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**Skarn-type copper mineralisation in the
vicinity of Belstone Consols Mine,
Okehampton, Devon**

K E Beer, G S Kimbell and M J Bennett

BRITISH GEOLOGICAL SURVEY

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Mineral Resources Series

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Mineral Reconnaissance Programme Report 101



BRITISH GEOLOGICAL SURVEY

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DATA PACKAGE

This report contains a brief summary of geochemical, geophysical and drilling work carried out around the former Belstone Consols Mine on the northern margin of the Dartmoor National Park. A comprehensive data package is available at a current (1989) cost of £1000 sterling plus VAT.

This includes:

- A - Consultation with available staff of the British Geological Survey who were engaged upon these studies.
- B - Examination of the retained halves of the drillhole cores.
- C - A detailed data package containing the items listed below.
 - 1 "Report on geochemical surveys around Belstone Consols Mine, near Okehampton, Devon." A comprehensive account which includes a full listing of 26 stream sediment analyses (XRF) and 323 soil analyses (AAS, colorimetric and XRF).*
 - 2 "Geophysical surveys in the Belstone area, Devon." - a discussion of the surface geophysics carried out.
 - 3 Supplement to the above geophysical report including an assessment of the drilling results.
 - 4 Geophysical data plots.
 - 5 "Drilling at Belstone Consols Mine, near Okehampton, Devon." Detailed discussion of the lithology, mineralisation and geochemistry of the four drillholes. It includes full lithological logs of the drill cores and a complete listing of the depths and XRF analyses of split core samples.*
 - 6 Geophysical borehole logs.

* Analytical data can be supplied in digital format.

Subject to staff or ex-staff availability it may be possible to arrange for a brief on-site examination at cost.

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

SUMMARY

This report summarises geochemical, geophysical and drilling investigations carried out on copper-arsenic-zinc mineralisation around the former Belstone Consols Mine, situated on the northern margin of the Dartmoor Granite and just inside the Dartmoor National Park. Significant concentrations of metalliferous sulphides are restricted to the Meldon Chert Formation of the Lower Carboniferous sequence and predominantly to calc-silicate rock-types within that formation. Although examined only within a limited area around the former mine, similar strata occur as a narrow belt with a strike length of some 22km between Sourton Tors and Drewsteignton.

The main drainage crossing this belt is flooded by minerals derived from the granite and stream sediments provide little evidence of the location, nature or richness of any sulphide ores. Soil geochemical surveys, however, do indicate clearly the presence and the general composition of near-surface mineralisation, even when sited on steep valley slopes or over rather narrow ore beds. Definition into discrete sulphide-rich beds appears possible but exact location of the structures is somewhat less certain.

Surface geophysical surveys immediately to the west of Belstone Consols Mine detected and traced a number of horizons of contrasting resistivity and chargeability, and have provided a new insight into the geological structure of that area. Most of the geophysical markers do not relate directly to potentially economic mineralisation, although higher chargeability values were observed over the principal mineralised zones revealed by subsequent drilling. Magnetic surveys indicate that pyrrhotite is no more than a minor constituent of the mineralisation in the vicinity of the mine.

Drilling proved the presence of significant copper and arsenic mineralisation, surprisingly with little zinc. Although cobalt is not important as an accessory metal, high values of bismuth are quite common. Tin is well developed in most calc-silicate lithologies but is undoubtedly present mainly as replacements in the garnets. Metal values were not as rich as had been hoped but locally did exceed 3%. The mineralisation is wider spread than anticipated and the worked ore beds cannot be identified with certainty. It seems, however, that a previously unknown mineralised horizon can be recognised higher in the Meldon Chert Formation.

INTRODUCTION

Mineralised skarn-type beds within the Meldon Chert Formation to the north of the Dartmoor Granite have been exploited in two formerly productive copper mines and explored in several other trials (Edmonds and others, 1968). The latter explorations of these seemingly lensoid deposits had not proceeded below drainage adit depth and, therefore, it is probable that further bodies of copper and zinc might yet be found within this belt. It must be recalled that skarn development is also found on the southern margin of the Dartmoor Granite and around parts of the Bodmin Moor and Hensbarrow Granites. A better understanding of the north Dartmoor occurrences, therefore, could have wider application in the peninsula.

Copper-arsenic-zinc mineralisation can be traced intermittently from the vicinity of Sourton Tors [SX 543898]* to near South Zeal [654935] in both limbs of an anticline overturned to the south in the Lower Carboniferous sequence (Fig. 1). The two productive mines, Belstone Consols [632945] and Ramsley [652931], are both situated in the northern (upright) limb and are separated by the Sticklepath Fault Zone (Fig. 4). The former working reported four mineralised beds (Fig. 3), and the latter three (Dines, 1956). Presumably the close proximity of these mines reflects some local geological control upon the concentrated deposition of sulphide ore minerals and logically, therefore, the best prospects of finding further viable copper ore lie nearby. As yet this control has not been determined with certainty but it may be advocated that the nearby Sticklepath Fault zone has acted as a channelway for the movement of mineralising fluids.

From the available production records (Burt and others, 1984) it is apparent that only high grade copper ores were sold from both mines. Belstone is said to have had no concentration mill and this suggests that the ore must have been selectively mined (or selectively hauled to surface). If so, there must be reasonable expectations that good grade ore still exists within the mine perimeter.

Ramsley Mine is situated inconveniently for exploration by geochemical and geophysical methods and the dissection of its mineralised beds by elements of the Sticklepath Fault Zone would confound any drilling attempts. In consequence, the current surveys were concentrated upon the area around Belstone Consols Mine where gentle land slopes are conducive to all these approaches.

GEOLOGICAL SETTING

Modern remapping of the geology of the Okehampton (324) Sheet was described by Edmonds and others (1968). The relevant part of the succession recognised by them is quoted in Table 1.

The thicknesses given in Table 1 are those measured at Meldon (Fig. 1). Thick dolerite dykes associated with the Lower Carboniferous rocks usually cut across the strike of the sediments but locally they appear to be interbedded. Only in an anticlinal core at Meldon are the lowest strata exposed; the rocks are hornfelsed and chiastolite-bearing as the area under consideration lies inside the thermal aureole of the Dartmoor Granite; the rocks are also more or less affected by metasomatism.

Lower Carboniferous strata are disposed in two overturned sharp anticlines at Meldon; farther east they occur in a single structure which appears to be more upright. This configuration creates a very narrow outcrop which almost faithfully follows parallel to the granite margin (Fig. 1) and between the two is a synclinal trough of hornfelsed or slaty Crackington Formation sediments. The outline of the folding is marked by the double outcrop of Meldon Chert Formation with its prominent development of durable cherts and cherty mudstones and its variably textured calc-silicate rocks.

* Unless otherwise indicated all localities in this report lie in the Ordnance Survey National Grid square designated SX.

Table 1. Geological succession in north Dartmoor

Upper Carboniferous:		
Crackington Formation	Shales with thin sandstones	??
Lower Carboniferous:		
Meldon Chert Formation	Cherts, shales and lensoid limestones; local alteration to calc-silicate rocks.	75m
Meldon Shale and Quartzite Formation	Shales, locally chialstolite-bearing, and quartzites; some tuffs.	150m
Carboniferous and Devonian:		
Meldon-slate-with-lenticles Formation	Slaty hornfels with thin siltstones.	??

It is with the calc-silicate rocks that metalliferous sulphide mineralisation is usually associated. For the main part the ores are not preserved at the surface and, with the exception of one stream exposure [569919] in Red-a-ven Brook, their characteristics are determinable only from mine waste samples. Near Meldon Quarry [570925] there is a high proportion of pyrrhotite associated with abundant sphalerite and less chalcopyrite and arsenopyrite. The calc-silicate rocks are highly garnetiferous (and Sn-bearing) and are accompanied by some white wollastonite-rich variants which contain yellowish green malayaite (El Sharkawi and Dearman, 1966). In the east, at Belstone and Ramsley, the ore is more pyritic and less sphaleritic and the host rocks either highly garnetiferous or axinitic. The ores and host rocks at Belstone Consols have been well described by Smith (1878). Cobalt and bismuth are reported by Dines (1956) in the ores at Ivy Tor Mine [627934].

Two types of faulting have been observed in the area. Most apparent are the NW-SE trending structures which cut both granite and Carboniferous rocks. Some have a significant lateral displacement, the largest being along the Sticklepath Fault. In fact, this is really a wide fault zone comprising several en-echelon fault planes; within it the Ramsley mineralised beds are broken up into short sections. The detailed mapping (Fig. 4) revealed several strike faults affecting the Lower Carboniferous outcrops; they are believed to have a normal sense of downthrow.

PREVIOUS MINING AND EXPLORATION

There is no authentic record of when the bedded sulphide ores of north Dartmoor were first worked but it seems that exploration began in the western end of the belt. De la Beche (1839) mentions mining for tin on Longstone Hill, probably at Forest Mine [561912] which now lies beneath the Meldon Reservoir; tin here is almost certainly present as stanniferous garnet, perhaps with a little malayaite, and has never had any commercial value. The dumps contained abundant arsenopyrite and Collins (1912) reported copper from workings 24 fathoms (45m) deep in 1870. Nearby Meldon [570918] and Homerton [555907] mines may also be of this later date.

Ramsley Mine (also worked as Wheal Emily and as Fursdon Mine) is reported as producing intermittently from 1859 to 1911, but may have been started as early as 1840 (D.G. Broughton, pers. comm.). Sales of copper ores from Belstone Consols (known after 1878 as Mid-Devon Copper Mine) extend from 1860 to 1891, though surface trenching on the Main Lode outcrop predates this. Ivy Tor Mine was working during part of this period (1860-1867) but has no known output. At one stage these three mines were all operated by the same company. Production recorded from Ramsley totals 10,410 tonnes, much of it at 6.33% Cu; from Belstone Consols the output was 3,120 tonnes with most at 9.23% Cu (Burt and others, 1984). It is likely, however, that this record is incomplete.

During its final years from 1899 to 1911 the Ramsley Exploration Syndicate, then managing Ramsley Mine, tried to re-open the Belstone Consols Mine and undertook exploration of the ground between the two properties. It probably also encouraged work at Ford Mine [643935]. Farther east it acquired the lease of Gooseford (or Throwleigh) Mine [672925] upon which trial workings had previously been established. Seemingly none of these underground explorations were successful. Halstock Mine [608941] was re-explored around the same date but is believed to have worked previously in 1870.

Renewed interest at both Ramsley and Belstone mines was displayed briefly in the early 1950s but no work seems to have ensued. The exploration boom of 1960 onwards generated only minor interest in the north Dartmoor area; Noranda Kerr (UK) Ltd. endeavoured to lease sufficient area between Okehampton [587952] and South Zeal to make a modern exploration programme worthwhile. This proved to be very difficult, due in part to the indifference of land owners, to the conservationist opposition, and largely to local unfamiliarity with exploration and mining procedures. Some geochemical drainage surveys were carried out but the results are unknown; suffice it to observe that the company pulled out of SW England shortly after.

