

British Geological Survey



Mineral Reconnaissance Programme

Exploration for gold in the
South Hams district of Devon

MRP Report 121
Technical Report WF/92/2

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R C Leake, D G Cameron, D J Bland, M T Styles
and K E Rollin

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SUMMARY

Panned drainage samples collected from the area south of a line between Plymouth and Brixham in Devon (roughly equivalent to the South Hams District) show that gold is widely distributed over much of the area. At 44 out of 450 sites the concentration of gold in the panned concentrate exceeds 0.5 ppm. Drainage gold anomalies are present over the entire Lower Devonian sequence and the Start Complex but are less frequent over the Middle Devonian rocks which occur in the north-west of the area. Other metallic elements determined in the samples suggest that there is no simple pathfinder for gold and the factors influencing its concentration are complex. Many of the grains are very intricate in shape with projections which could not survive if transported in the streams for anything more than trivial distances from source.

The internal compositional characteristics of the gold are highly variable and of particular interest. One type of grain contains variable concentrations of palladium, often showing intricate growth zonation. In some areas the gold is enriched in silver rather than palladium and there is a regularity of distribution which suggests zonation of grain type, reflecting differences in source. Other grains, essentially of pure gold, have a more irregular distribution.

Follow-up overburden sampling by hand auger was carried out along reconnaissance traverses up to 9 km long and by shorter lines in areas of interest. Pit digging and power augering to a maximum depth of 7.3 m showed, in the area south of Brownstone, near Holbeton, that gold is present in head and weathered bedrock, as well as in near-surface overburden. Anomalies are concentrated along an east-west zone at the bottom of the valley. There is a correlation between gold and cassiterite abundance in the overburden but there are also a few gold-rich samples with little cassiterite.

Geophysical surveys in the Brownstone area showed VLF anomalies and a 0.5 mGal positive gravity anomaly coincident with a local galvanic resistivity low and chargeability high. Four holes drilled to test the source of anomalies in the east-west zone of anomalous gold in overburden, intersected mostly black slate, pyritiferous in part, and widespread lensoid vein quartz often with minor carbonate, particularly as euhedral rhombs lining voids. The depth extension of the east-west anomalous zone of gold at surface comprises a zone of intense oxidation alteration, brecciation and carbonate veining. Samples from this altered zone contain minor levels of gold, reaching a maximum of 380 ppb, whereas elsewhere gold concentrations are very low. The fourth hole, drilled about 200 m west of the other three, did not encounter an altered zone but intersected pyritiferous black slate with vein quartz and carbonate containing minor gold (maximum 54 ppb) and widespread minor sphalerite and galena in fracture coatings.

At Churchill, near Marlborough, close to the boundary of the Start Complex with Lower Devonian rocks to the north, soil traverses delineate a zone of enrichment in As, Sb, Ba, Mn, Fe and Cu. Pit samples within the zone show isolated gold anomalies (maximum 710 ppb). Rock samples collected from a new road cut in a mixed volcanic-sedimentary sequence show evidence of extensive albitisation, probable potassium feldspar alteration and anomalous concentrations of As and Sb. The geochemistry of the weathered rock is similar in many respects to that associated with veining and alteration in coastal sections near Wadham Rocks which is characterised by potassium feldspar alteration and enrichments in As, Sb, Cu and Au (maximum 400 ppb). Further zones with

anomalous concentrations of As and Sb occur throughout the region, some with associated scattered gold enrichments.

Two major phases of mineralisation are thought to be responsible for the gold anomalies in drainage and soil. The first comprises polymetallic mineralisation associated with zones of intense hydrothermal alteration and predates the main deformation of the rocks. In the second phase, which accounts for the vast majority of the gold grains in drainage, saline oxidising solutions carrying precious metals circulated within and beneath the Permo-Triassic red-bed sequence which had been deposited on the eroded Devonian surface. Deposition of gold occurred where conditions became more reducing, particularly within Devonian rocks by reaction with pyritiferous slates and other reactive rocks.

INTRODUCTION

Previous MRP reports (Leake et al., 1988, Leake et al., 1990) have described the occurrence of gold at a number of sites in drainage in the western part of south Devon, between Plymouth and the river Avon, areas outlined in figure 1. This report combines these results with those pertaining to samples collected further east, so as to comprise all the data from the area of Devon lying south of a line between Plymouth and Brixham (Figure 1), roughly equivalent to the South Hams District. Follow-up work has been carried out to try and trace the source of several anomalies spread throughout the area, though in most cases it has been of a preliminary nature. More detailed follow-up work, including drilling, was carried out in the Whympton area (Figure 1) and the results of this work are available from BGS as a data package. Similar detailed work was carried out in the Brownstone area and the results of this are included in this report. Gold-bearing mineralisation which occurs in coastal exposures around Wadham rocks is also described.

The internal structure of gold grains from South Devon is frequently complex with many features of considerable interest. Particularly important are the presence of palladium and platinum-rich compositions in intimate association with gold of more normal composition and the occurrence of a wide range of selenide inclusions in some varieties of gold. The microchemical mapping of these grains has been illustrated in Leake et al. (1990) and is described in detail in Leake et al. (1991).

GEOLOGY

A general geological map of the area taken from the 1:50,000 Geological Survey mapsheets, originally mapped at the end of the last century by Ussher, is given in Figure 2. The interpretation of the geology is undergoing active reappraisal as a result of remapping at 1:10,000 as part of the BGS South Devon Project and present ideas on the environment of formation of the rocks and the subsequent history of tectonism are provisional. So far, mapping has been carried out only in the west of the region.

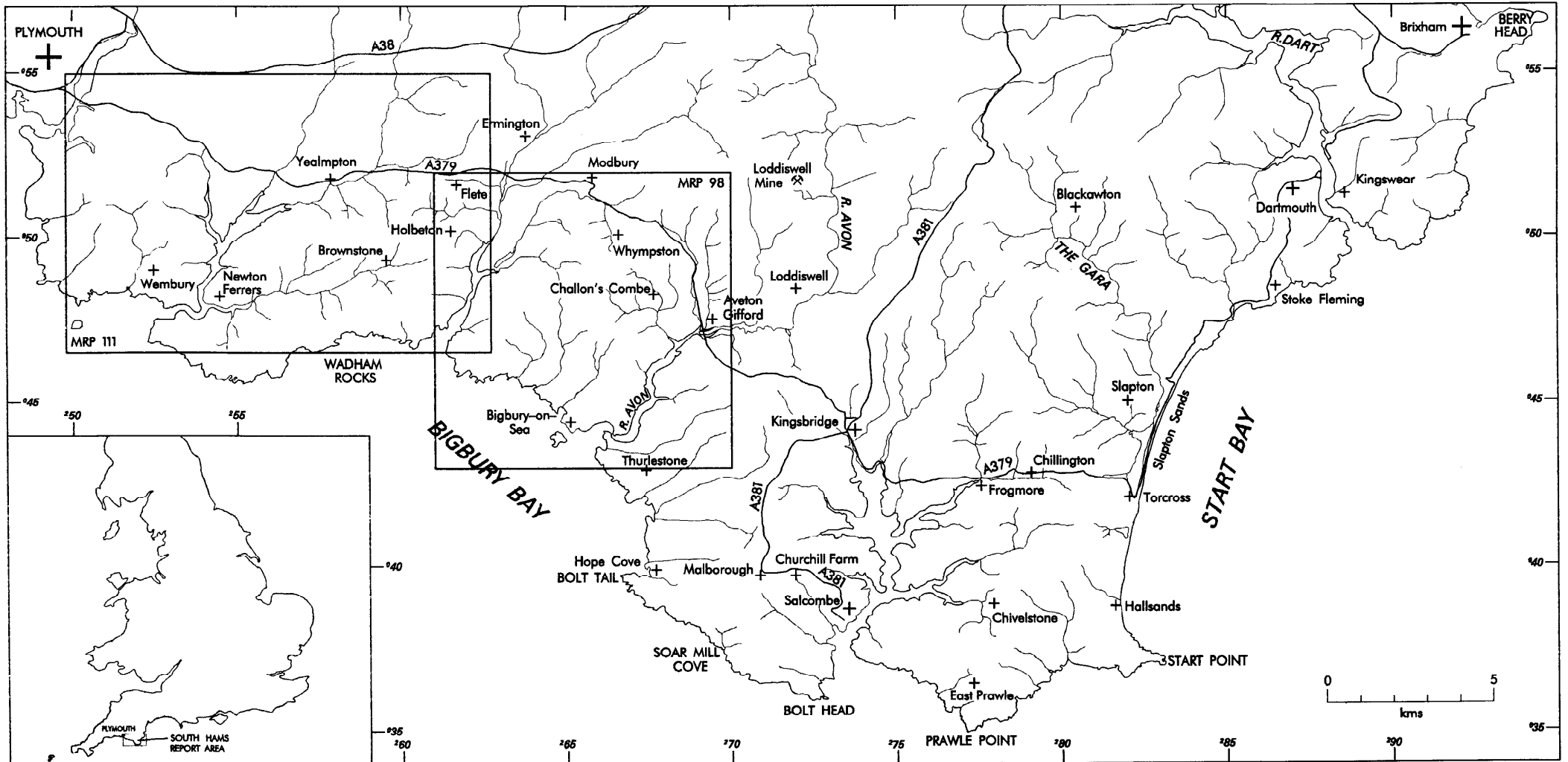


Figure 1 Location of survey area

Most of the area is underlain by sedimentary and volcanic rocks of Lower Devonian age. The oldest unit within this sequence, the Dartmouth Group, consists of slaty mudstones and siltstones varying in colour from pale grey to purple and containing some thick arenaceous units and sporadic mafic tuffs and lavas. Sedimentological study of coastal exposures of Dartmouth Group sediments along the east side of Plymouth Sound (Smith and Humphreys, 1989) recognised three facies associations. These were interpreted as deposition in a shallow perennial lake, a deeper lake with unstable margins and a distal fluvial environment respectively, from north to south. These environments fit within a highly unstable rift setting. Overlying the Dartmouth Group are, in turn, the predominantly argillaceous Bovisand Formation with thin sandstones, minor thin mafic volcanics, phosphatic sediments and limestones and the predominantly arenaceous Staddon Formation. The Lower Devonian rocks are succeeded to the north by the argillaceous Jennycliff Formation and other units of Middle Devonian age, including relatively thick sheets of alkali basalt and local limestone units.

In the extreme south of the area, rocks exhibiting a higher grade of regional metamorphism form the Start Complex. The components of this unit are mostly quartz and mica schists interbedded with hornblende schists derived from mafic igneous rocks of primitive MORB-like composition. The results of geochemical mapping using soil samples, carried out as part of the follow-up of drainage anomalies, suggests that a separate and distinct unit may exist between the Start Complex *sensu stricto* and typical Dartmouth Group sedimentary rocks. The main feature of this North Start unit, which appears to be fault bounded and of varying outcrop width, is the presence of a significant amount of mafic volcanic material of relatively evolved composition, quite unlike the MORB-like composition of the typical Start volcanics.

Volcanic rocks

A group of 126 mafic igneous rocks have been analysed by XRF for major elements and a range of trace elements by Caleb Brett International, St Helens, Merseyside. In addition, most samples were analysed for Au by acid digestion followed by solvent extraction and an atomic absorption finish by the same laboratory. The samples comprise 15 from the Start Complex, 19 from the newly recognised North Start unit, 36 from sections of the Dartmouth Group on both sides of the Erme estuary, 19 from boreholes within the largely dacitic Whympston volcanic complex, 3 from boreholes at Brownstone Farm and the rest from the coastal section between Wadham Rocks and Carswell Cove. Apart from the Wadham Rocks area, which is described below, gold above the concentration of 20 ppb was detected in 6 samples, 4 from the same rock type exposed on both sides of the Erme estuary (B), one from a further locality in the Erme estuary (C) and one from a new road cut through the North Start unit at Churchill Farm (A). The content of selected elements in these samples is given in Table 1.

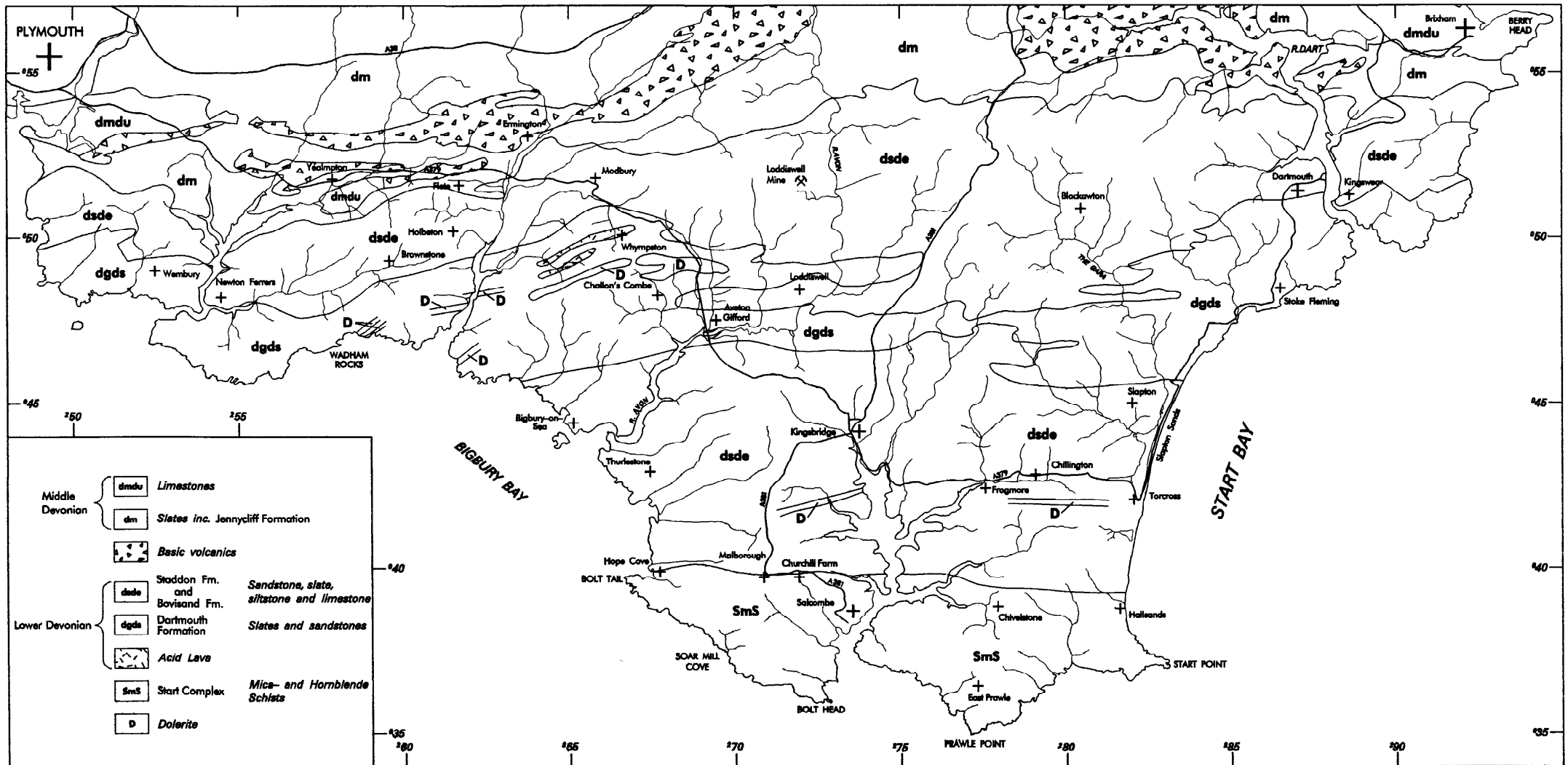


Figure 2 Simplified geological map of survey area

Table 1 Analytical data for gold-bearing mafic igneous rocks

	A	B(E)	B(E)	B(W)	B(W)	C
Na ₂ O%	5.64	1.93	0.55	3.40	4.12	2.39
P ₂ O ₅ %	0.36	0.77	0.72	1.53	1.52	0.64
K ₂ O%	0.57	1.04	3.88	1.83	2.93	1.96
TiO ₂ %	2.42	3.21	3.13	3.64	3.73	2.67
Fe ₂ O ₃ %	13.23	18.39	17.66	13.12	24.13	25.95
Cu ppm	50	17	63	8	14	12
As ppm	23	311	193	15	3	6
Nb ppm	16	36	38	28	30	27
Au ppb	31	88	70	563	27	22

Localities: A [²⁷¹⁹0399], B(E) [²⁶²⁰0478], B(W) [²⁶¹⁷0478], C [²⁶¹⁴0474]

It is probable that there is a primary association between Au and the Fe-rich mafic volcanic rock exposed in the Erme estuary (B, E and W in Table 1) as 4 out of 8 analysed samples contain detectable Au, while the adjacent slate does not. Both lavas and tuffs may be present in this volcanic unit, now highly sheared and consisting of plagioclase crystals in a foliated chloritic matrix with larger grains of magnetite and goethite after pyrite, surrounded by pressure shadows. Vesicles filled with quartz have also suffered later deformation. Chemically, the evolved mafic volcanic exposed on both sides of the Erme is enriched in Ti and particularly P compared with other igneous rocks from the Lower Devonian of the south Devon (Figure 3). Two groupings of analyses are apparent for this unit in Figure 3, one showing less extreme enrichment in P, with compositions similar to samples from the Start Boundary unit and to some mafic volcanics within the Whympton volcanic complex. In contrast, in the sample from Churchill Farm (A in Table 1), it is more likely that that gold was introduced as part of the hydrothermal activity which affected a large volume of rock in the area.

GOLD-BEARING MINERALISATION NEAR WADHAM ROCKS

Gold-bearing mineralisation with pyrite and intense potassium feldspar and carbonate alteration is exposed in a coastal section to the east of Wadham rocks. At the western end of the zone, which terminates against a west-north-west-trending fault with significant lateral displacement, is a landslide and there are many large boulders of mineralised rock derived from this on the beach. Further east, the mineralised zone is exposed in situ for about 100 m as far east as Ryder's Hole where it is probably displaced by a north-west-trending fault. East of Ryder's Hole, gold has been detected by chemical analysis in loose blocks of mineralised quartz veins and 500 m further east, at Carswell Cove, less intense but similar mineralisation is exposed.

The mineralised rocks around Wadham Rocks, which strike nearly parallel to the coast, consist of slates, a volcanic horizon a few metres thick, siltstone and sandstone. Veining and hydrothermal alteration are conspicuous in the zone and seem to be preferentially associated with the volcanic unit. Interlocking laths of potassium feldspar have replaced the original plagioclase within the most intensely mineralised zone. Thus, chemically, these altered volcanics are characterised by high concentrations of K (maximum 9.39% K₂O) and low concentrations of Na as shown in Figure 4a. In contrast, east of Ryder's Hole, volcanics across strike and to the south of the

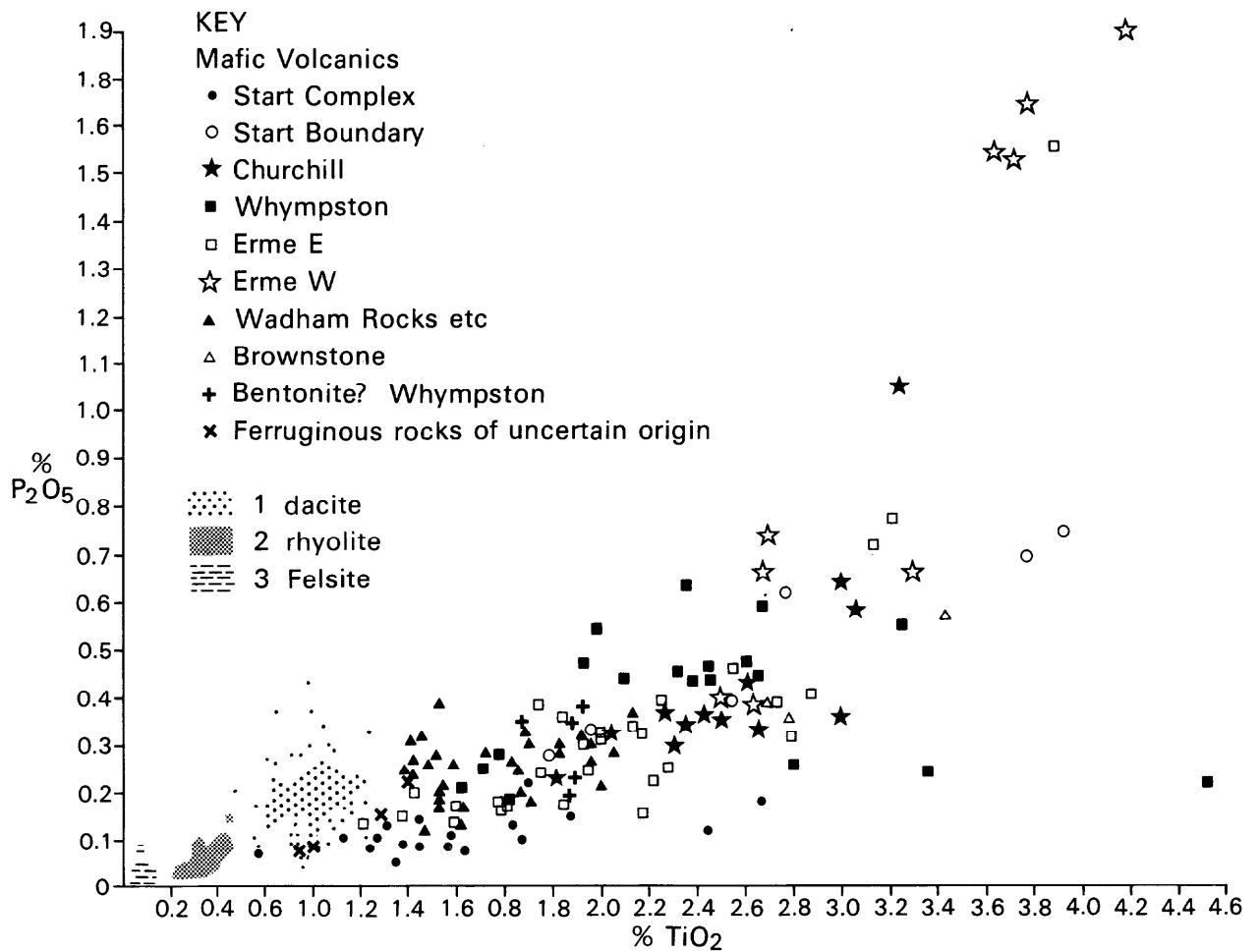


Figure 3 Concentration of P₂O₅ and TiO₂ in igneous rocks of the Start Complex and the Lower Devonian of South Devon. Mafic volcanic rocks separated by locality. Start Boundary rocks probably part of North Start unit. General fields of Whympston dacite, rhyolite and felsite (= intrusive rhyolite) are shown by ornament.

