Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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No. 46

Gold mineralisation at the southern margin of the Loch Doon granitoid complex, south-west Scotland

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Gold mineralisation at the southern margin of the Loch Doon granitoid complex, south-west Scotland

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2 Geochemical and geophysical investigations around Garras Mine, near Truro, Cornwall
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SUMMARY

Following the identification of gold in a panned concentrate sample from the diverted headwaters of Glenhead Burn, south-east of Loch Trool in Galloway, Scotland,and the discovery of native gold with arsenopyrite in a quartz vein upstream of this site, a programme of geochemical exploration of the margin and aureole of the Loch Doon plutonic complex in the drainage basin was initiated. Since rock samples showed a highly significant positive correlation between gold and arsenic levels a soil grid was sampled in the contact zone and analysed for arsenic, together with copper, lead and zinc. Several arsenic anomalies with levels exceeding 1000 ppm were found within the pluton and its aureole and seven shallow boreholes were drilled to test their source. Geophysical surveys using magnetic, Slingram EM, VLF and IP methods were carried out but none showed anomalies which correlated with zones of high arsenic in soil.

In the area around the headwaters of Glenhead Burn, the Loch Doon plutonic complex is intrusive into a sequence of graded turbidites of probable Caradocian age. In the northern part of the area, steeply-dipping greywacke horizons young consistently to the north while in the south there is evidence of several tight upright folds. South of the area there is a large-scale reclined fold developed in the siliceous mudstones, shales and cherts of a "black shale belt", though a major strike fault may separate the two sequences. Swarms of concordant minor intrusive rocks of quartz monzonite and granodiorite, which predate the pluton, have been encountered in its aureole. Major differences in chemistry exist between these minor intrusions and the composition of the margin of the plutonic complex.

A pervasive phase of metasomatism has affected the sedimentary rocks throughout the area, producing veins and lenses of fine granular quartz accompanied by actinolite, salitic pyroxene, fine magnetite and pyrrhotite, and occasionally carbonate, chalcopyrite, sphalerite, pyrite, sphene, clinozoisite, epidote and apatite. These are surrounded by greener envelopes rich in actinolite which grade into normal hornfelsed sediment. Close to the pluton, clinopyroxene is more conspicuous and better-formed in both altered and unaltered hornfelsed rock. Chemical data indicate that two types of metasomatically altered zones occur, one enriched in calcium and some manganese and strontium, and the other enriched in silicon. The minor igneous rocks are unaffected by the metasomatism but show contact metamorphism due to the pluton.

Two phases of gold-bearing, arsenic-rich mineralisation have been recognised. The earlier comprises disseminations of pyrrhotite, arsenopyrite and pyrite in the margins of monzonitic minor intrusions and disseminations of arsenopyrite in the adjacent metasediments. This mineralisation occurs in zones up to at least 18 m thick with arsenic levels reaching 3000 ppm and gold 0.16 ppm in samples of around one metre of core. It is probable that the majority of soil arsenic anomalies, particularly the lensoid variety trending parallel to the strike, originate from this type of mineralisation. Superimposed upon this are a series of discordant quartz veins and stringers trending roughly south and cutting all rock types. These may be richly mineralised with arsenopyrite and some pyrite and may contain minute grains of native gold. Surrounding the veins is a prominent alteration envelope of sericitic material, commonly with conspicuous disseminated arsenopyrite. Individual veins range up to 30 cm thick but thicker stockwork zones also exist. Arsenic levels in 200-300 g samples of veined material reach over 3.5% and gold assays up to 8.8 ppm have been obtained. A separate minor phase of sphalerite and galena mineralisation also occurs within the area, usually in association with carbonate veinlets.

INTRODUCTION

A geochemical drainage survey of the Loch Doon granitoid complex and its environs (Figure 1) (Dawson and others, 1977; Leake and others, 1978), was carried out by the IGS as part of a programme of mineral reconnaissance on behalf of the Department of Industry. During this survey a few grains of gold were identified in a panned concentrate sample collected from the diverted headwaters of the Glenhead Burn (Figure 2). More detailed examination of the stream discovered boulders of the Loch Doon granite containing arsenopyrite-rich quartz veins. A similar vein was also found in a stream-side exposure near the granite margin upstream of the drainage sample site. Mineralogical examination showed the vein to contain a few small grains of native gold. This discovery led to the initiation of a follow-up survey of the contact zone of the Loch Doon granite.

The Loch Doon granitoid complex (Figure 1) is intruded into the thick Siluro-Ordovician turbidite sequence which forms the Southern Uplands of Scotland. The sedimentary lithologies range from shale and mudstone to pebble conglomerates, but in the Glenhead Burn area medium-grained greywacke is the most common rock type with a structurally complex zone of siliceous mudstone and subordinate chert cropping out in the southern part. A major strike fault may separate these two lithological units. The strata are vertical or steeply dipping with an approximately east-west strike representing a local variation from the regional north-east to south-west strike seen throughout the Southern Uplands. The Loch Doon

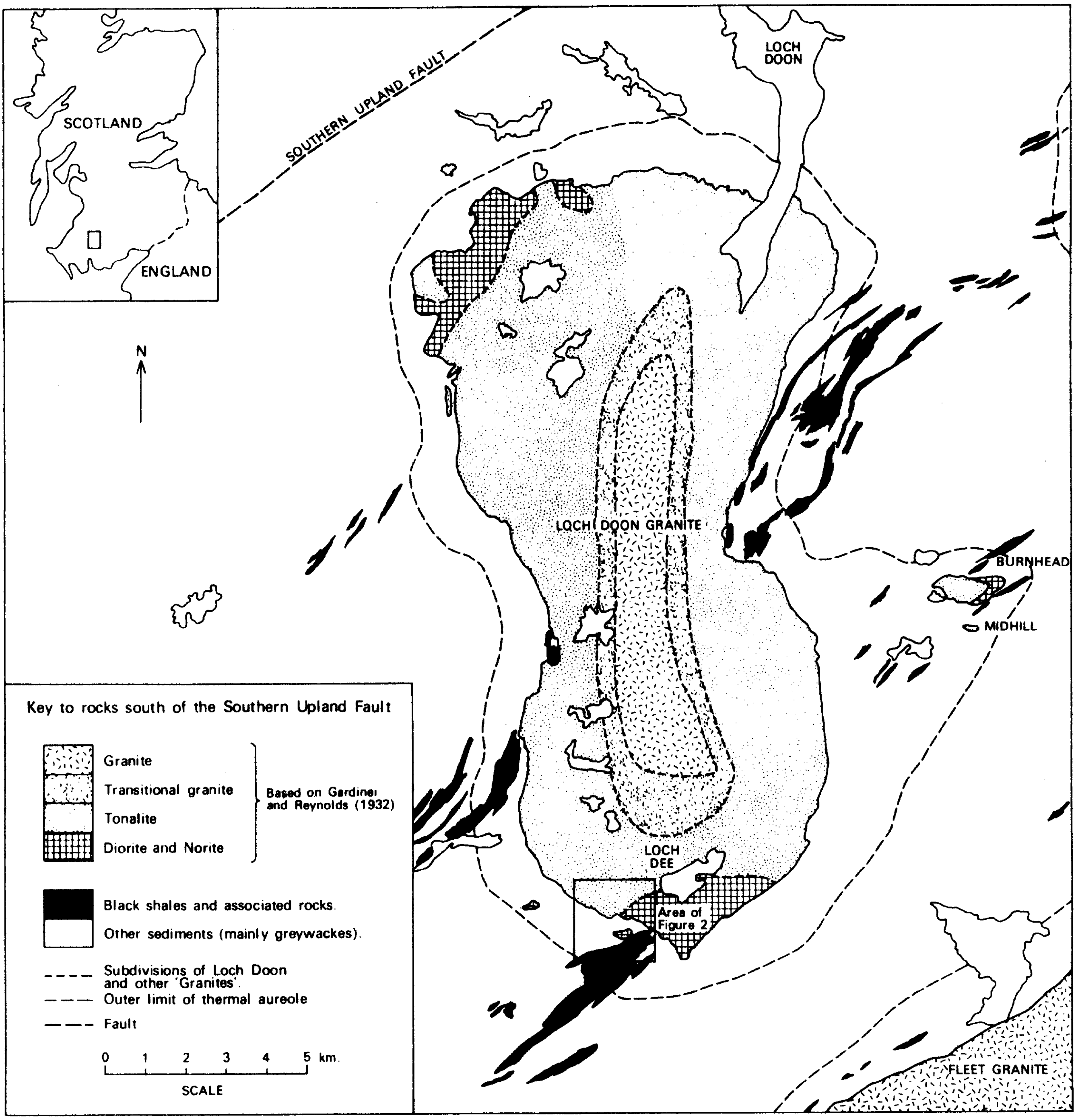


Fig.1 Map of Loch Doon granitoid complex showing location of survey area

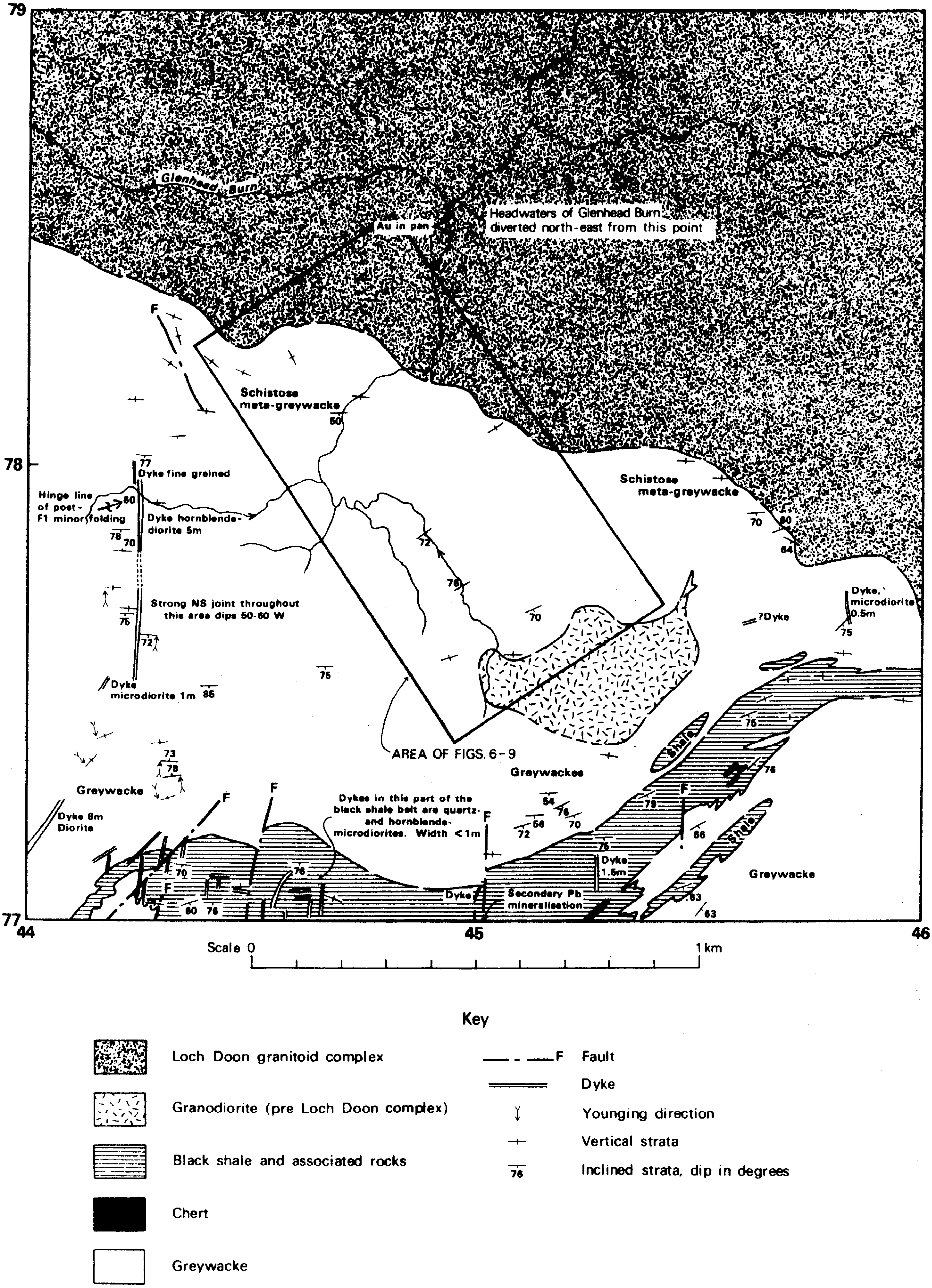


Fig.2 Geological map of survey area

granitoid complex itself is zoned and shows a continuous lithological variation from granite in the centre of the pluton to hypersthene-diorite or norite at the margin (Figure 1; Gardiner and Reynolds, 1932; G.C. Brown and others, 1979). During intrusion of the pluton, thermal metamorphism converted the finer-grained rocks in the contact zone to an andalusite-cordierite hornfels with local development of garnet.

EXPLORATION

Quartz-arsenopyrite veins were discovered in situ at several sites within the contact zone of the Loch Doon granite on either side of Glenhead Burn. Analyses of a few samples of veins and veined rock, by instrumental neutron activation, showed levels of gold between 0.35 ppm and 8.8 ppm and demonstrated the significant positive correlation between gold and arsenic levels (Figure 3) showed by all the rock types in area. Furthermore, the most auriferous sample also contained 90 ppm Ag, 1600 ppm Pb and 125 ppm Bi though these elements were not enriched in the other samples. Accordingly, an orientation soil survey on a grid spacing of 5 m was conducted around an exposure containing several arsenopyrite-rich veins, and the soil samples analysed for arsenic. Samples of both A and C horizon soils were obtained from most sites for comparison, as the area is marked by considerable overburden thickness variations and the widespread development of peat. Comparison of both sample types showed similar distribution patterns and element concentration levels. The cumulative frequency plots of both sample types (Figure 4) illustrate the close correlation between the two, with only slightly higher levels occurring in the C horizon samples. It was therefore concluded that only one sample would suffice for further soil sampling and that arsenic levels in both A and C horizons could be directly compared even when the nature of the soil meant that only A horizon material could be obtained.

As the orientation survey showed that arsenic levels in soil reached over 1000 ppm, and that anomalies were much more widespread than could be accounted for by any extensions of the visible vein mineralisation, a grid covering a much larger area of the contact zone was sampled (Figures 6-9). Samples were obtained using a hand auger and were mostly of C horizon; but in areas of very thin soil or deep peat, A horizon samples were collected. The samples were analysed for As by XRF and most of them also for Cu, Pb and Zn by AAS after hot nitric acid digestion. Cumulative frequency plots for these four elements are shown in Figure 5 and the distributions of As, Cu, Pb and Zn anomalies in Figures 6 to 9 respectively. Because of the considreable variation in overburden thickness, in what originally was a series of three stepped corries occupied by a hanging glacier, the soil maps are plotted on a base containing topographical information taken from surface observations and air photographs to assist in the evaluation of the influence of the secondary environment upon the soil geochemistry.

Figure 6 shows that As anomalies are widespread with several samples containing levels in excess of 1000 ppm Most anomalies are elongated in a direction approximately parallel to the strike of the country rocks and, although mostly within the aureole, some cross the contact into the margin of the Loch Doon pluton. The distribution of anomalies appears more complex in the area adjacent to the pluton in the north-east of the area but the strike trend is still apparent. In the centre of the area anomalies are sparse but this may be due, at least in part, to a greater thickness of overburden in the centre of the corrie basin which could mask arsenic enrichment arising from mineralisation in the bedrock.

Lead anomalies (Figure 7) are generally of much smaller amplitude than those for arsenic and their distribution differs in detail, particularly in the north-east of the area. A series of Pb anomalies follows the line of the stream towards the northern part of the area, probably derived from secondary dispersion of lead down the stream. Agreement between anomalies is best in the southern part of the area where lead levels tend to be highest. The distribution of the low amplitude zinc anomalies (Figure 8) generally agrees with those of lead except for their absence along the line of the Glenhead Burn and also in the contact zone in the north-east of the area. Copper anomalies (Figure 9) are much less abundant than those of the other elements but tend to correlate with the lead and zinc anomalies in the southern part of the area.

Orientation magnetic, Slingram EM and IP surveys were carried out over the ground containing high As anomalies adjacent to the granite margin in the north-eastern part of the area. Little EM response was obtained, while IP results showed a general increase in chargeability and decrease in resistivity from the pluton to the metasediments. In detail, neither IP nor resistivity anomalies showed any clear correlation with soil As anomalies. Further magnetic and VLF surveys were carried out over most of the area covered by the soil sampling and are shown in Figures 10-13. The survey showed little magnetic variation within the granite but strong variation within the country rocks, with large (1000 gammas) localised magnetic anomalies mostly parallel to the strike (Figure 13). The source of these anomalies is uncertain though borehole intersections have shown that some basic intrusions do occur. Broader, lower-amplitude (100 gammas) magnetic anomalies also occur in the contact aureole and a borehole intersection suggests that pyrrhotite disseminated in concordant intrusive rocks, particularly of grandiorite composition, may be the source of some of these. The VLF in-phase contour map (Figure 10) shows a steep positive gradient or crossover, giving high Fraser-filter values (Figure 12), approximately following the contact zone of the pluton but with the maximum anomaly about 80 m south of the exposed contact. This suggests that the highest grade of hornfelsed sedimentary rocks have a VLF response similar to that of the plutonic rocks. There are also some broad low-amplitude anomalies within the pluton which may reflect discontinuities in composition.

