 0000	3	6	62	20	4	2.28	350	22	3060	40930	820	240	0.29	2.82			
33	4027 9994	3	15	133	52	2	5.34	980	45	4560	2918	180	200	0.37	1.30			
34	4000 9943	3	6	112	20	1	5.01	900	38	5620	474	190	260	0.43	0.20			
35	3998 9870	3	18	170	20	1	5.04	1120	38	6290	1085	230	230	0.55	0.86			

All results are in ppm except Fe and Ca (%) and U (ppb).

Results less than the detection limit are entered at half the detection limit.

For stream sediments, W was also determined but all results were less than the detection limit except No. 24 (7 ppm).

For panned concentrates, Sb was also determined, but all results were less than detection limit except Nos. 5 (12 ppm), 28 (14 ppm), 29 (12 ppm), 31 (13 ppm) and 33 (17 ppm).

**Table 2** Summary statistical data for 35 analyses of stream sediments and panned concentrates

<i>Element</i>	<i>Mean</i>	<i>Geometric mean</i>	<i>Standard deviation</i>	<i>Maximum</i>	<i>Minimum</i>
<b>Stream sediments</b>					
Cu	31.3	24.1	26.6	115	10
Pb	40.8	38.4	16.9	100	20
Zn	259	234	122	670	80
As	371	230	447	2290	28
Mo	1.95	1.65	1.06	5.0	<1
Fe	52700	51500	11300	76700	31000
Mn	7180	5940	4570	25600	1170
Cr	170	164	45.1	257	74
Co	45	39.6	24.1	114	11
Ni	101	95.7	33.3	172	47
Y	29.1	28.6	5.22	39.8	13
Zr	293	286	65.8	451	169
Ba	544	513	207	1220	289
B	580	333	618	2310	56
Be	2.1	1.93	0.75	4.2	<1
V	128	125	26.1	194	74
<b>Panned concentrates</b>					
Cu	58.9	15.1	104	465	<6
Pb	31.8	20.1	56.5	334	<13
Zn	124	109	89.7	590	46
As	459	101	968	>3000	5
Mo	2.3	1.94	1.51	8	<2
Fe	51100	49300	13400	80200	22800
Mn	815	746	335	1570	350
Ni	43.4	40.4	16.0	72	20
Ti	6370	5600	4320	22100	3060
Ba	4100	1190	8350	40930	323
Sr	274	260	113	820	180
Zr	201	197	40.8	320	130
Ca	5680	5560	1110	7900	2900
<b>Waters</b>					
U (ppb)	1.74	1.43	0.89	3.68	<0.40

All results are in ppm except U in water.

in this data set it would by definition always give one anomalous sample for each variable. Threshold levels for variables whose distributions did not clearly define two populations were therefore set arbitrarily by comparison with results from similar regional surveys over the Criffel–Dalbeattie granodiorite complex and its environs (Leake and others, 1978a) and the Fleet granitic complex and its environs (Leake and others, 1978b). Setting threshold levels had apparently also proved a problem in these areas, but for want of other criteria the base of the highest (i.e. most anomalous) class defined in these surveys was used as a guide to set threshold levels for the Fore Burn area. No comparative data were available for U in water, As, Y and Be in sediment and As, Mo, Sr and Ca in panned concentrate, and for these elements more general comparisons were made with surveys using similar methods elsewhere in the United Kingdom. For W and Sb in panned concentrates all results above the detection limits were regarded as unusual and therefore anomalous. For Au no direct comparisons were possible because of the extra large initial sample but the result of 0.01 ppm Au on a simultaneously determined panned sample from intermediate rocks believed to be barren suggested that the Fore Burn result was distinctly anomalous.

Using the comparative survey criteria, levels of Pb, Zn, Mo, Ba, Fe, Ni, V, Mn, Cr, Co, Y, Be and Zr in sediment and Pb, Zn, Mn, Fe, Ni, Mo, Sr, Ca and Zr in panned concentrate were considered to be mainly related to background variation in unmineralised rocks with only occasional anomalous 'outliers' related to mineralisation or some other enrichment process. As, Cu and B values in sediments and Cu, As, Ba and Ti in panned concentrates all contained several high results which might be related to mineralisation. For three of these, As, Ba and Ti in panned concentrates, precise thresholds could be set from the cumulative frequency graphs: Ba has binormal form with an inflexion point at 610 ppm; Ti shows a similar break at 0.75%; As has a sigmoidal form which indicates that results above 150 ppm include 99% of those belonging to the upper population. Threshold levels together with the distribution of anomalous results relevant to the mineralisation are shown in Figure 6.

#### *Inter-element relationships*

Inter-element relationships are summarised by the correlation matrix (Table 3) which was used as the basis of a four-factor analysis. Factor one (Table 4) can be related to tourmalinisation and sulphide mineralisation. Factor two is related to variation in the abundance of detrital minerals (represented by Zr) and is negatively associated with clay or precipitate mineral phases. Factor three is caused by rocks of basic composition, and factor four by barite mineralisation. The factor analysis shows

clearly the distinctive behaviour of Ba, probably representing a barite mineralisation, which, it indicates, is quite separate from the tourmalinisation and sulphide mineralisation represented in factor one. The amount of Fe in the sulphide minerals is clearly not significant when compared with Fe in other mineral phases, but Mo and Ni are apparently present in significant amounts, a fact not evident from the absolute amount of the elements in the samples. There is no evidence from these relationships for Pb–Zn mineralisation.

#### *Indications of mineralisation*

High levels of B and As occur in stream sediments across most of the area (Figure 6), but the highest levels of both these and Cu and Mo are located in the Fore Burn where it passes through a gorge exposing highly altered and tourmalinised rocks with locally abundant sulphides. Concentrations of these elements gradually fall off downstream except for some increases in the lowermost sample (NS 4290 0048, No. 22). Above the gorge section there is a marked cut-off with the levels of B, Cu and As falling sharply. It is not clear how much this pattern, and the apparently more widespread occurrence of high B and As values in sediment compared with Cu or As in panned concentrates, reflect the distribution of bedrock mineralisation and how much they are affected by other factors such as zones of active stream erosion and mobility in the secondary environment. Certainly the apparent fall-off downstream in the Fore Burn is to some extent misleading, for significant sulphide mineralisation is recorded in the stream bed at NS 4264 6002, well below the section giving the highest metal values. This, coupled with the increases at the lowermost site, indicates downstream rejuvenation of metal anomalies. From a comparison of the Cu, As, Mo and B results in the sediments and concentrates, it is probable that tourmalinisation and sulphide mineralisation together are concentrated near the line of the Fore Burn and extend weakly north-westwards across the interfluvium. The appreciable level of Au in a panned concentrate taken from the Fore Burn suggests that gold accompanies the sulphide mineralisation. The lack of visible gold suggests that it is present in very small grains or inclusions within other minerals. High Cu and Ba and moderate As in a panned concentrate at NX 4039 9827 (No. 28) suggests that weak mineralisation may occur along the line of the Southern Uplands Fault.

Ba results show a distinctive areal distribution, with sharply anomalous values in panned concentrates. Mineralogical examination of the samples confirmed coarse-grained barite as the cause. High levels occur along the Fore Burn accompanying B-As-Cu anomalies, but isolated anomalies elsewhere give a distinctive overall pattern which supports the evidence of the factor analysis that there is a separate episode of barite

