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 Institute of Geological Sciences on behalf of the Department of Industry. The information contained herein must not be published without reference to the Director, Institute of Geological Sciences.

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No.63

Exploration for volcanogenic sulphide mineralisation at Benglog, North Wales

INSTITUTE OF GEOLOGICAL SCIENCES

Natural Environment Research Council

Mineral Reconnaissance Programme

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Exploration for volcanogenic sulphide mineralisation at Benglog, North Wales

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SUMMARY

Exploration for volcanogenic sulphide mineralisation around Benglog is one of three investigations designed to assess the metallogenic potential of the Ordovician Aran Volcanic Group.

Detailed geological mapping in the Benglog area enabled an interpretation of the volcanic environment, critical to such an assessment, to be made. The eruptive rocks are acid and basic in composition; the acid rocks are mostly ash-flow tuffs derived from outside the area, whereas the basic rocks have a local derivation. They are all interbedded with dark grey or black silty mudstone and were probably erupted in a submarine environment. Contemporaneous dolerite sills were intruded into wet sediment.

This environment was suitable for volcanogenic exhalative sulphide deposits to form and indications of a metallogenic horizon were found at the top of the Y Fron Formation in the form of abundant pyrite, minor pyrrhotite and minor base metal enrichment.

Soil samples, analysed for copper, lead and zinc, were collected and geophysical surveys were carried out along eleven east-west trending traverse lines 300 m apart across the volcanic succession. Indications were found of minor vein mineralisation at dolerite intrusion margins and locally along faults. Very high chargeability and low resistivity anomalies over mudstones did not spatially coincide with geochemical anomalies in soil, but the secondary redistribution of metals in soils and variable thickness of overburden precluded confident interpretation of the source of many soil anomalies. Geochemical drainage data, in conjunction with rock analyses, show strong barium enrichment in mudstones which could be volcanogenic in origin but related to two separate eruptive episodes.

The findings of the survey were inconclusive. An environment suitable for the formation of volcanogenic exhalative sulphide deposits was established, but the geochemical and geophysical surveys located only minor vein mineralisation and tenuous indications of other styles of mineralisation. Recommendations are made for further work.

INTRODUCTION

GEOLOGICAL SETTING AND BACKGROUND OF INVESTIGATION

The periphery of the Harlech Dome (Figure 1) contains folded volcanic and sedimentary rocks of Arenig to early Caradoc (Costonian) age, called the Aran Volcanic Group by Ridgway (1976). The group unconformably overlies the Cambrian sedimentary and late Tremadoc volcanic rocks of the Harlech Dome. The Ordovician volcanic rocks are interstratified with dark grey mudstone and much of the volcanic activity took place in a subaqueous environment. There are some indications of subaerial eruption, however, and it is now generally accepted (see review by Allen, 1982) that the Ordovician volcanism of North Wales took place in a chain of volcanic islands along the southern margin of the Iapetus ocean. The Ordovician magmatism is compositionally strongly bimodal in both the extrusive and intrusive phases. Pillow basalts and rhyolitic ash-flow tuffs occur throughout the Aran Volcanic Group. Concordant and semi-concordant sheets of dolerite are interstratified with the volcanic rocks and there are some large acid intrusions variously described as granophyre, quartz-latite porphyry, keratophyre, rhyolite and microtonalite.

The total area underlain by this volcanic belt falls well within that of many ancient and modern volcanoes, and Ridgway (1976) suggested that these rocks are remnants of a single stratovolcano sited on the Harlech Dome. There is no evidence of a vent in the dome, however, and Rast (1969) suggested that eruption took place from fissures along the Bala Fault. The thickest development of the volcanic pile is in the vicinity of Cader Idris, and the succession attenuates to the south-west from Cader Idris and to the north and north-east. On Arenig, many components of the succession seen further south have wedged out. In the area north of Ffestiniog, Bromley (1968) suggests that eruption was purely local, forming a series of pyroclastic cones.

It is possible, therefore, to identify several minor generally submarine eruptive centres stretching between Cader Idris and the Moelwyn Hills, and the whole of the belt offers a favourable environment for the formation of volcanogenic stratabound sulphide deposits.

Stratabound massive sulphide deposits associated with volcanic rocks of Ordovician age

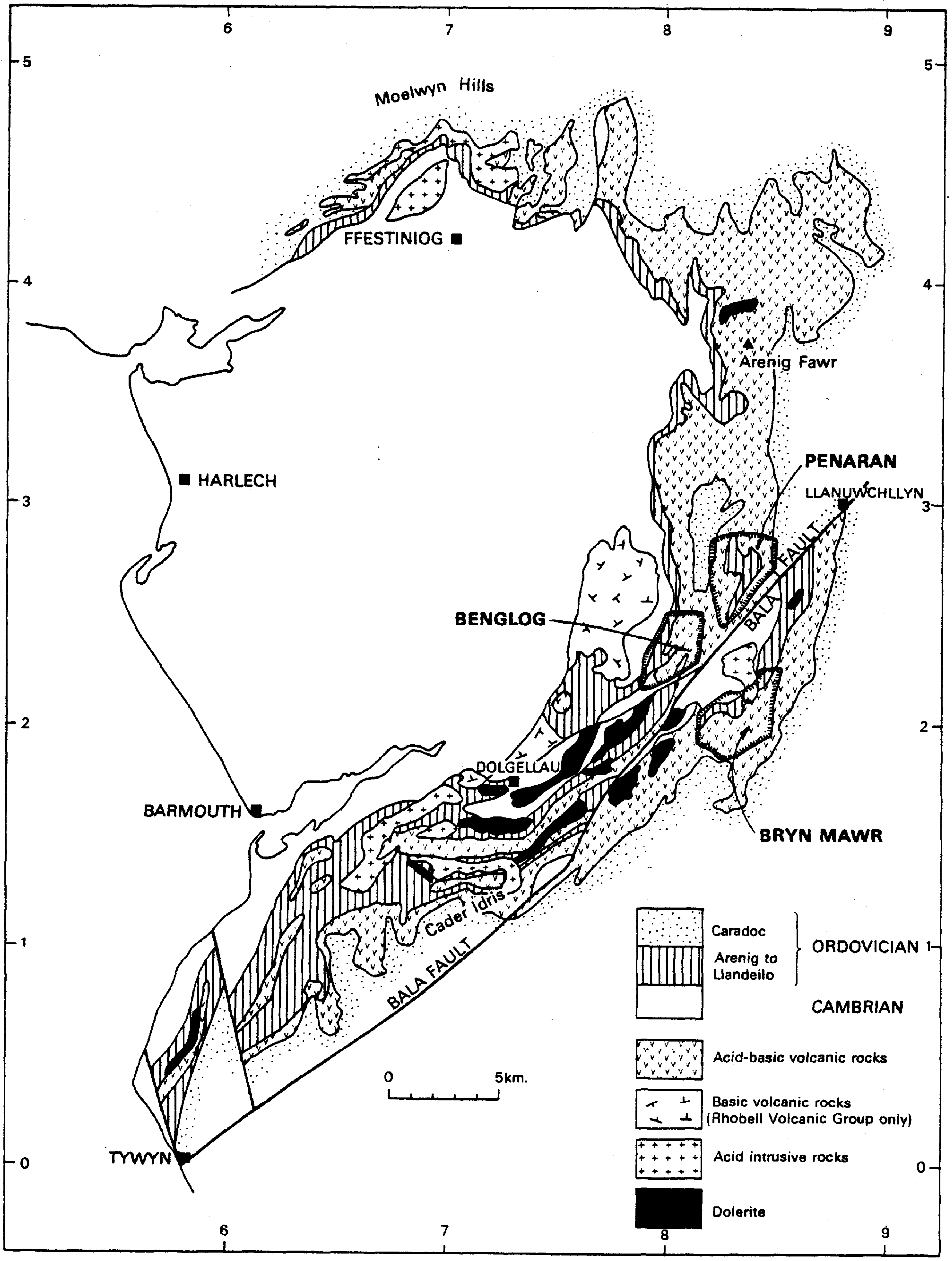

Figure 1: Geological sketch map of the Harlech Dome periphery showing the locations of the Benglog, Penaran and Bryn Mawr areas

are known in North Wales only at Parys Mountain (Ixer and Pointon, 1980). However, indications of base-metal enrichment in the Harlech Dome periphery were obtained during the early stages of the geochemical drainage survey of this part of Merioneth (Cooper and others, in preparation) and during investigations reported by Allen and others (1979) which suggested that stratabound sulphides might be associated with these volcanic rocks. Volcanogenic sulphide deposits may lie at one or more stratigraphic levels within a volcanic succession, and it is usual for several deposits, or sub-economic metal concentrations, to occur at each of these levels. Locating these deposits, which may be of small overall dimensions is, therefore, greatly aided by the early recognition of the metallogenic horizons.

Three areas, in the middle part of the volcanic belt, named Benglog, Bryn Mawr and Penaran, were selected for detailed study on the basis of known geology and drainage survey results. Each area contains a section through the Aran Volcanic Group and there are indications of mineralisation in all three. The object of the study was to use detailed geological mapping, geochemistry and geophysics to search for the stratigraphic horizons most likely to be metal-bearing. This report is about the investigation carried out in the area around Benglog.

BENGLOG AREA

The area lies to the north of Rhydymain, about 8 km NE of Dolgellau (Figure 2). The terrain is rugged, but drift deposits extensively mask the bedrock, being thickest and most extensive in the south. The main rivers, the Afon Eiddon and Afon Melau, flow between steep, scree-covered valley sides and in places have cut narrow gorges.

Two parts of the area were investigated during an early phase of the Mineral Reconnaissance Programme and are reported by Allen and others (1979). These areas, designated Benglog and Hengwrt Uchaf in their report, gave indications of volcanogenic sulphide mineralisation and it was the main objective in this survey to investigate these further. Eleven traverse lines spaced 300 m apart and trending E–W were surveyed over the principal volcanic formations. At their western ends they overlapped with the uppermost Cambrian formations and on the east they stopped within the lower part of the uppermost units of acid ash-flow tuff. Geophysical surveys were conducted and soil samples were collected along these lines. The total traverse length was 15 km. Some constraints on the position and extent of the traverses were imposed by settlement and growing crops in the south, by dense conifer plantations in the north-west and by precipitous slopes in the east. Geophysical measurements encountered some problems from cultural noise in the south, whereas soil samples suffered contamination near farms.

The area lies within the region covered by the Harlech Dome geochemical drainage survey, but additional samples were collected to supplement the regional data. Rock samples were also collected for analysis and mineralogical investigation, partly to seek the cause of the geophysical anomalies and partly to examine the possibility of there being evidence of a geochemical halo at a specific stratigraphic level.

GEOLOGY

The sedimentary rocks at the base of the Aran Volcanic Group rest unconformably on dark grey muddy siltstone of the upper Cambrian Cwmhesgen Formation. The late Tremadoc Rhobell Volcanic Group is absent. The Aran Volcanic Group shows considerable lateral as well as vertical variation (Figure 3). It has been divided into a number of formations defined largely on their volcanic content (Table 1). They show a regular alternation of acid and basic divisions. Dark grey or nearly black siltstone occurs within and between the volcanic units throughout the group.

ALLT LŴYD FORMATION

This formation rests unconformably on grey siltstone of Tremadoc age (Dol-cyn-afon Member) of the Cwmhesgen Formation. The lower part of the Allt Lŵyd Formation consists of very dark siltstone with numerous laminae and thin beds, locally bioturbated, of very pale grey sandstone. Northwards along strike thin oolitic ironstones are interbedded with the siltstones, but these have not been seen in the Cae'r Defaid area. The upper part of the formation consists largely of coarse volcanic sandstone and conglomerates with some interbedded lithic tuffites, lithic tuffs and rare bands of vitric tuff towards the top. The volcanic sandstones are typically thickly bedded, light bluish grey to dark greenish grey and consist largely of altered plagioclase and fragments of andesitic 'feldspar porphyry'. Less common fragments include siltstone, acid igneous material, and rarely quartzite. Quartz generally forms less than 10% of the rock. Matrix consists of sericite with some chlorite and varying proportions of calcite. Opaque minerals including leucoxene and hematite/goethite are commonly concentrated in laminae.

The lithic tuffites contain over 50% of volcanic debris which consists mainly of feldspar porphyry fragments, together with a small proportion of other volcanic and sedimentary fragments and rare shards. Opaque minerals are locally abundant and may be concentrated in laminae. These include rounded grains of magnetite, leucoxene after ilmenite and, more rarely, pyrite. Pyrite also occurs as a secondary euhedral overgrowth. Matrix is variable and consists of chlorite, quartz and sericite

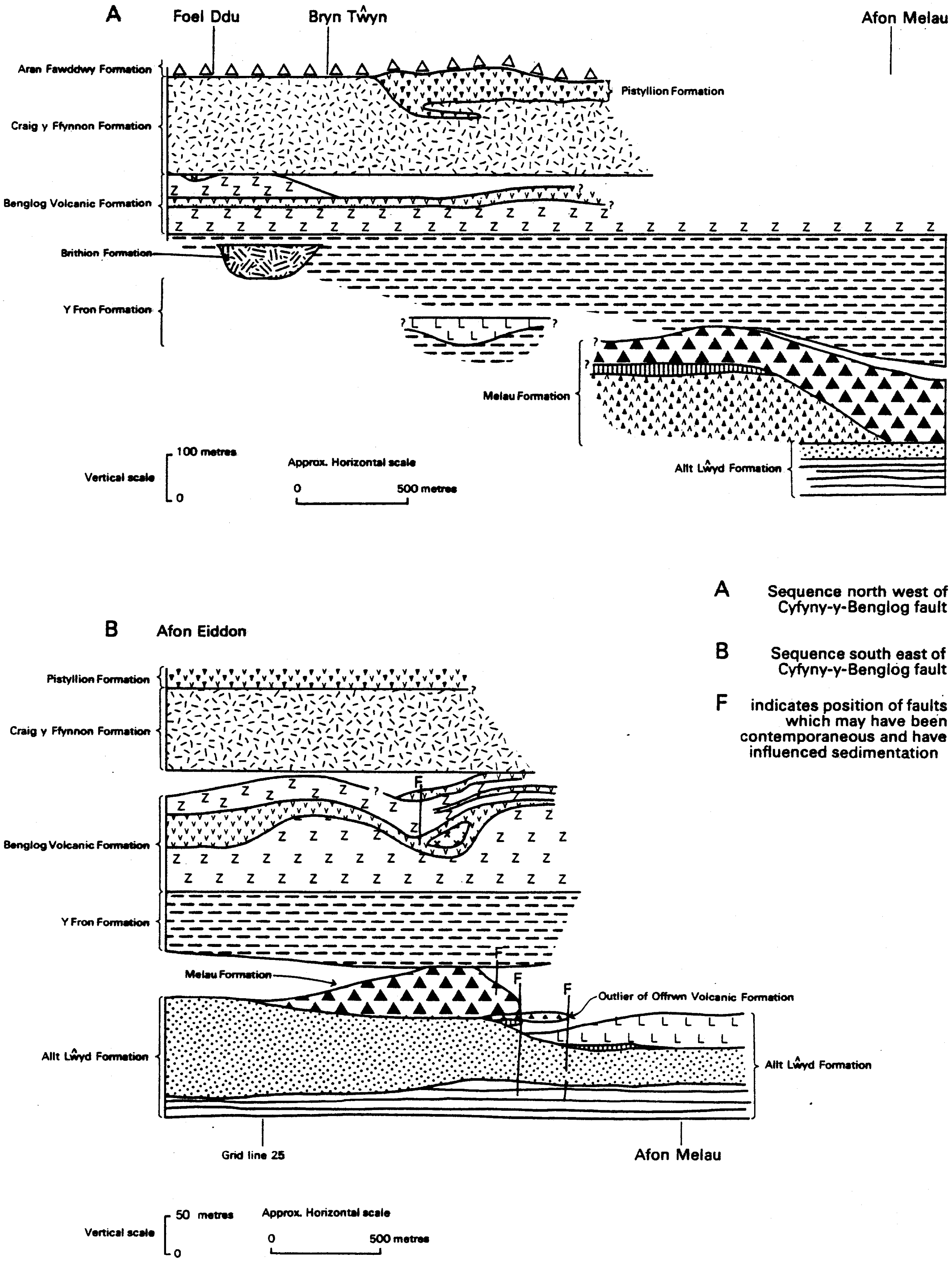

Figure 3 : Schematic diagram showing variations within 'unfolded' Aran Volcanic Group. Lithological ornament as in Figure 2.