At about the same time, at the western end of the mineralised belt, Consolidated Goldfields Ltd. were looking at the pyrrhotitic sulphide beds as a possible resource for sulphuric acid production. In 1966 the Geological Survey studied magnetic sulphide mineralisation at Sourton Tors using ground geophysics and drilling (Beer and Fenning, 1976).

Enquiries since that time have come to nothing, most apparently foundering on the widely declared opposition of the Dartmoor National Park Committee to any form of mining in their bailiwick.

GEOPHYSICAL SETTING

The North Dartmoor area has been covered by an aeromagnetic survey which was commissioned by the Geological Survey in 1958. The average separation of the N-S flight lines was 400m and the nominal ground clearance 500ft (152m). The data were collected in analogue form but have recently been digitised. Total magnetic field variations (after removal of a standard linear geomagnetic field) are displayed as a simplified contour map in Fig. 2a and as a shaded-

relief image (illuminated from the north) in Fig. 2b. A conspicuous belt of magnetic anomalies encircles the northern margin of the Dartmoor Granite. On a broad scale the anomalous belt is dominated by two major reversely polarised anomalies separated by the Sticklepath Fault. A dextral displacement across this fault is evident, together with a reduction in anomaly amplitude over a zone extending several kilometres to the east of the fault

The shaded-relief image (Fig. 2b) does not provide the quantitative amplitude information of a contour map but is more effective in defining structural trends. With illumination from the north, magnetic minima generate shadows on their northern limbs and bright illumination on the southern limbs. To the west of the Sticklepath Fault the image reveals, in addition to the main minimum, a subsidiary minimum with the same trend approximately 1.5km farther north and two parallel minima between the main feature and the granite. The latter appear to extend from about [530890] (just west of Sourton Tors) eastwards as far as [590930] and, with a small hiatus, possibly as far eastwards as the Sticklepath Fault.

One of these aeromagnetic features has been investigated in detail at Sourton Tors. The cause was found to be pyrrhotite in Upper Carboniferous slates, which was considered to have been derived largely from remobilisation and conversion of the syngenetic pyrite content of the sediments under the thermal influence of the granite (Beer and Fenning, 1976). The envelope of mineralisation was inferred to be determined largely by the radial thermal gradient imposed by the granite. This is reflected on a regional scale by the way the belt of magnetic disturbance follows the granite margin in the region to the SSW of Sourton Tors (extreme SW corner of Figs. 2a and 2b). A particularly interesting feature of this region is the way the overall zone of disturbance follows the granite margin with a reasonably consistent width (typically 2-3km, a similar width to the observed thermal aureole) while individual anomalous features follow the strike of the Carboniferous rocks but are truncated when their trend takes them too far from the granite margin. The implication is that pyrrhotite-rich zones form where the combination of thermal conditions and Carboniferous lithology are suitable.

The longer wavelength aeromagnetic anomalies occurring on the north side of the Lower Carboniferous outcrop are due to deeper sources and have not been investigated by drilling. Fenning (in Edmonds and others, 1968) suggests their cause to be basic igneous (doleritic?) rocks. An alternative explanation is that these anomalies are, like those at Sourton Tors, due to pyrrhotite mineralisation. Thompson (1988) has observed that magnetic remanence dominates the magnetisation of pyrrhotite-bearing rocks, and that the direction of this magnetisation is strongly influenced by cleavage and bedding planes. He modelled the magnetic anomalies to the north of Dartmoor by assuming the pyrrhotite-rich horizons to follow a northward dipping bedding/cleavage direction, with the magnetisation vectors directed upwards along this direction. The tops of the bodies lie directly beneath the magnetic minima. Where deeper sources were modelled, their tops lay at estimated depths of 200-400m. Thompson also makes the suggestion that the reduced magnetic anomaly amplitude immediately to the east of the Sticklepath Fault is a result of destruction of pyrrhotite in the high temperature, oxidising environment prevalent in faulted rocks adjacent to the recently

emplaced granite. This hypothesis requires Variscan dextral movement on the Sticklepath Fault, which is compatible with the model of Holloway and Chadwick (1986). A decrease in anomaly magnitude could also result from the effect of complex deformation on the total magnetisation of rocks in which anisotropy of magnetisation is pronounced.

A model for the geophysical setting of the north Dartmoor region is therefore proposed in which the major magnetic anomalies are due to pyrrhotite mineralisation concentrated in Carboniferous rocks that are of favourable lithology and were subjected to heating by the intruding granite. Four principal magnetic horizons are evident from the aeromagnetic data in the region between Sourton and the Sticklepath Fault. The depth to the tops of these increases with distance from the exposed granite boundary, and this may reflect the northward dip of an isograd marking the limit of pyrrhotite formation. From its position, the main magnetic horizon on the north side of the Lower Carboniferous outcrop may be equivalent to that drilled at Sourton Tors (ie. close to the Crackington Formation/Meldon Chert Formation boundary). This is only a simple model intended to explain the broad aeromagnetic trends. Ground surveys, including those conducted as part of this study (see below), indicate a more complex anomaly pattern than the airborne survey.

SURFACE GEOCHEMISTRY

As a precursor to soil sampling an attempt was made to determine the lateral continuity of Belstone Consols mineralisation by stream sediment geochemistry. Twenty-six samples were collected and were analysed by XRF for As, Ba, Bi, Ca, Ce, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, Th, Ti and Zn. In the crucial rivers, the Taw to the east and East Okement to the west of the mine workings, the sediments were flooded with minerals from the nearby granite. The chemical results yielded little evidence to substantiate either the presence or the location of sulphide mineralised horizons and it may be that similar results discouraged continuance of the Noranda programme.

Failure to define any lateral extensions to the mineralisation, combined with geographical and access considerations, prompted the limitation of soil sampling to an area immediately around Belstone Consols and another on the valley slopes between Ivy Tor and Ford mines (Fig. 5). This programme, firstly, was expected to confirm the number and sub-outcrop of mineralised beds at Belstone, examine the adjacent area for further parallel beds, and establish their near-surface extent. Secondly, it was expected to indicate the position and length of those structures tried at Ivy Tor and Ford mines, and establish the relationship between these two beds. It was also thought of importance to compare the form, tenor and amount of mineralisation in the two fold limbs.

The five northern limb traverses were sampled at 10m intervals and yielded 213 soil samples. On the southern limb collection was spaced at 20m because of the steep slope involved; the six lines provided a further 110 samples. After drying, disaggregation and screening, sub-samples were analysed by AAS for Ag, Co, Cu, Ni, Pb and Zn, by colorimetric determination for W, and by XRF for As, Ba, Ca, Ce

Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, Ti and Zn. For ease of comparison, statistical summaries of the analytical results are set out separately for the two limbs in Tables 2 and 3.

Table 2. Summary of AAS and colorimetric analytical data for soils

	Northern limb			Southern limb		
	Range	Mean	Median	Range	Mean	Median
AAS analysis(in ppm):						
Ag	0-5	1.545	1	0-2	0.864	1
Co	5-390	33.66	25	5-40	15.45	15
Cu	35-3770	362.5	170	5-160	59.18	45
Ni	15-110	41.85	35	5-75	31.73	25
Pb	20-1250	54.69	40	30-120	53.45	50
Zn	40-810	120.2	110	10-300	108.7	100
Colorimetric analysis (in ppm):						
W	0-40	4.014	0	0-20	3.318	0

Table 3. Summary of XRF analytical data for soils (in ppm)

	Northern limb			Southern limb		
	Range	Mean	Median	Range	Mean	Median
As	50-3997	739.7	548	8-1307	366.3	370
Ba	128-927	315.1	315	150-416	281.2	282
Ca	1370-83000	18027	11550	430-26470	7115	4540
Ce	5-92	48.63	49	4-100	47.67	44
Cu	33-3297	384.5	193	5-208	68.40	48
Fe	35910-234150	99603	91530	11180-136310	65094	67940
Mn	290-24060	3183	2150	80-10480	2469	1550
Mo	0-23	5.568	4	0-11	3.791	4
Ni	10-142	44.94	39	4-96	34.21	23
Pb	9-1198	58.66	42	30-170	62.25	58
Sb	0-73	16.70	14	0-21	6.218	5
Sn	14-689	123.5	89	16-186	68.05	59
Ti	2540-11770	5915	5920	3450-7510	5332	5200
Zn	59-925	158.2	151	18-367	135.3	133

Within these results lies a clear implication that the northern limb contains a higher degree of mineralisation than the southern one, though there are significantly anomalous levels of all the sulphide ore metals in both. Fe and Ca ranges also suggest that metasomatic calc-silicate rocks are more intensively developed in the north. It might be deduced, therefore, that the northern limb holds the greater potential for further viable ore-bodies.

Traverse plots for each of the main ore metals, if considered in conjunction with the mine section (Fig. 3), can be converted into interpretations of the outcrops for the four worked Belstone "lodes". Assuming a strike approximately east-west and ignoring any details of the mapped geology (Fig. 4), the joining of these inferred outcrops yields the simple "lode" pattern displayed in Fig. 7. While this pattern may be accepted as reliable in the immediate vicinity of the mined area (ie. the area controlled by the mine section), its validity

farther out, particularly to the west, is doubtful. In the southern limb the situation is confused by a strike fault, but it appears that the beds tried at each mine may well be separate structures.

From this treatment there would seem to be indications of two previously unrecognised structures within the northern limb. One of these, north of the mine workings, has a similar geochemical signature to most of the worked "lodes" and, because of its situation, has been labelled No. 3 North Lode. The other, well to the south, seems to be recognisable from its anomalous Sn signature and in consequence has been called the Tin Lode. An additional structure is also indicated in the southern limb, lying to the north of both the Ivy Tor and Ford beds.

The Ivy Tor Lode lies close to the upper margin of the Meldon Chert Formation and appears to occupy a stratigraphical position similar to that of the inferred "No. 3 North Lode". It is tempting, therefore, to equate these two. No correlation can be offered for the other beds, however. It might seem that calc-silicate horizons which were mineralised at Belstone are attenuated or merged over the fold hinge to be represented by fewer and smaller structures in the south.

SURFACE GEOPHYSICS

Electrical, electromagnetic and magnetic methods were employed in the geophysical investigations of the Belstone area. Initially, a series of reconnaissance dipole-dipole IP/resistivity and magnetic traverses was undertaken (Lines A-I in Fig. 6). Because the Meldon Chert Formation had been shown to carry various forms of sulphide mineralisation, the first traverses were sited to cross outcrops of this sequence (or locations where it is apparently concealed as a result of strike faulting) at suitable positions along a 4km strike section of the Lower Carboniferous outcrop. This phase of the study revealed enough features of potential interest to merit continued investigation.