DRILLING

Seven inclined boreholes were drilled to investigate the source of several soil arsenic anomalies and their positions

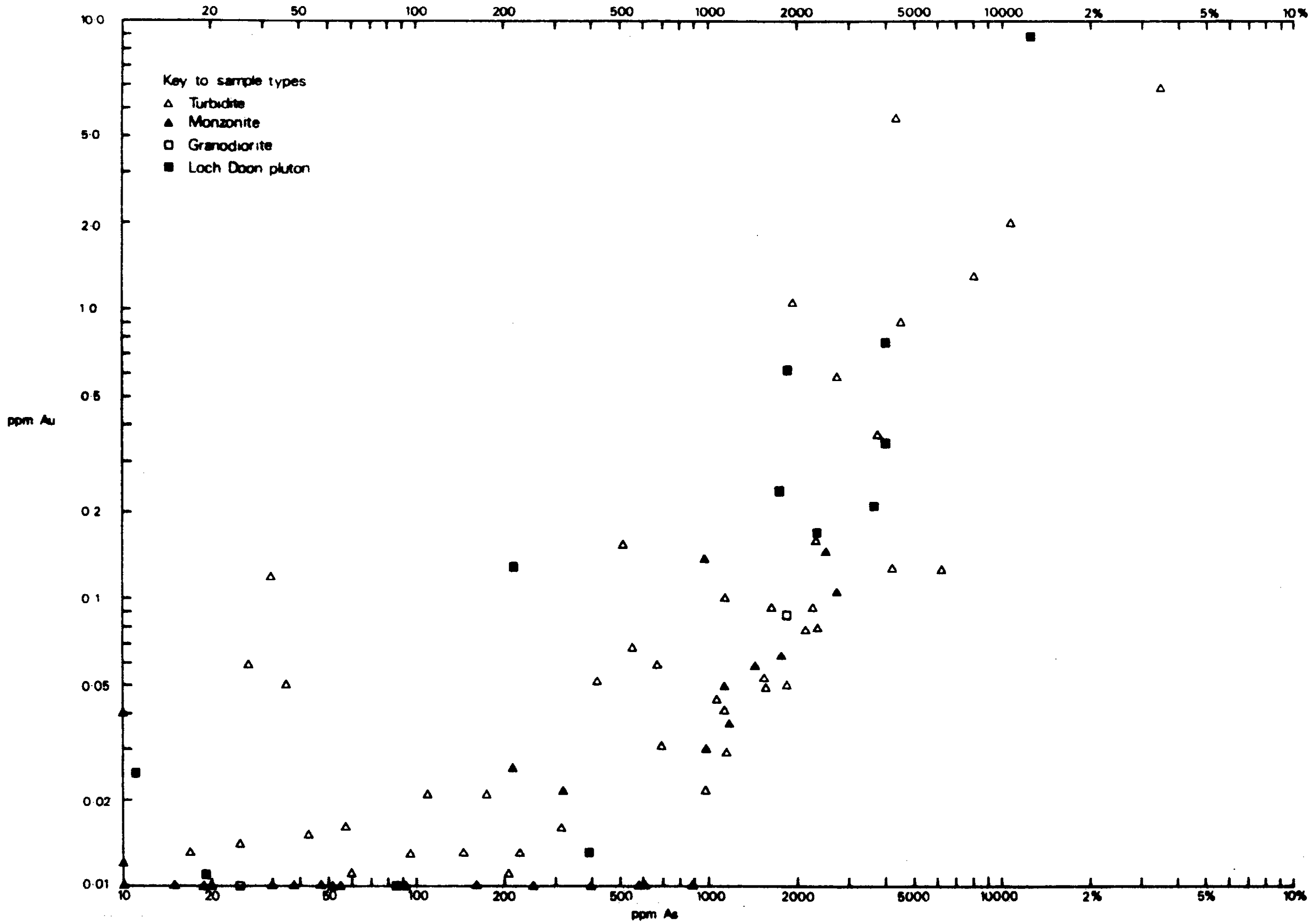


Fig.3 Relationship between Au and As in rock and drill core samples

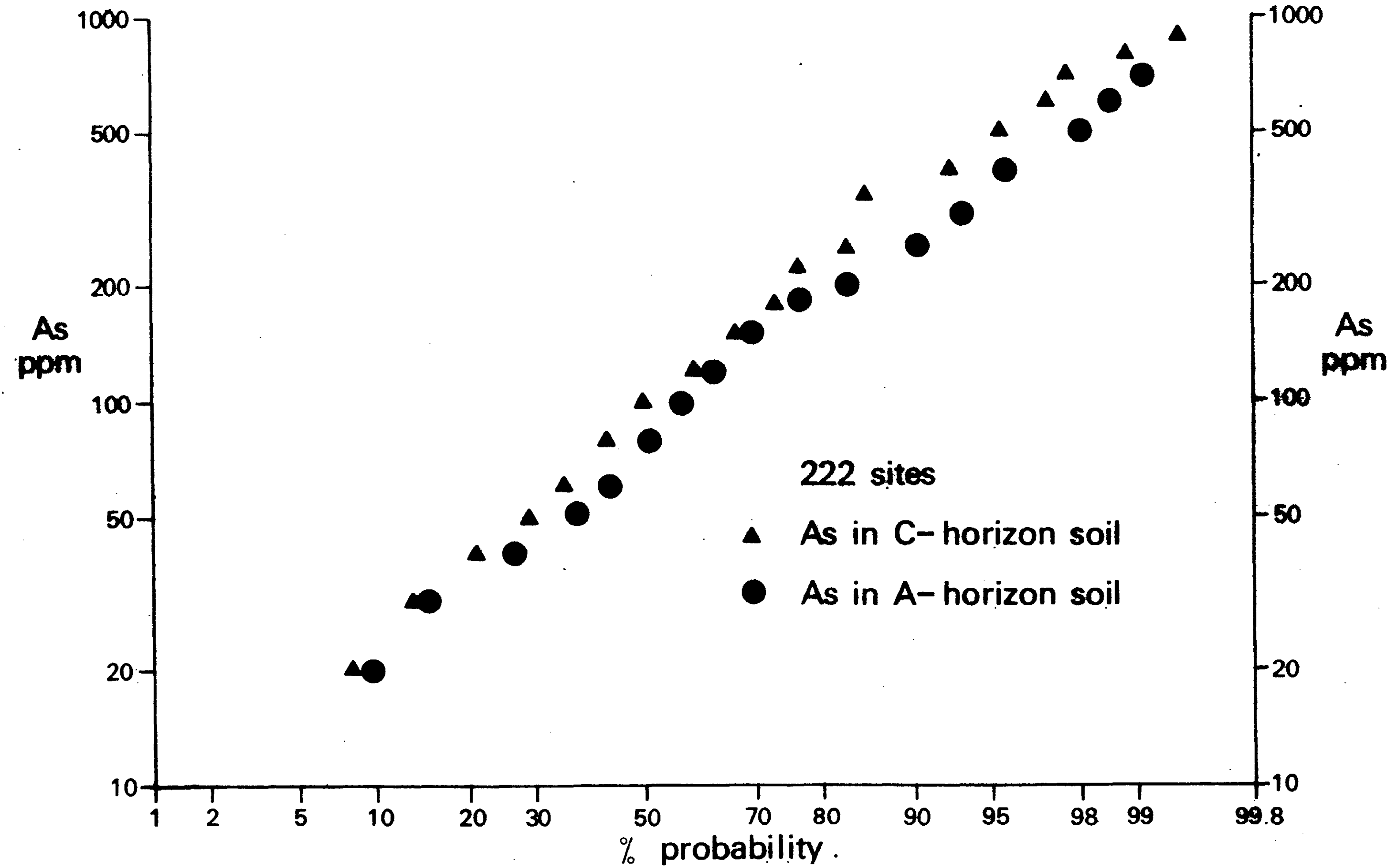


Fig. 4 Cumulative frequency plot for As in A and C horizon soil samples, orientation survey