Table 1 Formations within the Aran Volcanic Group in the area around Benglog

Lithological unit	*Approximate thickness in metres*	*Predominant rock types*
Aran Fawddwy Formation	base only	Acid tuff
Pistyllion Formation	0 to 100–120	Basic tuff, tuffite and siltstone
Craig y Ffynnon Formation	105 to 215	Acid tuff
Benglog Volcanic Formation	110 to 165	Crystal tuff (andesitic) and basic lava
Y Fron Formation	90 to 300	Siltstone with local acid to basic tuffs
Melau Formation	0 to 220	Basic tuff and tuffite with minor lavas
Offrwm Volcanic Formation	0 to 8	Acid tuff
Allt Lŵyd Formation	90 to 154	Banded siltstone and sandstone passing up into volcanic sandstone and lithic tuff

with some secondary calcite. The lithic tuffs consist almost entirely of clasts of feldspar porphyry with some feldspar in a sparse chloritic groundmass.

A thin tuffaceous mudstone horizon overlies the lithic tuffs and tuffites. It contains large concretions of chlorite and collophane, interpreted as algal structures which are indicative of shallow water conditions. To the south-west an oolitic ironstone occurs at a similar horizon.

OFFRWM VOLCANIC FORMATION

On Cae'r Defaid the thin tuffaceous mudstone is locally overlain by 7 to 8 m of banded fine-grained acid ash tuff, consisting of recrystallised shards. It occurs at the same horizon as the Offrwm Volcanic Formation to the south-west from which it is separated by faulting. It dies out to the north and east.

MELAU FORMATION

This formation overlaps the Offrwm Volcanic Formation to rest on the Allt Lŵyd Formation and is itself overlapped by the overlying Y Fron Formation. The Melau Formation consists of basic tuffs and tuffite with minor, thin lavas and hyaloclastites. There is a marked variation in thickness of both the tuffites and tuffs. In the Afon Melau the thickness of the basic tuff is estimated at 220 m but at Cae'r Defaid, less than 2 km to the north-west, this is reduced to 33 m and dies out within 1.5 km along strike to the north. About 1 km to the north-east of the Afon Melau the basic tuffite underlying the tuff reaches an estimated thickness of about 130 m, but it is not represented in the Afon Melau section.

The tuffs, which are soft and weather to a brown rubble, are poorly exposed away from the river valleys. They are bedded and agglomeratic at the base passing upwards into fine grained, more massive material. The tuff is made up of basic scoria generally cemented by calcite, though in places there is a matrix of sericite or quartz mosaic. Leucoxene/sphene occurs abundantly throughout and pyrite and magnetite sparingly.

Intercalated lavas and hyaloclastite are basaltic in composition but are generally much altered. Feldspar is albitized; chlorite, stilpnomelane, leucoxene, calcite and minor quartz replace the original mafic minerals.

The tuffites, which consist of rounded fragments of vesicular basalt, some fragments of tuff and siltstone in a muddy matrix, occur to the north of the Afon Melau and are well exposed only in the gorge of the Afon Eiddon. Here the tuffite is agglomeratic (clasts average 5–10 cm long but reach up to 50 cm) but contains some silty laminae towards the top.

Y FRON FORMATION

This is a purely local name used here to cover the thick unit of siltstone and interstratified volcanic rocks which rests locally on the Melau and Allt Lŵyd formations and underlies the Benglog Volcanic Formation. It appears to thin out to the east but the exposure is poor and the geology complicated by faulting and intrusions. There is room for about 230 m of siltstone overlying the Melau Formation in the south and about 90 m between the Allt Lŵyd and Benglog Formations in the north. The siltstone is grey to almost black in colour and consists of silt-size quartz grains in a matrix of sericite, quartz, chlorite and carbonaceous material. The siltstone is commonly tuffaceous with scattered feldspars and lithic clasts or with tuffaceous laminae. The darker siltstone contains pyritous laminae. Feldspar clasts become increasingly abundant in the top 1–2 m underlying the crystal tuff.

To the east of Cefn-y-braich a thick unit (62 m) of lithic tuffite is interbedded with the siltstone in a fault-bounded block. The tuffite contains largely euhedral feldspar and rare volcanic quartz crystals together with a variety of basic and acid volcanic fragments, chloritic fiamme and quartzose siltstone in a groundmass largely of chlorite with some calcite, quartz, sericite and leucoxene/sphene.

A unit of acid ash-flow tuff, 76 m thick, occurs beneath the Benglog Volcanic Formation on Ffridd Bwlch-main. It occurs in a fault-bounded block and is probably equivalent to the Brithion Formation which crops out in the Aran Mountains. It is similar in appearance and composition to the acid tuffs of the Craig y Ffynnon and Aran Fawddwy formations. On the south end of its outcrop [SH 8112 2388] the tuff is sericitised and brecciated with some iron staining of the rock. The area may represent the site of localised fumarolic activity.

BENGLOG VOLCANIC FORMATION

This formation consists predominantly of crystal tuffs generally of andesitic composition with thin bands of tuffaceous siltstone and intercalated basic lavas in the upper part. The base is exposed in a low crag [SH 8021 2436] where there is a gradual increase in the crystal content of the underlying siltstone.

The crystal tuffs are dark greenish grey and fairly uniform in appearance. They are thickly bedded and consist of ash to lapilli grade clasts of altered feldspar in a matrix of chlorite with some calcite. Stilpnomelane and leucoxene occur in most of the rocks. Scattered throughout are fragments of black siltstone, generally less than 15 cm long, and larger bombs of ?dacite, up to 60 cm long. Towards the top of the formation there is a general decrease in the crystal content and a proportional increase in the fine grained component. Fragments of scoria and pumice appear together with shards and rounded euhedral quartz crystals. Interbedded reworked tuffs show a banding of fine and coarse grained material and contain laminae of detrital opaque minerals including magnetite, pyrite and ?chalcopyrite.

Near the top of the formation is an agglomeratic mass flow deposit but in general the crystal tuff is interpreted as air-fall tuff deposited into shallow water in which siltstone accumulated during periods of volcanic quiescence. Numerous thin basalt lavas occur on Benglog, one containing pillow structures. They consist of feldspars ranging from andesine to labradorite with interstitial augite and chlorite. Sub-ophitic textures are developed in places and the lavas may be indistinguishable from the associated doleritic intrusions.

CRAIG Y FFYNNON FORMATION

This acid ash-flow tuff is correlated with an equivalent horizon in the Aran Mountains to the south. In this area, the tuff rests on the underlying Benglog Volcanic Formation with some apparent disconformity cutting out the upper part of the crystal tuff on the western slopes of Foel Ddu. The formation consists of greenish grey, massive acid tuff with scattered feldspar crystals and a few lithic clasts in a fine grained recrystallised groundmass which shows little evidence of welding.

PISTYLLION FORMATION

The formation is developed locally on the eastern side of Craig y Benglog and south of Bryn Twyn. It is a basaltic horizon separating two acid formations and consists of lensoid units of basic tuff and tuffites interbedded with siltstone and tuffaceous siltstone, intimately associated with dolerite intrusions and peperites.

ARAN FAWDDWY FORMATION

This overlies the Pistyllion Formation in places and elsewhere rests on the Craig y Ffynnon Formation. It is an acid ash-flow tuff consisting of scattered feldspars and some acid lithic clasts in a recrystallised ash-grade groundmass with sparsely distributed pyrite cubes.

ENVIRONMENT OF DEPOSITION

The volcanic rocks of the Aran Volcanic Group were erupted into shallow shelf seas. The banded siltstones and sandstones of the Allt Lŵyd Formation are tidal flat deposits. The area was gradually covered by epiclastic material derived from contemporaneous volcanoes to the south. This was reworked and deposited in a fluvio-deltaic environment, but towards the top of the formation the lack of reworking in the lithic tuffs suggests they were air-fall deposits that fell on an emerged surface, probably only temporarily raised above sea level.

A period of relative volcanic quiescence and a marine transgression is indicated by the thin siltstone horizon which overlies the Allt Lŵyd Formation. The algal structures within this siltstone are normally associated with shallow water to partially subaerial conditions. This period was followed by the eruption of the acid tuff of the Offrwm Volcanic Formation which represents only the feather edge of a thick ash-flow tuff deposited to the south. The basaltic material of the Melau Formation above it shows a rapid change in thickness along strike and this material may have been erupted from a number of separate volcanic vents in shallow seas, each acccumulating an independent ring of tuff, tuffite and lava or hyaloclastite.

The longest period of volcanic quiescence is marked by the thick siltstone in the Y Fron Formation, but volcanicity did continue, as demonstrated by the tuffaceous horizons within it. There is meagre evidence that the basin of deposition did not continue far to the east of Benglog as this siltstone horizon appears to thin abruptly onto the slopes of Ffridd Arw, where it rests on basic tuffite of the Melau Formation.

The Benglog Volcanic Formation appears to follow conformably in this area although it overlaps some of the lower horizons to the north. This is one of the few formations which shows a range in chemical composition. The andesitic crystal tuffs are largely air fall deposits. Although there may have been emergence during the deposition of the lower part of the formation the intercalated silty bands, reworking textures and pillow lavas, suggest at least shallow water deposition. Mass flow deposits are confined to the top of the sequence. The upper boundary of the crystal tuffs with the overlying acid tuff formation is gradational with a gradual reduction in the crystal content and an increase in the fine ash material.

The acid ash-flow tuffs of the Craig y Ffynnon and Aran Fawddwy Formation dominate the upper part of Aran Volcanic Group. These beds represent several pulses of acid ash-flow eruption. The deposition of the siltstone of the Pistyllion Formation marks a temporary break in the eruption of acid tuffs. Deposition may have taken place in isolated fault-bounded basins rather than uniformly over the whole area. The associated basaltic rocks were probably erupted from a number of scattered vents and the small area of outcrop of the Pistyllion Formation, south of Bryn Twyn, probably represents the remnants of a single such cone. As in northern Snowdonia volcanism appears to have been strongly bimodal in composition.

STRUCTURE

In general the rocks strike NNE and dip to the ESE at angles varying between about 33° and 71°, the steeper dips being in the older beds to the west. The succession youngs to the south-east. The structure of the area is dominated by a number of north-east trending faults, sub-parallel to the Bala Fault. The strongest of these are the Cyfyny y Benglog Fault and one parallel to it 400 m to the south. The downthrow on these is generally to the north-west. Faults belonging to a conjugate set trending north-west have a downthrow mainly to the north-east. Movement on many of these faults may have been initiated during sedimentation and volcanism. Cleavage is developed locally in these rocks and strikes roughly north, dipping steeply to the west.

INTRUSIONS

There are only dolerite intrusions in this area, some of which are gabbroic at the core. They consist mainly of andesine or labradorite, locally albitised to albite or oligoclase, and augite altered to tremolite–actinolite or chlorite. Other secondary minerals include calcite, leucoxene and stilpnomelane with minor quartz and epidote. Opaque minerals include magnetite, ilmenite and pyrite.

Many of the intrusions are sills or laccoliths although, in detail, contact with the country rock may be complex and discordant with evidence of stoping preserved in many places. Dykes, which are comparatively rare, may have been feeders to the pillow lavas. On the south-east side of Craig y Benglog and on Ffridd Arw large, complex, discordant dolerites and gabbros appear to follow north-east trending faults which may have been used as conduits for contemporaneous intrusions of dolerites. A few plug-like intrusions occur.

On the eastern face of Craig y Benglog a complex of dolerite and dolerite breccia intrudes siltstone and tuffite of the Pistyllion Formation producing peperites. These consist of rounded blebs of vesicular lava (up to about 15 cm long) in a matrix of siltstone, tuffaceous siltstone or tuffite. Some are developed around a core of dolerite, which takes a plug-like form, suggesting that the magma was vesiculated and fragmented as it intruded into unconsolidated sediment.

DRIFT

Thick boulder clay covers the southern half of the area, the fill line reaching to about 300 m OD. Above this line boulder clay is thin and patchy except in the upper reaches of the Afon Eiddon where there is a thick spread, in places greater than 20 m thick, at about 330 to 380 m OD. Boulders are locally derived and contained in a blue-grey clay matrix. Over much of the area, especially where there is siltstone, the solid rock is concealed under a cover of head or soliflucted deposits though this in not generally very thick. Scree is extensively developed on the south-east face of Craig y Benglog.

Peat occurs in patches both on solid and drift. River alluvium is largely restricted to the upper part of the Afon Eiddon, above about 310 m, and at least one well-developed terrace occurs.

MINERALISATION

Disseminated pyrite, occasionally with pyrrhotite, is locally abundant in rocks of the Allt Lŵyd Formation. South-west of Drws Melau [SH 7914 2293] it occurs within interbedded volcanic sandstone and banded black siltstone. In the Afon Melau [SH 7959 2220] and on the southern slopes of Moel Cae'r-Defaid [SH 7985 2301] the overlying volcanic sandstone is the host and in the Afon Melau [SH 7940 2277] the lithic tuff, tuffites and volcanic sandstone in the uppermost part of the formation contain abundant pyrite.

There is a record of minor disseminated galena in basic tuff of the Melau Formation (Allen and others, 1979) from the lower part of the Afon Melau [SH 7968 2168], and veinlets of pyrite are present in a quarry in this formation at SH 7961 2191. In general this formation contains little sulphide.

Pyrite is most abundant within the upper part of the Y Fron Formation. It occurs within the mudstone as finely disseminated crystals and in framboids, some of which are distorted by cleavage indicating a pre-cleavage, probably diagenetic origin. Veinlets of pyrite with quartz, chlorite and hematite cross the rocks but they also are disrupted and folded by the cleavage. In places [SH 8018 2375] pyrrhotite is the main sulphide, though in lesser quantities. Pyrite also occurs, locally abundantly, within the lower part of the Benglog Volcanic Formation. Again it is mostly disseminated with a trace of chalcopyrite and, in places, pyrrhotite. However, there is evidence that some of the sulphide may be detrital. Sulphides are scarce or absent in formations higher than the Benglog Volcanic Formation.

There is some evidence that there is an association between mineralisation and faulting. In the Afon Eiddon, pyrite and arsenopyrite occur associated with quartz veining in siltstone adjacent to a fault [SH 8075 2326] and in irregular veins in lithic tuffs also adjacent to a fault [SH 8068 2285], both in the Melau Formation. Near Pen-y-rhiw [SH 8143 2308] a thin vein of barite occurs along a minor fault plane in brecciated Craig y Ffynnon Formation rocks marginal to a dolerite. At this locality and several others, the mineralisation is most likely to be associated with dolerite intrusion. Pyrite is disseminated in many dolerite bodies and tends to be in higher concentrations at the brecciated margins. A minor dolerite intrusion low in the Afon Eiddon [SH 8247 2232] is faulted and contains pyrite, with chalcopyrite in veins and chalcopyrite and sphalerite in vesicles.

Old workings and trials occur around Benglog cottage and two adits are located above scree on Craig y Benglog. The latter are driven into dolerite [SH 8060 2403] and probably followed a quartz-galena vein, fragments of which are present in the scree below it. Three old workings close to the cottage are largely collapsed and tips are grassed over. The nearest [SH 8057 2362] is almost completely overgrown, but a thin quartz vein is visible in the roof of the adit entrance. About 200 m north-west of this working [SH 8035 2368] are two old workings close together, more or less along a fault line obscured by scree. The lower working appears to be a shaft. The tip is grassed over, but contains abundant richly pyritic black mudstone and fragments of crystal tuff. To the north-east and a little higher up the slopes is a collapsed adit in crystal tuff. There is no tip, but loose blocks around the adit contain disseminated pyrite and chalcopyrite.

