Natural Environment Research Council
Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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 The information contained herein must not be published without reference to the Director, British Geological Survey.

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No. 69

Base metal mineralisation associated with Ordovician shales in south-west Scotland

BRITISH GEOLOGICAL SURVEY

Natural Environment Research Council

Mineral Reconnaissance Programme

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Base metal mineralisation associated with Ordovician shales in south-west Scotland

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Mineral Reconnaissance Programme Reports

On 1 January 1984 the Institute of Geological Sciences was renamed the British Geological Survey. It continues to carry out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects; it also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

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SUMMARY

Several narrow, lenticular belts of black cherty mudstone and siltstone (the Moffat Shales), alternating with thick greywacke sequences, strike north-east to south-west across Galloway with uniformly steep dip. In the Penkiln Burn area, 13 km NNE of Newton Stewart, one such belt is hornfelsed and considerably broadened near the south-west margin of the Loch Doon granitic pluton. Base metal anomalies in drainage and overburden are spatially associated with the broadened section of the shale belt, which is host to weakly disseminated and epigenetic Pb–Zn–Cu mineralisation.

Within the Moffat Shale sequence highly siliceous mudstone and siltstone are interbedded with chert, greywacke and possibly thin tuffaceous horizons. The broadening is structurally controlled, caused by the interference of early structures with a major reclined fold plunging to the south-east. Several phases of faulting and minor intrusion have been recognised, and the abundance of dykes is an unusual geological feature of the area.

Lead is particularly enriched in drainage samples, reaching approximately 1% in pan concentrates collected close to a mineralised gossan-like zone. The main lead-bearing mineral identified in the anomalous concentrates, and the *in situ* gossan material, is the secondary lead phosphate plumbogummite. Overburden sampling proved anomalous metal values extending for 2.3 km along strike and 500 m across strike. Lead again shows the greatest enrichment, with values ranging up to about 0.5%, in soil close to the gossan. Zinc and copper give a weaker response in both overburden and drainage, but drilling showed that zinc, in the form of disseminated sphalerite, has a greater incidence at depth than was suggested by the surface anomalies.

Three varieties of mineralisation have been recognised. The earliest consists of fine disseminations, chiefly of sphalerite and pyrite, in the hornfelsed sediments. It is characterised by zinc levels between 500 and 1000 ppm over several metres of drill core; lead levels rarely exceed 300 ppm. The second phase of mineralisation occurs in thin quartz veinlets, which in this case contain accessory sphalerite, galena and pyrite. Where the veining is intense, lead concentrations reach 7000 ppm and those of zinc 1500 ppm, but these values persist over only a few tens of cm of core. Finally, a low-temperature mineral assemblage in which plumbogummite is dominant is associated with the altered margins of dykes and gossan-like zones occupying a north–south fault system. Lead levels in the dyke margins range up to 1.5% in zones generally less than 50 cm thick, but 4.5% Pb has been recorded in one specimen from the exposed gossan.

Fine stratiform pyrite laminae in mudstone interbedded with chert containing disseminated pyrite and sphalerite suggests that at least some of the early mineralisation is synsedimentary. Later mineralisation phases are, however, structurally controlled and the origin of the majority of the base metal mineralisation remains problematical. The unusual abundance of minor intrusions in the mineralised zone is strong circumstantial evidence for an igneous source.

Full details of the soil geochemical surveys and the geophysical surveys are available for inspection at the Keyworth office of BGS.

INTRODUCTION

PREVIOUS EXPLORATORY WORK

A geochemical drainage survey of part of Galloway was initiated in 1970 during a uranium exploration project sponsored by the UKAEA, and was later extended as part of the Mineral Reconnaissance Programme. Results arising from this latter work (Dawson and others, 1977; Leake and others, 1978a and b) showed that substantial base-metal anomalies were associated with the outcrop of Lower Palaeozoic black, siliceous mudstone and shale to the south of the Loch Doon granitic pluton (Figure 1). Subsequent, more detailed investigations confirmed the presence of metalliferous mineralisation around the headwaters of the Penkiln Burn, approximately 13 km NNE of Newton Stewart. Mineralisation was found at outcrop as a complex intergrowth of goethite, limonite, plumbogummite ($PbAl_3(PO_4)_2(OH)_5.H_2O$) beudantite ($PbFe_3AsO_4SO_4(OH)_6$) and malachite in a north–south fault zone cutting the black mudstone and shale. These encouraging results stimulated detailed follow-up work on the south-eastern flanks of Lamachan Hill (Figure 2). The area of interest falls within the Ordnance Survey 1:50 000 New Galloway and Glentrool (77) sheet and the Loch Doon (8E) sheet of the 1:50 000 geological map of Scotland.

SCOPE OF INVESTIGATIONS DISCUSSED IN THIS REPORT

Geological mapping at a scale of 1:10 000 was carried out over approximately 6 km² of ground and led to the formulation of a new structural interpretation for the geological relationships of the black shale and mudstone sequence (Stone, 1981b). In conjunction with the mapping, geophysical and geochemical investigations covered the central part of the area. Geophysical work involved magnetic and VLF surveys whilst the geochemical programme consisted of the systematic collection and analysis of soil samples. All of the methods applied were severely hampered by the dense tree cover in the southern sector.

On the basis of the results obtained, nine cored boreholes were sited. These provided approximately 410 m of core (depth range of holes = 15.3 to 114.9 m) which, together with a number of specimens collected at outcrop, were the subject of laboratory studies. The holes were drilled by an IGS team using light-weight Winkie and JKS 300 equipment.

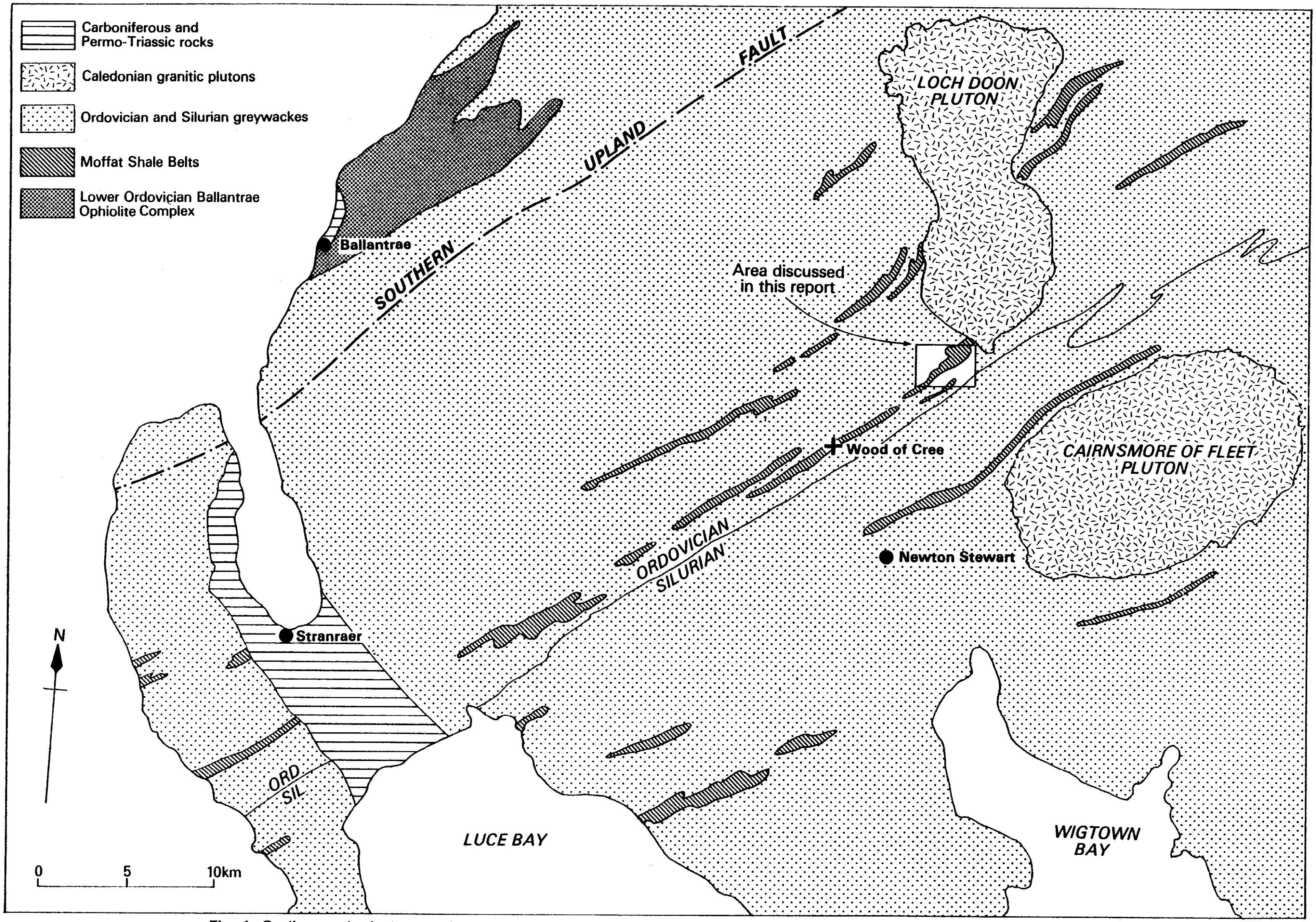


Fig. 1 Outline geological map of part of South-west Scotland showing the location of the area discussed in this report

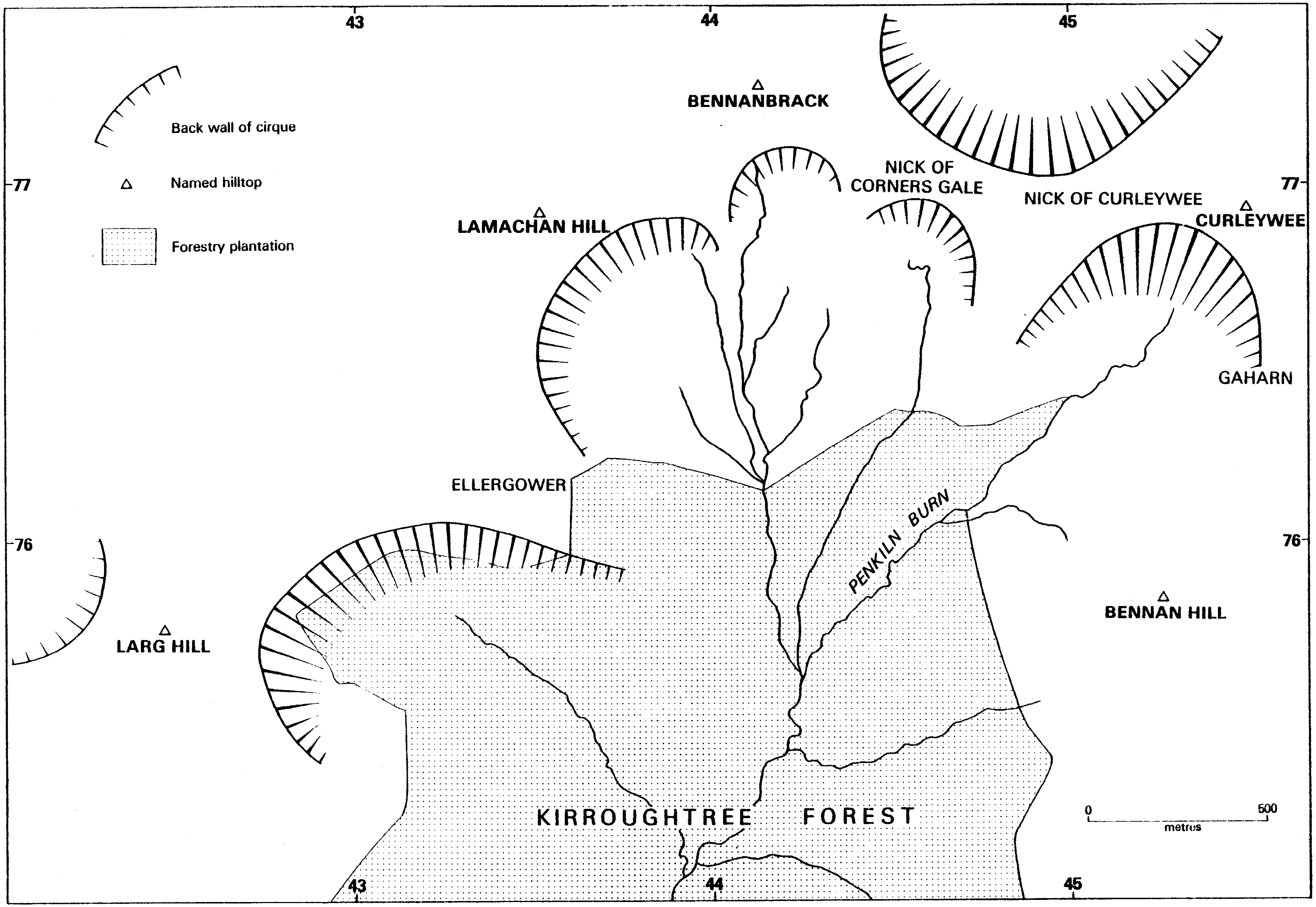


Fig. 2 Principal geographical features around the head of Penkiln Burn.

PHYSIOGRAPHY OF THE PROJECT AREA

The catchment basin of the Penkiln Burn is formed by a series of southward-facing cirques the back walls of which rise to the arete-like ridge linking Larg Hill, Lamachan Hill (717 m), Bennanbrack, Curleywee and Bennan Hill (Figure 2).

Exposure is widespread along the ridge and in cliffs beneath which are, however, partly obscured by scree. The scree also partly covers glacial deposits formed at the margins of cirque glaciers during the final stages of the last glaciation of the south-west of Scotland approximately 10 500 years ago. However, one well-preserved, crescentic moraine ridge can be seen in the cirque immediately south-east of Lamachan Hill. This glacial feature is formed mainly of large angular blocks of greywacke derived from the back wall of the cirque; the uppermost blocks on the crest of the ridge have in places been sorted into crude polygons by periglacial effects. Behind the ridge deep (>1 m) peat has formed over the cirque floor. Solid rock in this and the other cirque basins in the area may thus now be buried beneath a considerable depth of scree, peat and till. At the cirque thresholds bedrock is commonly exposed but from there the ground falls away steeply towards the Penkiln Burn valley with a rapidly decreasing proportion of rock outcrop. Peat and till become thicker and more widespread downslope with the few rock outcrops forming roches moutonnees or glacially streamlined knolls. Below approximately 420 m elevation very little rock is exposed and deep peat deposits (>1.5 m locally) overlie till which in places contains a high proportion of cobbles, small boulders and sandy lenses and may exceed 5 m in thickness. This lower part of the area studied has been extensively planted with sitka spruce and lodgepole pine which now form dense and impenetrable plantations (Figure 2). From its cirque-defined catchment basin the Penkiln Burn flows generally southward to join the River Cree at Newton Stewart.

GEOLOGY

REGIONAL GEOLOGY OF THE SOUTH OF SCOTLAND

In Britain the northern sector of the Caledonides fold belt (the orthotectonic Caledonides) is essentially a high-grade metamorphic terrain whereas the southern sector (the paratectonic Caledonides), although containing highly deformed strata, has suffered only low-grade metamorphism. The boundary between the orthotectonic and paratectonic Caledonides probably lies in the vicinity of the Southern Upland Fault and coincides with a continental margin, beneath which oceanic crust was consumed at a north-westerly dipping subduction zone during the Lower Palaeozoic (Dewey, 1969; Phillips and others, 1976).

When the present Atlantic Ocean is closed so that the continents are restored to their pre-Mesozoic relationships (e.g. Smith and Briden, 1977) Britain and Ireland are brought into close proximity to Newfoundland and Greenland. The continuity of the Laurentian continental foreland outcrops in east Greenland, north-west Scotland and Newfoundland is then emphasised. In Scotland the Dalradian Supergroup originated in a late Precambrian to Cambrian ensialic basin within this foreland (Harris and others, 1978); a probable analogue is the Fleur de Lys Supergroup of Newfoundland (Kennedy, 1975). Ophiolite complexes at Ballantrae (Figure 1) and in Newfoundland are generally believed to represent oceanic crust obducted onto the continental margin from a series of back-arc basins (Dewey, 1974).

South-east of the Southern Upland Fault a systematic sequence of stratigraphically distinct, steeply dipping greywacke–shale units trends NE–SW separated by major strike faults. Within each individual unit the dominant direction of stratigraphic younging is to the north-west, but overall, progressively younger units crop out sequentially towards the south-east (Walton, 1965; Leggett and others, 1979). This trend is particularly well defined in the north-western half of the Southern Uplands but becomes more confused south-eastwards. The fault-bounded units are thought to have originated as an accretionary wedge, formed above a subduction zone consuming the Lower Palaeozoic Iapetus oceanic plate (McKerrow and others, 1977; Leggett and others, 1979). The wedge built up as successive thin layers of sediment were sheared from the surface of the downgoing plate and underthrust beneath a stack of similar slices. Some rotation of the sedimentary pile may have been caused by the underthrusting but final rotation to the present sub-vertical attitude was probably caused by continental collision as the Iapetus Ocean finally closed. Post-tectonic granitic plutons intruded into the folded sedimentary sequence have been dated at c. 400 Ma (Halliday and others, 1980) and provide a minimum age for orogenesis. The project area at the head of Penkiln Burn is adjacent to the south-west margin of one of these granitic bodies, the Loch Doon pluton (Figure 1).

STRATIGRAPHY OF THE PROJECT AREA

Throughout the Southern Uplands lenticular outcrops of the Silurian and Ordovician Moffat Shale trend NE–SW, parallel to the regional strike (Figure 1). Originally these were interpreted (Peach and Horne, 1899) as inliers formed from the cores of tight anticlines, but more recent interpretations (e.g. Leggett and others, 1979) have suggested that the shale belts mark the lines of major strike faults.

From the south-west margin of the Loch Doon granite a belt of shale, from which Peach and Horne (1899) collected Upper Ordovician graptolites, trends south-west (the Carrick (8W) and Loch Doon (8E) sheets of the 1:50 000 geological map of Scotland). A section through this shale belt is well exposed in a road cutting at Wood of Cree [NX 379 715] (Figure 1) where dips are generally steep and the several horizons of shale exposed range from a few cm to 15 m in thickness (Stone, 1980). The outcrop of the shale belt continues intermittently towards the north-east until, near the margin of the Loch Doon granite, a considerable broadening of the outcrop from less than 50 m to about 1 km occurs (Figure 3) with no overall change in dip and no significant topographical influences. A reconnaissance geochemical survey of this area (Leake and others, 1978b) showed a significant lead–zinc–copper drainage anomaly to be associated with the broadened part of the shale belt.

The clastic sedimentary rocks surrounding the black shale belt range in lithology from quartz-pebble conglomerate to laminated siltstone. Thin interbedded horizons of graptolitic shale (<20 cm) crop out locally, notably in the vicinity of Ellergower [NX 4355 7605]. The younging direction of the greywackes can be readily determined from cross lamination and grading whilst convolute lamination, slumping and channelling are well-developed at some exposures. Pale-weathering calcareous concretions up to 25 cm in diameter and usually nucleated on a clast of fine-grained siltstone or shale are

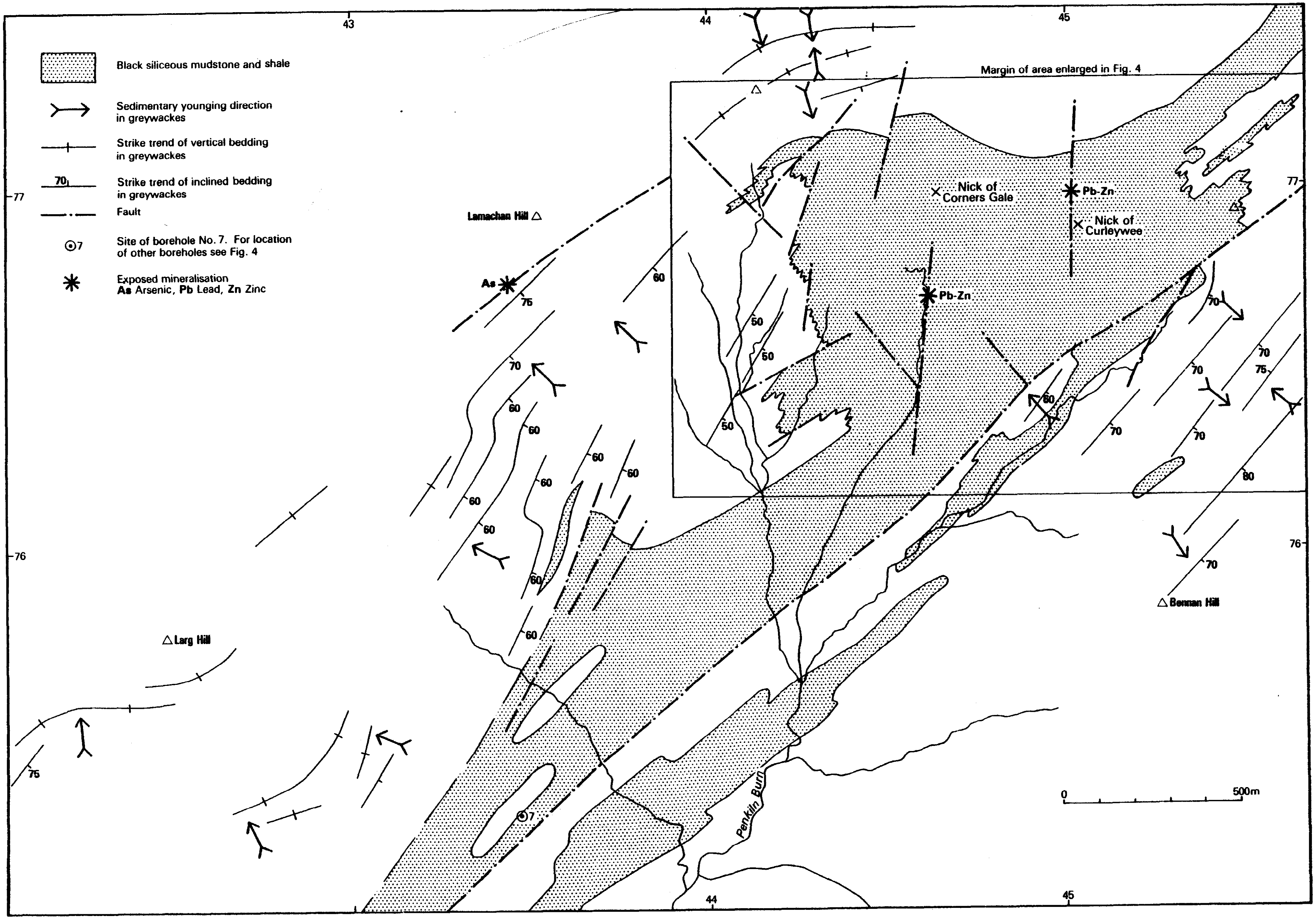


Fig. 3 Geological map of the area around the head of Penkiln Burn

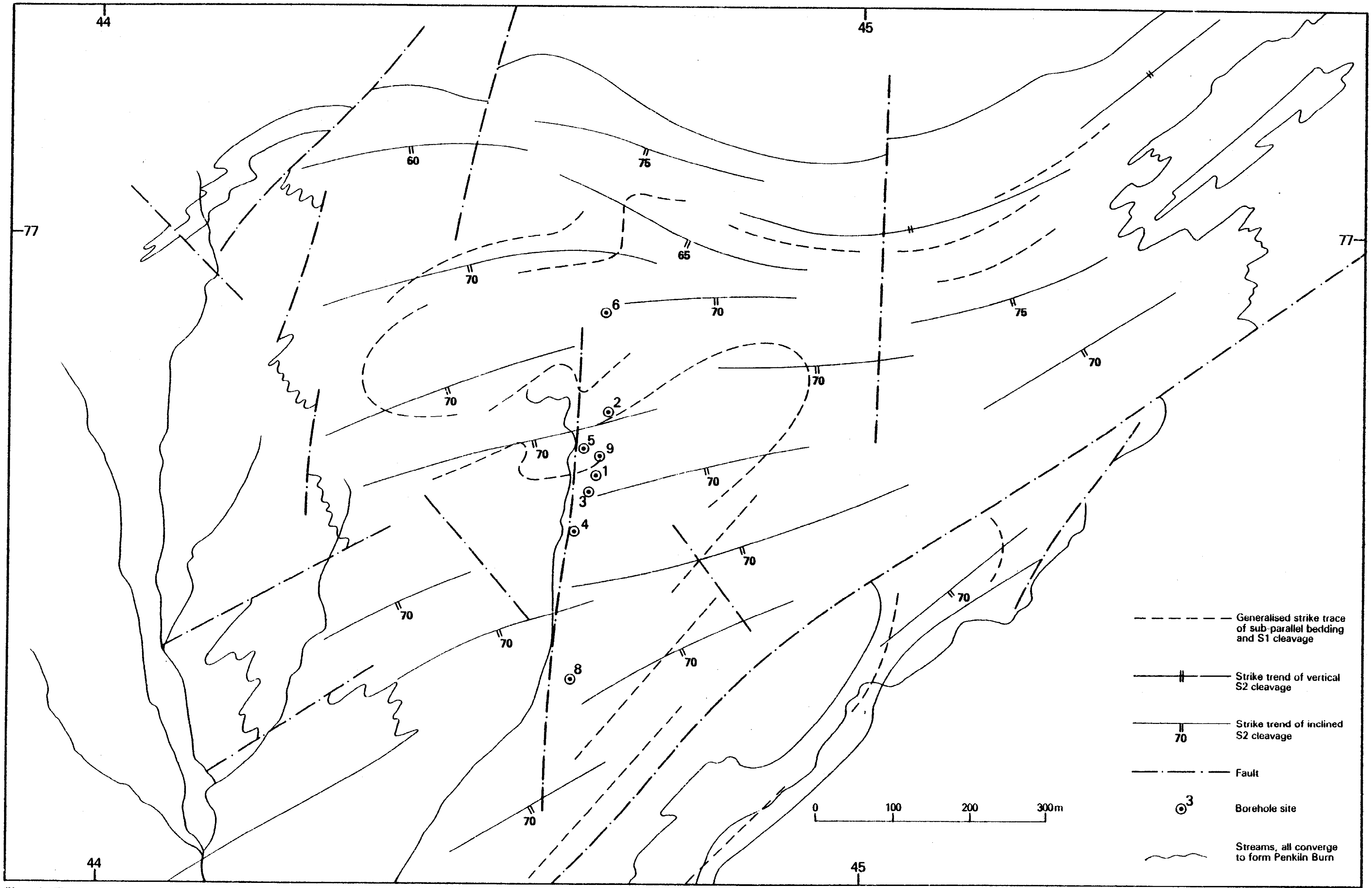


Fig. 4 The main structural elements in the broadened section of the shale belt

widely distributed in the more massive greywacke units.