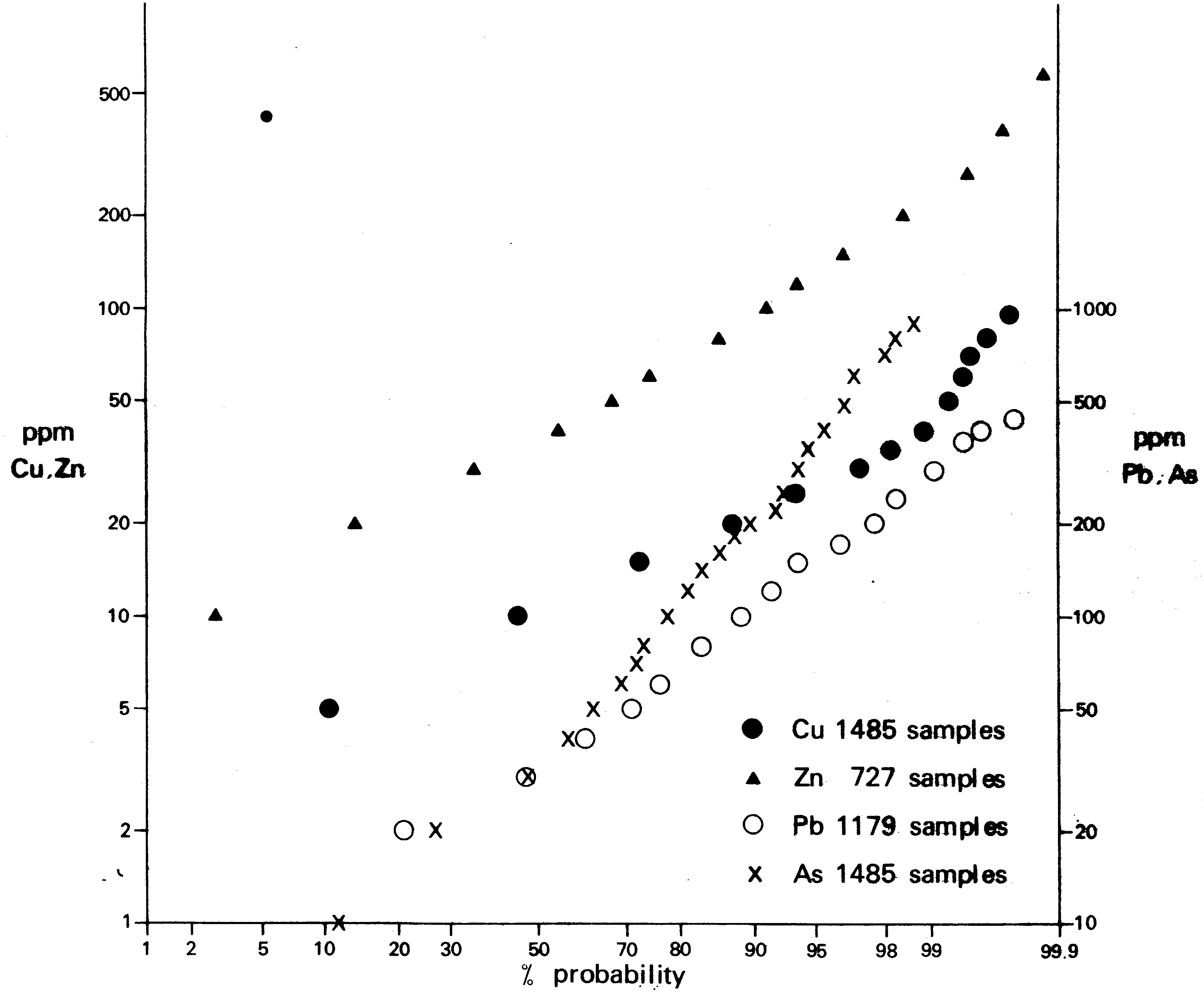


Fig.5 Cumulative frequency plot for AS,Cu,Zn,& Pb in soil samples, main survey

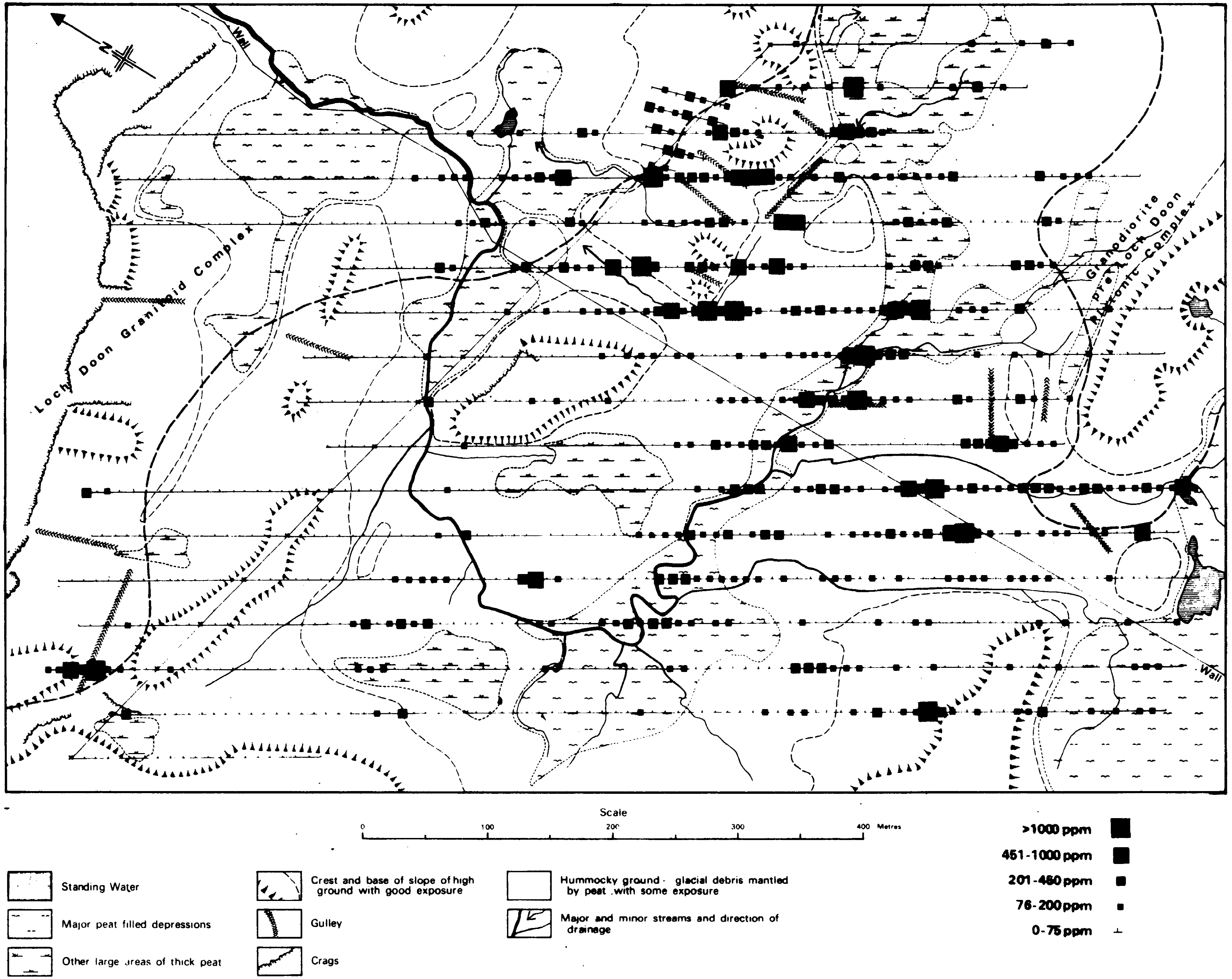


Fig 6 Distribution of As in soil

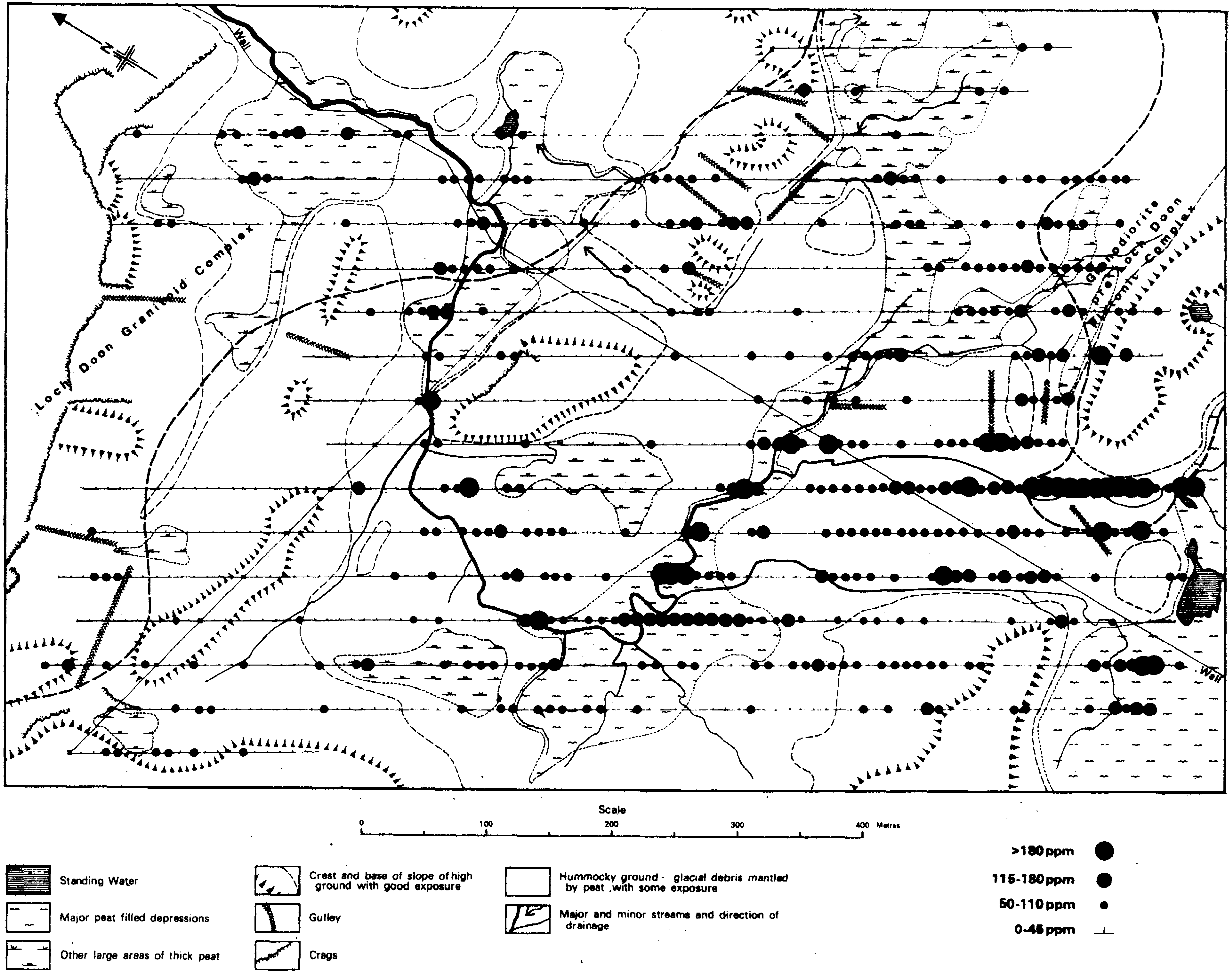


Fig 7 Distribution of Pb in soil

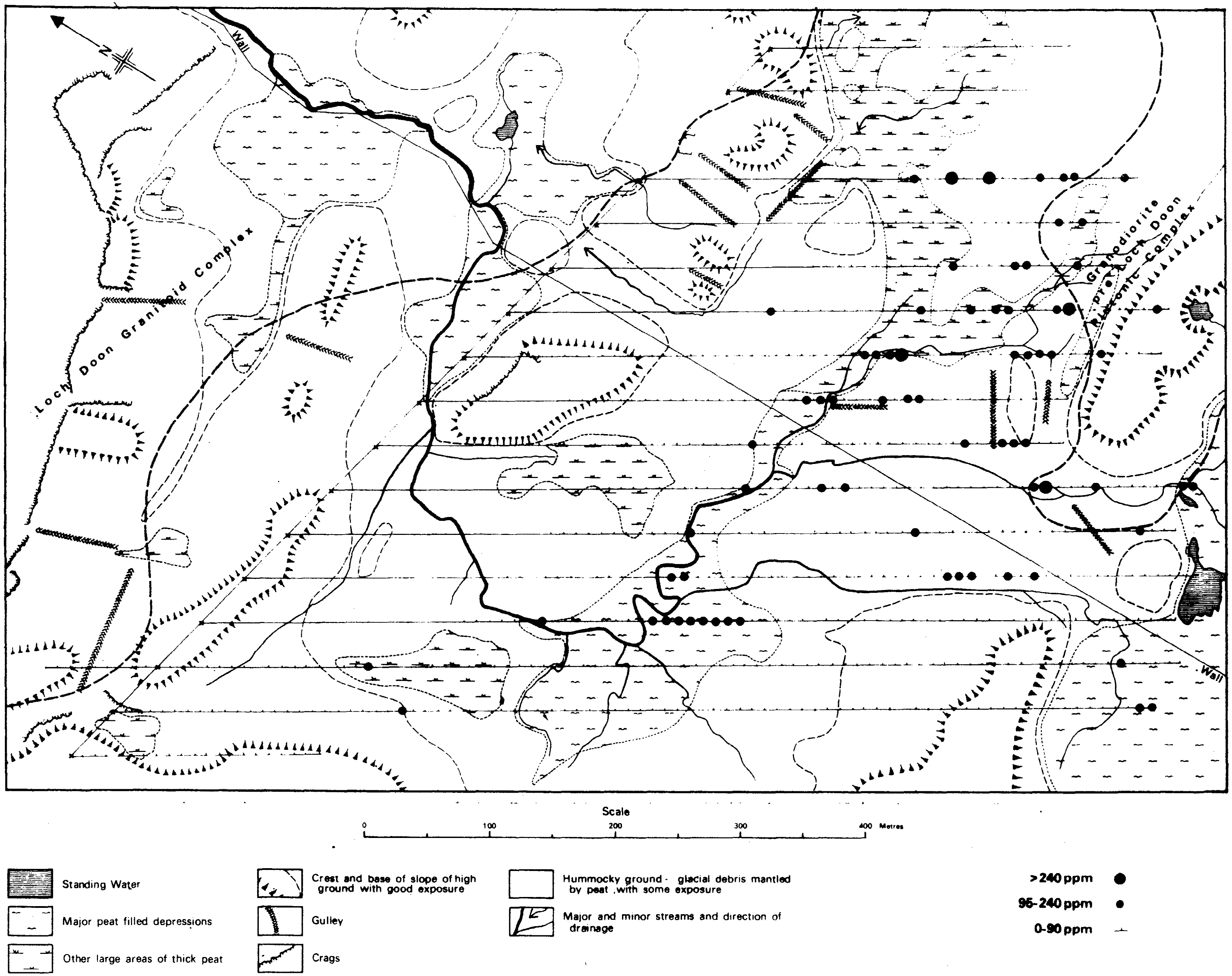


Fig 8 Distribution of Zn in soil

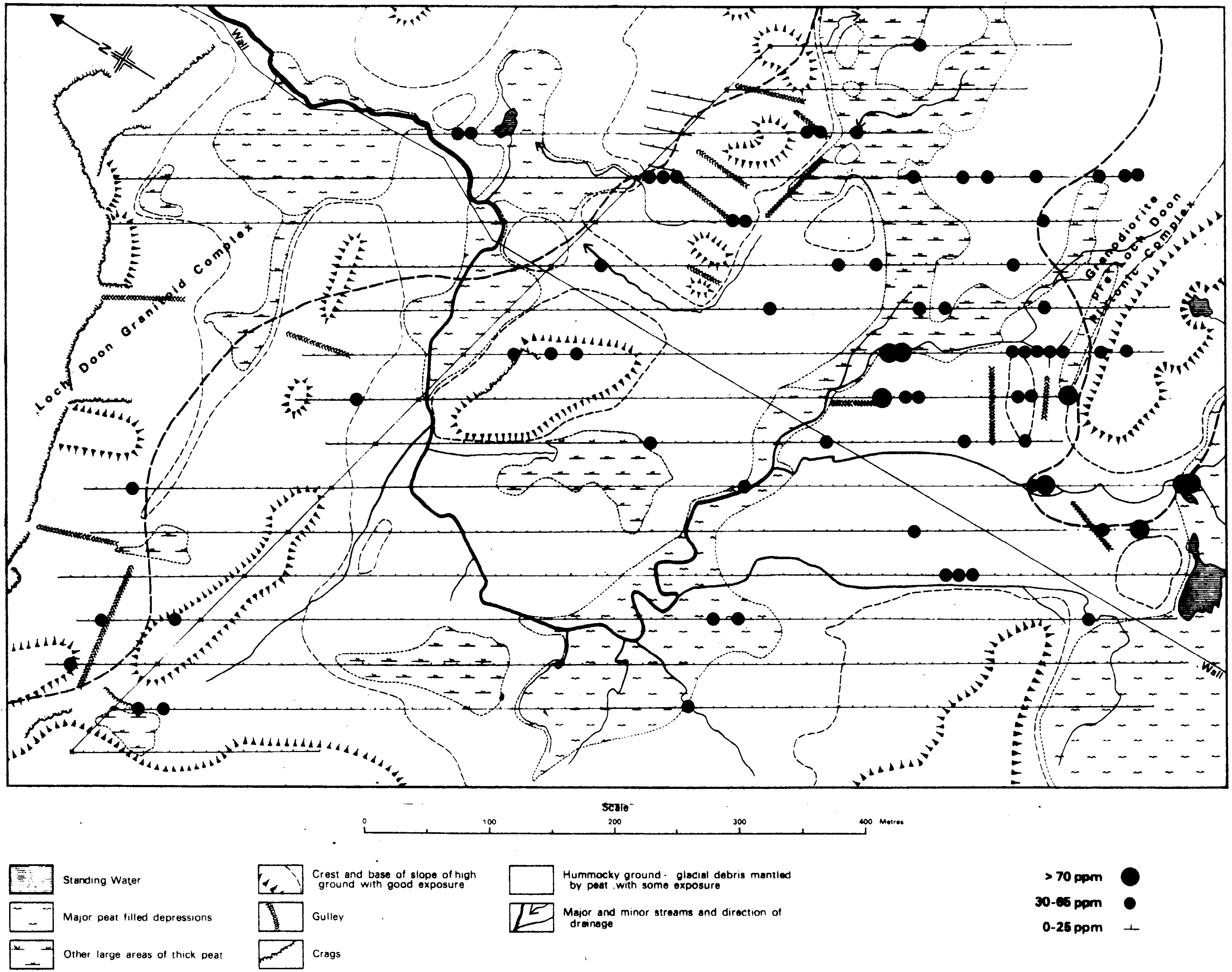


Fig 9 Distribution of Cu in soil

Fig. 10 VLF in-phase

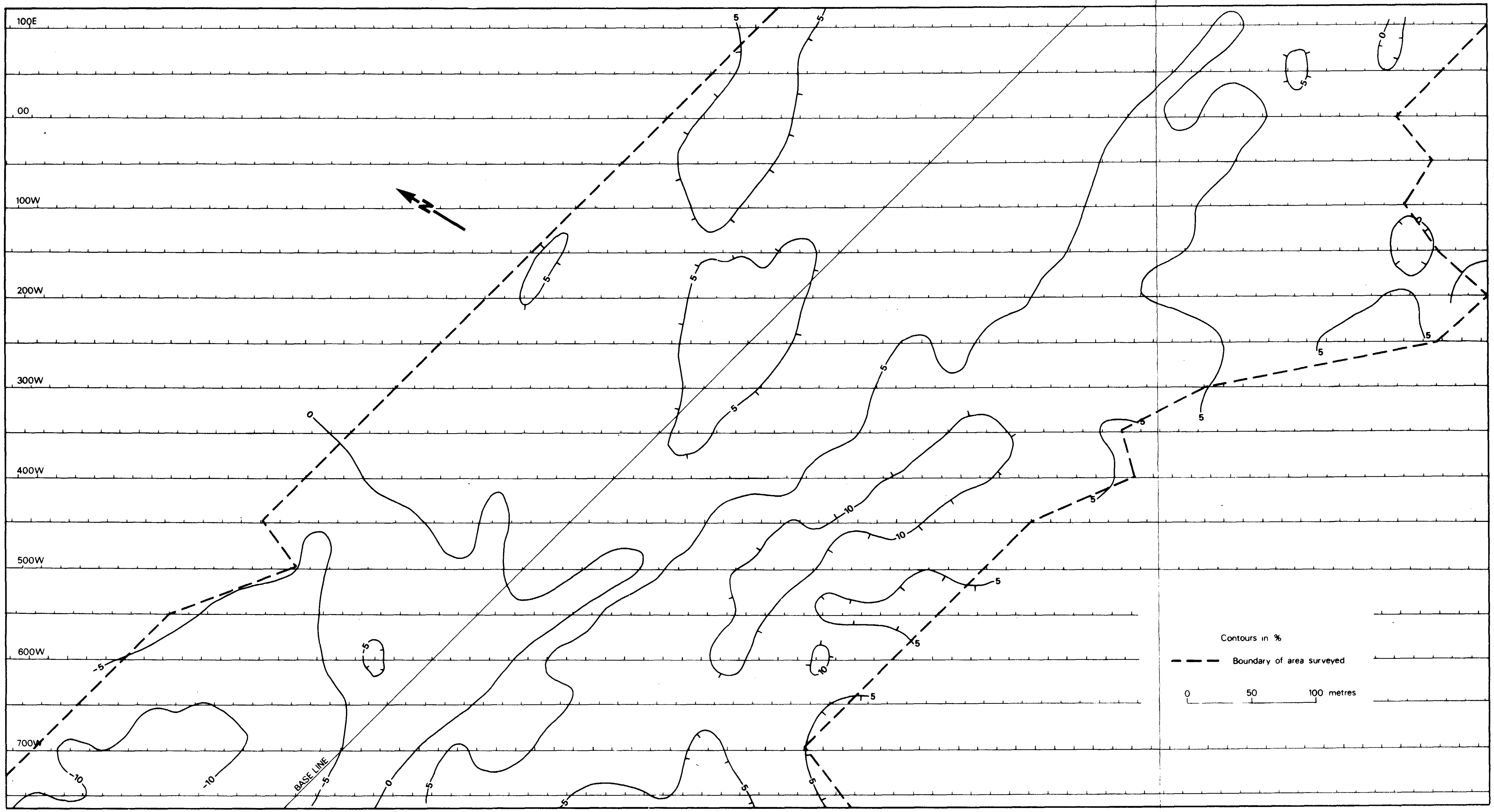


Fig.11 VLF out-of-phase

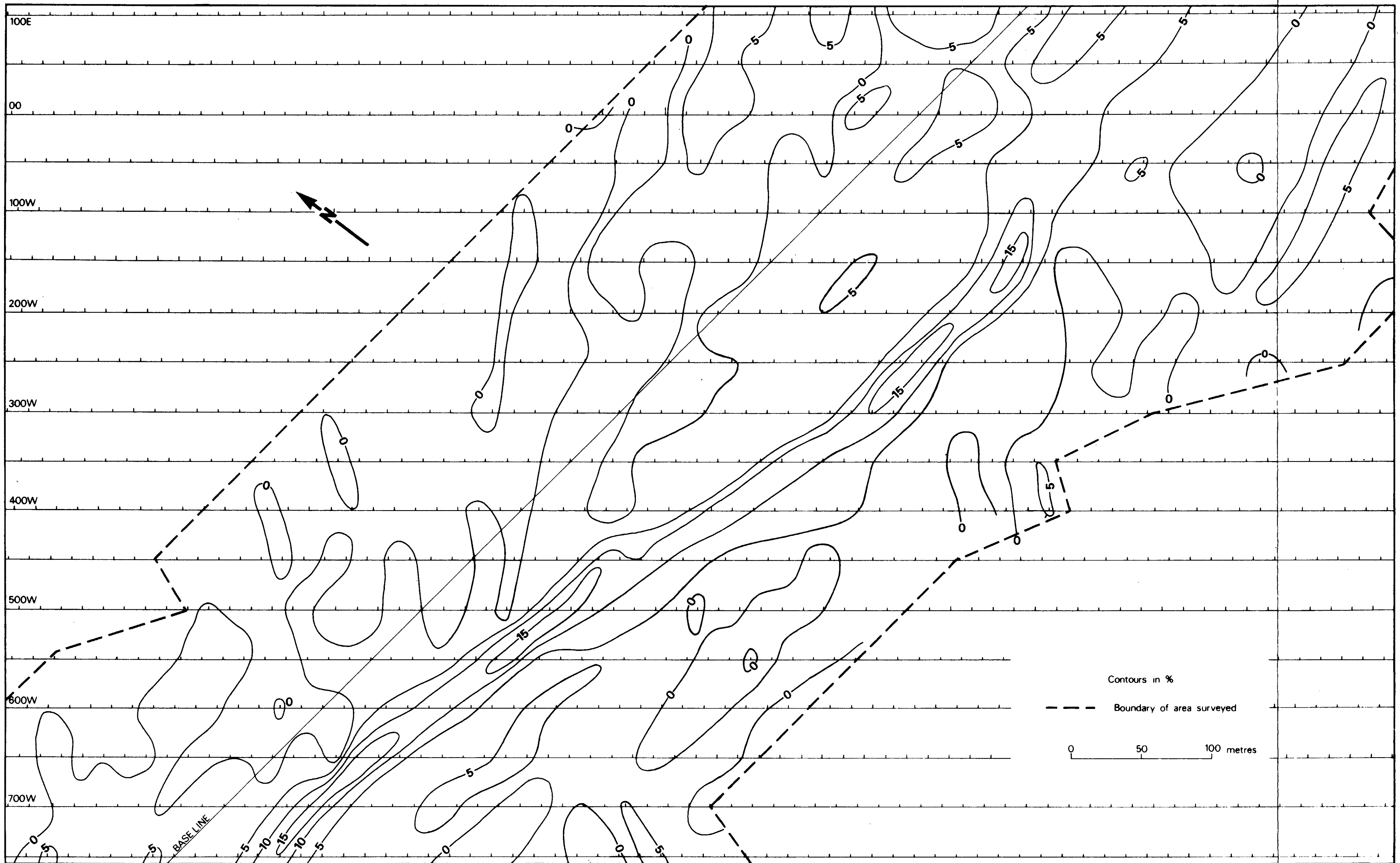


Fig.12 VLF filtered in-phase

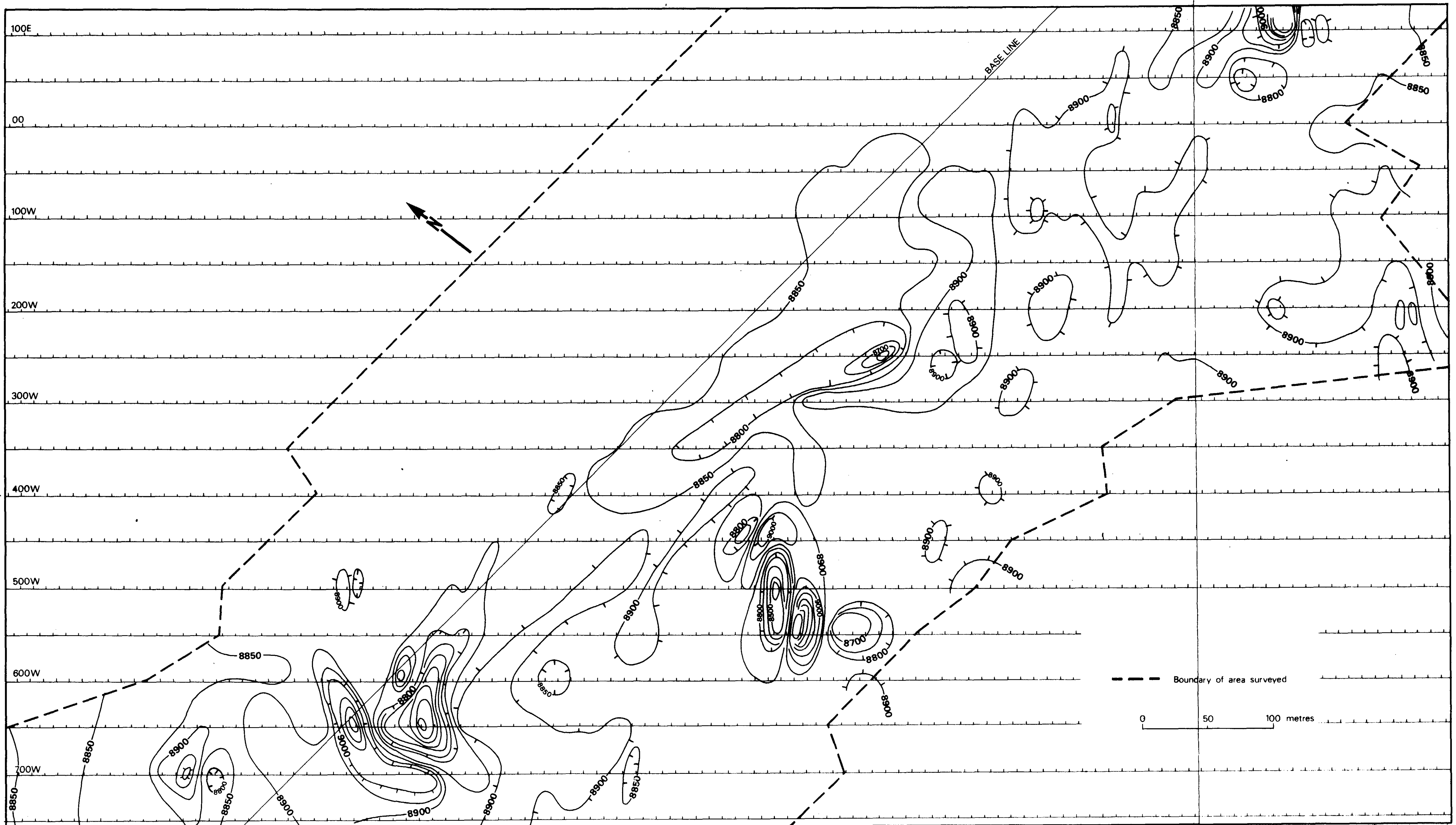


Fig.13 Total magnetic field (relative to a datum of 48,000 nT)

are shown in Figure 14. They were sited so as to cover as much of the area as possible and were orientated both perpendicular and subparallel to the strike of the country rocks so as to investigate various models of mineralisation distribution. Boreholes 1 and 2 were drilled with the lightweight IGS Winkie drill while the remainder were drilled with the IGS JKS 300. Graphic logs of the boreholes, together with assays of Au, As and Zn, are plotted in Figures 15 to 21.

GEOLOGY

A systematic sequence of stratigraphically distinct, steeply dipping Lower Palaeozoic greywacke units trends north-east to south-west across the Southern Uplands. The units are separated by strike faults and individually young to the north-west, but as a whole they young to the south-east (Walton, 1965: Leggett and others, 1979). The area investigated lies in one of the most southerly of the Upper Ordovician units with greywackes probably Caradocian in age. The stratigraphical relationships within the Southern Uplands were originally explained in terms of large-scale monoclinal folds and strike faulting with downthrow to the south (Walton 1965). More recently this has been refined (McKerrow and others, 1977; Leggett and others, 1979) and the Southern Uplands are now regarded as the rotated remains of an accretionary wedge formed above a subduction zone consuming the Lower Palaeozoic Iapetus oceanic plate. The wedge built up as successive thin layers of sediment were sheared from the surface of the downgoing plate and underthrust beneath a stock of similar slices. Shear planes formed where the weakest lithologies, the black shales and mudstones, were present and the black shale belts of the Southern Uplands now mark the sheared, faulted junctions between stratigraphically distinct greywacke sequences. 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.

The sediments suffered polyphase deformation during their accretion (Walton, 1965; Weir, 1979). Within the upper Glenhead Burn drainage basin (Figure 2) only three distinct groups of fold structure were observed, their inter-relationship uncertain:-

1. **Tight, upright folds.** Across the northern part of the area grading and rare cross-lamination show that the greywacke horizons young consistently to the north. A similar trend is observed in the borehole cores but, in the south-west (Figure 2), a rapid alternation of younging direction indicates the presence of several tight, upright folds with a wavelength of about 10 m. No fold hinges were observed but stereographic analysis shows a π-axis plunging gently to the north-east.

2. **Open monoforms.** Distinct from the zones of tight folding, several small monoforms occur in parts of the area where the greywackes are otherwise uniformly upright and consistently young north. These folds typically have an axial surface dipping moderately to the south-east, axes plunging moderately east and a wavelength of about 8 m.

3. **Compressed boudins.** Within the metagreywackes, close to the margin of the Loch Doon pluton, small-scale boudinage of the relict sedimentary banding is common. The long axes of the boudins are sub-vertical, indicating along-strike extension, but in places the boudines have been compressed and folded about a very similar axis implying a reversal of the stress regime.