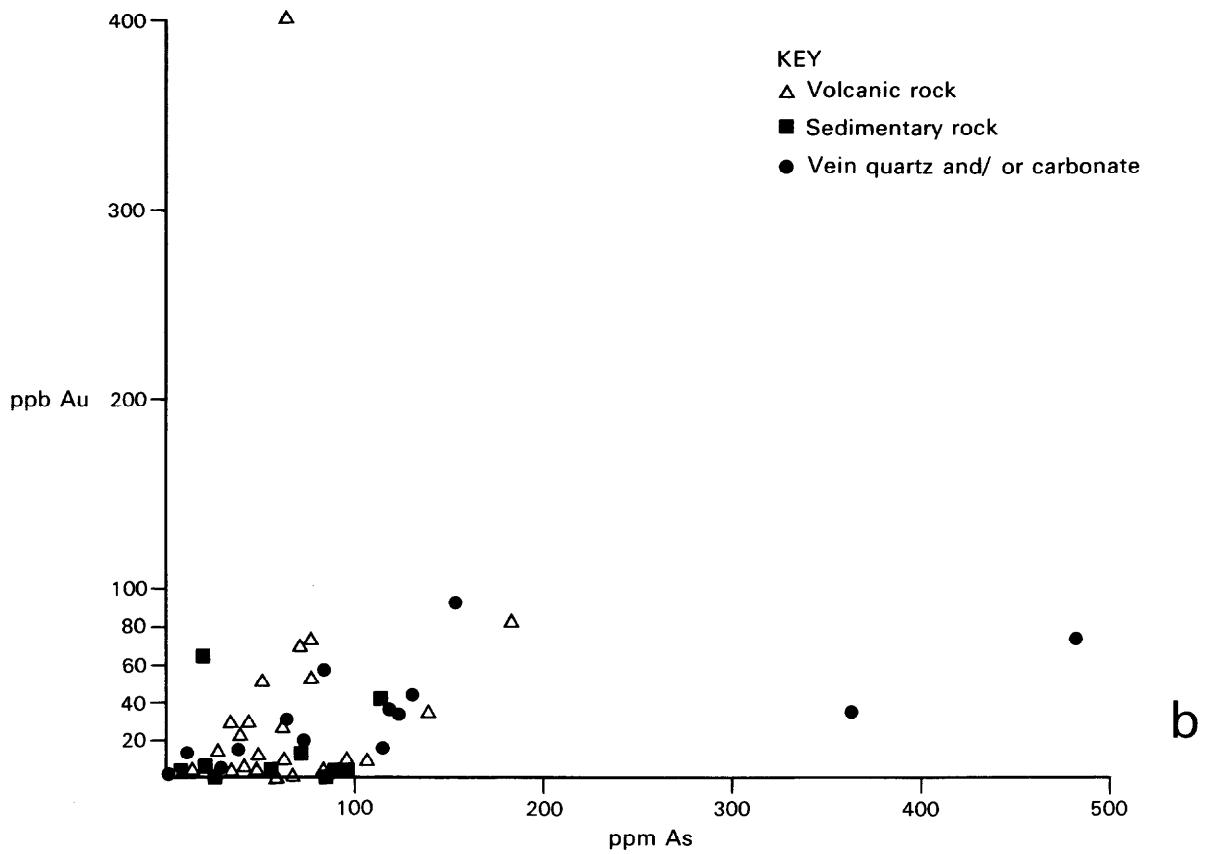
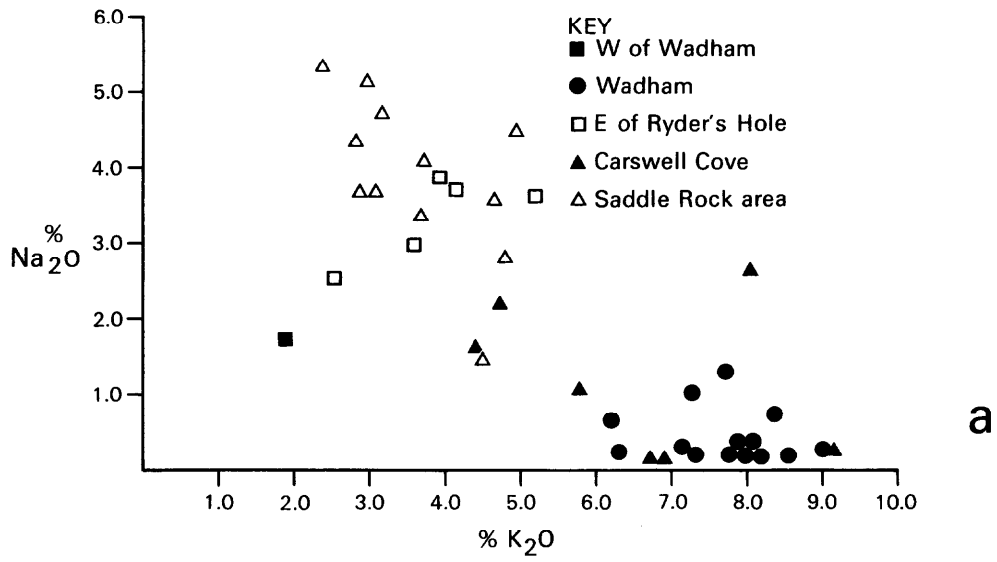


Figure 4 a) Na₂O and K₂O contents of mafic igneous rocks from near Wadham Rocks and progressively further east (Ryder's Hole, Carswell Cove and Saddle Rock). b) Concentration of Au and As in rock samples from the Wadham Rocks area.

mineralised belt, are similar in overall composition but have not suffered potassium feldspar alteration, so that their K and Na contents are correspondingly lower and higher respectively (Figure 4a). A volcanic rock from the area to the west of the fault which displaces the mineralised zone near Wadham Rocks is not enriched in either K or Na (Figure 4a).

The mineralised rocks from east of Wadham Rocks are also cut by at least four generations of quartz veinlets, sometimes with associated potassium feldspar, and there are also similar thicker quartz veins. These veins are usually strained, having been deformed during the Hercynian orogeny. Analyses of the thicker quartz veins shows that many of them contain minor amounts of Au along with other metals as shown in Table 2.

A phase of hydrothermal activity also postdates the deformed quartz veins. It occurs in brittle fractures within the vein quartz and consists mostly of carbonate. Thicker veins consisting largely of euhedral dolomitic rhomb carbonate also occur; Table 2 includes two samples rich in this type of veining.

Pyrite is widespread in the mineralised zone, though in many cases much of it has been converted into goethite. Malachite is conspicuous on some surfaces and Cu concentrations of up to 1090 ppm have been found. Chalcopyrite was found in one section, partly altered to secondary copper sulphide. Sphalerite and galena occur particularly in quartz veins from the area east of Ryder's Hole.

Table 2 Analytical data for quartz and carbonate veins east of Wadham Rocks

		Q(A)	O(A)	Q(B)	O(B)	O(B)	C(A)	B(A)
MgO%	1.51	0.10	0.45	0.17	0.20	0.04	10.49	6.09
K ₂ O%	0.79	0.20	2.54	1.61	0.59	0.38	2.16	1.53
CaO%	1.05	0.05	0.26	0.04	0.06	0.05	23.22	9.58
Cu ppm	6	200	40	32	177	36	32	50
Zn ppm	<3	2	96	25	507	6	116	63
As ppm	<1	363	112	130	38	119	184	63
Sb ppm	7	8	15	16	3	2	137	26
Pb ppm	<2	7	9	44	427	19	113	33
Au ppb	2	33	35	43	15	36	1	31

Q = Quartz vein, C = Carbonate vein, B = Carbonate breccia

Localities (A) west of Ryder's Hole, (B) east of Ryder's Hole

No discrete native gold has been observed in mineralised samples, though high intensity spots on backscatter electron images were located and checked for gold by electron microprobe, but found to be As-rich. However, chemical analyses of both veins and veined rock suggest that Au is more closely associated with As than with any other element. A general correlation between the two elements is apparent in Figure 4b for mineralised veins, sedimentary rocks and volcanics, though with a considerable range in Au/As ratios. Microchemical mapping of pyrite grains show that As is concentrated at the margin of euhedral grains (Plate 1) and larger irregular grains (Plate 2). In the euhedral grains a well-developed As-enriched rim is present (Plate 1), but in the larger grains As distribution is more complex and two concentration levels of As are present (Plate 2). Growth zones at the edge of the larger grain, with variable, but low, concentrations of As, are truncated by

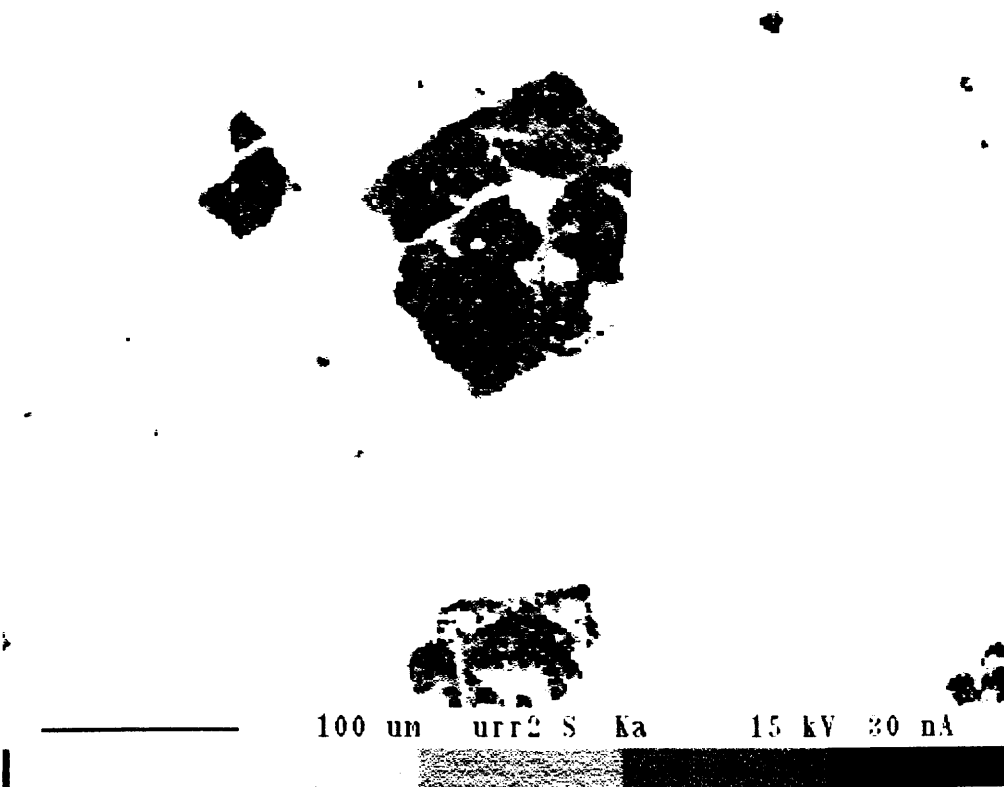
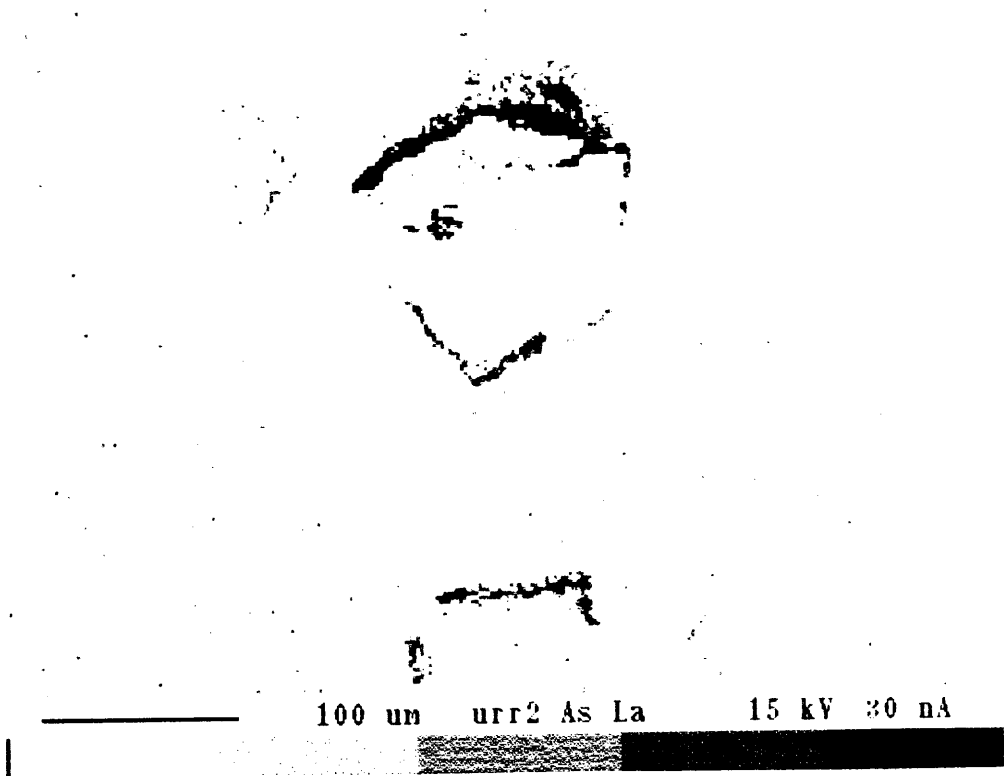


Plate 1 Microchemical maps showing the distribution of As and S in a polished section of pyrite-rich altered volcanic rock from near Wadham Rocks.

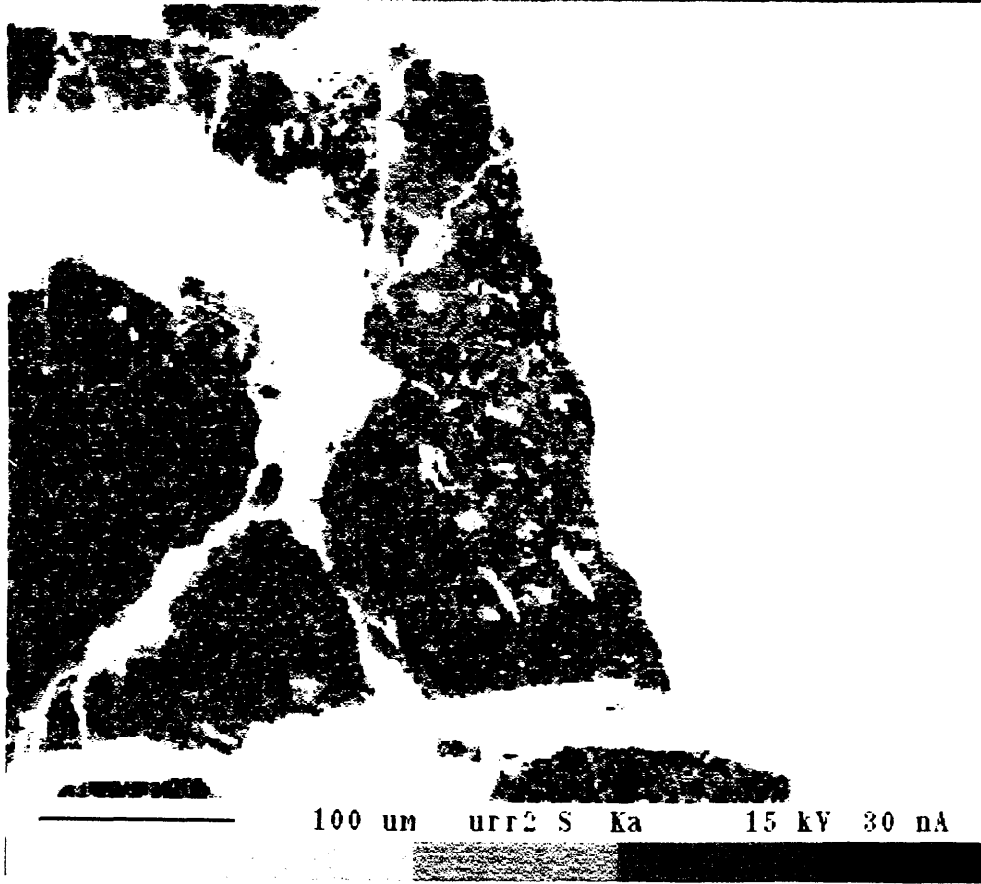
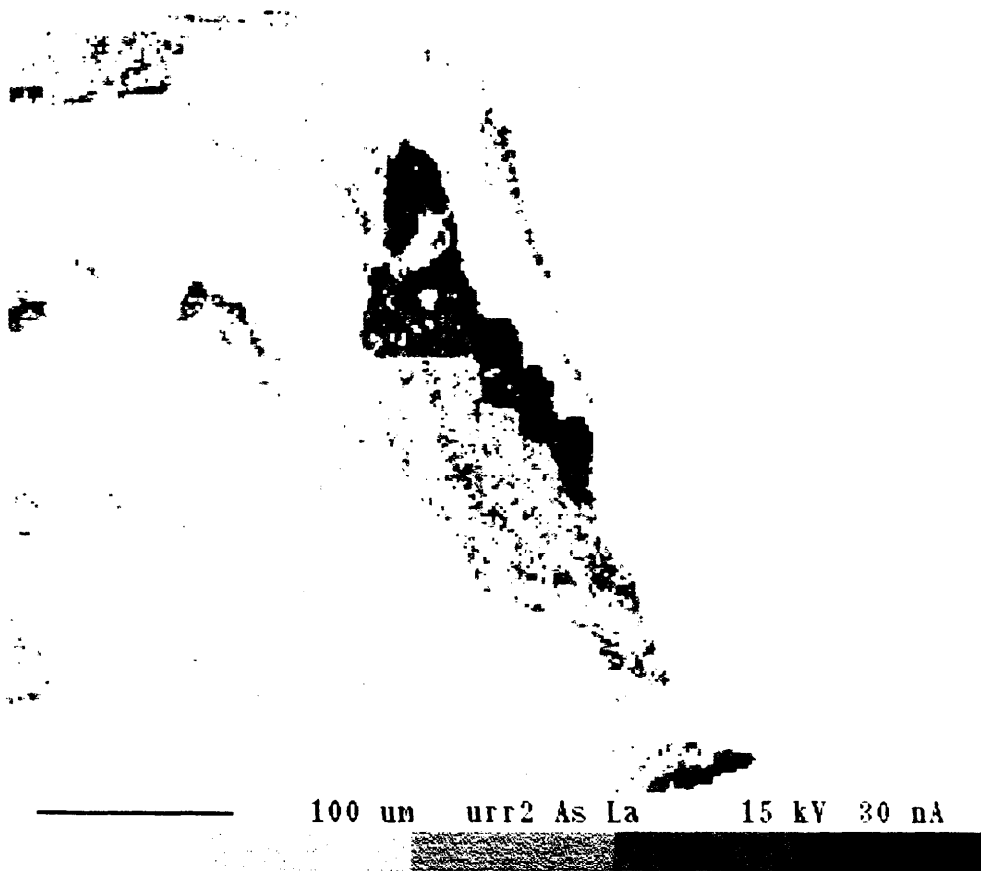


Plate 2 Microchemical maps showing the distribution of As and S in a polished section of pyrite-rich altered volcanic rock from near Wadham Rocks. S depletion corresponding to zone of maximum As enrichment in pyrite can just be seen.

anhedral pyrite containing significantly more As. Quantitative electron microprobe point determinations indicate that the As concentration in the rims of the anhedral grains is between 0.46 and 0.73 % As, while a maximum of 2.49% As was determined at the edge of an altered pyrite. Occasional inclusions of arsenopyrite occur within the pyrite and, within As-rich zones, minute inclusions of Co-rich gersdorffite have been observed.

At Carswell Cove, volcanics which have suffered intense potassium feldspar alteration occur but concentrations of Au and As are generally lower than at Wadham Rocks. Up to 300 m east of Carswell Cove and obliquely across strike, near Saddle Rock, similar volcanic rocks are relatively enriched in Na (Figure 4a) and in some examples this is clearly the result of albitisation, with Na introduction. This alteration is probably spatially related to the potassium feldspar-rich zone and represents either peripheral Na redeposition of material leached from the K-rich alteration zone or a separate but related phase of alteration.

Antimony is also enriched in several samples of mineralised material, in particular volcanics and carbonate-rich veining, to a maximum level of 137 ppm. However, it does not show the same degree of correlation with Au as As. Other metallic elements and the total concentration of pyrite do not correlate with Au contents.

In the absence of visible gold occurrences, it is difficult to establish which of the several phases of hydrothermal activity to have affected the area is associated with gold mineralisation. There is no clear evidence to suggest that the gold is associated with the post-deformation carbonate-rich veining, rather than pre-deformation veining and alteration. The widespread association of Au and As throughout the zone tends to indicate that the major phase of gold enrichment was pre-deformation, but within a late episode when As-enriched pyrite was deposited over or replaced pre-existing As-poor pyrite.

The mineralisation near Wadham rocks has some features in common with epithermal gold mineralisation as defined in broad terms (Panteleyev, 1988; Henley, 1990). Thus the mineralisation occurs in association with a complex zone dominantly of quartz veins, showing evidence of repeated cycles of mineralisation. Enrichments of Au and some Ag are associated with enhanced levels of As and Sb and minor amounts of base-metal sulphides are also present within some quartz veins (Table 2). Hydrothermal alteration is pronounced in the mineralised zone with widespread introduction of potassium feldspar, Fe-bearing carbonate, silica and pyrite. However, evidence of a spatial and temporal association between mineralisation and volcanism is lacking. Models of vertical zonation in epithermal mineralising systems (Panteleyev 1988) suggest that the Wadham Rocks mineralisation may have formed within the relatively deep part (around 1 km depth) of such a system.

OTHER GOLD-BEARING MINERALISATION

Further gold-bearing mineralisation has been discovered by coastal rock sampling at Soar Mill Cove within the Start Complex (Figure 1,2). Three of six samples of vein material from this locality contain >10 ppb Au by analysis, to a maximum of 190 ppb. In two samples, detectable Au is accompanied by enrichment in As (maximum 255 ppm) and Sb (maximum 22 ppm). This

association, together with the presence of potassium feldspar with the quartz in the veins, suggests some similarity with the mineralisation at Wadham Rocks.