The black shale belt consists mainly of siliceous mudstone and siltstone interbedded with horizons of chert and fine-grained greywacke. Throughout the succession soft sediment deformation is widespread with slump folds and sedimentary dykes well developed. Fragmentary graptolites were recovered from several exposures of mudstone. The principal detrital components of the greywackes (Fortey, 1981; Skilton, 1981) are quartz, quartzite, chert, felsite and plagioclase together with subordinate K-feldspar. Accessory minerals include yellow tourmaline, rutile and zircon. Intraformational conglomerates also occur within the mudstone sequence and some, which are very matrix-rich, may have formed by mass-flow movement. The clasts within these conglomerates are entirely sedimentary in origin and consist of lithologies encountered elsewhere in the local successions; they include small pyrite nodules. Pyrite also occurs in fine laminae parallel to bedding in some mudstones.

Highly altered material forming thin layers within the typical heterogeneous mudstone, shale and greywacke was observed in Borehole 1 (Figure 4) and may originally have been tuffaceous. The layers are formed of pale brown, massive and unlaminated rock in sharp contact with the finely layered lithologies. They contain between 40 and 60% coarse angular and broken crystal fragments set in a brownish, fine-grained matrix rich in biotite. Altered feldspar and quartz grains are the dominant crystal fragments with lesser amounts of fresher plagioclase, and aggregates of mafic minerals which are possibly lithic fragments. The feldspar content is much greater than in the typical coarser greywackes found in the area. The proportion of fragments to matrix varies between the different horizons encountered but all have the same general appearance. Similar, but less distinctive horizons of possible tuff were noted in Boreholes 3 and 4.

The palaeoenvironment suggested by the assemblage of features observed is a lower fan encroaching on a basin plain (Walker, 1979). The tuff and abundant chert implies local vulcancity but an outcrop of lava reported by Peach and Horne (1899, p. 388) was not found.

Much of the area studied lies within the thermal aureole of the Loch Doon granite and in this zone the fine-grained rocks have been hornfelsed (Gardiner and Reynolds, 1932) with the widespread development of andalusite and cryptic cordierite in argillaceous horizons, (Fortey, 1981). Secondary garnet is seen occasionally in the more cherty lithologies. Decussate biotite in some greywackes, graphite in pelites, and thin veins containing penninite and epidote, also indicate thermal metamorphism (Fortey, 1981; Skilton, 1981).

FOLDING WITHIN THE PROJECT AREA

The main structural elements of the area based on new geological mapping at a scale of 1:10 000 are illustrated by Figures 3 and 4.

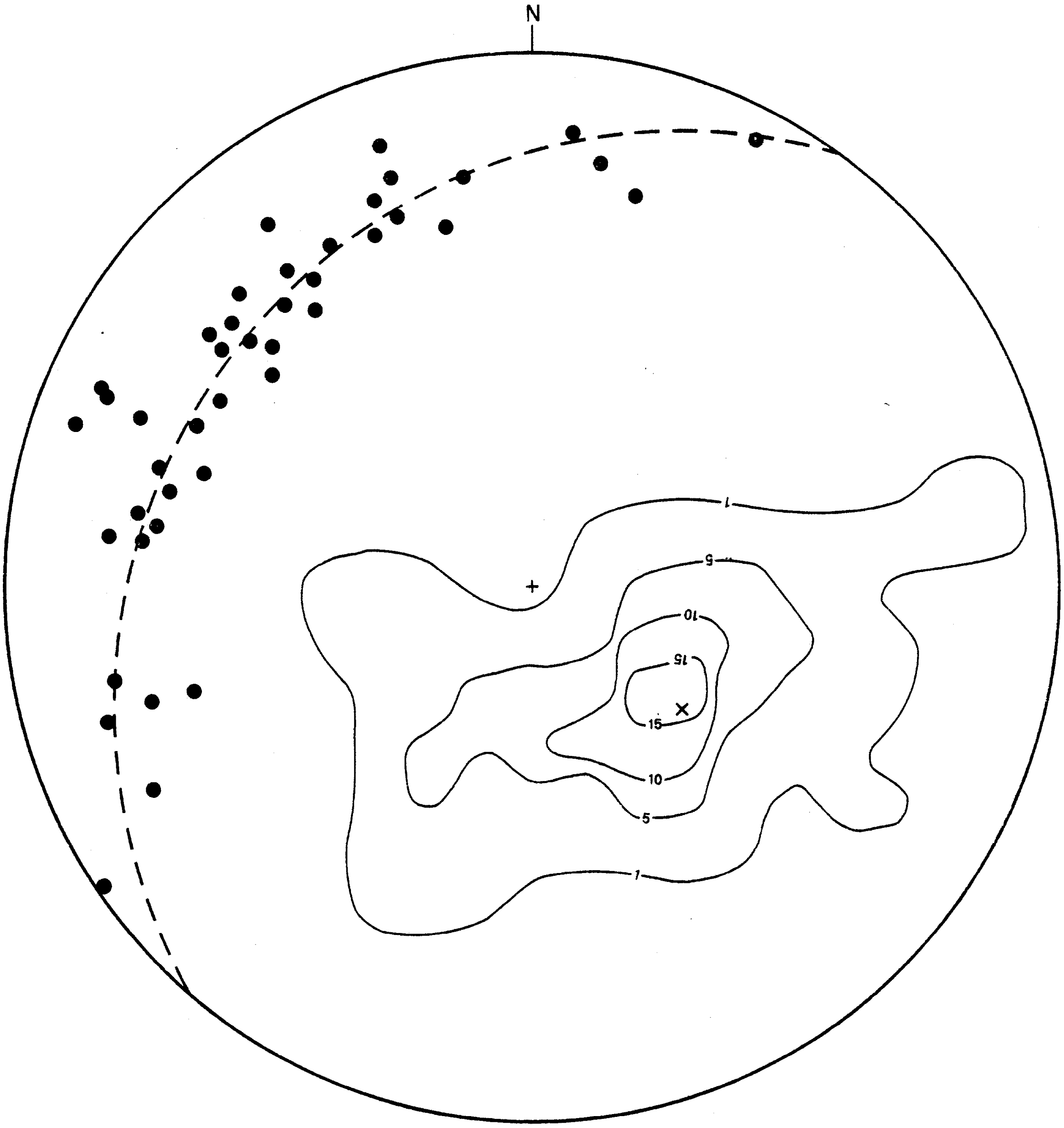
In the Wood of Cree section (Figure 1) bedding features are well preserved in the greywackes on either side of the black shale belt (Stone, 1980). From the alternation of younging direction a series of tight folds can be identified with wavelengths of about 10 m, upright axial planes and axes, derived from π — plots of bedding, plunging approximately 20° to the north-east. In the greywacke sequences on either side of the broadened part of the black shale belt an alternation of younging direction is also seen in steeply inclined beds around Bennanbrack [NX 4415 7725] and Gaharn [NX 4560 7645]. The π — plots of bedding from these areas again show axes plunging approximately 20° to the north-east.

Within the black shale belt early NE-trending structural elements are partially obscured by later folding, and a possibly associated cleavage which locally crenulates the earlier fabrics but does not appear to be axial planar to the F2 folds. In some places a penetrative cleavage (?S1) is developed subparallel to the bedding (SS) suggesting that early, tight or isoclinical folds (F1) may have developed in the black shale belt. These would be of the same style as the F1 folds described from the adjacent greywackes. However, the S1 fabric is more commonly defined by thin zones of sheared mudstone enveloping elongate clasts (length < 10 cm) of coarser-grained lithologies, some of which are finely veined by quartz. The overall effect is a tectonic melange-like fabric with the relationship of the clasts suggesting a response to compression. It is, however, frequently very difficult to distinguish between this tectonic brecciation fabric and that of a well-cleaved intraformational conglomerate. If the melange-like breccias are as widespread as is suspected, then significant tectonic thickening of the sequence may have occurred without the development of macroscopic folds.

The bedding and locally associated S1 fabric show variations in attitude (Figure 4) reflecting a post-F1 phase of folding. This is well demonstrated 200 m south of Nick of Corners Gale where a minor F2 hinge is well defined by thin greywacke horizons within siliceous mudstone. A π-plot of bedding from this exposure gives an F2 axis plunging 58° to 143°. The mean π axis for the F2 folding derived from total poles to SS and the sub-parallel S1 fabric from the whole area plunges 60° to 128° (Figure 5). Associated with the F2 folds is a cleavage (S2) which ranges from irregular fractures spaced up to 10 cm to a pervasive crenulation. It is only locally axial planar to the F2 structures, a relationship also illustrated megascopically in Figure 4. However, the overall variation in the attitude of S2 (Figure 4) suggests that both it and all earlier fabrics may have suffered open folding on a steeply plunging axis. A π-plot of poles to S2 indicates an axis plunging 70° towards 175° but since there is no planar fabric evidence for this late (F3) phase of folding its existence must remain in doubt. The intensity of the possible F3 structures seems to increase north-eastwards towards the granite margin, and so F3 and the forceful intrusion of the pluton may be related. Intrusion was certainly later than the F2 folding since the hornfelsing of the fine-grained rocks post-dates the S2 fabric. Other deflections of the regional strike at the margins of the Loch Doon pluton have been described by Oertel (1955). In view of the uncertain post-F2 tectonic history the F2 axial direction can best be defined as plunging approximately 60° to the south-east. Since this is also the approximate orientation of the axial plane dip the F2 folds are reclined structures.

Small, minor fold hinges, many with an ambiguous relationship to fabric, are widely exposed throughout the black shale belt. Some clearly fold the S1 fabric, and are therefore regarded as F2 structures, but even within this group a wide range of hinge orientation was observed. When minor F2 hinges are plotted stereographically and contoured (Figure 5) a small peak coincides with the π-axis for F2 calculated from SS attitudes: a plunge of 60° towards 128°.

A minor structural effect occurring in both the black shale belt and the greywackes in the Gaharn area is dextral kink banding. The axial planes of these features are vertical and tend approximately north–south.



× F2 TT axis plunges 60° to 128°

● Poles to SS and the sub-parallel S1 fabric.

103 minor fold hinges contoured at 1, 5, 10 and 15% concentration per unit area

Fig. 5 Equal area, lower hemisphere stereogram projection

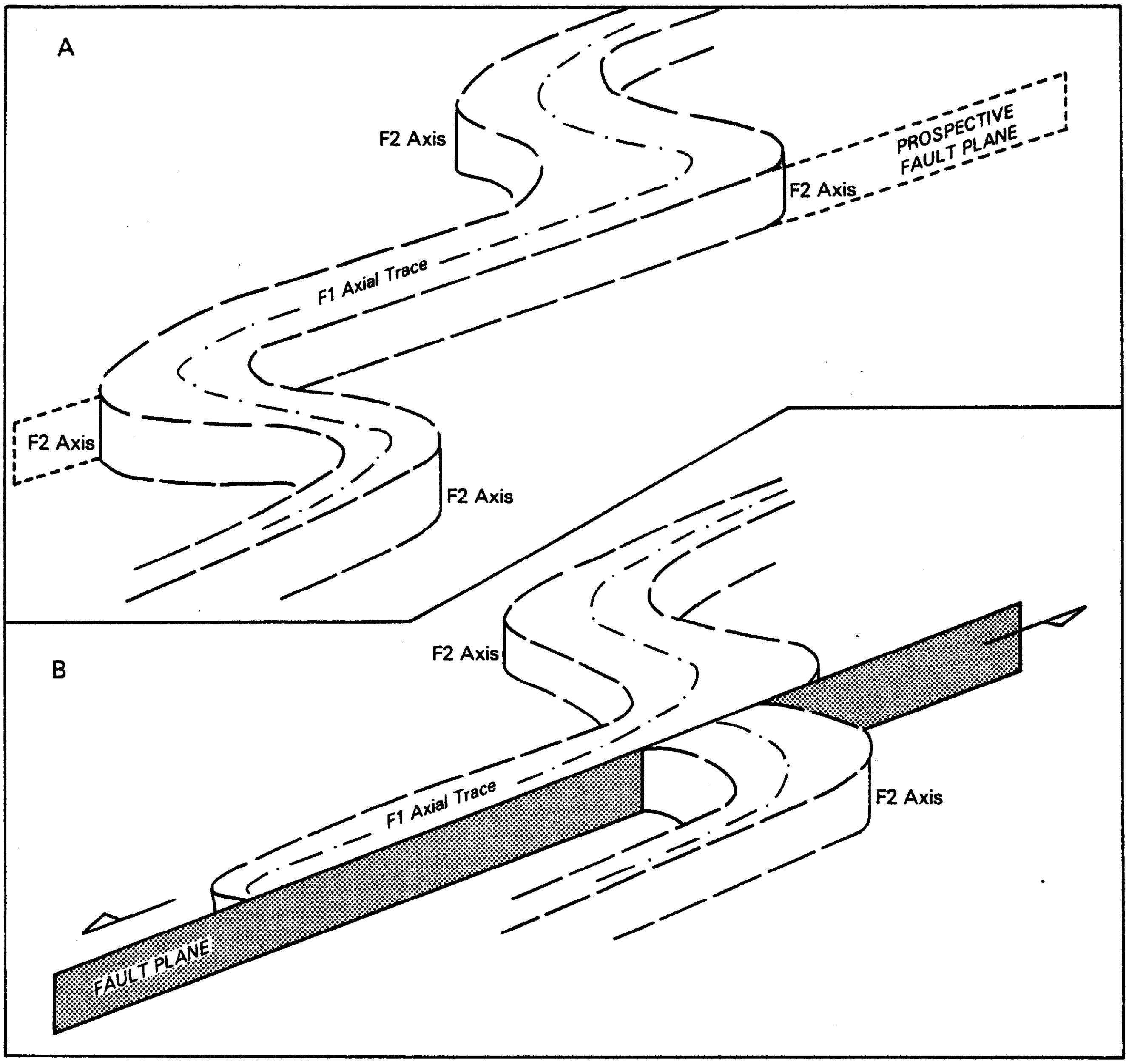


Fig. 6 Schematic model of major structural relationships within the black shale belt:
A. Post F 2 folding, pre faulting B. After sinistral strike faulting

FAULTING WITHIN THE PROJECT AREA
Three major fault trends occur within the black shale belt, north-east strike faults and a possibly conjugate pair of north-west and NNE faults. Of the two major strike faults crossing the area mapped, (Figure 3) the north-westerly is well exposed in the greywacke sequence on Lamachan Hill [NX 4345 7672] and may extend north-eastward where it partially defines the northern margin of the shale belt. The south-eastern margin is formed by another strike fault, which separates the main outcrop of shale and a smaller belt cropping out along the Penkiln Burn [NX 4498 7634]. At several localities small shears strike at about 040–050° and produce a sinistral offset before merging with the S2 cleavage. Hence it is possible that movement along the major strike faults (trending approximately 045°) was also sinistral and occurred subseqent to the F2 fold phase. A comparison may also be justified with the Whithorn area 35 km to the south where Rust (1965) found that sinistral strike wrenches outnumbered those with a dextral offset in the ratio 59:12. Assuming a post-F2 sinistral displacement along the south-eastern marginal strike fault, the small shale belt cropping out along Penkiln Burn originated at some distance south-west of the main part of the shale belt outcrop (Figure 6).

The two sets of minor faults, one trending NW–SE and the other NNE–SSW, have a complex inter-relationship, with small lateral offsets, and may form a conjugate pair. They appear to post-date the major strike faults and certainly cut the S2 fabric.

MINOR INTRUSIONS WITHIN THE PROJECT AREA
Numerous dykes crop out in the area mapped (Figure 7), and dykes were intersected in all of the boreholes. They range in thickness from less than 1 cm up to about 10 m but can only rarely be followed for more than 20 m. The entire dyke suite is dioritic, the commonest rock type being a porphyritic hornblende microdiorite containing

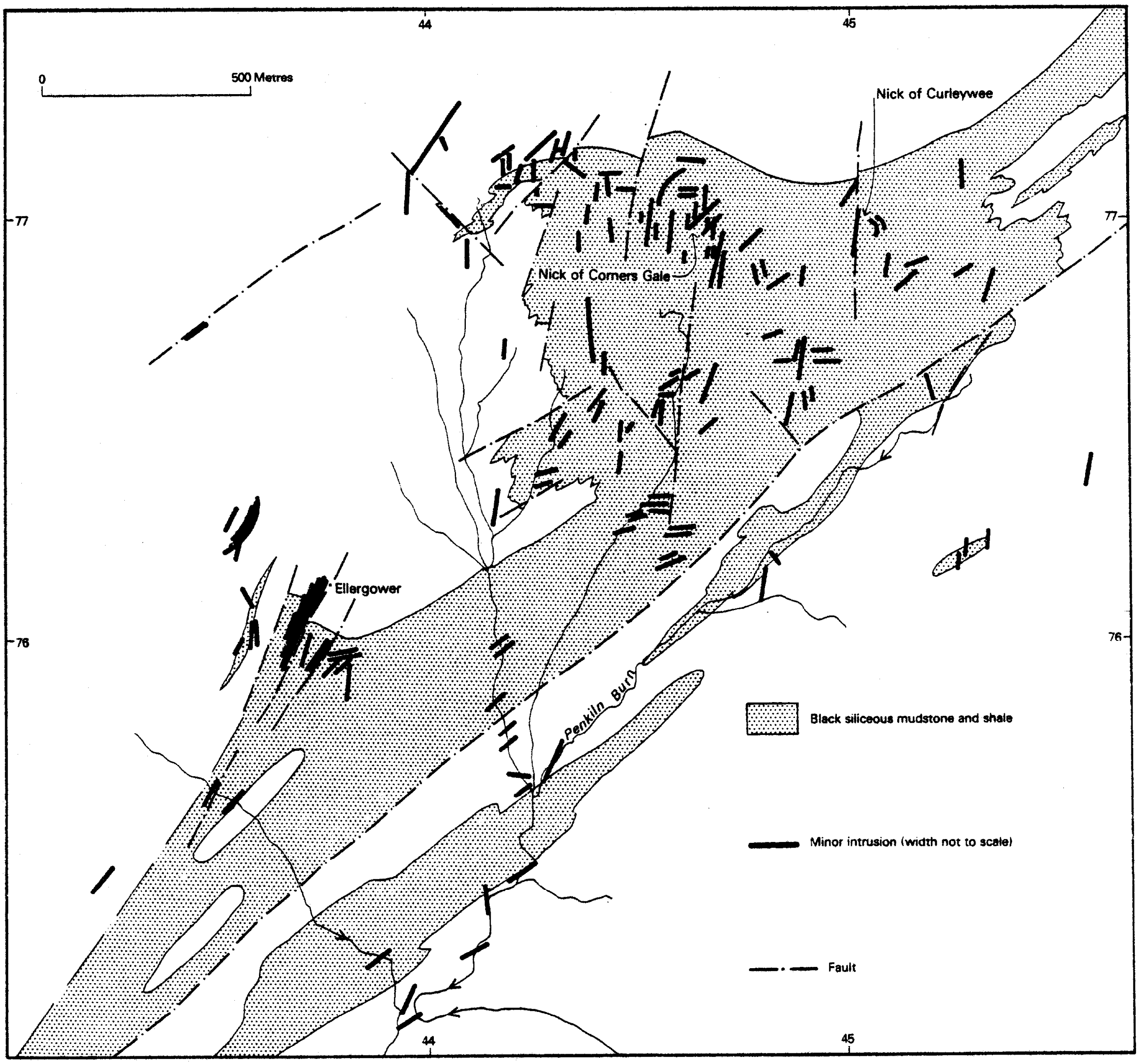


Fig. 7 Distribution of minor intrusions within the broadened section of the shale belt

significant interstitial quartz (the porphyrites of Teall in Peach and Horne, 1899, p. 625). When considered in terms of their chemical composition they fall within the quartz-monzodiorite field of Streckeisen (1976). Less common are spessartite lamprophyres, meladiorites, microtonalites, dacites and quartz-microdiorites.

Many of the dykes seen in the borehole sections and several of those observed at outcrop have been completely altered hydrothermally to aggregates of chlorite, sericite and goethite. However, others are largely unaltered and in these the phenocryst content varies from around 5 to 60% with labradorite and aggregates of chlorite and/or actinolite the main forms present. Some of the mafic phenocrysts have a core of primary hypersthene. The matrix consists of plagioclase laths accompanied by amphibole, chlorite and biotite and minor but variable amounts of hypersthene, quartz, magnetite, apatite and possibly alkali feldspar. Flow lineation is visible, particularly around phenocrysts but no amygdales have been observed.

Several distinct phases of minor intrusion can be recognised. At Nick of Curleywee [NX 4505 7695] a dacitic sheet is folded tightly, probably about an F1 hinge. The sheet and sub-parallel bedding are folded and cut by the S2 spaced cleavage and so the intrusion is definitely pre-F2 and possibly pre-F1. Several dykes of quartz-microdiorite and porphyritic hornblende microdiorite at Nick of Corners Gale have sinuous outcrops and although no fabric relationships could be proved they are also regarded as pre-F2, and possibly pre-F1.

The post F2 dykes intruded into the black shale belt can be readily subdivided into two phases: those parallel to the S2 cleavage, which are usually slightly sheared, and those cross-cutting the S2 cleavage, which are only rarely sheared. The first group, consisting mainly of hornblende microdiorites, were intruded probably after the formation of the S2 cleavage but before the wrench movement along the strike faults and the accompanying late shearing along the S2 planes. They are cut by the NW–SE and the NNE–SSW faults. Those dykes which cut across the S2 fabric have a predominantly north or NNE trend and range in composition from hornblende microdiorites to very quartz-rich microdiorite approaching microtonalite. The distribution of the dykes is partially controlled by the

NNE–SSW faults but some of the dykes with this trend are also slightly sheared. These sheared dykes may represent a separate pre-NNE faulting suite, faulting and dyke intrusion may have been partially contemporaneous, or there may have been some later reactivation of the faults. However, the majority of the dykes which cut the S2 fabric are unsheared and were probably intruded after the conjugate faulting.

Within the greywacke sequence the majority of the minor intrusions are approximately conformable with the bedding. However, two intrusive phases are clearly shown at Ellergower where a hornblende microdiorite dyke about 10 cm thick is intruded into a much thicker (>2 m) quartz-rich microdiorite. Several dykes cut across the bedding of the greywackes and one of these, an unusual meladiorite up to 8 m thick, is in turn cut by a NW–SE fault.

Although the dykes can be divided into three and possibly four suites on the basis of relative age, there is no corresponding compositional distinction. The only petrographic trend identified was a slight decrease in the proportion of quartz-rich dykes from the pre-F2 to the post-F2 pre-faulting suite. This was followed by an increase in the proportion of quartz-rich dykes in the post-strike faulting suites. The position of the meladiorites is ambiguous. Despite these variations, most of the dykes in each of the suites are composed of hornblende-microdiorite.

All of the minor intrusions studied from within the project area appear to be petrologically and chemically related. They are distinct from both the group of concordant granodioritic and monzonitic minor intrusions which crop out to the north of the shale belt (Leake and others, 1981) and the adjacent marginal facies of the Loch Doon pluton (Gardiner and Reynolds, 1932; Leake and others, 1981). Age relationships are more difficult to assess but the actinolite and possible biotite which replace the original mafic minerals in the dykes at the head of Penkiln Burn may have been produced by contact metamorphism in the thermal aureole of the Loch Doon pluton. Alternatively, the alteration may have a hydrothermal origin. If the first supposition is correct the dykes would have been intruded prior to the last thermal event at Loch Doon, which probably coincided with the K-Ar dates of about 400 Ma obtained from other large Caledonian plutonic bodies in Galloway (Halliday and others, 1980). Most of the unsheared NNE–SSW dykes do not appear to have suffered thermal metamorphism and were probably intruded subsequent to the granite and hence to the F3 fold episode.

STRUCTURAL SYNTHESIS

The broadening of the black shale belt can be explained in terms of the interference of a major reclined fold with earlier structures. The earliest folds (F1) are seen in the greywacke sequences adjacent to the black shale belt as upright or steeply inclined, tight and isoclinal structures with axes plunging gently north-east. Folds of the same style may also occur within the black shale belt but there the S1 fabric is generally defined by zones of sheared mudstone enveloping clasts of siltstone and fine-grained greywacke to produce a tectonic melange-like structure.

The second phase of deformation (F2) is best developed in the black shale belt, with only an overall deflection of strike from the regional average of about 050° to about 030° in the surrounding greywackes. Variations in bedding and S1 cleavage attitude within the black shale belt define an antiform — synform system with a wave-length of about 600 m and axis plunging approximately 60° towards the south-east. The cleavage apparently associated with this reclined folding is not axial planar. Local variations (Figure 3) may be the result of minor F2 folding congruous with the major F2 structure in the black

Table 1 A summary of the structural and igneous history of the Penkiln Burn area

	Folding	*Faulting*	*Igneous activity*
	N–S vertical kink bands		
			Dyke intrusion, main trend is NNE–SSW
F3	Open, axes plunge steeply S		
		Minor NW–SE and NNE–SSW conjugate faults	Possible dyke intrusion, main trend is NNE–SSW
		Major sinistral wrench movement on strike faults	
			Dyke intrusion, main trend is parallel to S2 planar fabric
F2	Close, reclined, axes plunge c. 60° towards SE		
F1	Upright, tight-isoclinical, axes plunge gently NE		
			Sheet intrusion, definitely pre-F2 probably pre-F1

shale belt.