Correlation with the initial geochemical studies suggested that subsequent investigation should be concentrated around the former Belstone Consols Mine site. In the event, the ground selected lay immediately to the west of the former mine, an area least troubled by man-made conductive artifacts and free from the possible effects of underground water-filled cavities.

Reconnaissance traverse A, across the old workings of the mine, indicated relatively high chargeabilities and low resistivities over the Meldon Chert Formation, inferred to be due to the combined effects of mineralisation, relatively conductive shale strata and water-filled cavities. The magnetic response is subdued, so significant concentrations of pyrrhotite are considered unlikely. The dipole-dipole array used did not provide sufficient resolution to permit interpretation as discrete mineralised beds. Pronounced IP/resistivity anomalies were obtained in the area to the west of the former mine workings (reconnaissance traverses E and G); again the magnetic response is subdued. According to the most recent 6-inch geological mapping, the source of these anomalies lies within the Crackington Formation (Upper Carboniferous), which is a less promising

host to economic mineralisation than the underlying Meldon Chert Formation. Because geochemical copper and arsenic anomalies also appear to extend into this area, further detailed geophysical investigations were undertaken to resolve the conductive structures and examine their relation to known mineralisation.

The detailed investigations comprised IP/resistivity surveys using gradient and Wenner arrays, very-low-frequency electromagnetic (VLF-EM) traverses and self-potential (SP) and VLF-resistivity trials. The improved resolution obtained using these methods enabled the identification and detailed mapping of a number of geophysical marker horizons. These were:

1. A belt of low-resistivity rocks, the axis of which coincides with the northern edge of the zone of most conspicuous mineralisation as identified by the surface geochemical surveys. Higher chargeabilities are associated with this belt in places, although the correlation is not exact.
2. A belt of low resistivity/high chargeability black pyritic mudstones within the Crackington Formation. These rocks also produced a strong SP effect.
3. A high resistivity/low chargeability calc-silicate horizon in the upper part of the Meldon Chert Formation
4. A low resistivity/high chargeability horizon in the lower part of the Meldon Chert Formation.
5. A pronounced increase in resistivity and accompanying decrease in chargeability at or slightly below the top of the Meldon Chert Formation.

Of the above list, only the first-mentioned appears to correlate with a mineralised horizon located by surface geochemistry and drilling (see discussion in the Borehole Geophysics section); however, valuable structural information is provided by the mapping of all these markers. In particular, a major fault to the west of the mine workings was defined by the displacement of geophysical markers and a structure proposed which accounts for the westward extension of the geochemical anomalies (which could not be explained in terms of the previous geological mapping without invoking significant up-slope migration of geochemical anomalies).

Results achieved at Belstone show that geophysics can play a role both in the initial reconnaissance and in the detailed investigation of the north Dartmoor mineralised belt. Nevertheless, it is clearly essential that such geophysical work is combined with a suitable programme of soil geochemistry.

DRILLING

A combination of the foregoing geochemical and geophysical results was used to formulate a diamond drilling programme restricted to four drillholes totalling about 1100 metres. Problems arose over Planning Permission to drill in the National Park and the start was delayed by the necessity for a Public Inquiry. In deference to the fears of both landowners and conservationists, minor modifications were made to the sites and the four holes were drilled as shown in Figure 8. Completed drilling totalled 958m.

The philosophy behind the sitings was a simple one. BHs 1 and 3 were located to each side of the former workings, these seeking to examine the margins of the exploited mineralisation. Such holes were intended to establish whether the grades left unworked or undeveloped are such as to be of commercial interest at the present time. BH 2, to the east, was intended to penetrate the mineralisation close to the western margin of the Sticklepath Fault zone, in an area where geochemistry had indicated lower metal contents and perhaps fewer mineralised beds. A nearby un-named shaft testifies to some mining in this area, perhaps at shallow depth. The final hole, BH 4, was designed to examine both geophysical and geochemical anomalies in an area which also contains evidence of unrecorded underground working. As a guide to the mineralised beds expected to be encountered in each hole, a series of inferred sections (eg. Fig. 9) were prepared using interpretations of the soil geochemistry and assuming a northerly stratal dip of about 70 degrees.

Despite differences of hardness between the lithologies, drilling proved to be relatively easy with the holes remaining reasonably on course and high core recoveries being returned. Major core losses occurred mainly in the broken near-surface layers and in fault zones. One of the latter, encountered in BH 1 at an inclined depth of 37-50m, yielded a steady supply of water in artesian flow. In BH 4 another major fracture zone so affected progress as to necessitate abandonment before reaching the scheduled completion depth. This hole also had an artesian flow but one small enough to permit terminal capping. It might seem, then, that some of the local faults carry large amounts of water (particularly during the wet winter months?) which could pose problems to drilling or to eventual mining. Pertinently, Mr. D.G. Broughton (pers. comm.) reports that Belstone Consols Mine was said to have closed after an inundation with which the pumps could not cope.

CORE GEOLOGY

Within these drillholes are represented the lowest parts of the Crackington Formation, probably all of the Meldon Chert Formation and the uppermost strata of the Meldon Shale and Quartzite Formation. The last two are seen in the graphic log of Fig. 10.

In general the lithologies encountered were little different from those anticipated, though calc-silicate horizons were perhaps less common and more clustered than expected; some however are thick and match the descriptions of Smith (1878). Correlation of these beds, and indeed of all the Meldon Chert Formation lithologies, from hole to

hole is not very satisfactory and seems to suggest that there is rapid and marked lateral facies variation. It can be argued that this is mainly the result of patchily localised or lensoid metasomatism, an alteration which may not necessarily reflect differences of original composition.

Limestone (marble) bands are reported in BHs 1 (Fig. 10) and 3, located presumably at an identical stratigraphical horizon near the base of the Chert Formation; their different thicknesses suggest a lensoid shape thinning westwards. Similar marble is not seen in BH 2, it probably being faulted out. It seems worth emphasising that this band of marble helps lay to rest the fallacy that calc-silicate rocks are derived predominantly from original limestones; in the north Dartmoor area they are developed from cherts which may themselves be altered argillaceous rocks.

Perhaps the most significant feature of the core geology is the thicknesses of Meldon Chert sequence encountered. In BH 4, in the extreme west, it was about 80m - the same as reported from the type area at Meldon (Edmonds et al, 1968). One might be excused, then, for assuming this drillhole to contain the complete succession. But BHs 1 and 3 each show about 230m of strata which can be ascribed with confidence to the Meldon Chert Formation and in neither is it possible to recognise any major intra-formational faulting, either as discrete movement structures or through lithological groupings which can be recognised as repeated. On such considerations it has to be advanced that the formation as seen locally in Belstone Consols is much thicker than elsewhere. In concert with this expansion there is an increase in the number, though not necessarily the size, of the calc-silicate beds.

Such a very marked thickening of the succession raises a question of particular economic significance. Has the increased number of calc-silicate beds permitted a more intensive degree of mineralisation in this area, this in turn being reflected in greater mining success? It is evident in the cores, as it is implicit in Smith's description (1878), that a large proportion of the sulphide deposition is located in calc-silicate lithologies. Within our four drillholes, however, this mineralisation is nowhere sufficiently strongly and consistently developed as to obviously constitute the beginnings of an ore body.

The mineralogical composition of this metallisation calls for some comment. As suggested by the ground geophysics there is only a small content of pyrrhotite in the ores, most of the iron sulphide being pyrite. Sphalerite is also rather poorly represented, except for occasional localised rich bands and veinlets. Chalcopyrite is the common copper ore with only rare developments of the richer "grey" copper sulphides, chalcocite and bornite. Arsenopyrite is almost ubiquitous and may be locally rich.

CORE GEOCHEMISTRY

Sampling of this drill core presented a problem. Ideally it would have been desirable to sample each of the lithologies independently, this in particular being true for the calc-silicate rocks. However, frequent interbanding of thin lithological variants made this impractical. Economic considerations require a sampling approach tailored to the distribution of major mineralised zones, but these are difficult to recognise with certainty by visual examination alone. The median course utilised was to sample at near-regular intervals of one metre, irrespective of lithology. Scattered samples representative of their specific lithologies were extracted from the Crackington Formation and the Meldon Shale and Quartzite Formation; the Meldon Chert Formation was continuously sampled.

A total of 636 samples was obtained by mechanical splitting of the core. After crushing, fine grinding and sub-sampling, they were analysed by XRF for Ca, Fe, Mn and Ti oxides and for Ag, As, Ba, Bi, Co, Cu, Sn, W, Y, Zn and Zr by the Analytical Chemistry Unit of the British Geological Survey. Ranges of levels for each analysed element in the four separate drillholes are shown in Table 4 and in Fig. 10 the ore metal geochemistry of BH 1 is depicted in graphic form against the lithology. A close correlation between sulphidic ore deposition and the calc-silicate rocks can be appreciated in this diagram and limitation of metallisation to the Meldon Chert Formation is particularly evident.

Table 4. Ranges of metals in Belstone drillholes
(Oxides in per cent, elements in ppm)

	BH 1	BH 2	BH 3	BH 4
CaO	0.66-27.53	0.45-26.83	0.13-28.85	0.12-28.88
Fe ₂ O ₃	1.63-27.63	3.74-18.58	2.34-20.99	1.75-13.19
MnO	0.04-4.77	0.07-2.55	0.02-4.13	0.02-1.57
TiO ₂	0.06-2.10	0.14-1.25	0.09-1.30	0.12-0.94
Ag	0-7	0-4	0-3	0-1
As	6-35238	18-24215	3-6249	2-1343
Ba	0-1248	9-1531	0-1870	0-1133
Bi	0-539	0-348	0-650	0-125
Co	0-315	6-47	0-62	0-91
Cu	11-32713	29-7601	16-6008	15-6459
Sn	0-816	0-657	0-1608	0-1637
W	0-58	3-161	0-244	0-22
Y	9-67	22-40	11-45	16-177
Zn	17-13999	23-773	14-1724	11-5377
Zr	31-423	45-210	28-727	45-1899

It may be assumed that almost all the copper is located in the chalcopyrite. Zinc, predominantly in the form of sphalerite, has a more erratic distribution and would seem at best to represent a possible by-product. In this category also is bismuth, the mineral

form of which has not been determined. On the other hand cobalt, which was also recorded from Ivy Tor Mine (Dines, 1956), appears to be relatively insignificant in the Belstone drillholes. Arsenopyrite is the repository for all the arsenic content of these cores but, although almost ubiquitously present, it is unlikely to be of any commercial interest at the grades determined to date.