**Table 3** Summary of significant inter-element correlations in stream sediment and panned concentrate data

<i>Element</i>	<i>Above 99% significance</i>	<i>Above 99.95% significance</i>
<b>Stream sediments</b>		
Be	Co <sub>S</sub>	Y <sub>S</sub>
B	Mo <sub>S</sub> Ni <sub>S</sub> Ni <sub>P</sub>	Cu <sub>S</sub> As <sub>S</sub> Cu <sub>P</sub> As <sub>P</sub> Mo <sub>P</sub>
V	Cu <sub>S</sub> Zn <sub>S</sub> Y <sub>S</sub>	Fe <sub>S</sub> Cr <sub>S</sub> Co <sub>S</sub> Ni <sub>S</sub> Ni <sub>P</sub>
Cr	Fe <sub>S</sub> Co <sub>S</sub>	Ni <sub>S</sub> V <sub>S</sub> Ni <sub>P</sub>
Mn	Mn <sub>P</sub> - Zr <sub>P</sub>	Pb <sub>S</sub> Zn <sub>S</sub> Fe <sub>S</sub> Co <sub>S</sub>
Fe	Ca <sub>P</sub> Mo <sub>S</sub> Cr <sub>S</sub> - Zr <sub>P</sub>	Zn <sub>S</sub> Pb <sub>S</sub> Mn <sub>S</sub> Co <sub>S</sub> Ni <sub>S</sub> V <sub>S</sub>
Co	Cu <sub>S</sub> Pb <sub>S</sub> As <sub>S</sub> Mo <sub>S</sub> Cr <sub>S</sub> Be <sub>S</sub> - Zr <sub>P</sub>	Zn <sub>S</sub> Fe <sub>S</sub> Mn <sub>S</sub> Ni <sub>S</sub> V <sub>S</sub>
Ni	Cu <sub>S</sub> Zn <sub>S</sub> Y <sub>S</sub> B <sub>S</sub> Cu <sub>S</sub> As <sub>S</sub> Mn <sub>S</sub> - Zr <sub>P</sub>	Fe <sub>S</sub> Cr <sub>S</sub> Co <sub>S</sub> V <sub>S</sub> Ni <sub>P</sub>
Cu	As <sub>S</sub> Co <sub>S</sub> Ni <sub>S</sub> V <sub>S</sub>	Mo <sub>S</sub> B <sub>S</sub> Cu <sub>P</sub> As <sub>P</sub> Ni <sub>P</sub>
Zn	Ni <sub>S</sub> - Zr <sub>S</sub> V <sub>S</sub> Mn <sub>P</sub>	Pb <sub>S</sub> Fe <sub>S</sub> Zn <sub>S</sub> Co <sub>S</sub> Zn <sub>P</sub> - Zr <sub>P</sub>
As	Cu <sub>S</sub> Co <sub>S</sub>	Mo <sub>S</sub> B <sub>S</sub> As <sub>P</sub>
Y	Ni <sub>S</sub> V <sub>S</sub>	Be <sub>S</sub>
Zr	- Zn <sub>S</sub> Zr <sub>P</sub>	- Pb <sub>S</sub> - Zn <sub>P</sub>
Mo	Cu <sub>P</sub> Fe <sub>S</sub> Co <sub>S</sub> B <sub>S</sub> Cu <sub>P</sub>	Cu <sub>S</sub> As <sub>S</sub> As <sub>P</sub>
Ba		Ba <sub>P</sub>
Pb	Co <sub>S</sub> Zn <sub>P</sub> - Zr <sub>P</sub>	Zn <sub>S</sub> Fe <sub>S</sub> Mn <sub>S</sub> - Zr <sub>S</sub>
<b>Panned concentrates</b>		
Ca*	Mo <sub>S</sub> Fe <sub>S</sub>	
Ti	Mn <sub>P</sub>	Fe <sub>P</sub>
Mn	Zn <sub>S</sub> Mn <sub>S</sub> Ni <sub>S</sub> Ti <sub>P</sub>	Zn <sub>P</sub> Fe <sub>P</sub> Ni <sub>P</sub>
Fe	Zn <sub>P</sub> As <sub>P</sub>	Mn <sub>P</sub> Ni <sub>P</sub> Ti <sub>P</sub>
Ni	B <sub>S</sub>	Cu <sub>S</sub> Cr <sub>S</sub> Ni <sub>S</sub> V <sub>S</sub> Cu <sub>P</sub> As <sub>P</sub> Fe <sub>P</sub> Mn <sub>P</sub>
Cu	Mo <sub>S</sub> Ni <sub>S</sub> Ba <sub>P</sub>	Cu <sub>S</sub> B <sub>S</sub> As <sub>P</sub> Ni <sub>P</sub>
Zn	Pb <sub>S</sub> Fe <sub>P</sub> Ni <sub>P</sub> Mn <sub>S</sub>	Zn <sub>S</sub> - Zr <sub>S</sub> Mn <sub>P</sub>
As	Ni <sub>S</sub> Fe <sub>P</sub> Mn <sub>P</sub> Ba <sub>P</sub>	Cu <sub>S</sub> As <sub>S</sub> Mo <sub>S</sub> B <sub>S</sub> Cu <sub>P</sub> Mo <sub>P</sub> Ni <sub>P</sub>
Sr	Ba <sub>P</sub>	
Mo	U <sub>w</sub> Cu <sub>P</sub> Ba <sub>P</sub>	B <sub>S</sub> As <sub>P</sub>
Zr	- Pb <sub>S</sub> - Fe <sub>S</sub> - Mn <sub>S</sub> - Co <sub>S</sub> - Ni <sub>S</sub>	- Zn <sub>S</sub>
	Zr <sub>S</sub>	Ba <sub>S</sub>
Ba	Cu <sub>P</sub> As <sub>P</sub> Mo <sub>P</sub> Sr <sub>P</sub>	
Pb		
<b>Water</b>		
U*	Mo <sub>P</sub>	

\* All data log-transformed except variables asterisked.

p = panned concentrate s = stream sediment w = water

**Table 4** Four-factor loading graph computed for the drainage area

<i>Factor Loading</i>	1	2	3	4
+0.9				
	Cu <sub>s</sub>	As <sub>p</sub>		
+0.8	B <sub>s</sub>	Cu <sub>p</sub>	Zn <sub>s</sub> Pb <sub>s</sub> Mn <sub>s</sub> Co <sub>s</sub>	
+0.7			Fe <sub>s</sub>	Ba <sub>s</sub>
+0.6	Mo <sub>s</sub> As <sub>s</sub> Ni <sub>s</sub>	Ni <sub>p</sub> Mo <sub>p</sub>	Ni <sub>s</sub>	Ba <sub>p</sub> Sr <sub>p</sub>
+0.5	Cr <sub>s</sub>	Ba <sub>p</sub>	Y <sub>s</sub> Be <sub>s</sub>	Mo <sub>p</sub>
+0.4	Y <sub>s</sub> V <sub>s</sub> Co <sub>s</sub> Be <sub>s</sub>	Fe <sub>p</sub> Mn <sub>p</sub>	Zn <sub>p</sub>	
+0.3				
-0.3				
-0.4			Pb <sub>p</sub>	
-0.5		Zr <sub>s</sub>	Ni <sub>p</sub>	Cr <sub>s</sub> V <sub>s</sub>
-0.6				
-0.7			Zn <sub>p</sub> Mn <sub>p</sub>	
-0.8		Zr <sub>p</sub>	Fe <sub>p</sub> Ti <sub>p</sub>	
-0.9				

All variables log transformed prior to analysis; U and Ca excluded. Broken lines represent an arbitrary significance level calculated following the method described by Kaesler (1969).  
 s and p indicate respectively stream sediment and pan concentrate.