A possible third phase of deformation (F3) produced gentle folds with axes plunging 70° towards 175° but no planar fabric. In view of the increase in F3 intensity towards the north-east, the F3 folding may be associated with the intrusion of the Loch Doon granite. That event is certainly later than the F1 and F2 folding since the hornfelsing of the fine-grained rocks post-dates both of the planar tectonic fabrics. Other deflections of the regional strike trend at the margins of the Loch Doon pluton have been described by Oertel (1955).

The relationship between the fold phases identified and the history of faulting and minor intrusion is summarised in Table 1.

The synthesis presented has many similarities to the deformation histories described from other parts of the Southern Uplands (summarised by Walton, 1965). Early isoclinal folds (F1) are widespread and may have originated in association with early NW-directed underthrusting at the base of an imbricate subduction complex (Legget and others, 1979). Such a compressional regime would also be appropriate for the formation of the S1 melange-like fabric.

If they originated as above, the early structures must then have been rotated and steepened prior to the F2 folding which, in the black shale belt, involves reclined folds. These are similar in style to the F3 structures described from the Whithorn area (Rust, 1965) where wrench movement on strike faults was accompanied by folding on steeply plunging axes. However, the sequence of events described from Whithorn is not strictly compatible with the black shale belt where the wrench faulting probably post-dates the F2 folding.

The attitude of the reclined F2 structure is primarily responsible for the broadening of the black shale belt. Weir (1979) has proposed that this phenomenon may be caused by the exposure of different structural levels of a shale horizon which curves to become shallower at depth. Such a model does not seem appropriate to the black shale belt considered here (Stone, 1981a) since local structural differences alone are sufficient to explain the observed broadening. There is also no significant change in dip between the narrow part of the belt at Wood of Cree and the broadened section exposed marginal to the Loch Doon pluton.

The steeply plunging F3 folds in the black shale belt do not appear to have counterparts elsewhere in the Southern Uplands. None would be expected if the F3 folds are indeed a local effect associated with the intrusion of the Loch Doon granite.

DRAINAGE GEOCHEMISTRY

INTRODUCTION

A reconnaissance drainage survey of the Penkiln Burn and adjacent catchment basins was carried out in 1974 and augmented in 1976. The sampling and analytical procedures followed are described fully in Leake and others (1978a) and a brief preliminary interpretation of the data is given in Leake and others (1978b).

Around the headwaters of the Penkiln Burn substantial lead anomalies were found in both minus 100 BSI sieved sediment and panned concentrate samples, with lead levels reaching 490 ppm and 1240 ppm respectively. The highly anomalous results for both sample types indicated that dispersion was taking place over a considerable portion of the stream sediment size spectrum and suggested that the source of the anomaly was probably extensive. The relatively long dispersion train for lead (at least 3 km down the main stream) also suggested derivation from a large source area (Leake and Smith, 1975).

Maps showing the distribution of Cu, Zn and Pb in both sieved sediment and concentrate samples collected during more extensive follow-up surveys in the Penkiln Burn and adjacent drainage basins are shown in Figures 8 to 13. The maps are plotted in terms of class intervals chosen mostly from breaks in slope in the cumulative frequency plot for each element.

COPPER

Sieved sediment samples containing relatively high copper levels are mostly derived from the upper reaches of Penkiln Burn (Figure 8), an area underlain by the main outcrop of Ordovician black shales and associated rocks. This distribution probably reflects the presence of pyrite, which is more abundant in the shales and mudstones than in the surrounding greywackes. The highest levels of copper occur in samples from the central of the three streams at the head of the Penkiln Burn drainage basin, with levels reaching 560 ppm Cu towards the source of the stream. These anomalies largely reflect exposed base metal mineralisation, since malachite has been observed in gossan outcropping at the head of the stream.

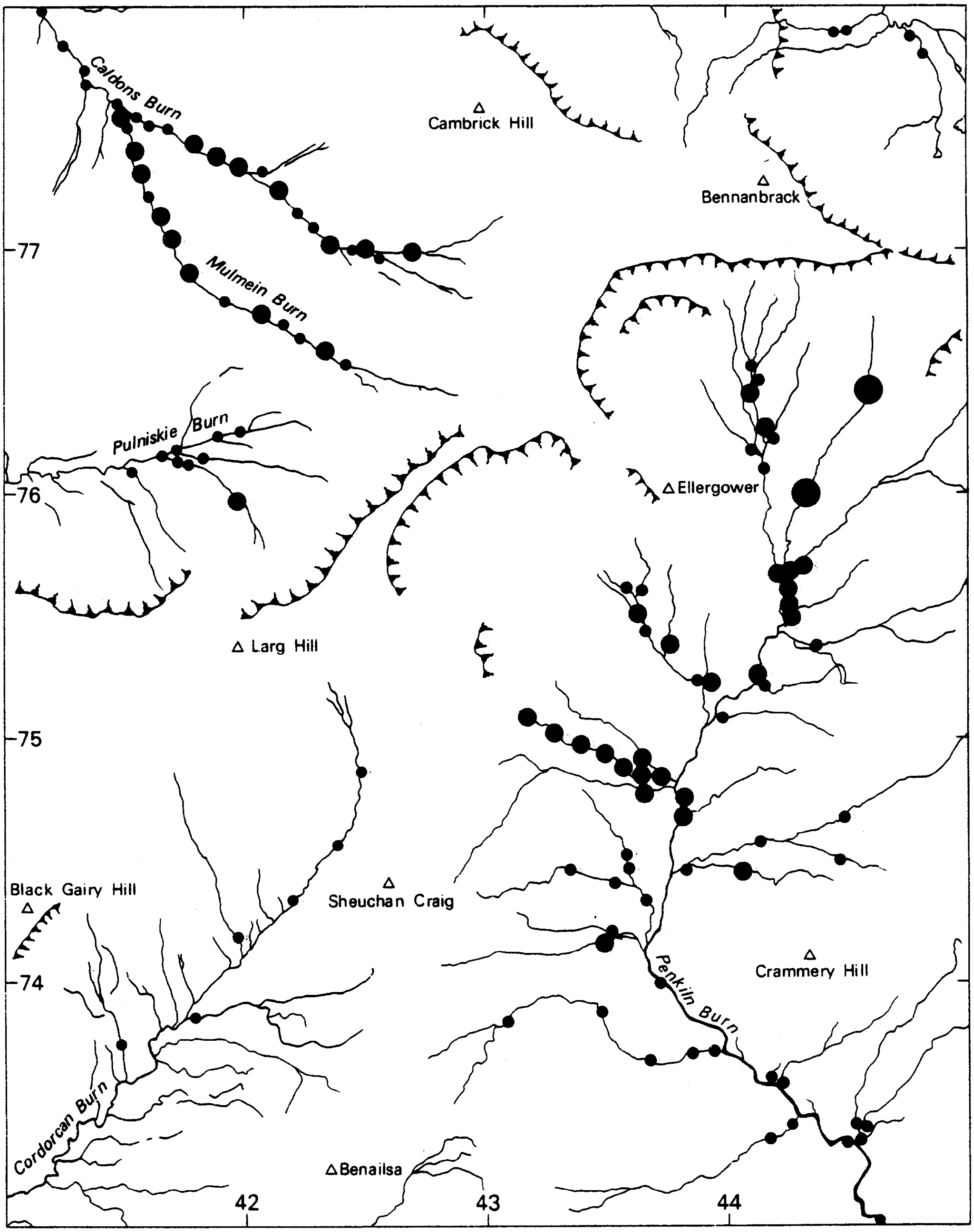
High levels of copper also occur in sieved sediment samples from the upper reaches of Caldons Burn and its tributary Mulmein Burn (Figure 8). No black shales occur in the vicinity but the streams cut the strike extension of arsenic-gold and base metal mineralisation found farther north-east around the headwaters of the Glenhead Burn (Leake and others, 1981).

The maximum copper anomalies in panned concentrates (Figure 9) coincide with those detected in sieved sediments from the central stream at the head of the Penkiln Burn basin. Elsewhere there is very little correlation, with no copper enrichment associated with either the main outcrop of black shale and mudstone or the Caldons Burn–Mulmein Burn area. The panned concentrate anomalies which do occur are scattered throughout the Penkiln Burn drainage basin, those in the western part of the area showing some corelation with anomalous lead levels. In the eastern sector of the drainage basin the copper in panned concentrate anomalies reflect slight enrichment associated with a well-defined zone of high Mg, Ca, Ti, Mn, Fe, Ni, Sr and Nb (Leake and others, 1978b). Within this zone the stream sediment is rich in such detrital minerals as ilmenite and orthopyroxene.

ZINC

The pattern of zinc distribution in sieved sediments is relatively diffuse (Figure 10), but a spatial relationship does exist with the outcrop of black shale and mudstone. However, there is no correlation between the higher zinc levels and the several well-defined anomalies in other elements: for example, the zinc content of closely spaced samples obtained from the central tributary at the head of the Penkiln Burn drainage basin increases to around 350 ppm as the outcropping mineralisation is approached (cf. Figure 3), but falls to 240 ppm in the immediate vicinity of the mineralisation where copper and lead levels are at a maximum.

The source of the relatively high levels of zinc in some sieved sediment samples from Pulniskie Burn was not traced, but since no other elements show corresponding



COPPER IN SEDIMENT

- 0 - 25 ppm
- 30 - 65 ppm
- > 65 ppm

Fig. 8

Scale

0 500 1000 m

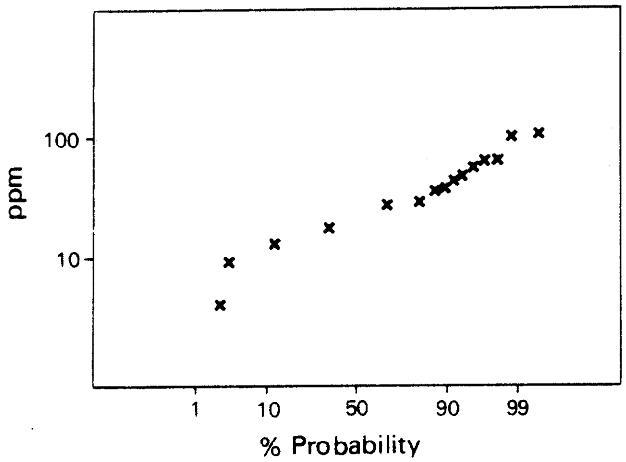
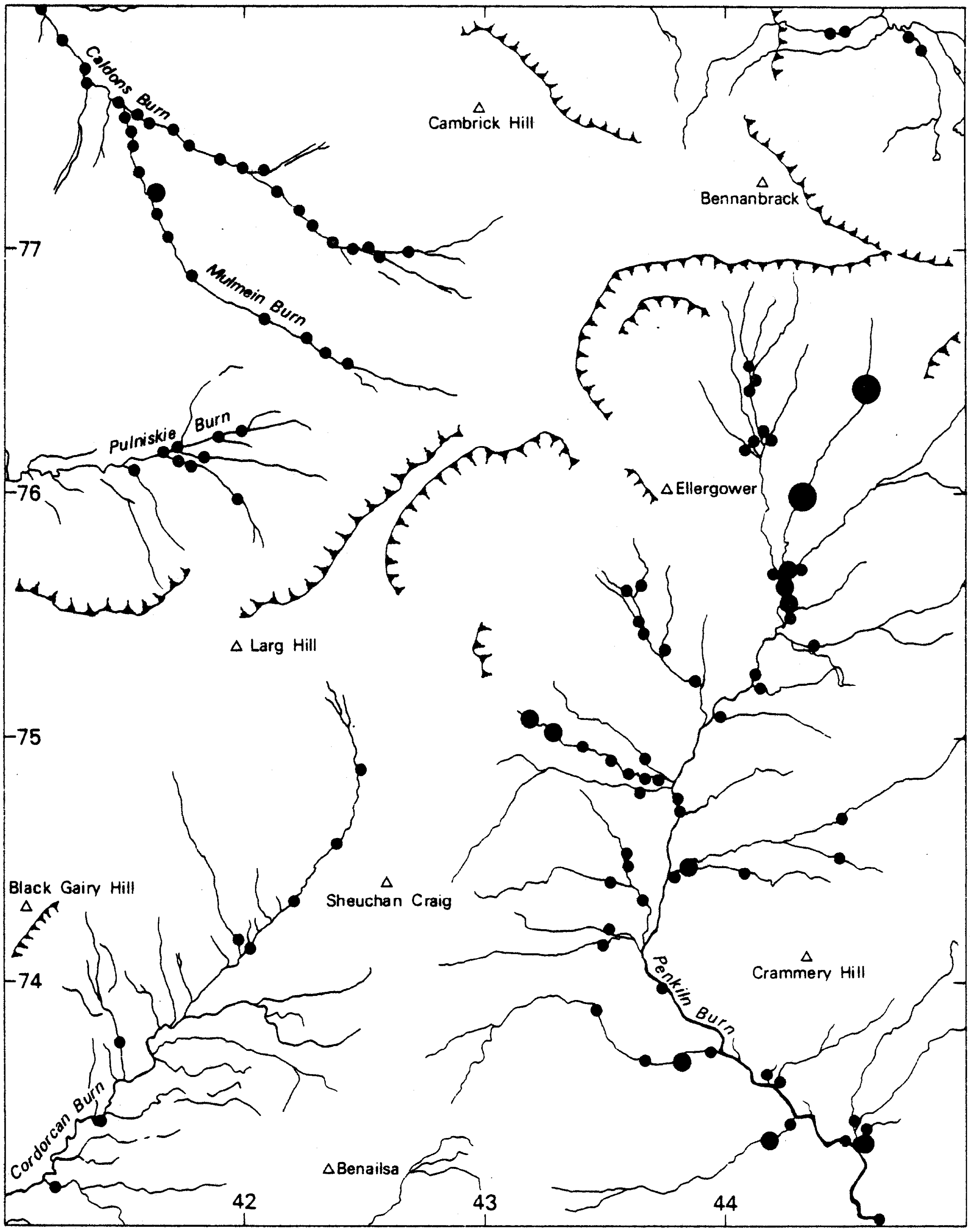