Tin levels are elevated in most of the calc-silicate horizons but it is certain that tin is located almost entirely within the structure of the garnets and has no commercial significance. Tungsten is a more perplexing ore metal; generally it is present only in very minor quantities but over much of the top half of BH 2 anomalously high amounts are reported. The best of these values tend to occur with thicker developments of calc-silicate facies, suggesting the possible presence of scheelite, a mineral recorded from the Ramsley waste dumps by Kingsbury (1966).

No attempt has been made to bulk the samples into "high grade" or "low grade" metalliferous zones or to derive average grades from any other form of clustered combination. cursory examination of the results shows that such a procedure would yield average figures which could be only disappointing if quoted or used out of context. Table 4 demonstrates that only BH 1 carries copper mineralisation at values believed to be of potential commercial interest (this assumed at 2% Cu for lode mining operations), nevertheless all four drillholes show some encouragingly high metal levels.

As with the lithology, correlations of the geochemistry from drillhole to drillhole are not immediately apparent and can only be achieved on assumptions of lateral variation, at times seemingly very marked ones. Given such wide degrees of latitude it is possible to formulate correlations in which the formerly worked mineralised beds can be tentatively recognised (see Conclusions).

BOREHOLE GEOPHYSICS

Geophysical logging of BH 1 was carried out by British Plaster Board Ltd. when the hole was at 284.38m, that is after it had penetrated the full thickness of the Meldon Chert Formation. The following logs were run:

- Self potential (SP)
- Single point resistance
- Gamma ray
- Density
- Neutron-neutron

A more complete suite of logs was planned, but the operation had to be curtailed when debris falling down the hole from a fault zone near the base of the casing started to interfere with the free movement of the sondes.

Parts of BH 3 and BH 4 were logged by the Applied Geophysics Unit of the British Geological Survey using Mount Sopris equipment. SP, single point resistance and gamma ray logs were run. BH 3 was logged to 298m (the maximum depth achievable with the equipment) and BH 4 was

logged when at 145m. The latter hole was subsequently drilled to 216m, but the extension was not logged geophysically. Trials were conducted in parts of BH 3 and BH 4 with an experimental IP sonde.

In BH 1, local concentrations of sulphide mineralisation were detected as narrow (typically less than 0.3m) SP spikes usually associated with minor resistance minima. The logs also provide useful lithological information. For example, calc-silicate rocks are characterised by high resistance, low gamma count and high density, whereas shales are associated with low resistance, high gamma count and low density. A broad (c. 70m) zone of lower resistance partially overlaps the zone of most conspicuous mineralisation in BH 1; the lower resistance appears to relate principally to lithology, with only a minor contribution apparent from observed conductive sulphide mineralisation. This suggests that the conductive zone detected by surface geophysics could be due in large part to the nature of the strata rather than the presence of metallic sulphide mineralisation. An IP response detected by the dipole-dipole traverse may be a more direct effect.

The logs for BH 3 and BH 4 were run in sections of those drill-holes where there was little conspicuous mineralisation, and variations observed in the logs are considered to be a primarily related to variations in lithology. In BH 3, the correlation between a high chargeability zone identified by surface geophysics and near-surface mineralisation may be a direct one, but this could not be tested by logging because of the presence of casing in the relevant section of the drillhole. Useful correlations with surface geophysical features were established: in particular a highly resistive calc-silicate horizon in BH 4 and a conductive horizon in BH 3 have been correlated with surface features.

CONCLUSIONS

In the area to the north of the Dartmoor Granite stream sediment geochemistry is an ineffective tool for recognising and locating stratiform sulphide mineralisation. Most of the drainage sediments are flooded by large amounts of granite derived material and much of the mobile metal content (Cu, Zn etc.) has been carried well away from site.

Closely spaced soil geochemical sampling along traverses aligned across the strike of the Lower Carboniferous strata, however, confirms the presence of metalliferous mineralisation in the underlying rocks and, it would seem, the level of metal-in-soil anomalies may indicate broadly the tenor of such mineralisation. But in unworked areas it is doubtful whether any resolution into individual mineral beds can be effected meaningfully. Although definition may be possible in ground of relatively gentle topography, on steep slopes the down-slope movement tends to confuse the picture and to distribute the metals over a wider area.

Around Belstone Consols Mine an attempt could be made to identify amongst the soil anomalies the signatures of formerly worked "lodes" and, knowing the general stratal dip, to plan a limited programme of diamond drilling designed to examine these structures at depth and outside the more intensely mined area.

Surface resistivity and IP surveys were rendered non-definitive as indicators of mineralisation by the presence of conductive and, at least in places, polarisable shale horizons. There is, however, an apparent correlation between higher chargeabilities measured by surface arrays and the mineralisation encountered in BH 1 and BH 3. Magnetic surveys around Belstone Consols Mine indicate a relative paucity in pyrrhotite, perhaps because temperature conditions were unsuitable for its formation, at least at the levels currently exposed. Because of the interest around the mine site, no detailed surveys were conducted on the steep slopes of the Taw valley, closer to the Dartmoor Granite; the geophysical approach may be of particular value there, where soil geochemistry can be confusing and reconnaissance traverses suggest the possibility of appreciable near-surface pyrrhotite.

The ground surveys strongly suggested a continuation of the Meldon Chert Formation into an area where it was not previously mapped at outcrop, and this was subsequently confirmed by the drilling. This success emphasises the special value of zones 3 to 5 (see Surface Geophysics), which provide information on the position of the Meldon Chert Formation and, therefore, anticipate positions for calc-silicate horizons potentially mineralised with metallic sulphide ores.

The location of major fault lines can be clearly identified by the truncation or displacement of the geophysically anomalous horizons recognised from surface geophysical measurements. This could be of prime importance in defining the probable extent and continuity of ore shoots or, as so dramatically found during drilling, warning of possibly dangerous water conduits.

Four drillholes were successfully sunk, each penetrating the full sequence of Meldon Chert Formation recognisable at each site. The lithologies encountered are similar to those found in the type area but the full thickness of the formation appears to be almost three times that recorded at Meldon. Correlation from hole to hole is difficult both in terms of lithology and of litho-geochemistry but, by considering lithology, mineralisation and geochemistry in conjunction, initially in a graphic form like Fig. 10, it is possible to attempt recognition of the worked "lodes" within the drillhole intersections. It is equally possible to effect a correlation between these intersections and the soil geochemistry. By this means a new "lode" is recognised to the north of, and above, the worked beds; in logical sequence this has been named "No. 3 North Lode".

Correlations derived in this manner are listed in Table 5. If these are to be believed then it must be accepted that the grade and composition of metalliferous mineralisation varies both markedly and rapidly between intersections. It is also true that these inferred structures were encountered at somewhat differing depths; the table includes these depths, approximated to the nearest five fathoms, for comparison against the former mining levels (Fig. 3).

Copper, zinc and arsenic grades are not averaged out over these assumed "lode" widths but a cursory scan through the chemical assays shows that such values would be disappointingly low. Table 4 shows

Table 5. Drillhole "lode" intersections

"Lode"	BH 2	BH 1	BH 3	BH 4
No. 3N	---	?51.5-59.5m (20 fm)	?32.4-51.4m (25 fm)	---
No. 2N	---	93.5-101.5m (40 fm)	?56.4-65.4m (30 fm)	---
No. 1N	30.9-33.9m	118.4-134.4m (50 fm)	102.4-105.4m (50 fm)	---
Main	52.9-72.9m	144.4-177.4m (65 fm)	129.4-165.4m (70 fm)	---
South	---	203.4-209.4m (85 fm)	205.4-242.4m (100 fm)	142.3-168.1m (60 fm)

that all the drillholes contain some intersections at an encouraging level of metal content and the economic potential of this area cannot be discounted without a more intensive diamond drilling exploration programme. From the analytical evidence to date there might seem to be a paucity of by-product metals. Cobalt in the cores appears to be disappointingly low despite interesting levels in the soil samples; this may signify surface scavenging by iron oxides or some shallow cobalt mineralisation in the west of the area. Very locally bismuth reaches interesting levels but its mineral form has not been ascertained. Tungsten, particularly prevalent in the drillhole nearest to the Sticklepath Fault Zone, is presumed to be in the form of scheelite and is of unlikely economic interest at such low grades.

ACKNOWLEDGEMENTS

The authors wish to record their appreciation of the assistance rendered in the field by many colleagues in the British Geological Survey. Particular thanks are offered to members of the Analytical Chemistry Unit who carried out all the determinations for these investigations. Without the willing co-operation of all landowners and the Parish Council these studies would have been impossible; we are grateful for their patience and understanding. Finally, before and during the hearing of the Public Inquiry the senior author was afforded invaluable support, advice and assistance by various staff of the Department of Trade and Industry, the Natural Environment Research Council and the Treasury Solicitors Department.

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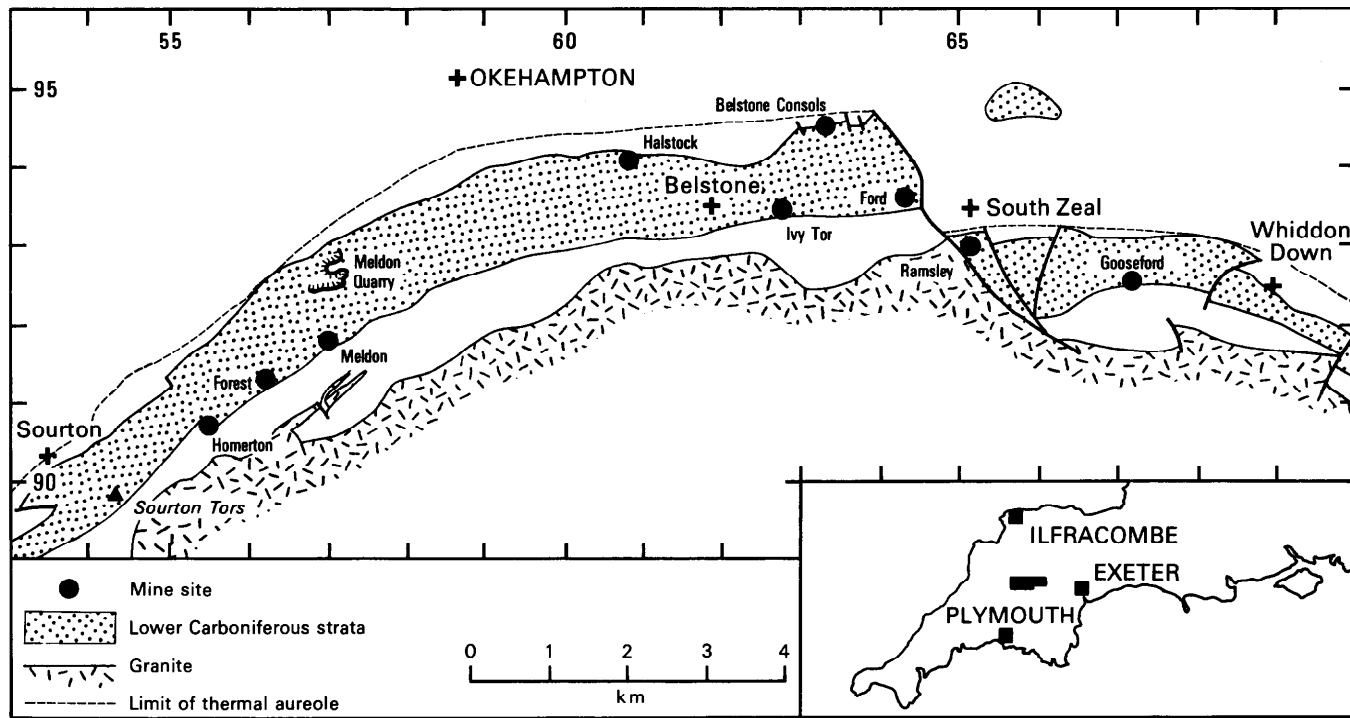