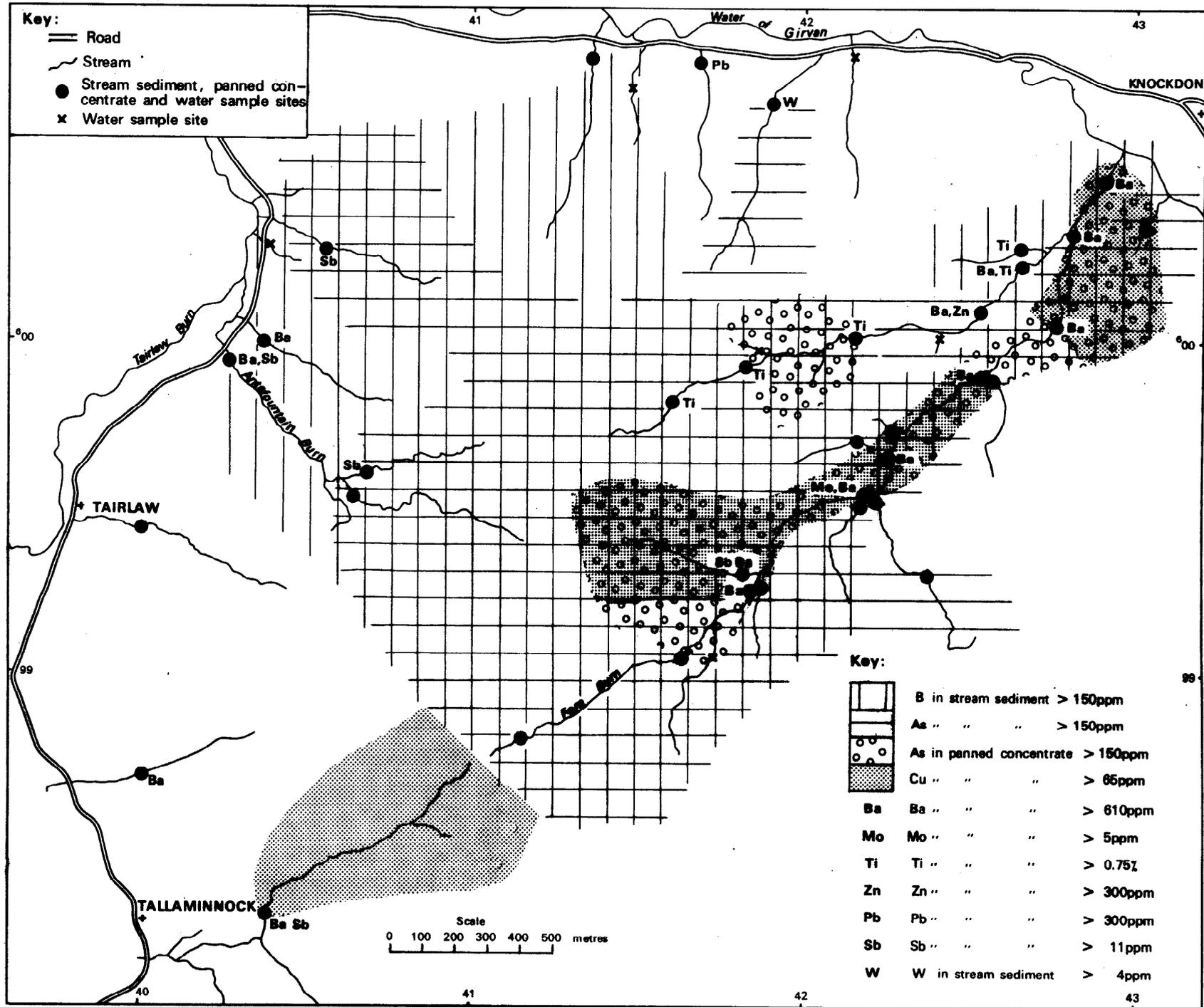


Fig 6: Distribution of anomalous drainage survey results for selected elements

mineralisation. There is no obvious relationship between anomalous Ba and rock type, which suggests a vein mineralisation. Sr, although positively correlated in panned concentrates with Ba, is not present in significant amounts.

High levels of Pb in a panned concentrate from a minor tributary of the Water of Girvan at NS 4168 0083 (No. 26) and Zn with minor Pb at NS 4252 0009 (No. 18) suggest, despite the findings of the factor analysis, that small amounts of Pb-Zn mineralisation may be present in the area.

The only values of Sb and W significantly above the detection limit were recorded from outside the main area of sulphide mineralisation. The Sb value (17 ppm) is accompanied by high Ba in panned concentrate [NX 4027 9994] and the W value (7 ppm) is with high As in stream sediment [NS 4190 0071]. Both values are modest and their source is uncertain.

Relatively high levels of V in several samples and a distinct group of anomalous Ti in panned concentrate results accompanied by high Cr in sediment values along the north fork of the Fore Burn are most likely to be derived from basic volcanic rocks.

Levels of other variables are unremarkable. The absence of high Sn levels supports field observations in suggesting that contamination from household and agricultural waste can be ignored in this survey and gives no support to the report of cassiterite in the area (Eyles and others, 1949).

A comparison of sediment and concentrate results indicates that Zn, Mn, Pb and, by correlation, Co are concentrated in the light fraction and the highest levels in sediment are found in first order streams. Field observations indicated that hydrous Fe/Mn oxide precipitates were only minor contributors to the very fine fraction, which probably explains the absence of distinctly anomalous levels of these elements in sediment. Pb values in sediment appear to be related to the proportion of organic matter. Ni and Fe show similar levels in concentrate and sediment, none of which is very high, and are related to the occurrence of both metals in a wide variety of mineral phases.

Low Co, V, Ni and Cr in sediment levels are recorded over the quartz porphyry in the northern part of the area. The highest levels of elements concentrated in the clay fraction are found in streams draining rocks south of the Southern Uplands Fault, and low values of Be appear to be associated with the volcanics, but in general variables do not clearly differentiate the mapped geological units. This may be attributed to the rapid alternation of lithotypes, the homogenising effect of drift deposits from which much of the sediment is derived, and the obscuring effects of alteration and mineralisation.

### *Summary*

There are clear indications from the drainage survey of Cu-As-B mineralisation and associated Mo enrichment concentrated along the line of the Fore Burn. Though Ba values are locally high in the Fore Burn, there is strong evidence of a widespread barite mineralisation, separate from the sulphide-tourmaline mineralisation in Fore Burn.

There are weak indications of a purely local Pb-Zn mineralisation. Rare high values of Sb and W were recorded, but their significance is uncertain.

## **ROCK GEOCHEMISTRY**

### *Sampling and analysis*

Twenty-three rock samples were collected from available exposures across the survey area (Figure 7). Each sample consisted of at least 2 kg of the freshest rock chips obtainable from two or more points within the sample site. The samples were crushed and a 12 g split was ground in a Tema mill with 3 g elvacite prior to pelletising and analysis for a range of elements by XRF. A further split was finely ground prior to analysis for major elements with the beta-probe. Results are shown in Table 5. A further six large (7 kg) samples of the most highly mineralised rocks were collected, a 2 kg portion retained for analysis by XRF as outlined above and the remainder crushed to pass 60 mesh BSS prior to concentration of a heavy mineral fraction using a vanner for the fine fraction (<120#) and a superpanner for the coarse material. The resulting concentrates were analysed for gold by a neutron activation method (Plant and others, 1976). The results of these analyses are given in Table 6 together with one other analysis of vein material.

### *Interpretation of results*

The small number of samples, wide range of types represented and additional variation related to mineralisation and alteration restricted statistical treatment of the data to a study of inter-element relationships based on Spearman-Rank correlation coefficients.

Extensive alteration of the rocks masked the primary rock geochemistry and blurred chemical differences between the major rock types. The small number of analysed samples in each group added to the uncertainty and though, on the basis of available data, the porphyries do perhaps contain less K<sub>2</sub>O, Rb, Sr, Zr, Ce and Zn than the microdiorites, the andesitic volcanic rocks show a wide variation in these elements and are not distinguishable from either group simply on the basis of their tabulated composition.

Inter-element relationships, based on the Spearman-Rank correlation coefficients, generated from the 23 rock samples (Table 5) are shown diagrammatically in Figure 8. Three elements F, Sn