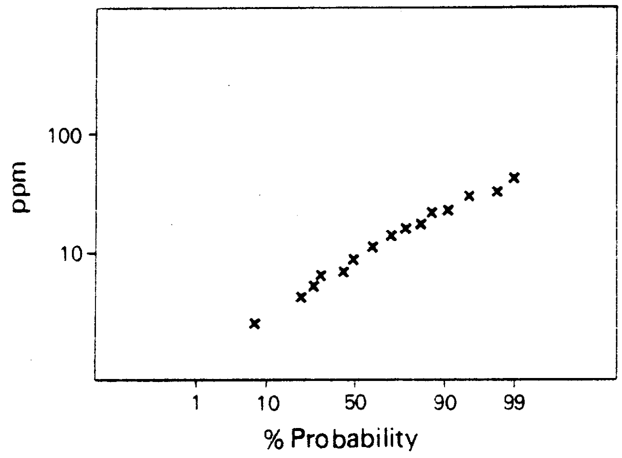
Fig. 8 Copper in sediment



COPPER IN CONCENTRATE

- ● 0 - 20 ppm
- ● 25 - 50 ppm
- ● > 50 ppm

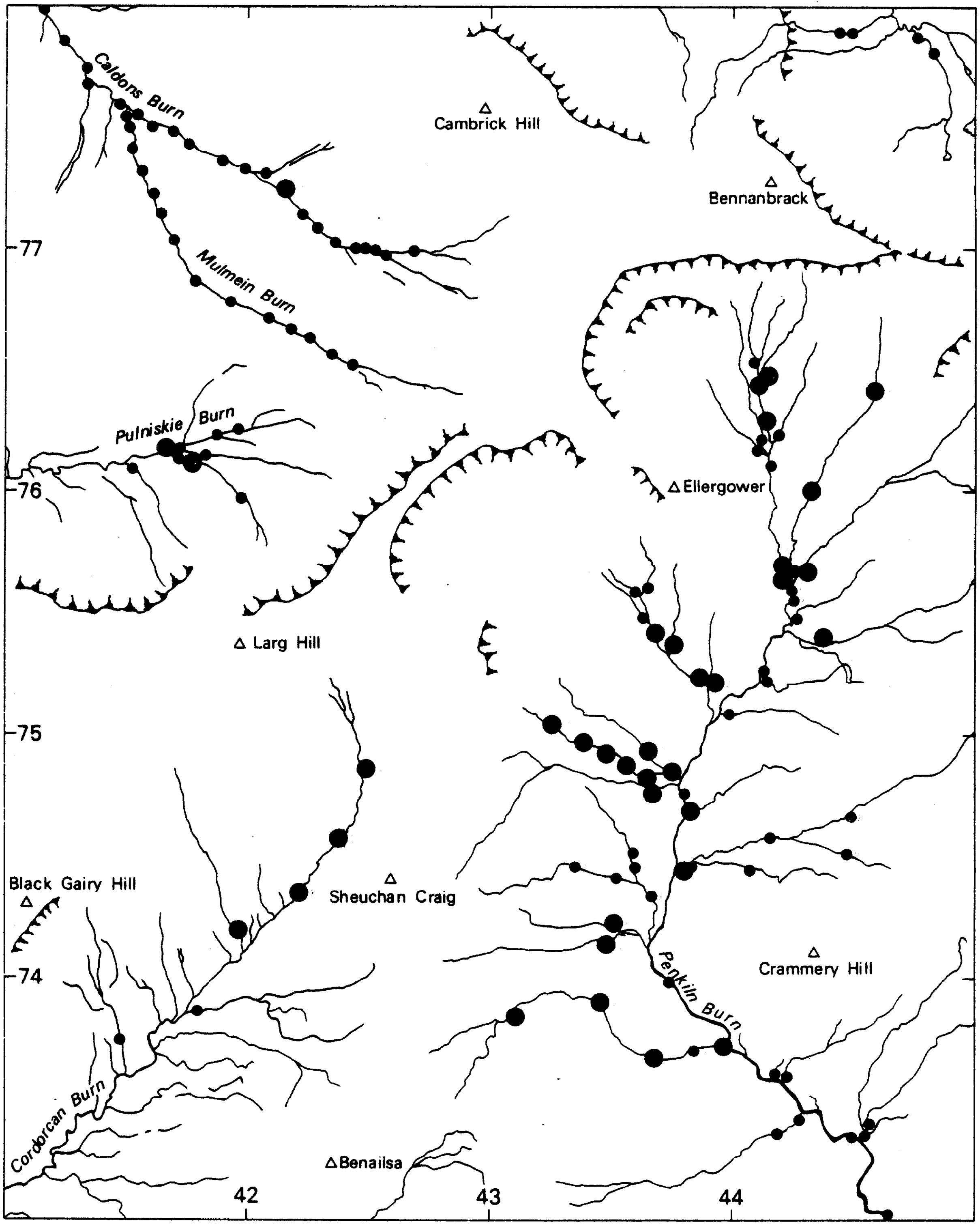
Fig. 9



Scale

0 500 1000 m

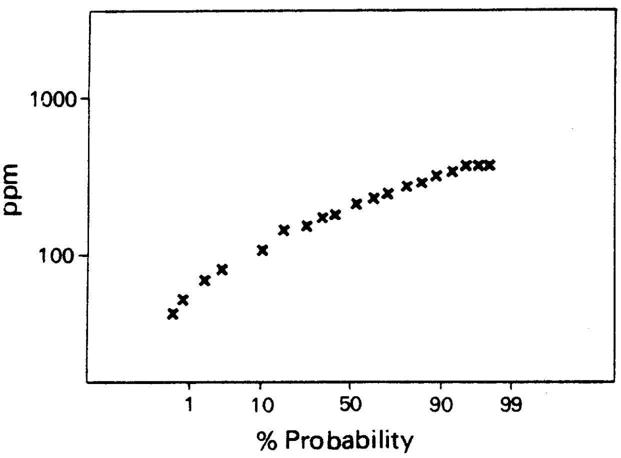
Fig. 9 Copper in concentrate



ZINC IN SEDIMENT

- 0 - 300 ppm
- 305 - 600 ppm

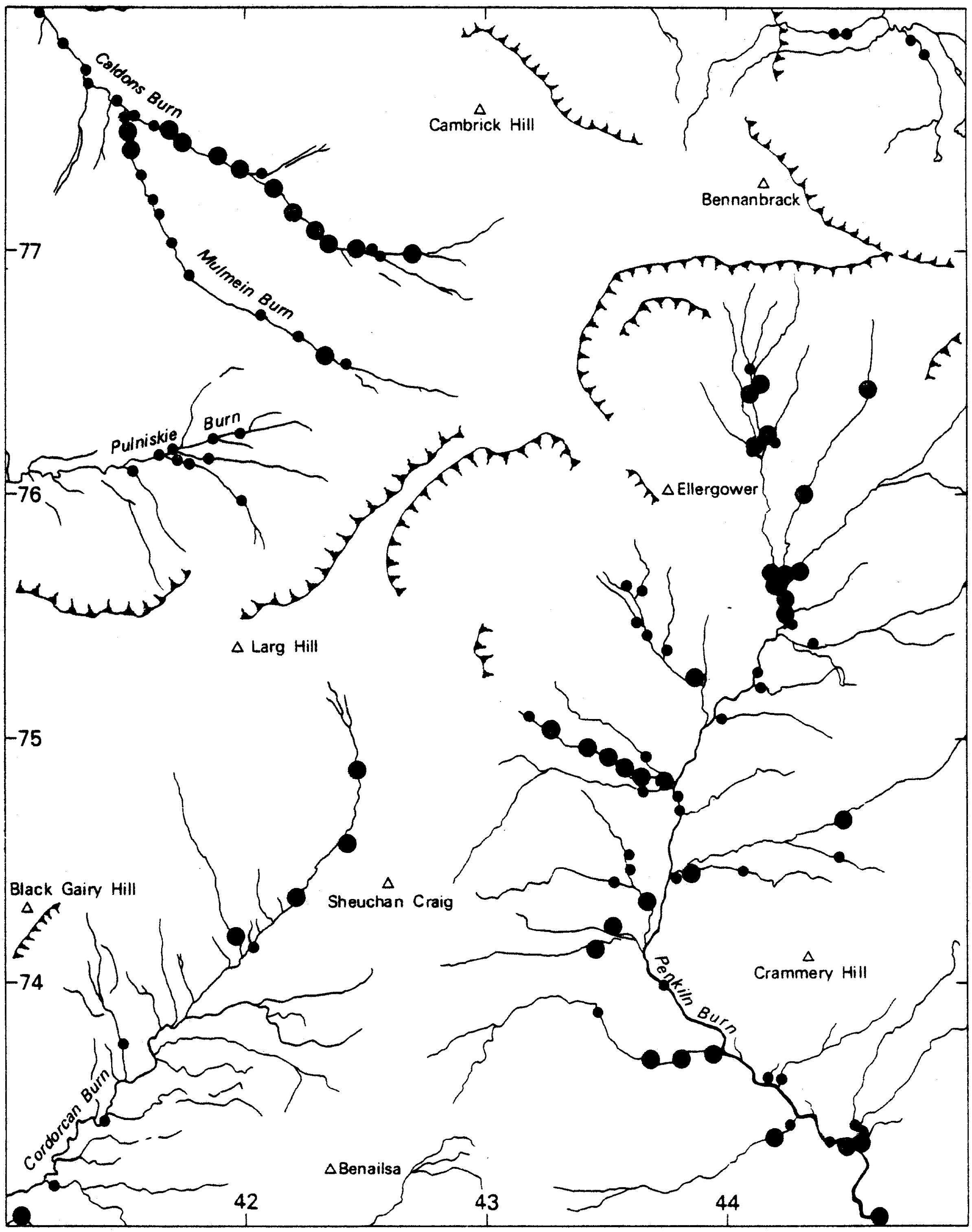
Fig.10



Scale

0 500 1000 m

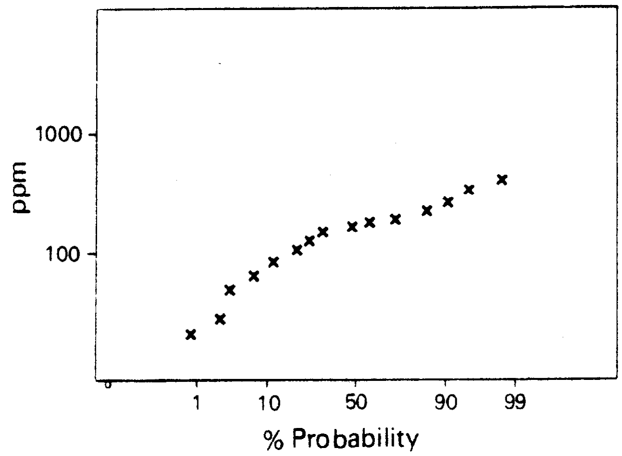
Fig. 10 Zinc in sediment



ZINC IN CONCENTRATE

- ● 0 - 150ppm
- ● >150ppm

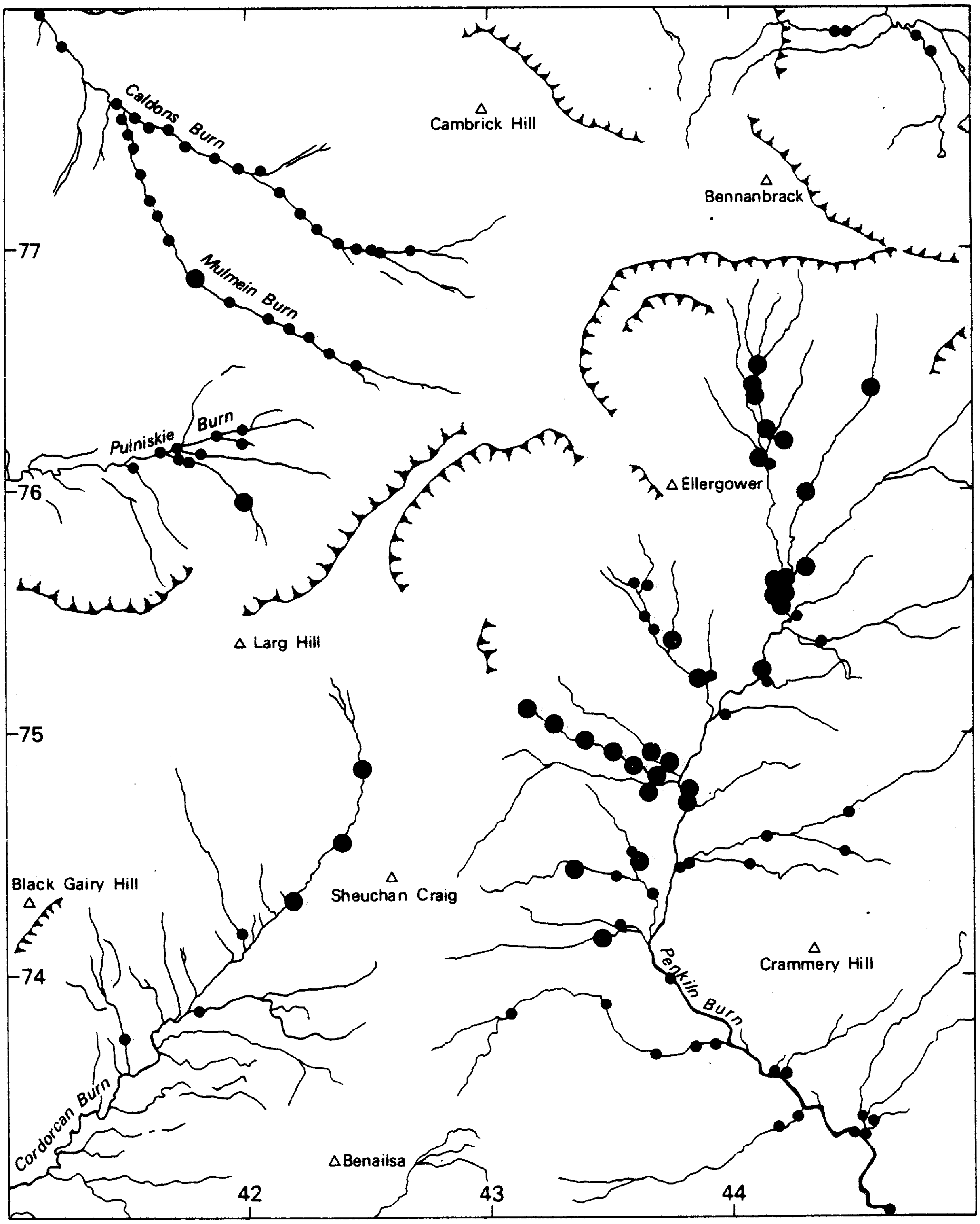
Fig.11



Scale

0 500 1000 m

Fig. 11 Zinc in concentrate



LEAD IN SEDIMENT

- ● 0 - 100 ppm
- ⬤ > 105 ppm

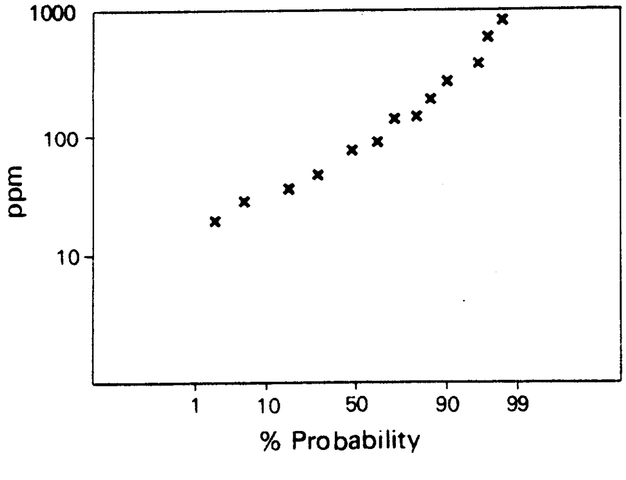
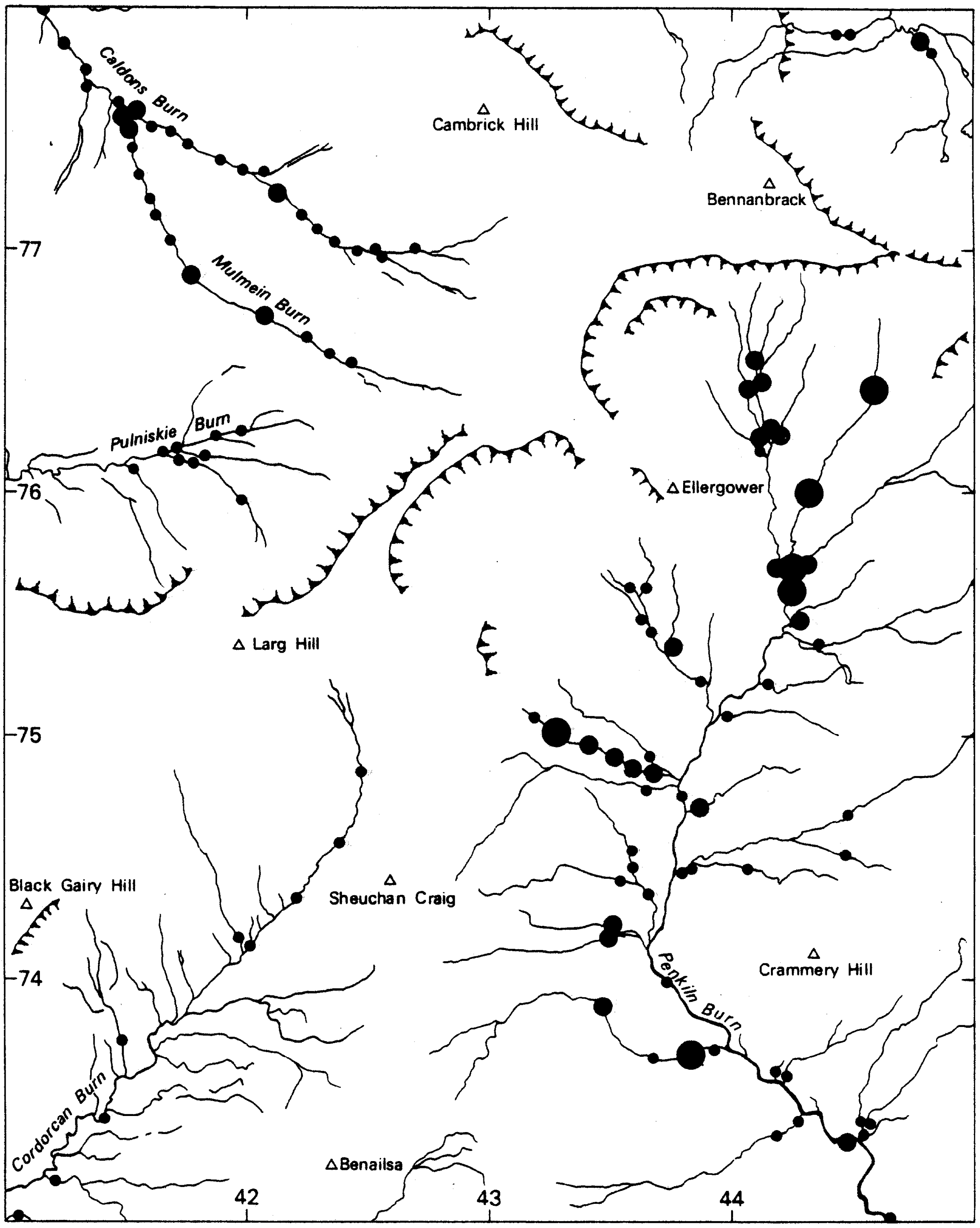


Fig.12

Scale

0 500 1000 m

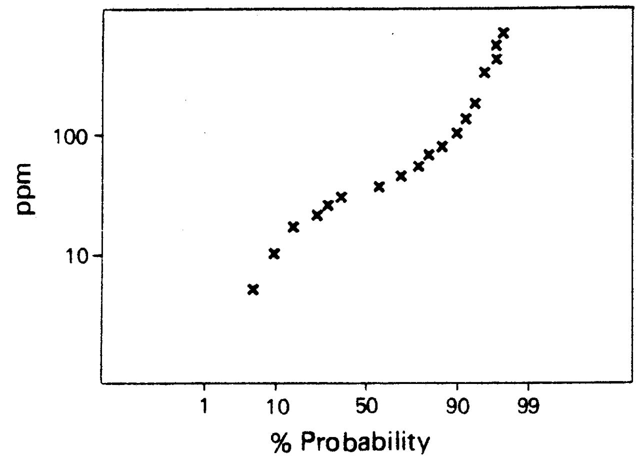
Fig. 12 Lead in sediment



LEAD IN CONCENTRATE

- 0 - 40 ppm
- 45 - 450 ppm
- > 450 ppm

Fig.13



Scale

0 500 1000 m

Fig. 13 Lead in concentrate

enrichment, mineralisation is probably not present. Zinc enrichment in samples from the head of Cordorcan Burn reflects the south-westwards strike extension of the black shale belt. Some mineralisation may occur in this area since lead levels are also anomalously high.

Zinc distribution in panned concentrate (Figure 11), although relatively uniform, does show some correlation with anomalous levels of copper and lead and so may reflect mineralisation. The levels of enrichment are low with, for example, only a small increase from about 180 ppm to 385 ppm Zn in closely spaced samples approaching the outcropping mineralisation in the central tributary at the head of Penkiln Burn. Small amounts of sphalerite have been identified in concentrates from the headwaters and some western tributaries of the Penkiln Burn but none was recorded to the east of the main stream. However, the spinels which occur in association with detrital ilmenite and orthopyroxene in the eastern part of the area have been shown by XRF scanning to contain signficant quantities of zinc.

LEAD

The distribution of sieved sediment samples containing anomalously high levels of lead (Figure 12) clearly reflects the outcrop of the mineralised black shale belt from the headwaters of Cordorcan Burn to the headwaters of Penkiln Burn. Superimposed on this widespread lead enrichment some streams contain sediment with exceptionally high lead content, of which the most obvious is the central tributary at the head of the Penkiln Burn drainage basin. In that stream lead levels in sieved sediment rise from 400 ppm 1 km downstream from the outcrop of mineralised gossan, to 7500 ppm in the vicinity of the outcropping mineralisation. Samples with lead levels reaching 1000 ppm also occur in other tributaries of Penkiln Burn in the head of the basin. Farther down the main stream lead levels are lower but in tributaries draining the south-west strike extension of the black shale belt lead content ranges up to 690 ppm in places.

The lead anomalies detected by panned concentrate analysis are more sharply defined than those derived from sieved sediments. The highest values of lead in concentrate (Figure 13) correlate with the lead in sieved sediment maxima; lead content rising to 1.1% in the vicinity of the outcropping mineralised gossan. The main lead-bearing mineral identified in the anomalous concentrates is the secondary phosphate plumbogummite, a mineral which also occurs in the gossan.

Elsewhere small anomalies in the western tributaries of Penkiln Burn are not coincident with those found in sieved sediment. Any mineralisation in this area is therefore liable to be of only local extent. The concentrate anomalies in Caldons and Mulmein Burns may reflect mineralisation along strike from that reported around the headwaters of the Glenhead Burn farther north-east (Leake and others, 1981).

GENERAL DISCUSSION OF RESULTS

The drainage survey shows that lead is the only element to occur in well-defined and high amplitude anomalies. Copper shows some agreement with lead but at much lower levels (560 ppm compared with 7500 ppm in the maximum sieved sediment anomaly) whereas zinc gives a very poor response in both sample types. However, subsequent drilling has shown that at depth sphalerite is widespread and very much more common than galena. This type of drainage anomaly where lead, contained in detrital grains of a secondary phosphate mineral, is predominant and zinc is largely absent indicates strong surface leaching. It is analogous to many anomalies derived from base metal mineralisation in France (Barbier and Wilhelm, 1978) where tundra climate was prevalent during the Pleistocene. Under these conditions it is unlikely that surficial geochemical sampling will give a true indication of the composition, nature and significance of the mineralisation.

SOIL GEOCHEMISTRY

INTRODUCTION

Soil sampling was undertaken in order to trace the source of the drainage anomalies around the head of Penkiln Burn. An initial sampling grid with an approximately 20 m × 20 m interval was laid out in the vicinity of the mineralised exposure south of Nick of Corner's Gale (Figure 3) and subsequently extended to cover an area of approximately 250 000 m^2. A lower density grid which had been laid out for geophysical measurements was used for the collection of further soil samples at an interval of 30 m × 50 m, covering a wider area, principally to the west of the headwaters of Penkiln Burn. Additional samples were collected over 2 km^2 of forestry plantations to the west of Penkiln Burn, and to the north of the ruined croft of Lamachan [4360 7449] within which area further drainage sample anomalies are located.

Full details of the soil geochemistry, including maps illustrating the distribution of copper, lead and zinc, are available for inspection at the Keyworth office of the IGS on application to the Head, Metalliferous Minerals and Applied Geochemistry Unit.

SAMPLING PROCEDURE, ANALYTICAL METHODS AND DATA PREPARATION

Both near surface A horizon and deeper B/C horizon samples were taken from several sites in an orientation survey around the exposed mineralisation. The analytical results from this survey showed a strong positive correlation between the two sample types, especially at anomalous sites. The most significant correlation was shown by lead but in general B/C horizon samples contained up to 50% higher levels at anomalous sites. The correlation was less evident at background levels of lead and most A horizon samples showed enrichment relative to the corresponding B/C horizon sample. Similar relationships were found between the sample types for zinc and copper, although the correlations were slightly weaker. Zinc was generally concentrated by up to 100% or more in the B/C horizon samples relative to the A horizon samples at both anomalous and background sites whilst copper showed a similar but less intense relative enrichment.

During the reconnaissance soil survey B/C horizon samples were taken whenever possible from depths up to 1.3 m using a hand auger. However, wide variation in overburden thickness and nature frequently prevented this and in places organic-rich material had to be collected. Both sample types were combined in the delineation of metal anomalies since the orientation survey had demonstrated a strong positive correlation between the two at anomalous sites. In addition the amplitude of the anomalies was high relative to the differences between sample types.

Table 2 Summary statistics for soil samples

Element	*Area**	*No. of samples*	*Max. level recorded ppm*	*Geometric mean ppm*	*Breaks ppm (percentile)*
Cu	N	878	1700	28	120 (97.5%)
	S	362	75	17	50 (97%)
Pb	N	878	11000	145	115 (40%), 330 (84%)
	S	362	670	83	130 (87%)
Zn	N	878	1900	70	85 (57%), 330 (97%)
	S	362	8600	69	54 (40%), 407 (99%)
Mn	N	367	2000	180	127 (30%), 650 (98.5%)
Ni	N	360	300	28	110 (97%)
Co	N	360	100	7.6	
Ba	N	160	944	228	160 (20%), 400 (98%)
	S	362	565	240	266 (30%)
As	N	160	185	48	89 (86%)
	S	362	418	34	
U	N	421	31	6.8	10.7 (86%)

*N = Northern area, poorly drained moorland
S = Southern area, artificially drained forestry plantation

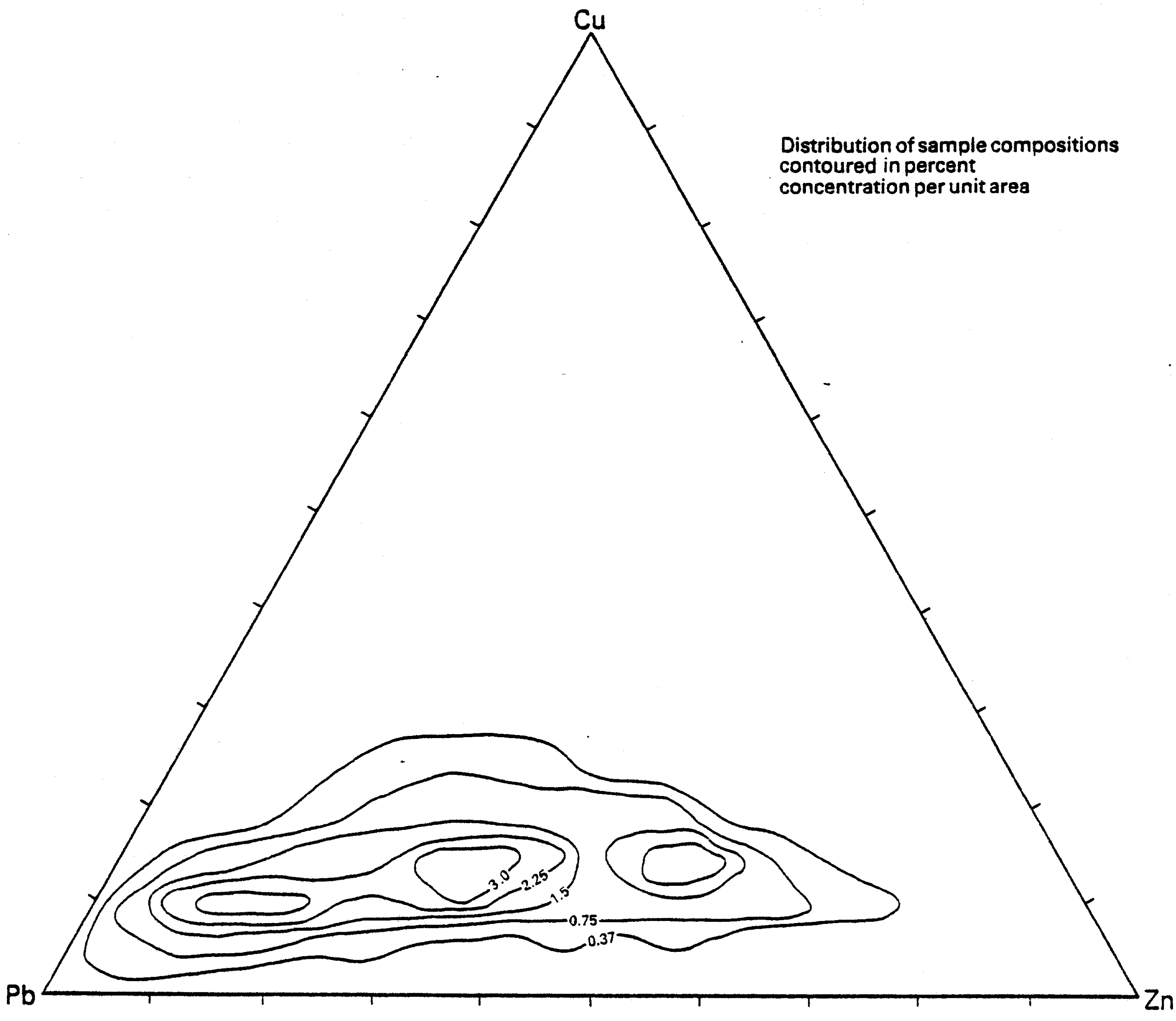


Fig. 14 Copper-Lead-Zinc in soil ternary diagram

The samples were dried in their bags, and then disaggregated before sieving to pass an 80 mesh BS cloth. The fine fraction was ground to approximately 200 mesh BS. For XRF analysis a 12 g subsample was taken to which 4 g of elvacite was added before grinding and pressing (Smith, 1971). The metals Cu, Pb, Zn, Ag, Ni, Co, Mn and Fe were determined by atomic absorbtion spectrophotometry whilst Ba and As were determined by XRF analysis.

The analytical results were collated by computer, and the locational data were added after transformation from user grid to National Grid coordinates. The positions of the samples in the forestry area were digitised from a Forestry Commission map of the fire-breaks, the output being National Grid coordinates. As the data distributions appeared to be lognormal, values were $\log_{10}$ transformed before statistical analysis. Apparent differences in element distribution were noted between samples from the poorly drained upland area and the artificially drained forestry plantations. The summary statistics are therefore presented separately in Table 2.

Correlation coefficients were calculated for the analyses from each area but were of limited value owing to the multimodal nature of much of the data. However, within each area lead correlates better with copper ($r = 0.44$–0.83) than with zinc ($r = 0.26$–0.49). Arsenic generally shows a good correlation with lead ($r = 0.53$).

A ternary diagram of Cu–Pb–Zn (Figure 14) illustrates the variation in base metal concentration. The data points lie in a narrow band of approximately constant gradient showing that the ratio of copper to zinc remains fairly uniform relative to the lead variation. This may reflect the greater mobility of copper and zinc in the soil.

DISCUSSION OF RESULTS FROM THE NORTHERN, UPLAND AREA

Around the headwaters of Penkiln Burn the uneven bedrock surface, in which abundant hollows are filled with peat and till, gives rise to varied sampling and geochemical dispersion effects. These have caused some local fluctuations in the magnitude of the observed metal values in overburden but these are small relative to the amplitude of the anomaly. Secondary concentration of mobile metals by iron and manganese oxides does not appear to be an important factor in the area.

Detailed examination of the results of the soil survey suggests that in the northern area two distinct anomaly trends are present. The dominant trend is approximately north–south and is best traced by the higher lead (Figure 15) and copper levels. An additional, albeit much weaker, north-easterly trend is also discernible, especially in zinc and when lower amplitude lead and copper anomalies are considered. The greatest amplitude soil anomalies tend to occur where the two anomaly trends intersect.

The main lead anomaly (Pb >330 ppm) is approximately linear and trends southwards from Nick of Corner's Gale for about 350 m (Figure 15). This follows the late north–south fracture zone in which mineralised gossan-like material is exposed and probably reflects the low temperature mineral assemblage (plumbogummite, beudantite etc) found there. The copper and zinc values also reflect this anomaly but the pattern of anomalous samples (Cu >120 ppm, Zn >315 ppm) is much less coherent. A similar but weaker anomaly pattern is developed coincident with another north–south fracture zone approximately 100 m west of Nick of Corner's Gale. The stream draining the main anomaly has redeposited mineralised material such that significant lead anomalies are found in alluvium up to 1 km downstream from the exposed mineralisation (e.g. [4444 7620], Figure 15 and [4424 7573], Figure 16).

The origin of the weaker, north-easterly anomaly trend is uncertain. It is approximately parallel to the regional strike and is spatially associated with the outcrop of black siliceous mudstone. However, there is no detailed correlation with local strike which departs considerably from the regional trend in the structurally broadened part of the mudstone outcrop (Figure 4) where there are also abundant minor intrusions. Locally the minor intrusions may influence the anomaly pattern, for example at [4437 7676], but the widespread nature of the low amplitude anomaly, especially that for zinc, makes it more probable that the NE–trending anomaly is associated stratigraphically with the black siliceous mudstone. Localised anomalies to the west of the main linear zone south of Nick of Corner's Gale may be partially the result of alluvial transport of mineralised material from the northern part of the black mudstone outcrop.

A curious feature of the anomaly pattern in the northern area is the extensive moderate lead anomaly to the north of Ellergower (Figure 15). At this point bedrock is covered by a considerable thickness of till and morainic material (probably >10 m) and the bulk of this material is greywacke derived from the south-eastern crags of Lamachan Hill where no signs of mineralisation are evident. The proximity of exposed black siliceous mudstone cut by numerous minor intrusions at Ellergower may be significant yet the anomaly apparently closes beyond the northern margin of the exposed rock.

DISCUSSION OF RESULTS FROM THE SOUTHERN, FORESTED AREA

Within the densely forested part of the Penkiln Burn area access is restricted and exposure is very rare. The field indications obtained, that almost all the area is blanketed by till, are confirmed by a study of pre-forestation aerial photographs, which also show that a large medial moraine ridge projects downstream from the south-east end of Ellergower (Figure 16). On most of the steeper slopes, towards the margins of the area sampled, bouldery colluvium overlies the till. Peat development is variable; over the lower, flatter parts of the area thicknesses of up to 1 m cover the till whereas on the colluvium-covered upper slopes peat is confined to the hollows between boulders.