Native gold occurs in association with quartz carbonate vein mineralisation at Loddiswell mine, about 2.5 km north of Loddiswell. The mineralisation, described in detail by Stanley et al. (1990), consists of tetrahedrite, bournonite, bismuthian jamesonite, chalcopyrite, galena and other sulphides in quartz, calcite, minor ferroan dolomite and magnesian siderite. Gold occurs as inclusions in the arsenopyrite. A sample panned from the dumps at the old workings contains 2.9% MnO, 81.5% Fe₂O₃, 555 ppm Cu, 330 ppm Zn, 175 ppm As, 43 ppm Ag, 760 ppm Sb, 2180 ppm Pb, 135 ppm Bi and 640 ppb Au.

REGIONAL DRAINAGE SURVEY OF SOUTH DEVON

Details of orientation work and the method of drainage sampling used for the regional survey of South Devon together with analytical methods are given in Leake et al. (1988) and (1990). Panned concentrate samples were obtained from all sites. In addition, at almost 50% of the sites a fine sediment fraction sample (effectively a minus 200 mesh BSS sample) was obtained, as described by Leake and Smith (1975). Summary statistics of the drainage concentrate data are given in Table 3 and of the fine sediment fraction data in Table 4.

In a drainage exploration for gold, multi-element data can frequently be used to provide more reliable indications of mineralisation, provided that pathfinder elements can be recognised which are more abundant and therefore easier to analyse than gold. In addition, elements which are dispersed in different ways to gold may also be valuable if they produce a larger dispersion halo. The environment in South Devon is not very favourable for mineral exploration using drainage sediment because relief is relatively low and streams poorly developed. In addition, the intensity of farming activity and settlement throughout the area leads to the widespread contamination of drainage sediment with metallic elements. Contamination with lead is so widespread that identification of a lead anomaly of natural origin is very difficult. Nevertheless multivariate statistical techniques may assist in the recognition of pathfinder and other anomalies of natural origin. Moreover, comparison of metal concentrations in a concentrate and a fine sediment fraction sample from the same site assists in recognition of geologically significant anomalies. For several elements, anomalies which are present over a wide range of the drainage sediment size spectrum are likely to be more significant than those present only in a coarse fraction. Thus, anomalies due to contamination are most likely to be heavily biased towards the metal in the concentrate sample while natural anomalies are more likely to be present in both concentrate and fine sediment samples. In contrast, sites where an element is enriched only in the fine-fraction sediment sample often reflect a general enrichment of the element in the regional source rocks, an organic rich drainage sediment or the presence of hydrous oxide precipitates.

Distribution of gold.

A map showing the distribution of gold in panned concentrate samples is shown in Figure 5. At 44 sites concentrations of Au exceed 0.5 ppm. Anomalies are widely distributed over the entire Lower Devonian sequence and the Start Complex but are less evident over the Middle Devonian rocks to the east of Plymouth.

Table 3 Summary statistics of chemistry of panned concentrate samples

	N	Mean	S.D.	Min.	Max.
MgO%	363	1.87	0.80	0.01	4.82
CaO%	473	1.13	1.59	0.04	16.45
TiO ₂ %	473	2.40	4.32	0.38	34.94
MnO%	473	0.15	0.13	0.02	0.98
Fe ₂ O ₃ %	473	11.12	5.76	2.30	42.51
S ppm	362	524	1286	64	18300
Cr ppm	308	168	105	3	939
Ni ppm	473	48	15	15	110
Cu ppm	460	53	128	4	2022
Zn ppm	473	109	87	10	1370
As ppm	473	26	35	<1	564
Rb ppm	442	66	25	1	215
Y ppm	390	26	9	8	85
Zr ppm	473	228	106	7	870
Ag ppm	377	0.8	1.9	<1	25
Sn ppm	472	665	1564	<1	13495
Sb ppm	473	9	17	<1	220
Ba ppm	473	529	3032	<10	49400
Au ppb	449	564	3364	<10	47700
Hg ppm	186	14	148	<1	2010
Pb ppm	473	255	821	10	12770
Bi ppm	367	1.8	3.3	<1	53

Table 4 Summary statistics of chemistry of fine fraction sediment samples

	N	Mean	S.D.	Min.	Max.
MgO%	224	1.60	0.76	<0.01	3.43
CaO%	225	0.75	0.84	0.15	10.66
TiO ₂ %	225	1.11	0.18	0.83	2.66
V ppm	190	132	23	82	233
Cr ppm	225	148	31	56	267
MnO %	222	0.22	0.27	0.03	1.94
Fe ₂ O ₃ %	225	7.97	1.60	3.07	16.88
Co ppm	191	29	21	11	295
Ni ppm	225	52	23	24	336
Cu ppm	225	43	29	8	306
Zn ppm	225	141	88	44	1168
As ppm	225	19	22	<1	199
Rb ppm	191	144	25	60	222
Sr ppm	191	101	50	53	555
Y ppm	190	34	4	20	53
Zr ppm	191	377	85	201	777
Mo ppm	190	0.6	1.0	<1	9
Ag ppm	191	0.7	1.0	<1	5
Sn ppm	224	22	117	<1	1389
Sb ppm	191	2.9	5.2	<1	41
Ba ppm	225	451	105	181	983
La ppm	190	43	8	21	88
Ce ppm	190	76	19	34	195
Pb ppm	225	47	43	10	494
U ppm	224	4.2	1.6	1	17

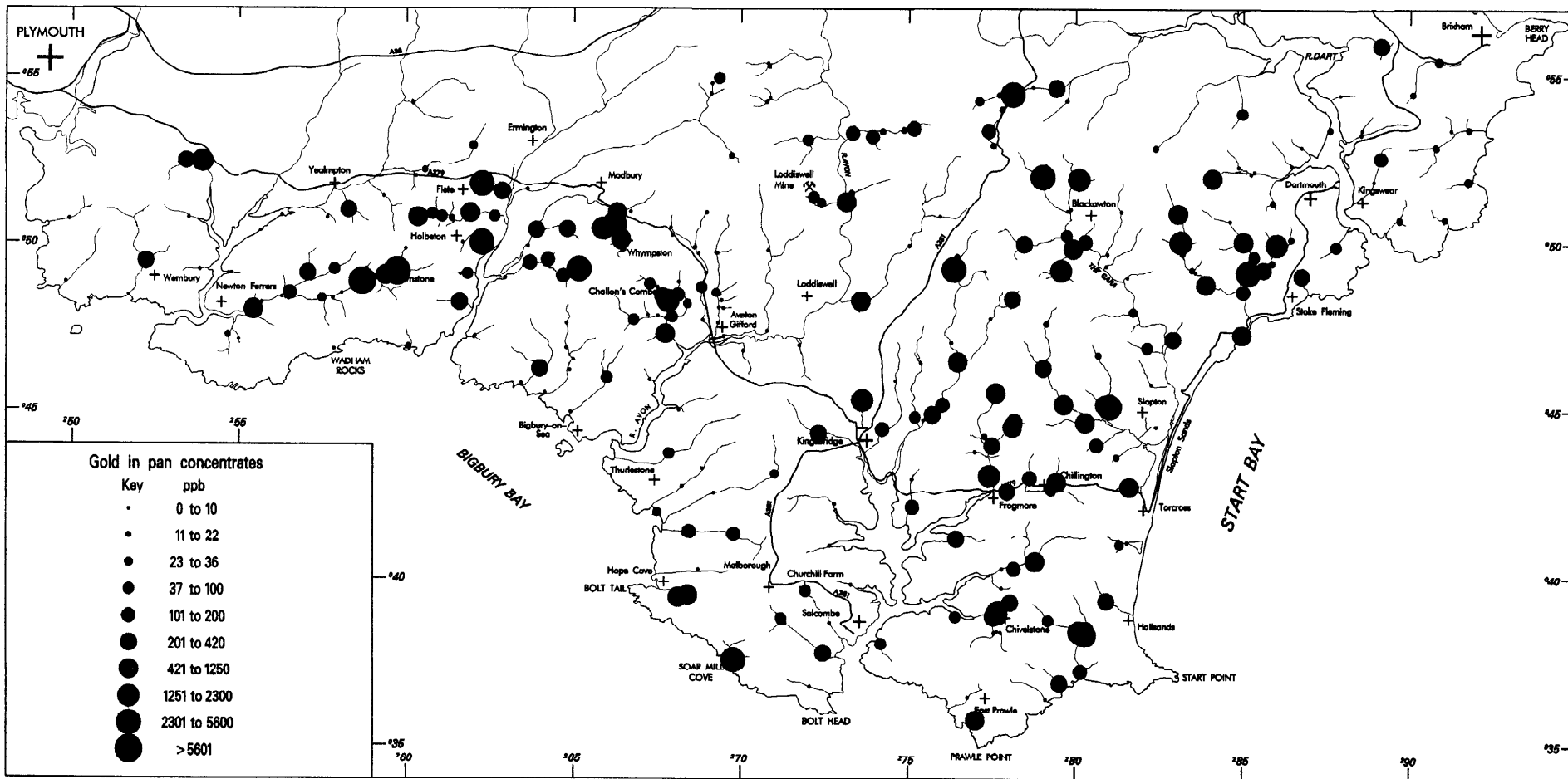


Figure 5 Distribution of gold in drainage panned concentrate samples.

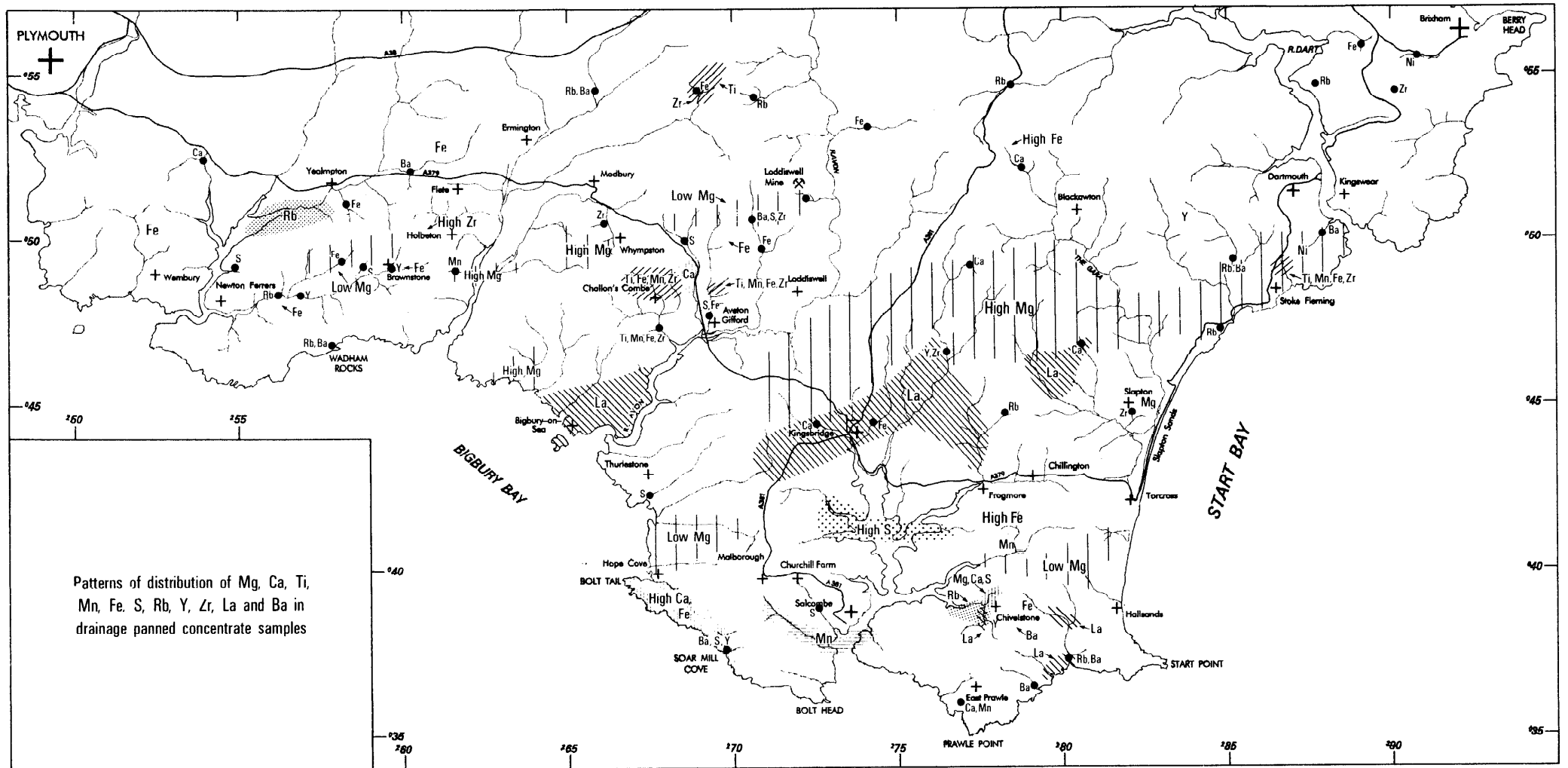


Figure 6 Patterns of distribution of Mg, Ca, Ti, Mn, Fe, S, Rb, Y, Zr, La and Ba in drainage panned concentrate samples.

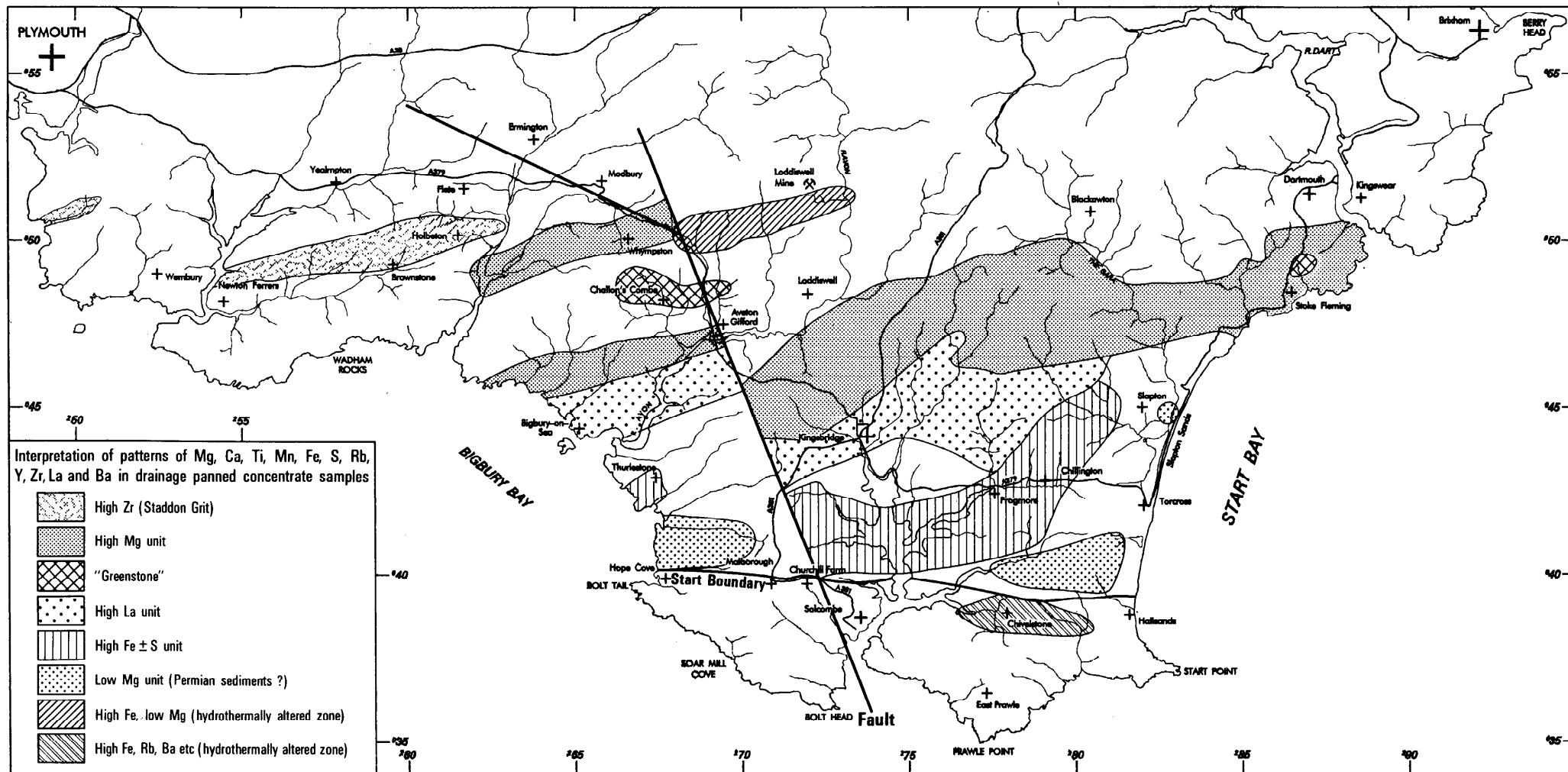


Figure 7 Interpretation of patterns of Mg, Ca, Ti, Mn, Fe, S, Rb, Y, Zr, La and Ba distribution in drainage panned concentrate samples.

Distribution of other elements.

Maps showing the distribution of Cu, Zn, As, Sn, Sb, Hg, Pb and Bi are shown in Figures 8-15. Other elements are not shown individually, but a map showing patterns of the distribution of Mg, Ca, Ti, Mn, Fe, S, Rb, Y, Zr, La and Ba is shown in Figure 6 and a geological/mineralisation interpretation of these is shown in Figure 7. Some patterns reflect the distribution of sedimentary and igneous rock units, including Permian rocks unconformably resting on the Devonian sequence. Separate units can be recognised within the Lower Devonian which are displaced northwards by a presumed fault near the centre of the area. Areas giving a similar signature to Permian rocks near Slapton may represent unexposed Permian or areas from which Permian rocks have relatively recently been removed by erosion. Two centres of hydrothermal activity comprising a zone of depletion of Mg and enrichment in Fe, S and Ba in the north of the area and a zone of enrichment of Fe, Rb, Ba and La in the south-east of the area are also recognised.

Copper

Most copper anomalies (Figure 8) are due to metallic contamination. Fragments of brass and copper wire have been identified at a number of sites. Chalcopyrite and malachite have also been identified in a few of the samples examined mineralogically, but it is impractical to define natural anomalies by detailed examination of every anomalous sample. However, some general empirical observations can be made. Samples where Cu is accompanied by a high concentration of Pb are likely to be contaminated with metallic material. Samples where copper is more likely to be of natural origin can be identified by association with elements like As, Zn, Fe, Mn or Ba rather than Pb, and by elevation of Cu in the corresponding fine sediment fraction samples.

The more significant copper anomalies (Figure 8) occur in four areas. These are a) over Middle Devonian rocks to the northeast of Yealmpton, b) around Brownstone c) in the area to the east of Modbury as far east as the Loddiswell mine and d) in the Start Complex, particularly to the east of Salcombe. The presence of several fine sediment samples with elevated Cu concentrations indicates that the Start Complex is generally enriched in copper compared with other rocks in the area.

Zinc

In concentrates, Zn distribution is much less influenced by metallic contamination than Cu, in part at least, because of the greater solubility of the element. Brass is the only metallic contaminant containing zinc identified in the concentrate samples. In some cases it has been corroded, with selective leaching of the zinc component. Zinc anomalies of natural origin occur to the north-east of Yealmpton, over Middle Devonian rocks and in the zone from east of Modbury to just east of Loddiswell mine (Figure 9). The source of the low amplitude anomalies to the south of Kingsbridge is unclear, but their association with slightly elevated concentrations of S suggests a natural origin. Zinc is a minor component of baryte-rich vein mineralisation near Soar Mill Cove. The source of the large amplitude anomaly to the east of Dartmouth is also unclear, but the absence of associated anomalies in Mn, Fe or As suggests an artificial source. Two high amplitude Zn anomalies in fine sediment samples (F in Figure 9), not associated with correspondingly high concentrate anomalies, are probably artificial in origin. East of Salcombe, lower amplitude anomalies of Zn in fine sediment samples are associated with anomalies of other elements in both sample types and may be of natural origin.

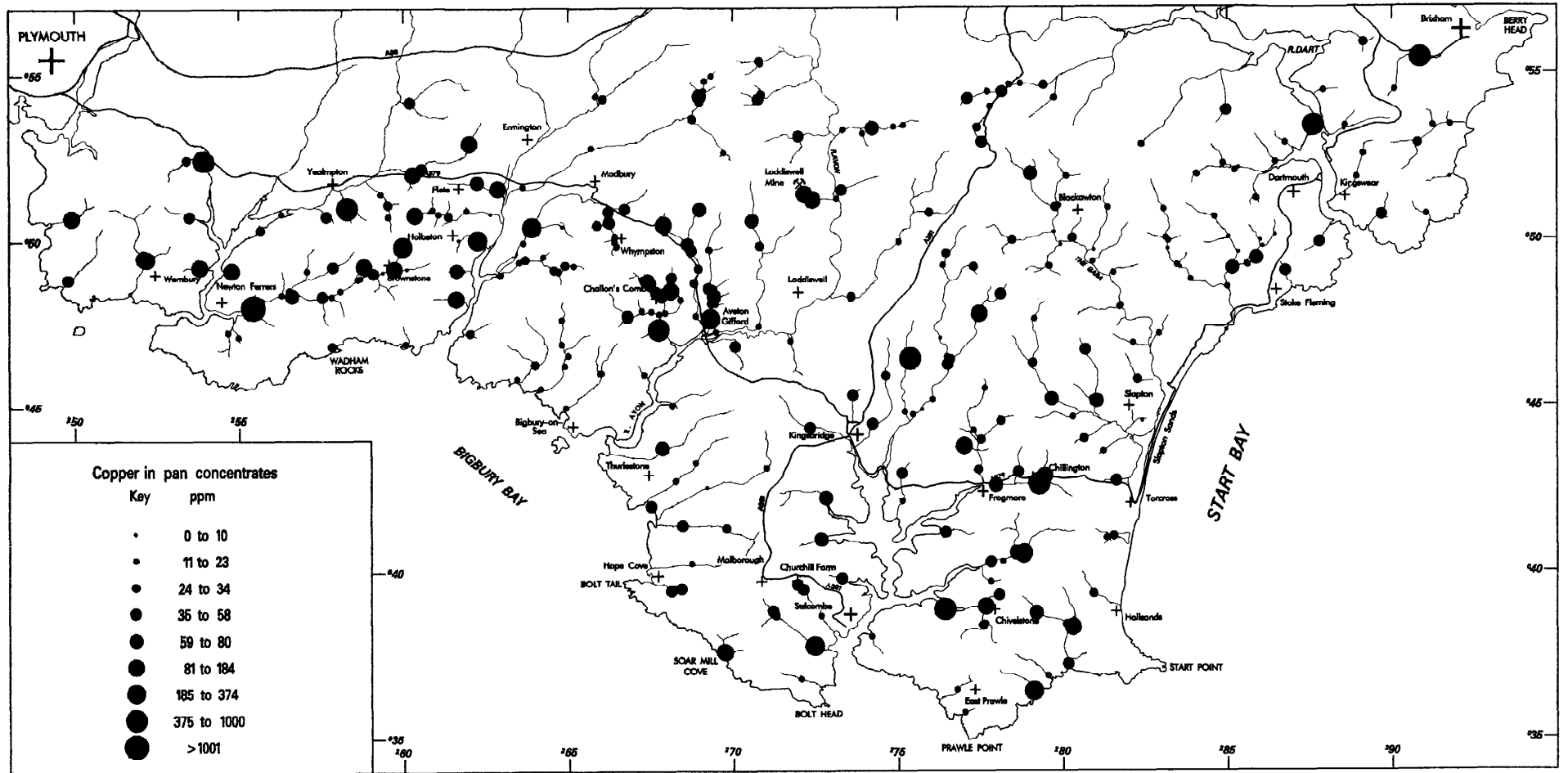


Figure 8 Distribution of copper in drainage panned concentrate samples.