In relation to the regional fold pattern (Weir, 1979) the tight, upright folds probably represent the earliest fold episode (F1) and were formed coevally with the major monoclines described by Walton (1965). The small-scale monoforms of the Glenhead area also have counterparts elsewhere in the open flexures (F2) of Weir (1979). They would be approximately congruous with either a major anticline or a large shear zone with southerly downthrow situated to the south. The latter model is compatible with the imbricate thrust structure suggested for the Southern Uplands (McKerrow and others, 1977; Leggett and others, 1979). The along-strike stretching and boudinage of the sedimentary banding may be related to the swing of strike in the Glenhead area away from the north-east to south-west regional trend, to an approximatley east-west orientation. This in turn is associated with a large-scale reclined fold developed in the siliceous mudstones and shales exposed in the south of the area. The reclined folding is responsible for the thickening of this part of the shale belt (Stone, *in press*). The subsequent compression of the boudins may be related to the forceful intrusion of the Loch Doon pluton which has produced a series of gentle folds with axes plunging 70° to 175° in the mudstone zone to the south (Stone, *in press*). Other deflections of the regional strike-trend at the margins of the pluton have been described by Oertel (1955).

North to north-east trending wrench faults, usually with a sinistral offset, cut the contact between the greywackes and the zone of black mudstone and shale exposed in the south of the area. Within the shale outcrops, some of the fault zones contain highly altered microdiorite dykes, the margins of which are associated with secondary lead mineralisation. The fault zones cannot be traced with any certainty across the metagreywackes and into the pluton, but a strong, approximately north-south, lineament does exist in the southern part of the igneous complex and may be related to the faulting seen farther south.

The Loch Doon granitoid complex (Figure 1) is a zoned pluton intruded aproximately 400 Ma ago (Halliday and others, 1980) during the final stages of the Caledonian Orogeny. It contains lithologies ranging continuously from granite in the core, through tonalite to hypersthene-diorite or norite at the periphery (Gardiner and Reynolds, 1932; G.C. Brown and others, 1979) although the drilling has shown considerable heterogeneity within the contact zone. Gardiner and Reynolds (1932) favoured a multiple intrusion model for the pluton, with hybridization producing the transitional rock types. However, more recently it has been suggested that the rock suite is gradational (e.g. G.C. Brown and others, 1979) and has evolved from a monzodiorite parental magma by crystal fractionation. Xenoliths are common towards the margins of the pluton, commonly forming 15% of the rock, occasionally up to 40% within the contact zone where considerable interlayering of intrusive rock and large metagreywacke rafts occurs. Some xenoliths are up to 10 m

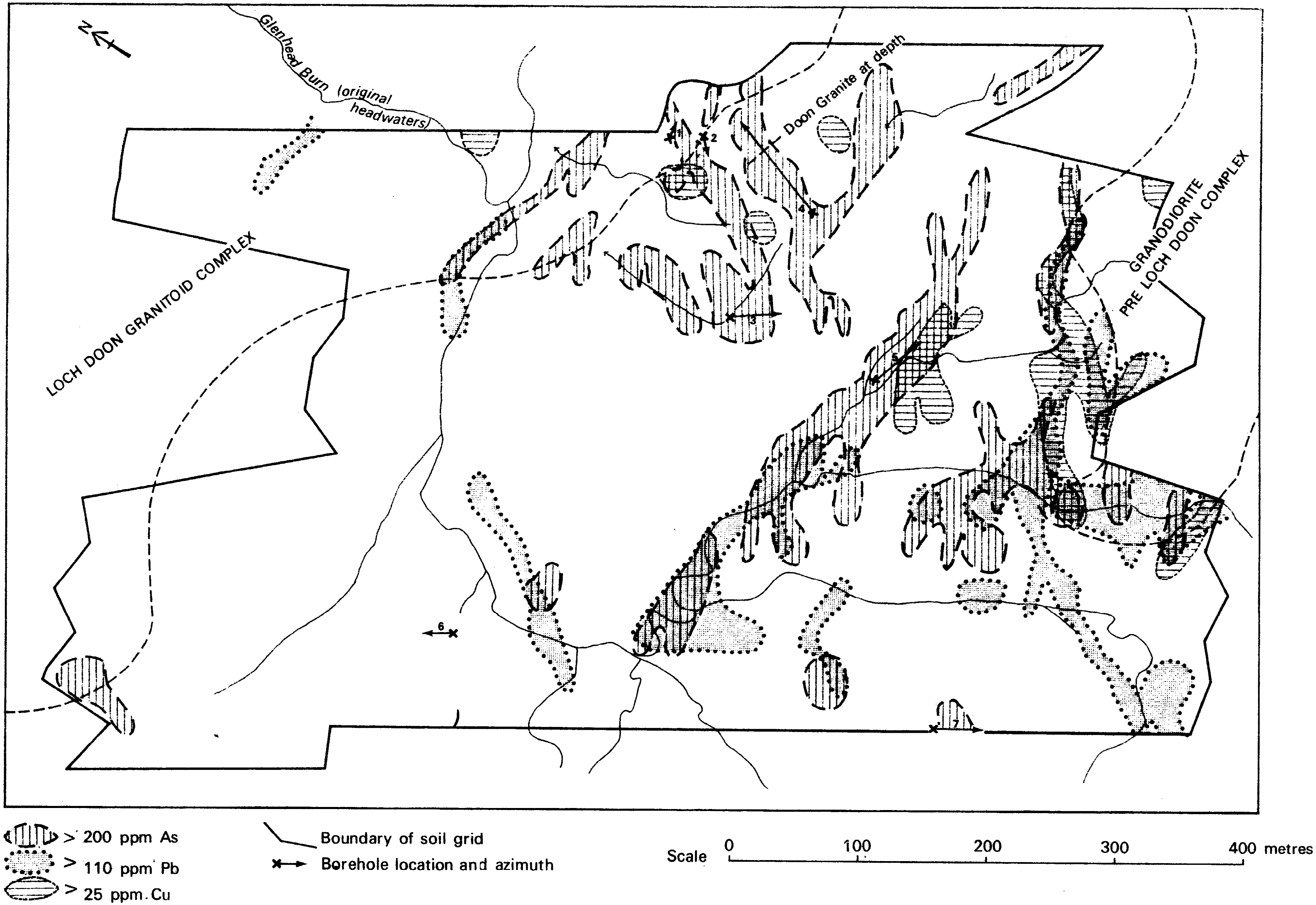


Fig. 14. Contour map of soil anomalies and location of drill holes

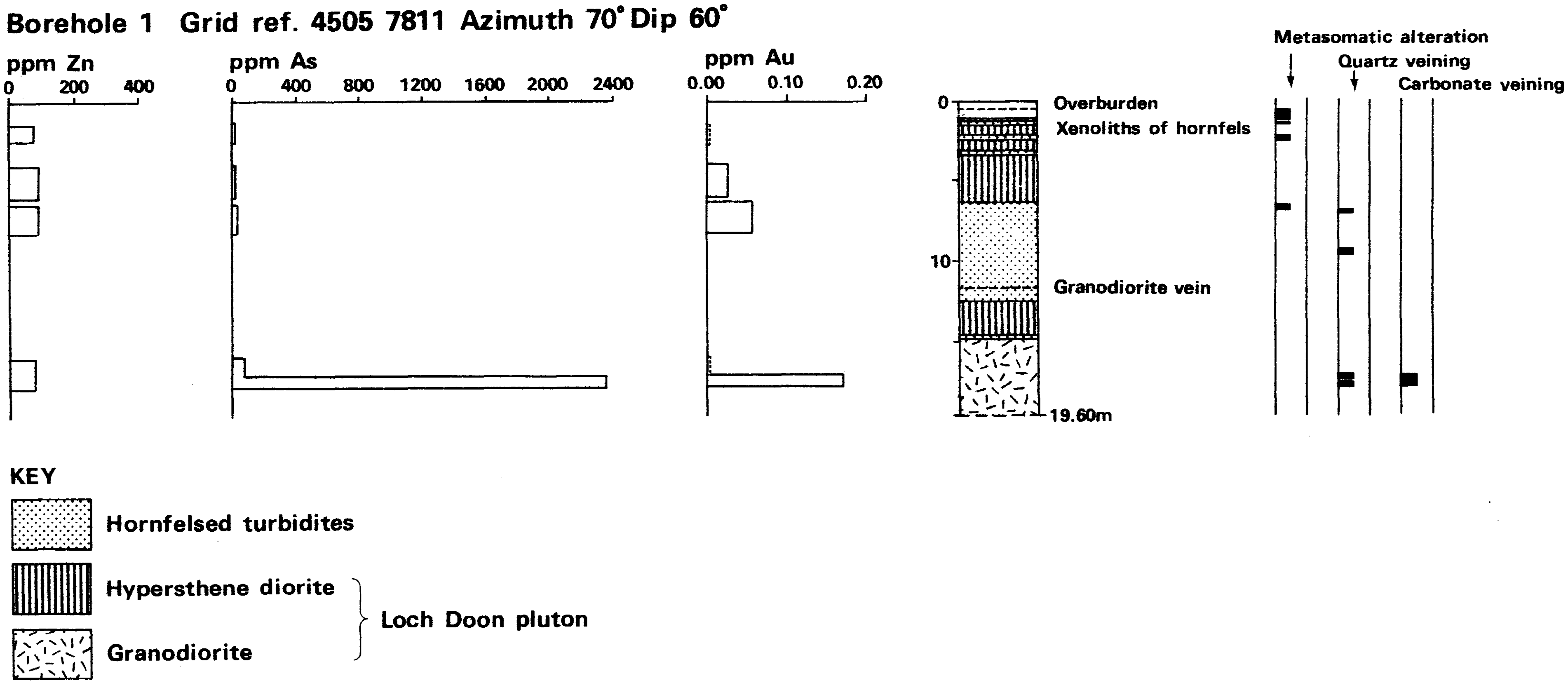


Fig. 15. Graphical log of borehole 1

Borehole 2 Grid ref. 4503 7809 Azimuth 210° Dip 60°

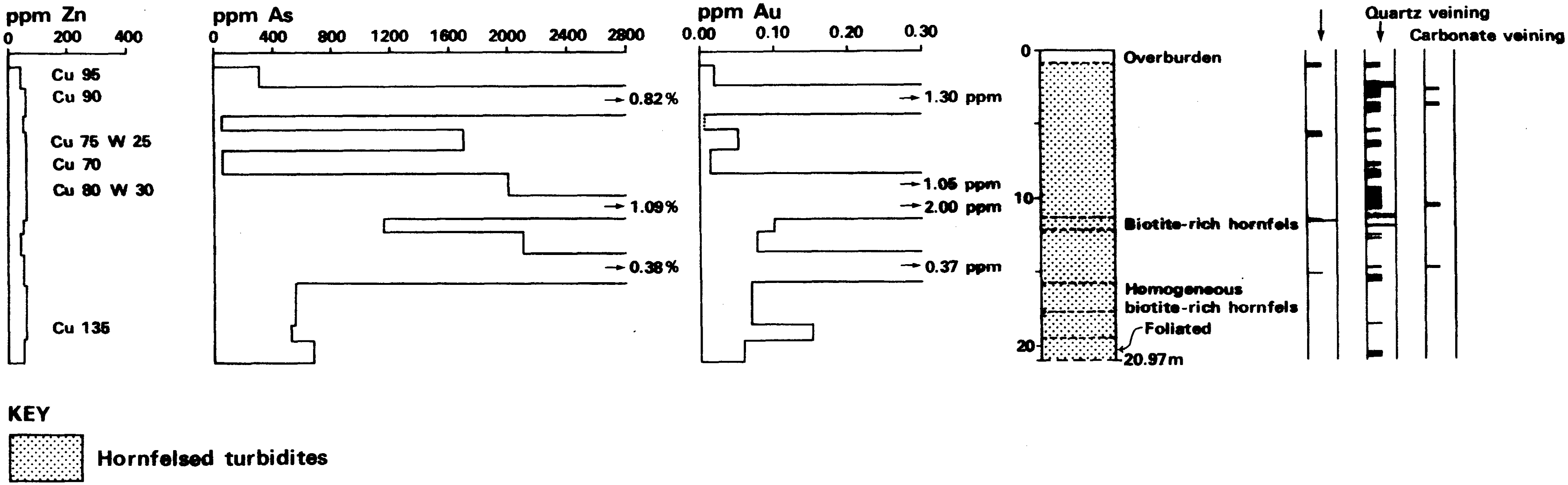
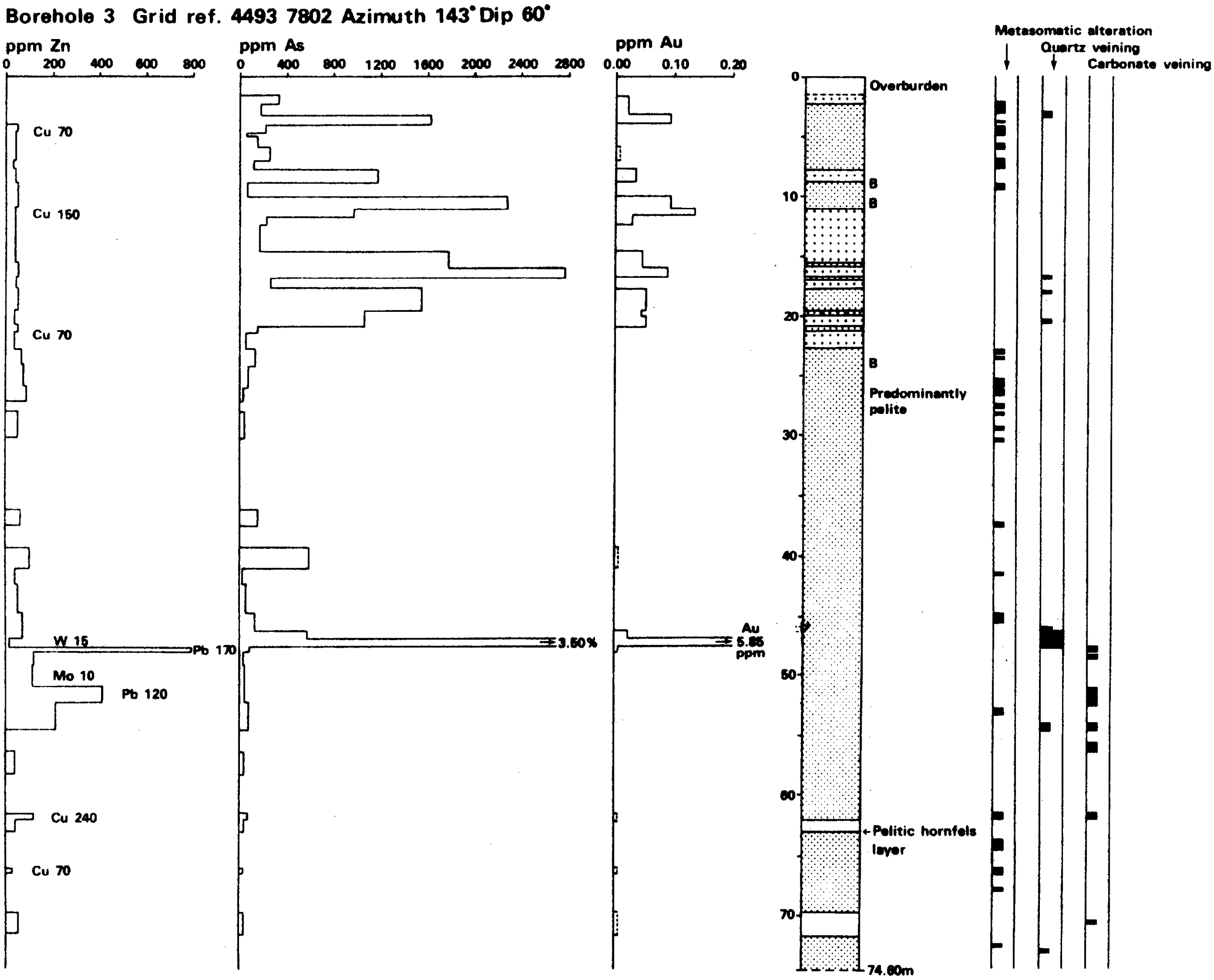