The effects of artificial drainage and forestation have probably enhanced the leaching of mobile base metals from the shallow overburden. Thus the median concentration of copper is only two-thirds that obtained from the northern area; an unusually large difference even if the rocks underlying the southern area are assumed to be unmineralised. However, despite the enhanced leaching and an uneven sample density caused by the difficulties of access, several zones of moderately anomalous lead levels (115–330 ppm) were detected. These approximately coincide with the probable sub-overburden outcrop of the black siliceous mudstone (Figure 16). Some downslope displacement may have occurred in the most extensive anomalous zone around [4350 7525] but it is noteworthy that the highest zinc level recorded from either the northern or the southern area (8600 ppm) occurs at [4376 7509] in an area of shallow overburden very close to one of the few exposures of mudstone in the southern area. Similarly, on the southern side of Ellergower zinc concen-

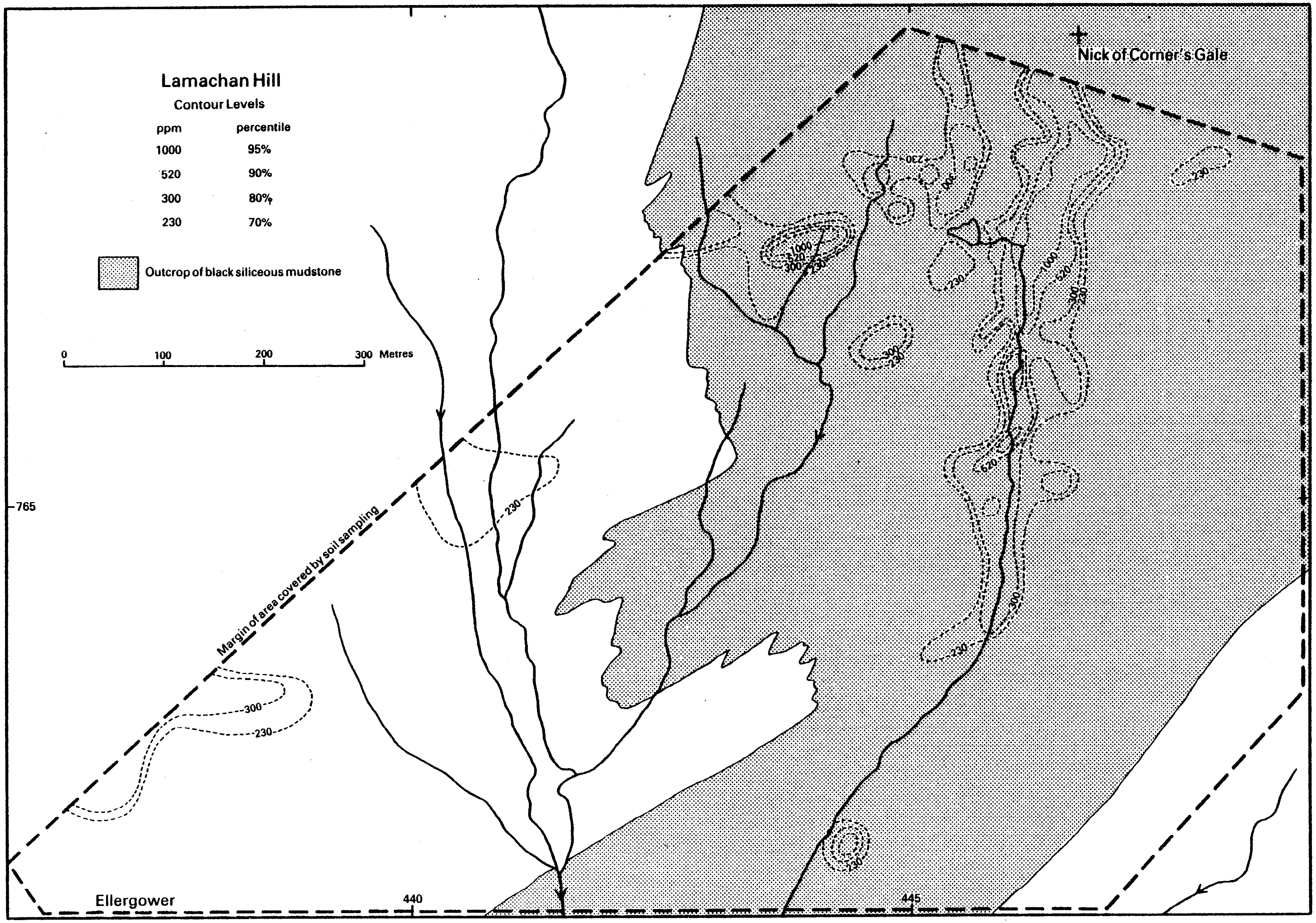


Fig.15 Lead in soil samples: northern area

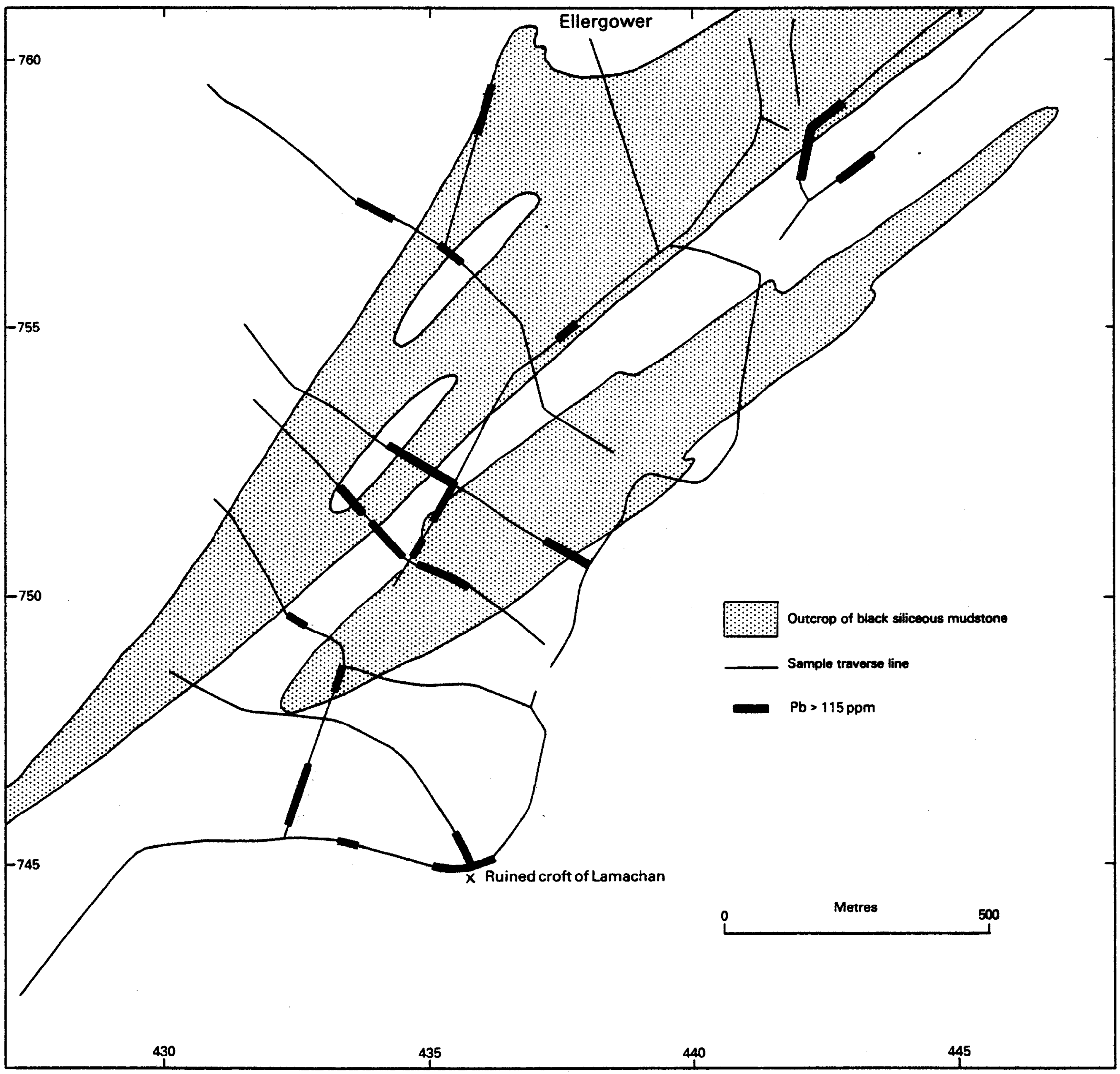


Fig. 16 Lead in soil samples: southern area

trations ranging up to 590 ppm lie close to an exposure of mudstone in an area of very thin overburden.

Anomalous levels of lead recorded in the vicinity of the croft of Lamachan (Figure 16) are more difficult to reconcile with the geology since the area concerned is covered by thick glacial deposits. There is no evidence for a close association with the black mudstone outcrop and it is possible that these anomalies are the result of either glacial or alluvial transport of mineralised material from the north.

CONCLUSIONS

The soil sampling programme has defined a major base metal anomaly, with lead as the dominant component, extending north and south from the exposed mineralised outcrop at the head of Penkiln Burn. At least 500 m of the fracture zone containing this mineralised outcrop may therefore be host to similar base metal enrichment. A second fault 100 m to the west of the fracture zone coincident with the main anomaly may be similarly mineralised. Beyond the margins of the main anomaly a generally high background level of lead and zinc produces a broad, low-amplitude anomaly trending north-east coincident with the outcrop pattern of black siliceous mudstone. Low grade mineralisation, in which zinc is probably dominant, may therefore be present over at least 2.5 km strike length of the black siliceous mudstone outcrop. The mineralising role of the abundant minor intrusions is uncertain but may be locally significant.

GEOPHYSICS

Magnetic and VLF surveys were carried out over the northern, unforested sector of the project area (Johnson, 1979). The irregular nature of the magnetic profiles obtained probably reflects the variable magnetite content and the complexity of the minor intrusions (Figure 7), many of which also contain pyrrhotite as an important accessory. VLF in-phase anomalies accurately define the southern and western margins of the electrically conductive, black, siliceous mudstone and shale outcrop but the results become more ambiguous northwards due to the influence of conductive clays within deep, drift-filled cirques. The area south of Nick of Corner's Gale (Figure 3) gave no significant geophysical response that could be reconciled with the exposed mineralisation, which is therefore presumed to be of limited depth extent. Full details of the geophysical surveys are held on Open File and may be inspected by arrangement with the Head of the Applied Geophysics Unit at the Keyworth office of the BGS.

MINERALISATION

OUTCROP

Disseminated pyrite and pyrrhotite is widely observable throughout the black mudstone sequence, but exposed base metal mineralisation is restricted to fault zones. The earliest described mineralised zone (Leake and others, 1978b) remains the largest known exposure. It occurs approximately 300 m south of Nick of Corner's Gale (Figure 3) and occupies 15–20 m of a north–south fault-controlled stream section. The orange-brown, highly altered rock is gossan-like in appearance. Mineralogical (Fortey and Easterbrook, 1976) examination showed it to contain a complex intergrowth of clay minerals and iron and lead secondary minerals, including kaolinite, gibbsite, illite, goethite, limonite, plumbogummite (Pb Al_3 $(PO_4)_2$ $(OH)_5.H_2O$) and beudantite (Pb Fe_3 AsO_4 SO_4 $(OH)_6$). Rare malachite has also been observed within this zone. Whole rock analysis of specimens from the main north–south fault zone (A1–3) and from a subsidiary east–west fracture system (B) gave the following results (in ppm):

	Cu	Pb	Zn	As	Ni	Ag	U	Hg	Cd	Au
A1	1800	45000	600	4000	90	7	54			
A2	2300	28000	900	3650	60					
A3				5000			55	0.13	1	<0.02
B	900	1380	580	260	60					

During geological mapping two more mineralised fault zones were located, both in relatively inaccessible areas beyond the limits of the detailed study (Figure 3). Both examples consist of highly altered doleritic rock within the fault zones. One exposure is situated about 80 m to the north of Nick of Curleywee (Figure 3) in a small waterfall. The dyke contained in the fault zone, which trends approximately north–south, has been altered to a soft yellow-brown material from which quartz, highly altered feldspar, goethite and a red, translucent mineral were isolated. When investigated by XRD methods (Fortey, 1976) a multiphase pattern indicative of quartz, clay minerals, possible monoclinic K feldspar and a plumbogummite–alunite–beudantite group mineral was obtained. The d-spacings suggest that the latter is probably plumbogummite (Pb Al_3 $(PO_4)_2$ $(OH)_5.H_2O$), gorceixite (Ba Al_3 $(PO_4)_2$ $(OH)_5.H_2O$) or crandallite (Ca Al_3 $(PO_4)_2$ $(OH)_5.H_2O$). Whole rock analyses of specimens collected across the mineralised zone (Figure 17) show a marked lead enrichment ranging up to 2.7% Pb in the centre of the altered dyke. The second mineralised exposure located lies at the top of the cliffs to the south-east of Lamachan Hill (Figure 3). Again a highly altered dolerite dyke within a fault zone is involved, but this exposure differs from the other two described in that the fault is a NE–SW strike fault and cuts across the greywacke sequence. The igneous rock has been extensively altered to an intergrowth of sericite, clay minerals, quartz, limonite and hematite, but the relict doleritic texture can still be seen in thin section. Whole rock analysis gave the following results (in ppm):

Cu	Pb	Zn	Ni	As
25	50	60	10	>10 000

However, no crystalline arsenic mineral was detected and it seems likely that the arsenic resides in the hydrated iron oxides (Fortey, 1981).

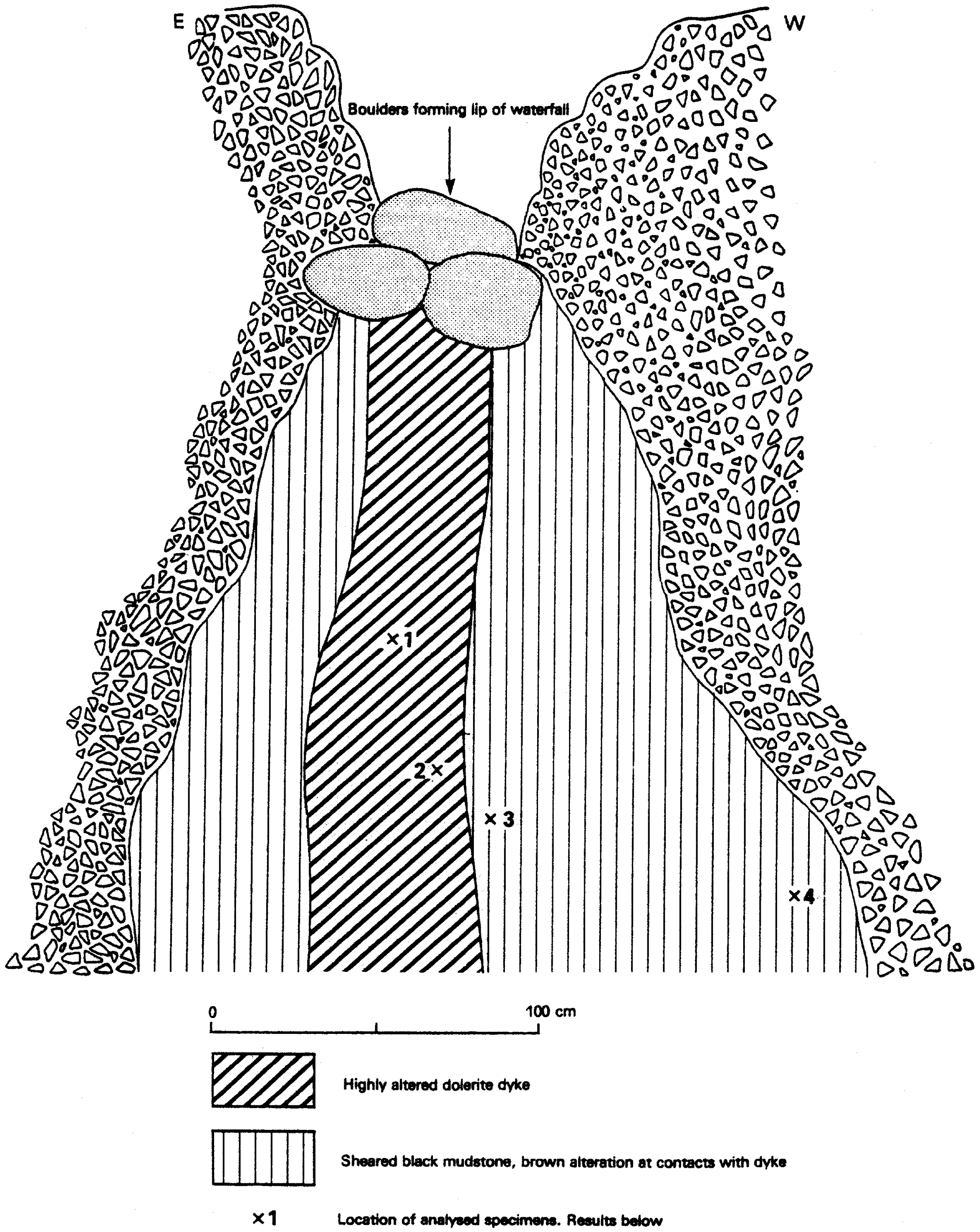
It is interesting to note that the lead-enriched dyke at Nick of Curleywee is only 1 km south of the known margin of Au-As-base metal mineralisation at Glenhead (Leake and others, 1981) whilst the arsenic-rich dyke at Lamachan Hill is approximately 2 km along strike from the Glenhead zone. At that locality concordant minor intrusions are believed to control the early phase of mineralisation.

BOREHOLE PROGRAMME

To investigate mineralisation at depth nine cored boreholes were drilled with inclined depths ranging from 15.3 to 114.9 m. All of the holes penetrated sequences of black siliceous mudstone, chert and greywacke cut by numerous doleritic intrusions. The core was examined petrologically (Fortey and Easterbrook, 1976; Fortey, 1981; Skilton, 1981), split and chemically analysed. Boreholes 1–4 were analysed for a range of elements by XRF methods; BHs 5–9 were analysed for copper, lead, zinc and nickel by atomic absorbtion spectroscopy and for arsenic by XRF. The location of the boreholes is shown in Figures 3 and 4, and positional and dimensional data are summarised in Table 3. Outline graphic logs of the boreholes, together with selected analytical data are shown in Figures 18–26.

Table 3 Positional data for Penkiln Burn boreholes

Borehole No.	*Depth m*	*Location NGR NX*	*Azimuth degrees*	*Inclination degrees*
1	33.2	4463 7668	345	78
2	17.6	4466 7676	335	74
3	22.9	4462 7665	313	75
4	15.3	4460 7661	115	70
5	57.8	4462 7671	340	70
6	48.0	4468 7689	340	70
7	45.10	4447 7526	315	65
8	45.75	4461 7641	315	65
9	114.95	4464 7670	315	65



Specimen No.	Cu	Pb	Zn	Ni	
1	650	27000	1150	100	ppm
2	540	5400	1350	100	ppm
3	45	800	80	10	ppm
4	55	20	70	150	ppm

Fig. 17 Analytical data from a mineralised outcrop seen in a vertical face at Nick of Curleywee

Penkiln Burn Borehole 1

Azimuth 345° Inclination 78°

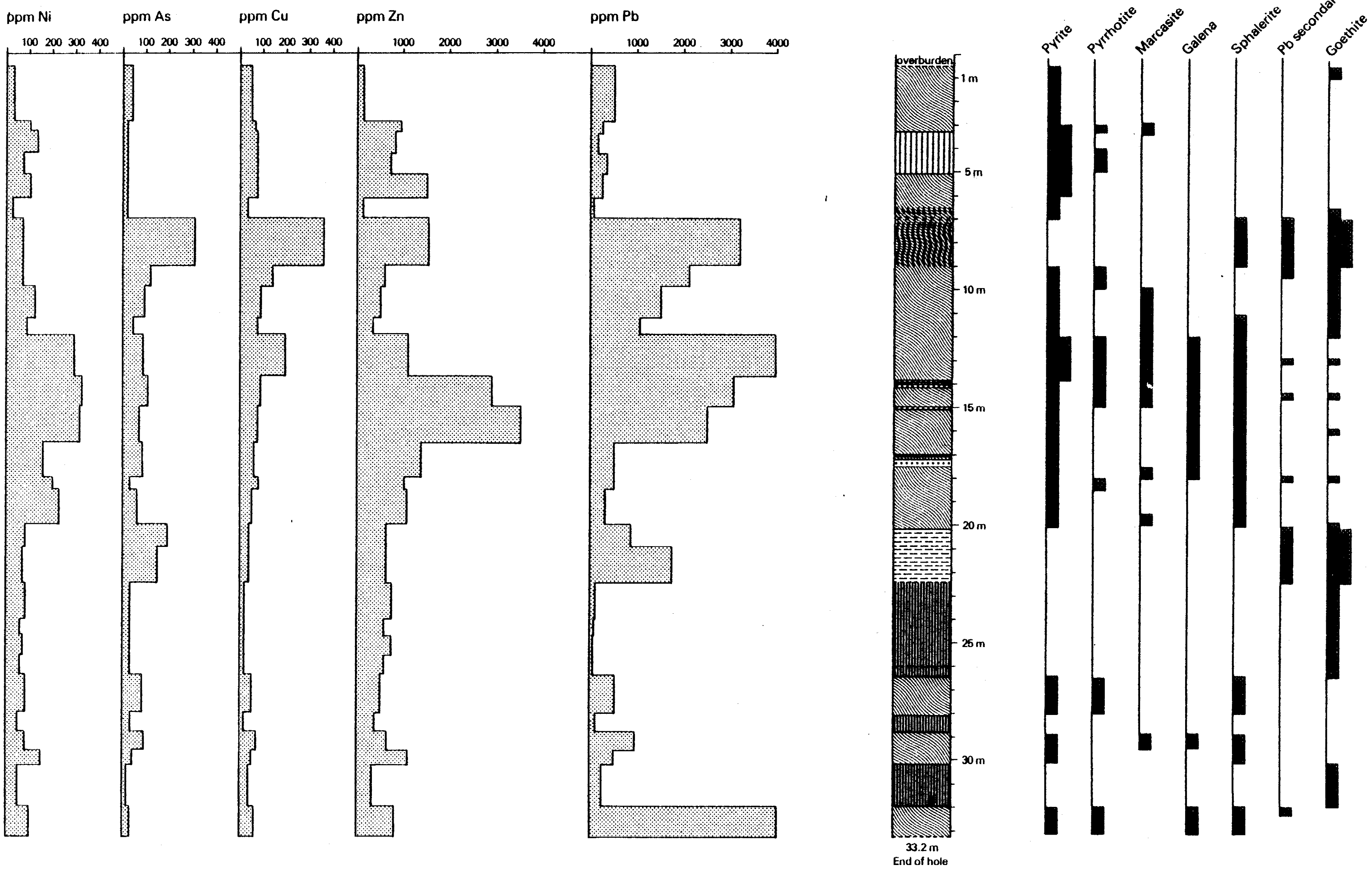


Fig. 18 Graphical log of Penkiln Burn Borehole 1 (For explanation see Fig. 21)

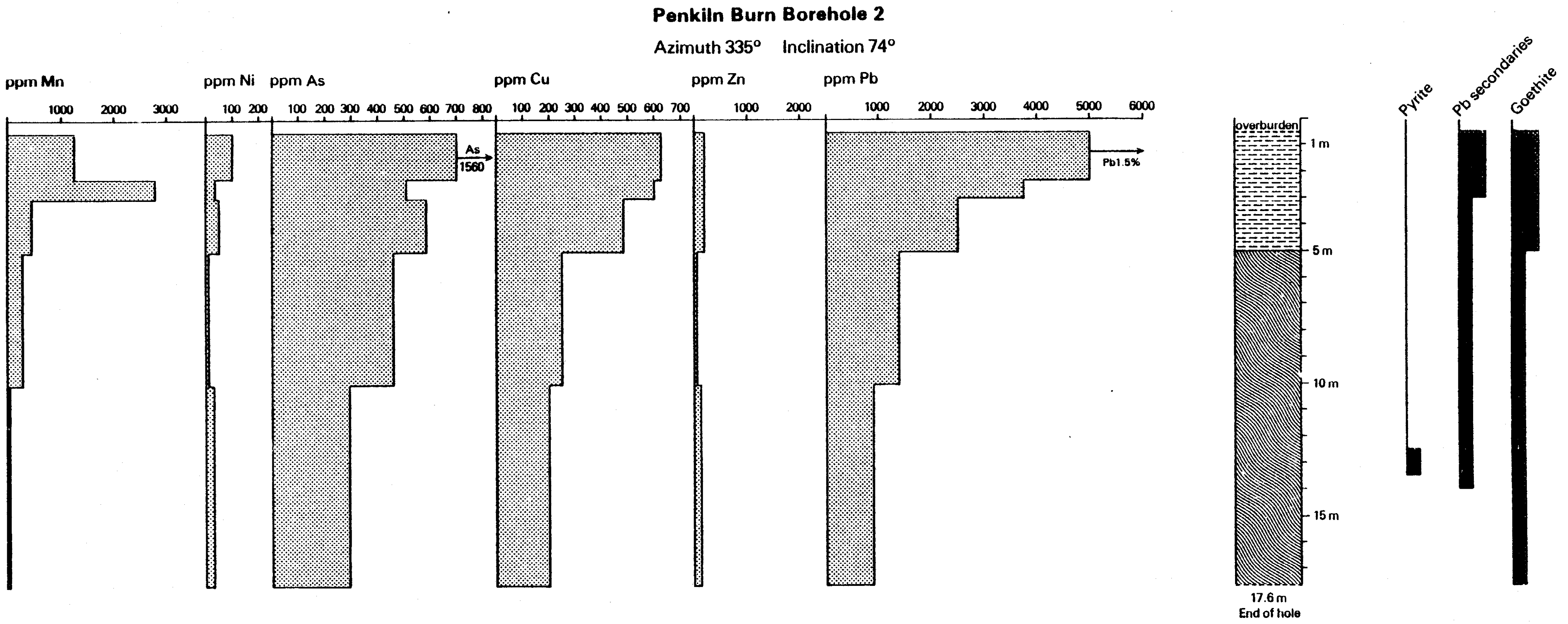


Fig. 19 Graphical log of Penkiln Burn Borehole 2 (For explanation see Fig. 21)