Figure 1 Location map

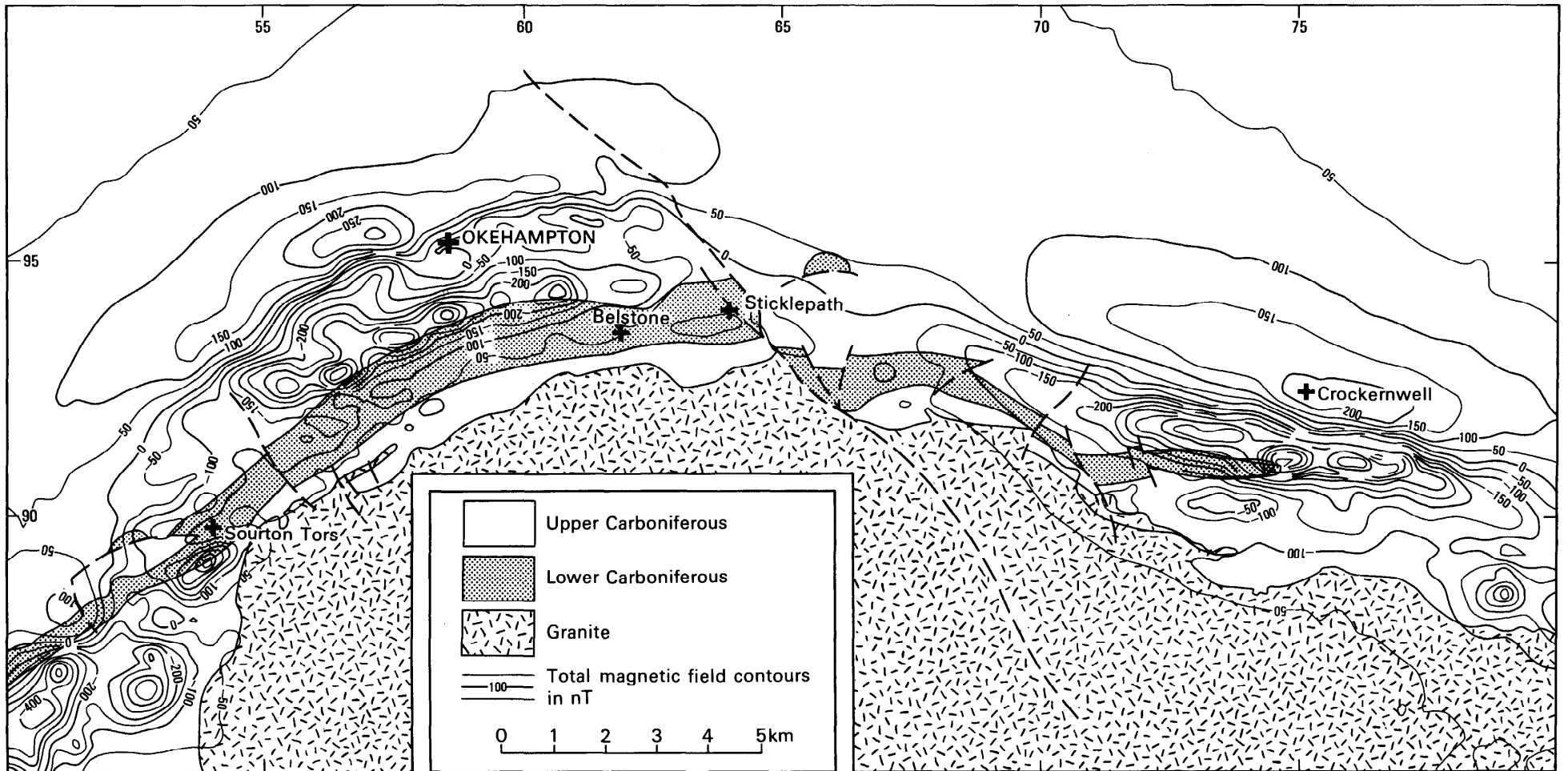
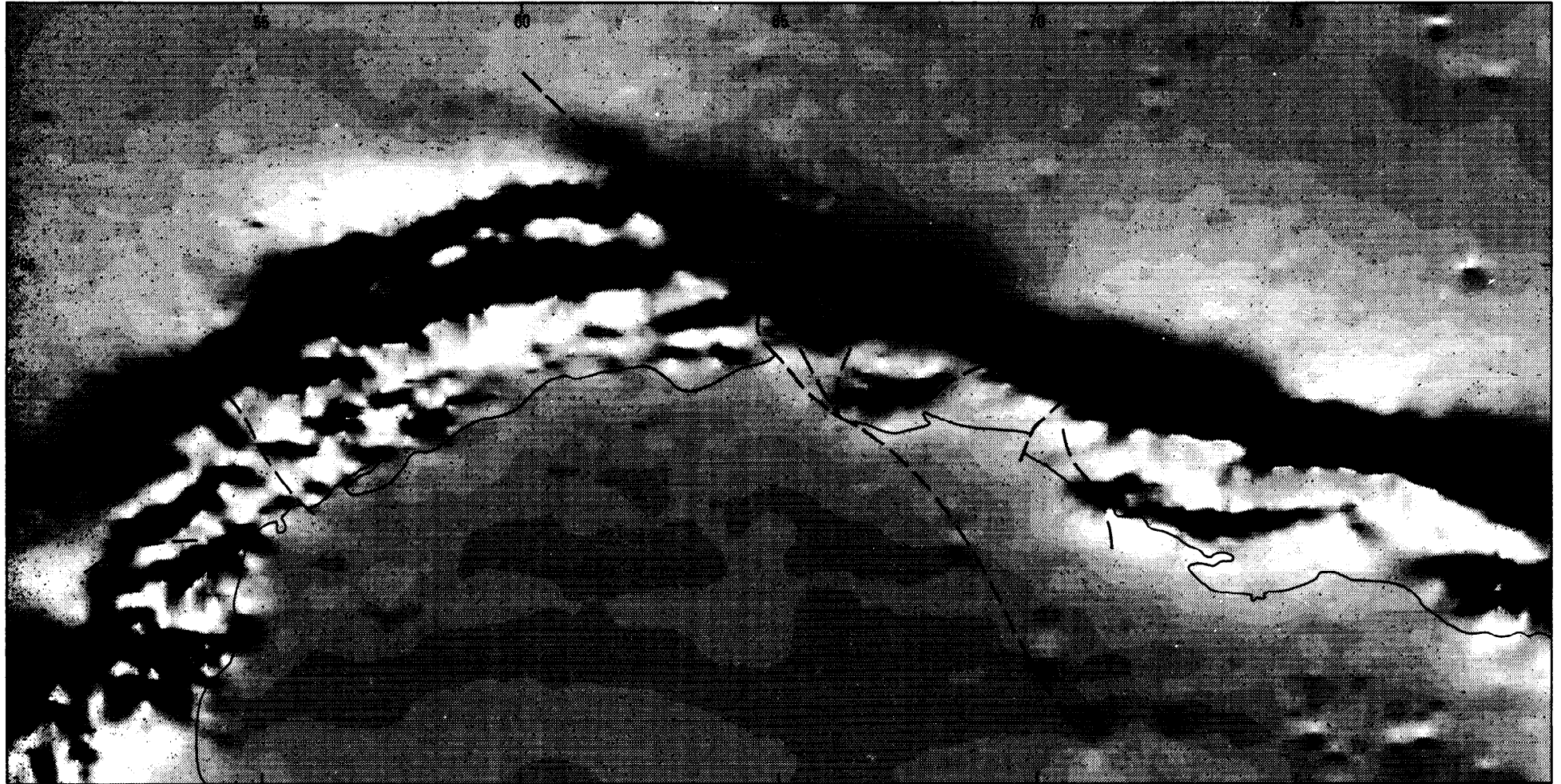


Figure 2a Simplified aeromagnetic map of the north Dartmoor area



— — Major Fault ——— Boundary of Granite

Figure 2b Shaded relief image (illuminated from the north) of aeromagnetic data from the north Dartmoor area