GEOCHEMISTRY

RECONNAISSANCE DRAINAGE SURVEY

Results of a reconnaissance drainage survey across the Harlech Dome and its periphery (Cooper and others, in preparation) showed many anomalies in and around this area. These are summarised in Figure 4. Threshold levels applied are those set for the whole survey from the analysis of cumulative frequency graphs. For metals anomalous in this area the threshold levels in stream sediment are Cu 41 ppm, Pb 111 ppm, Zn 201 ppm, Ba 951 ppm, Fe 8%, Mn 1.39%, Ni 110 ppm, V 155 ppm, Cr 70 ppm, As 105 ppm and Mo 12 ppm. In panned concentrates they are Pb 125 ppm, Zn 305 ppm, Ba 830 ppm, Sn 13 ppm and Ti 0.9%. The larger anomalies are shown in Figure 4 by underlining those which fall within the top 2.5% of the sample population. Cu, Pb, As, Ti, Mn, Ni and Sn anomalies are all weak, but some of the highest levels of stream sediment barium and zinc found in the Harlech Dome are recorded here. Barium in sediment levels reach 3000 ppm and zinc in sediment 1500 ppm. High barium in sediment is confined to the north-west part of the Benglog area and is invariably higher than the levels in the panned concentrates taken at the same sites, strongly suggesting that the barium carriers are not baryte or other heavy minerals. Zinc in sediment also tends to be similar to or higher than the levels in the panned concentrate, suggesting that co-precipitation with hydrous manganese or iron oxides may be at least partly the cause of the anomalies. At most sites, however, iron, manganese and cobalt in sediment are not particularly high, and it was concluded that although co-precipitation may be contributary causes to both the zinc and barium in sediment anomalies, bedrock enrichment in these elements was also likely.

Prominent zinc in panned concentrate anomalies are located downstream of the old workings on Craig y Benglog. They are accompanied by only relatively weak lead anomalies in both sediment and concentrate. The known workings, however, are believed to have been for lead, and

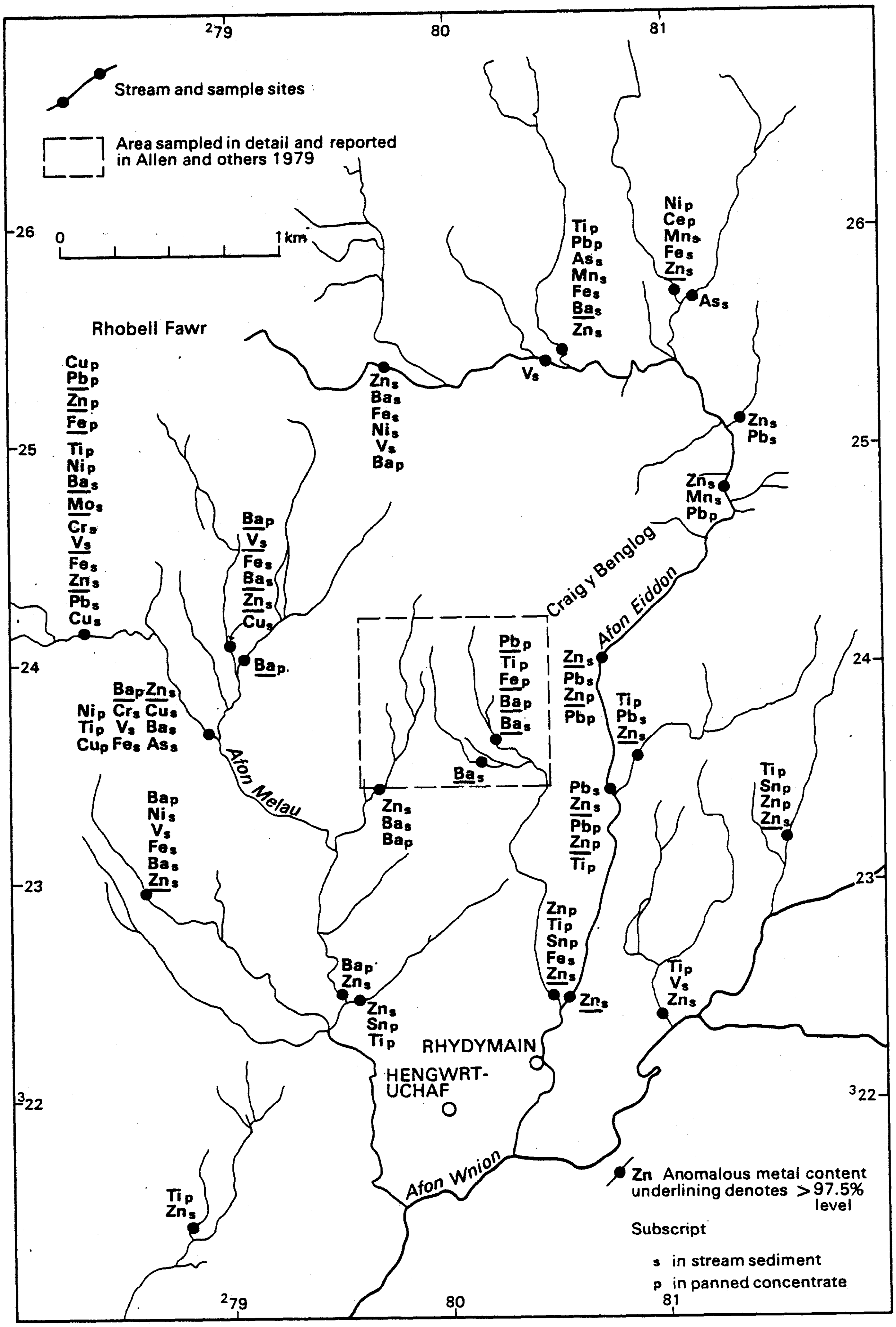

Fig 4 Anomalous results in the Benglog area from a geochemical reconnaissance drainage survey of the Harlech Dome

galena was the only ore mineral found on screes and tips above the stream. A possible explanation is that unexploited zinc mineralisation is present in the vicinity.

Weak anomalies in the south-east part of the area, characterised by the presence of Ti levels of about 1% in panned concentrate, are related to the presence of basic volcanic rocks. Zinc in stream sediment is also anomalous at most of these sites and occasionally lead in sediment and zinc in panned concentrate are also high. Though the high levels of zinc are mainly attributed to the presence of basic rocks, the occurrence of high levels of lead at some localities suggests that there may also be some mineralisation.

Though the most anomalous sites, for example at SH 7830 2415, drain catchments containing outcrops of the Cwmhesgen Formation, Rhobell Volcanic Group and basic intrusions, there is a consistent association of many of the larger drainage anomalies with the Cwmhesgen Formation and the mudstones within the Aran Volcanic Group. The latter association was briefly investigated earlier (Allen and others, 1979) where it was concluded that the metal anomalies (Pb, As, Ba, Fe, Ni and Zn) recorded are similar to those associated with mudstones near stratabound volcanogenic mineralisation.

SOIL SAMPLING SURVEY

Sampling and analysis

608 samples were collected at 25 m intervals along eleven east—west traverse lines spaced 300 m apart using 1.2 m long hand augers (Figure 5). Sampling of each site was from at least three holes. 150—200 g of material were collected from as deep as possible and, whenever possible, from below the organic-rich horizon. For this purpose an extendable (max. 3 m) hand auger was used in some areas of deep peat cover. The samples, described for convenience as 'soil', consist mostly of boulder clay, head and scree, with a few samples which are largely organic (peat).

Samples were dried, disaggregated and sieved. A 0.5 g portion of the -80 mesh fraction was digested in 1 ml of concentrated nitric acid and then by 3 ml of 72% perchloric acid at 180°C for three hours, prior to analysis for Cu, Pb and Zn by AAS (Atomic Absorption Spectrometry). Detection limit for each element was 2 ppm.

Results

The results are summarised in Table 2. Cumulative frequency curves were plotted for each element and analyses of the curves obtained were used to set the threshold levels (Lepeltier, 1969; Sinclair, 1976).

Copper levels are generally low, with a maximum value of 86 ppm. The log-scale cumulative fequency plot for copper showed an approximately lognormal form but in detail appeared to consist of two overlapping lognormal populations with similar standard deviations and median levels of 10 ppm and 16 ppm. The element levels, ranges and degree of overlap, suggest that both sample populations are related to background geology. Subsequent work, however, indicated that the higher population was related to soils collected over lowland areas and the lower to those collected from the acid soils of the peaty uplands. The threshold level was set at the 97.5% level of the upper population, making results >46 ppm anomalous.

The logscale plot of lead results yielded a binormal form (Parslow, 1974) with an inflexion point at 180 ppm, the 97.3% level of the sample population. Results >181 ppm were taken as anomalous.

The zinc plot was approximately lognormal in shape, small deviations from the straight line not forming any characteristic pattern. The threshold was set at the 97.5% level of the sample population, equivalent to the mean plus two standard deviations for a perfect distribution, making results >450 ppm anomalous.

Results were plotted in traverse line form (Appendix 1) and related to bedrock geology, drift deposits, sample depth, soil type and topographic features. The traverse diagrams identified a few high values which, whilst forming distinct peaks with respect to the local background, are not statistically defined as anomalous. For the purposes of interpretation, these prominent peaks were treated as anomalies, but attempts to make the procedure more rigorous by subdividing results into sub-populations related to local background proved impossible because of the complex interactions of bedrock geology, drift cover and secondary concentrations.

Interpretation

Levels of lead and zinc in the area as a whole are high and are therefore in broad agreement with the results of the drainage survey. In detail, however, the metal levels in soil are believed to be modified by secondary redistribution in the weathering zone and do not accurately reflect primary bedrock chemistry.

Some indications of this are:

i Soil results do not form clear patterns that can be related to the known geology, despite the presence of highly contrasting lithologies.

ii There are pronounced variations in Cu:Pb:Zn ratios in a north—south direction. This is approximately along strike, but low ground in the south covered largely by boulder clay gives way in a northerly direction to peat covered highland with thin, patchy boulder clay cover and acid groundwater.

iii Many anomalies coincide with seepage lines, boggy ground or organic-rich samples.

iv The results, particularly for zinc, are erratic

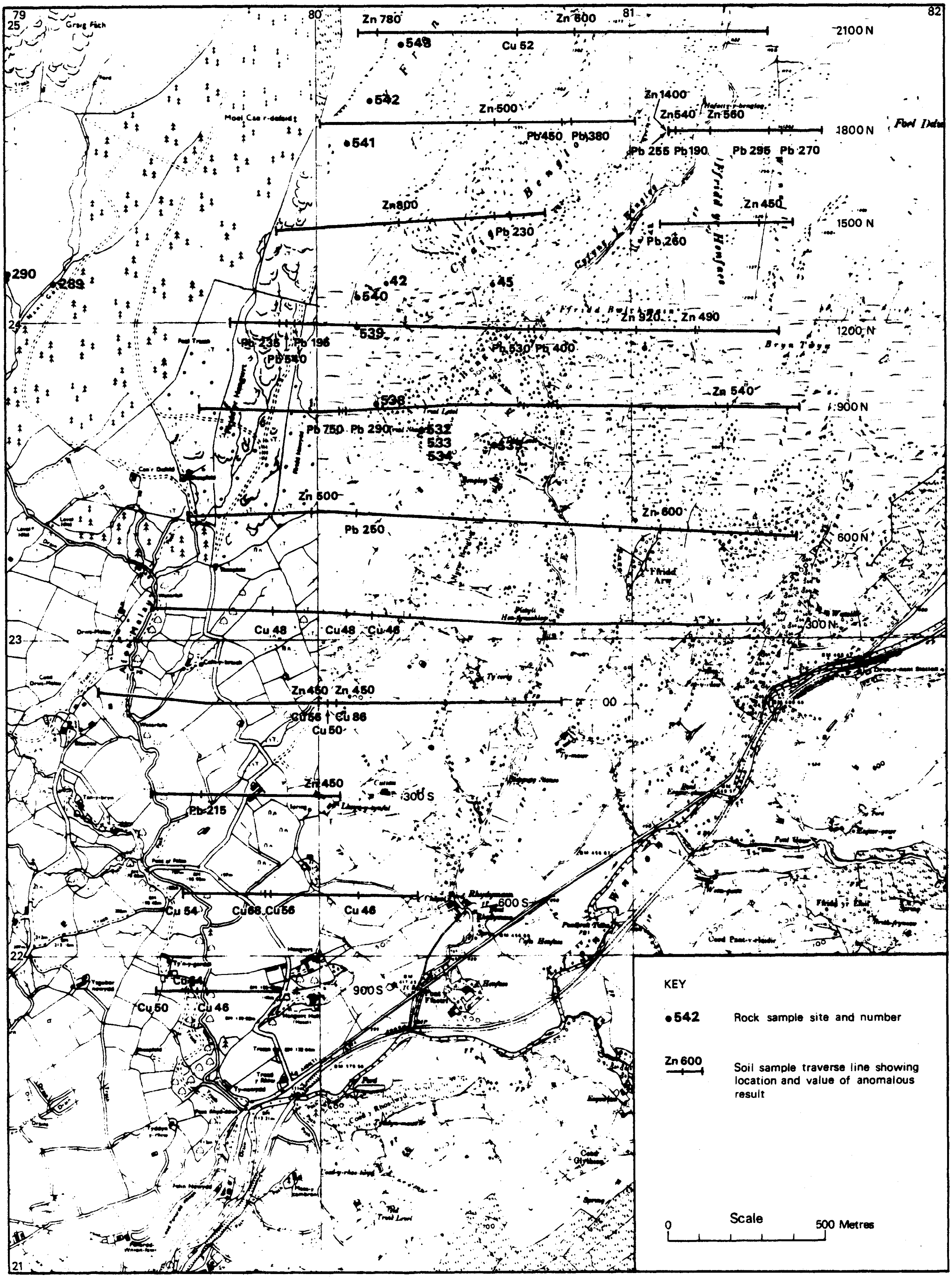

Fig. 5. Location of traverse lines, soil anomalies and rock sample sites

Table 2 Summary of analytical results in ppm for Cu, Pb and Zn in soil samples

	Median	*Mean*	*Standard Deviation*	*Geometric Mean*	*Geo. Mean + Geo. Dev.*	*Geo. Mean + 2 Geo. Dev.*	*Max.*	*Min.*	*Threshold*
Cu	14	16	10.61	13	25	47	86	2	46
Pb	65	80	59.12	69	113	185	750	20	181
Zn	120	140	121.81	104	233	524	1400	8	450

Correlation matrix

	Cu	Pb	Zn
Cu	1.000		
Pb	0.215	1.000	
Zn	0.556	0.417	1.000

99.95% Significance level = 0.15
n = 608

across bedrock of relatively uniform composition, such as dolerite.

v The results fail to reflect the known mineralisation around Benglog farm.

The north–south change in metal ratios can be clearly seen on the traverse plots (Appendix 1). In the south of the area (lines 900S to 00) copper results fall within the range 15–40 ppm; northwards they decrease and from line 600N are in the range 5–20 ppm, with most results less than 15 ppm on the two northernmost lines. Lead levels are generally within the same range on all lines but tend to fluctuate more rapidly in the north, while zinc results are distinctly low in a belt from line 1200N to 1800N where Pb>Zn. These variations are believed to be caused by the changes in 'soil' type northward. Copper, for instance, is more soluble in acid water and is probably being leached from the acid upland soils. Lead and zinc behaviour is more complex. Zinc is apparently being locally leached, transported and redeposited, probably in part controlled by iron and manganese behaviour, whilst lead distribution is at least in part controlled by complex formation with organic matter.