Penkiln Burn Borehole 3

Azimuth 313° Inclination 75°

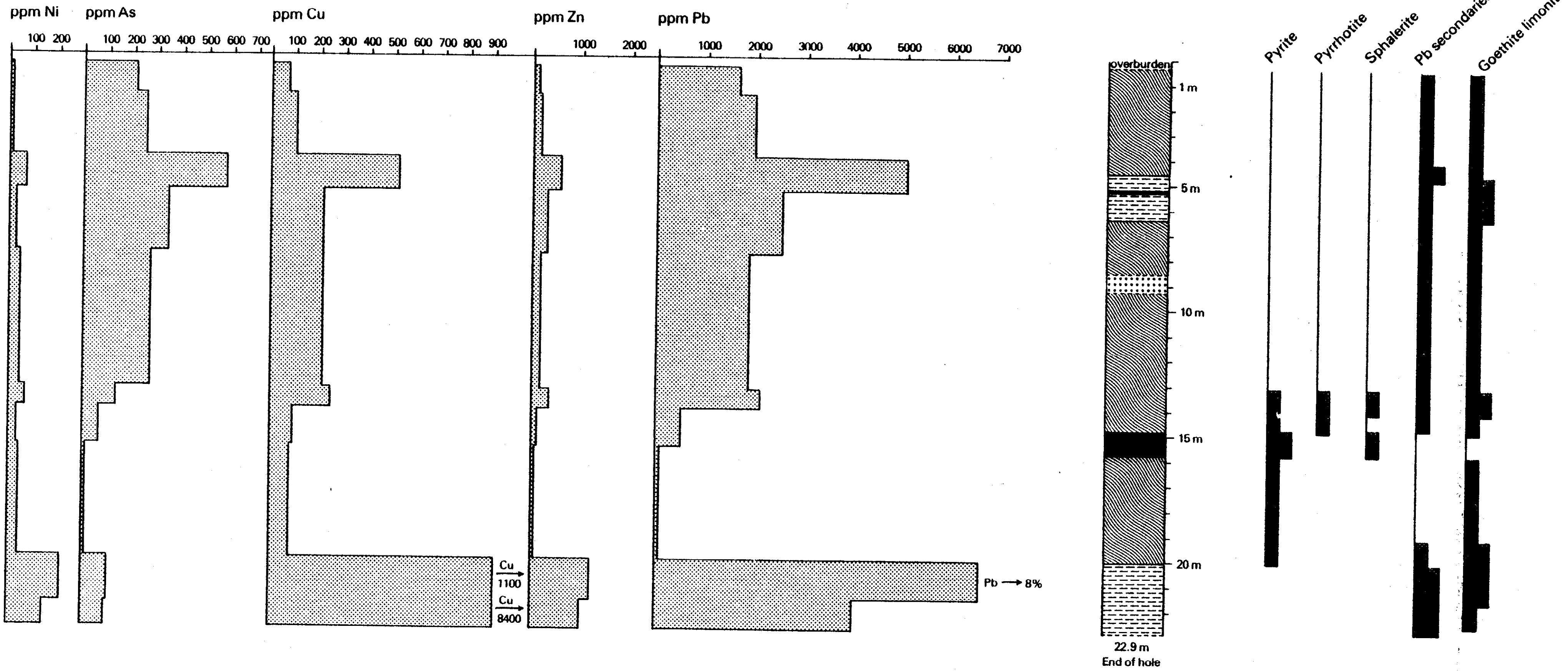


Fig. 20 Graphical log of Penkiln Burn Borehole 3 (For explanation see Fig. 21)

Penkiln Burn Borehole 4

Azimuth 115° Inclination 70°

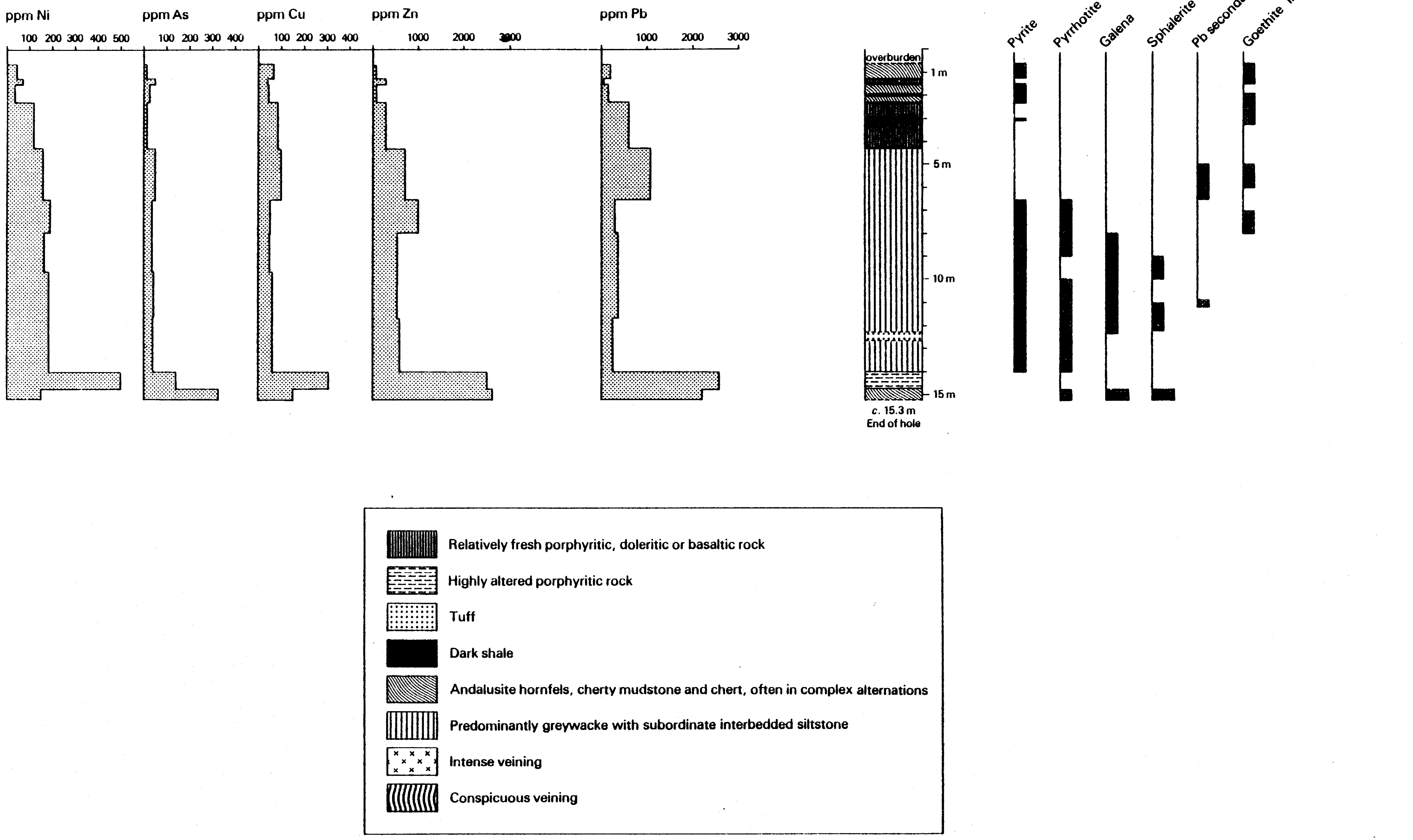


Fig. 21 Graphical log of Penkiln Burn Borehole 4

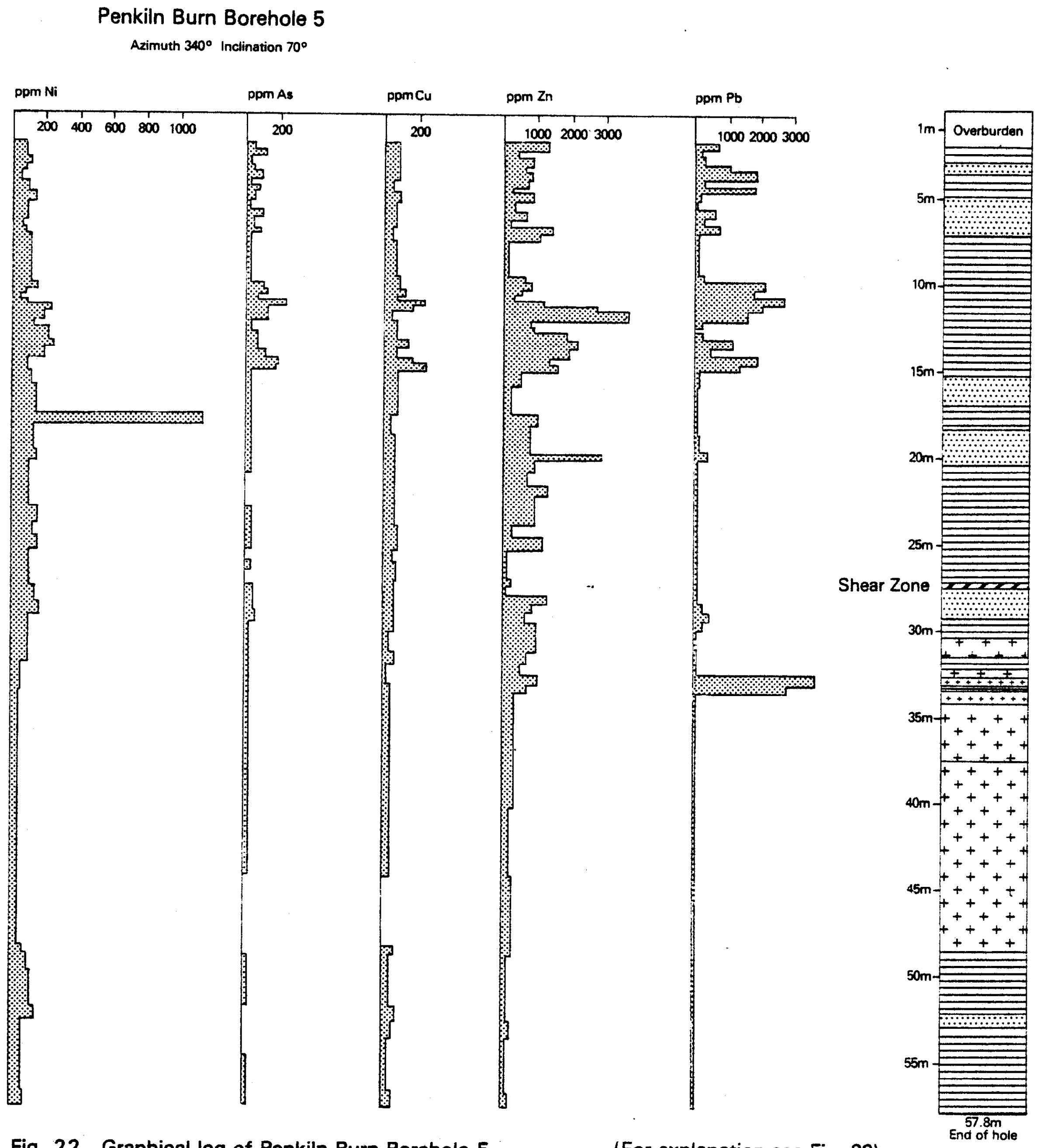


Fig. 22 Graphical log of Penkiln Burn Borehole 5 (For explanation see Fig. 26)

Penkiln Burn Borehole 6

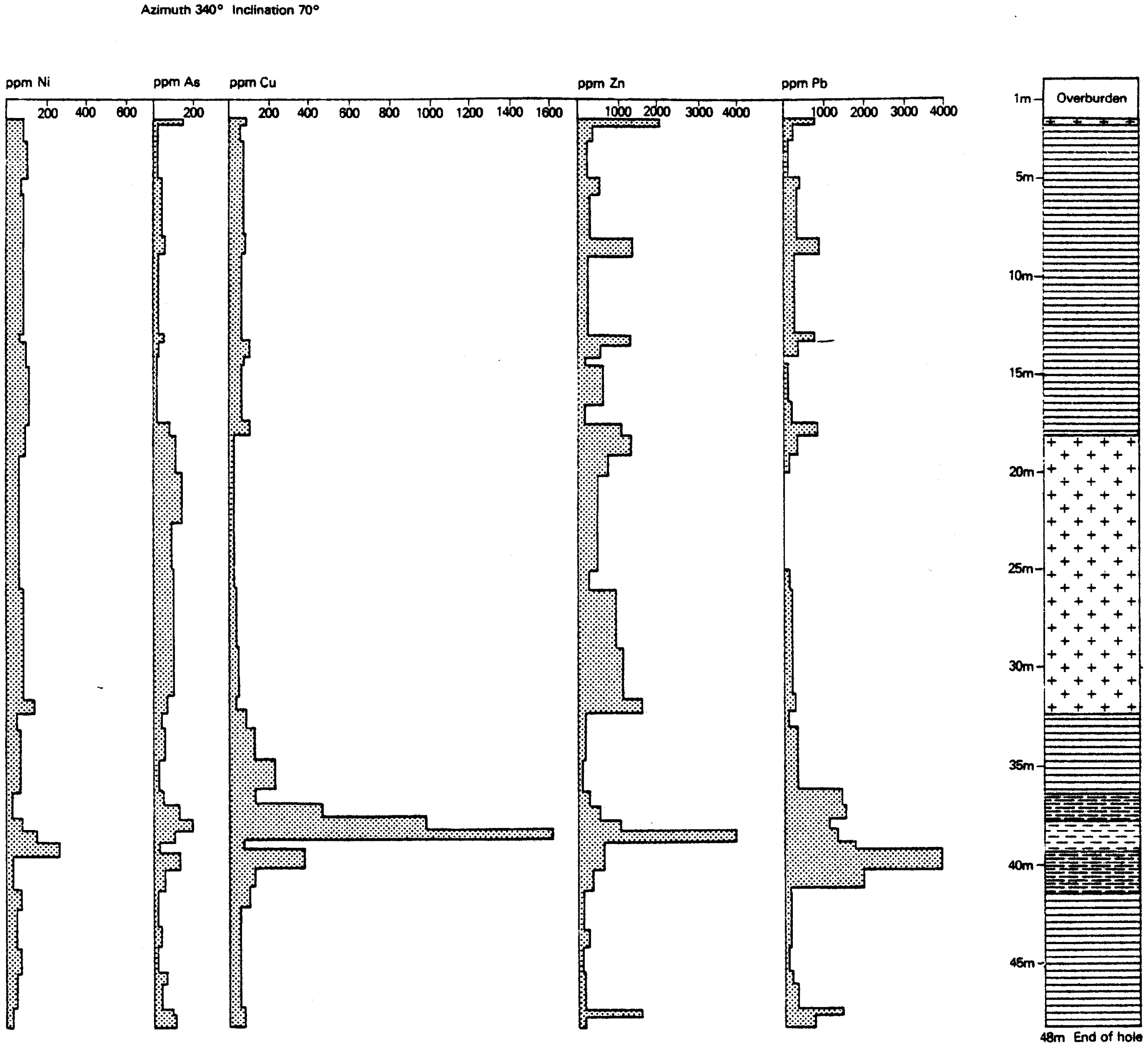


Fig. 23 Graphical log of Penkiln Burn Borehole 6

(For explanation see Fig. 26)

Penkiln Burn Borehole 7

Azimuth 315° Inclination 65°

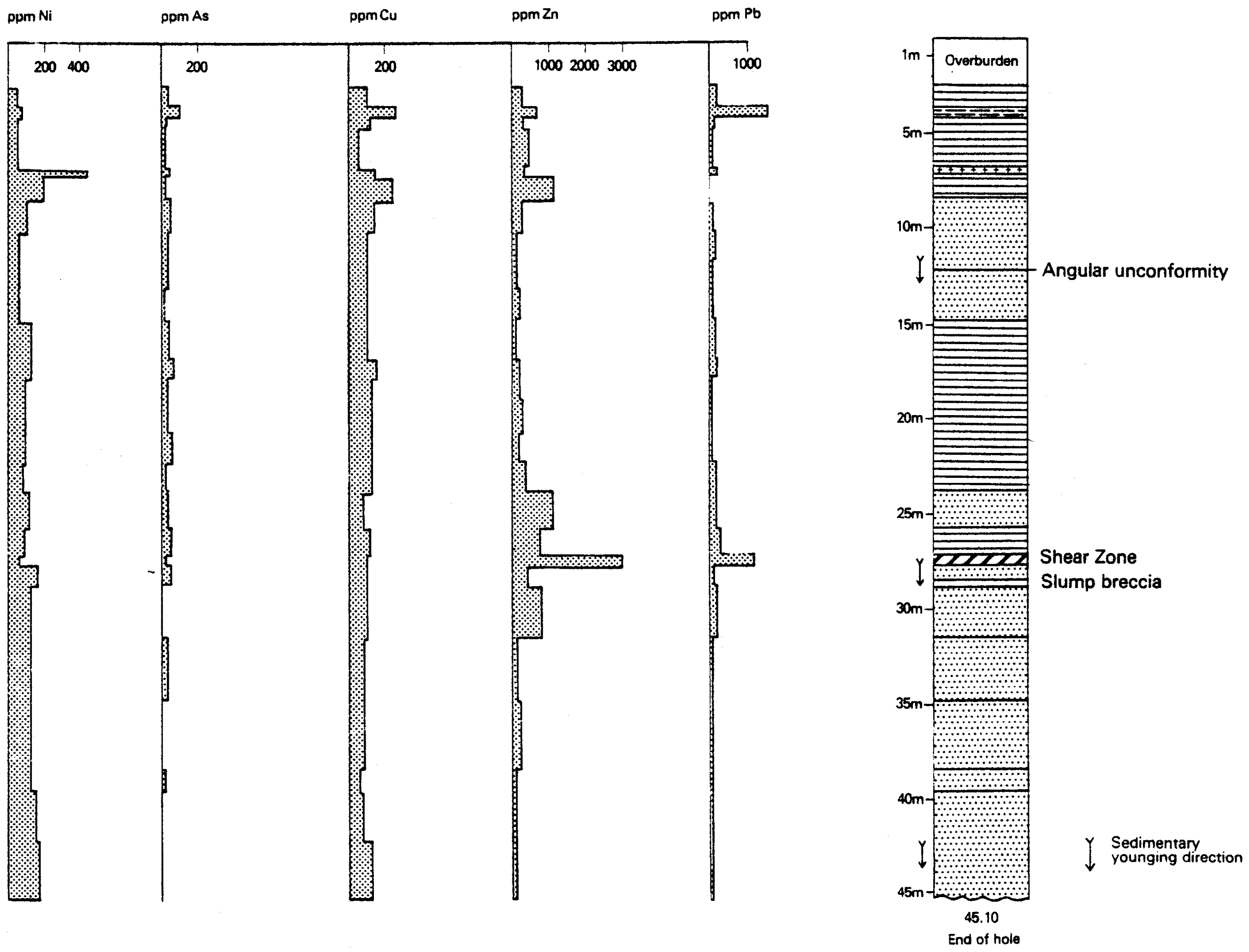


Fig. 24 Graphical log of Penkiln Burn Borehole 7

(For explanation see Fig. 26)

Penkiln Burn Borehole 8

Azimuth 315° Inclination 65°

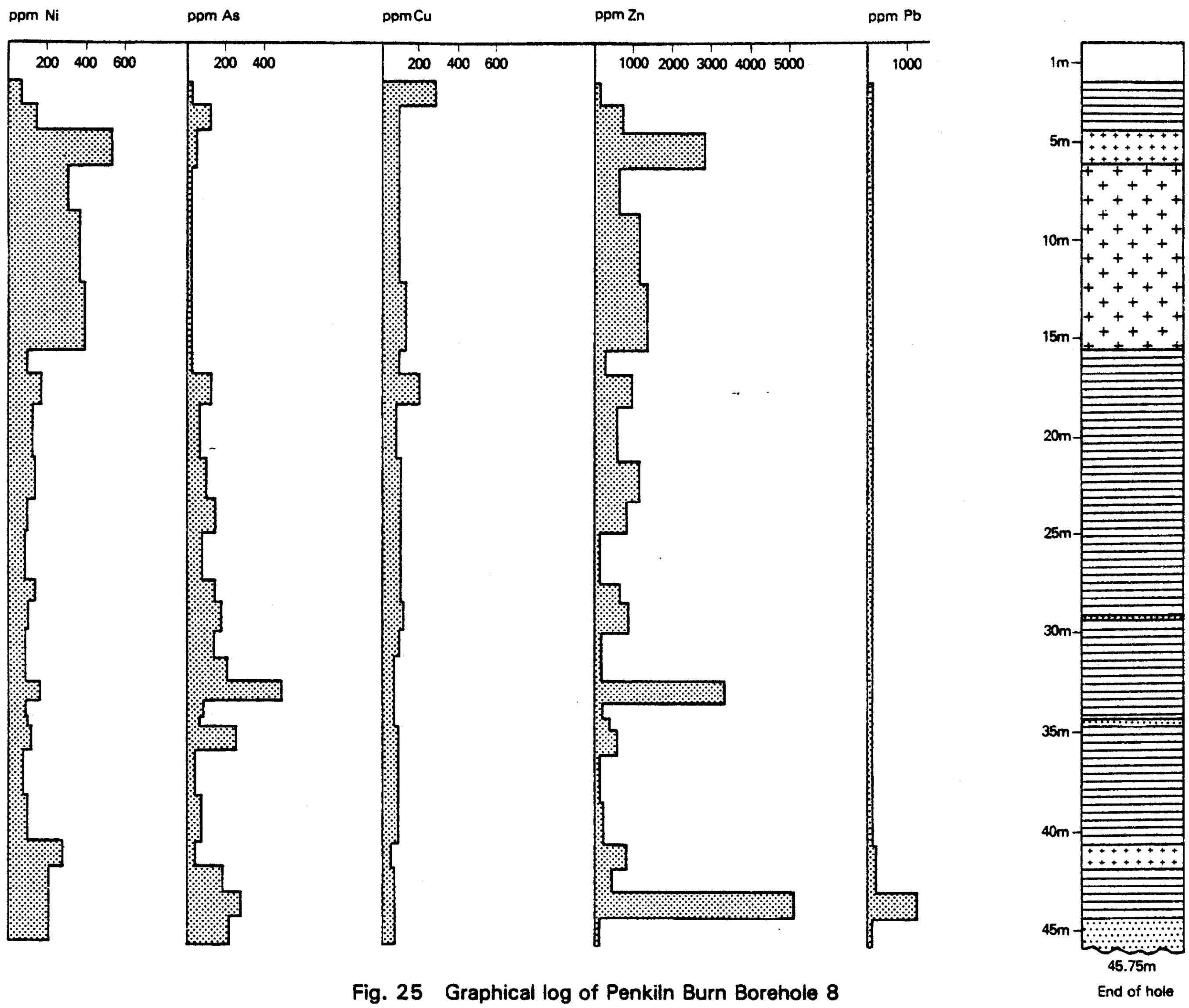


Fig. 25 Graphical log of Penkiln Burn Borehole 8

(For explanation see Fig. 26)

During the first phase of drilling, Boreholes 1-4 were sunk into the main geochemical soil anomaly at the head of Penkiln Burn (Figure 14) in the vicinity of the mineralised north–south fault zone. The encouraging results obtained were followed-up by a second phase of drilling with two objectives; to penetrate deeper into the zone already drilled (Boreholes 5 and 9) and to investigate weaker soil anomalies both along the fault zone (Boreholes 6 and 8) and along strike within the black shale belt (Borehole 7).

DISSEMINATED MINERALISATION IN SEDIMENTARY ROCK

The most widespread style of mineralisation recognised is the dissemination of sphalerite, pyrite, marcasite, pyrrhotite, rare chalcopyrite and covellite and possibly some galena through much of the black mudstone sequence. The possibility that significantly different mineralised populations are present is indicated by the contoured graphical plot of Zn:Pb shown in Figure 27. The unmineralised rock specimens form a well-defined compositional group at approximately 120 ppm Zn and 30 ppm Pb, fairly typical values for a mudstone-dominated distal turbidite succession (Turekian and Wedepohl, 1961). The mineralisation is not apparent as an enriched 'tail' to the unmineralised specimens but shows two quite separate peaks. One shows Zn enrichment to about 1000 ppm with no increase in Pb whilst the other shows a similar Zn increase accompanied by the elevation of Pb levels to around 300 ppm. In both cases Zn:Pb ratios are usually >2:1. The extension of the Zn + Pb enriched field by Pb levels rising to about 1000 ppm, and indeed part of the main peak itself could well be caused by the presence of very fine veins and alteration zones in the sediment, a separate style of mineralisation which will be discussed in section 5 below.

The Zn and Zn + Pb variations of the disseminated mineralisation have no stratigraphical significance and were found to alternate in BHs 1-5 and 7, although in BH 7 mineralisation is significantly less. The Zn enrichment only was encountered in BH 8 whilst the Zn + Pb variation only was encountered in BHs 6 and 9.