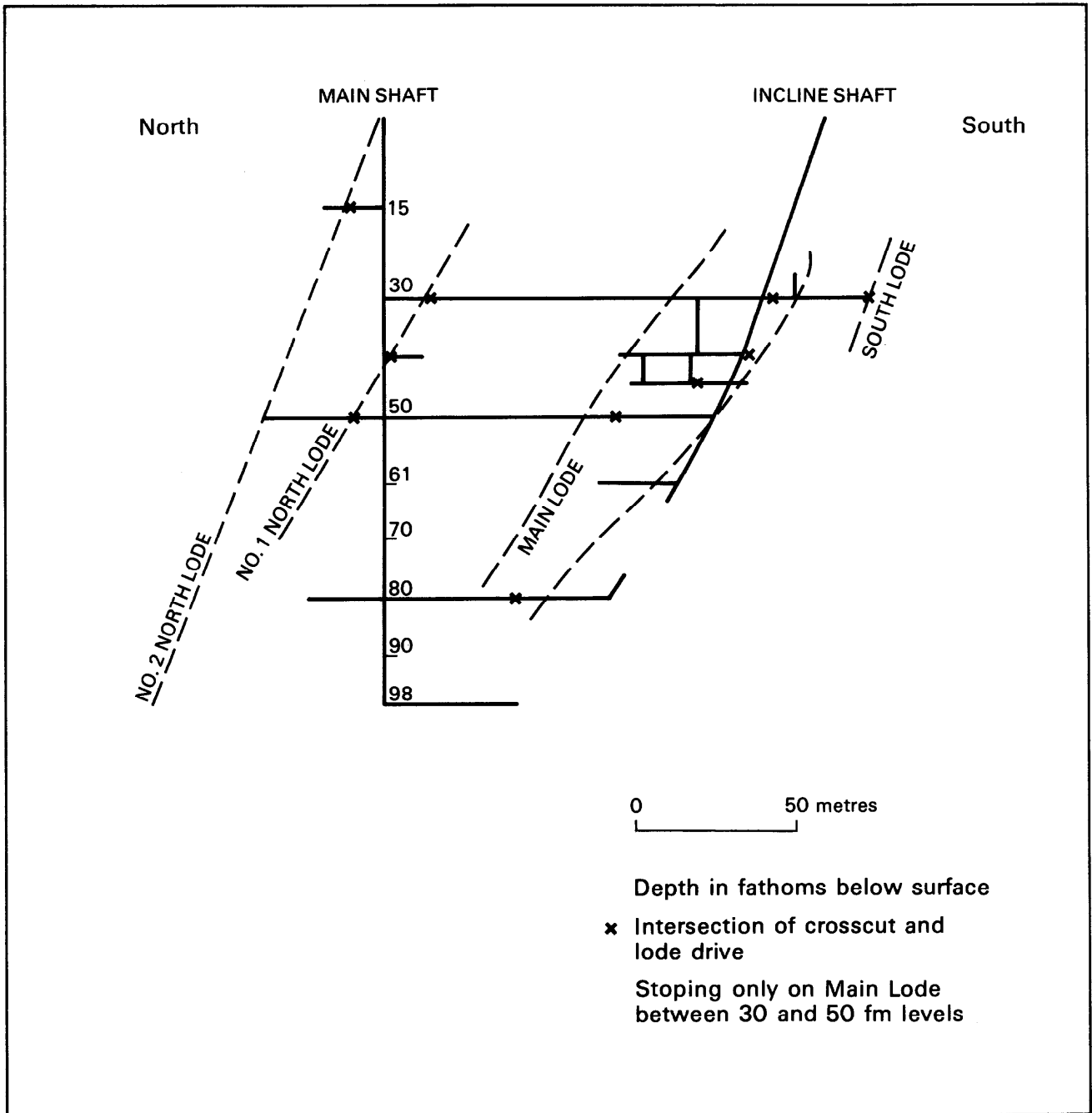


Figure 3 Transverse section of Belstone Consols Mine from AM 2861, dated 1892

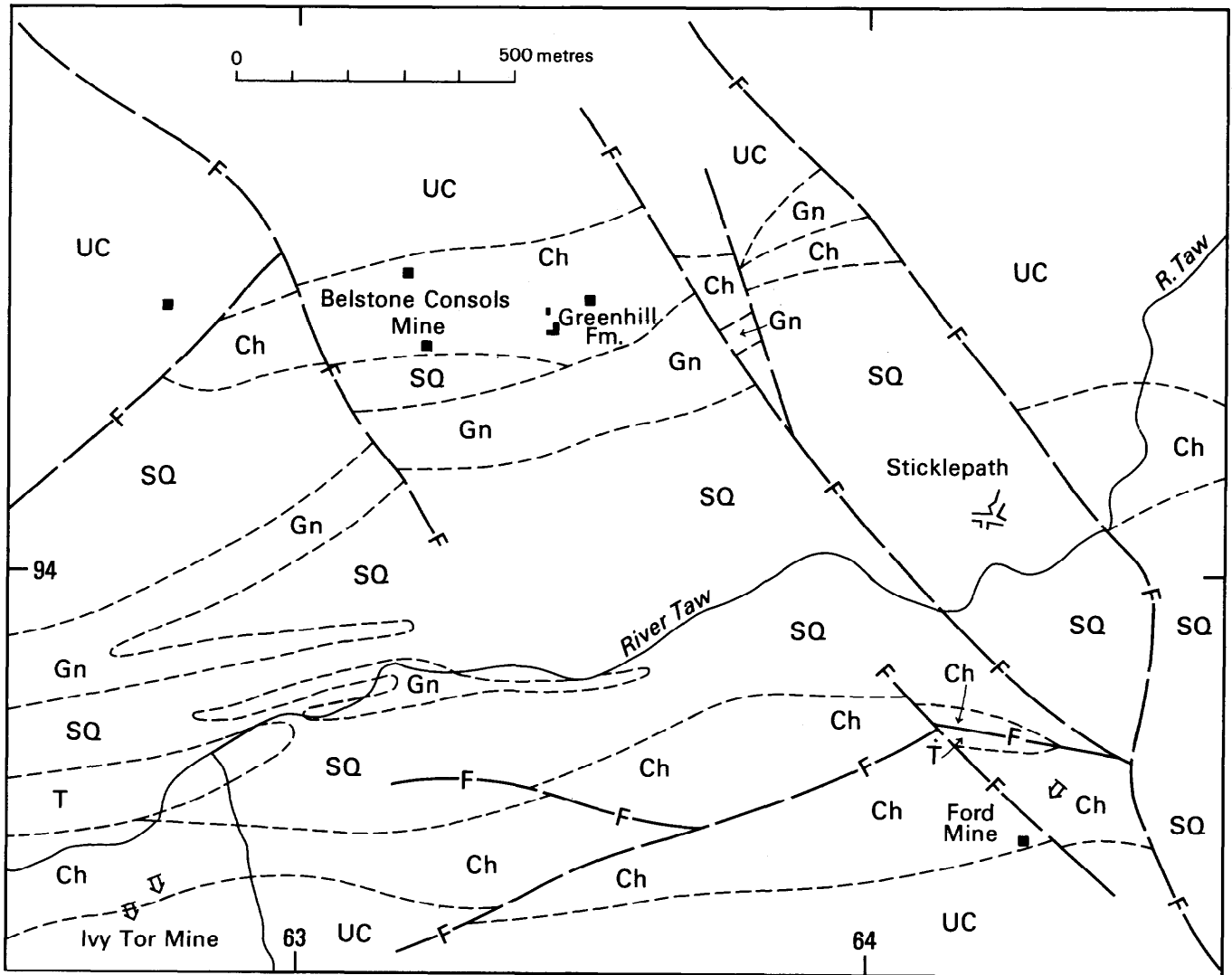


Fig.4. Geology of the Belstone Consols area

- | | | | |
|-------|---------------------|----|--------------------------------------|
| ■ | Shaft | UC | Upper Carboniferous |
| ◇ | Adit mouth | Ch | Meldon Chert Formation |
| - - - | Geological boundary | SQ | Meldon Shale and Quartzite Formation |
| - F - | Fault | Gn | Greenstone |
| | | T | Tuff and agglomerate |