Many anomalies can, in the first instance, be related to secondary concentrations in either till or A(F, H, O)-horizon soil. Without carrying out further work, it is impossible to decide whether these accumulations, which may be transported some distance from source, are drawn from background levels in the rocks or come from a mineralised source. There is a possibility that some may be related to fault-lines, the margins of basic intrusions, rocks of the Melau, Y Fron and Benglog formations and, in one case, contamination.

Fault-line anomalies

The most prominent fault-line anomaly, located at SH 8001 2281 on traverse 1200N, is over the major NE fault to the south of the Cyfyny y Benglog Fault. The anomaly lies close to a track and boggy ground, but the peak is over a drier part of the field. The fault juxtaposes a dolerite intrusion, Y Fron mudstone and Melau and Benglog Volcanic Formation at this point. A high background level of lead is present in soils to the west of the fault across the subcrop of the Y Fron Formation, and on the next traverse to the south a lead anomaly may also be related to the fault.

Several anomalies are associated with the Cyfyny y Benglog Fault. On traverse 300N (Appendix 1) a pronounced but not anomalous lead peak is situated over the faulted margin of a dolerite with Y Fron Formation mudstones [SH 7975 2309], and there is a zinc anomaly in soil over it at SH 7997 2340 on the next traverse to the north, though this sample was collected close to a wall in boggy ground.

The large two-sample lead anomaly at SH 8067 2398, which is most probably caused by vein mineralisation containing galena, formerly exploited in the hillside about here, is situated on the fault line but may not reflect mineralisation along it. Another pronounced anomaly close to this fault is located at SH 8111 2460. The samples were collected from a dolerite scree and the anomaly may, therefore, again not be directly related to the Cyfyny y Benglog fault. Known mineralisation associated spatially with this fault near Benglog Farm was not detected.

Two other zinc anomalies are located over faults, one in the Benglog Formation at SH 8026 2432 and the other in the Craig y Ffynnon Formation at SH 8082 2491. Both were collected from waterlogged ground, one close to a wall, and both may be interpreted as secondary concentrations though, as is the case with other anomalies in this group, metal levels may be enhanced by groundwater movement along the fault-line, carrying metals from mineralised or background sources.

Dolerite margin anomalies
High or anomalous metal levels closely associated with the margins of basic intrusives may be due to weak sulphide mineralisation or to the barrier effect of the boundary on groundwater movement. Besides the fault-line anomalies that are close to intrusive margins, anomalies in this group include the zinc anomalies SH 8131 2375 and SH 8120 2398, the copper anomaly at SH 8008 2308 and the lead anomalies at SH 8078 2464. Several other distinct lead peaks are located close to the margins of dolerite intrusions and peperite, for instance at SH 8072 2434 and SH 8093 2464. Although most if not all of these anomalies and local highs may be interpreted as secondary concentrations, the high levels of lead in areas where a low background in the bedrock might be expected confirms the observations at outcrop of base-metal mineralisation associated with the margins of the basic intrusions.

Lithology-related anomalies
The most prominent anomaly apparently unrelated to a geological boundary is that for lead in three samples collected over basic tuffs of the Melau Formation from around SH 7990 2400. The sample sites are close to outcrop in well-drained ground and most probably represent a localised mineralisation occurrence for adjacent traverses show no evidence of metal enrichment at this level. The Allt Lŵyd Formation immediately below the Melau Formation tuff here contains abundant pyrite, both disseminated and in veinlets, and a record of disseminated galena in exposures of this formation in the Afon Melau suggests that mineralisation is not necessarily of vein type. Other weaker anomalies of uncertain origin are located over the Melau Formation, e.g. high copper levels at SH 7984 2220 and SH 7947 2189; these may simply reflect a relatively high background generated by the basic volcanic rocks. A zinc anomaly at SH 8000 2250 is also located over the Melau Formation in thin drift, but field observation suggests that it is enhanced or even caused by contamination from the nearby farm.

Two small groups of anomalous values occur over the Benglog Volcanic Formation in the east of the area at the level of a basaltic sequence on traverse lines 1200N and 1800N [SH 8144 2460, SH 8140 2432]. These both appear to be secondary concentrations, as the samples were collected in waterlogged ground and one site is close to a wall, but they could also indicate metal enrichment in the bedrock at this level.

High results and anomalies over the Y Fron Formation at its junction with the Benglog Volcanic Formation are uncommon, suggesting that most of the sulphide seen in these rocks is pyrite or pyrrhotite. The most pronounced anomaly close to this junction is that for lead on the boulder clay margin at SH 8006 2373. The two anomalous samples were taken each side of a wall and are probably secondary concentrations, though they may be derived from an underlying metal enrichment in the area. The only other large anomaly over the Y Fron Formation, except for those related to faults, is a lead anomaly at SH 8012 2340 over the tuff-siltstone boundary. There is little evidence from the soil results, therefore, for any base-metal enrichment at this stratigraphic level and, in the north, metal levels in soils from above the Y Fron Formation tend to be fairly low and relatively constant (Appendix 1). This pattern may in part be a reflection of topography, as the mudstone outcrop usually forms a depression overlain by greater thicknesses of till than the adjacent volcanics and basic intrusives.

Disseminated pyrite and pyrrhotite is locally abundant in the rocks of the Allt Lŵyd Formation, but with the exception of the zinc anomaly at SH 8019 2492, which is interpreted as a secondary concentration, there are no soil anomalies over this formation.

Very little correlation of anomalies across traverse lines along strike could be discerned. In this area such a pattern does not necessarily preclude the presence of stratabound mineralisation for any correlations may be obscurred by the masking effect of thick but patchy till deposits, the presence of transported anomalies and the possible small size of any single mineralised body with respect to the distance between traverse lines, though more widespread metal enrichment might be expected at the metallogenic horizon. As seen on the traverse plots the soil results do not accurately reflect the immediately underlying bedrock, and it must be concluded that only limited weight should be given to the detailed spatial distribution of soil anomalies in any overall assessment of the potential of this area.

ROCK GEOCHEMISTRY

Rock samples were collected from the Y Fron Formation and from the tips of the old mine workings on low ground near Benglog Farm. At least 2 kg of each sample were crushed, mixed, and, for samples whose numbers are greater than 400, a sub-sample ground in a 'Tema' mill with

Table 3 Analyses of samples from mine tips

Sample No.	291	532	533	534	535
Ti	–	4250	2770	5740	1960
V	144	123	21	131	28
Cr	76	96	<5	140	<5
Mn	1051	340	1010	11310	180
Fe	69890	90400	40240	63800	66800
Ni	79	40	5	75	9
Cu	25	41	30	115	55
Pb	20	86	14	22400	74
Zn	90	48	25	454	13
As	18	78	8	36	49
Mo	6	4	2	4	8
Sb	–	<5	<5	126	<5
Sn	–	<4	<4	4	<4
B	–	77	<10	<10	38
Ba	1460	9040	32	260	8360
Rb	–	198	4	141	148
Sr	–	59	74	26	54
Zr	–	137	317	155	126
Th	–	13	10	68	6
U	–	3	3	<1	2

All results in ppm

291	SH 7845 2425	Dark shaly mudstone with carbonate and minor sulphide veinlets from tip by old shaft.
532	SH 8032 2367	Dark, carbonaceous, pyritiferous, ?tuffaceous mudstone from grassed over tip.
533	SH 8032 2367	Fine grain acid tuff with disseminated sulphide and thin ?carbonate veinlets from tip.
534	SH 8032 2367	Bulk sample of mineralised fragments from tip. Most of highly altered ?basic rock with minor galena.
535	SH 8057 2362	Pyritic basic tuff.

Table 4 Analyses of mudstones from the Y Fron Formation

Sample No.	538	539	540	541	542	543
Ti	6800	5880	6650	7580	7290	7760
V	123	154	118	107	123	106
Cr	78	77	107	94	83	86
Mn	1000	640	950	320	200	240
Fe	80800	57300	74700	67100	66200	62400
Ni	52	23	29	21	27	14
Cu	38	31	20	<6	13	6
Pb	36	32	32	23	14	16
Zn	163	65	87	90	75	64
As	34	23	16	6	7	2
Mo	<2	2	<2	<2	<2	<2
Sb	<5	<5	<5	<5	<5	<5
Sn	<4	7	<4	6	<4	<4
B	112	86	94	50	79	57
Ba	4825	2987	3660	1105	1180	1276
Rb	207	175	195	155	136	152
Sr	41	36	41	73	91	99
Zr	166	177	200	217	205	229
Th	13	11	15	10	10	13
U	1	<1	<1	2	<1	<1

All results in ppm

538	SH 8018 2375	Sheared, dark mudstone with pyrite disseminated and along joints.
539	SH 8013 2399	Sheared, dark mudstone with disseminated pyrite.
540	SH 8013 2409	Sheared, dark mudstone with disseminated pyrite close to fault.
541	SH 8010 2459	Laminated, dark silty mudstone.
542	SH 8017 2471	Laminated silty mudstone.
543	SH 8027 2489	Laminated silty mudstone.

Table 5 Analyses of mudstones from the Dolgellau Member of the Cwmhesgen Formation

Sample No.	289	290	443	444
Ti	–	–	6920	6890
V	755	778	–	–
Cr	76	61	–	–
Mn	165	127	340	330
Fe	71840	33620	68860	69950
Co	11	10	–	–
Ni	71	105	47	44
Cu	20	110	41	36
Pb	40	40	23	23
Zn	30	40	96	99
As	137	58	8	8
Mo	33	43	5	3
Sb	–	–	<5	<5
Sn	–	–	<4	<4
Ba	9100	8640	2680	2870
Rb	–	–	164	176
Sr	–	–	101	105
Ca	–	–	810	540
Zr	–	–	167	161
Ce	–	–	52	52
Th	–	–	13	14
U	–	–	6	5

289	SH 7916 2412	Dark shale with pyrite vein, outcropping in stream.
290	SH 7897 2414	Bulk sample of dark shale from outcrops along stream.
443	SH 7877 2925	Dark mudstone with lenses and aggregates of pyrite.
444	SH 7877 2925	Dark mudstone with lenses and aggregates of pyrite.

'elvacite' binder prior to pelletising and analysis for a range of elements by X-ray fluorescence spectrometry. B, V and Cr wer determined on another sub-sample by Optical Emission Spectrography (OES). Samples whose numbers are less than 300 were analysed by AAS for Cu, Pb and Zn following dissolution of a 0.5 g sub-sample in concentrated nitric acid for at least one hour, and for a range of other elements by OES.

With the possible exception of sample 534 (Table 3), the tip samples are likely to be gangue, wallrock and barren rocks intersected whilst driving shafts and adits. Two samples, numbers 532 and 535 (Table 3) show indications of weak enrichment in chalcophile elements and exceptionally high levels of barium. The sample of mineralised fragments (Table 3, 534), besides confirming the expected presence of lead-zinc mineralisation, suggested the presence of weak antimony mineralisation. The levels of arsenic and copper, however, are only weakly elevated, and the molybdenum level is close to background. The metal enrichment in this and the other tip samples suggests that the mineralisation exploited here is of low-temperature type and, therefore, the presence of silver, which was not determined, cannot be discounted.

The Y Fron Formation mudstone samples (Table 4) show chemical variation which reflects the higher silt content of samples 541–543. For example, the coarser samples contain more zirconium and less boron, copper and manganese than the dark mudstones.

When compared with mean analyses of shales and siltstones from elsewhere (e.g. Reedman, 1979; Beeson, 1980), it is clear that for most elements the composition of the Y Fron rocks is unremarkable but that their barium levels are exceptionally high, iron levels rather high and strontium levels very low. Samples 538–540, collected close to the junction with the overlying Benglog Volcanic Formation, show the most extreme results for these elements and may also contain weakly elevated levels of lead, zinc, rubidium and arsenic. One of the samples of mudstone collected from a tip (Table 3, no. 532) is also thought to come from this horizon. It shows a strong chemical similarity to the Y Fron rocks, except for even higher levels of barium and some chalcophile elements.

Analyses from various localities (e.g. Reedman, 1979; Rosler and Lange, 1972) suggest that barium is rarely enriched in black shales and iron levels are also generally lower than in the Y Fron mudstones. Analyses of dark shales and mudstones from the Dolgellau Member of the Cwmhesgen Formation in this area (Table 5, nos. 289, 290) also show that these rocks contain high levels of barium and iron and have very low levels of calcium, demonstrating that barium enrichment is not confined to a single stratigraphic unit in this area. Thin-section examination of the Y Fron mudstone samples did not reveal the presence of a barium-essential mineral though one could be missed in small amounts. Baryte has been found in small amounts in this area, but the stream sediment and panned concentrate results indicate that it is most likely that barium is carried in a mineral of relatively low specific gravity such as barium muscovite, barium feldspar or even the rare tectosilicate cymrite. Cymrite and other relatively rare barium minerals were first described from North Wales in the manganese deposits at Rhiw (e.g. Spencer, 1942; Campbell-Smith and others, 1944). There is no obvious manganese association at Benglog and of the minerals identified in thin section muscovite, which occurs as abundant felted masses in one sample only (no. 532), appears to be the most likely barium carrier.

Compositionally, the barium-rich shales and mudstones from this area appear similar to barium-rich Ordovician shales from the Oslo region of Norway where low strontium levels are also reported (Bjorlykke and Griffin, 1973). Descriptions of cymrite-bearing pyritiferous shales from New Zealand (Soong and Olivecrona, 1975) are also similar to those of Benglog rocks but no analyses are quoted.

The New Zealand occurrence, together with others in Alaska (Brosge, 1960; Runnels, 1964), France (Aye and Strauss, 1975), and Scotland (Fortey and Beddoe-Stephens, 1982), all indicate the frequent association of barium-rich shales with volcanic rocks and stratabound sulphide deposits. Studies of geochemical dispersion about 'Kuroko style' massive sulphide deposits have reported barium and base-metal enrichments in host rocks around the ore deposits, with lithogeochemical anomalies extending for considerable distances at the same stratigraphic level as the mineralisation (e.g. Shiikawa and others, 1974; Thurlow and others, 1975). Lateral dispersion in the order of 3 km was reported from the Buchans, Newfoundland, deposit (Thurlow and others, 1975) but vertical (across strike) dispersion is generally much less, except in the vicinity of any feeder zone. At Buchans the widespread dispersion of base-metal and particularly barium anomalies in sedimentary and volcanic rocks led to the conclusion that barium enrichment was caused by metal rich volatiles accómpanying volcanism related to mineralisation subsequent to magmatic crystallisation.

In the area around Benglog barium enrichment is not confined to a single stratigraphic level. It is, however, most likely to be localised. Very large barium in stream sediment anomalies, which are most probably derived from these rocks, are found near outcrops of the Cwmhesgen Formation only in this general area and immediately north of the Rhobell Volcanic Group. Drainage results from sites over the outcrop of the Cwmhesgen Formation in the northern part of the Harlech Dome around Cwm Prysor and Arenig, for example, show no highly anomalous barium levels (Figure 6). It may also be significant that, of the four samples from the Cwmhesgen Formation, the two which carry very high levels of barium come from the Benglog area, though the variation could be attributed to sampling different stratigraphic levels.

A purely local enrichment of Ba in rocks of both the Y Fron and Cwmhesgen Formations is unlikely to be simply a product of sediment provenance and depositional environment. The spatial distribution of Ba anomalies in stream sediments suggests an association with the Rhobell Volcanic Group and Kokelaar (1979) reported Ba levels of more than 4% in some volcanic rocks of the Rhobell Volcanic Group. This suggests that two Ba metasomatic events may be represented in the area, a late Tremadoc event and a younger one coincident with the end of deposition of the Y Fron Formation.