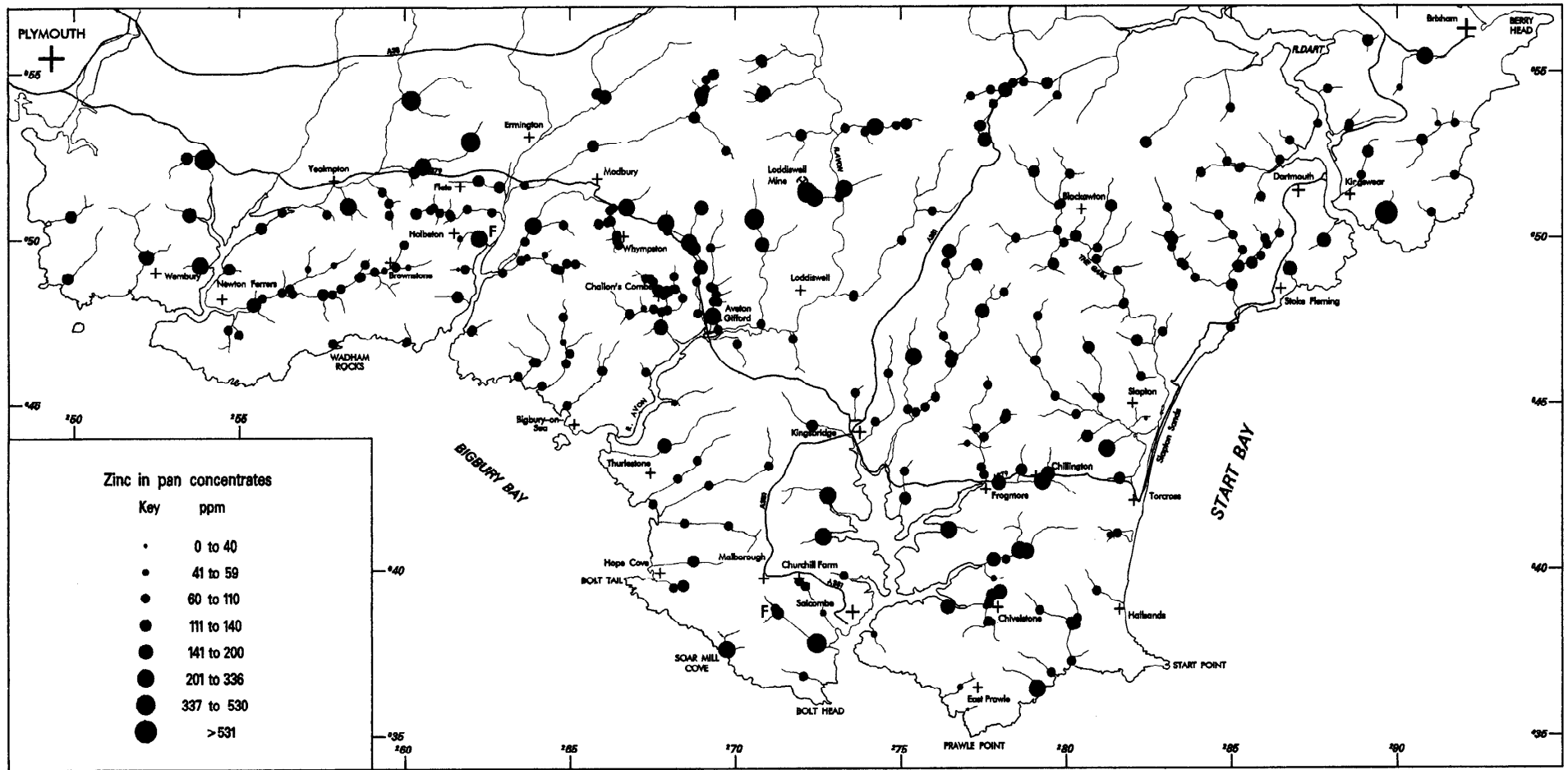


Figure 9 Distribution of zinc in drainage panned concentrate samples.

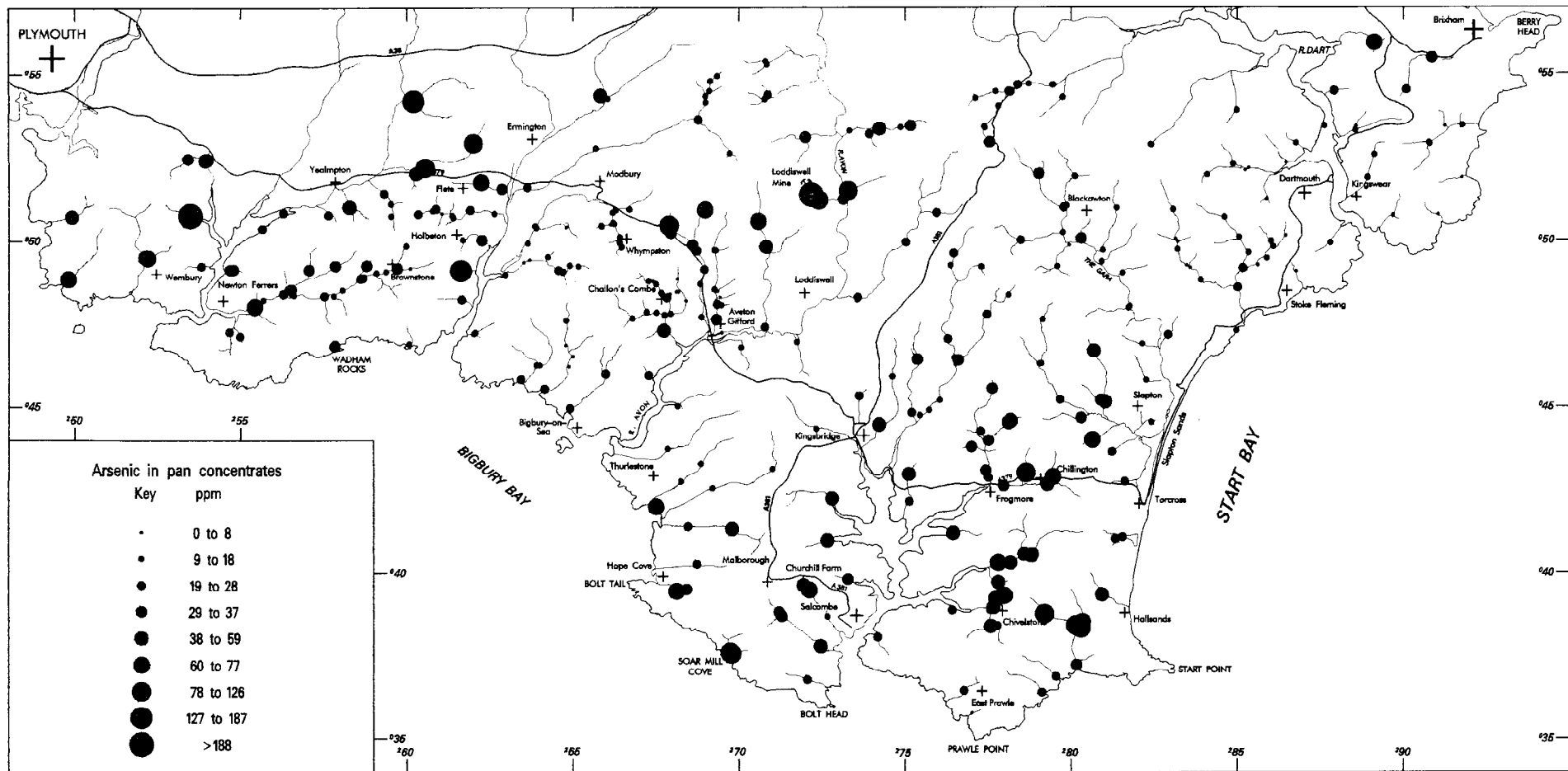


Figure 10 Distribution of arsenic in drainage panned concentrate samples.

Arsenic

Most of the arsenic anomalies are of natural origin. A group of anomalies is associated with the outcrop of Middle Devonian rocks to the east of Plymouth (Figure 10) where concentrations of Fe, Zn and, particularly, Hg are also anomalous, but there is no indication of an enrichment in Au. A similar group of anomalies occurs within a ENE-trending zone from east of Modbury to east of the Loddiswell mine. Elevated concentrations of Fe, S, Zn, Sb, Pb and, to a lesser extent, Ni, Cu, Bi and Ba are also associated with these samples but Au abundances are relatively low. The number of anomalous elements is similar to those found in a sample panned from dump material at the Loddiswell mine but proportions of the elements are different, particularly with respect to Cu, Zn, As, Pb and Bi. Interpretation of these data suggests that vein mineralisation seen at Loddiswell to trend about north-west (Stanley et al., 1990), is superimposed on a wider anomalous zone characterised, in particular, with enrichment in Zn and As.

Low amplitude As anomalies are associated with samples from Soar Mill Cove, where baryte is also present. Arsenic is also enriched in a zone trending roughly east-west within the Start Complex to the east of Salcombe, in association with Sb. This zone is marked by Au anomalies, in contrast to other areas of As enrichment. Enrichment in Fe and Ba is more loosely associated with the same zone. Some enrichment in As is also associated with samples from the Start Complex to the north-west of Salcombe, at sites to the east of Kingsbridge and, to a lesser extent, in samples from south of Yealmpton. At most sites where both panned concentrate and fine sediment samples have been obtained, As concentrations are more than twice as high in the former as in the latter. The high amplitude As anomaly to the south of Plymouth is also enriched in Fe and Sb but not in most other metallic elements.

Silver

Relatively high concentrations of Ag characterise a group of samples from around Challon's Combe (Figure 11). At one of the sites in the north of this area a grain of native silver was recovered from the concentrate. A microchemical map of this grain shows it to be made up mostly of relatively pure silver, but with several small patches relatively rich in copper. Mercury is also enriched in more diffuse areas and a concentration of 13.8% Hg was found in a surface point analysis of the grain. Some correlation between Ag enrichment and the presence of greenstones is also suggested by the Ag anomaly in the ilmenite-rich sample from south of Dartmouth, the other area where a significant amount of greenstone occurs. The available data on the distribution of gold grain compositional types, described below, suggests that native silver is most likely to occur where the gold is Ag-rich rather than Pd-rich. The source of the high amplitude Ag anomaly near Newton Ferrers is not clear. Though this site is contaminated with much metallic material, silver is not a metal normally associated with domestic or agricultural waste.

Tin

The range of Sn concentrations is very high, from less than 10 ppm to over 1%. Cassiterite is very widespread and sometimes abundant in the drainage sediment from South Devon (Figure 12). In appearance, it is variable and variegated in colour from pale yellow to dark red, as in other parts of south-west England. At four sites, isolated spherical or multiple spherical grains of a tin-mercury amalgam have been recovered, the origin of which is enigmatic. One grain has been mapped and shows a discontinuous marginal zone enriched in Sn and depleted in Hg. The distribution of Sn concentrations shows that the highest levels occur in the north, except in the centre of the area, where values as low as 15 ppm are found. This geographical distribution is difficult to equate with

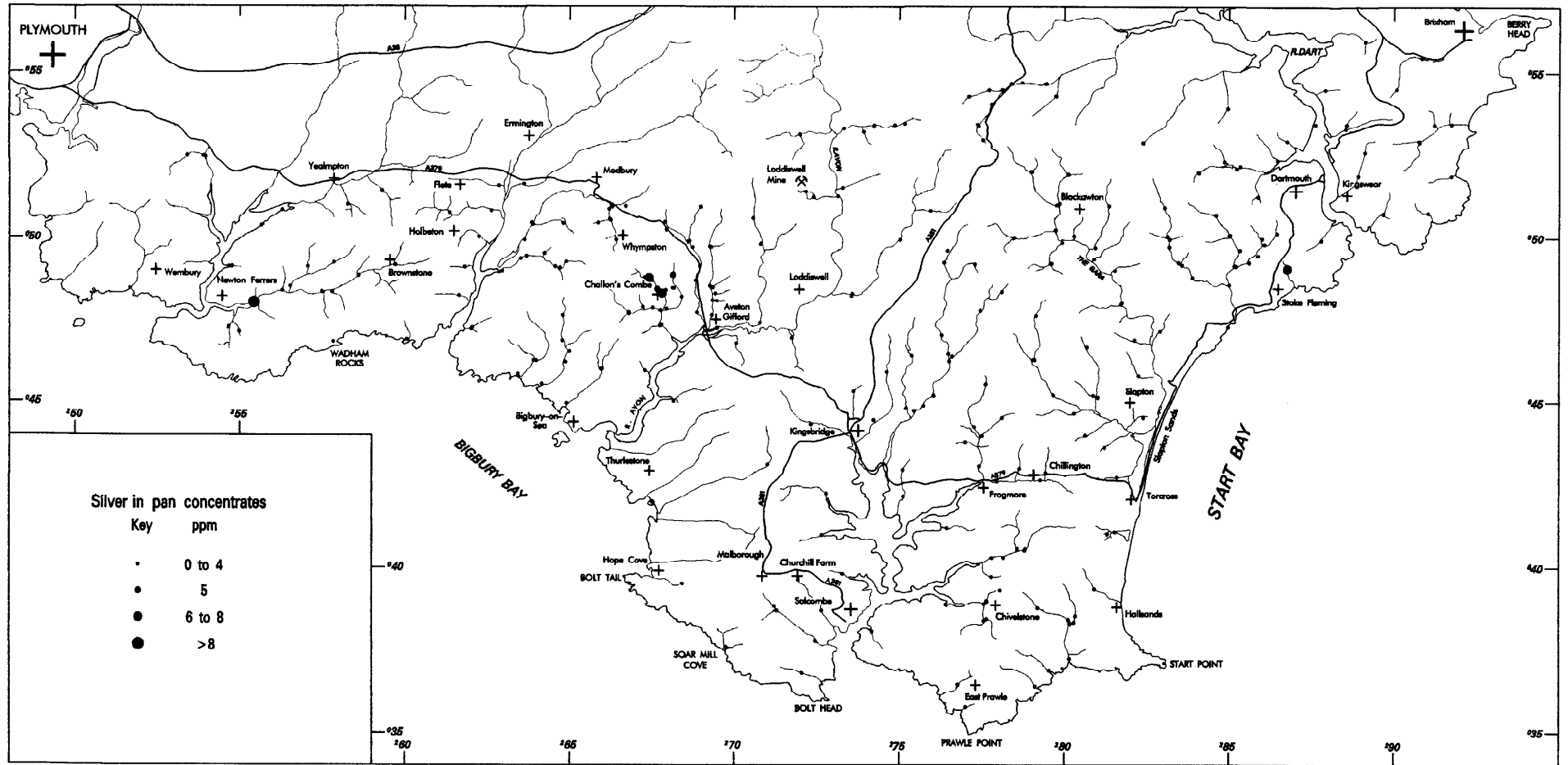


Figure 11 Distribution of silver in drainage panned concentrate samples.

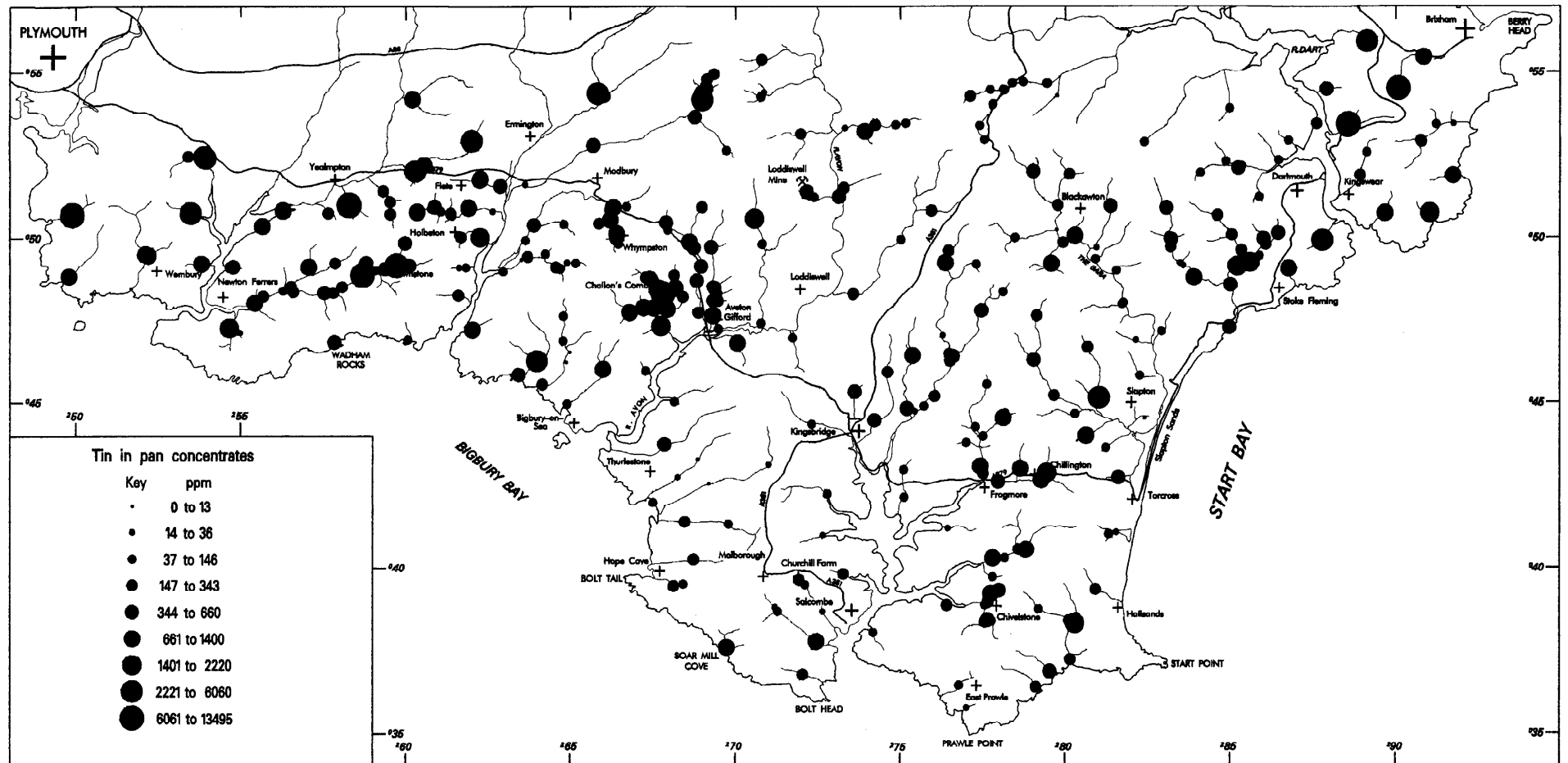


Figure 12 Distribution of tin in drainage panned concentrate samples.

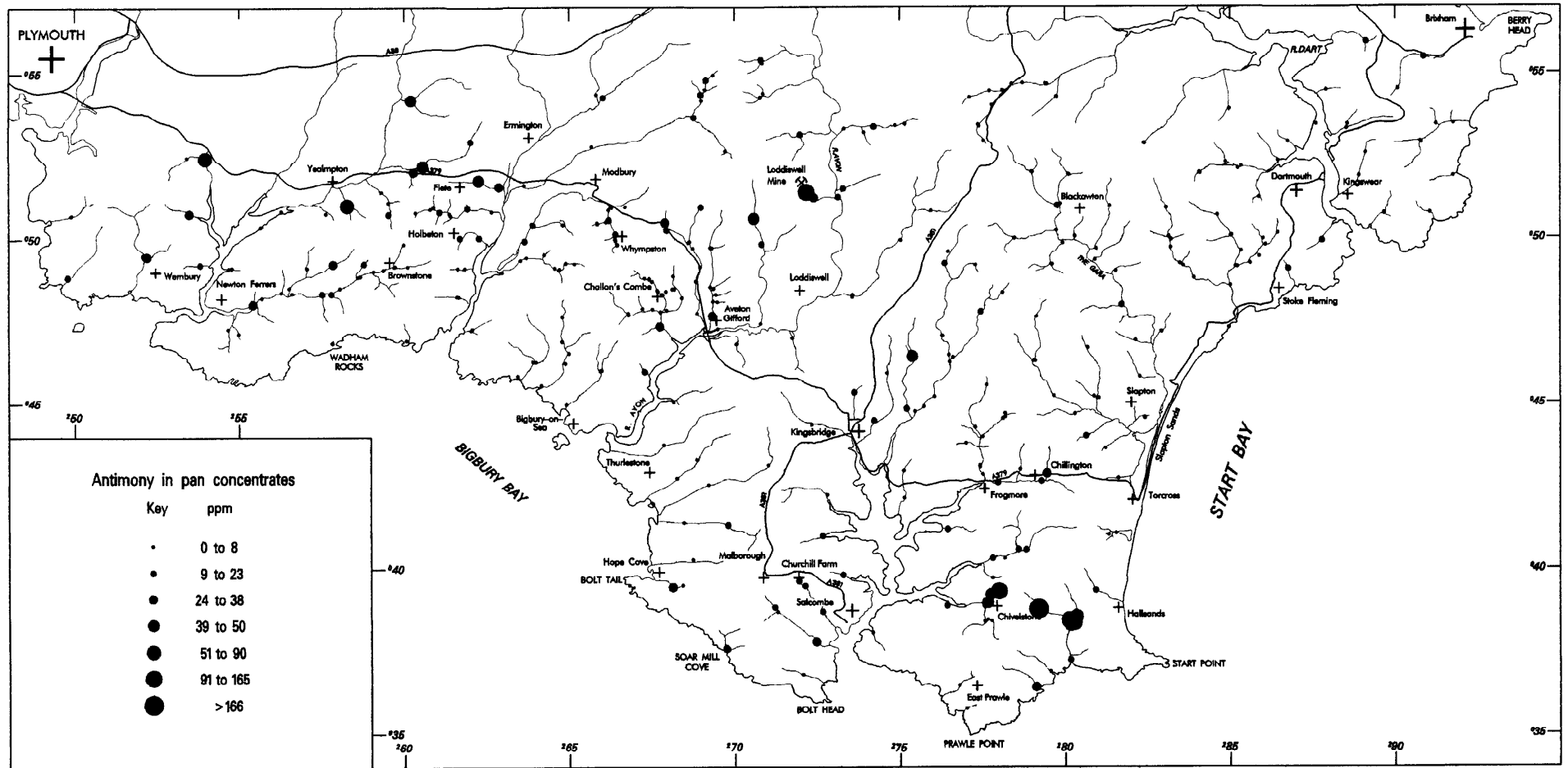


Figure 13 Distribution of antimony in drainage panned concentrate samples.