Fig. 16. Graphical log of borehole 2

Borehole 3 Grid ref. 4493 7802 Azimuth 143° Dip 60°



KEY TO BOREHOLE LOGS 3 AND 4

Hornfelsed turbidites

Monzonite minor intrusions

Granodiorite minor intrusions

Basic minor intrusion

Hypersthene diorite — Loch Doon pluton

B Breccia

Fig.17 Graphical log of borehole 3

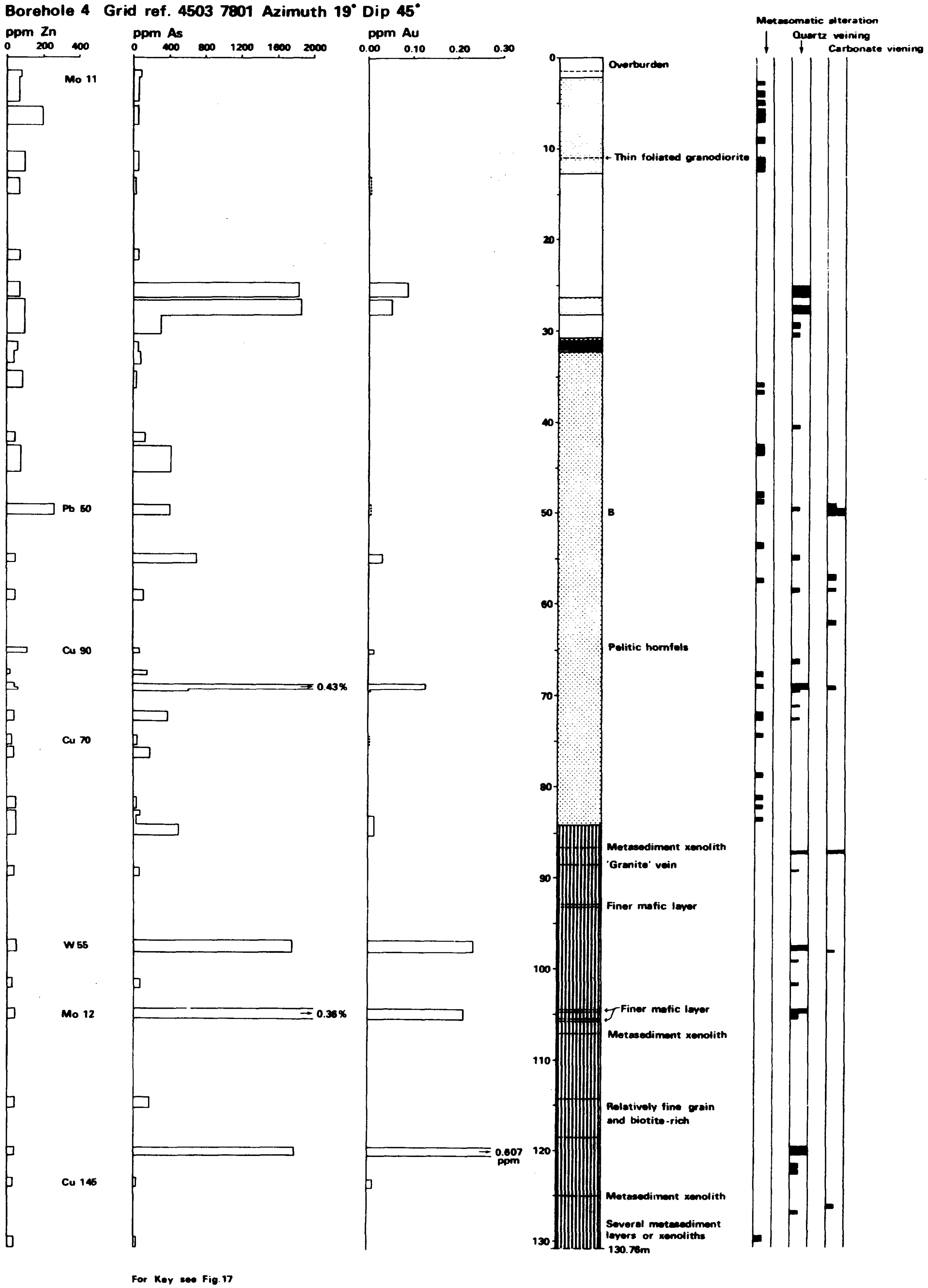


Fig. 18. Graphical log of borehole 4

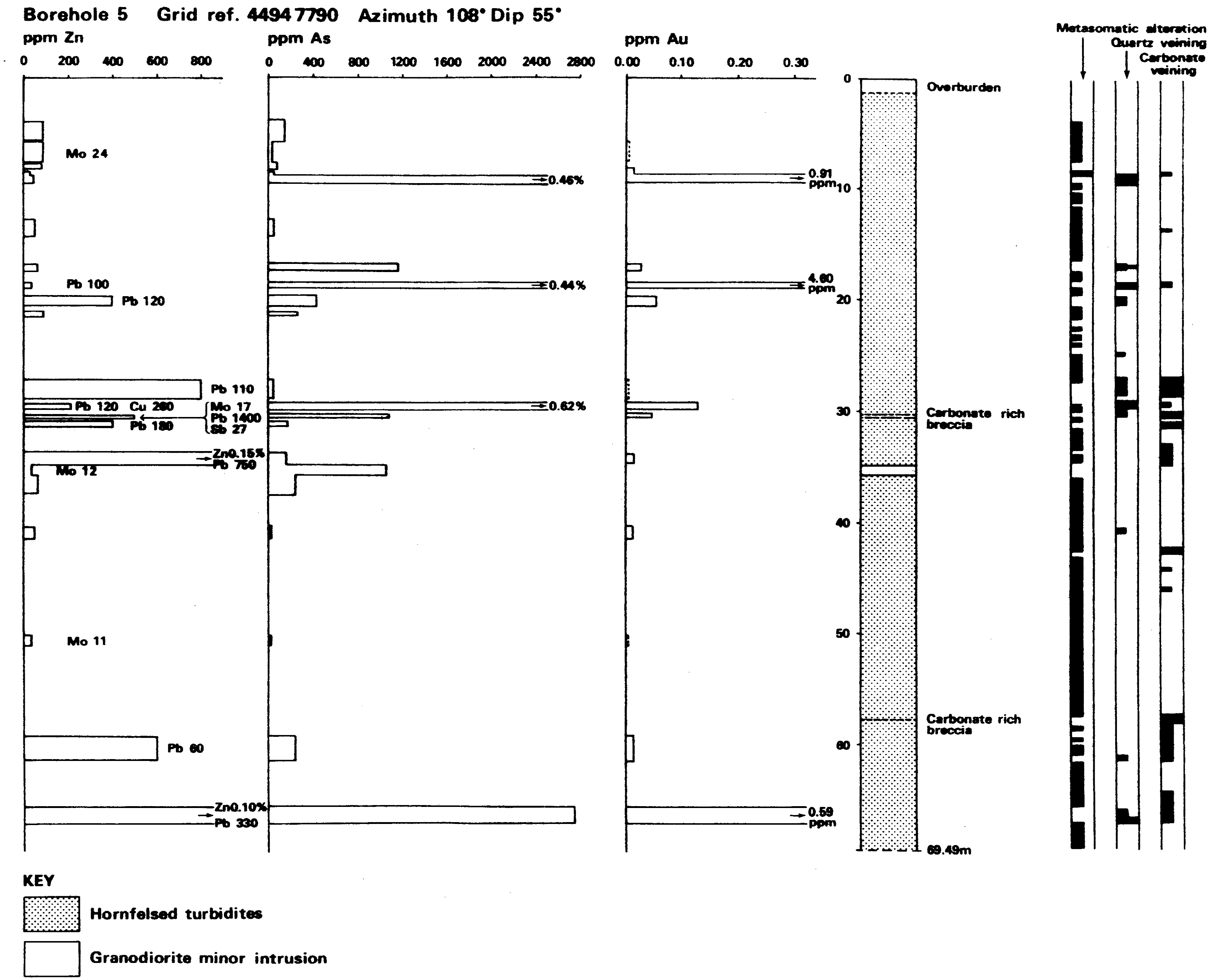


Fig. 19. Graphical log of borehole 5.

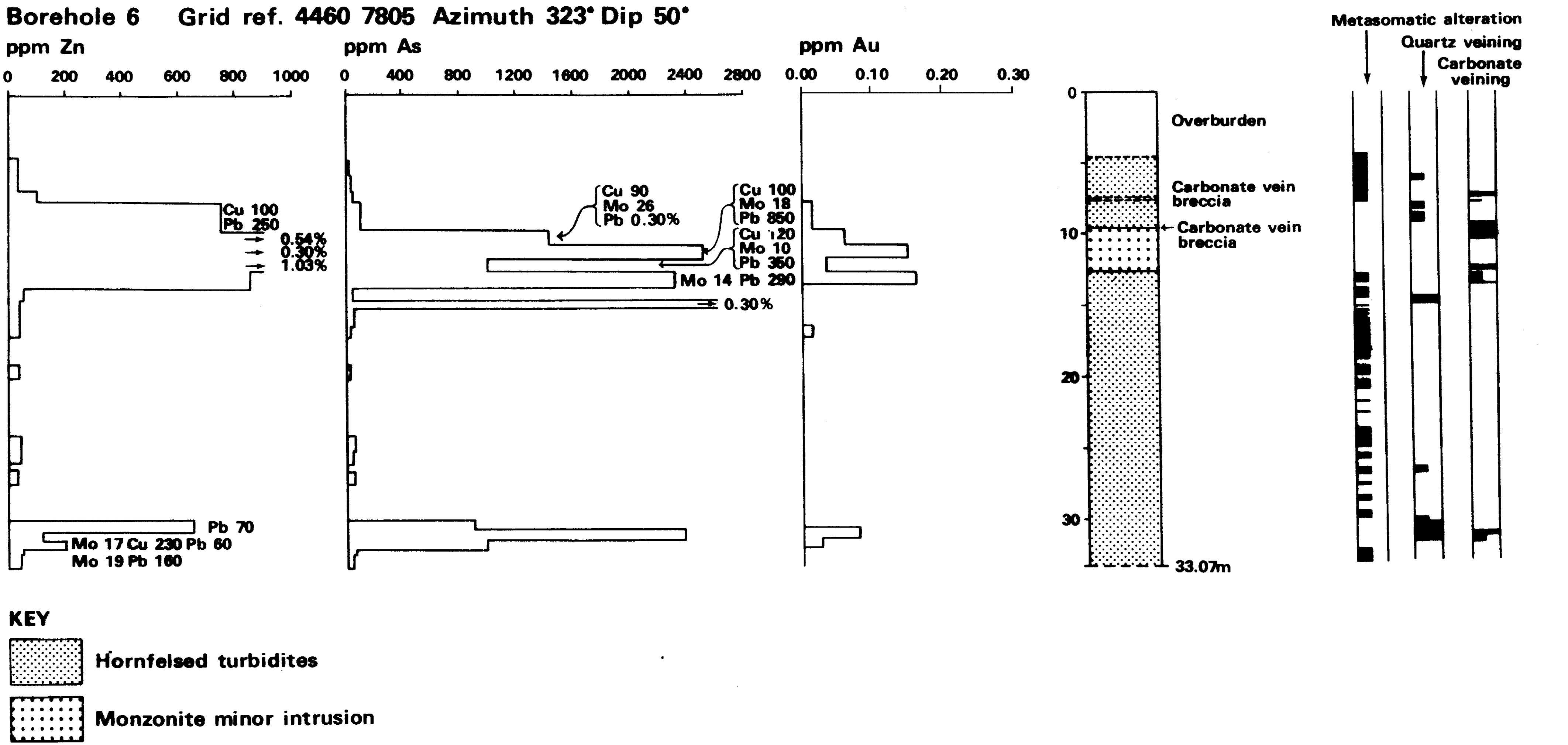


Fig. 20. Graphical log of borehole 6.

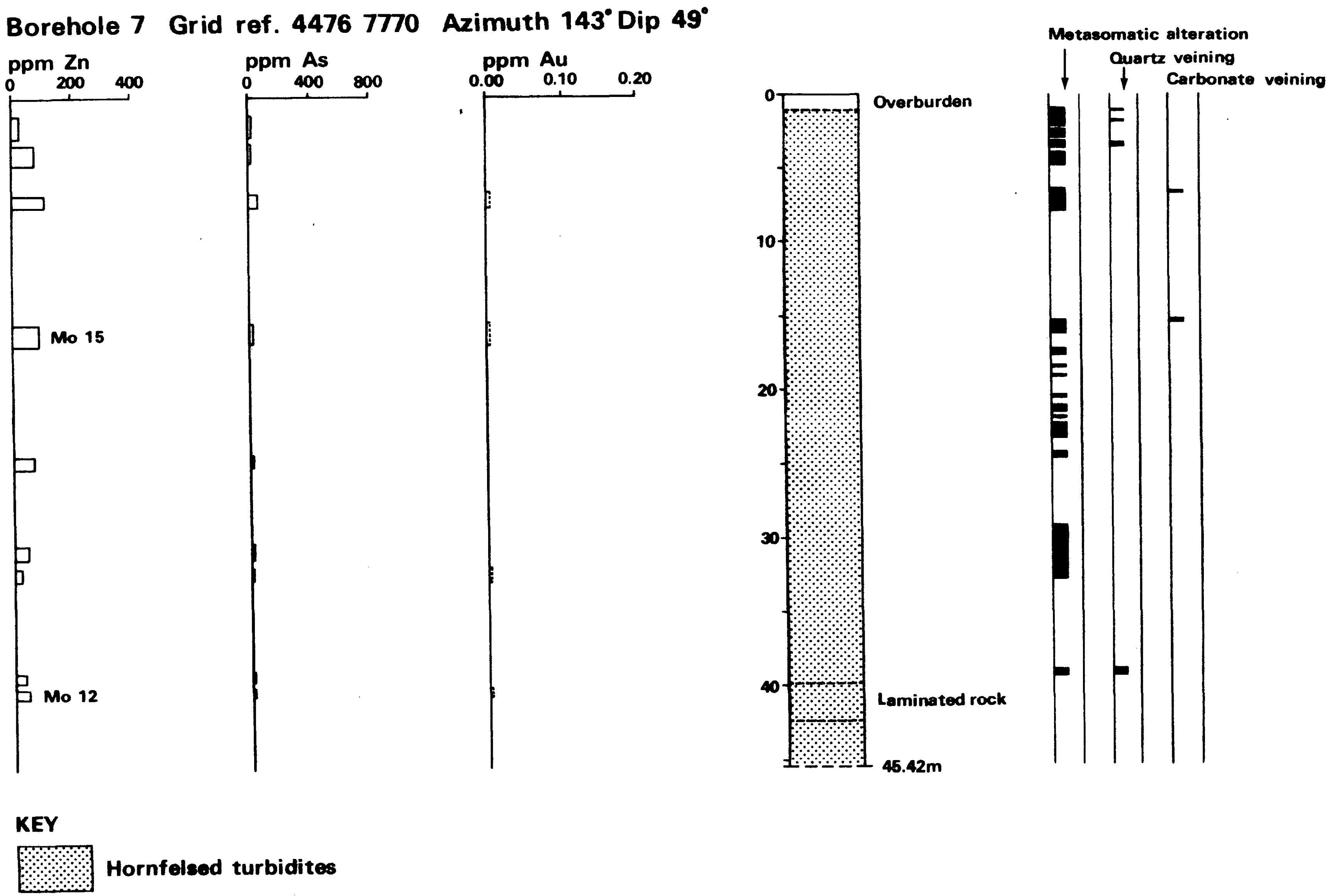


Fig. 21. Graphical log of borehole 7.

in diameter. G.C. Brown and his co-workers have described two types of xenoliths: hornfelsed greywacke and autoliths of igneous material. The latter occur throughout the pluton and are consistently more basic than the local host rock. The presence of such a high proportion of xenoliths posed some problems in mapping the granite-metagreywacke contact at outcrop, but in the borehole cores the contact was invariably sharply defined.

Of the Caledonian granites in the south-west of Scotland, the Loch Doon pluton probably exposes the lowest structural level (G.C. Brown and others, 1979). The highest level seen is the major subvolcanic complex centred on Black Stockarton Moor, much of which predates the intrusion of the Criffel pluton exposed immediately to the east (Leake and Brown, 1979; Leake and Cooper, in prep.).

Three main varieties of minor intrusive igneous rocks have been encountered in the aureole of the Loch Doon plutonic complex around the headwaters of Glenhead Burn. There are swarms of concordant quartz monzonites, swarms of concordant granodiorites, and intersecting discordant porphyritic quartz micromonzodiorites. The discordant intrusions occur chiefly within the black shale and mudstone sequence to the south of the area (Figure 2) and are rare further north. There is also an irregular ovoid outcrop of granodiorite, within the area but its relationships to the other intrusions are unclear. All of these intrusions appear to have suffered thermal metamorphism due to the intrusion of the Loch Doon pluton.

Petrographical features of these rock types and of the marginal facies of the adjacent Loch Doon pluton are given in Table 1.

ROCK CHEMISTRY

IGNEOUS ROCKS

The chemical compositions of the various types of igneous rock intersected by the boreholes, and of a suite of discordant intrusions from within the chert-mudstone belt to the south of the area, are shown in Table 2. It is clear that each type falls within a clearly defined and restricted chemical compositional field and that for many elements there is little or no overlap between these fields. Some of the compositional differences are illustrated graphically in Figures 22-25.

The most obvious chemical difference between the varieties of igneous rock lies in the significantly greater Ni, Cr and Mg (and to a lesser extent Zr) contents of the plutonic rocks compared with those of the minor intrusive rocks. The monzonitic minor intrusions from borehole 6 contain similar levels of Cr to the plutonic rocks but these samples are heavily mineralised with base metal sulphides. The strong positive correlation between Cr and Rb in these samples and a lack of a similar association in other monzonite samples may indicate that some of the chromium occurs in the muscovite of hydrothermal origin which accompanies the mineralisation.

These significant differences in refractory elements for similar levels of silica suggest that the origin of the two rock types is not closely related in a way that would be expected if they were all on the same magma crystallisation descent line. Magmas either of the composition of the monzonite or granodioritic minor intrusions could not have produced the marginal hypersthene diorites by precipation of plagioclase, orthopyroxene and clinopyroxene in the manner suggested by G.C. Brown and others (1979). Since the minor intrusions predate the pluton they may represent primitive magma composition as they were probably emplaced relatively rapidly into the upper crust from a relatively deep source. Thus the marginal variety of the Loch Doon pluton within the drainage basin of Glenhead Burn either represents a crystal cumulate from a separate magma of different composition; or its origin involved processes other than simple fractional crystallisation from a common source magma of deep origin. Such processes may include changes in melt source with time as a result of changes in the amount of melting of a metasediment component as suggested by Halliday and others (1980) or successive phases of emplacement and partial melting as the concentration of heat energy rose upwards in the crust.

The large compositional difference between the monzonitic and granodioritic concordant intrusions also suggests differing origins in either source or time or both. This also applies to the discordant intrusions; but since they occur south of the boundary of the chert-mudstone belt, which may have been the locus of major fault movement both in the horizontal and vertical sense, they may originally have been emplaced further away from the concordant intrusions. Overall, the history of magmatism in the area is both complex and varied and it therefore seems unlikely to have followed the simple path envisaged by G.C. Brown and others (1979).

SEDIMENTARY ROCKS

The chemical compositions of the turbidites intersected in the 7 boreholes are illustrated in Tables 3 and 4. Compositional differences between the sedimentary rocks from the different boreholes, excluding the xenoliths from within the Loch Doon pluton, are slight, particularly for such immobile elements as Ti, Ni, Y, Zr, Nb and Th. Pelitic rocks, which form a small proportion of the turbidite sequence, are recognisably different in many chemical components. There are also similarities between the immobile element contents of the pelitic rocks and the xenoliths from the margin of the Loch Doon intrusion, which may indicate that the greywackes are preferentially ingested by the pluton.