The only analyses of volcanic rocks available from the Benglog prospect are of the tip samples reported in Table 3 and of two samples, one a basic crystal tuff from the Benglog Formation and the other an acid tuff from the Craig y Ffynnon Formation, collected for a previous investigation (Allen and others, 1976). These are shown in Table 6 together with analyses of other rocks from the Aran Volcanic Group collected to the north of the Benglog area for the same investigation. With respect to the possibility of barium enrichment of the volcanic rocks, the results are ambiguous. The tip samples yield conflicting results: one, a pyritic basic tuff (Table 3, no. 535), contains very high barium and possibly elevated levels of arsenic, lead and molybdenum whilst two others, which contain vein mineralisation (Table 3, nos. 533, 534), show the expected base-metal enrichment but low barium contents. The two samples of volcanic rocks from Benglog (Table 6, nos. 42, 45) contain background levels of chalcophile elements though some samples from further north contain relatively high levels of As for unmineralised rocks.

Barium levels are very variable, but some of the diversity can be related to acid-basic variation. K/Ba ratios, which might be expected to reduce variation related to the acid-basic factor, are also variable, with the highest and lowest ratios recorded in the two samples from Benglog. The K/Ba variation may be related to varying proportions of sediment or crystal layering in the tuffaceous rocks, but it may also be caused by Ba metasomatism.

Base of slope scree samples collected during the initial investigations at Benglog and comprising Benglog and Craig y Ffynnon Formation rock debris were only analysed for Cu, Pb and Zn (Allen and others, 1979). The analyses showed no base-metal enrichment except for high lead in

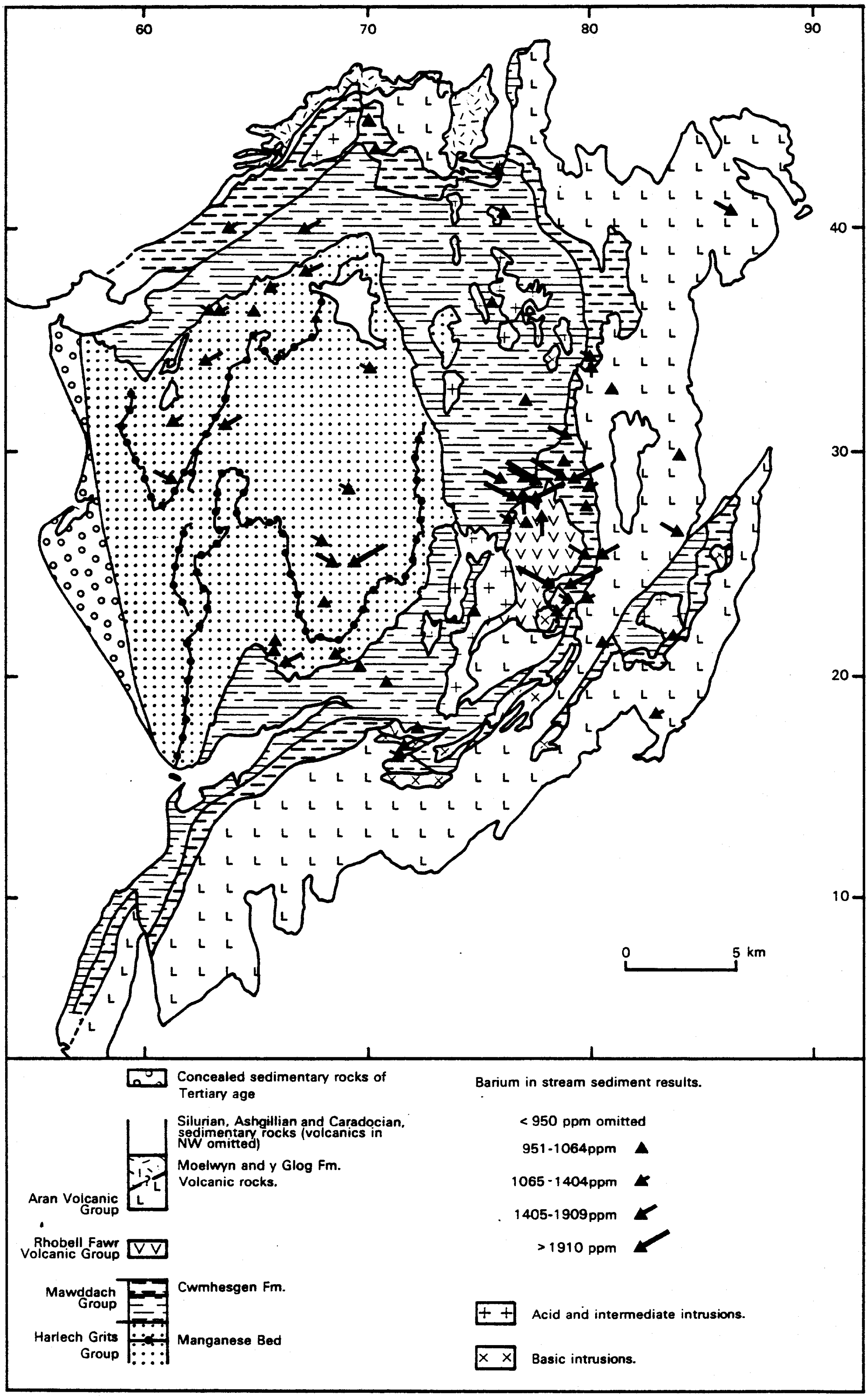

Fig 6. Distribution of barium anomalies in stream sediment samples from the Harlech Dome.

Table 6 Analyses of some volcanic rocks from the Aran Volcanic Group

Lithology	Sample No.	Grid reference	SiO_2	Al_2O_3	TiO_2	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cu	Pb	Zn	As	Mo	Ba	Zr	K/Ba
Craig y Ffynnon Formation																				
Acid tuff	45	SH 8053 2411	70.5	12.3	0.34	4.9	0.10	0.60	1.00	5.80	1.00	0.08	<3	20	90	<3	2	157	635	53
Benglog Volcanic Formation																				
Basaltic lava	41	SH 8055 2899	51.2	13.5	2.76	13.7	0.24	3.82	4.16	4.88	0.36	0.35	15	10	120	5	<2	308	265	9.7
Basaltic lava	59	SH 8038 3260	50.3	15.4	2.84	13.0	0.19	4.18	2.72	5.59	0.12	0.33	20	<5	160	20	<2	40	268	25
Crystal tuff	34	SH 7971 3214	51.5	16.3	1.17	12.8	0.37	2.94	2.59	4.80	1.72	0.44	<3	10	190	15	<2	326	95	44
Crystal tuff	61	SH 8041 3331	61.3	13.9	1.45	9.8	0.33	1.56	4.76	3.40	0.76	0.32	5	20	160	10	<2	514	503	12
Crystal tuff	42	SH 8022 2410	52.0	15.8	1.55	14.2	0.37	2.31	3.74	5.17	0.76	0.47	10	10	210	<3	<2	959	192	6.6
Crystal tuff	39	SH 8045 2887	69.2	13.9	0.53	5.0	0.16	1.32	1.21	2.88	4.00	0.09	<3	20	140	10	<2	1935	409	17
Crystal tuff	62	SH 8048 3434	62.0	13.9	0.88	8.8	0.13	1.00	0.79	0.17	4.96	0.13	<3	20	160	20	2	1629	808	25
Hyaloclastite	40	SH 8051 2893	59.8	11.8	2.11	6.8	0.30	1.82	6.45	4.74	0.32	0.22	15	10	210	10	<2	57	155	46
Allt Lŵyd Formation																				
Tuff within sandstone	32	SH 7943 3222	53.4	14.8	1.30	12.9	0.40	2.31	4.52	4.20	0.68	0.45	5	10	190	15	<2	466	458	12

Ag was also determined, all results ⩽2 ppm
*Total iron as Fe_2O_3

two samples caused by vein mineralisation. It is concluded, therefore, that insufficient lithogeochemical information is available to judge whether there is any pervasive barium or other enrichment in the Aran Volcanic Group at Benglog, to support a volcanic origin for barium enrichment in the mudstone. Detailed rock sampling and analysis is required to clarify this point.

GEOPHYSICAL SURVEYS

Earlier work had shown a strongly conductive body coincident with the Y Fron Formation, which gave both airborne and ground electromagnetic (EM) anaomalies (Allen and others, 1979). Neither the source nor the extent of these anomalies had been proved, so further work was carried out over a larger area using different methods. Because horizons containing massive sulphide bodies are usually weakly mineralised over a much wider area, the induced polarisation (IP) method was used, as it will respond to low sulphide concentrations. Total magnetic field measurements were made on all traverses and the two most northerly lines were surveyed by very low frequency EM (VLF-EM). For the IP work, the dipole-dipole array was used with 50 m dipoles at a constant 100 m centre-to-centre separation.

RESULTS AND DISCUSSION

Maps bearing contours of apparent resistivity and chargeability, and profiles of total magnetic field are given as Figures 7–9.

The electrical properties of the rocks in the Benglog area show wide variations: chargeability rises to 160 ms and falls to 4 ms; resistivity varies from less than one ohm metre to over 5000, while spontaneous potentials were so large in places that IP readings could not be made. Magnetic variations were more moderate. One large anomaly had a 600 nT amplitude, but few others exceeded 150 nT.

Despite its wide variation, apparent resistivity shows clear correlation with bedrock lithology (Figure 7). In particular, many of the siltstone units have extremely low resistivities, while dolerite bodies and tuffs give high values. The Y Fron siltstone, which gave the earlier EM anomalies, is particularly conductive: its resistivity decreases gradually upwards until values as low as one ohm or less are seen near its junction with the resistive Benglog Volcanic Formation. The westerly dips interpreted from the earlier results (Allen and others, 1979) must now be treated with caution: the gradational western boundary of the conductor shown by the resistivity survey negates the assumption of an 'infinite thin dyke'.

The continuation of the Y Fron siltstone SSW to the Afon Melau on the north side of the Cyfyny y Benglog Fault is also accompanied by low resistivities, though much less spectacularly so than in the north. More strongly anomalous values occur over the upper part of the siltstones south of the fault. These low values extend northwards into an area of poorly exposed ground beyond the mapped limit of these rocks, suggesting an unexposed extension to the siltstone. Other areas of low resistivity accompany thin bands of siltstone in the Melau Formation in the south and south-west, and again suggest that these sediments are more extensive than outcrop evidence indicates. In the extreme south a strong anomaly [SH 7995 2220], which occurs over drift-covered presumed extension of the Y Fron Formation, is likely to be due to an iron waterpipe.

There is no simple relationship between the resistivity map and geochemical anomalies.

The high conductivity of some of the siltstones is probably due to high carbon contents, although the darker, more carbonaceous units often contain pyritous laminae, and these may contribute. The causes of conductivity in Cambrian dark shales have been investigated during earlier work (Allen and others, 1979), and it seems likely that similar mechanisms apply to these Ordovician conductive rocks.

Chargeability shows more or less the same pattern as resistivity (Figure 8). Three main zones of high chargeability over siltstones can be seen: the Y Fron Formation siltstone to the north and south of the Cyfyny y Benglog Fault, and the thin mudstone in the Melau Formation in the south. In addition, most of the Allt Lŵyd formation gives moderately high chargeabilities.

Over the northern part of the Y Fron Formation the highest values obtained (~120 ms) lie just to the west of the axis of minimum resistivity, although many readings could not be taken due to the combination of low resistivity with strong spontaneous potentials. The area south of the Cyfyny y Benglog Fault gives values up to 160 ms, and a broad area in excess of 100 ms. As on the resistivity map, the anomalous body extends 300 m beyond the mapped northern limit of the siltstone. The third anomaly, in the Melau Formation, is narrow but very strong, reaching 160 ms.

There is clearly a tendency for the highest chargeabilities to coincide with the less extreme resistivity lows. IP is a surface effect on conducting grains in the rock. If the charge on these grain surfaces can leak away through a fairly conductive matrix, or if the conducting grains are in sufficient concentration to be in contact with one another, there will be little build-up of induced polarisation on these surfaces, giving relatively low chargeability. Work on Cambrian dark shales (*in* Allen and others, 1979) showed that networks of pyrite laminae and/or carbonaceous grains in contact are the cause of high

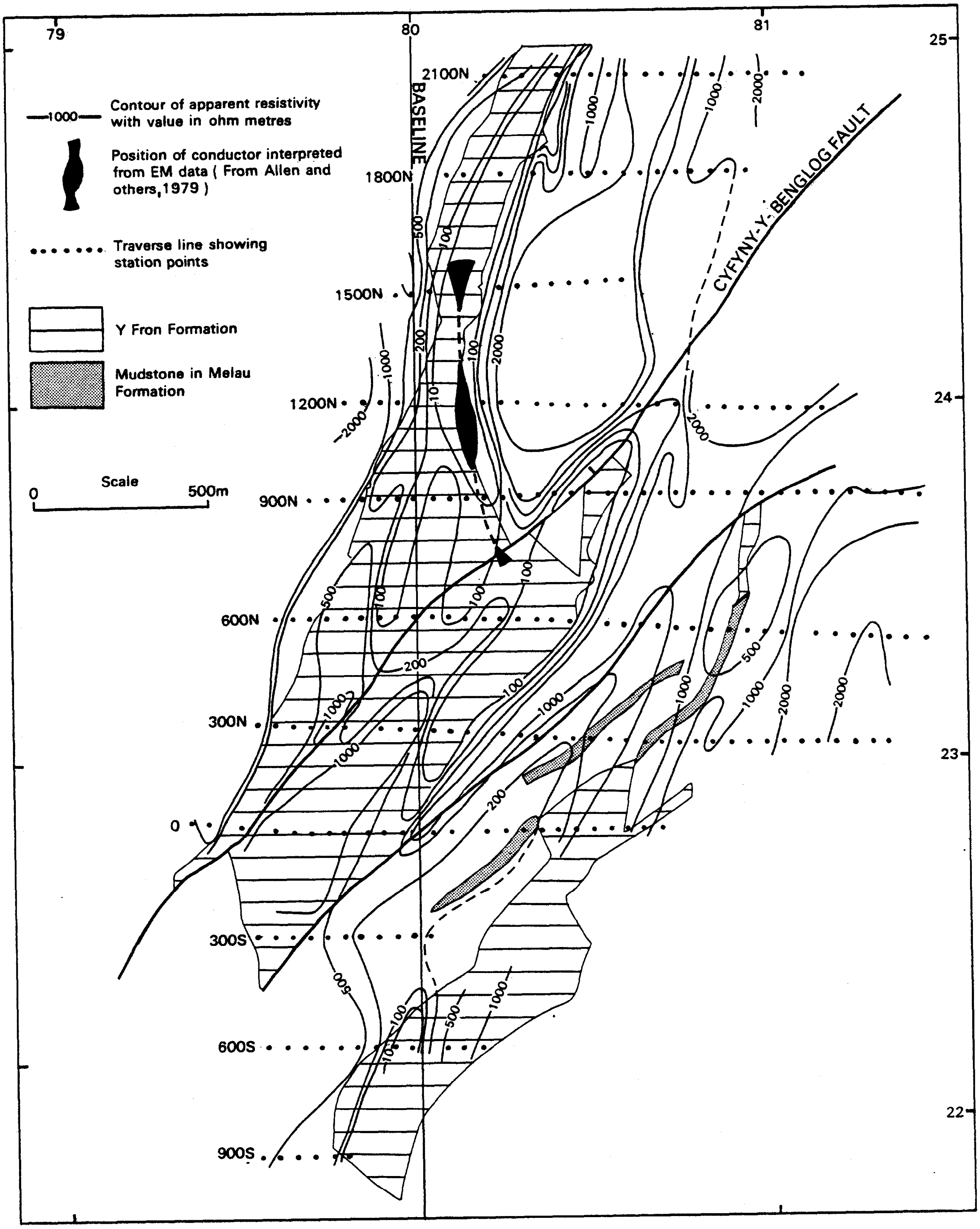

Figure 7: Apparent resistivity contour map.