**Table 5** Rock analyses

No.	Grid reference	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Ni	Mn					
<i>Feldspar porphyry</i>																	
1*	NX 4199 9950	62.47	13.93	0.43	4.94	2.48	4.06	5.12	0.79	0.25	<5	490					
2†	NX 4218 9956	52.32	12.43	0.62	10.25	4.76	6.28	2.00	0.10	0.17	129	1340					
3*	NX 4227 9963	57.01	15.56	0.71	2.80	3.14	6.19	7.44	0.78	0.27	24	340					
<i>Tonalite</i>																	
4*	NS 4270 0024	56.73	16.58	1.11	6.75	3.98	4.15	5.67	2.32	0.22	40	960					
<i>Quartz microdiorite</i>																	
5*	NX 4229 9972	52.66	18.85	1.06	6.43	3.25	5.35	2.43	1.78	0.20	25	770					
6*	NX 4218 9996	46.45	12.58	0.59	6.45	4.83	2.73	3.44	2.43	0.14	45	800					
7	NX 4202 9989	57.77	15.95	0.93	7.44	5.69	3.22	5.17	2.22	0.20	55	690					
8	NX 4205 9998	65.17	14.05	0.76	5.20	4.29	3.02	5.19	1.35	0.16	54	800					
<i>Andesitic volcanic rocks</i>																	
9†	NX 4227 9961	50.74	18.72	1.22	7.21	3.74	5.40	1.82	2.53	0.19	37	670					
10†	NX 4209 9953	44.57	11.48	0.77	7.91	6.65	10.85	2.21	1.41	0.13	144	1100					
11†	NX 4157 9928	53.41	15.40	1.02	6.80	4.80	6.29	3.23	1.57	0.21	213	1050					
12	NX 4055 9850	46.17	14.26	0.94	11.36	8.67	5.00	3.45	0.30	0.15	147	1140					
13†	NX 4055 9850	54.42	19.43	1.25	8.69	3.06	2.94	0.03	4.27	0.24	216	840					
14†	NX 4205 9952	58.46	16.49	0.85	6.60	1.96	3.26	7.83	0.66	0.39	7	610					
15†	NX 4204 9951	64.42	16.93	0.34	6.09	1.37	1.22	7.36	0.90	0.19	22	390					
16†	NX 4207 9953	56.68	15.34	0.59	11.22	1.70	1.31	5.73	0.38	0.29	33	430					
<i>Tuffaceous sediments, tuffs and agglomerates</i>																	
17†	NX 4194 9943	69.52	16.89	0.36	3.97	1.65	1.00	0.34	2.51	0.18	14	120					
18†	NX 4195 9946	63.98	10.74	0.34	14.63	2.22	0.74	0.79	0.21	0.18	27	250					
19*	NX 4177 9918	53.86	7.49	0.12	4.23	6.84	12.00	<0.01	1.06	0.05	10	420					
20*	NS 4255 0011	56.77	15.17	0.79	6.16	5.23	6.98	3.78	1.98	0.15	131	720					
21*	NX 4166 9948	—	—	—	—	—	—	—	—	—	34	180					
<i>Sandstone</i>																	
22*	NX 4180 9920	71.01	9.59	0.75	3.41	2.62	5.34	<0.01	0.50	0.21	30	370					
<i>?fault breccia</i>																	
23†	NX 4185 9926	31.62	2.79	0.10	6.67	11.06	21.59	<0.01	0.02	0.05	5	900					
		Cu	Pb	Zn	As	Mo	Sb	Bi	W	Ba	Rb	Sr	Y	Ce	Zr	Nb	U
<i>Feldspar porphyry</i>																	
1*		143	<13	26	55	<2	<11	<4	3	2936	21	209	16	<21	180	6	<3
2†		2233	<13	44	>3000	2	<11	86	2	57	4	339	18	<21	152	5	<3
3*		39	<13	14	45	<2	12	<4	4	90	23	270	22	25	203	8	3
<i>Tonalite</i>																	
4*		14	17	101	39	<2	<11	<4	<2	542	66	519	25	36	251	8	<3
<i>Quartz micro diorite</i>																	
5*		91	<13	53	40	<2	<11	<4	<2	148	59	231	26	37	237	13	<3
6*		26	<13	79	26	2	11	<4	<2	547	104	542	25	24	195	6	<3
7		37	<13	88	34	2	11	<4	<2	460	67	609	26	34	252	8	<3
8		22	<13	93	22	3	11	<4	<2	687	40	571	20	45	238	12	4
<i>Andesitic volcanic rocks</i>																	
9†		12	<13	43	48	<2	11	<4	3	255	81	145	22	34	164	7	<3
10†		25	<13	53	126	2	11	<4	<2	91	50	200	13	<21	104	5	<3
11†		8	<13	49	57	<2	14	<4	<2	203	66	255	22	33	151	9	<3
12		<6	<13	81	12	<2	<11	<4	<2	158	11	209	18	29	134	9	<3
13†		33	16	78	143	<2	34	<4	17	255	88	109	27	44	176	11	<3
14†		2793	<13	66	307	9	16	9	5	101	17	183	36	56	231	7	4
15†		3207	<13	150	672	3	74	4	2	73	27	140	20	52	301	9	4
16†		3436	33	103	<3000	18	93	108	7	86	12	203	23	57	235	9	5
<i>Tuffaceous sediments, tuffs and agglomerates</i>																	
17†		24	<13	14	222	2	<11	<4	3	116	53	178	18	47	227	12	3
18†		267	181	21	<3000	41	21	373	15	30	9	303	5	19	125	4	3
19*		9	16	16	610	<2	<11	<4	3	112	28	217	9	31	108	6	<3
20*		36	17	56	10	<2	<11	<4	<2	544	40	509	22	27	158	7	<3
21*		21	22	14	803	<2	<11	<4	8	77	18	116	20	59	225	16	4
<i>Sandstone</i>																	
22*		22	<13	18	90	<2	<11	<4	3	84	12	232	21	46	290	13	<3
<i>?fault breccia</i>																	
23†		7	<13	9	1000	<2	<11	<4	3	2895	1	373	10	<21	65	4	<3

\* Moderately/highly altered/mineralised rock † Intensely altered/mineralised rock  
 F and Sn were also determined, but all results were less than the detection limits (F ≈ 0.1%, Sn 9 ppm) except No. 18 (Sn = 16 ppm).

**Table 6** Analyses of highly mineralised rock and vein samples.

No.	Samples	Grid reference	Ti	Ni	Mn	Fe	Cu	Pb	Zn	As	Au
24	5 cm vein in ?volcanics	NX 4204 9951	3100	76	320	103560	>10000	42	652	>3000	0.92
25	Massive sulphide lens	NX 4204 9952	3720	57	410	201360	6613	278	178	>3000	1.39
26	Disseminated sulphide in tonalite	NS 4268 0001	3390	97	370	78360	596	<13	17	>3000	1.15
27	5 cm vein in ?tonalite	NS 4267 0000	3540	1610	410	133300	>10000	14	3	>3000	1.24
28	Sub parallel sulphide veinlets in ?tonalite	NS 4269 0001	2270	343	1710	139050	4518	13	26	>3000	—
29	Disseminated sulphide in altered andesite	NX 4207 9954	5490	17	150	72910	575	13	21	943	0.04
30	Sulphide in breccia	NX 4183 9921	3810	73	580	102950	2654	184	48	>3000	0.66

No.	Samples	Grid reference	Ba	Rb	Sr	Ca	Ce	Zr	U	Mo	Sb	Bi	Sn	W
24	5 cm vein in ?volcanics	NX 4204 9951	71	13	184	6410	24	289	4	34	1404	113	<9	<2
25	Massive sulphide lens	NX 4204 9952	30	12	321	3850	<21	154	3	123	121	521	21	21
26	Disseminated sulphide in tonalite	NS 4268 0001	29	4	85	13810	<21	224	4	22	40	68	<9	9
27	5 cm vein in ?tonalite	NS 4267 0000	32	7	314	11410	23	91	<3	410	28	29	31	2
28	Sub parallel sulphide veinlets in ?tonalite	NS 4269 0001	169	28	204	32670	22	41	<3	29	77	103	10	<2
29	Disseminated sulphide in altered andesite	NX 4207 9954	45	6	217	6150	22	219	<3	11	<11	7	<9	5
30	Sulphide in breccia	NX 4183 9921	117	22	234	23180	32	182	<3	2	33	49	17	4

All results are in ppm.

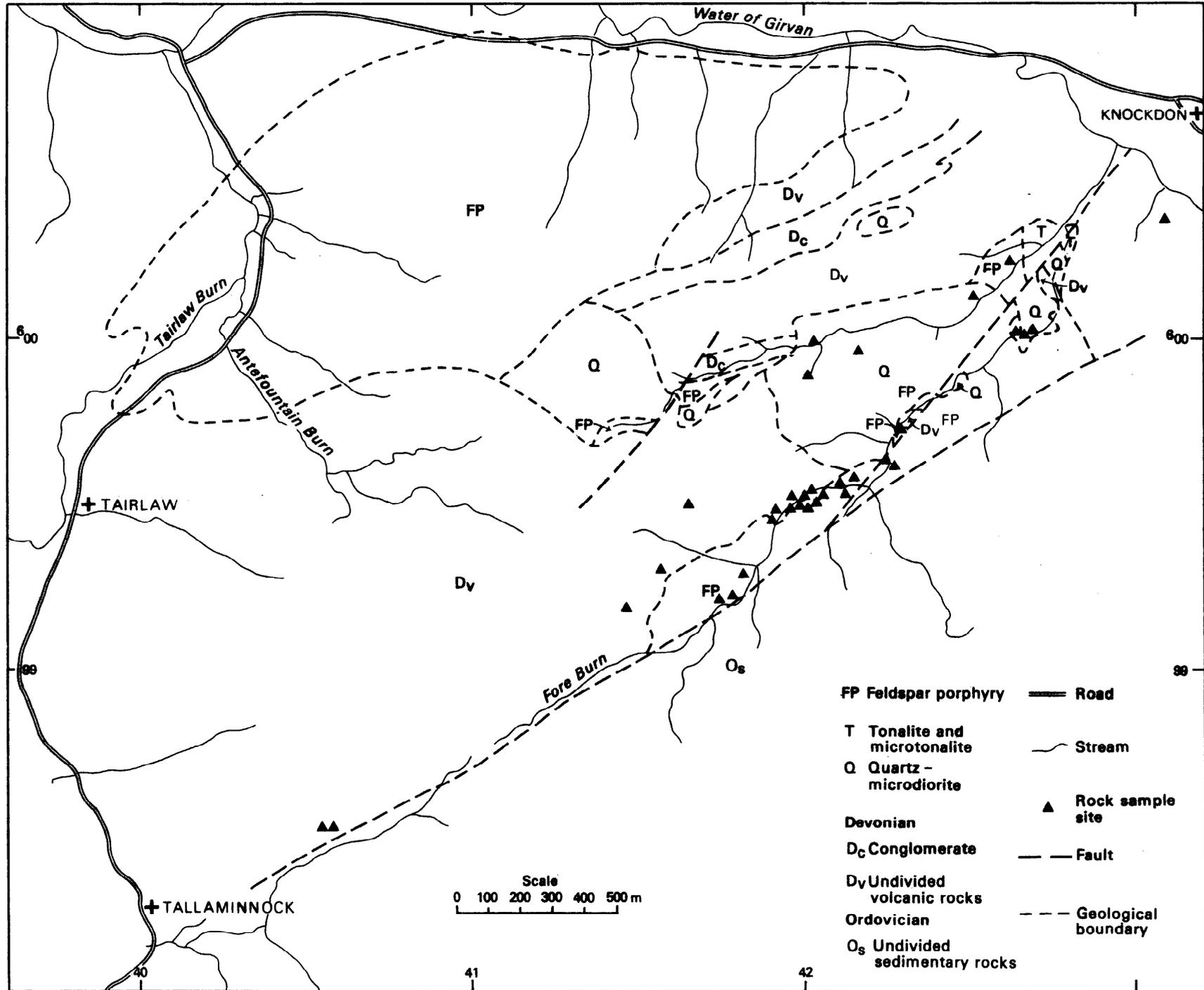


Fig.7. Location of rock sample sites.

and U were omitted because all the results were close to or below the theoretical analytical detection limit. Apparently high, potentially spurious, correlations between variables whose distributions contain one or two abnormally high values amongst results which appear to be uniform because they are close to or below the detection limit (Sb, Mo, W, Pb, Bi) have been downgraded.