The presence of disseminated copper and arsenic

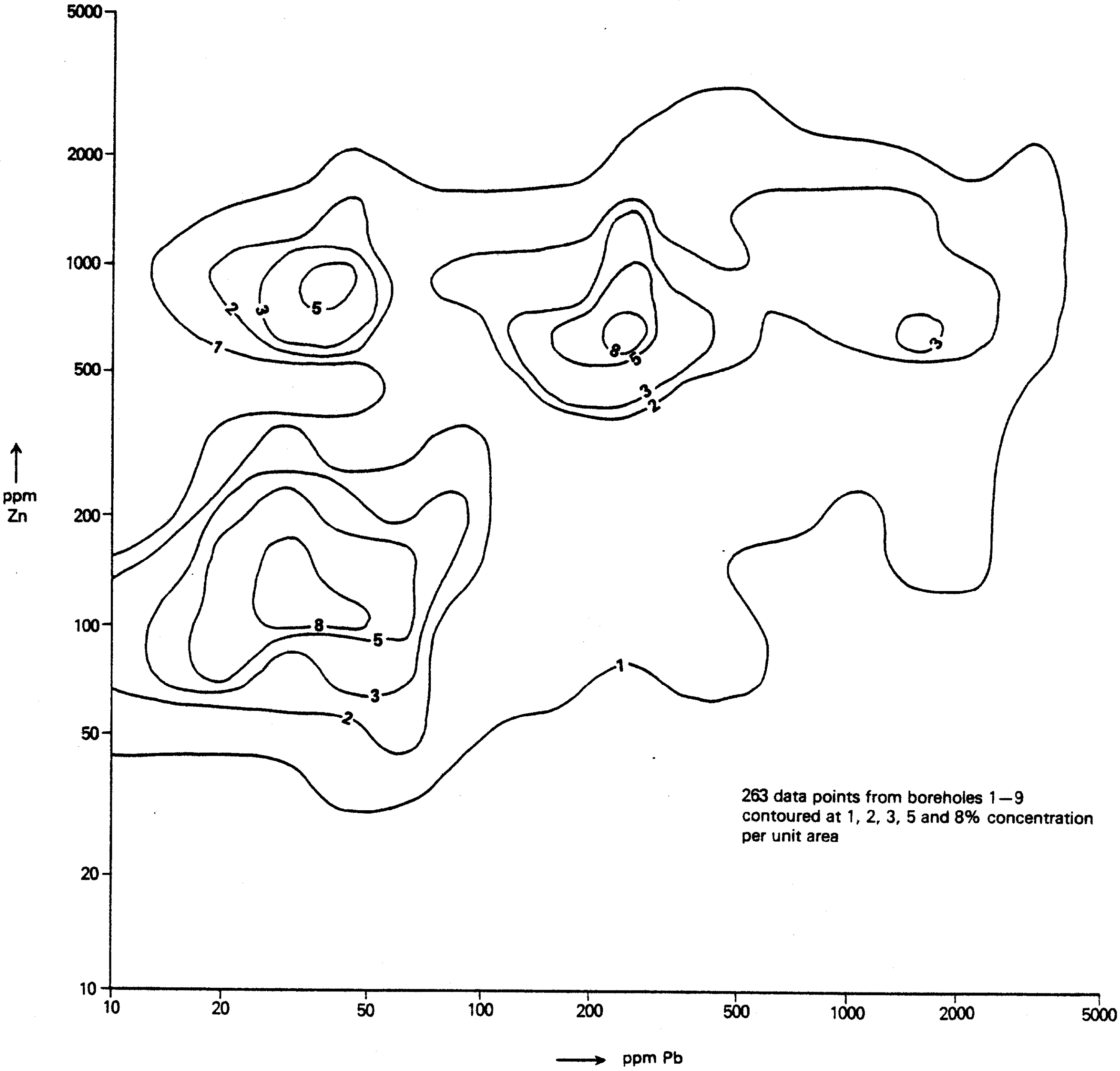


Fig. 27 Zn and Pb levels in the distal turbidite sequence

mineralisation in the turbidite sequence is illustrated by the contour plot in Figure 28. Again a well-defined group of unmineralised rocks with background contents of Cu ≃ 70 ppm and As ≃ 20 ppm is apparent. Extending from this is a field of joint Cu and As enrichment to about 400 ppm and 200 ppm respectively, but of greater interest is the As enrichment with no corresponding increase in copper (notwithstanding one specimen showing the reverse trend) manifest in BH 8. Since this borehole produced nothing but specimens showing Zn only enrichment (Figure 27) it is possible that a third disseminated mineralisation variety exists; namely Zn + As. However, no crystalline source for the arsenic was identified and as the mudstone in BH 8 contains many very fine veins, it is also possible that the arsenic enrichment may be part of the vein mineralisation (see section 5 below). Further, it may be significant that BH 8, unlike the other boreholes around the head of Penkiln Burn, is situated outside the hornfelsed zone at the margin of the Loch Doon pluton.

In BHs 1, 3 and 4 the probable tuff horizons contain considerably greater than average amounts of zinc and lead, both of which range up to 3000 ppm (Figure 29), and are slightly above average in arsenic (Figure 30). The tuff horizons also differ from the turbidite sequence in having a greater abundance of Ca, Ti, Mn, Fe, Co and Ni (Table 4) but this, in part at least, reflects the increased basic volcanic component in these rocks.

Significantly, in the same area, BH 9 encountered two horizons of chert both of which are considerably enriched in lead (290 and 1040 ppm) and zinc (1120 and 3900 ppm) and are marginally above average in copper and arsenic (Figures 29 and 30). These chert horizons are host to abundant finely disseminated sulphide minerals, including pyrite and sphalerite, and are interbedded with mudstone containing fine, stratiform pyrite laminae over approximately 20 m of core (Figure 31). The whole assemblage is highly suggestive of synsedimentary, exhalative mineralisation. The same process could possibly be responsible for all of the widespread disseminated mineralisation observed.

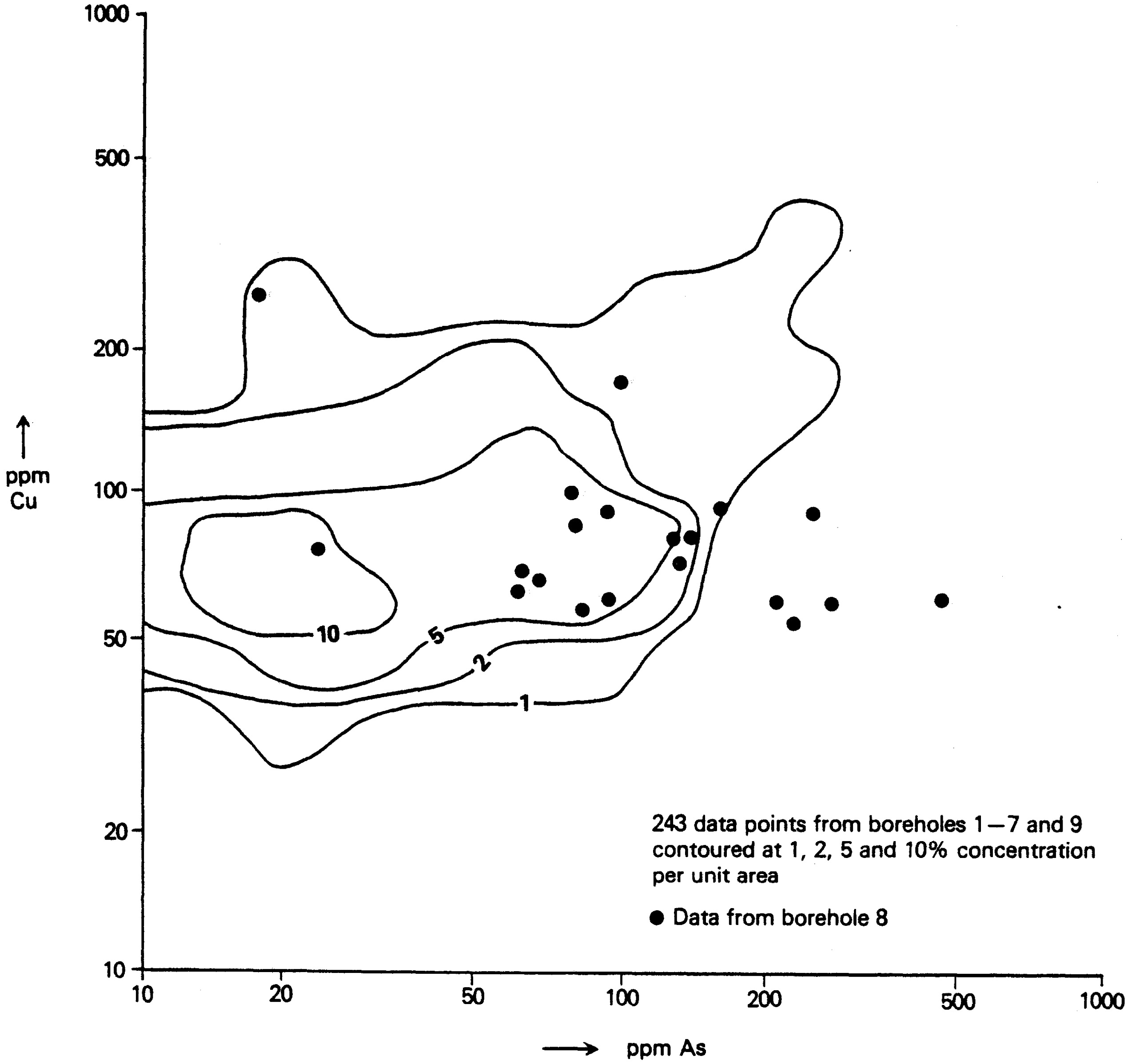


Fig. 28 Cu and As levels in the distal turbidite sequence

Table 4 The metal content of typical distal turbidite lithologies compared with the metal content of similar unveined sequences containing tuffaceous horizons.

	Normal turbidite (n = 8)		*Turbidite with tuffaceous horizons (n = 5)*	
	Mean	*Range*	*Mean*	*Range*
CaO%	0.11	0.05–0.32	1.20	0.55–1.77
TiO_2%	0.71	0.67–0.74	0.87	0.82–0.91
Mn ppm	211	140–280	572	410–740
Fe_2O_3%	4.26	3.87–5.45	7.51	6.94–7.96
Co ppm	26	10–40	56	40–80
Ni ppm	88	25–135	248	160–330
Cu ppm	57	25–75	71	28–112
Zn ppm	823	130–1500	1970	1000–3500
As ppm	30	17–79	70	28–112
Pb ppm	303	50–550	1384	320–3500

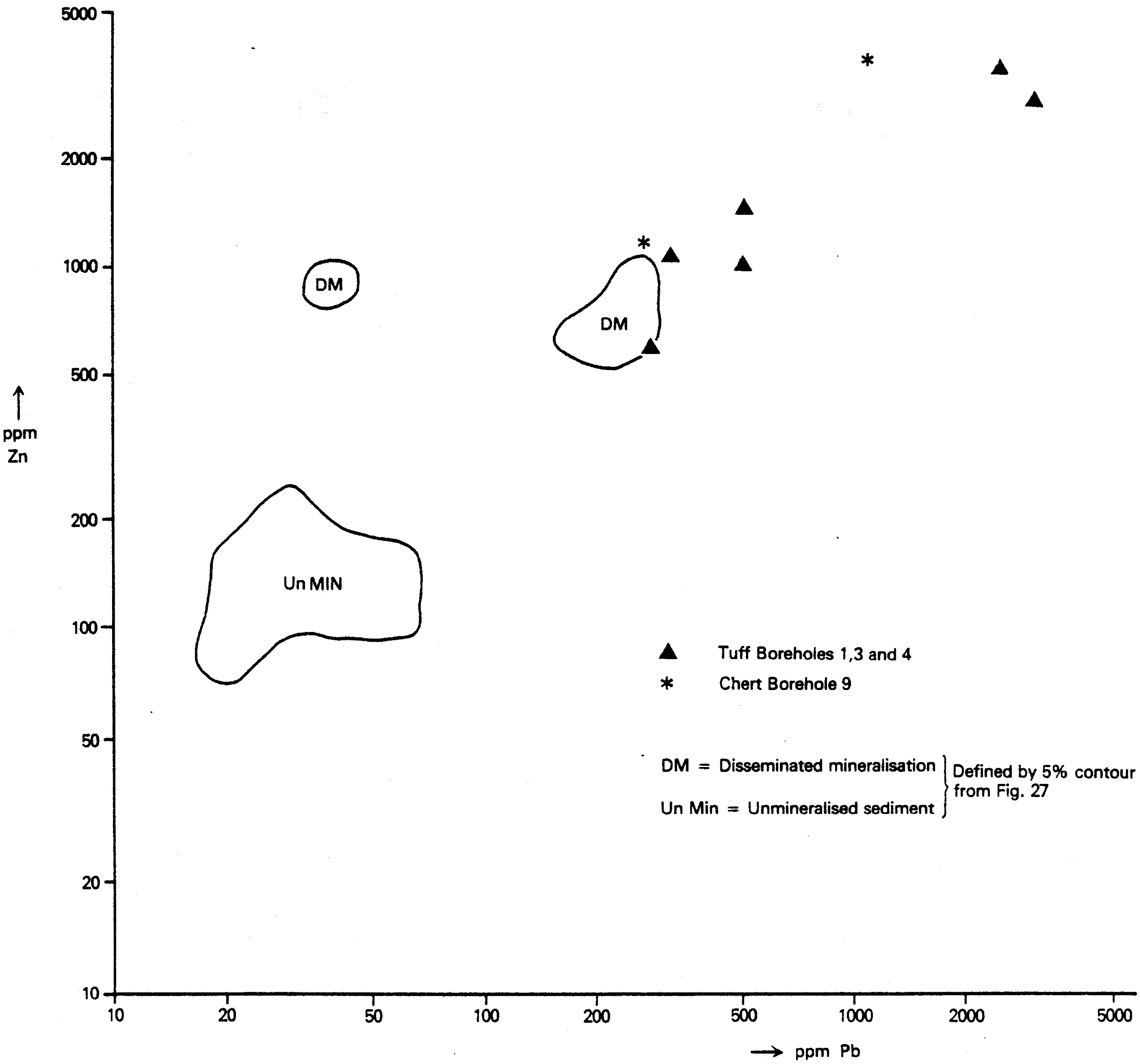


Fig. 29 Zn and Pb levels in tuff and chert

MINERALISATION IN MINOR INTRUSIONS
A considerable range of metal values is shown by the fresh, unaltered minor intrusions cored (Table 5). Most are significantly higher in lead and zinc than normal doleritic rocks (Figure 32), the most consistent enrichment being shown by minor intrusions from BH 6 where lead ranges up to about 800 ppm and zinc to about 2000 ppm. Copper levels are about average or slightly deficient (Figure 33) with one notable exception in BH 3 where 8400 ppm was recorded. Finely disseminated sulphides were detected in several specimens and are probably the cause of the base metal enrichment. Very slightly enhanced arsenic levels are apparent in most of the minor intrusions (Figure 33), samples from BH 6 consistently showing the highest levels. Minor intrusions from BH 6 are thus the most mineralised of those sampled and show higher than normal levels of lead, zinc and arsenic. It may be significant that of all the boreholes number 6 was the closest to the proven Au-As-base metal mineralisation at Glenhead, 1.2 km farther north, where minor intrusions are thought to be a major control (Leake and others, 1981). However, at Glenhead the base metal mineralisation is always associated with calcite veining whereas all of the lithologies in the Penkiln Burn area are generally poor in carbonate.

Nickel enrichment is apparent in some of the dykes and may be caused by an increase in the pyrrhotite content. In BH 8 nickel values range up to about 500 ppm and are accompanied by higher than normal levels of zinc. Both metals increase in quantity towards the margins of the intrusion and this mineralisation may be of a different style since the minor intrusions from BH 8 are noticeably higher in zinc, nickel and copper but lower in lead and arsenic than the intrusions elsewhere (Figures 32 and 33).

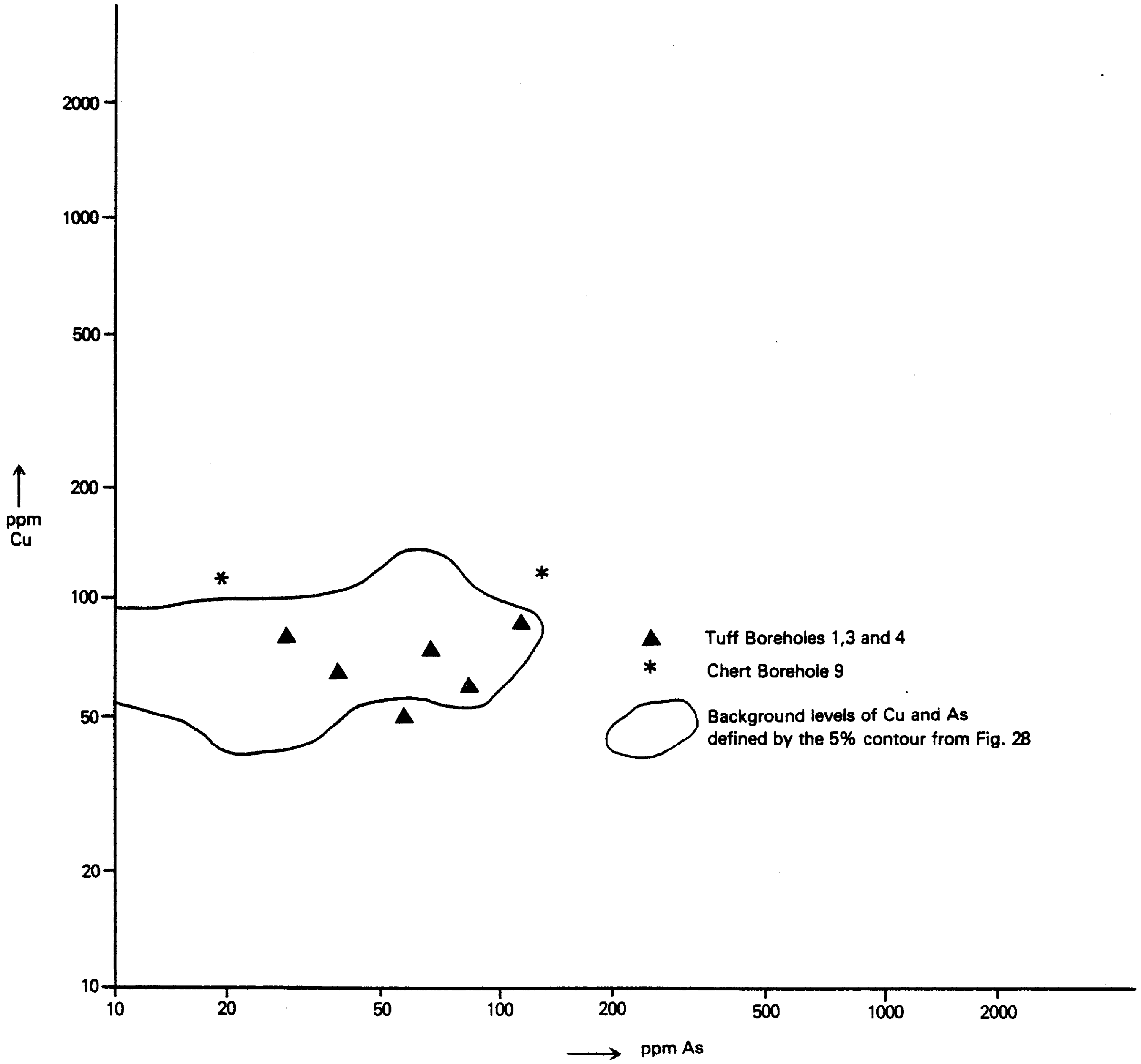


Fig. 30 Cu and As levels in tuff and chert

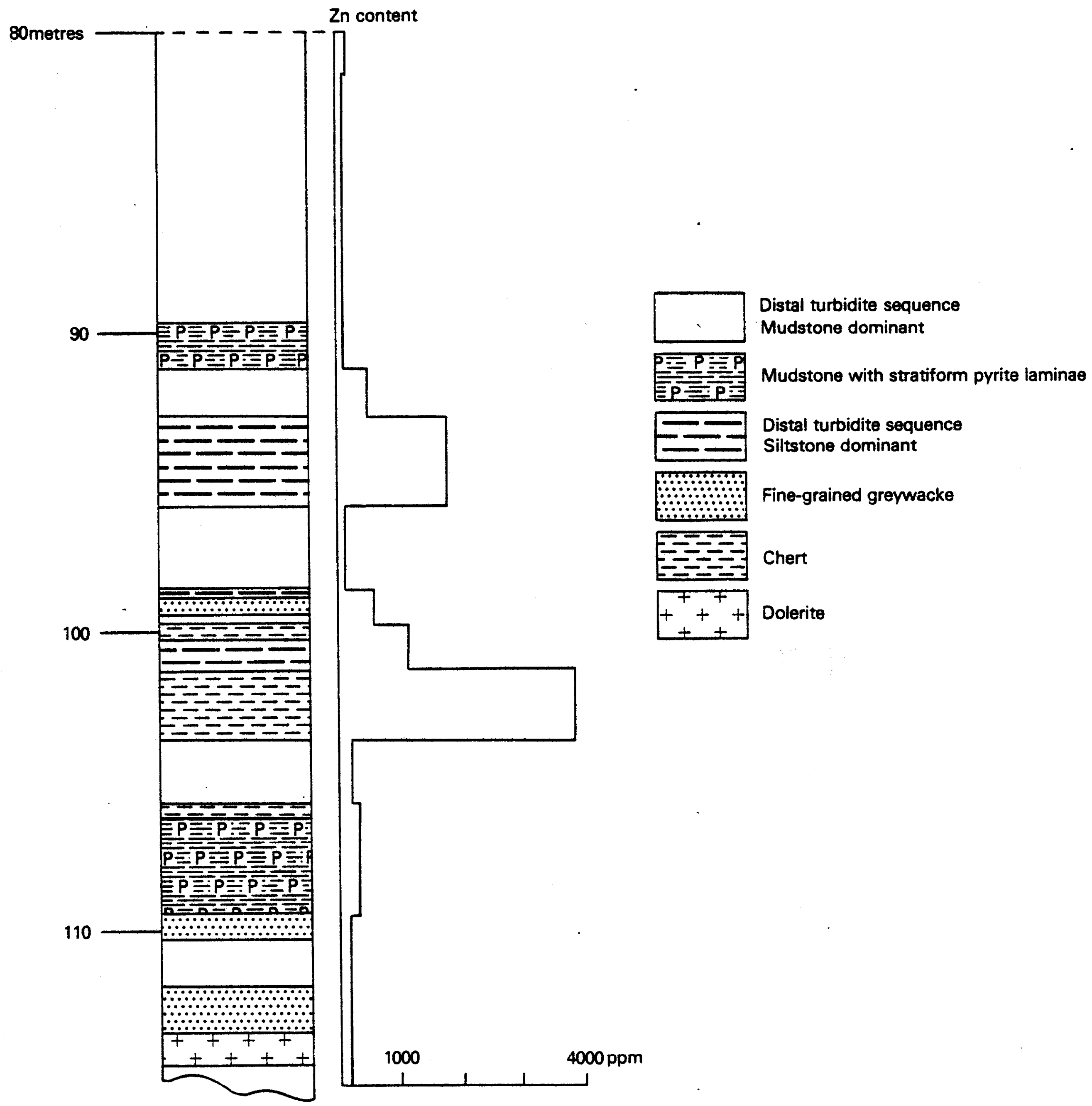


Fig. 31 Zinc enrichment in chert and siltstone associated spatially with stratiform pyrite laminae at the base of Borehole 9