Geology as mapped
by E.A.Edmonds

Figure 4 Geology of the Belstone Consols area

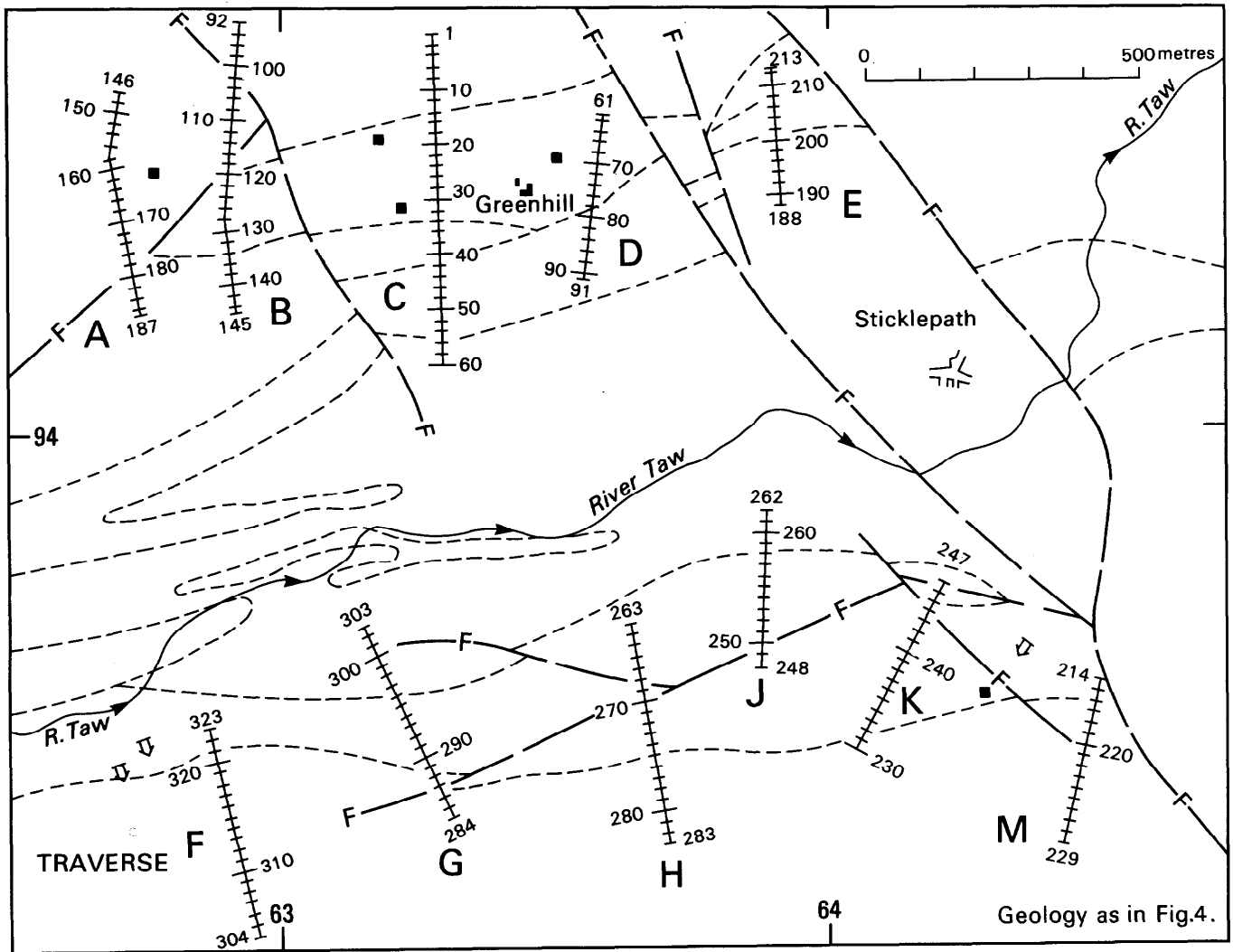


Figure 5 Location of soil sampling traverses

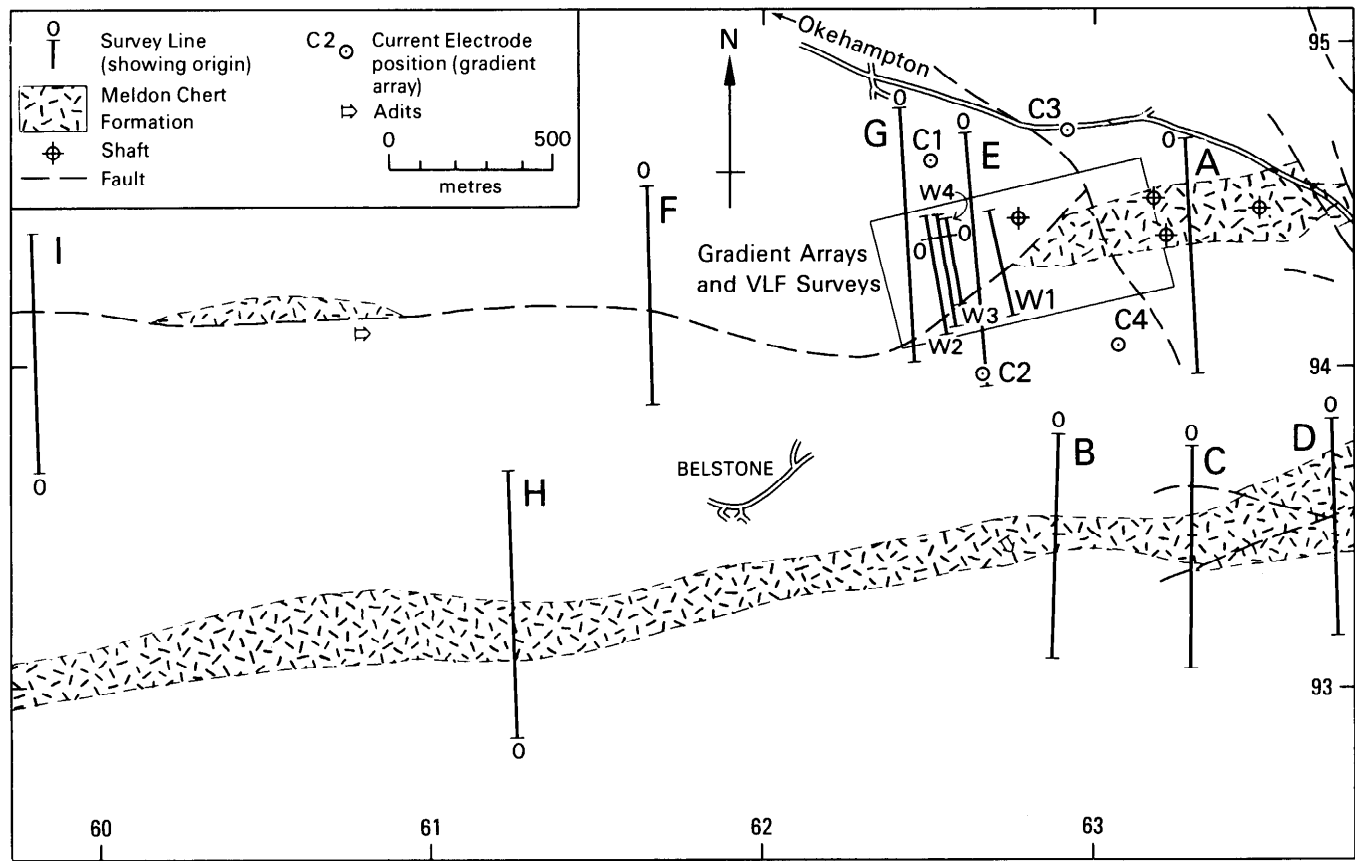
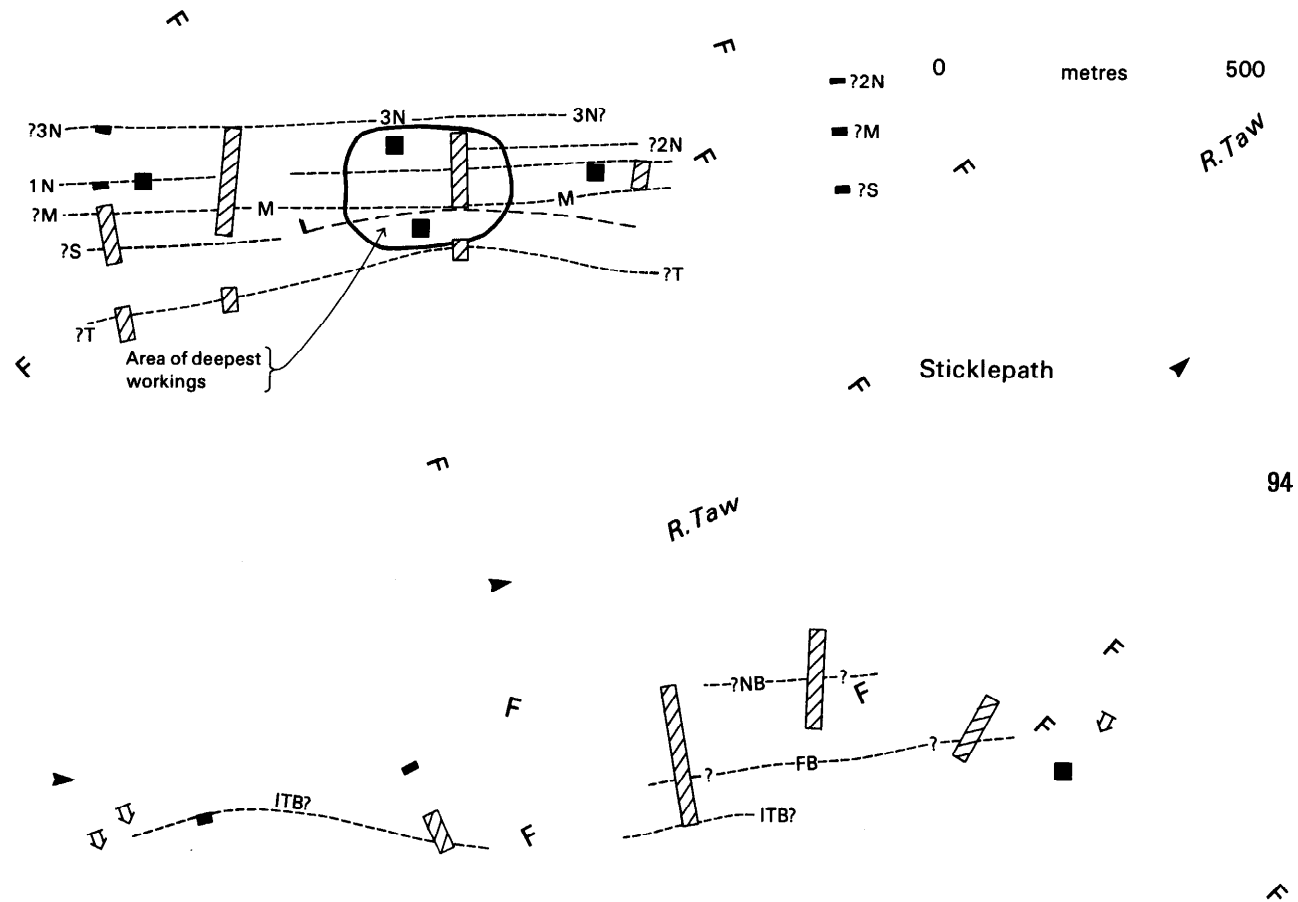


Figure 6 Location of geophysical traverse lines



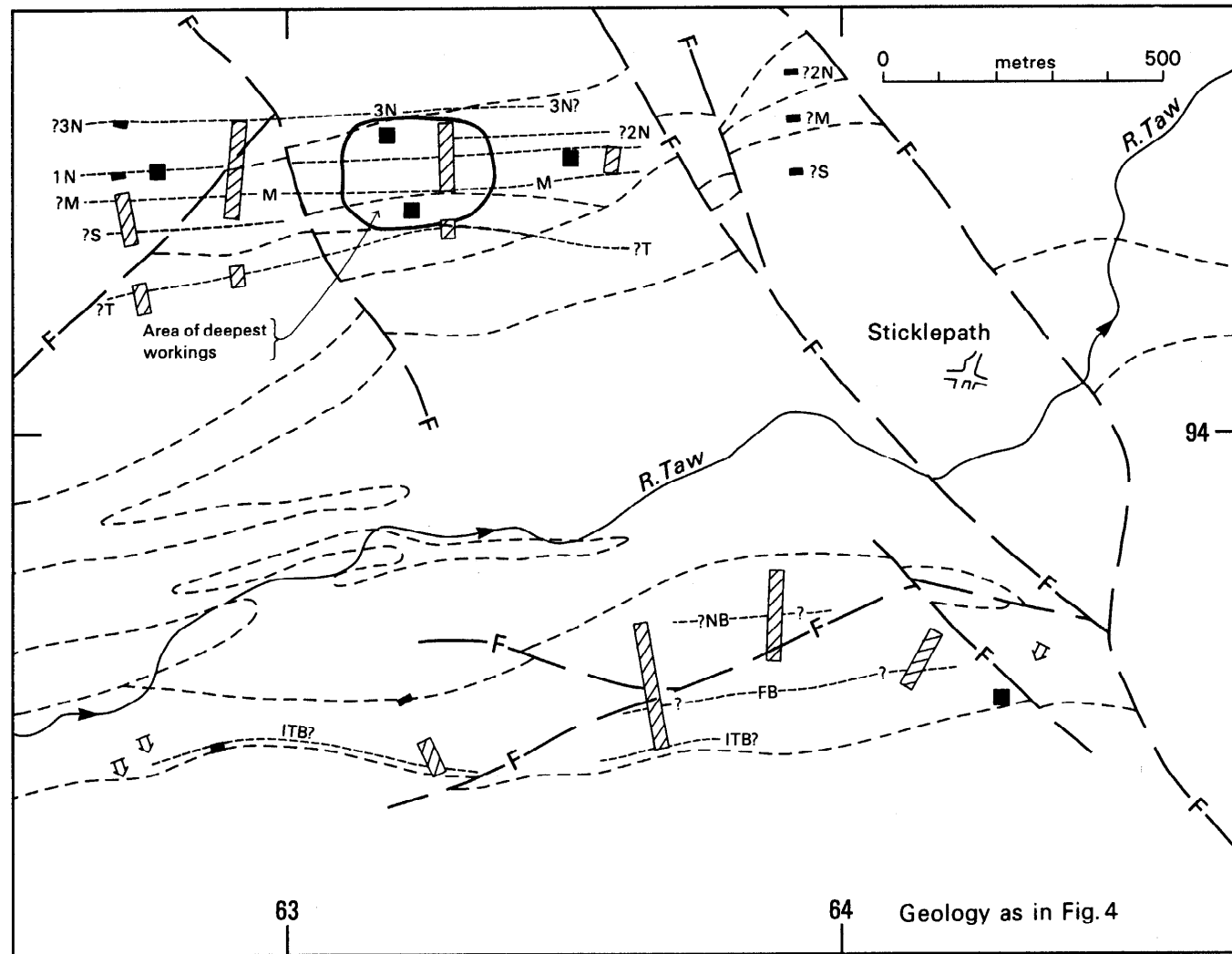
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Geology as in Fig. 4