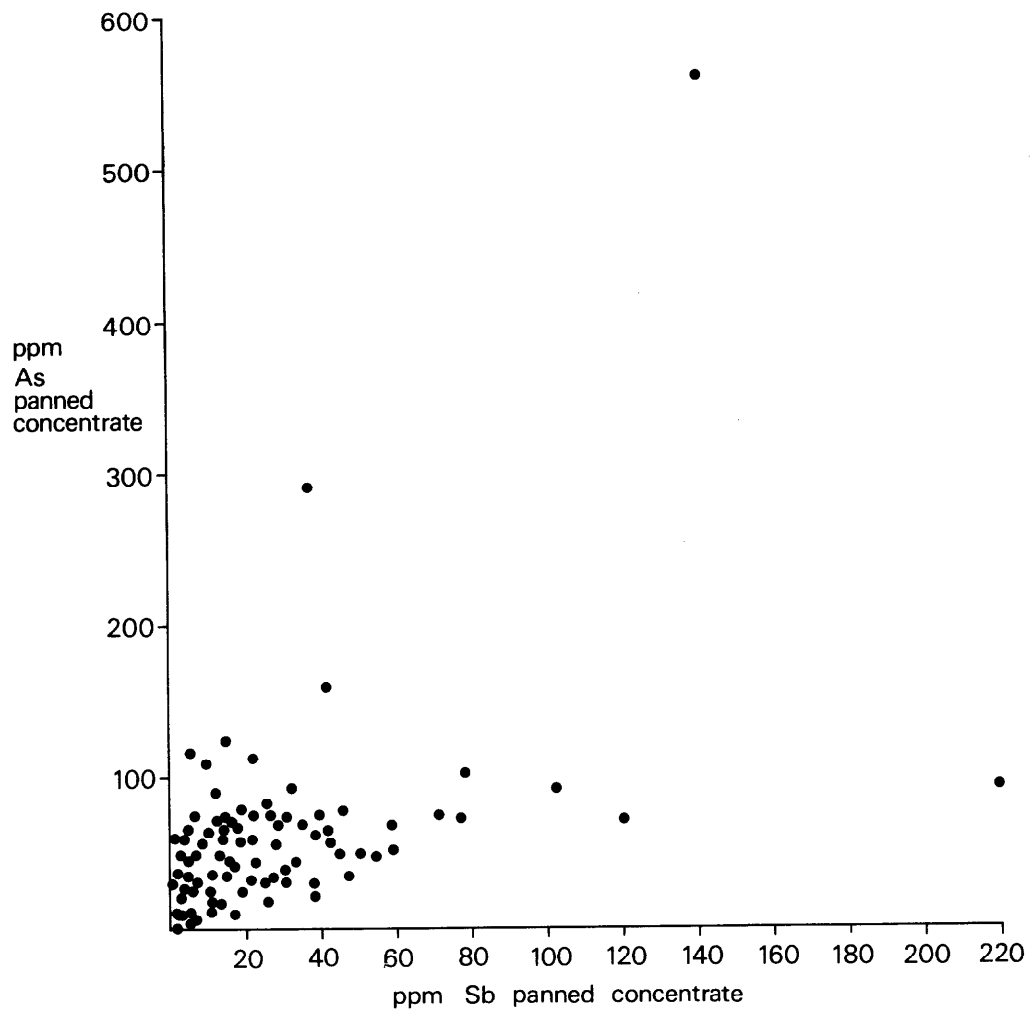


Figure 14 Comparison of arsenic and antimony contents of drainage panned concentrate samples.

derivation from the Dartmoor granite and its aureole in a one-stage process. Rather, it suggests that some other factor is also involved in cassiterite distribution. At Brownstone and Challon's Combe, Au and Sn are closely associated but at Whympston and sites further east and south, this is not the case. At Brownstone the east-west valley follows a soft and highly altered zone, in which at some time in the recent geological past, head may have accumulated and then been winnowed, leading to upgrading of relatively coarse-grained heavy detrital minerals like cassiterite and gold. In contrast, where Sn levels associated with Au anomalies are much lower, this process probably did not occur to the same extent.

Antimony

Four main types of Sb anomaly (Figure 13) can be recognised in the drainage data. Some low amplitude anomalies of probable artificial origin can be recognised where there is no corresponding Sb anomaly in the fine sediment samples, where there is no corresponding As anomaly and where Pb concentrations are particularly high. These anomalies reflect the use of small amounts of Sb to harden lead metal. The three remaining groups of anomalies are natural in origin and can be distinguished in terms of Sb/As ratios. Anomalies associated with the Middle Devonian rocks to the east of Plymouth are greatly enriched in As relative to Sb (Figure 14). Less enriched in As relative to Sb, is the zone of anomalies trending ENE from east of Modbury to east of the Loddiswell mine. Much more enriched in Sb relative to As (Figure 14) are the group of anomalies to the east of Salcombe, around, and to the east of Chivelstone.

Mercury

Relatively few samples have been analysed for Hg and the coverage is patchy. The Hg is present overwhelmingly as cinnabar but Sn-Hg amalgam and native mercury have been recovered from concentrates from four and two sites respectively. Minor amounts of cinnabar have been observed in several samples not analysed for Hg. Highest amplitude Hg anomalies occur in the region of Middle Devonian rocks to the east of Plymouth (Figure 15). The 2000 ppm Hg present in one sample suggests a significant source of the element to the west of Ermington. Smaller amplitude anomalies indicate that separate sources are present within Middle Devonian and Lower Devonian rocks. There is no correlation between Hg and Au in the concentrate samples.

Lead

Lead present in contaminants greatly exceeds lead of natural origin in the concentrate samples. Lead shot is particularly common but other contaminants, such as lead glass, are also present. Pyromorphite, galena and cerussite grains, of natural origin, have been recovered from some samples but their contribution to overall Pb concentrations is small. All high amplitude Pb anomalies (Figure 16) are dominated by material of artificial origin. Some lower amplitude anomalies are probably largely of natural origin where they are associated with a significant amounts of Zn and/or As. Though the fine sediment fraction sample does not reflect Pb-rich metallic contamination to the same extent as the concentrates, it can still contain fine material derived from the alteration of contaminants at heavily contaminated sites.

Bismuth

The highest amplitude Bi anomaly is associated with the anomalous zone around Loddiswell mine. Other anomalies are of lower amplitude and are less clearly associated with mineralisation. At many of the other sites with relatively high concentrations of Bi (Figure 17), high levels of metallic contaminants are present.

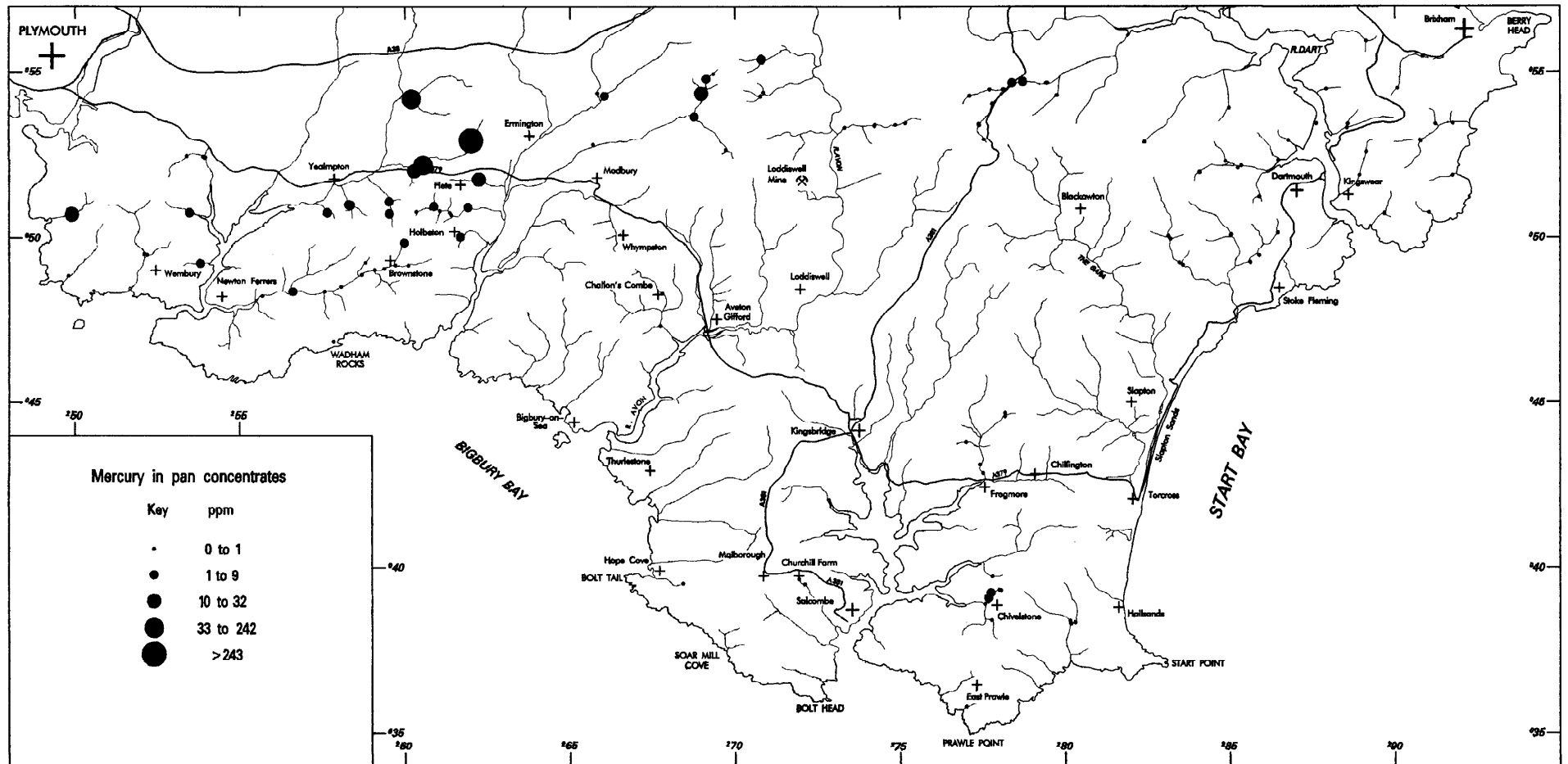


Figure 15 Distribution of mercury in drainage panned concentrate samples.

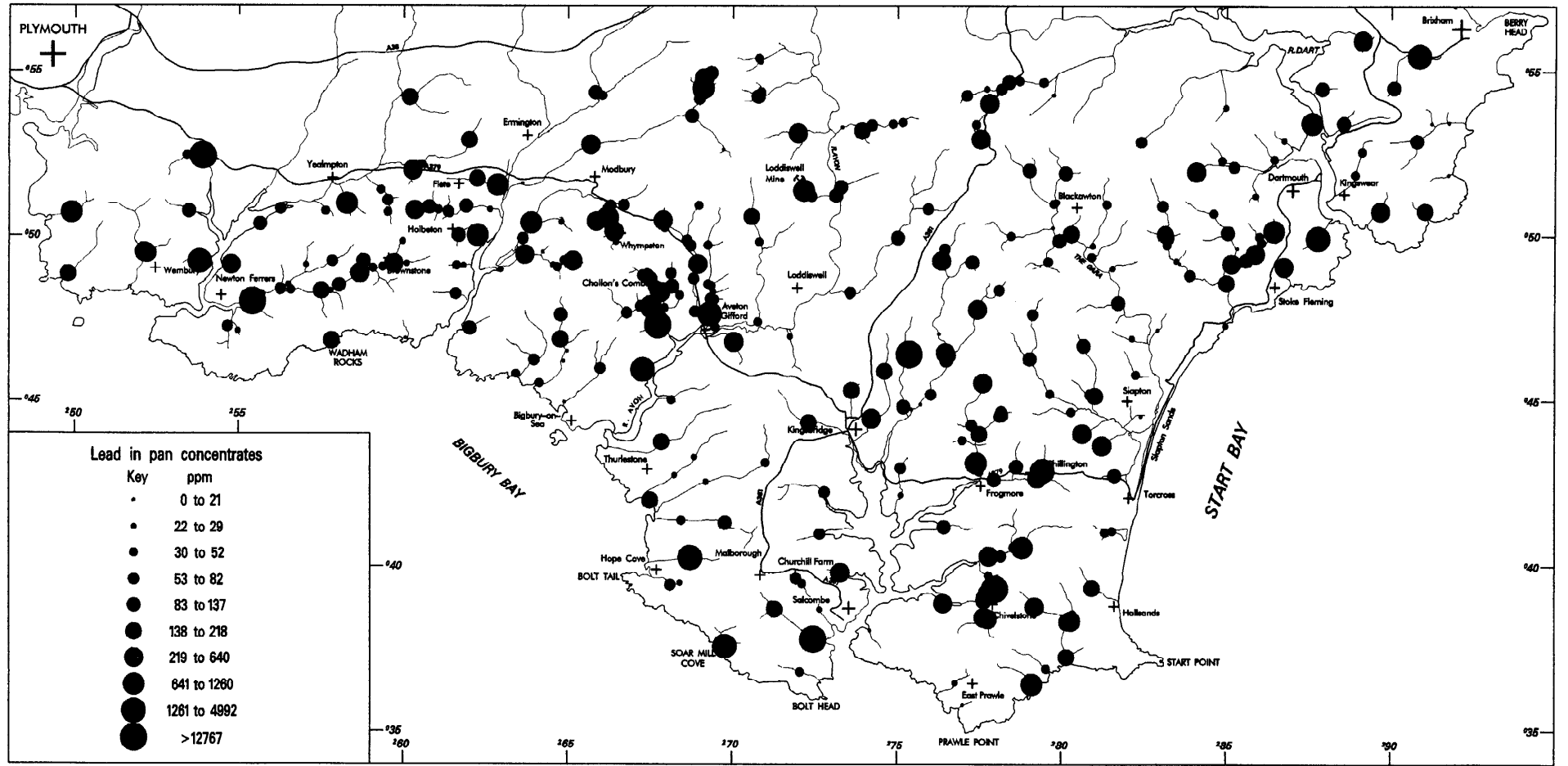


Figure 16 Distribution of lead in drainage panned concentrate samples.

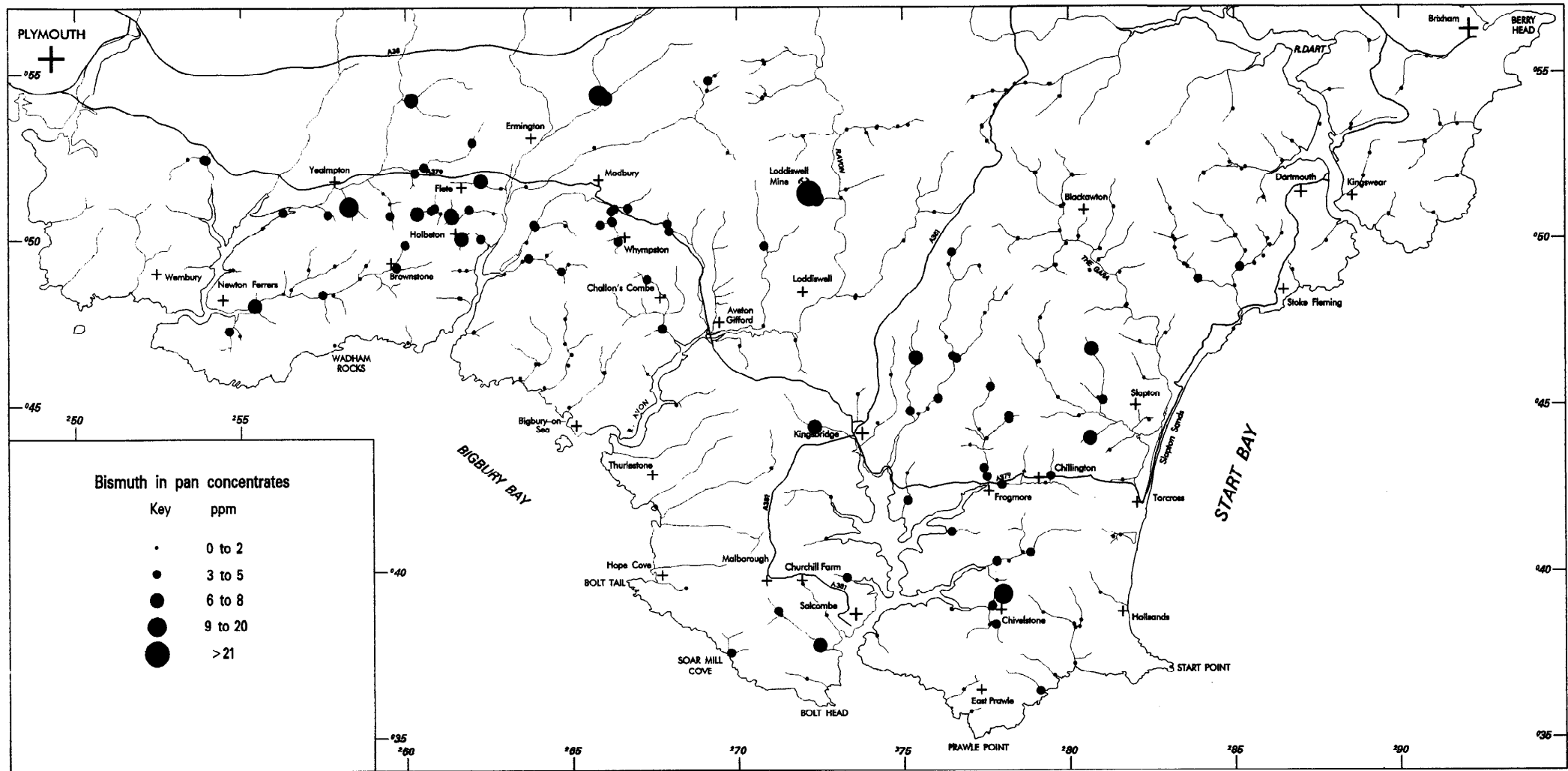


Figure 17 Distribution of bismuth in drainage panned concentrate samples.

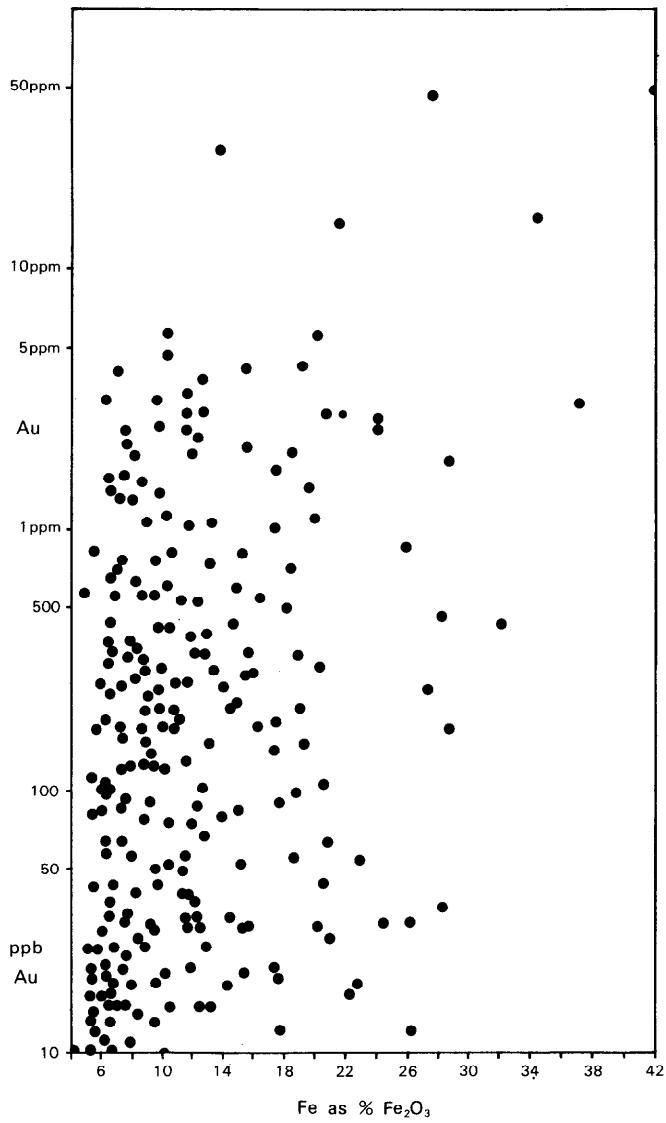
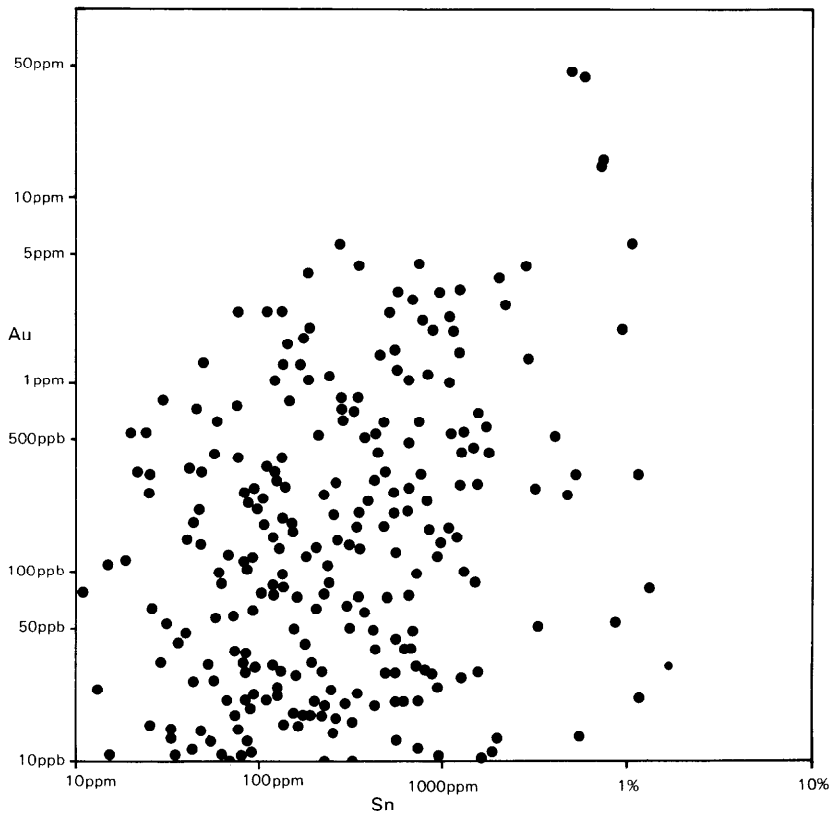


Figure 18 Relationship between concentrations of gold and iron and gold and tin in drainage panned concentrate samples.