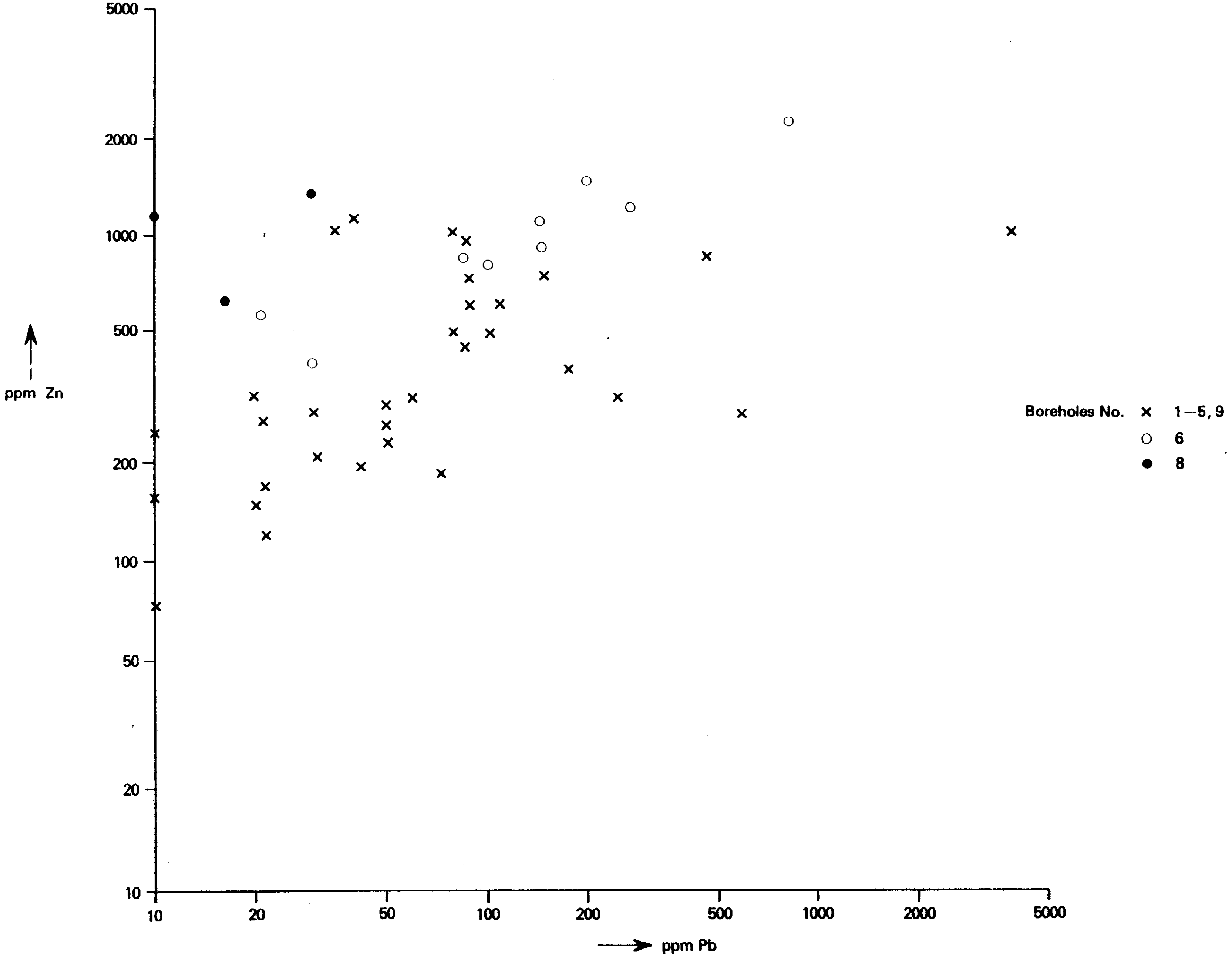


Figure 32 Zn and Pb levels in fresh dykes

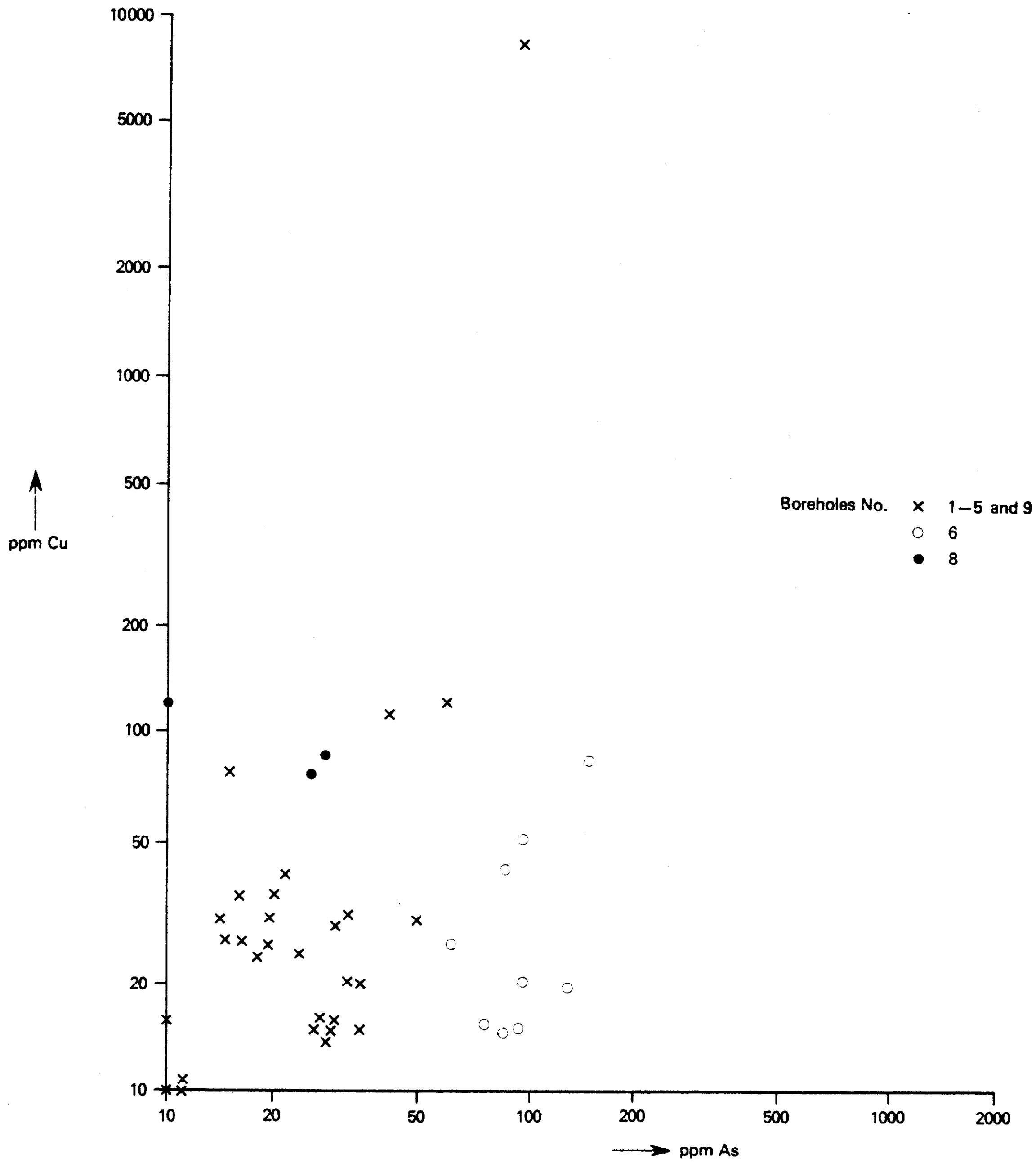


Figure 33. Cu and As levels in fresh dykes

MINERALISATION RELATED TO VEINING AND ALTERATION

In some exposures and throughout the borehole core fine veinlets, usually < 1 mm thick, cut the mudstone sequence and to a lesser extent the minor intrusions. The veinlets consist predominantly of quartz and minor K-feldspar but some also carry accessory pyrite, marcasite, pyrrhotite, sphalerite or galena. Rarer sulphide minerals amongst the vein constituents are chalcopyrite and covellite. The most economically important sulphides within the veinlets are galena and sphalerite, the former occurring as fine dustings within some of the thicker quartz veins whilst the latter is found both within the quartz veins and as discrete stringers. Alteration of the veinlets is widespread, with clay minerals, limonite and hematite forming the bulk of the rock in some heavily veined zones. Despite the alteration sphalerite, galena, pyrite, marcasite and rare malachite have all been recognised in highly altered, clay-rich veins. The clay is probably derived from the alteration of feldspar in the veins but it is difficult to decide whether this alteration involved further addition or subtraction of metals. Minor intrusions which have been extensively veined and altered contain significantly more potassium, iron and lead and much less calcium and sodium than the unaltered rocks (Table 5) but results from the sediments are ambiguous.

The igneous and sedimentary rocks containing abundant veining form a distinct population in terms of lead and zinc content (Figure 34). Lead levels reach 7000 ppm, significantly greater than those shown by specimens containing only disseminated mineralisation, but zinc levels are, on average, only slightly higher than those shown by the disseminated mineralisation. The copper and arsenic content of the veined and altered sedimentary rocks are generally only slightly higher than those for specimens showing only the disseminated mineralisation (Figure 35). A possible exception is seen in BH 8 where the source of high arsenic levels in mudstone carrying abundant fine quartz veins was not established. The arsenic may thus be associated with either the

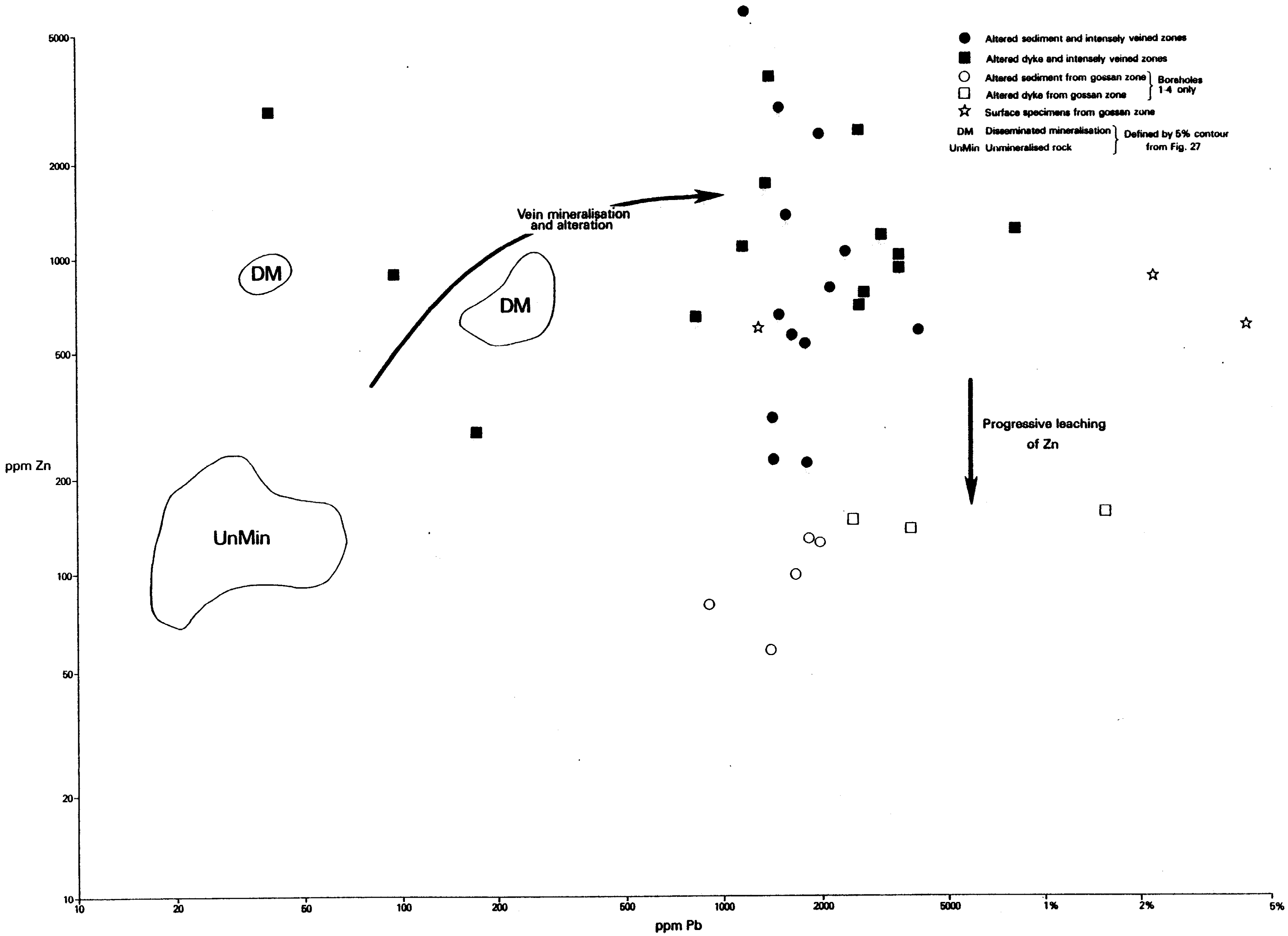


Fig. 34
Zn and Pb levels in altered rock

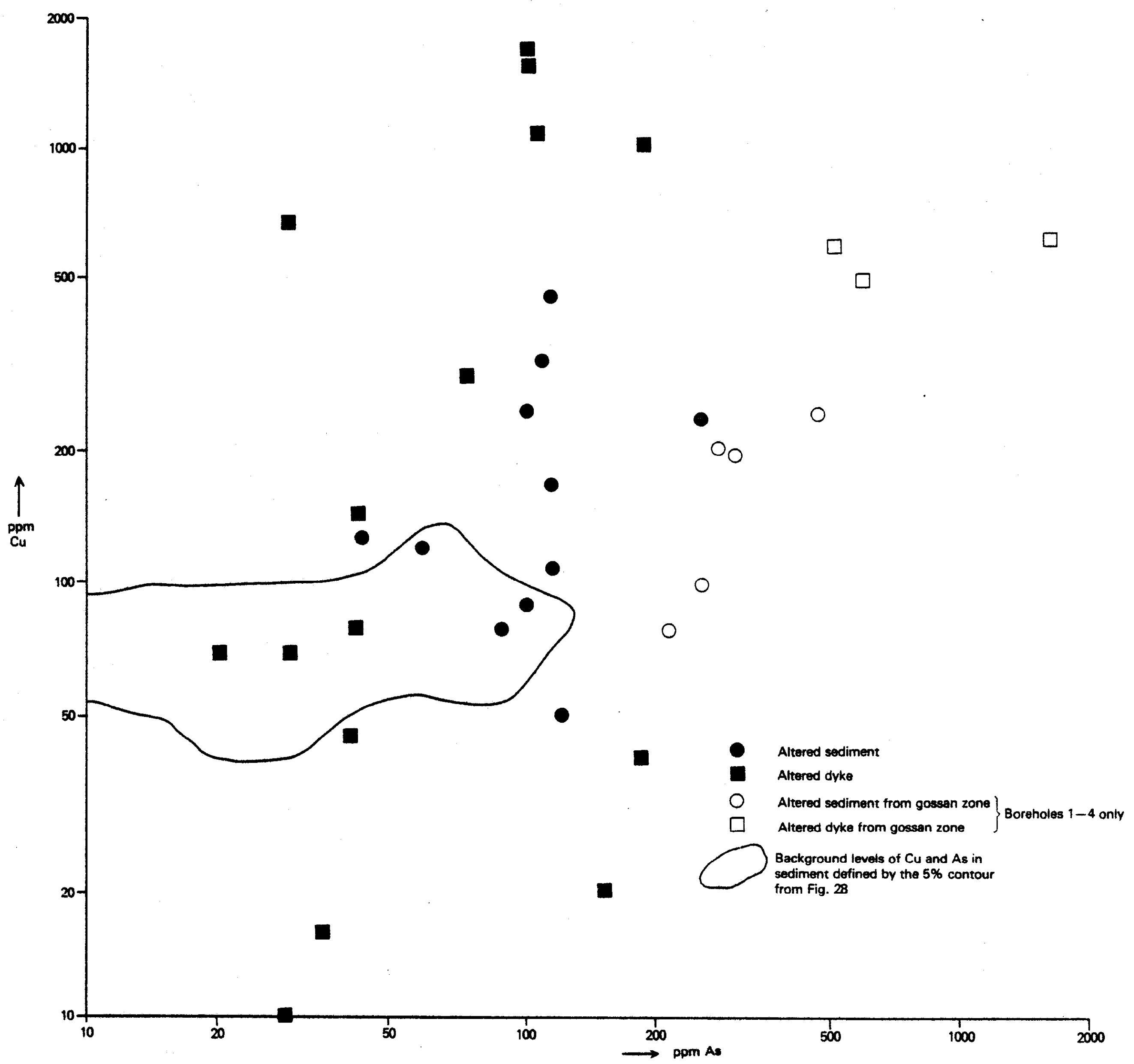


Fig. 35 Cu and As levels in altered rocks

disseminated or the vein mineralisation. In the igenous rocks copper content in particular shows great variability (Figure 35). However, the specimens containing the highest levels of copper recorded are adjacent to fresh igneous rock containing 8400 ppm Cu and so may reflect a mineralisation style specifically related to the minor intrusions. Nickel is also enriched in some of the mineralised and altered minor intrusions, with levels reaching 500 ppm.

In the most highly altered igneous and sedimentary rocks, and particularly at the margins of minor intrusions, an unusual assemblage of secondary lead minerals was detected. This style of mineralisation is particularly well developed in association with north–south faults and forms the bulk of the exposed base metal mineralisation described above from gossan-like zones. The best examples were seen in BHs 1–4 at shallow depth beneath the exposed 'gossan'. Both mineralogically and chemically this mineralisation is very distinctive and is probably of low temperature origin. Typically microspheroids of green plumbogummite, which from electron microprobe scanning contain major amounts of lead, aluminium and phosphorus, less iron and minor copper, zinc, vanadium and sulphur, are surrounded by darker green microcrystalline beudantite consisting of iron and lead in major amounts, less sulphur and phosphorus and minor levels of copper, zinc, arsenic and aluminium. Other minerals in concentric growth around the plumbogummite are goethite, limonite and sometimes malachite. In places these crustiform coatings have developed into wire-like growths one example of which, from electron probe analysis, contained approximately 20% Pb, 1.8% As, 0.2% Cu and 0.2% Zn (Fortey and Easterbrook, 1976; Fortey, 1975).

Chemically the igneous rocks affected by this mineralisation are extremely depleted in sodium, magnesium, silicon, potassium, calcium and barium and are markedly enriched in aluminium (Table 5). The rocks most affected have extremely low Zn:Pb ratios due to the virtual absence of zinc (Figure 34), whilst levels of arsenic and copper reach 1560 ppm and 620 ppm respectively (Figure 35). These element abundances indicate that, although considerable leaching of zinc may have taken place from already mineralised rocks in the fracture

Table 5 Chemical analyses of discordant minor intrusions from BHs 1–4

	Fresh: 9 specimens		*Altered: 4 specimens*		*Highly altered: 3 specimens*	
	Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*
Na_2O	3.11	2.29–4.36	0.61	0.33–1.08	0.09	0.08–0.11
MgO	4.30	3.52–4.86	3.94	2.11–6.75	0.55	0.43–0.61
Al_2O_3	15.28	14.7–16.2	17.1	15.8–18.9	27.1	25.2–28.9
SiO_2	62.92	61.0–64.8	55.0	54.7–55.2	45.4	41.6–49.5
P_2O_5	0.21	0.17–0.23	0.21	0.16–0.26	0.15	0.08–0.28
S	0.01	—	—	—	—	—
K_2O	2.94	2.19–3.52	4.35	3.50–5.09	1.01	0.87–1.28
CaO	3.43	2.29–4.36	0.64	0.27–1.32	0.05	0.02–0.12
TiO_2	0.89	0.80–0.96	0.93	0.86–1.00	1.18	1.09–1.35
Mn	462	320–640	418	240–680	1503	420–2810
Fe_2O_3	6.58	6.01–7.15	11.80	9.04–14.9	9.99	5.87–15.9
Co	23	15–30	29	20–45	55	25–100
Ni	75	47–147	219	80–456	116	42–215
Cu	*	15–8410	*	10–1100	567	480–620
Zn	551	280–1000	1253	660–2500	150	140–160
As	37	15–93	126	72–184	883	505–1560
Ba	684	382–790	549	488–593	59	44–68
Pb	*	50–3900	*	850–8000	*	2500–15000
Sb	3	1–8	7	0–19	28	17–42
Zn:Pb	3.9	0.3–8.1	0.56	0.15–0.96	0.04	0.01–0.06

*Exceptionally wide range renders mean of little value
Major oxides and S are given in %, trace elements in ppm

zones, there has also been a significant addition of other elements rather than an upgrading caused by selective leaching.

SUMMARY OF MINERALISATION HISTORY

Synsedimentary mineralisation has produced disseminated sulphide enrichment in the black siliceous mudstone sequence of two and possibly three types: Zn only (Zn ≏ 1000 ppm), Zn–Pb (Zn ≏ 1000 ppm, Pb ≏ 200 ppm) and possibly Zn–As (Zn ≏ 1000 ppm, As ≏ 100 ppm). Associated cherts and tuffs are also mineralised. Fine, stratiform pyrite laminae occur in places but throughout the mineralised sequence the original bedding is considerably disrupted by soft sediment deformation and tectonism.

Several phases of approximately syntectonic igneous activity resulted in the intrusion of dykes, some of which are mineralised. Most are significantly enriched in lead (Pb ≏ 100 ppm), zinc (Zn ≏ 1000 ppm) and to a lesser extent arsenic (As ≏ 100 ppm), but a minority show zinc, nickel and copper enrichment with lower than average levels of lead and arsenic. Two contrasting mineralisation styles may therefore be present, but it proved impossible to relate these to any specific phase of dyke intrusion.

Both igneous and sedimentry rocks are in places extensively veined by quartz and minor K-feldspar; the veins also contain a variety of sulphides including galena and sphalerite. The most significant effect is enrichment in lead to 2000–5000 ppm. This phase of mineralisation may be related to the later periods of dyke intrusion or may be a separate event following intrusion. The veins are often altered to a quartz–clay–iron oxides–sulphides complex but it is difficult to decide whether the alteration process involved further addition or subtraction of metals.

Secondary lead minerals are found within some of the altered vein complexes but this style of late, low-temperature mineralisation is best developed in association with north–south faults. Plumbogummite and beudantite are the most important secondary minerals present. In the fault-controlled, gossan-like zones lead levels remain high, ranging from 1000 ppm up to 4.5%, but zinc has been almost entirely removed. However, total element abundances suggest that despite leaching of the zinc from already mineralised rock, there has also been some addition of metals. Thus, these zones do not represent a true gossan since mineralisation there is not entirely the result of upgrading through selective leaching.

DISCUSSION OF ORIGIN AND SIGNIFICANCE

Despite the presence of likely synsedimentary, exhalative mineralisation, the origin of the major part of the base metal mineralisation remains problematical. However, the unusual abundance of minor intrusions in the mineralised zone is circumstancial evidence for an igneous source.

The disseminated mineralisation in the Penkiln Burn mudstone sequence has some similarities with shale-hosted sulphide mineralisation elsewhere in the world. Typical of these deposits are the Canadian and Australian examples at Sullivan and McArthur River respectively, both of which consist essentially of Fe–Pb–Zn sulphides in carbonaceous and calcareous shales with no direct volcanic associations. Despite this, the shale-hosted deposits have often been included in discussions of volcanogenic massive sulphides as a distal variation (e.g. Hutchinson, 1973). More recently the mineralising role of highly saline seawater circulating in deep convection cells (Russell and others, 1981) and expelled formation water (Badham, 1981) has been considered. The former is envisaged as operating in a rift zone under regional tensional stress and so may not be appropriate to the Penkiln Burn situation where a compressive regime is believed to have been dominant. However, the possible pre-tectonic minor intrusions suggest that a high geothermal gradient may have existed locally, which could have initiated the convection of circulating seawater. The Penkiln Burn disseminated mineralisation does have some volcanic connections in that mineralised tuff horizons occur within the mudstone sequence, whilst in the Southern Uplands generally basalts are regarded as the stratigraphic base to the mudstone successions. Most of the basalts associated with upper Ordovician sequences such as that at Penkiln Burn have chemical affinities with ocean-floor tholeiites (Lambert and others, 1981), but 90 km along strike to the north-east the alkaline Wrae Hill volcanics were probably erupted from a submarine 'within plate' volcanic edifice (Leggett, 1980) during the Caradocian stage. A volcanic source for the disseminated mineralisation at Penkiln Burn is therefore not out of the question.

The later phases of mineralisation at Penkiln Burn probably involved both hydrothermal effects and remobilisation of the disseminated sulphides. If this process was associated with one of the periods of minor intrusive activity it is likely to have occurred before 400 Ma, the age of the post-minor-intrusion Loch Doon pluton. However, evidence from other examples of vein mineralisation in southern Scotland suggests that the main mineralising event took place during the Carboniferous at about 320 Ma (Moorbath, 1962; Ineson and Mitchell, 1974). The final, low temperature hydrothermal mineralisation at Penkiln Burn produced the plumbogummite-beudantite assemblage, a very unusual style with no known parallels in south-west Scotland. Its age and precise mode of formation remain uncertain.

Although individual specimens from Penkiln Burn reach ore grade it is unlikely that the deposit as a whole would prove economic. However, the recognition of disseminated, stratabound mineralisation within the Ordovician of the Southern Uplands, coupled with the recently described stratabound arsenopyrite mineralisation from the Silurian near Langholm (Gallagher and others, 1983) is a major advance. Stratabound mineralisation had not been previously discovered within the Southern Uplands and these two occurrences should stimulate further exploration, guided by the primary and, more particularly, the secondary mineralisation controls established in the course of this investigation.

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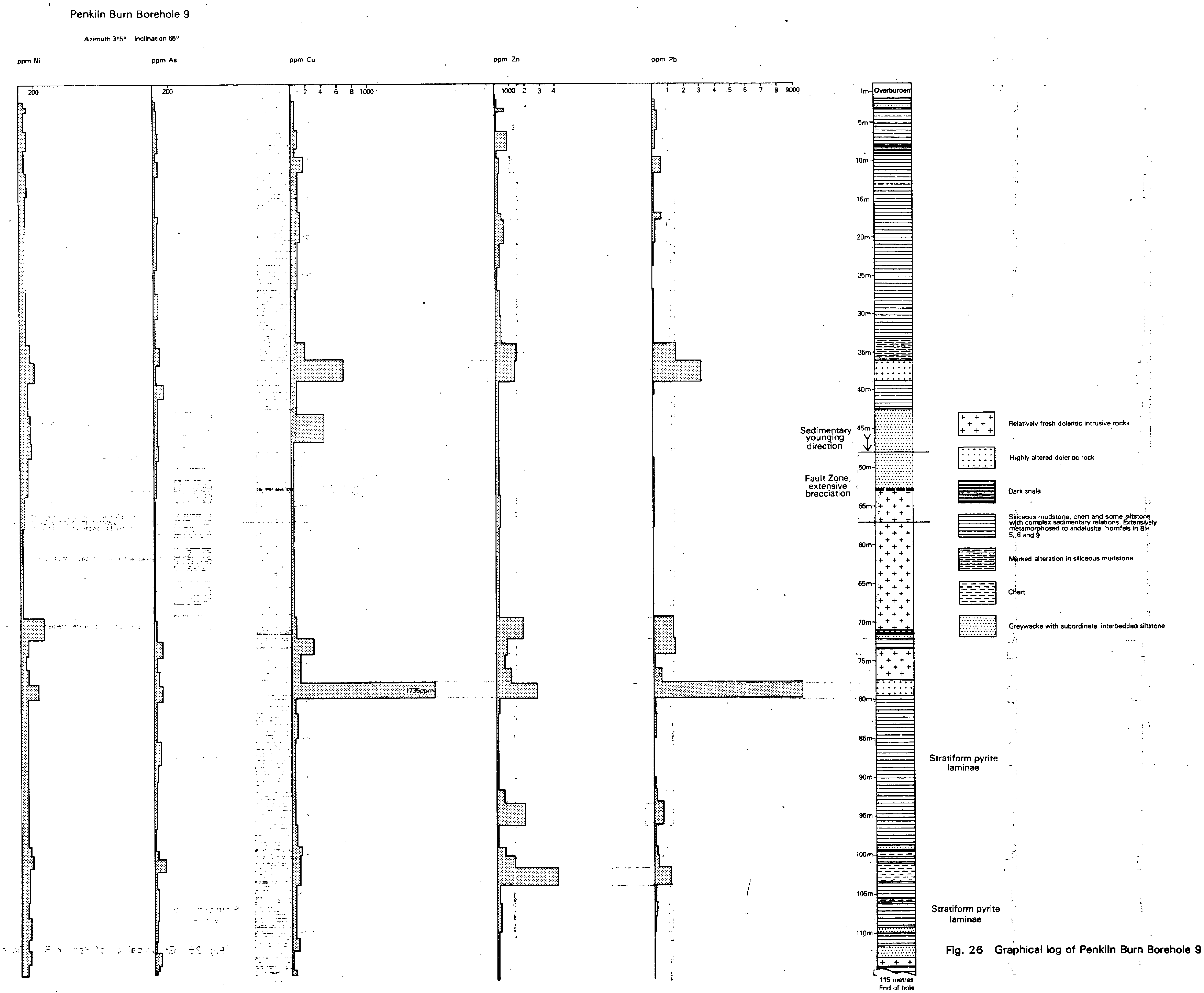

Fig. 26 Graphical log of Penkiln Burn Borehole 9