The significant correlations (Figure 8) indicate that there are two major groupings of elements. The first is dominated by chalcophile elements (Cu, As, Mo, Sb, Pb, Bi) and is related to sulphide mineralisation. The second is related to a combination of primary rock composition and alteration. All the extreme variation in the analyses can be related to alteration. Overlapping sub-groups of elements may be identified with tourmaline (Na-?Si-?Al), sericite (K-Rb-Al), carbonate (Mg-Ca), apatite (P-Y-REE) and chlorite/secondary amphiboles (Mg-Mn-Ni-Ti-Al-Si). An inter-related group of so called 'stable' elements (Nb-Ce-Zr-Y-?Ti-?P), normally regarded as immobile during many alteration processes (e.g. Winchester and Floyd, 1977) may also be discerned. The position of Fe and to a lesser extent Zn between the two groups reflects their significant contributions to mineralisation as well as primary rock chemistry and alteration. Ba and Sr show independent behaviour; the former is believed to be related to barite mineralisation whilst the latter is believed to be distributed between mineral phases related to several different processes. Gold was only determined on six samples, but these are sufficient to indicate an affinity with the chalcophile group. Within the limits of uncertainty caused by the upper calibration limit of arsenic, the most significant rank correlations (>95% confidence level) are with As, Fe and Mo.

There is an apparent inverse relationship between many of the elements which characterise the alteration and primary rock chemistry, and the sulphide mineralisation group. This is believed to be at least in part unreal, and generated by the 'closure effect' (if elements in sulphides are increased other elements must decrease in a constant sum situation). Drainage data and mineralogical evidence suggest a close association between the two.

#### *The sulphide mineralisation group*

Correlation amongst the chalcophile elements is not high, because enrichment in individual elements is very patchy. Pyrite is present in the majority of the rocks, but compared with the bulk chemistry Fe enrichment is apparently small in all but the most highly mineralised samples. Most of the analytical results for chalcophile elements can, however, be matched with the mineralogy of the samples. Barite, identified in sample 1 of Table 6, is likely to account for all the high Ba values. Cu levels above 40 ppm reflect the presence of chalcopyrite, whilst enhanced levels of As, Sb and Au

are readily accounted for by observed arsenopyrite, tennantite-terahedrite and native gold. Rare sphalerite and galena have also been identified but no discrete mineral phases were found to account for the high levels of Mo (samples 25, 27; Table 6) and Bi (samples 18 and 25 in particular).

Analysis of the massive sulphide lens (Table 6, No. 25) suggests the presence of very small amounts of Sn and W in the mineralisation. The lack of any high Ba contents in the most highly mineralised samples supports other evidence in suggesting that the barite and sulphide mineralisations are unrelated.

It is uncertain whether mineralisation involving the elements Sn, Pb, Zn and Ni is restricted to veins and massive sulphide lenses, or whether disseminated enrichments are either too weak to be discriminated from the normal background in the rocks or are below the analytical detection limit.

In conclusion, therefore, the sulphide mineralisation centred on the Fore Burn involves widespread enrichment in As and Fe, more local concentrations of Cu and occasional patchy enrichments in Pb, Zn, Sb, Mo, Ni, Co, Bi and Au. Small increases in Sn and W locally accompany sulphide development but Ba mineralisation is separate.

#### *The alteration group*

Element associations identified by the correlation coefficients and whole rock element concentrations can be readily matched against petrographic observations on alteration. In particular the highest K<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> results match intense sericitisation. Coincident high MgO and CaO suggests that some of the intense carbonate veining observed in these samples is dolomitic. The highest P<sub>2</sub>O<sub>5</sub> contents correlate with abundant apatite, which is a secondary mineral in these rocks. However, the agreement between Na<sub>2</sub>O and tourmalinisation is poor in some samples. This is partly because much Na<sub>2</sub>O is held in plagioclase, but this does not explain the lack of Na<sub>2</sub>O and CaO in two tuff samples (Table 5, Nos. 17 and 18), both of which contain appreciable tourmaline. Silicification and chloritisation are observed petrographically and in the inter-element relationships, but do not noticeably change the overall rock composition.

K and Rb levels together with K/Rb ratios (max. 403 min. 193, median 268 for 16 igneous rocks, Figure 9) suggest that with one exception (Table 5, No. 13) only minor changes have occurred in these elements. The lack of substantial reductions in K/Rb ratios in highly altered rocks suggests that the alteration was not produced by fluids from a late stage magmatic source (Ambrust and Gannicott, 1980). Rb/Sr ratios (maximum 0.807, minimum 0.052, median 0.118 for 16 igneous rocks) are more erratic. Ba levels suggest that two samples, a breccia and a porphyry are substantially enriched in this element. A Rb-Ba-Sr triangular plot (El Bouseily and El Sökkary, 1976) of the igneous rocks shows this clearly and also