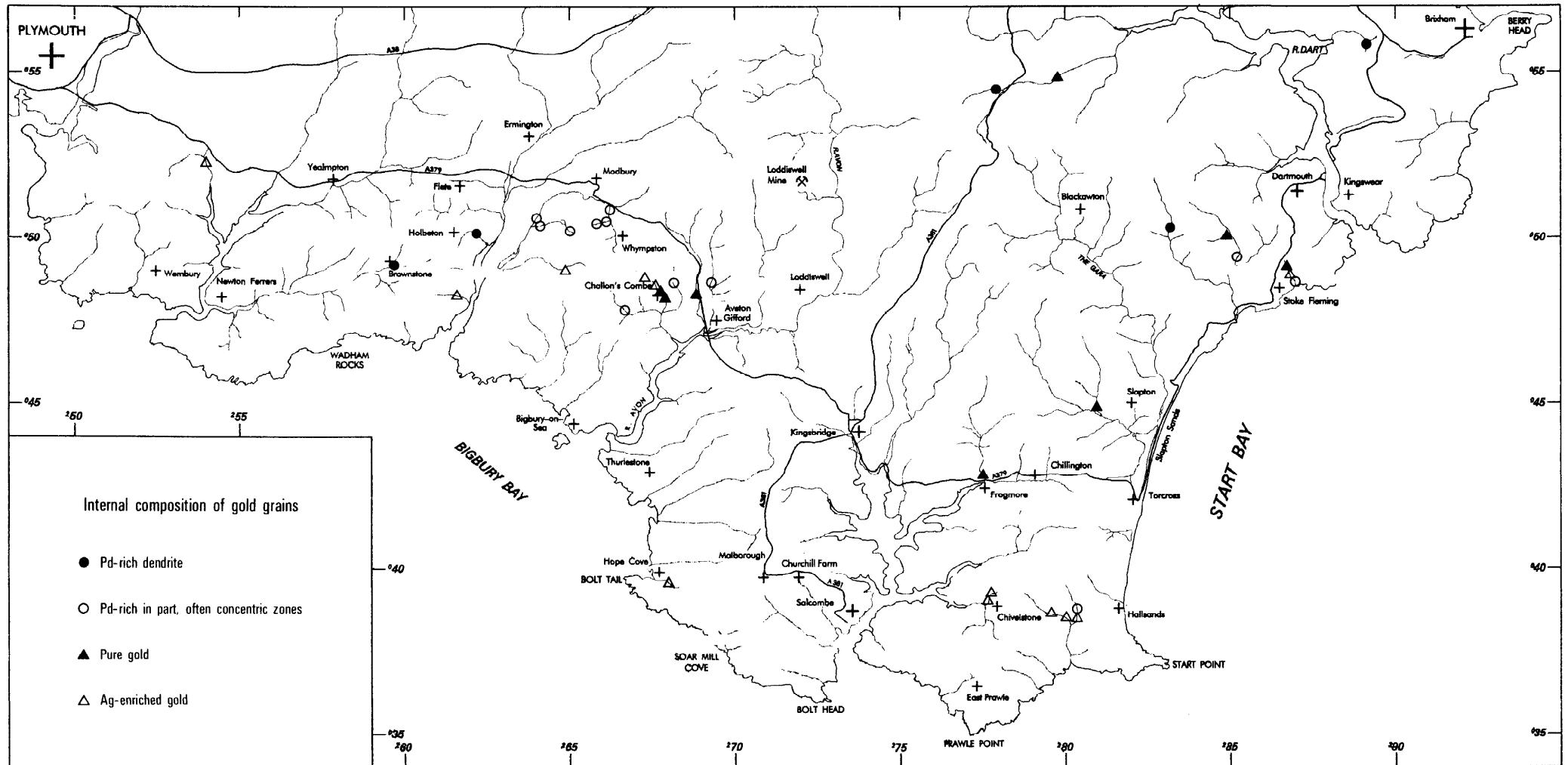


Figure 19 Distribution of gold grain core varieties.

Principal component analysis

As all the elements were not determined in all the samples, a series of runs of the SAS principal component procedure were employed on different numbers of elements. In general the principal components are similar for different runs but some differences exist. Au shows the greatest positive correlation with Fe and Sn, in the data as a whole, and plots of Au against Fe and Sn are shown in Figure 18. In each case there is a considerable scatter in the data which can be resolved to some extent in the eigen vectors of the principal component analyses. The first two principal components reflect background geological factors, while the third principal component is more complex but reflects mostly the presence of a significant amount of baryte at the site just inland from Soar Mill Cove. Gold does not contribute significantly to any of these three principal components. The fourth principal component contains a small contribution from Au but is dominated by Mg and negative As and reflects the Dartmouth Group which is enriched in Mg and depleted in As. It also reflects a depletion in Mg in the north of the area, over the Middle Devonian rocks, but relative enrichment in As and Sb. The partial correlation of Au with principal component 4 indicates some preferential association of the element with the Dartmouth Group, also suggested to some extent by the distribution of Au anomalies and the virtual absence of Au anomalies over the outcrop of Middle Devonian rocks. Principal component 5 is dominated by Sn, W and negative Mg and reflects the distribution of cassiterite. Gold also shows some correlation with this principal component, probably indicating a natural upgrading of heavy minerals at certain drainage sites and upgrading due to the panning procedure. Principal Component 6 is dominated by Cu, Pb and negative Au and reflects general contamination of the drainage sediment with heavy metals and a negative correlation of Au with this material. Principal component 7 is largely dominated by Au.

The drainage geochemical data suggest that there is no clear pathfinder for gold and that factors influencing Au distribution are complex. There is no indication of a general correlation between Au abundances and those of As and Sb, a relationship very commonly found elsewhere in Britain and present in the gold-bearing mineralisation at Wadham Rocks.

Gold grain composition

The results of a detailed study of precious metal grain composition from five locations in the western half of the area, using electron microprobe microchemical mapping and point analyses, are given in Leake et al. (1991). Limited further work using these techniques has been carried out on further gold grains from two regions in the eastern half of the area and on isolated grains from other sites throughout the area. Grains have been classified into six compositional types (Leake et al., 1991) for the western part of the area and five of these types have also been found in the east. Some Ag-rich compositions (37-50% Ag) have been determined from point analyses in the new material, particularly from east of Salcombe, which exceed the maximum Ag level found previously (31.6% Ag).

As grain compositions are mapped from the whole area it is increasingly apparent that there are regional patterns of gold grain type distribution. Figure 19 shows the distribution of four types of grain based on the composition of the core, neglecting crack-fills and rims. South of Modbury, grains containing significant amounts of Pd give way southwards to grains relatively rich in Ag, but with no detectable Pd, and southwards again to Pd-bearing grains. A grain of native silver was also recovered from the same area as the Ag-rich gold grains. This distribution pattern suggests that

zonation in grain types is present, reflecting differences in mineralisation at source. On the basis of the model put forward in Leake et al. (1991), to account for the history of grain growth, the Pd-rich zones may represent deposition under more oxidised conditions than the Pd-poor and Ag-rich zones. Almost all grains obtained from the south of the area are enriched in Ag rather than Pd, representing a regional signature. Dendritic grains seem to occur only in the north of the area, in a zone trending east-north-east to reach the east coast at Hope's Nose. The distribution of grains of pure gold seems to be more complex but further samples from the centre of the area are required to establish whether a pattern to their distribution exists.

The distribution of grains with penetrating Ag-enriched gold (Figure 20) seems largely to be confined to two general areas, one around Whympston and the other in the south of the area. These areas may have been the loci of a phase of stress induced corrosion of the grains (Leake et al. 1991). Grains with Ag-enriched gold in rims are also concentrated in the Whympston area (Figure 21) but in other respects their distribution differs from that of grains with Ag-enriched crack fills. Further material is required, particularly from the centre of the area, to establish the significance of this and whether a relationship between rim and core type is present.

There is also evidence that the distribution of gold grains containing selenide inclusions is regular. They only occur within relatively Ag-enriched gold, either in intragranular films or in overgrowths or in the body of grains with a high general Ag content. The largest selenide inclusions, which are always clausthalite (PbSe), occur in grains from the south of the area.

FOLLOW-UP OVERBURDEN SAMPLING

Detailed overburden sampling was carried out to try and trace the source of the large amplitude Au anomalies in drainage at Whympston and at Brownstone (Figure 1). Details of the work carried out at Whympston are available from BGS as a data package. Information on the work carried out at Brownstone is presented below. In addition, overburden sampling with a hand auger was carried out on a series of traverses, up to 9 km long, in the southern part of the area to supplement the drainage sampling. The data from this work are also included in this report. This work was augmented by limited further soil sampling and pit digging in areas of interest to obtain samples of sufficient volume for a meaningful estimate of Au content to be made.

Brownstone

Overburden sampling around the high amplitude precious metal anomaly to the south of Brownstone Farm was carried out in two stages. The locations of the sample sites are given in figure 23. The first stage comprised orthodox soil sampling with a hand auger, supplemented at selected sites with pit digging to obtain a bulk sample from the base of the hole, generally between 0.7 and 0.8 m deep. Comparison of the map of Rb contents for the depth range 0.5-1.0 m, in figure 23, with that of Rb at the 3-4 m depth reveals the location of the soil and pit samples. The pit samples comprised about 28 kg of overburden, which were then sieved to provide a minus 2 mm fraction and panned to constant volume (150 ml). At a latter stage precious metal grains were extracted by superpanner and gold concentrations estimated by a combination of weighing the extracted grains and chemical analysis of the residual concentrate. The second stage of overburden sampling was accomplished with a Minuteman power auger and reached a maximum depth of 7.3

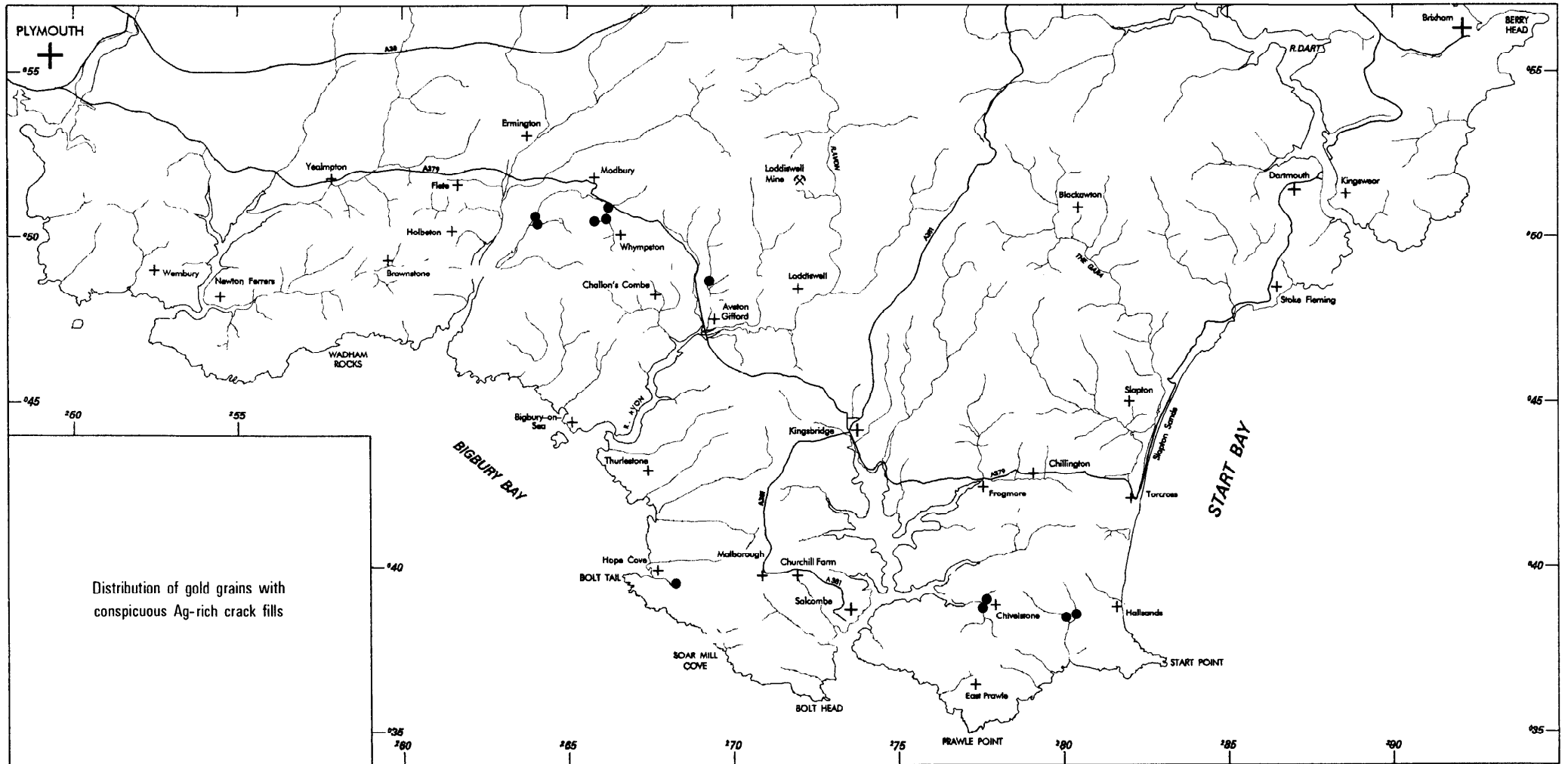


Figure 20 Distribution of gold grains with penetrating Ag-enriched gold.

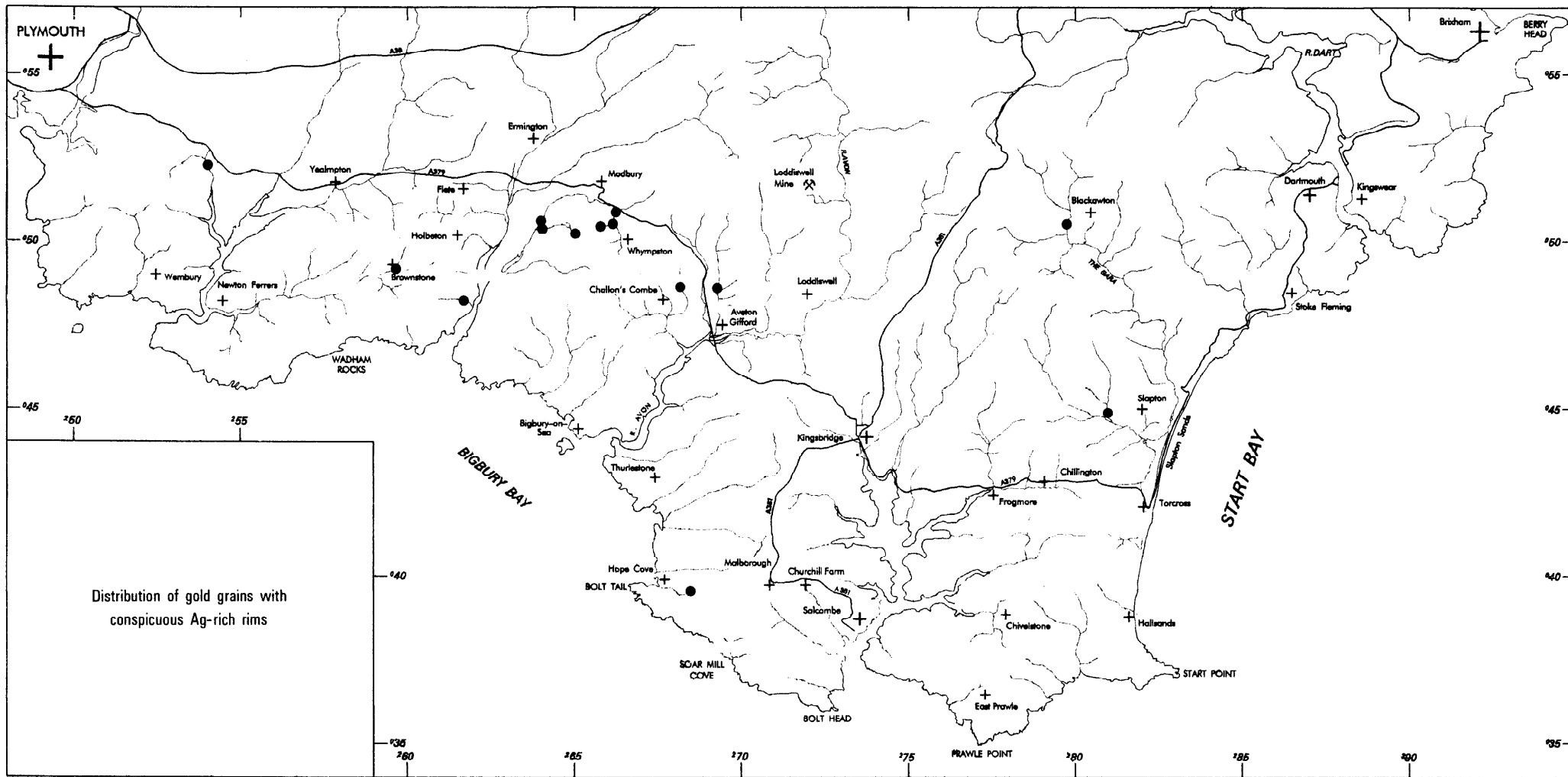


Figure 21 Distribution of gold grains with Ag-enriched overgrowth.

m. Several samples were usually obtained at various depths from each hole and panned to give a heavy mineral concentrate from which precious metal grains were also recovered after superpanning. Panning was carried to approximately the same degree as in the pit samples; because of the smaller amount of material recovered from the auger flight, this produced a concentrate weighing typically between 20 and 40 g. Elements determined in the overburden samples were selected from the range S, K, Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Zr, Sn, Ba, Pb, Au and Pd. Summary statistics of these data are given in Table 5.

Table 5 Summary statistics of chemistry of panned overburden samples from the Brownstone area

	N	Mean	S.D.	Min.	Max.
Depth m	225	3.00	1.77	0.60	7.30
S ppm	183	1530	5515	29	55630
K ₂ O%	183	2.97	1.21	0.55	5.56
TiO ₂ %	225	0.98	0.28	0.46	3.58
MnO%	225	0.10	0.26	<0.01	3.70
Fe ₂ O ₃ %	225	7.65	3.65	1.81	40.66
Ni ppm	225	46	22	<1	103
Cu ppm	225	66	261	<1	2375
Zn ppm	225	70	90	6	1180
As ppm	225	17	13	<1	89
Rb ppm	225	102	51	18	218
Zr ppm	225	337	236	145	2125
Sn ppm	225	72	157	<1	1389
Ba ppm	183	413	134	121	907
Pb ppm	225	16	26	2	345
Au ppb	223	682	3510	<1	32350
Pd ppb	72	21	130	2	1104

Compositional profiles of five holes are shown in Figure 22.

A great deal can be deduced about the controls of gold distribution from the geochemistry of the overburden samples and particularly from chemical variation in relation to depth. Closely following the main stream course is a zone, up to 50 m wide, in which exotic alluvial material is dominant in the uppermost overburden (above 1.8 m). Samples of this type are characterised by low concentrations of K, Fe, Ni, Rb, Ba and to a lesser extent Ti (which are, in contrast, relatively high in the argillaceous rocks underlying the area of the stream confluence at Brownstone), but relatively high concentrations of Zr and Sn. Holes 1, 4 and 38 (Figure 22) contain material of this type at the top. The extent of this zone can be illustrated by the comparison of Ni and Rb concentrations at different depths in Figure 23. A few of these near surface samples are rich in gold, but equally high concentrations of Au are present at greater depths, as in holes 1 and 15 (Figure 22). Below 2 m or less, most of the overburden samples in the south of the area have a similar chemistry and are derived from weathered bedrock rather than exotic overburden. In these samples, concentrations of most elements (K, Ti, Fe, Ni, Rb, Zr and Ba) are constant and do not change significantly with depth (holes 1, 15 and 16, Figure 22). In the north of the area, underlying bedrock is dominantly arenaceous and basal auger samples derived from this are relatively

depleted in K, Ti, Ni, Zn, Rb and Ba but enriched in Zr. The distribution of Ti suggests that a thin mafic volcanic unit may trend east-west through the area of the confluence.

A number of other features are superimposed on the bedrock geochemistry. At a few sites, concentrations of S are enhanced (Figure 24) due to the presence of pyrite, both as individual grains and as fine disseminations in fragments of country rock. In this respect the Brownstone area differs greatly from the Whympton area where, within the volcanic rocks, pyrite is not preserved above about 40 m of the present land surface. Associated with the pyrite-rich samples are elevated concentrations of Cu (Figure 24) and As (Figure 25). Correlation between As and S levels is relatively strong, suggesting that As is present within the pyrite. Agreement between Cu and S is much less strong, with high and low Cu types being distinguishable, probably reflecting the presence or absence of Cu-rich phases, of which chalcopyrite, chalcocite, malachite, cuprite and native Cu have been identified in the samples. Gold concentrations show no correlation with amounts of pyrite or Cu. The sulphide-rich samples occur on either side of the confluence, possibly continuing to the west along an east-west trending zone.