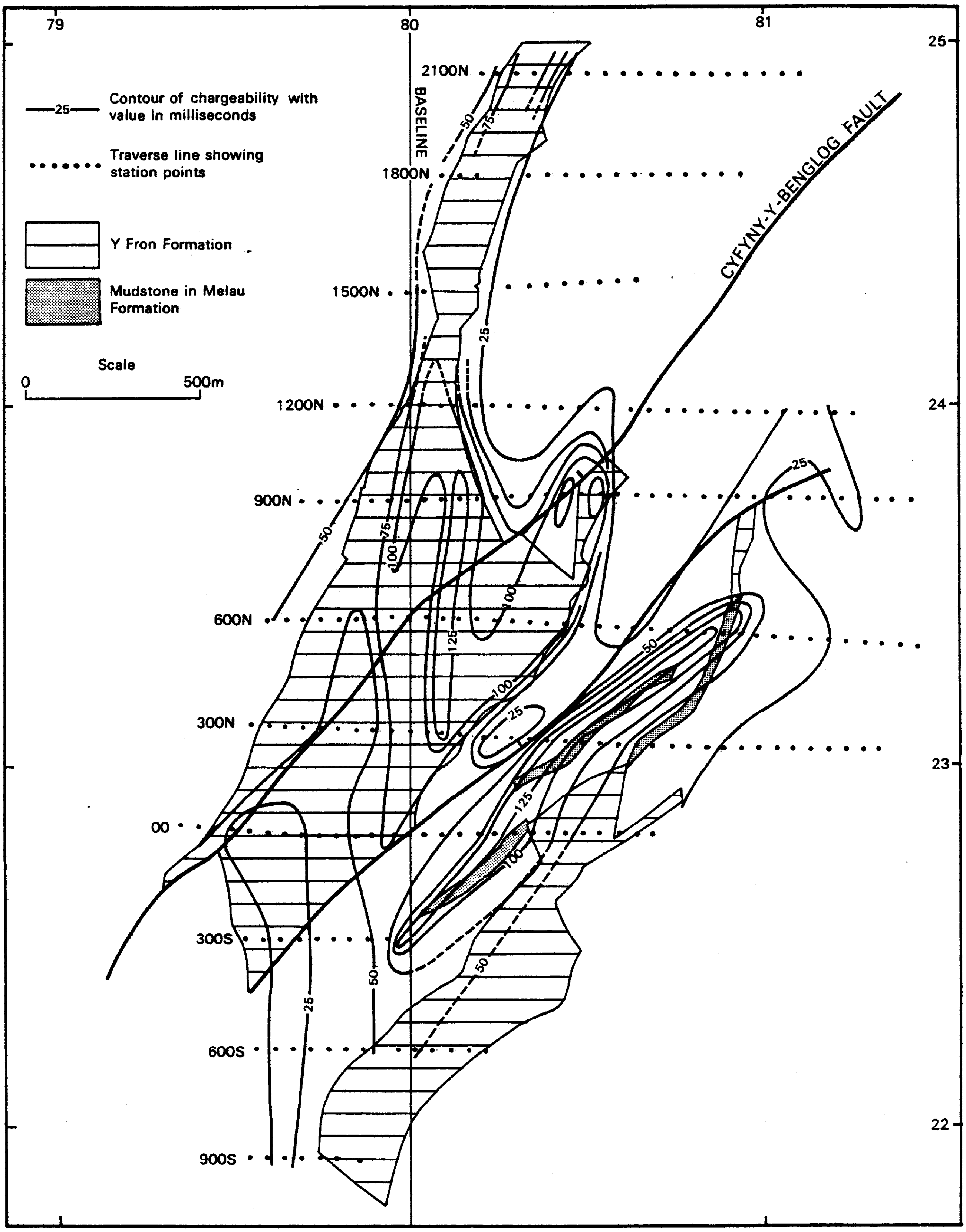

Figure 8: Apparent chargeability contour map.

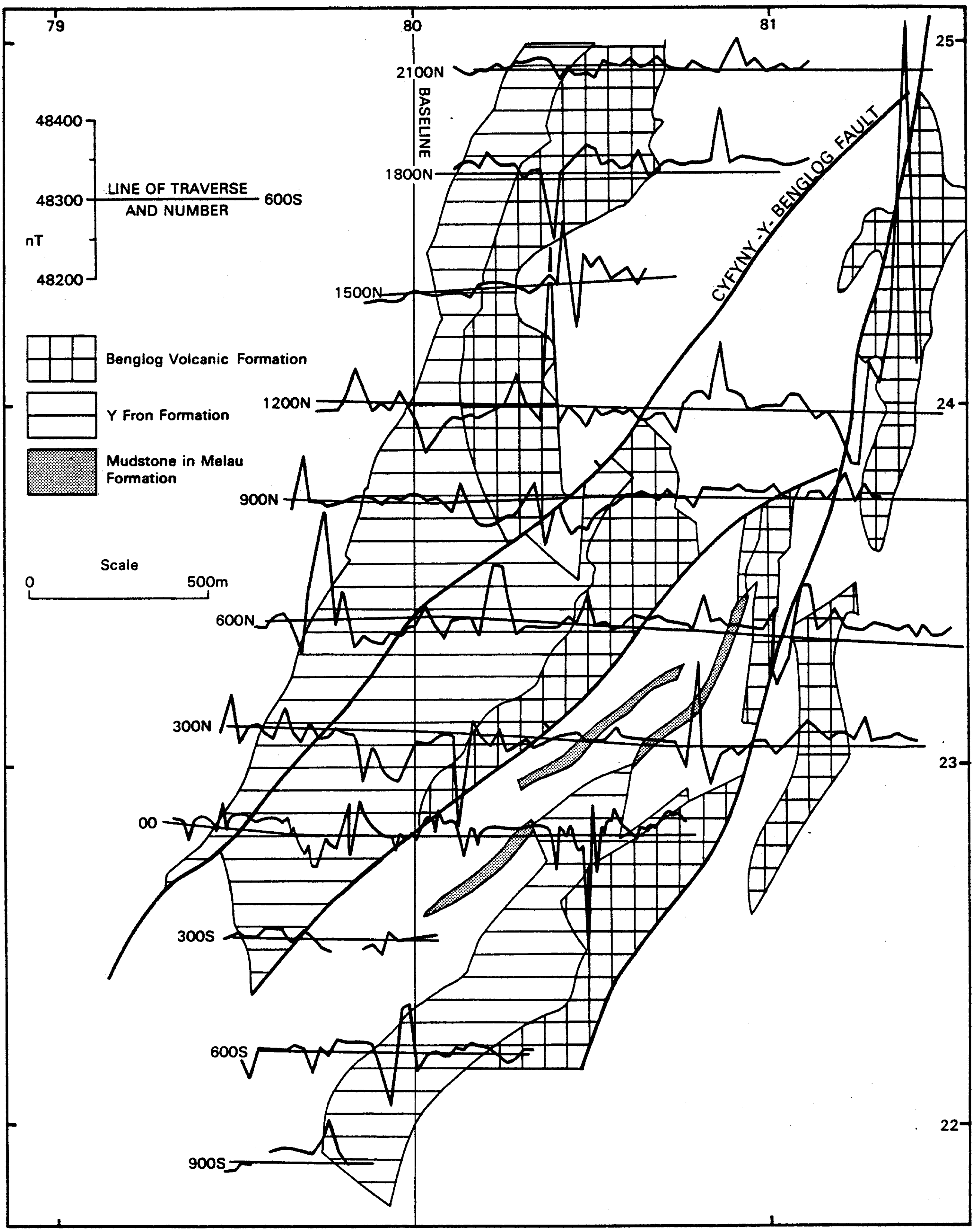

Figure 9: Magnetic field profiles.

conductivity in these rocks, and this effect is likely to be at work here also.

No obvious spatial pattern emerges from the magnetic survey (Figure 9). No geological unit has a characteristic magnetic expression; the magnetic anomalies are isolated and cannot be followed from line to line. There is a statistical pattern however: both anomalies over 200 nT occur in tuffs of the Benglog Formation, and, of ten anomalies of 100–200 nT, five lie over siltstone and four over dolerite intrusions. None of the magnetic anomalies coincides with a geochemical anomaly.

The single strong peak over the Benglog Volcanic Formation at the eastern end of L 1200N has no obvious explanation, though detrital magnetite has been seen in this formation. It is almost 100 m wide and reaches a maximum of 600 nT. To its west lies a broad low, suggesting a steeply dipping source with some depth extent.

Some conclusions may be drawn from the magnetic results. A stratiform source is indicated for much of the magnetism, as most anomalies occur over siltstones or sequences of thin tuffs. The localised nature of the anomalies could be the result of the complex faulting, but probably indicates localised sources for the magnetic minerals including magnetite, which in the Benglog Volcanic Formation is probably detrital, and pyrrhotite, which has been found in both the Y Fron Formation and the Benglog Volcanic Formation and may be diagenetic, epigenetic or have a direct volcanic source.

SUMMARY

On geophysical grounds four areas should be considered for further investigation. These are the two areas of Y Fron Formation separated by the Cyfyny y Benglog Fault, the Melau Formation siltstone and the strong magnetic anomaly at SH 8135 2395. Correlation with geochemical anomalies is poor, which could be interpreted as an absence of base-metal mineralisation associated with the geophysical anomalies. This may be an invalid conclusion, however, because of the secondary nature of many of the geochemical anomalies. The high conductivity of the siltstones is probably due to carbonaceous matter, although sulphides may play a part. The source of the large magnetic anomaly is not known, but elsewhere local concentrations of pyrrhotite appear to be the main cause of magnetic anomalies.

CONCLUSIONS

1 Geological mapping and modelling indicate that the environment during the eruption of the volcanic rocks at Benglog was suitable for the formation of exhalative massive sulphide deposits. Disseminated pyrite and pyrrhotite are present in all rocks below and including the lower part of the Benglog Volcanic Formation and they are especially abundant in mudstone near the top of the Y Fron Formation. The boundary between the Y Fron and Benglog Volcanic formations, therefore, was considered to be the most likely metallogenic horizon.

2 Lead mineralisation is known in veins in the area, spatially associated with the Cyfyny y Benglog Fault, and has been worked on a small scale. Minor occurrences of base-metal mineralisation have been found in association with the margins of dolerite intrusions.

3 Ground geophysical surveys showed very high chargeability coinciding with low resistivity associated with parts of the Y Fron Formation, and a less intense anomaly associated with mudstone in the underlying Melau Formation. These are attributed to the presence of carbonaceous matter, pyrite, and locally pyrrhotite in the rocks. The Allt Lŵyd Formation gives moderately high chargeabilities attributable mainly to disseminated pyrite. Erratic magnetic anomalies probably indicate local concentrations of pyrrhotite mainly in the Y Fron and Benglog Volcanic formations and in dolerite.

4 The geochemical reconnaissance drainage survey revealed weak anomalies of Cu, Pb, As, Ti, Mn, Ni and Sn, and high levels of Ba and Zn in stream sediment. The Ba is not likely to reflect baryte mineralisation. Both barium and zinc anomalies may in part reflect co-precipitation with hydrous manganese or iron oxides, but associated metal values suggest that there is also enrichment in the bedrock locally.

5 The soil sample survey showed several lead and zinc anomalies and some weaker copper anomalies. The majority were attributed in the first instance to secondary concentration phenomena within the weathering zone, and in most cases it was not possible to establish whether these high metal concentrations were derived ultimately from a mineralised source or background levels in bedrock. Some anomalies were spatially related to faults, the margins of basic intrusions, and the exploited vein-style mineralisation. The only anomaly directly attributable to possible mineralisation not of vein type is a cluster of high lead values over basic tuffs of the Melau Formation. The soil survey failed to demonstrate base-metal enrichment associated with any geophysical anomalies and there is no indication of widespread Cu, Pb or Zn enrichment at any particular geological horizon. However, because many of the soil anomalies are the product of secondary redistribution they do not accurately reflect bedrock compositions and only limited weight can be given to their spatial distribution.

6 A small number of rock samples from the Cwmhesgen and Y Fron formations was analysed and showed strong Ba enrichment in both forma-

tions. There is some evidence of slight base-metal enrichment in mudstone from the upper part of the Y Fron Formation. Whether or not this, and the high Ba values, are due to sedimentary provenance and depositional environment has not been determined, but stream sediment results for the Harlech Dome, a few analyses of Aran Volcanic Group rocks and comparison with areas of volcanogenic massive sulphide mineralisation suggest that the Ba enrichment may be volcanogenic and could be related to both the Rhobell Volcanic Group magmatism and the younger Ordovician episodes.

RECOMMENDATIONS

The findings of this investigation are inconclusive. Weak mineralisation can be demonstrated in veins, at dolerite margins and associated with faults. It has been shown that a metallogenic horizon may exist at the top of the Y Fron Formation but the presence of volcanogenic stratabound base-metal deposits within it has neither been demonstrated nor ruled out. Barium enrichment of sediments, possibly related to volcanism and mineralisation, has been found.

The following further work is recommended as a means of elucidating some of the remaining assessment problems without the high cost of subsurface exploration at the present stage:

1 Analysis of rock samples from the Cwmhesgen, Allt Lŵyd, Melau, Y Fron and Benglog formations for K, Na, Ba, Rb, Sr, Ca, Mg, Fe, Mn, Cu, Pb, Zn and possibly other elements, to establish the presence or absence of a lithogeochemical dispersion halo related to volcanogenic sulphide mineralisation.

2 Sequential partial extraction of soil samples for Pb and Zn to try and resolve the cause of soil anomalies.

3 Analysis of samples of vein mineralisation for elements associated with low temperature mineralisation at the periphery of volcanic centres, notably Ag, but also Au and Hg.

4 If geochemical results indicate the presence of mineralisation, a gravity survey of the areas of greatest potential to distinguish between graphite and sulphide as sources of the strong IP and resistivity anomalies, and thereby outlining a drilling target.