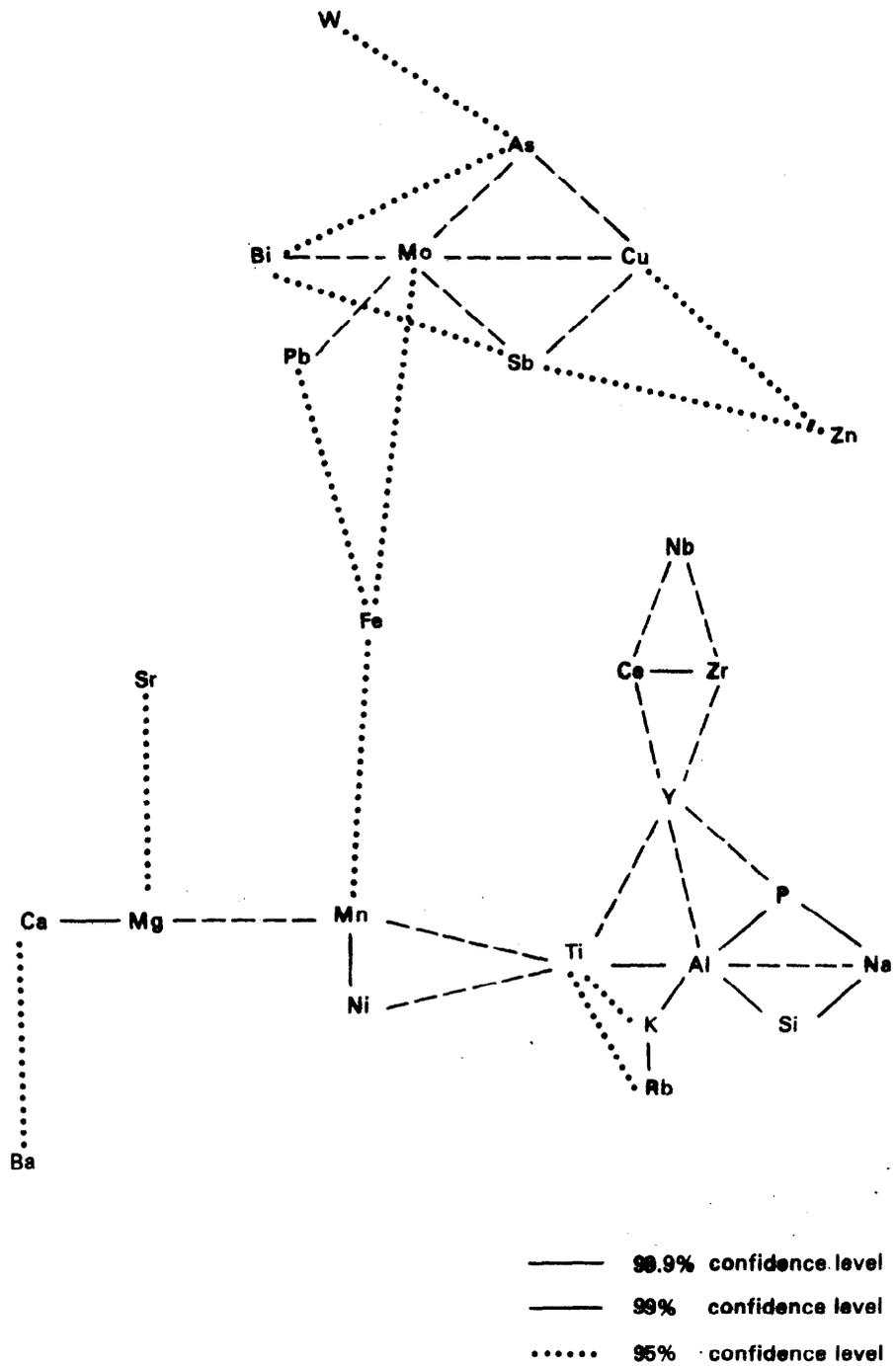
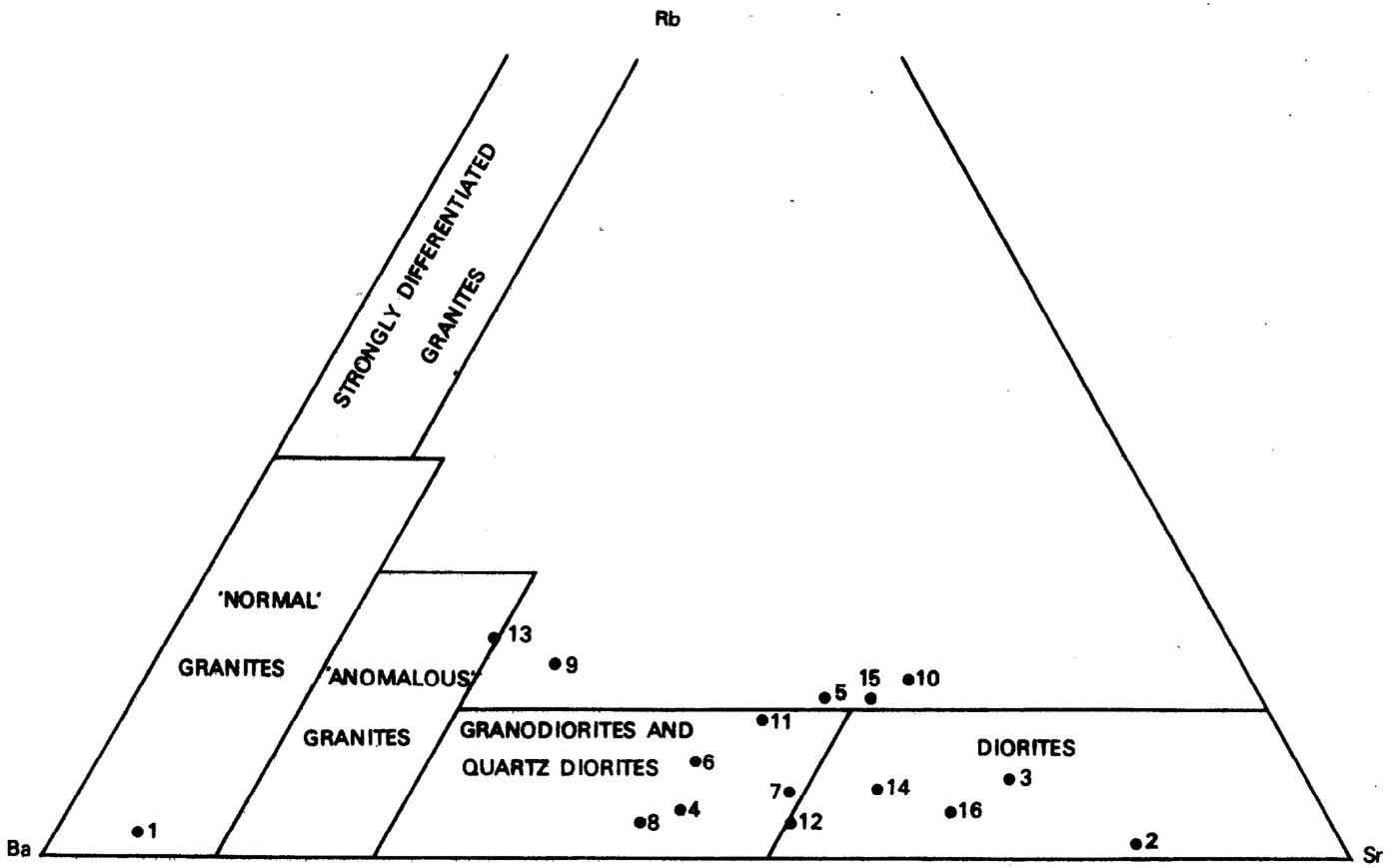
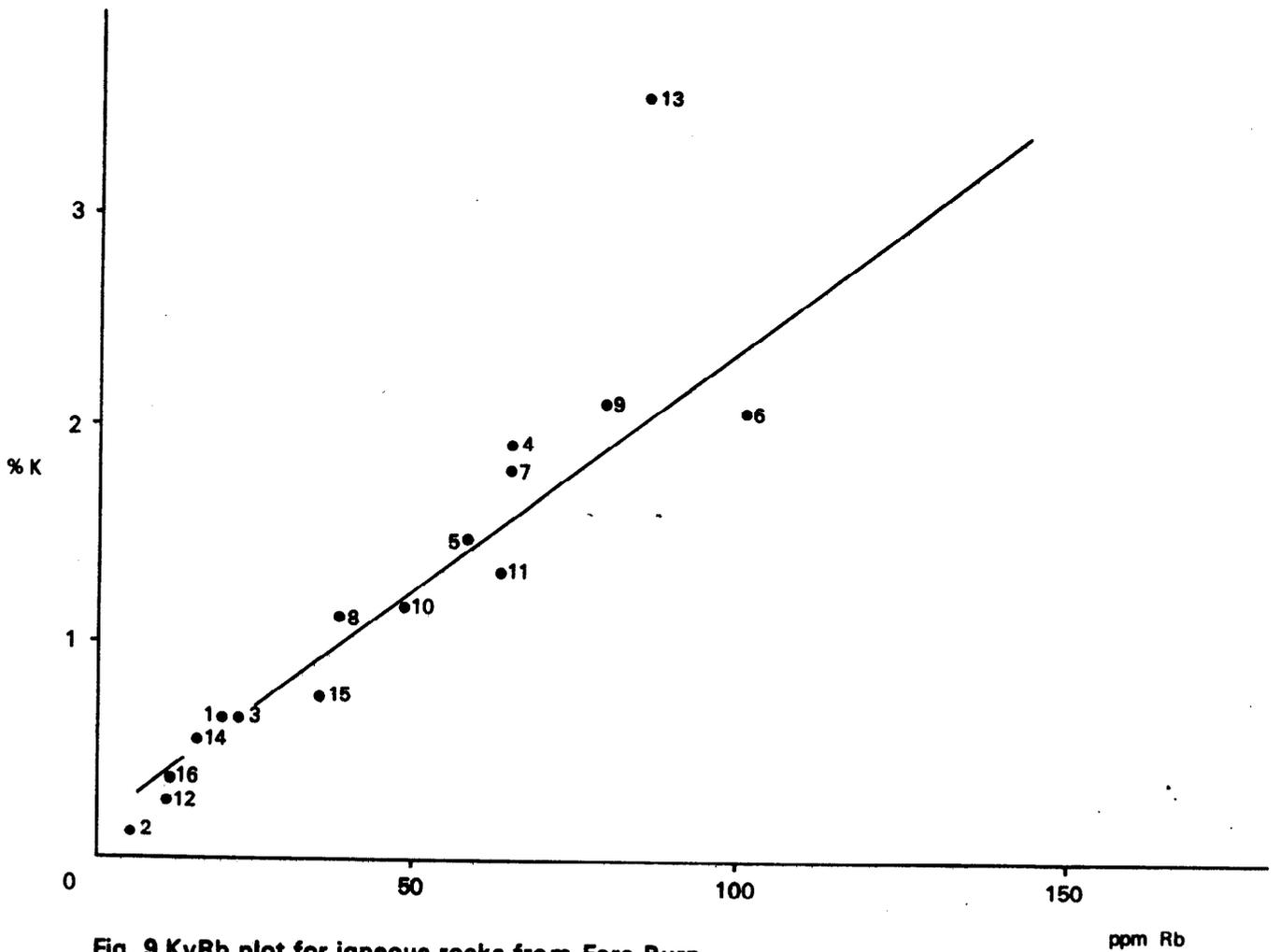


Fig 8. Diagrammatic interpretation of inter-element relationships in rock samples.



suggests that Rb is slightly enriched in highly sericitised samples (Figure 10).