CONTACT METAMORPHISM

All the sedimentary rocks and concordant intrusions have suffered contact metamorphism as a result of the intrusion of the Loch Doon pluton. The turbidite samples from borehole 7, which was sited about 650 m from the margin of the pluton, contain biotite in a fine mosaic with quartz, accompanied by chlorite and pale green actinolite within the more pelitic rocks, and fine biotite and actinolite within the matrix of the coarser greywackes. The mineralogy of the sedimentary rocks from borehole 5 (250 m from pluton) and borehole 6 (220 m from pluton) is similar to that above, though the grain size of the more

Table 1. Petrography of igneous rocks

	Quartz	Alkali Feldspar	Plagioclase	Biotite	Amphibole	Pyroxene	Other minerals	Ore minerals
Quartz monzonite concordant intrusions	10-20% interstitial, decreases towards centre	Minor, increases towards centre	An 40-45% unzoned, sericitic alteration of cores. Some poikilitic grains	Major mafic phase, in knots or associated with other mafic grains	Pale actinolitic hornblende associated with biotite as alteration product of pyroxene. Late poikilitic amphibole in parts	Augitic; alteration advanced at margin	? relicts of rounded olivine, partly replaced by pyrrhotite. Minor sphene and apatite.	Pyrrhotite main sulphide, concentrated at margin with arsenopyrite and minor chalcopyrite. Pyrrhotite often in interstitial grains
Foliated grandiorite concordant intrusions	Up to 60%	?	Variably sericitised, some parts completely altered	Common, forming incipient schistosity; also in mafic clots; partly altered to chlorite	Actinolitic hornblende relicts in mafic clots; partly altered to chlorite	Relicts in mafic clots; small grain pale green diopsidic pyroxene in least altered rocks	Sphene common accessory	Pyrrhotite commonest sulphide with minor chalcopyrite; often in association with mafic clots
Discordant porphyritic quartz micro monzodioritic intrusions	Minor, in matrix	Minor, in matrix	Predominant in matrix. Labradorite phenocrysts from 2%-50% of rock	Usually minor component of matrix	Hornblende ± actinolite/chlorite intergrowth in matrix. Phenocrysts of actinolite common	Hypersthene minor component of matrix. Often hypersthene cores to actinolite phenocrysts or fresh hypersthene	Apatite conspicuous accessory mineral. Chlorite often pseudomorphs mafic phenocrysts	Trace magnetite. Highly altered rocks contain secondary Pb phosphate minerals
Monzodiorite (hypersthene diorite) — of Loch Doon pluton	Minor, interstitial	Up to 15%. Often incipient perthitic texture in larger laths	40%. An 33% — An 48%. May be zoned	Occurs as large plates	Pale green hornblende rimming clino-pyroxene	Prismatic diopsidic augite, associated with or enclosed in biotite. Elongate pink hypersthene		Minor pyrrhotite, pyrite and magnetite
Quartz monzodiorite of Loch Doon pluton	Up to 15%	Up to 15%	Predominant. Minor sericitic alteration of more albitic plagioclase	Red in colour. Contains euhedral zircons	Pale green hornblende in least altered rocks		Rare apatite; calcite common in altered rocks	Up to 2% pyrrhotite occasional pyrite and trace arsenopyrite

Table 2. Average composition of igneous rocks

	Monzonitic minor intrusions BH3			Monzonitic minor intrusions BH5			Granodiorite minor intrusions			Loch Doon pluton			Average Hypersthene Diorite (Brown et al)	Discordant intrusions		
	Mean	St Dev	Range	Mean	St Dev	Range	Mean	St Dev	Range	Mean	St Dev	Range		Mean	St Dev	Range
Na_2O[1]	* 2.46	0.15	2.23-2.58				* 3.67	0.37	3.26-4.13	** 3.01	0.48	2.45-3.30	3.20	3.11	0.24	2.29-4.36
MgO[1]	* 4.70	0.61	3.90-5.58				* 2.29	0.28	2.03-2.55	** 6.50	1.88	5.20-8.65	5.30	4.30	0.37	3.52-4.86
Al_2O_3[1]	*15.18	0.57	14.20-15.60				*16.25	0.50	15.7-16.9	**14.83	0.70	14.23-15.60	15.71	15.28	0.48	14.7-16.2
SiO_2[1]	*57.52	0.97	56.5-58.7				*64.16	0.94	62.8-64.8	**58.68	3.96	54.2-61.7	61.17	62.42	0.99	61.0-64.0
P_2O_5[1]	* 0.22	0.01	0.20-0.23				* 0.19	0.01	0.18-0.21	** 0.33	0.08	0.27-0.38	0.37	0.21	0.02	0.17-0.23
S[1]	* 0.86	0.10	0.70-0.97				* 0.56	0.17	0.45-0.80	** 0.09	0.09	0.02-0.15		0.01	—	—
K_2O[1]	* 3.57	0.65	2.56-4.38				* 3.50	0.60	3.04-4.32	** 2.68	0.30	2.34-2.90	3.30	2.94	0.38	2.19-3.52
CaO[2]	6.14	0.67	5.54-7.69	7.20	0.89	6.39-8.23	3.62	0.45	2.63-4.14	5.41	0.61	4.38-6.55	4.51	3.43	0.62	2.29-4.36
TiO_2[2]	1.11	0.04	1.04-1.17	1.09	0.22	0.98-1.24	0.75	0.02	0.71-0.78	0.97	0.16	0.75-1.36	1.00	0.89	0.05	0.80-0.96
Mn[2]	847	193	630-1190	1337	301	1050-1650	534	76	440-630	655	111	550-930		462	111	320-640
Fe_2O_3[2]	8.02	1.77	6.64-12.79	7.52	0.27	6.87-8.28	4.69	0.21	4.42-4.99	6.57	0.98	5.47-9.02	5.77	6.58	0.37	6.01-7.15
LoI (H_2O)	* 1.02	0.27	0.71-1.28				1.12	0.57	0.68-1.96	1.41	0.39	1.16-1.86				
B[3]	18	8	<10-32	26	5	22-31	24	14	<10-44	* 17	5	<10-26				
Cr[3]	62	46	13-164	210	60	161-277	30	6	22-40	*219	27	174-252				
Co[4]	28	16	20-70	57	15	40-70	16	2	15-20	19	3	15-25		23	4	15-30
Ni[2]	13	12	5-43	39	23	16-62	9	5	1-14	104	23	76-159		75	32	47-147
Cu[4]	63	34	40-150	103	15	90-120	32	5	25-40	39	40	7-145				15-8410
Zn[4]	39	6	30-50	6200		2950-10250	70	18	40-100	55	21	30-88		551	249	280-1000
As[2]	884		45-2750	1643		994-2510	334		25-1830	863		10-3620		37	24	15-93
Rb[2]	82	6	73-92	149	47	96-187	74	8	62-84	* 82	6	76-92	113			
Sr[2]	536	45	443-583	437	126	333-577	505	27	475-543	*614	21	585-636	627			
Y[2]	23	1	21-25	19	4	16-24	14	2	12-17	* 18	1	16-20	22			
Zr[2]	185	13	160-197	179	12	168-191	171	5	161-175	*214	28	186-278	225			
Nb[2]	8	1	6-10	9	2	8-11	8	1	7-9	* 10	1	8-12				
Ba[2]	857	76	710-940	463	44	419-507	679	85	586-800	898	142	604-1081	958	684	136	382-790
Pb[4]	13	5	10-20	1400		350-3000	14	8	10-30	14	4	10-20				50-3900
Th[2]	9	2	7-12	13	5	10-19	9	2	6-10	* 9	2	6-11				
No. Samples	10,*5			3			7,*4			12,*8,**3			5	9		

1 = determined by Beta probe
2 = determined by XRF
3 = determined by OES
4 = determined by AAS

Mn, B, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Ba, Pb and Th quoted in ppm, rest in %

Table 3. Chemical composition of sedimentary rocks

	Xenoliths		Increasing distance from Loch Doon pluton												Pelitic turbidites		Metasomatically altered turbidites				Veined turbidites			
	BH1		BH2		BH4		BH3		BH6		BH5		BH7				A type		B type		Quartz		Carbonate	
	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.	M.	S.D.				
CaO^2	7.10	0.04	4.63	0.64	6.05	1.19	6.73	1.02	6.33	1.34	5.49	1.65	6.61	0.84	3.91	0.93	8.35	0.51	6.11	0.42	4.91	1.06	13.39	7.20
$TiO_2{}^2$	1.09	0.04	0.93	0.11	0.96	0.07	0.96	0.07	0.91	0.05	0.92	0.05	0.96	0.05	1.11	0.09	0.93	0.12	0.83	0.10	0.85	0.16	0.72	0.21
Mn^2	1010	85	495	68	873	129	891	114	915	136	889	156	893	147	684	98	1008	171	800	169	779	301	2378	1564
$Fe_2O_3{}^2$	9.18	0.26	7.30	0.73	8.54	0.50	8.43	0.57	8.25	0.85	8.24	0.51	8.44	0.63	8.80	1.42	8.33	0.92	7.33	0.83	7.65	1.41	8.21	2.04
Cr^3	—	—	—		170	62	124	49	161	36	159	41	157	30	120	63	130	46	161	44	173	54	123	36
Co^4	20	—	22	8	22	3	23	3	24	8	23	4	21	3	29	7	23	7	19	3	29	8	28	13
Ni^2	80	20	59	19	52	8	51	10	51	7	64	9	53	6	87	35	45	5	51	7	58	10	61	26
Cu^4	83	39	60	30	45	16	45	41	53	51	52	49	43	9	59	19	52	22	46	18	106	98	35	18
Zn^4	72	31	55	7	75	60	100	151	174	270	307	403	61	28	88	23	35	10	73	39	79	73	448	
Rb^2	54	—	—	—	69	22	70	18	75	31	87	24	68	27	114	17	44	13	63	14	78	24	108	43
Sr^2	822	—	—	—	393	59	398	69	367	74	361	71	329	66	321	75	408	44	332	73	228	98	277	130
Y^2	25	—	—	—	20	2	19	2	20	4	20	2	21	2	23	3	19	2	19	3	15	5	24	6
Zr^2	200	—	—	—	145	16	145	14	145	22	140	8	146	24	195	24	144	11	127	10	117	31	129	55
Nb^2	11	—	—	—	8	3	7	1	7	2	7	1	7	2	13	2	7	1	6	1	7	2	8	3
Ba^2	584	250	414	54	446	112	488	105	424	86	522	135	371	114	613	217	322	52	358	88	413	60	472	293
Pb^4	13	4	15	5	15	10	24	35	57	86	170	336	17	5	14	5	12	4	20	8	54	41	455	
Th^2	6	—	—	—	6	2	6	2	7	2	7	1	6	1	9	1	4	1	6	1	7	2	8	2
No Samples	2		13		19		25		18		19		9		5		6		4		7		4	

2 = Determined by XRF
3 = Determined by OES
4 = Determined by AAS

CaO, TiO_2, Fe_2O_3 quoted as %, rest as ppm.
M. Mean.
S.D. Standard Deviation

Table 4. Major element analyses of sedimentary rocks

	Hornfelsed turbidites with minor metasomatic or hydrothermal alteration							Turbidites with significant metasomatic alteration		Turbidites veined with carbonate
	Increasing distance from Loch Doon Pluton							A type	B type	
Na_2O[1]	2.80	2.85	2.48	1.84	2.57	1.81	2.55	2.30	2.34	0.71
MgO[1]	5.84	5.49	5.43	5.32	5.16	7.56	5.22	4.00	3.46	6.59
Al_2O_3[1]	14.6	15.5	14.5	14.8	15.4	15.5	14.4	14.5	13.0	14.3
SiO_2[1]	57.8	58.3	59.9	58.6	54.3	56.0	59.6	60.5	65.3	50.9
P_2O_5[1]	0.22	0.20	0.19	0.21	0.22	0.17	0.19	0.21	0.16	0.28
S[1]	0.39	0.33	0.27	0.52	0.53	0.24	0.14	0.27	0.54	0.21
K_2O[1]	1.60	2.38	2.48	2.71	3.68	3.27	1.86	1.70	1.91	3.97
CaO[2]	6.92	5.21	5.67	5.36	6.19	3.92	6.86	8.74	6.15	11.26
TiO_2[2]	0.95	0.95	0.91	0.96	0.97	0.92	0.89	0.70	0.68	0.84
Mn ppm[2]	900	540	730	750	840	920	770	890	680	1910
Fe_2O_3[2]	8.24	7.97	7.62	7.85	8.71	8.60	8.01	6.87	6.10	8.67
L.O.I. minus S	1.13	1.61	1.01	2.40	2.23	2.54	0.71	0.80	0.73	2.61

1 = Determined by Beta probe
2 = Determined by XRF

All values in % except Mn.

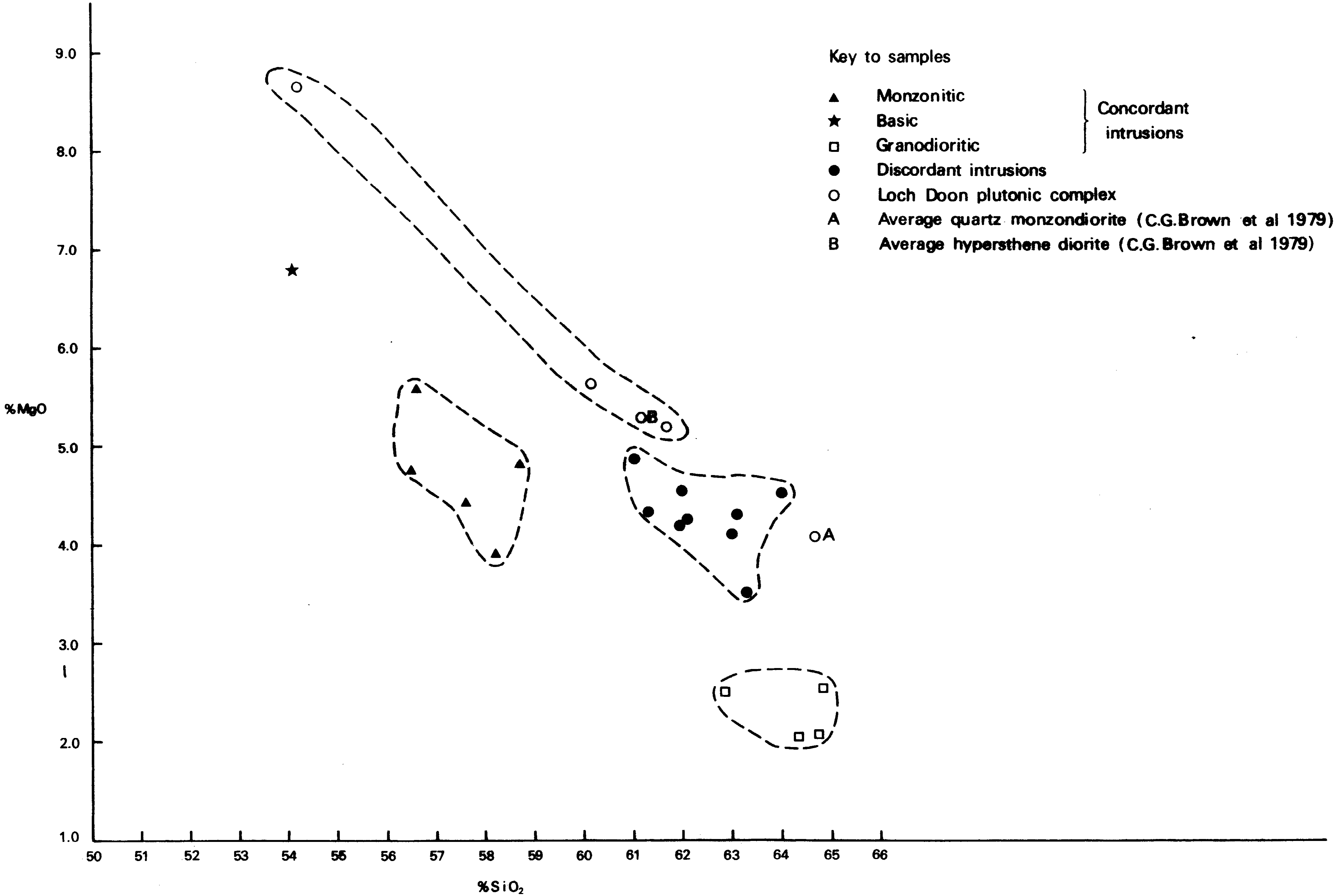


Fig. 22 MgO v SiO_2 for igneous rocks

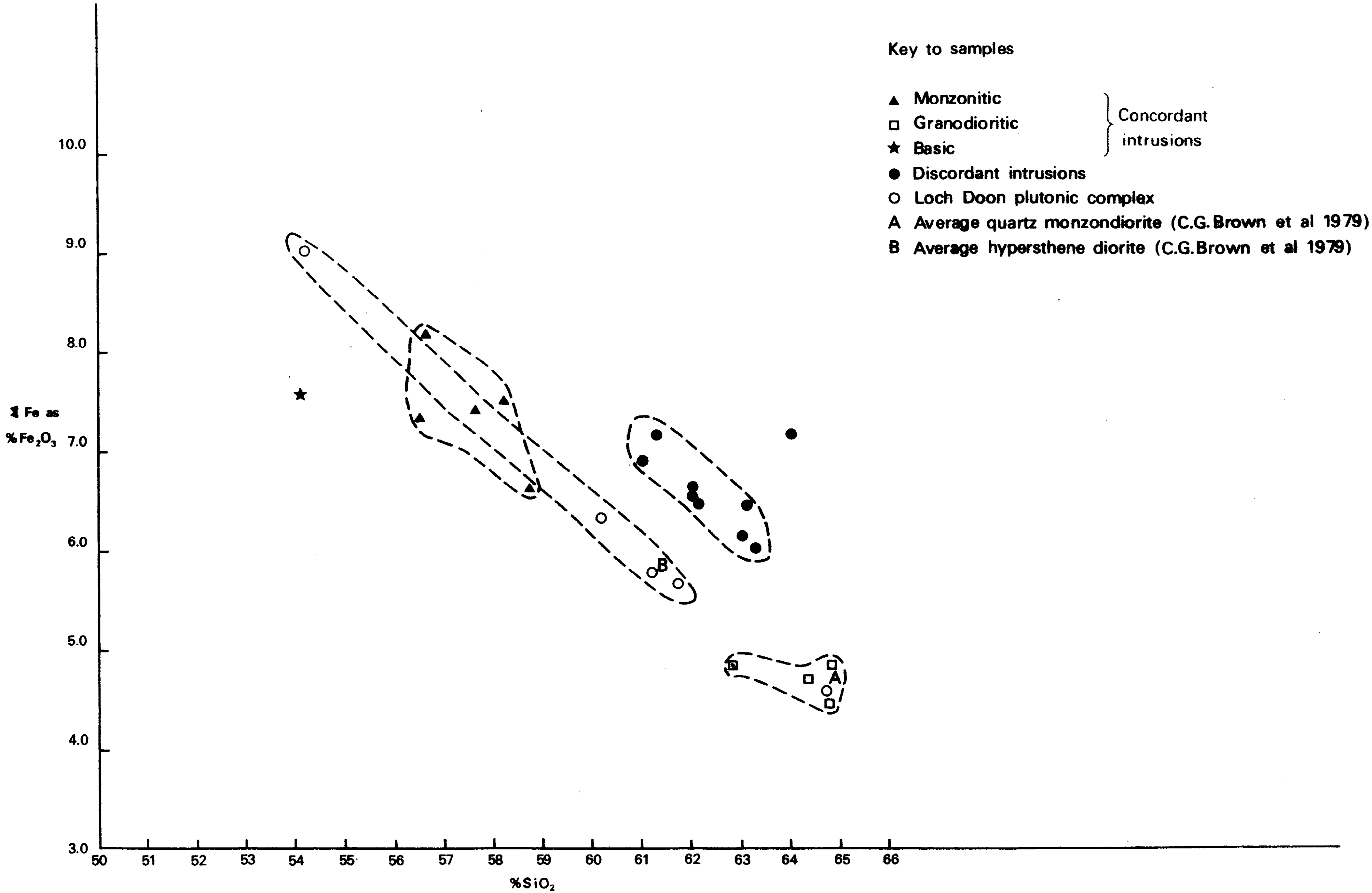


Fig. 23. ΣFe as Fe_2O_3 v SiO_2 for igneous rocks.