The two sites in the extreme west of the area contain anomalous concentrations of Pb and Zn in the basal samples. In these samples total S increases with Pb and Zn down the holes (hole 38, Figure 22). There is no evidence of an association of gold with the base metals in these samples.

At some sites there is evidence of enrichment of Mn and Fe, which may reflect hydrothermal introduction of these elements as carbonate minerals within veins. At the most anomalous site, several pieces of black manganese oxide were recovered. The distribution of Mn anomalies (Figure 24) suggests that both east-west and roughly north-south veining may exist in the area.

The concentration of Sn within the overburden samples (mean 72 ppm, maximum 1389 ppm) is much less than in the drainage samples from the same area (typically 5000-7500 ppm). Gold concentrations, on the other hand, are generally of similar magnitude in overburden and drainage samples. In several profiled holes the concentration of Sn reaches a maximum at around the 2 metre depth and then decreases below this. Gold shows some tendency to follow the same pattern (as in hole 4, Figure 22) but there are also anomalies from greater depths where Sn levels are relatively low (hole 1, Figure 22). Nevertheless most of the samples with anomalous Au contents are enriched in Sn above background levels. Both the Au and the Sn anomalies below 1m depth (Figures 25 and 26) tend to follow an east-west zone just to the north of the west-flowing tributary of the Brownstone stream and a zone just north of the main stream further to the west. In contrast, Au anomalies from north of the confluence are closely associated with the alluvium associated with the present stream course (Figure 26).

Gold anomalies occur in samples from all depths up to 5.4 m, but the presence of cassiterite in many of these samples suggests that heavy minerals, possibly of exotic origin, may have accumulated in cracks within weathered bedrock near surface. In 2 out of 18 holes, gold is accompanied by background concentrations of Sn and in the more anomalous of these, elevated Mn and Fe levels suggest that ankeritic carbonate veining may be present at the site.

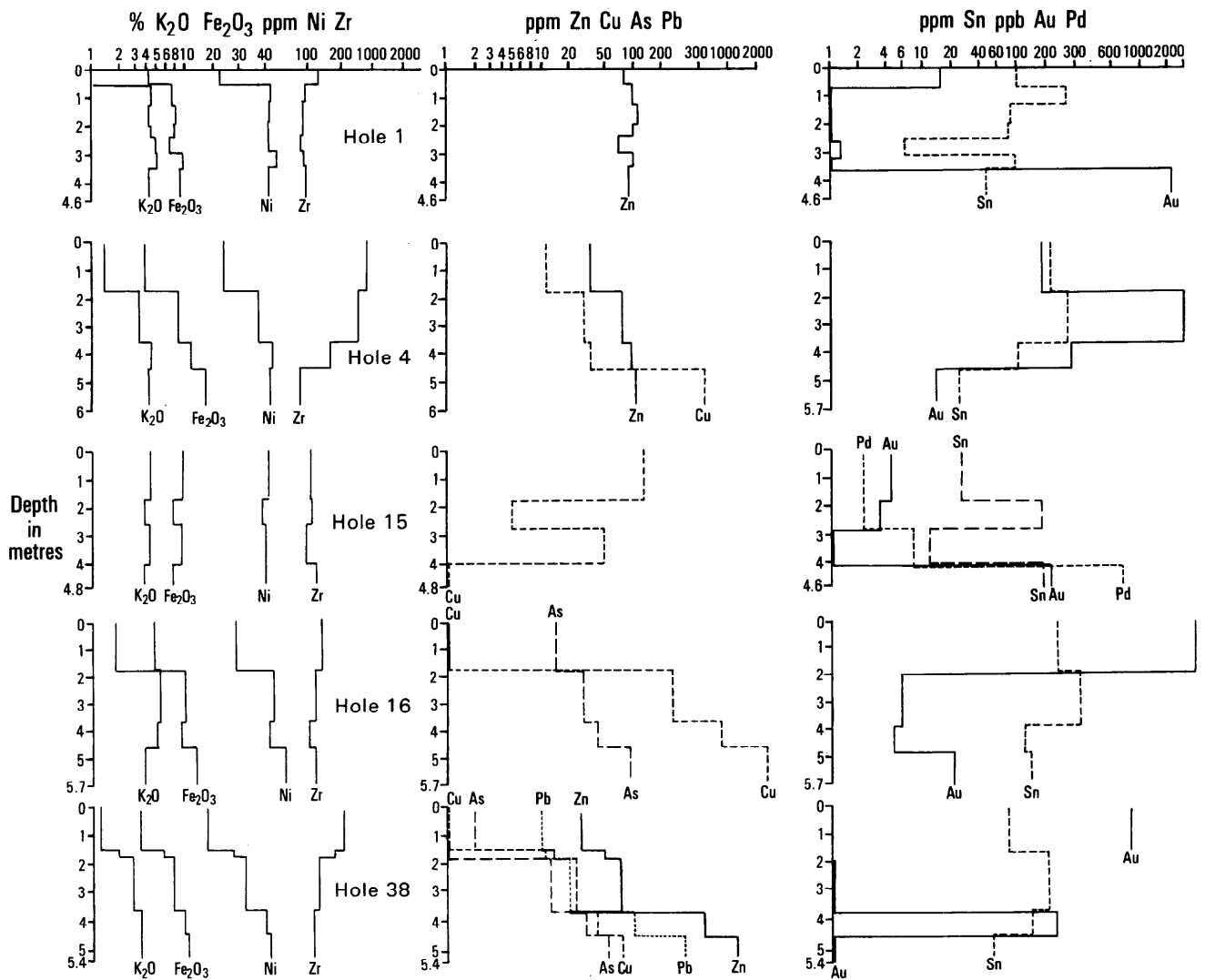


Figure 22 Profiles of K_2O , Fe_2O_3 , Ni, Zr, Zn, Cu, As, Pb, Sn, Au and Pd concentrations in panned overburden samples down four Minuteman holes, in the Brownstone area.

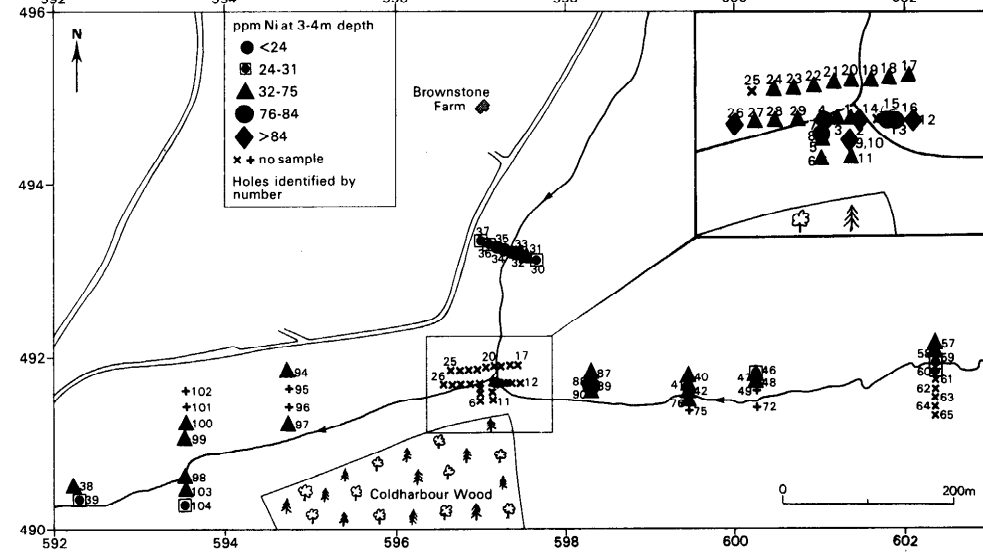
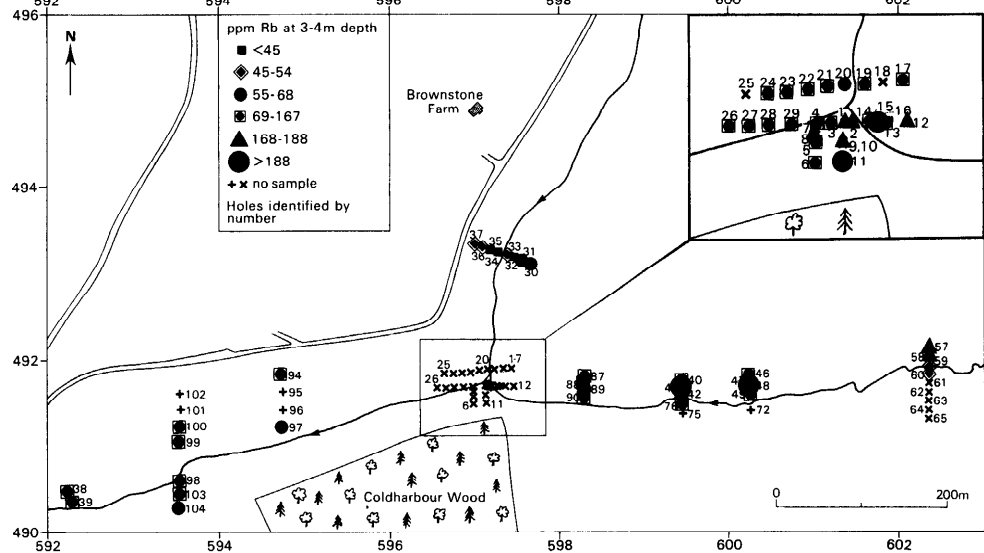
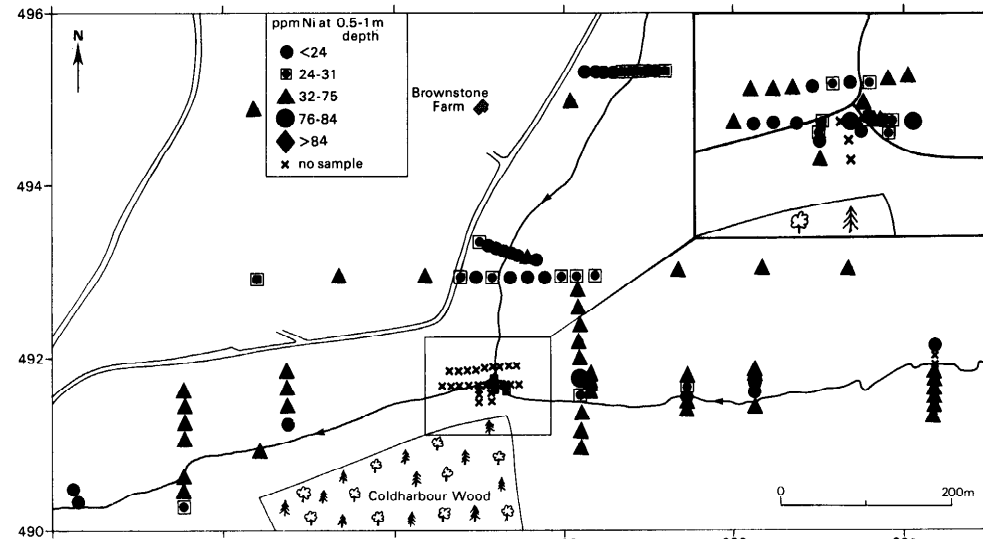
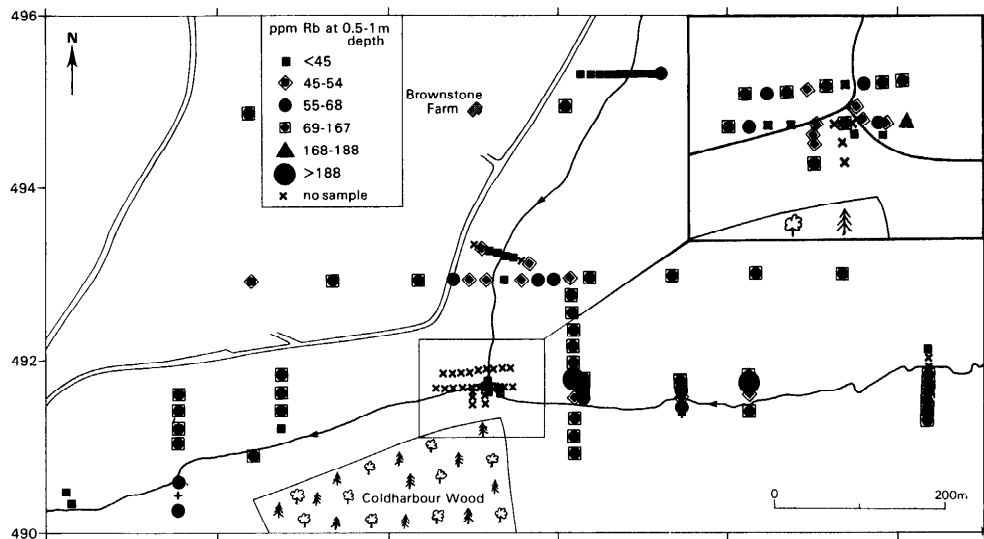


Figure 23 Distribution of Rb and Ni in panned near-surface overburden samples and in panned power auger samples from 3-4 m depth, in the Brownstone area.

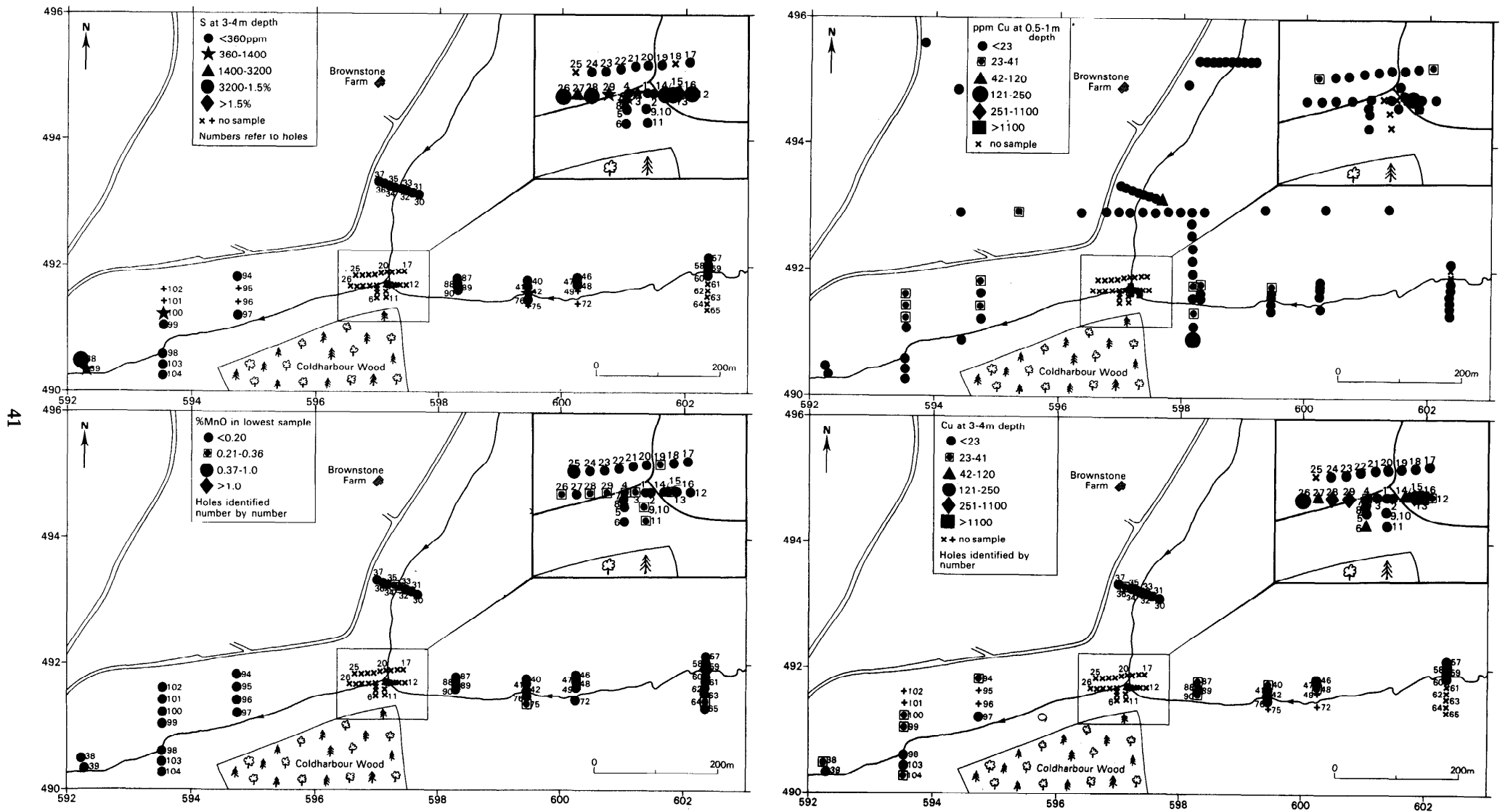


Figure 24 Distribution of S and Mn in panned power auger samples and of Cu in panned near-surface overburden samples and in panned power auger samples from 3-4 m depth, in the Brownstone area.

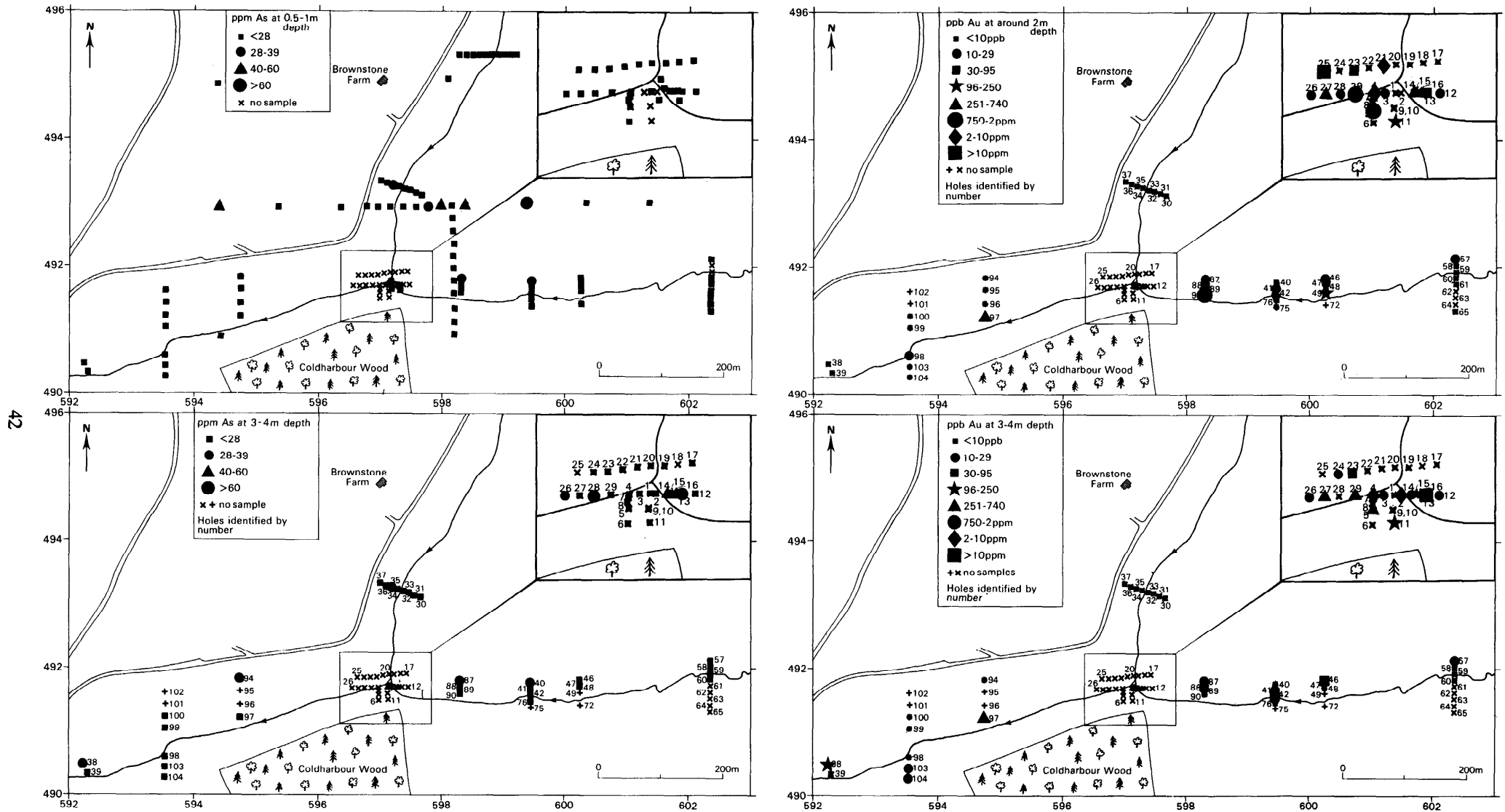
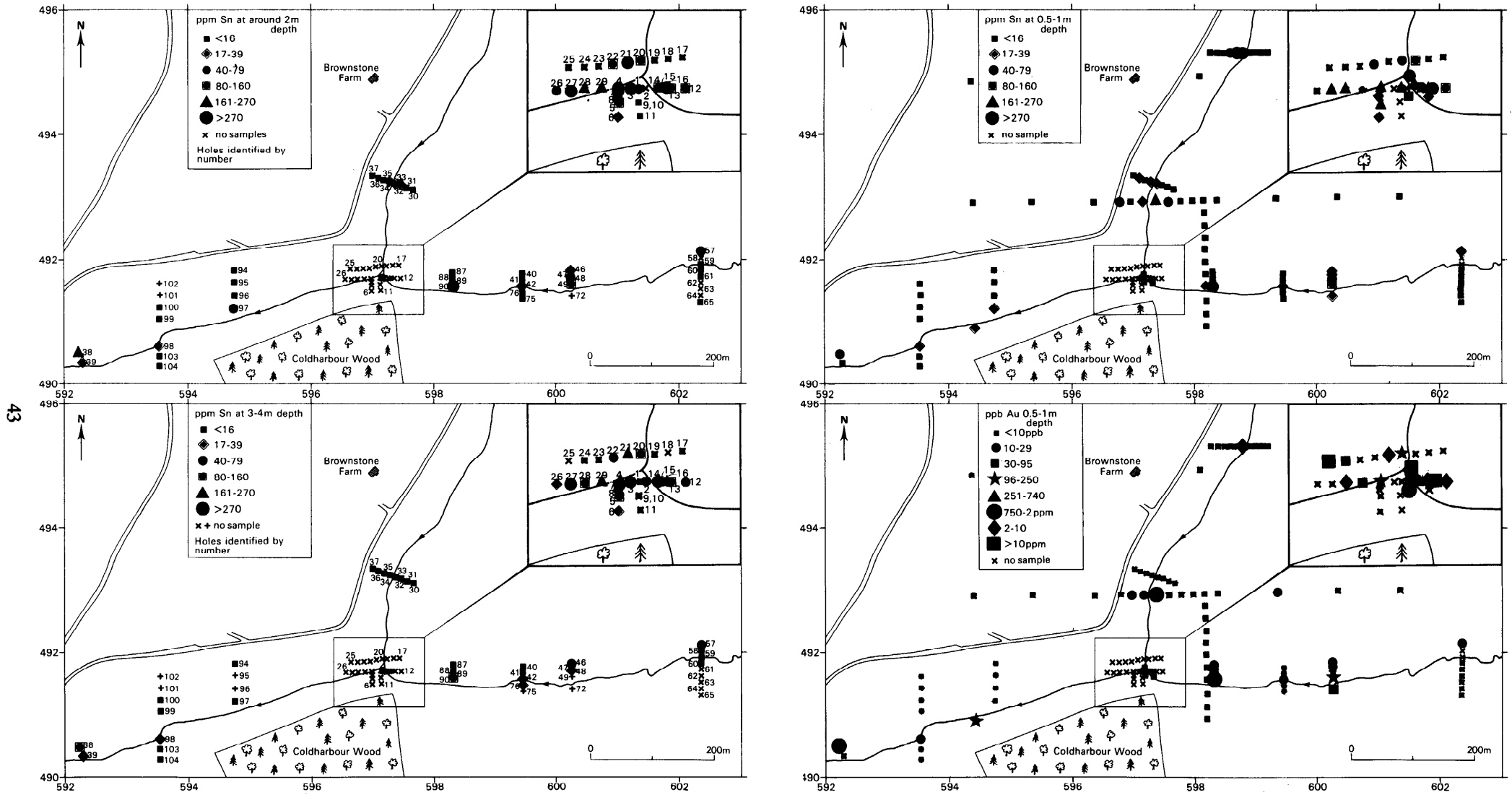


Figure 25 Distribution of As in panned near-surface overburden and panned power auger samples from 3-4 m depth and of Au in panned power auger samples from the Brownstone area.