#### *The 'stable' elements*

An inter-related group is formed by elements often termed stable (Nb, Zr, Ce, Y, Ti and P) because of their apparent immobility when subjected to many alteration and mineralisation processes (e.g. Winchester and Floyd, 1979; Pearce and Gale, 1977). At Fore Burn alteration was locally intense and the inter-element groupings suggest that some of the variation in at least Ti, Y and P may be related to alteration processes. Williams and Cesbron (1977) showed that elsewhere the Ti mineral rutile could be used as a guide to alteration zoning around porphyry copper deposits, implying some mobility, and studies on various types of alteration in Cornwall showed that whilst little change in Ti, Y, REE, P and Zr levels was associated with chloritisation all are apparently affected by intense tourmalinisation (Alderton and others, 1980). Examination of Russian and other studies (e.g. Deitrich, 1968) suggests that the mobility of these elements is caused by the presence of fluids rich in soda and halogens; Y, for instance, forms compounds of the form  $\text{Na Y F}_4$  (Mineyev, 1963). The lack of fluorite and the low levels of fluorine (<0.1%) recorded in the Fore Burn rocks suggest that soda metasomatism was the principal cause of any stable element mobility.

When it is taken into account that some decreases might be expected due to the 'closure' effect there is no obvious relation between the levels of Nb, Zr, Ce, Y, Ti and P in the rocks and the degree of alteration or mineralisation, so the large scale addition or removal of these elements is not likely to have occurred. However, several of these elements are concentrated in minerals, such as apatite, which are secondary, indicating at least a local redistribution of the elements within a small volume of rock during alteration.

Scattergrams of various combinations of P, Ti, Y, Ce, Zr and Nb and more complex plots against comparative data (Pearce and Cann, 1973; Winchester and Floyd, 1977; Pearce and Norry, 1979) for the volcanic rocks show the presence of a closely knit group of five rocks with coherent stable-element chemistry despite a wide variation in the type and degree of alteration (e.g. Figure 11). These five samples (Table 5, Nos. 9–13) show linear 'trends' on scattergrams with increasing levels of all 'stable' elements roughly corresponding with increasing silica contents. The three other samples of volcanic rock (Table 5, Nos. 14–16) show much less cohesion, related to relative excesses of Ce, Zr or  $\text{P}_2\text{O}_5$  and lack of  $\text{TiO}_2$ . It is considered significant that these three samples are the most highly altered and mineralised and contain large amounts of soda, much of which is believed to have been introduced. The conclusion is reached that in the closely knit group of five volcanic samples the stable element chemistry

represents the original composition in these elements, though there may have been some small-scale redistribution associated with recrystallisation, whilst in samples 14, 15 and 16 some larger scale modification has occurred. All the stable element plots (e.g. Figure 11) indicate that the volcanic rocks are of calc-alkaline composition and suggest that they were formed in a continental margin or island arc environment.

The intrusive samples are generally less altered than the volcanic rocks but show a greater degree of scatter on stable element plots than the closely knit group of volcanic rocks. The reason for this is uncertain, but there is no clear link with degree of alteration and it is suggested that the cause of scatter is the presence of the elements in a relatively large number of primary and secondary mineral phases and variable crystallising conditions compared with the volcanic rocks. The low Nb levels in the intrusive rocks (Pearce and Gale, 1977) suggests that they formed in a similar tectonic setting to the volcanic rocks. However, ratios of other stable elements enable the intrusive rocks to be clearly discriminated from the main group of volcanic rocks. The sharpest discrimination is given by a Ce v Zr plot (Figure 12) which displays two quite distinct 'trends' for volcanic and intrusive rocks with the exception of one highly altered sample of volcanic rock (No. 15) and the highly mineralised rocks (Table 6). The reason for the two trends is uncertain but the pattern suggests that Ce and Zr have behaved coherently during both magmatism and all but the most intense alteration, and may indicate that they are the elements, probably with Nb, least affected by alteration. The distinct grouping of volcanic and intrusive rocks could indicate selective alteration of volcanic rocks, fundamental differences in the original magma, or differences in crystallising conditions. As the most altered volcanic rocks shift into the field of the intrusive rocks on these plots and the overall chemistry of both groups is calc-alkaline the third possibility is preferred.

#### *Comparison of drainage survey and rock geochemistry results*

The main findings of the drainage survey were confirmed by the rock analyses. These are a major, localised Cu-As mineralisation accompanied by B-Na-rich alteration, and a separate Ba mineralisation. However, the drainage survey failed to detect Bi, Sb and Co mineralisation found in rock samples from the banks of the Fore Burn, whereas the Ba anomalies (up to 4%) found in the panned concentrates from the same stream were not fully explained by the rock sampling. The latter discrepancy might be caused by poor rock sampling, the relative difficulty of detecting barium minerals in thin section, and the extreme sensitivity of the panned concentrate sampling method for detecting elements held in discrete heavy minerals. The Cu:Sb ratio in the mineral-

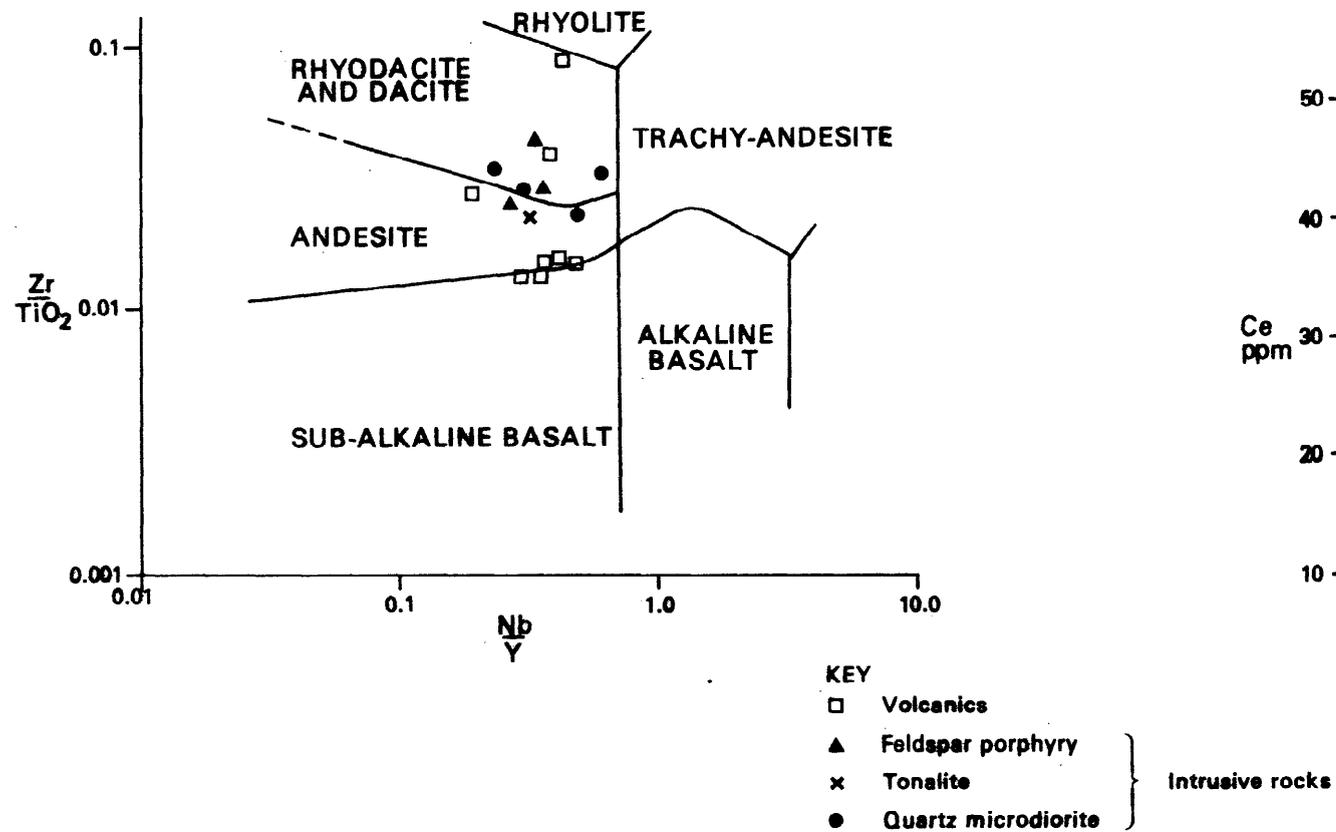


Fig. 11  $Zr/TiO_2$  v  $Nb/Y$  plot for igneous rocks from Fore Burn, showing the fields delimited by common volcanic rocks taken from Winchester and Floyd 1977.