ACKNOWLEDGEMENTS

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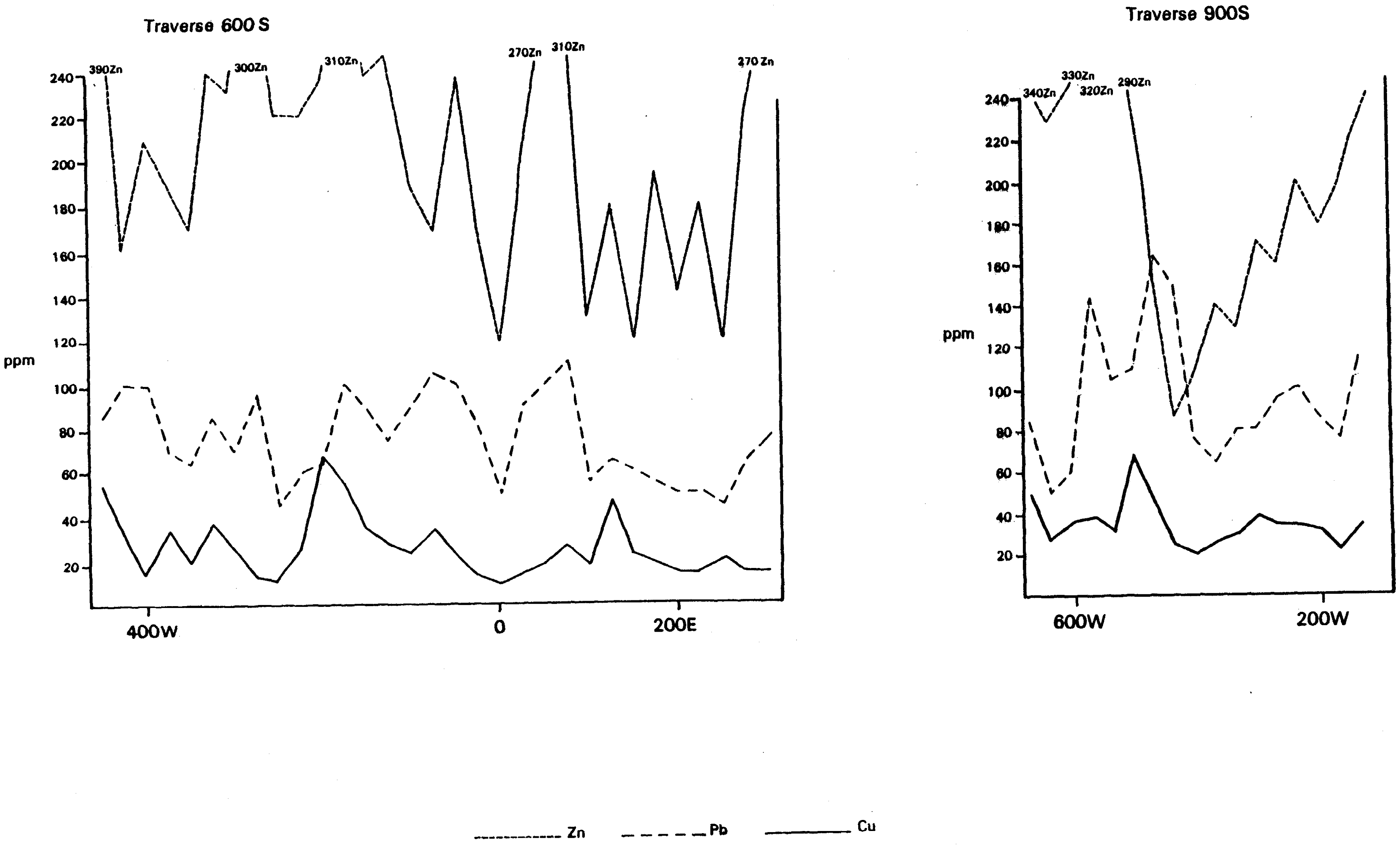
APPENDIX 1

Copper, lead and zinc in soil samples, plotted along traverse lines

A	i	Traverse lines 900S, 600S
A	ii	Traverse lines 300S, 0S
A	iii	Traverse lines 300N, 600N
A	iv	Traverse lines 900N, 1200N
A	v	Traverse lines 1500N, 1800N
A	vi	Traverse line 2100N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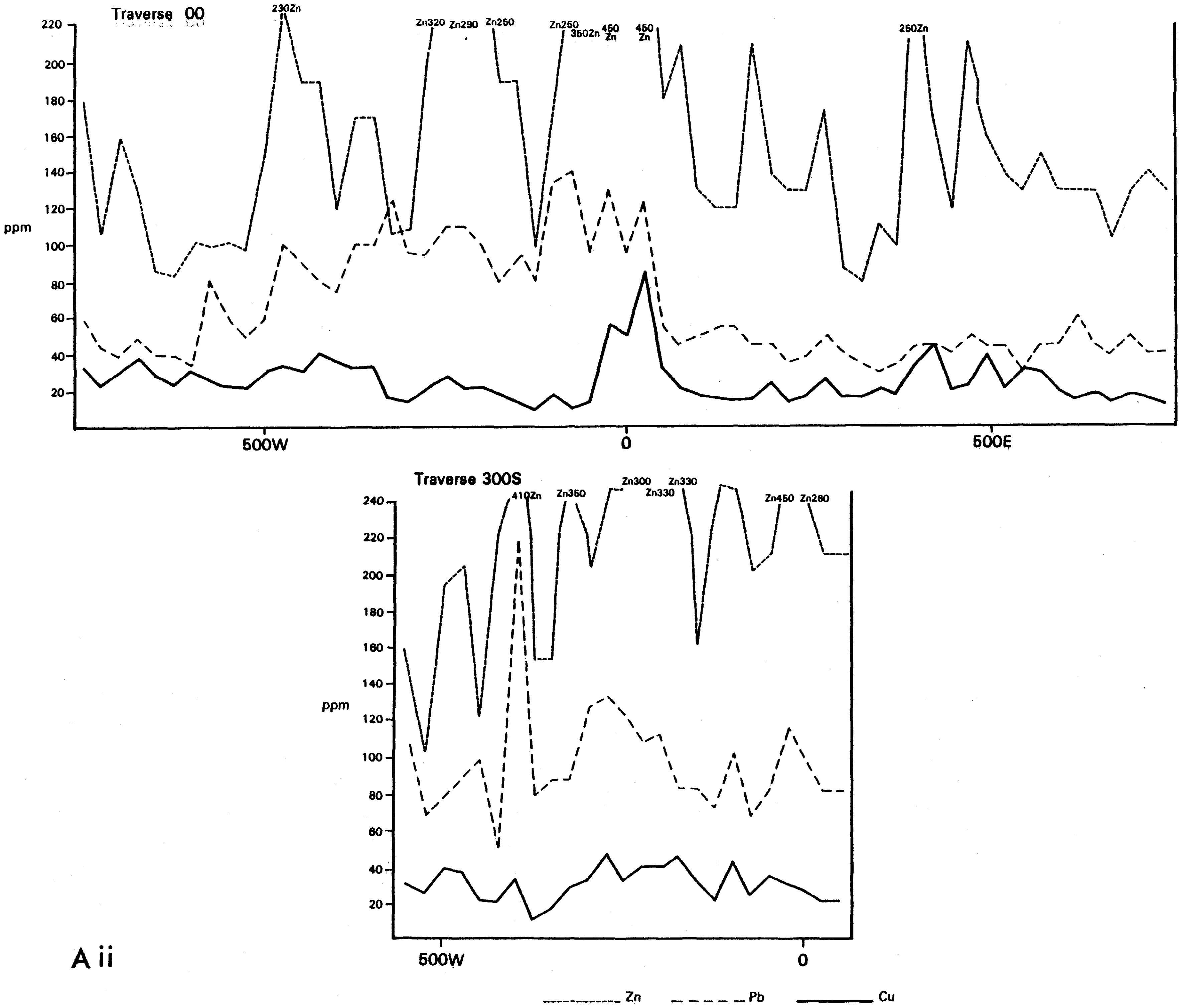
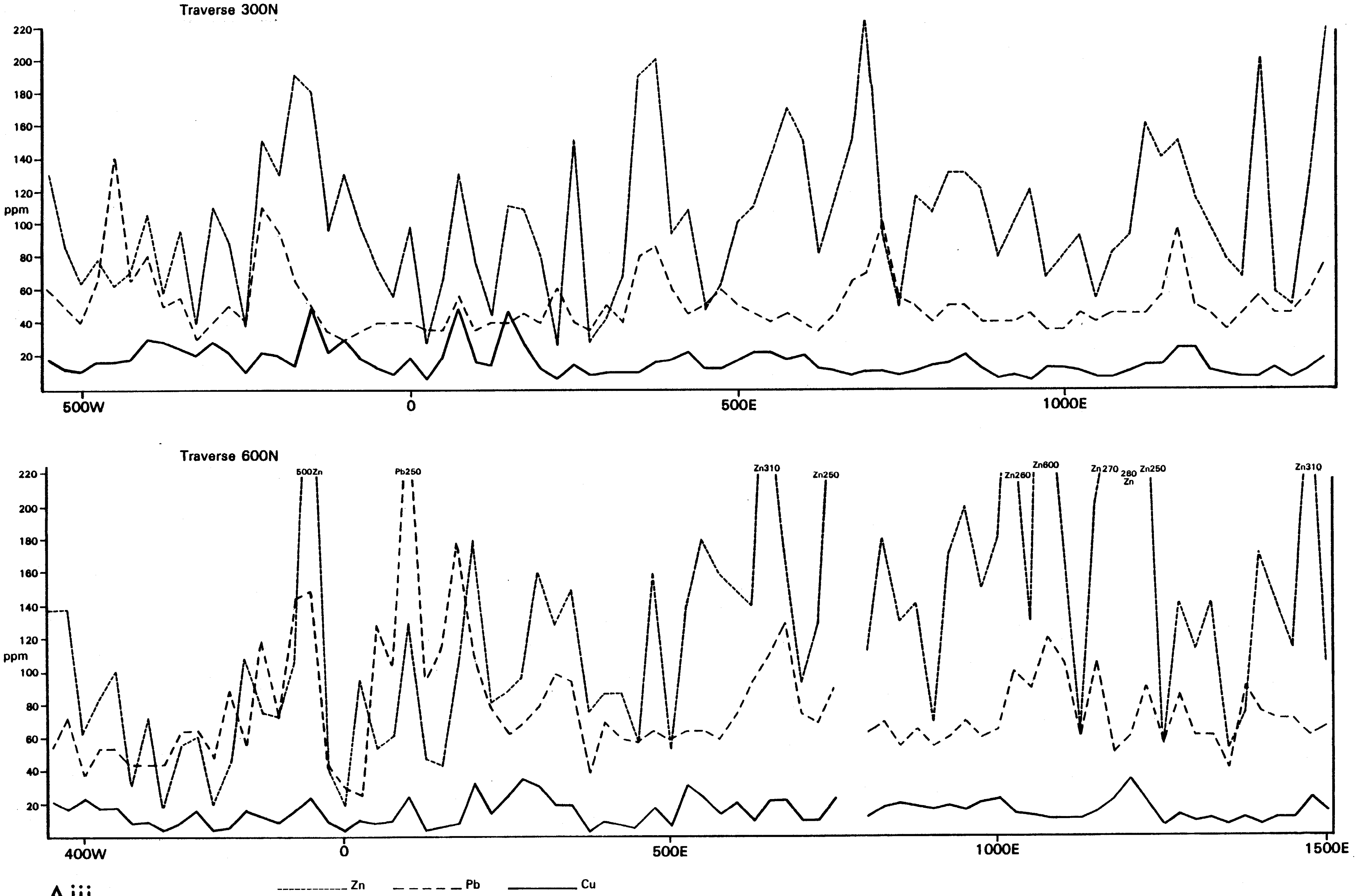
300Zn
310Zn
270Zn
310Zn
270 Zn
240
220
200
180
160
140
120
100
80
60
40
20
ppm
400W
0
200E
Traverse 900S
340Zn
330Zn
320Zn
290Zn
240
220
200
180
160
140
120
100
80
60
40
20
ppm
600W
200W
Zn
Pb
Cu

Ai


Traverse 00
ppm
220
200
180
160
140
120
100
80
60
40
20
230Zn
Zn320
Zn290
Zn250
Zn250
350Zn
450 Zn
450 Zn
250Zn
500W
0
500E
Traverse 300S
ppm
240
220
200
180
160
140
120
100
80
60
40
20
410Zn
Zn350
Zn300
Zn330
Zn330
Zn450
Zn260
500W
0
Zn
Pb
Cu

A ii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160
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ppm
100
80
60
40
20
500W
0
500E
1000E
Traverse 600N
500Zn
Pb250
Zn310
Zn250
Zn260
Zn600
Zn 270
280 Zn
Zn250
Zn310
220
200
180
160
140
120
ppm
100
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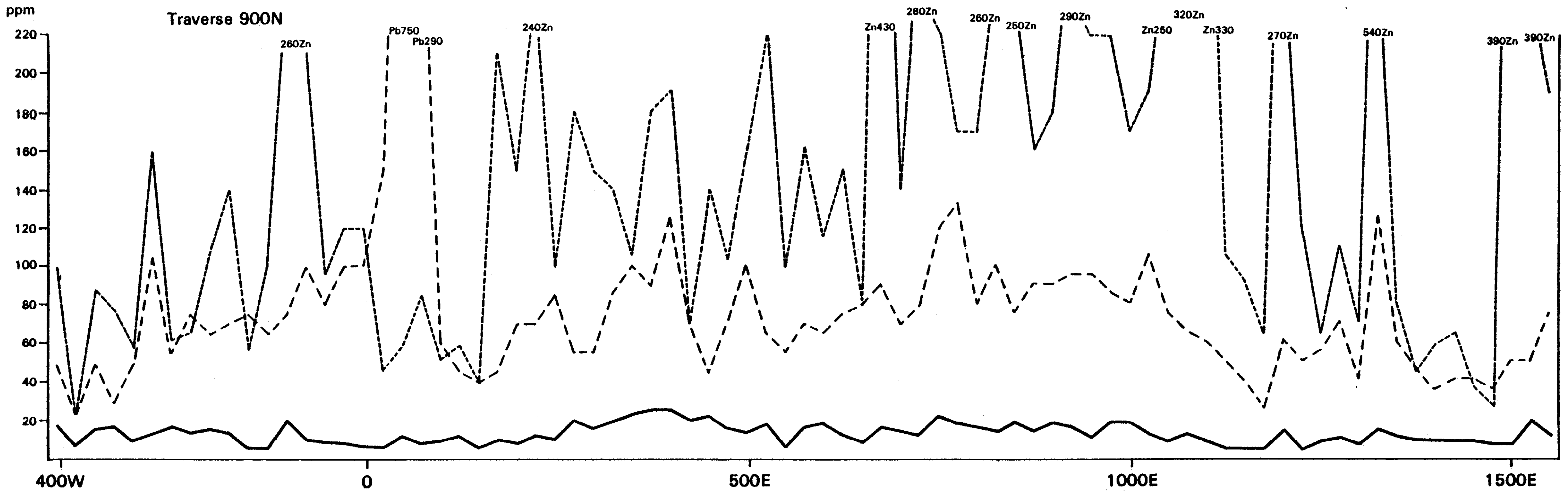
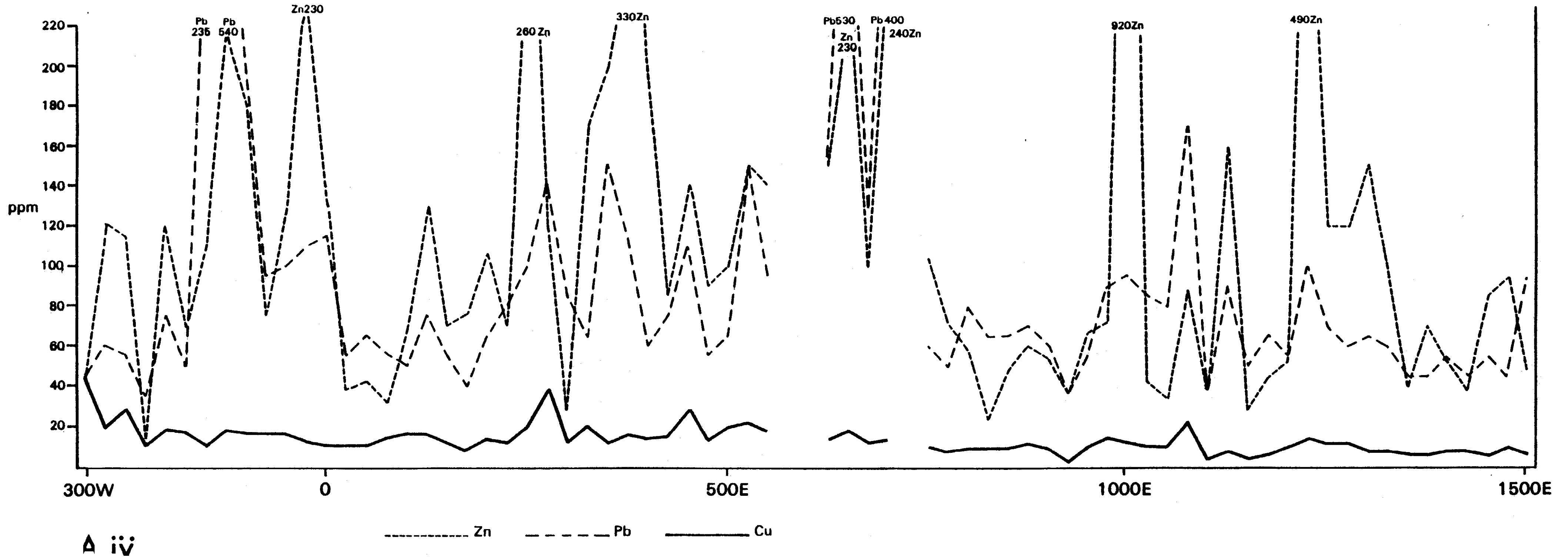
40
20
400W
0
500E
1000E
1500E
Zn
Pb
Cu