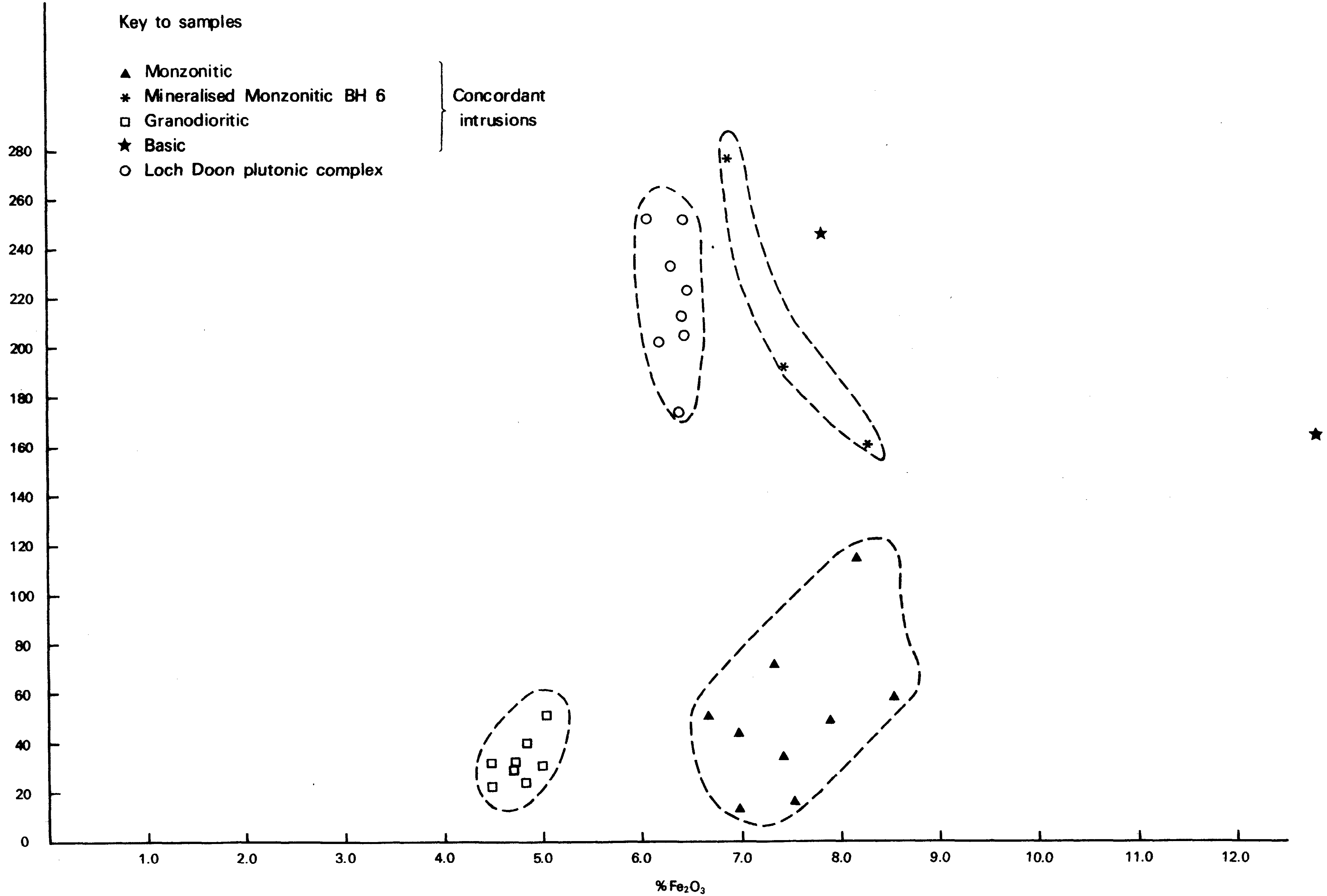


Fig. 24. ΣFe as Fe_2O_3 v Cr for igneous rocks.

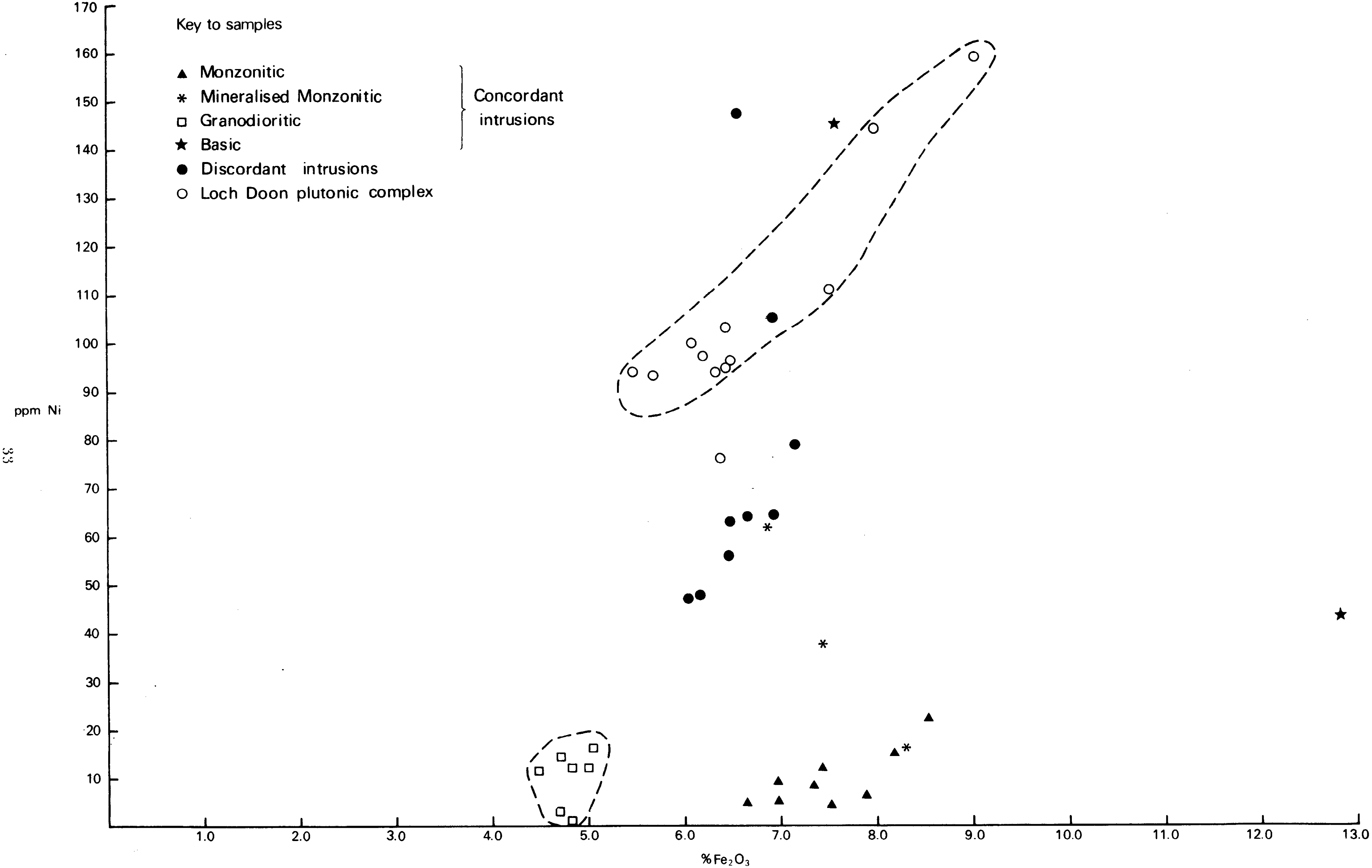


Fig. 25. ΣFe as Fe_2O_3 v Ni for igneous rocks.

biotite-rich rocks is significantly coarser and plagioclase tends to be a more conspicuous component. In borehole 3, sited about 120 m from the pluton contact, hornfelsing has produced significantly coarser-grained rocks, a darker green, more hornblendic amphibole and a salite clinopyroxene in addition to plagoclase, biotite and the actinolite, which is significantly better formed than in the previous boreholes.

Closer to the pluton in borehole 4 are isolated occurrences of cummingtonite and hypersthene in rocks of unusually mafic composition. In other rock types the mineralogy is similar to that seen in borehole 3, though biotite is significantly coarser-grained and takes on a conspicuous sieved texture nearer to the pluton. Within 10 m of the plutonic contact the hornfelsed greywacke takes on a much more granitic texture with irregular lenses of more biotite-rich rock; and up to 3 m from the contact a few grains of hypersthene and poikilitic kaersutite occur. The xenoliths of metasediment in the Loch Doon pluton comprise granulites, either consisting of clinopyroxene and plagioclase or relatively rich in fine biotite. The concordant monzonitic rocks have the general appearance of a hornfels such that they can be difficult to distinguish with the unaided eye from some types of metamorphosed greywacke. The granodiorites frequently have a foliated texture and are more distinctive. A variable sequence and intensity of hydrothermal alteration often complicates the mineralogy of these intrusions and intimate associations between the mafic minerals, such as biotite and amphibole replacing clinopyroxene, may be either late magmatic or due to contact metamorphism. Within the monzonite the late amphibole appears similar in composition to the actinolites from the hornfelsed sediments.

METASOMATISM

A pervasive phase of metasomatism has affected the sedimentary rocks throughout the area. In borehole 7 (650 m from the margin of the pluton) metasomatically altered zones are abundant and consist of irregular veins, lenses or layers of pale green to white granular rock. These stand out conspicuously against the dark brownish unaltered biotite-rich hornfels. Frequently the metasomatically altered areas are zoned, with a core of fine-grained quartz accompanied by actinolite, salitic clinopyroxene, conspicuous fine magnetite and pyrrhotite, and sometimes with minor sericitic patches, a few pyrite grains and some irregular granular sphene crystals. The cores are surrounded by greener envelopes containing a greater proportion of actinolite together with fine magnetite and ilmenite. This grades, with a decrease in actinolite content, into normal schistose biotite hornfels. Within the cores there are often irregular quartz veins containing a few relatively coarse grains of pyrrhotite with minor chalcopyrite. There are also small carbonate veinlets accompanied by relatively coarse salitic pyroxene, clinozoisite and, rarely, epidote and apatite and a few grains of ruby red sphalerite, probe analysis of which are shown in Table 5. Lenses of green actinolite-rich rock without a quartz-rich core are also frequent. Most of the altered zones are roughly parallel to the sedimentary layering of the hornfels though a significant number are discordant. Both concordant and discordant quartz and feldspathic veinlets with actinolitic envelopes also occur.

Table 5. Microprobe analysis of ruby-red sphalerite (BH7)

	Fe	8.74%
	Mn	0.18%
	Cd	0.05%
	Zn	57.10%
	S	33.58%
	TOTAL	99.65%
Molecular%		
	FeS	13.7%
	MnS	0.3%
	CdS	0.1%
	ZnS	85.0%
		99.1%
	Ag	<0.015%
	Sn	<0.014%
	Mo	<0.026%
	Hg	<0.060%
	In	<0.011%

In borehole 5, the metasomatically altered zones and vein envelopes are mineralogically similar, though the cores are more frequently irregular masses of vein quartz, sometimes with relatively coarse actinolite. Pale green zones, rich in clinopyroxene with conspicuous pink sphene but only minor amounts of opaque minerals, are more obvious than in borehole 7. In boreholes 3 and 4, closer to the pluton, clinopyroxene becomes more conspicuous and relatively large feldspar laths or minor biotite also occur within the metasomatically altered zones. As in the minerals of the surrounding fresh hornfels, the pyroxene and accompanying opaque minerals and sphene are better crystallised and coarser grained. Irregular veins containing quartz, clinopyroxene, amphibole, carbonate, clinozoisite, pyrrhotite and chalcopyrite also occur. According to microprobe analysis the clinopyroxene is compositionally similar to that within the metasomatically altered zones. The veins usually have a pale pyroxene-rich envelope grading outwards into a greener actinolite-rich zone and finally into an opaque-mineral-rich biotitic zone similar in silicate mineralogy to the normal hornfels. Within 10 m of the contact with the Loch Doon pluton, metasomatised zones can still be discerned though they are less obvious, consisting of relatively coarsely crystalline pyroxene with minor opaque minerals and biotite and without actinolitic envelopes: a xenolith of similar material has been observed within the margin of the Loch Doon pluton.

The chemical compositions of turbidite samples relatively rich in metasomatically altered lenses and veinlets are compared in Tables 3 and 4 with relatively unaltered turbidites. The data suggest that altered zones are of two types. Type A, which from borehole logging appears the commoner, shows enrichment in Ca and to a lesser extent Mn and Sr and depletion in Mg, Ni, Zn, Rb and Ba relative to the less altered turbidites. Type B, which exhibits enrichment in Si and depletion in many other elements, shows some similarity with the composition of rocks invaded by later quartz veins, except in Ca and metallic-element contents. Water content of samples rich in metasomatically altered material is substantially lower than that in most of the fresher turbidite samples. There appears to be no significant enrichment either in gold or in base metals associated with the metasomatic alteration, even though chalcopyrite and sphalerite can frequently be observed in minor amounts.

The abundance of the metasomatically altered zones is portrayed graphically on the diagramatic logs of each borehole (Figures 15-21). There appears to be no spatial relationship between the intensity of metasomatic alteration and proximity to the margin of the Loch Doon pluton. Metasomatically altered rock is most frequent within borehole 5 (250 m from margin of pluton). In fact, the metasomatism predates the emplacement of the pluton since there is evidence of a change from amphibole-rich assemblages to pyroxene-dominant assemblages which varies in parallel with a similar change in mineralogy of the unaltered hornfels as the margin of the pluton is approached. As stated earlier, a xenolith of granular pyroxene-rich rock identical to metasomatised rock near to the plutonic contact has been observed within the margin of the pluton itself.

None of the concordant intrusive igneous rocks appears to have been affected by the metasomatic alteration; and there is no evidence to suggest an increase in the abundance or intensity of the metasomatism adjacent to either variety of concordant intrusion. In fact, metasomatised zones seem largely absent or indistinct in the sedimentary rocks within the swarm of monzonitic intrusions in borehole 3 (Figure 7). This may indicate some partial obliteration due to recrystallisation and mineralisation originating from these intrusions.

The metasomatic alteration represents the earliest recognisable event of significance within the area, in response to a rise of heat energy and fluid movement. The altered rocks have similarities with silicate skarns described in association with granodioritic rocks from many parts of the world. The zonation in mineral composition away from an igneous source, which is characteristic of such skarns, however, does not appear to be developed in the area. Probe analysis of actinolites from boreholes 3, 5 and 7 (Table 6) show only slight variations in Mg to (Mg + Fe + Mn) ratios but more significant variations in Al, Ti and Na contents. The Ti contents increase markedly from borehole 7 to borehole 5 to borehole 3, as the pluton is approached, and may reflect the temperature increase due to contact metamorphism, an effect commonly observed in amphiboles (Ernst, 1968). The amphibole Al and Na contents are highest in borehole 5, lower in borehole 3 and markedly lowest in borehole 7. These compositional differences may be of premetamorphic origin, reflecting a gradient away from the original source of activity to which borehole 5 is nearer than boreholes 3 and 7. Table 6 shows that there are some resemblances betwen the composition of the actinolites and that of both metasomatic and veinlet amphiboles from the propylitic alteration zone associated with porphyry-style copper mineralisation within the Black Stockarton Moor subvolcanic complex, adjacent to the Criffel plutonic complex further south in Galloway (Leake and Brown, 1979; Leake and Cooper, in prep.).

MINERALISATION

DISSEMINATED ARSENIC-GOLD MINERALISATION

This type of mineralisation, identified particularly in borehole 3, shows a clear spatial relationship with the swarm of concordant monzonitic intrusions (Figure 13). The form of the mineralisation is predominantly as disseminations of pyrrhotite, arsenopyrite and pyrite within the margins of the igneous rocks and as arsenopyrite disseminated in the surrounding hornfels. Arsenopyrite also occurs within the metasomatically altered clinopyroxene-rich zones, together with pyrrhotite, and in association with pyrite and pyrrhotite in clinopyroxene veinlets with sericitic envelopes. Thin stringers of arsenopyrite with or without pyrrhotite also occur in both igneous and sedimentary rocks. Arsenic levels in rocks affected by this mineralisation, which forms a zone at least 18 m thick, reach about 3000 ppm and generally are higher in the turbidites than the igneous rocks. Gold levels associated with this mineralisation reach 0.14 ppm, and values of the ratio Au/As range from 3 to 14×10^{-5}. No significant enrichment in base metals or in other elements is associated with this mineralisation.

Similar mineralisation is associated with the monzonitic intrusion intersected by borehole 6, though it is largely confined to the intrusion itself. It takes the form of disseminations, segregations and stringers of arsenopyrite together with disseminated pyrite and some pyrrhotite. Lenses of richly disseminated arsenopyrite also occur in the biotite-rich hornfelsed turbidite immediately adjacent to the intrusion. Minor arsenopyrite also occurs, together with pyrite and biotite, in a metasomatically altered pyroxene-rich layer within the turbidites close to the intrusion. In this mineralised zone, which is about 3.2 m thick, arsenic levels reach 2500 ppm and Au levels 0.16 ppm while Au/As cover the same range as in borehole 3. As the intrusion is also quite richly mineralised with galena and sphalerite, with up to 0.3% Pb and 1.0% Zn in a later phase in association with carbonate veining, it is difficult to tell whether any of the relative enrichment in Mo (to 26 ppm), Sb (to 10 ppm) and Rb and Cr (see Table 2) in the intrusion is associated with the earlier arsenopyrite mineralisation. The form of the gold associated with the arsenopyrite mineralisation is unknown since no gold minerals have been observed and no gold detected in microprobe analyses of arsenopyrite.

It is probable that the majority of arsenic anomalies in soil, particularly the lensoid type trending parallel to the local strike, originate from disseminated mineralisation of the type described above, associated with the concordant monzonitic intrusions. No significant arsenic or gold mineralisation appears to be associated with the concordant granodioritic intrusions, although they are usually relativly rich in disseminated pyrrhotite.

Table 6. Microprobe analyses of actinolites

	BOREHOLE 3			BOREHOLE 5		BOREHOLE 7	BLACK STOCKARTON MOOR	
	D	D	V	D	D	D	D	V
SiO_2	50.20	49.75	49.89	49.14	48.93	53.93	46.39	51.13
TiO_2	0.89	0.84	0.70	0.78	0.76	0.19	0.52	0.15
Al_2O_3	4.23	4.59	4.93	5.02	4.73	1.76	5.96	3.49
FeO	13.62	13.80	14.70	14.20	14.79	13.59	19.40	15.47
MnO	0.30	0.36	0.23	0.35	0.25	0.46	0.21	0.16
MgO	13.42	13.42	12.67	13.37	13.51	14.59	9.37	12.60
CaO	11.60	11.74	11.89	11.30	11.48	11.79	12.04	13.47
Na_2O	0.45	0.41	0.43	0.58	0.51	0.10	0.74	0.45
K_2O	0.26	0.33	0.34	0.22	0.20	0.06	0.55	0.17
TOTAL	94.97	95.27	95.80	94.97	95.16	96.47	95.17	97.08

All Fe expressed as FeO

Number of ions on basis of 24 (O, OH)

Si	7.502	7.434	7.436	7.375	7.332	7.874	7.168	7.563
Al4	0.498	0.566	0.564	0.625	0.668	0.126	0.832	0.437
Z	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al6	0.247	0.242	0.302	0.263	0.168	0.177	0.252	0.171
Ti	0.100	0.094	0.078	0.088	0.086	0.021	0.060	0.017
Fe^3	0.000	0.000	0.000	0.000	0.140	0.000	0.126	0.000
Fe^2	1.625	1.628	1.775	1.613	1.557	1.570	2.375	1.913
Mn	0.038	0.046	0.029	0.044	0.032	0.057	0.027	0.020
Mg	2.990	2.989	2.815	2.991	3.018	3.175	2.158	2.778
Y	5.000	5.000	5.000	5.000	5.000	5.000	5.000	4.900
Fe M4	0.077	0.096	0.058	0.169	0.157	0.089	0.006	0.000
Ca	1.858	1.880	1.899	1.817	1.843	1.844	1.994	2.135
Na M4	0.066	0.024	0.043	0.014	0.000	0.028	0.000	0.000
X	2.000	2.000	2.000	2.000	2.000	1.962	2.000	2.135
NaA	0.065	0.094	0.081	0.155	0.148	0.000	0.222	0.129
K	0.050	0.063	0.065	0.042	0.038	0.011	0.108	0.032
A	0.115	0.157	0.145	0.197	0.186	0.011	0.330	0.161
Mg/(Mg + Fe* + Mn)	0.63	0.63	0.60	0.62	0.62	0.65	0.46	0.59

Fe* = Fe^{2+} obtained after minimum Fe^{3+} calculation from amphibile stoichiometry
D = disseminated in metasomatically altered rock or veinlet envelope
V = veinlet mineral

Minimum Fe_2O_3 recalculation based on formula $A_{0\text{-}1}\ X_2\ Y_5\ Z_8\ O_{23}\ (H_2O)$

VEIN GOLD-ARSENIC MINERALISATION

In all boreholes except 7, and at a number of exposures, a series of sharply discordant, roughly south-trending quartz veins has been observed. These are often richly mineralised with arsenopyrite and, in a few examples, minute grains of native gold have also been observed. A microprobe assay of a gold grain gave 86.4% Au and 11.1% Ag with a trace of Cu. Arsenopyrite is concentrated at the margin of the quartz veins but also occurs as stringers and segregations within the body of vein quartz. The native gold occurs chiefly within the vein quartz but a few grains have been observed within arsenopyrite. Several of the quartz veins also contain variable amounts of carbonate, needles of rutile and minor amounts of pyrite in association with the arsenopyrite. Surrounding the veins is a prominent alteration envelope of pale orange and green rock consisting of quartz, muscovite, chlorite and carbonate in a sericitic matrix. The alteration envelope, particularly adjacent to the vein, commonly contains abundant disseminated arsenopyrite associated with chlorite. Within the alteration envelope several thin quartz stringers, with large euhedral arsenopyrite grains, are common, and calcite veinlets accompanied by arsenopyrite and sometimes marcasite may also occur. Detailed examination of these rocks suggests a complex history of veining with additional barren quartz veinlets both pre- and post-dating the arsenopyrite mineralisation. Preliminary investigation of the quartz veins indicates that they contain abundant inclusions filled with liquid carbon dioxide.