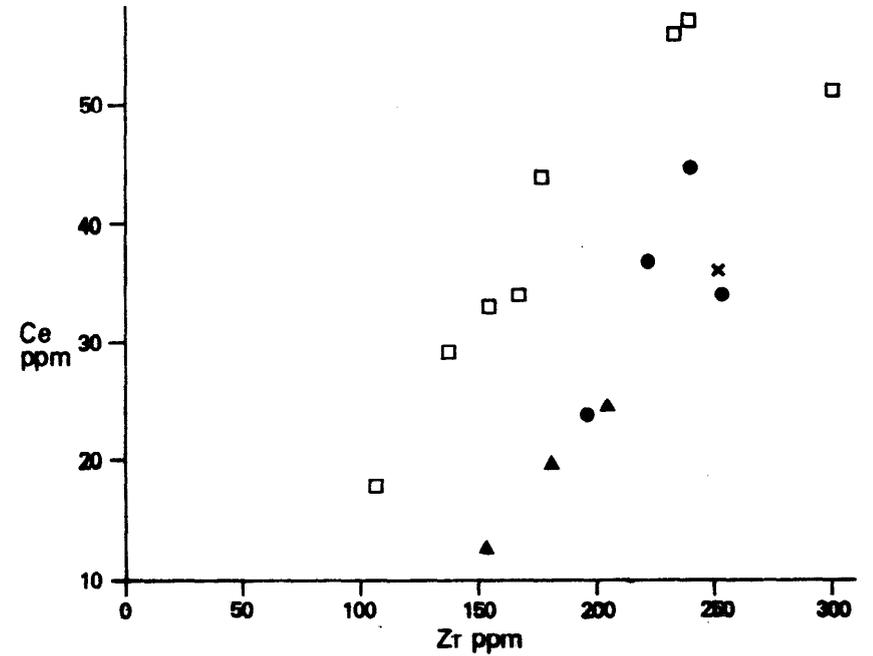


Fig. 12  $Ce$  v  $Zr$  plot for igneous rocks from Fore Burn

ised rocks, usually greater than 30, suggests that the failure of the stream sampling to detect the weak Sb mineralisation may be due to the high detection limit for Sb. Furthermore, the tetra-hedrite does not form large independent grains which would facilitate upgrading in the pan. The weak Co mineralisation was not detected in drainage samples because the element was only determined in sediment samples where the small amount in heavy minerals was masked by that held in clay and precipitate fractions. Bi was not determined in any of the drainage sample types. Gold was not detected by visual inspection of the panned concentrates because it occurs as very small grains enclosed within sulphide phases.

## DISCUSSION ON MINERALISATION

There are a number of unusual characteristics of the Fore Burn mineralisation, the most outstanding being the association of tourmaline and apatite with an essentially low temperature assemblage of sulphide minerals. Tourmalinisation on the scale recorded at Fore Burn is most commonly associated with high temperature hydrothermal Sn-W-Au mineralisation around granites.

However, tourmaline is now known also to be associated with porphyry copper deposits. It is present in several Canadian deposits in minor amounts, for instance at Bell Copper (Carson and others, 1976) and Morrison (Carson and Jambor, 1976). In a few deposits tourmaline is a major alteration product, notably at Mount Nansen (Sawyer and Dickinson, 1976), at Casino (Godwin, 1976) in the phyllic and potassic alteration zones, and at Schaft Copper (Fox and others, 1976).

There appear, therefore, to be two main possibilities for the origin of the Fore Burn mineralisation. Firstly, it could represent high and medium temperature hydrothermal mineralisation of Cornish type, essentially of vein form, infilling brecciated rocks and altering adjacent wall rocks. Though the mineralisation is most intense along the breccia zone there is patchy disseminated mineralisation, particularly of arsenopyrite, over an unusually large area here. The Sn, W and Au mineralisation is very weak; the style of alteration and lack of enrichment in LIL elements is unusual, and the zonation very poor for a Cornish type deposit. There is also no obvious granitic source in the vicinity, for tourmalinisation is usually close to or within the granitic intrusion.

The comparison between Fore Burn and known tourmaline-bearing porphyry coppers is much better. At Schaft for example an elongate breccia zone in andesitic volcanic rocks contains tourmaline and sulphides, some of which are relatively low temperature (Pb-Zn) minerals. There appears, however, to be no Sb and As at Schaft, which also contains gypsum.

Tennantite-tetrahedrite, common in Fore Burn, is also found in porphyry coppers, for instance at Chuquicamata (Lopez, 1939) but not usually in association with tourmaline. Apatite is also known in porphyry coppers. According to Williams and Cesbron (1977), apatite associated with the porphyry copper deposits that they had examined fluoresced a bright orange in ultraviolet light, whereas apatites of other origins do not show this characteristic colour. The secondary apatites from Fore Burn did not display the characteristic fluorescence, but they did show a similar anhedral form and richness in inclusions to those described by Williams and Cesbron (1977).

The general comparison with porphyry coppers is good in other respects. For example the Cu-Mo-Au association with very low Pb-Zn is typical and the pervasive tourmaline-sericite-carbonate-chlorite alteration affects a large body of rock at Fore Burn. Arsenopyrite also is not unknown in Canadian calc-alkaline porphyry copper deposits, though not in the same abundance as at Fore Burn. Perhaps the best comparison, however, is with the copper-bearing breccia pipes at Mount Nansen. Here Sawyer and Dickinson (1976) described quartz, tourmaline and apatite in breccia pipes which are surrounded by zones of mineralised and altered rock. The orebody is Cu-Mo-Au and veins peripheral to it contain gold and silver with arsenopyrite, stibnite, galena and sphalerite. Both the metal assemblage and alteration here are very close to Fore Burn.

It is concluded, therefore, that on the available data the Fore Burn mineralisation fits a porphyry copper model better than any alternative. The alteration and mineralisation together are most intense in association with the breccias along Fore Burn, but there is abundant tourmaline in the conglomerates and adjacent breccias in the upper parts of the major tributary on the west, and there is evidence from the drainage survey of tourmaline and arsenopyrite mineralisation over an area of about 4 km<sup>2</sup>, though petrographic examination of rocks from the area suggests that the alteration is patchy. It is likely that only the upper and outer parts of a porphyry system are exposed here and that the locally intense mineralisation seen at surface is structurally controlled.

Finding an age and a magmatic source for the mineralisation are not easy. Tourmaline has been found in rocks along the Southern Upland Fault identified as crush rocks, though it is not certain that the tourmalinisation post-dated faulting. Tourmaline has been found in small amounts at the Black Stockarton Moor copper prospect (Brown and others, 1979) and it is abundant locally within the Cheviot granite, both of early Devonian age. The age of the Fore Burn mineralisation, by comparison with them, might not be younger than early Devonian. Whether the mineralisation preceded or is younger than the

fault, however, it is likely that the magmatic source is not exposed. The main breccias are preferentially associated with fault lines rather than any particular intrusive rock. The quartz-microdiorite intrusions, which are not intensely altered, are possibly thin and sheet-like but the tourmalinisation of the conglomerates suggests that the open framework of the sedimentary rocks has facilitated migration of hydrothermal fluids from source below the quartz-microdiorite sheet.

## CONCLUSIONS

1 Disseminated sulphide mineralisation, with appreciable amounts of gold in a finely disseminated form within sulphide phases, is associated with a string of breccia bodies in early Devonian magmatic rocks along the Fore Burn. The metal assemblage is dominated by As and Cu, and also contains lower amounts of Au, Mo, Sb, Bi, Co, Ni, Pb and Zn. The principal alteration minerals are tourmaline, sericite, carbonate, chlorite and apatite. Alteration and mineralisation are most intense in the zone of breccias, but not confined to it. There is no evidence of metal or alteration zoning.

2 The mineralisation compares in style with that associated with certain porphyry copper deposits in Canada. Tourmaline and arsenopyrite occur throughout about 4 km<sup>2</sup> of this area and it is believed that this, and other evidence, indicate that the upper and outer parts only of a porphyry system are exposed here. The exposed intrusive rocks are mostly sheet-like in form and are likely to pre-date the magmatic source of the mineralising fluids, which is believed to be at depth. The age of the mineralisation is probably early Devonian.

3 Widespread barite mineralisation is believed to be a separate event from the main sulphide mineralisation.

4 Metal concentrations at surface are not present in amounts to be of immediate economic interest. Chargeability values are generally low and do not give any indication of widespread near-surface concentrations of sulphides. Three small areas of low resistivity, one of which coincides with moderately high chargeability, contain massive sulphide in veins at surface and may indicate the presence of more extensive mineralisation at relatively shallow depths.

5 It is considered that sufficient indications of copper and gold mineralisation are present to justify further investigations. Specifically, the geophysical anomalies around the gorge in the Fore Burn and possibly the one to the north-west should be investigated further with expanding dipole-dipole array IP and multifrequency or time-domain EM surveys, followed if necessary by drilling.

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