Aiii

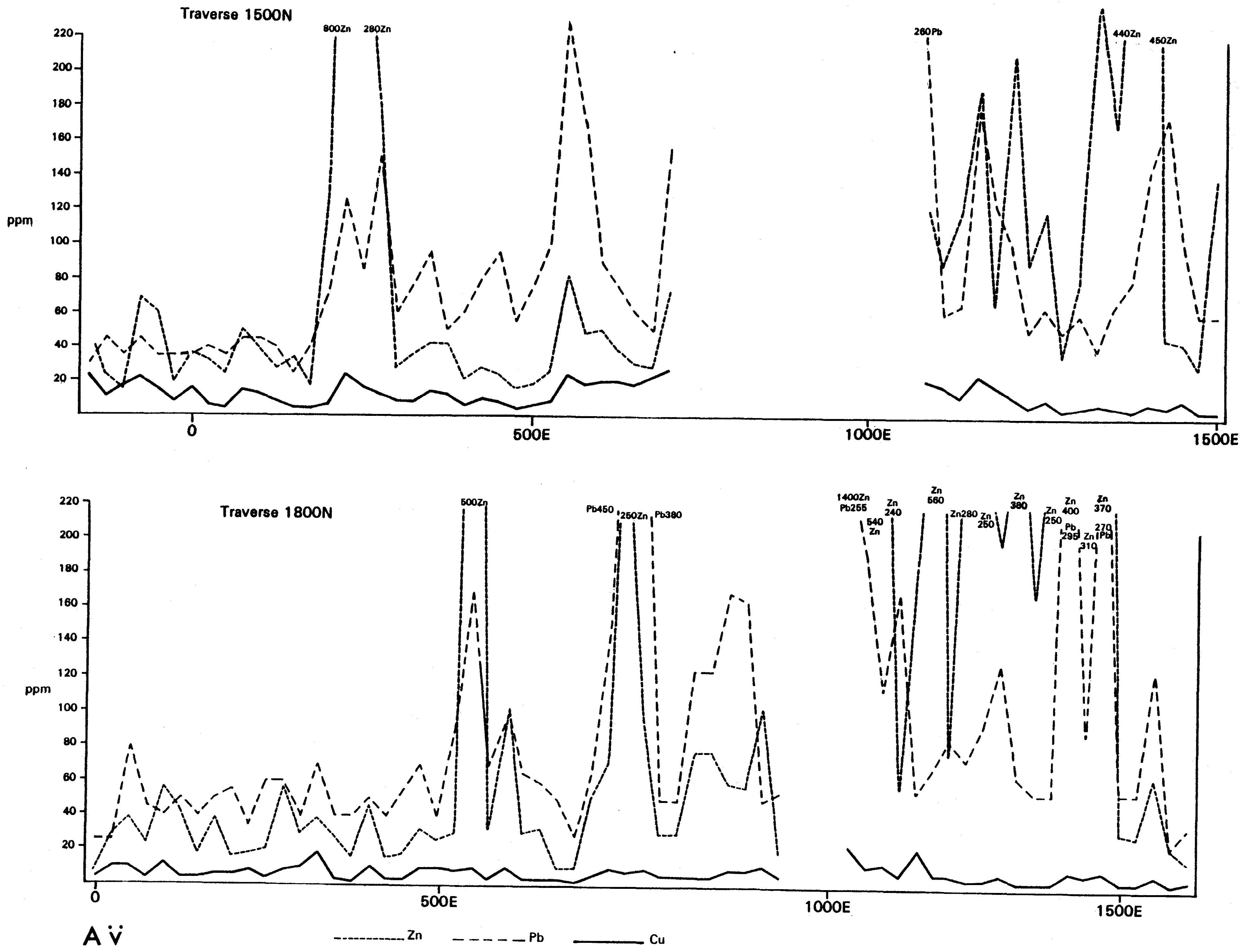
Traverse 900N



Traverse 1200N



A iv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450Zn
ppm
220
200
180
160
140
120
100
80
60
40
20
0
500E
1000E
1500E
Traverse 1800N
500Zn
Pb450
250Zn
Pb380
1400Zn
Pb255
540
Zn
Zn
240
Zn
560
Zn280
Zn
250
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Pb
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Zn
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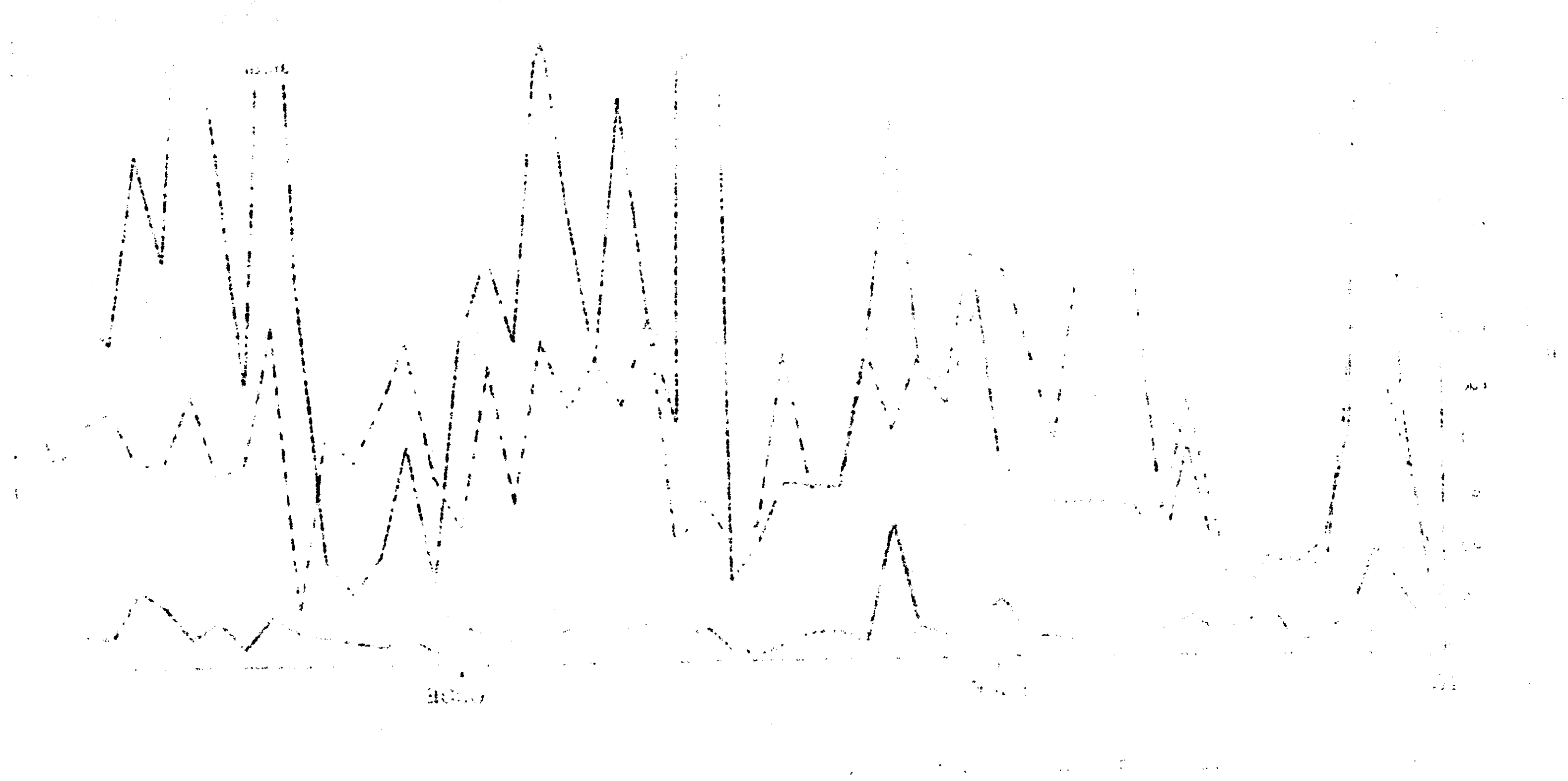
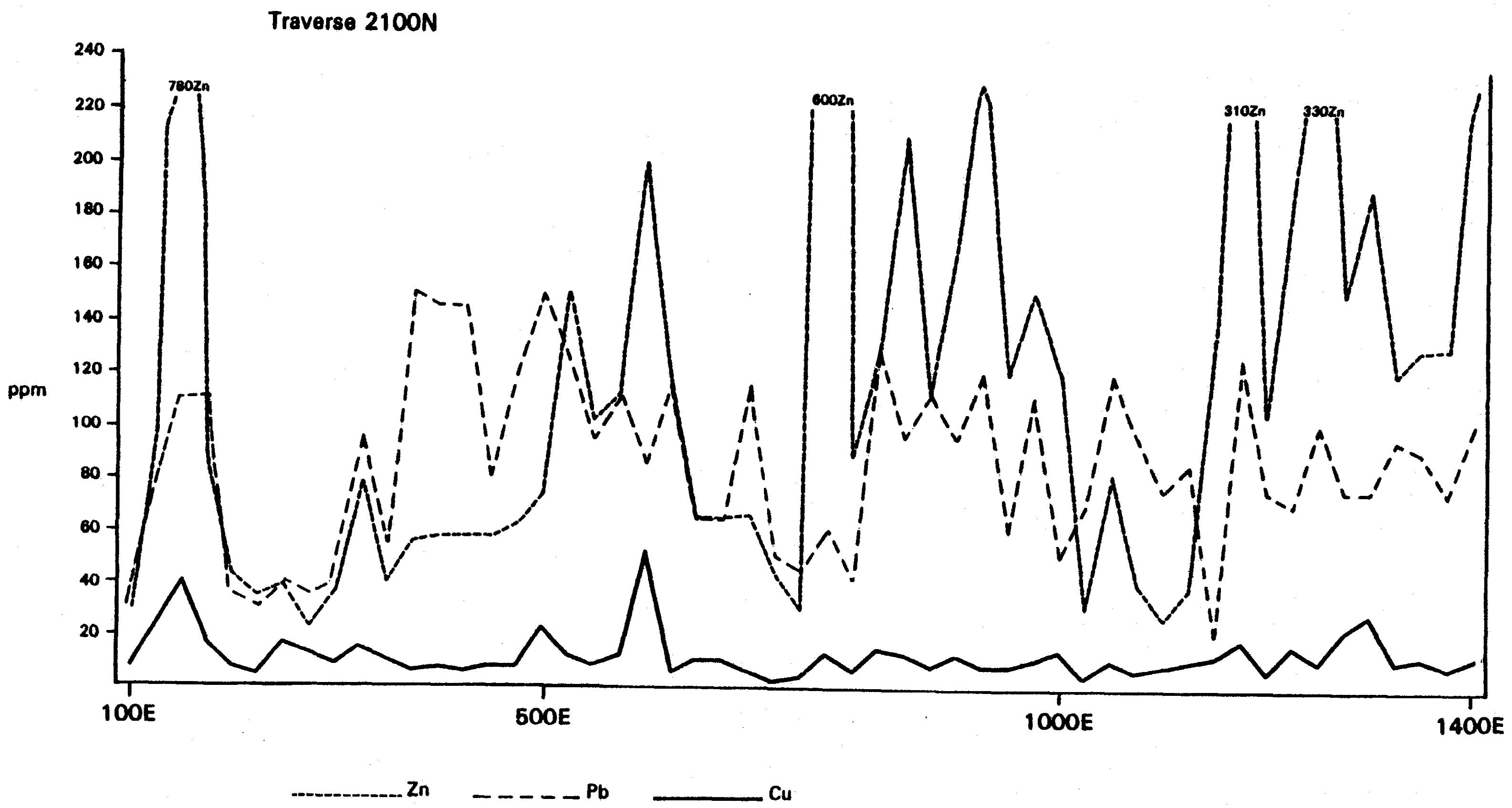
270
Pb
Zn
Pb
Cu

A V




Traverse 2100N
ppm
240
220
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120
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330Zn
100E
500E
1000E
1400E
Zn
Pb
Cu

A vi

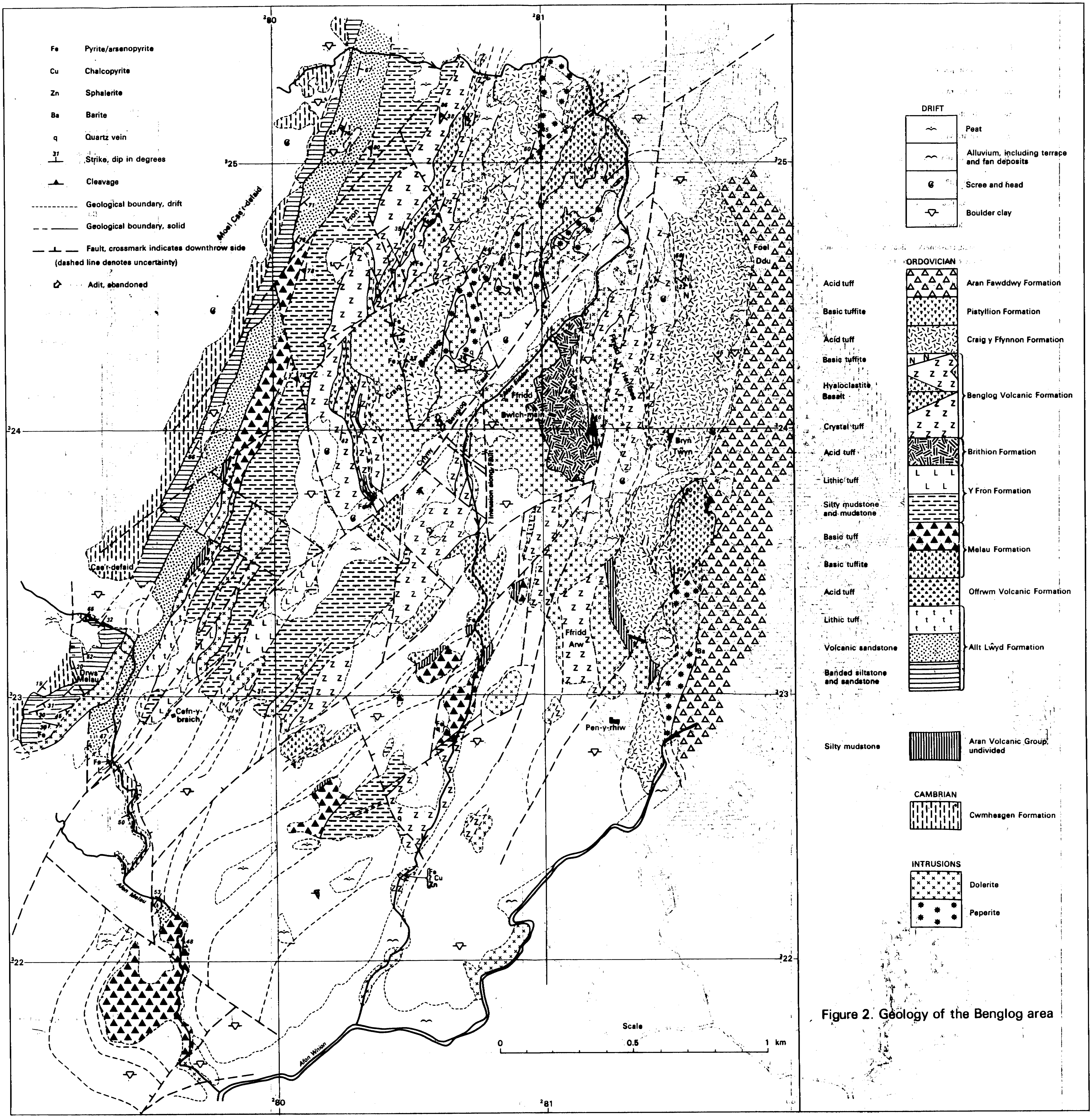

Figure 2. Geology of the Benglog area