The arsenical quartz veins intersected in boreholes range up to 30 cm thick (surrounded by a zone 80 cm thick of veined and mineralised rock). The majority are a few centimetres thick and arsenopyrite may also occur as stringers without vein quartz. Arsenic levels in 200-300 g samples of material from veins c.10 cm wide reach 3.5%, and gold values reach 8.8 ppm. Most of the gold is probably in the native form, since microprobe analysis of arsenopyrite failed to detect the element at the 0.02% level. Higher gold levels could have been obtained from individual veins from borehole 2, since assays of between 1 and 2 ppm were obtained from composite samples between 1.4 and 1.7 m long. Within the veined material there is a considerable range in Au/As ratios, from 2 to 105 x 10^{-5}, but in general the ratios are higher than in samples containing the disseminated arsenic mineralisation. Tungsten is a minor component of the vein mineralisation with levels reaching 55 ppm in a sample of veined material from the margin of the Loch Doon pluton. It appears that tungsten concentration decreases markedly away from the pluton; and the element is undetectable in material from borehole 5. Other elements found in one gold-rich vein from within the Loch Doon granite are 1600 ppm Pb, 125 ppm Bi and 90 ppm Ag but with no associated Zn. In borehole 5, two possibly similar veins containing up to 100 ppm Pb but no Zn also have relatively high gold levels and in one case the highest Au/As ratio. Table 3 indicates that turbidites affected by quartz veining show slight enrichment in Cr and Cu compared with unveined sediments, but they show relative depletion in most other elements.

The discordant quartz veins cut both the Loch Doon pluton and its aureole and occur both in stockworks and as isolated veins. No indication of the incidence of the veins can be obtained from the geochemical survey, since it is impossible to distinguish anomalies derived from disseminated and vein mineralisation on the basis of the elements determined. Some conclusions can be drawn as to their abundance from the borehole logs, although the orientation of many of the holes was not optimum to intersect the veins. With the exceptions of that cut by boreholes 7 and 2, it is apparent that about 6% of the rock is influenced by mineralisation within and around these quartz veins. No veins occur in borehole 7 but borehole 2 shows a much greater incidence of this type of mineralisation with about 50% of the core giving indications of significant arsenic mineralisation. The veins appear no more abundant in the margin of the pluton than in the adjacent sediment aureole. Outcrop evidence suggests that veins within the pluton occur chiefly in a zone up to 100 m wide parallel to the contact, except for a wedge of rock, possibly fault bounded, about 400 m north of the contact. In this, quartz veinlets mineralised with arsenopyrite often cut feldspathic pegmatite veins. Air photograph interpretation of some 20 km^2 around the area shows a south trending fracture pattern to be dominant with a further grouping of lineations in the north-east quadrant (Figure 26) some of which probably reflect the bedding of the turbidites. Several linear features with a north-west trend are interpreted as faults because of their strength and considerable strike length of up to 2 km.

BASE-METAL MINERALISATION

Evidence of zinc and lead mineralisation is common in boreholes 5 and 6 , rare in boreholes 3 and 4 and absent in the remainder. In all cases sphalerite and galena, sometimes with marcasite or pyrite and minor chalcopyrite, are associated with carbonate veinlets, quartz-carbonate veins or carbonate-rich breccia zones. In borehole 6 the base metal mineralisation appears to be spatially related to the monzonitic minor intrusion though veinlets with sulphide cut both the igneous rock and the surrounding hornfels. Elsewhere this mineralisation is distributed more randomly with no apparent association with any of the igneous activity. Some carbonate veins cut and displace arsenopyrite stringers with alteration envelopes, though in general the age relationships between the two mineralisation types is less clear. Within the arsenic-rich zone in and around the monzonitic intrusion in borehole 6 some of the carbonate veins contain arsenopyrite as well as the base-metal sulphides, which may indicate local remobilisation of the arsenic. Detailed examination of the veining suggests a complex history, though most of the base-metal mineralisation is probably relatively late and some at least may postdate the discordant quartz-arsenopyrite veins.

In samples containing base-metal mineralisation, with one exception, zinc levels always exceed those of lead. Zinc to lead ratios vary from 2 to 7 while levels reach 1.0% Zn and 0.3% Pb. Only in a carbonate breccia is the lead content at 1400 ppm, greater than zinc, at 500 ppm. The samples richest in lead contain up to 3 ppm Ag. Copper levels reach 250 ppm in a few samples but there is no significant positive correlation between copper and either

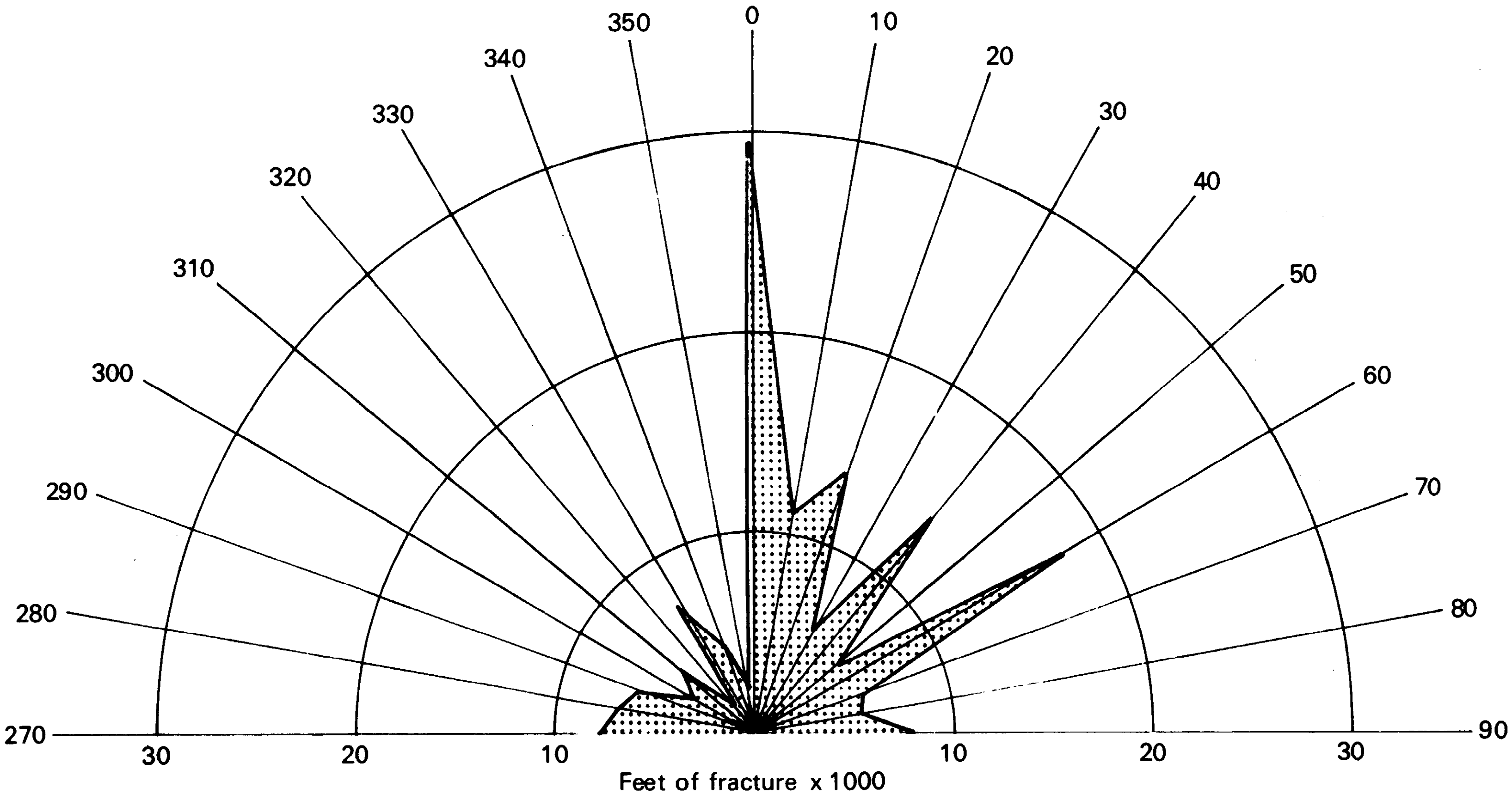


Fig. 26. Rose diagram of fracture traces

zinc or lead nor between base-metal and arsenic and gold levels. The chemical analyses in Table 3 indicate a positive correlation between the base metals and calcium and manganese due to the association with carbonate veins. Rubidium is the only other element which shows a significant positive correlation with the base-metals.

The source of the base-metal mineralisation is not apparent but the soil results (Figures 6-8) suggest that the amount of lead, copper and zinc increases towards the south of the area. Base-metal mineralisation also occurs over the watershed to the south, around the headwaters of Penkiln Burn (Leake and others, 1978), about one km from the southern boundary of the present area. This mineralisation is not associated with carbonate and may therefore be of different origin, especially as there may have been significant lateral movement along strike faults separating the two areas.

ORIGIN OF GOLD MINERALISATION

The mode and distribution of gold in the area around the headwaters of Glenhead Burn suggest that the mineralisation can be attributed to metasomatic and hydrothermal events within an evolving cycle of magmatism in which phases from granodiorite to diorite were emplaced at a moderately high level in the crust, somewhat below 3 km from surface. Gold mineralisation of this type is of worldwide distribution, occurrring in California and Oregon in the United States, orogenic belts in eastern Australia and also at several localities in Russia. A feature of the mineralisation in these areas, and one similar to the situation in the Glenhead Burn area, is the abundance of minor intrusions. This has suggested to many workers that there is a genetic association between the two, though it is generally apparent that ore emplacement was multiphase. A further characteristic of such deposits, particularly in Russia, is metasomatic alteration, over considerable areas and of various types including quartzose metasomatism, such as in the Maruntau deposit in Russia (Borodaevskaya and Rozhkov, 1977). In the Glenhead Burn mineralisation the wide distribution of metasomatically altered rocks, the common presence of actinolite, and the zonation of alteration zones around the metasomatically altered lenses suggest some similarity with the propylitic alteration around the porphyry-style copper mineralisation at Black Stockarton Moor (Leake and Brown, 1979; M.J. Brown and others, 1979), some 35 km distant across the regional strike. The depth of the present-day erosion surface of the Glenhead Burn area is considered to have been significantly greater than that at Black Stockarton Moor at the time of the respective mineralisation. This would account for the lack of porphyritic texture in the minor intrusions from the Glenhead Burn area compared with the abundance of this texture, and other manifestations of higher crustal level magmatism, at Black Stockarton Moor (Leake and Cooper, in prep.). The association of arsenic and minor gold with minor intrusive igneous activity is clearly demonstrable in the Glenhead Burn area. The abundance of CO_2-rich fluid inclusions in the later, discordant, gold-bearing quartz veins also indicates a magmatic source to this phase of mineralisation, but the control of the location of the veins is structural. This seems also to be the case in many gold deposits such as those near Great Falls, in Maryland (Reed and Reed, 1969) and the Klamath Mountains of California and Oregon (Hotz, 1971).

ASSESSMENT OF ECONOMIC POTENTIAL OF GOLD MINERALISATION

The economic potential of the gold mineralisation around the headwaters of the Glenhead Burn is difficult to assess from the limited information obtained from the geochemical surveys and drilling conducted to date. The work has shown that the use of arsenic as a pathfinder in soil surveys has limitations, since it is impossible to distinguish between anomalies caused by relatively wide zones of disseminated mineralisation, with low gold tenor, and those caused by veins or vein systems with higher gold tenor. On the basis of the boreholes drilled, the veined zone partly intersected in borehole 2 clearly shows the best overall grade (Figure 16), with 1.5 ppm Au over about 4.5 m. No evidence of coarse-grained gold has been found in the relatively small samples of veins taken, but if this were to occur, overall grades might be higher.

Other veins and vein swarms occur in the area and there is evidence to suggest that the richest gold concentrations occur in veins also containing lead but not zinc. Unfortunately, lead also occurs in a separate and widespread phase of base-metal mineralisation, which means that lead anomalies in soil cannot be used to detect gold-rich veins. Bismuth and silver levels may be of more use in detecting these veins since these elements appear to accompany the lead associated with the gold-rich veins. Other environments favourable for gold-rich mineralisation may occur where discordant quartz veins cut the concordant arsenic-rich zones, though no examples of veins cutting these zones were intersected in the boreholes.

POTENTIAL FOR GOLD MINERALISATION IN SURROUNDING AREA

The distribution of gold found in the pan during a drainage survey of the Loch Doon granite and its environs (Dawson and others, 1977) is shown in Figure 27. This demonstrates the widespread occurrence of gold and draws attention to three areas in particular. These are (a) north of the Fleet granite, around Maggot Hill, (b) the area around Moorbrock Hill, east and south-east of the Carsphairn granitoid complex, and (c) the area north of the same intrusion. In the Maggot Hill area, quartz veins with minor intrusions were located. No significant gold was detected in samples of this material but exposure in the area is very poor. Arsenopyrite was observed with the gold in pan samples from the Moorbrock Hill area but the source of these minerals was not established. Significant arsenopyrite was not detected in gold-bearing samples from north of the Carsphairn intrusion and was also absent from most of the other more scattered concentrate samples containing gold. The lack of consistent correlation between gold and arsenic in the area can also be

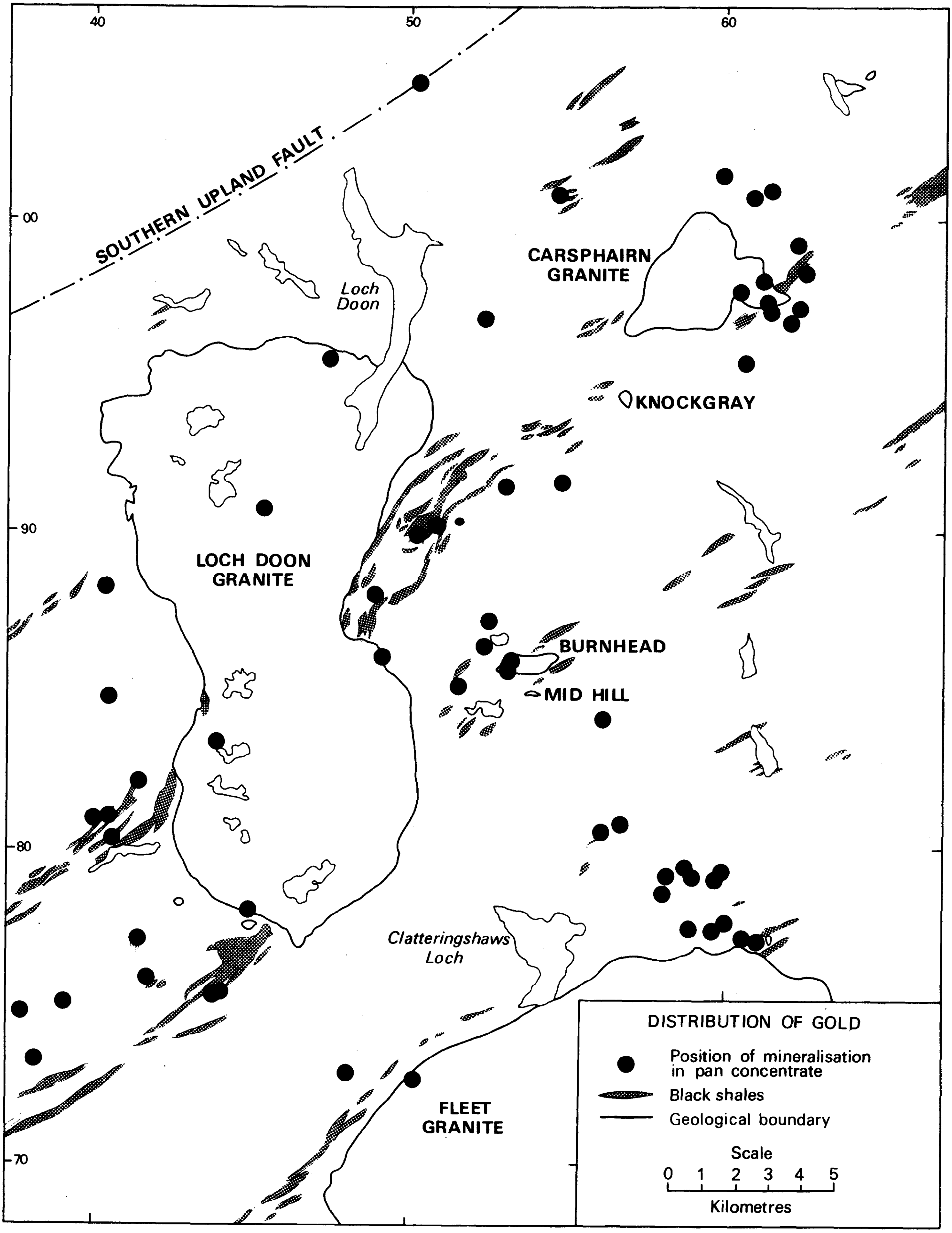


Fig. 27. Distribution of gold in panned concentrate samples around Loch Doon granite.

demonstrated by samples of arsenopyrite-rich vein material from the Palnure Burn trial (NX 4810 7018), which on analysis contained no detectable gold (Dawson and others, 1977). Arsenopyrite is common in the tonalitic facies of the small Burnhead intrusion but, though gold occurs in the concentrates from the area, it does not appear to be especially abundant.

It is difficult to establish whether all the above sites are centres of minor intrusive igneous activity, since the published geological maps do not necessarily give an adequate picture of the abundance of such intrusions. Concordant minor intrusive rocks occur in the Maggot Hill area and are probably more abundant than shown on the map, as exposure in the area is very poor. Minor intrusions also appear to be more abundant around Moorbrock Hill than elsewhere in the vicinity, but they are not in evidence north of the Carsphairn intrusion. The area around the Burnhead intrusion appears to contain no higher incidence of minor intrusions than other areas further north along the eastern side of the Loch Doon pluton; but to what extent variation in the degree of exposure influence this apparent distribution pattern is difficult to assess.

Nevertheless, in respect of the possible existence of centres of minor intrusive activity close to the margins of plutonic complexes, both the Maggot Hill and Moorbrock Hill areas appear to merit further investigation. Another feature of the Glenhead Burn area which may be a useful exploration criterion is the local flexure of strike. In this area the strike bends by about 60° within a 3 km wide zone. Such flexuring could have produced tensional stress regimes which would have facilitated the emplacement of minor intrusions and mineral veins.

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