- | | | | | |
|-------|-----------------------------------|---------------------|----------------------|---------------------------|
| ----- | Mineralised Horizons | 3N= Unworked bed? | M= Main Lode | ITB= Ivy Tor bed |
| ▨▨▨▨▨ | Location of high ore metal values | 2N= No.2 North Lode | S= South Lode | FB= Ford bed |
| | | 1N= No.1 North Lode | T= New tin-rich bed? | NB= Unworked northern bed |

Figure 7 Interpreted location of mineralised beds



- | | | | | |
|-------|-----------------------------------|---------------------|----------------------|---------------------------|
| ----- | Mineralised Horizons | 3N= Unworked bed? | M= Main Lode | ITB= Ivy Tor bed |
| ▨ | Location of high ore metal values | 2N= No.2 North Lode | S= South Lode | FB= Ford bed |
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Figure 7 Interpreted location of mineralised beds

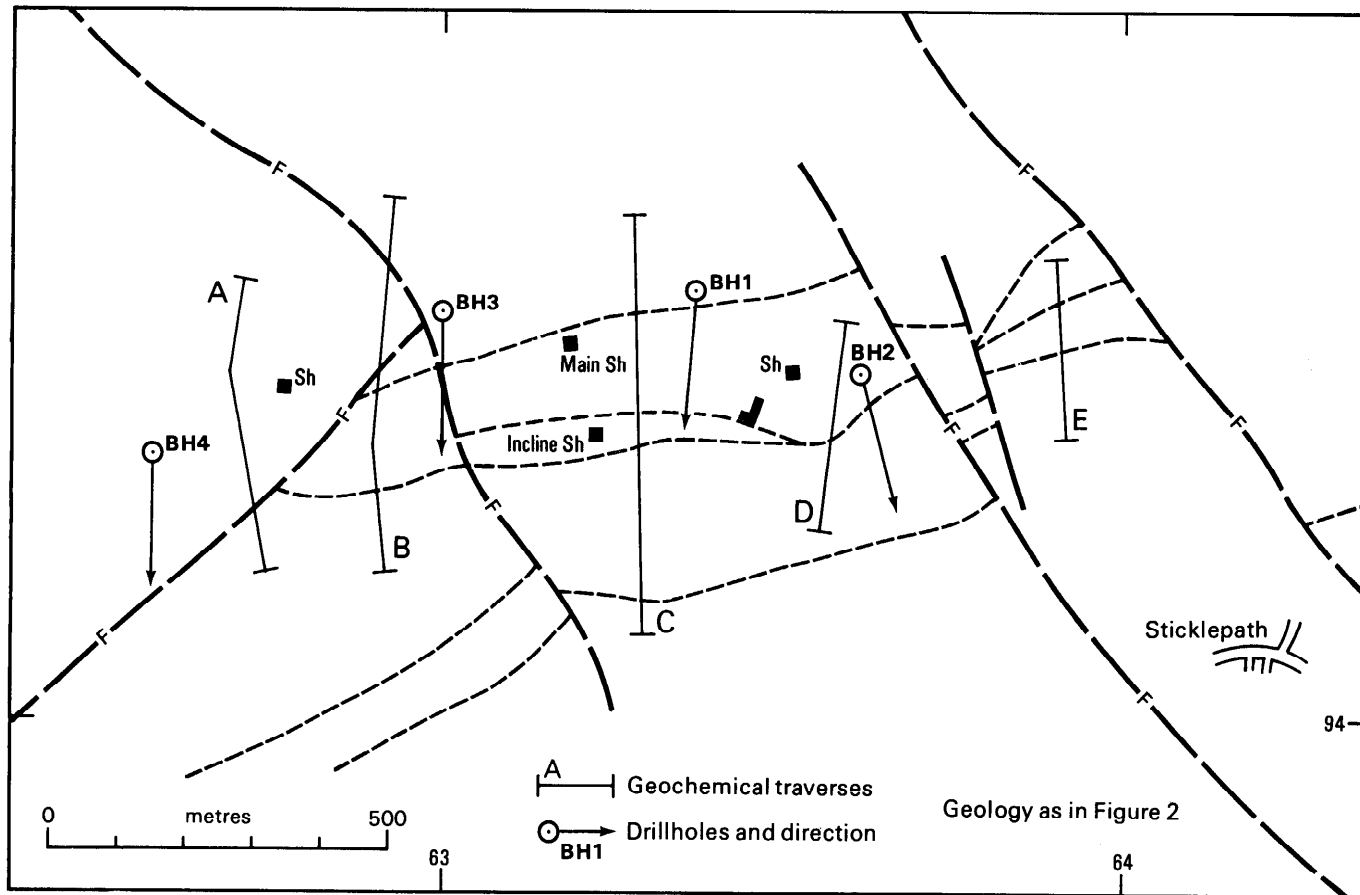


Figure 8 Location of diamond drill holes

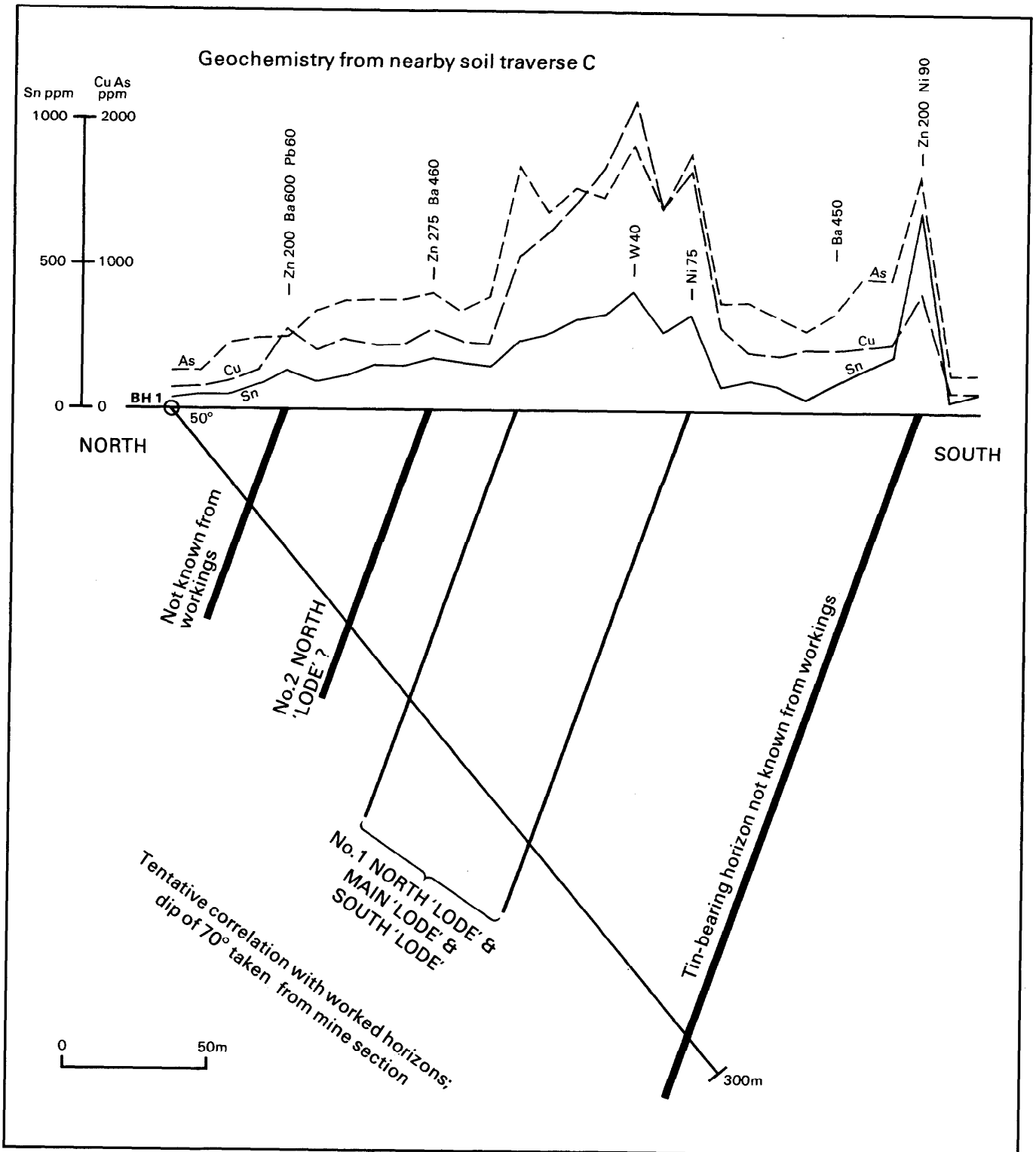


Figure 9 Inferred geology in plane of proposed BH 1

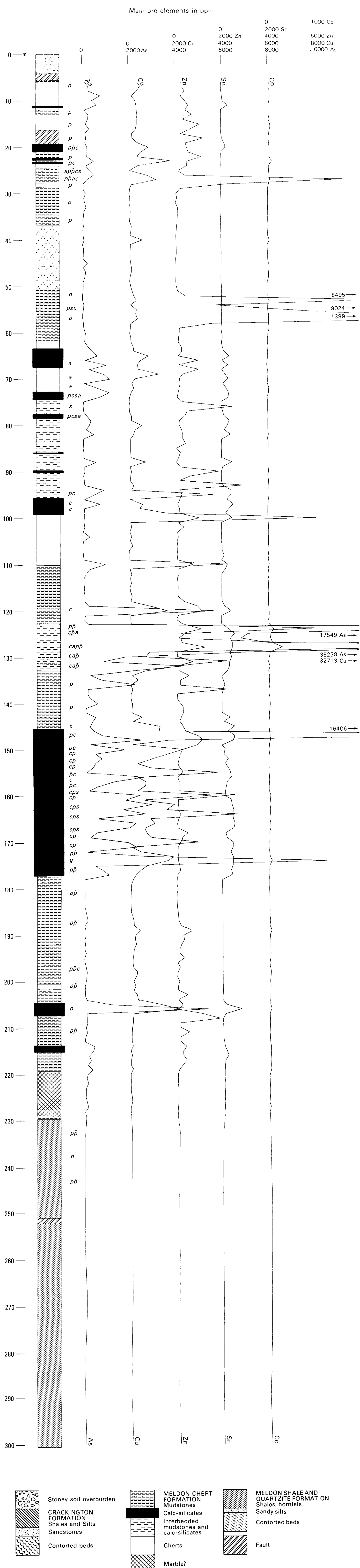


Figure 10 Graphic and geochemical log of BH 1