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Figure 26 Distribution of Sn in panned power auger samples and of Sn and Au in panned near surface overburden samples, from the Brownstone area.

Flete

Two overburden traverses were sampled in the area to the west of Flete House [2627 0514], in the vicinity of two moderately high amplitude Au anomalies in drainage samples (Figure 27). Soil samples were obtained by hand auger from depths between 0.7 and 1.0 m, and at 8 sites pits were dug to around 1.0 m depth and bulk samples taken and panned as described above. A minus 80 mesh BSS (180 micrometre) fraction of the soil samples was analysed for Ti, Mn, Fe, Ni, Cu, Zn, Rb, Zr, As, Sn, Sb, Ba and Pb and the panned pit samples were analysed for these elements, together with S, W, Au, Hg and Bi. High Ti contents delineate a body of mafic volcanics (V on Figure 27), probably of Middle Devonian age, which appears to lens out towards the west. Three different units of sedimentary rocks can be recognised on the basis of differing concentrations of Ni, Zr and other elements and the probable boundaries of these are shown in Figure 27. The Fe contents are clearly enriched in soils derived from the volcanic rocks, but not uniformly. Several other elements are enriched in the soils derived from the volcanic unit, of which the most obvious is Sb (Figure 27). Antimony concentrations reach 71 ppm in the soils and 92 ppm in the panned pit samples, but there is only the slightest enrichment in Au associated with this volcanic unit. Arsenic does not show a correlation with Sb in these samples. The highest Au concentrations, representing only low amplitude anomalies, are associated with samples from near the stream, one of which is also slightly enriched in Sn. This may indicate an association of gold with an east-west zone, followed by the stream as in the case at Brownstone, but the drainage sample indicates that there must be other sources to the north of this.

East of Hope Cove (Hope Barton - Galmpton area)

Soil sampling was carried out on three parallel lines between Hope Barton and Galmpton, to the east of Hope Cove [2675 0397] (Figure 1). The area lies within the Start Complex, just to the south of the Start Boundary and, in view of the absence of a modern geological map of the area, a geochemical map has been produced on the basis of the Ti, V, Cr, Ni, Rb, Sr, Zr and Ba contents of the soil samples. One of the lines crosses the Start Boundary which is clearly delineated by variation in the soil geochemistry. Five units have been recognised to the south of this. Immediately south of the Start Boundary is a unit (A in Figure 28) consisting mostly, if not entirely, of sedimentary rock chemically similar, in some respects, to the rocks north of the Start Boundary. South of this is another sedimentary sequence (B in Figure 28) containing one well-defined mafic volcanic unit and, further south, a mixed volcanic/sedimentary sequence (C in Figure 28). Soil samples derived from the mafic volcanic unit are enriched in Ti to a maximum of 1.7% TiO₂. South of the presumed fault is a unit (D in Figure 28) chemically similar to C, and probably representing mixed volcanics and sedimentary rocks. In the south of the area another sedimentary unit can be recognised (E in Figure 28).

Base metal anomalies (Ni, Cu and Zn) are shown in Figures 28 and 29. They are of low amplitude and lie mostly to the north of the presumed fault. Concentrations of Pb in the soils are low, with only three samples containing > 60 ppm, two of which are from north of the Start Boundary. Samples at the north end of the short soil line to the west of Hope Barton are richest in base metals (maximum 162 ppm Ni, 197 ppm Cu, 179 ppm Zn and 46 ppm Pb). The same samples are also enriched in Mn, Fe, As and Sb (maximum 1.09% Mn, 12.4% Fe, 203 ppm As and 17 ppm Sb). However, gold is not enriched in the corresponding panned pit samples. The sites of anomalies of possible gold pathfinder elements (Fe, As and Sb) are also shown in Figures 28 and 29. Iron is

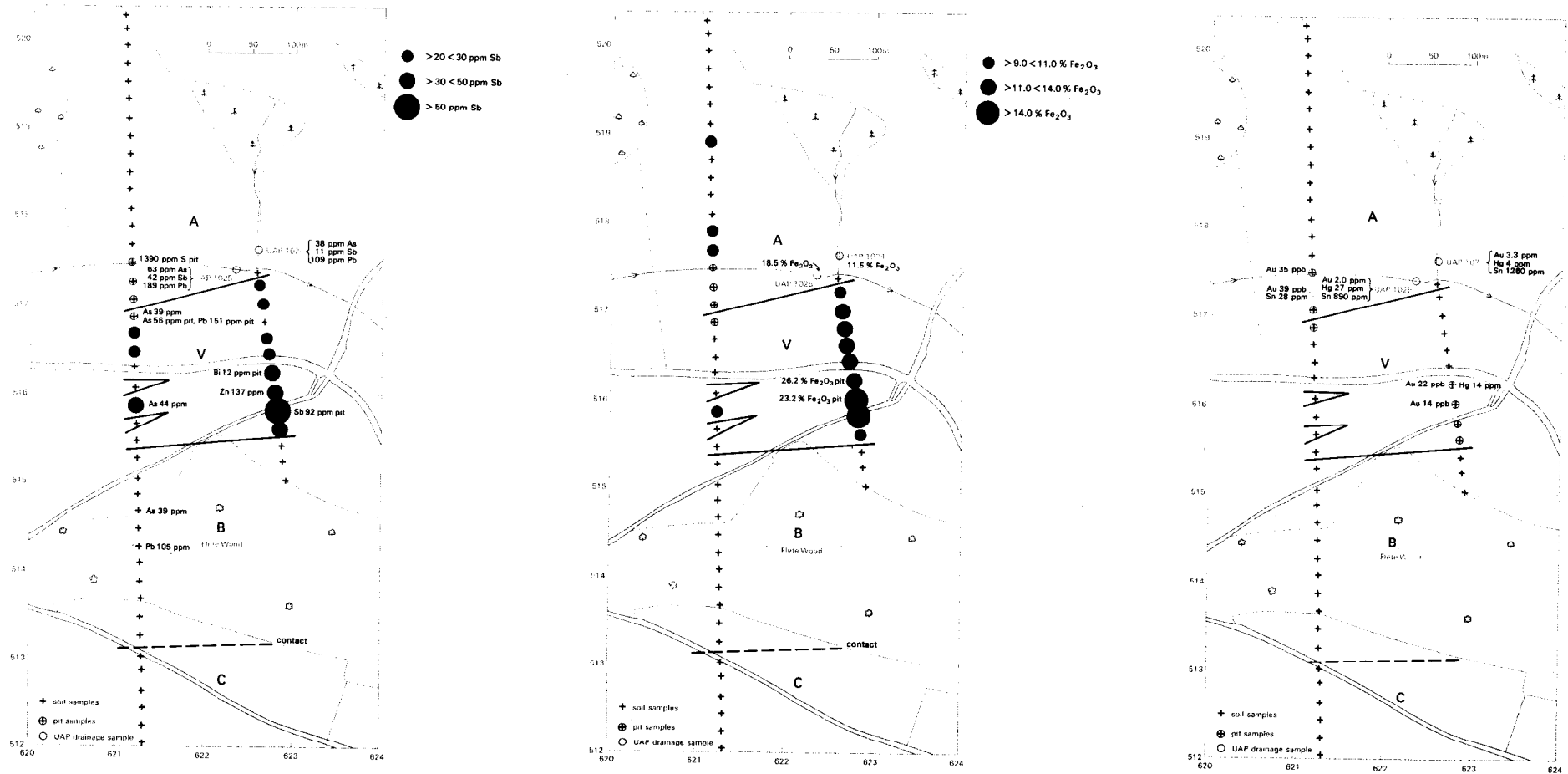


Figure 27 Distribution of Sb, As, Pb, Zn, Bi, S, Fe, Sn and Hg anomalies in overburden and panned pit samples and of panned pit samples with detectable (>10 ppb) Au contents in the area to the west of Flete House. Concentration of Au, Sn and Hg in nearby panned drainage samples also shown.

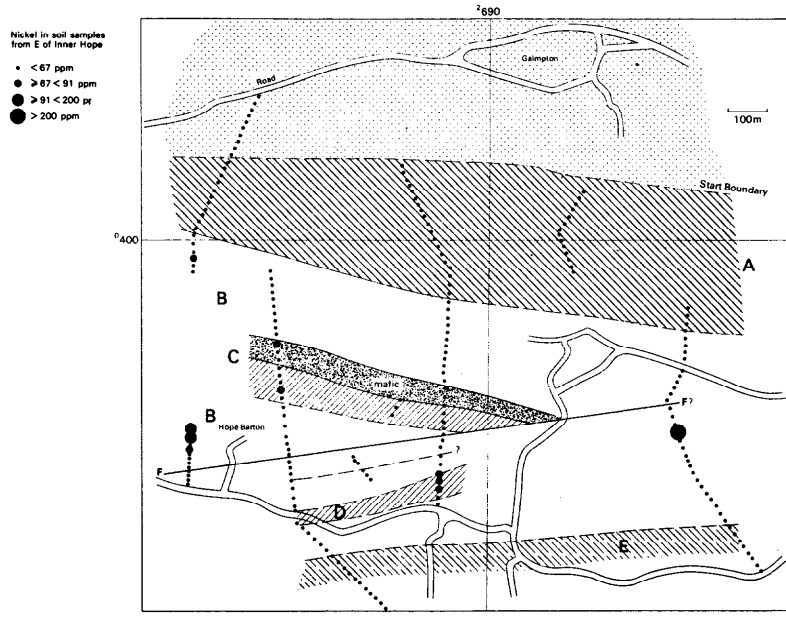
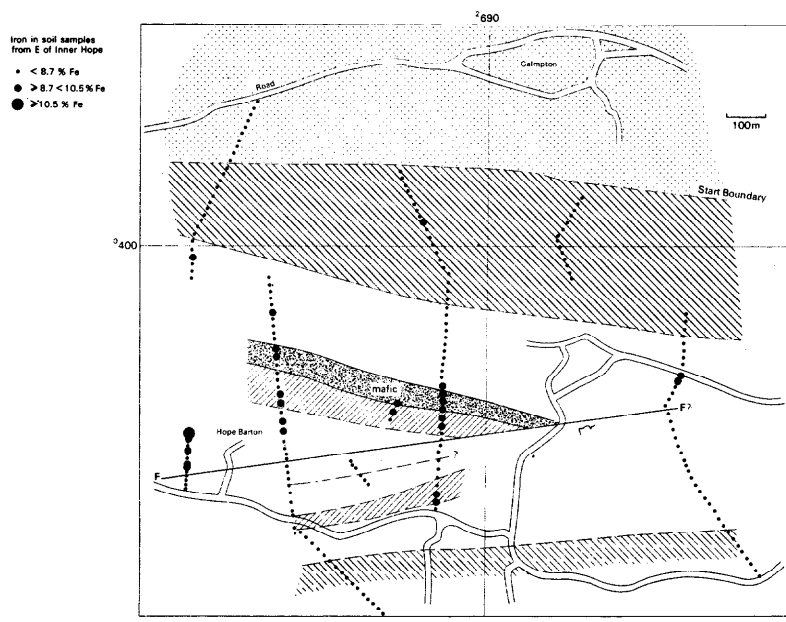
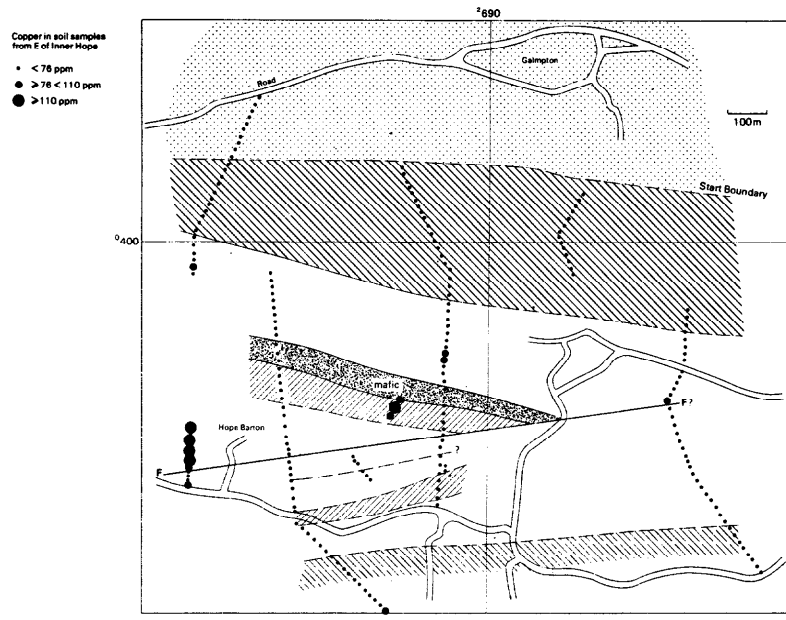


Figure 28 Distribution of Ni, Cu and Fe in soil samples from the Hope Barton area to the east of Inner Hope.



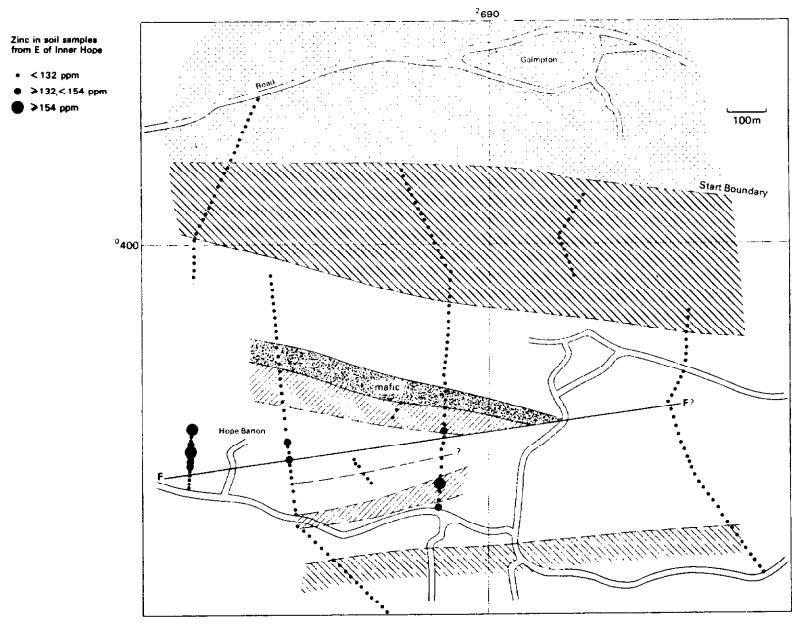
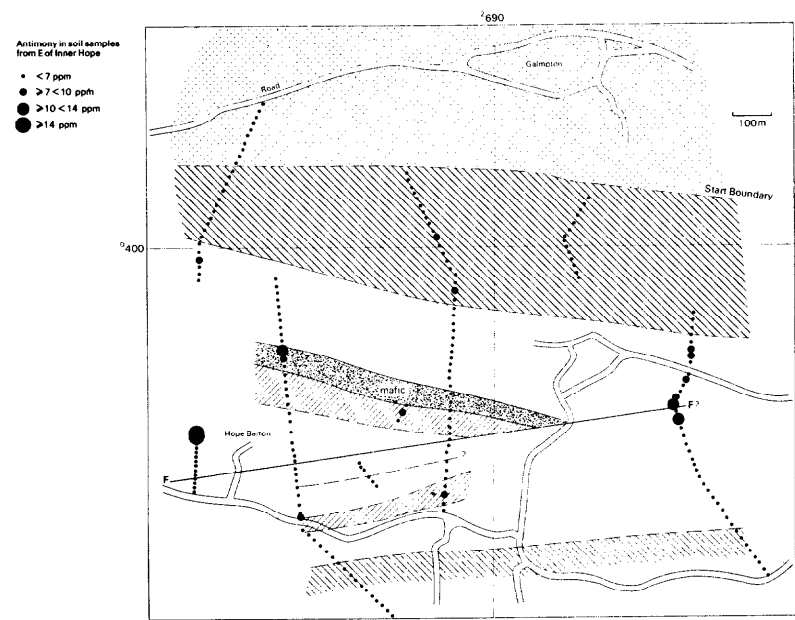
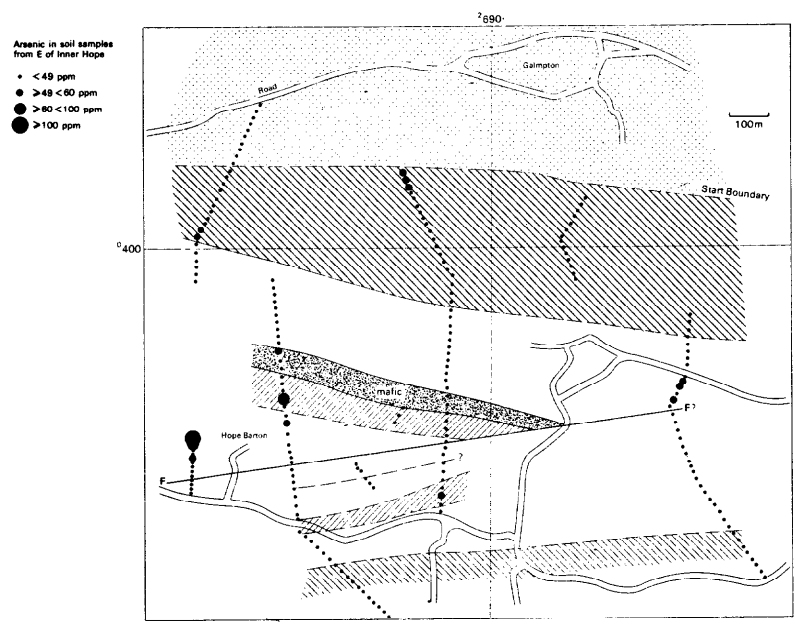


Figure 29 Distribution of Zn, As and Sb in soil samples from the Hope Barton area, to the east of Inner Hope.



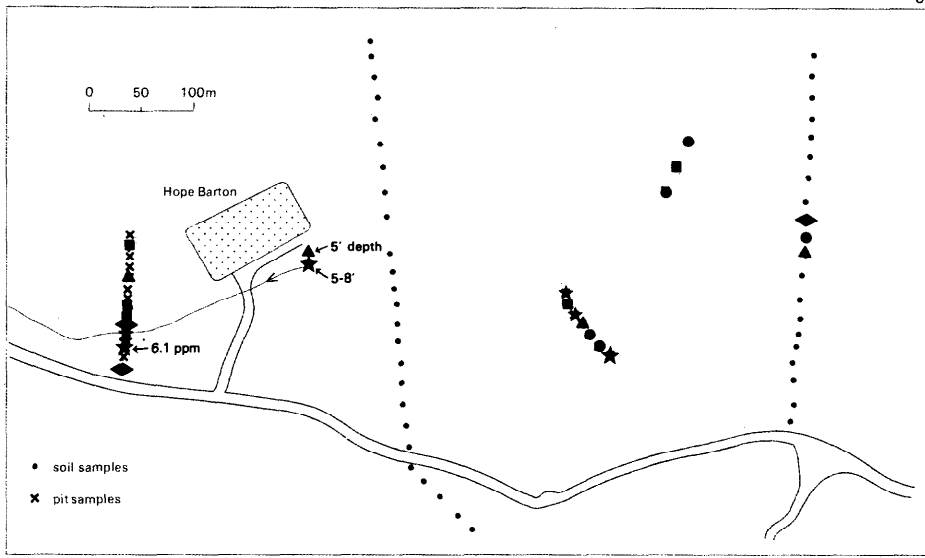
most concentrated in samples derived from the volcanic rocks and also in the region to the north of the presumed fault. As and Sb are also relatively enriched in some of the samples derived from the mafic volcanic unit and around the presumed fault in the east of the area.

Gold concentrations have been determined in 27 panned pit samples as shown in Figure 30. The gold is confined to a broad zone parallel to the presumed fault, within which the present stream flows. Overburden is deep in the centre of the valley, where excavations to produce a pond went down to about 2.5 m, but Au is also enriched in some samples on the south side of the valley where overburden is relatively thin. The Na content of these samples is also slightly enriched (Figure 30), possibly due to some degree of albitisation. Elevated concentrations of Sn (Figure 30) follow more closely the valley floor and thicker overburden, while base metal anomalies in pit samples (Figure 30), show no clear correlation with Au abundance. The general mode of occurrence of gold seems similar to the situation at Brownstone, described above. However, the internal composition of the gold differs from typical Brownstone material in the general absence of Pd but enrichment in Ag and the occurrence of relatively abundant and large selenide inclusions (Leake et al., 1991).

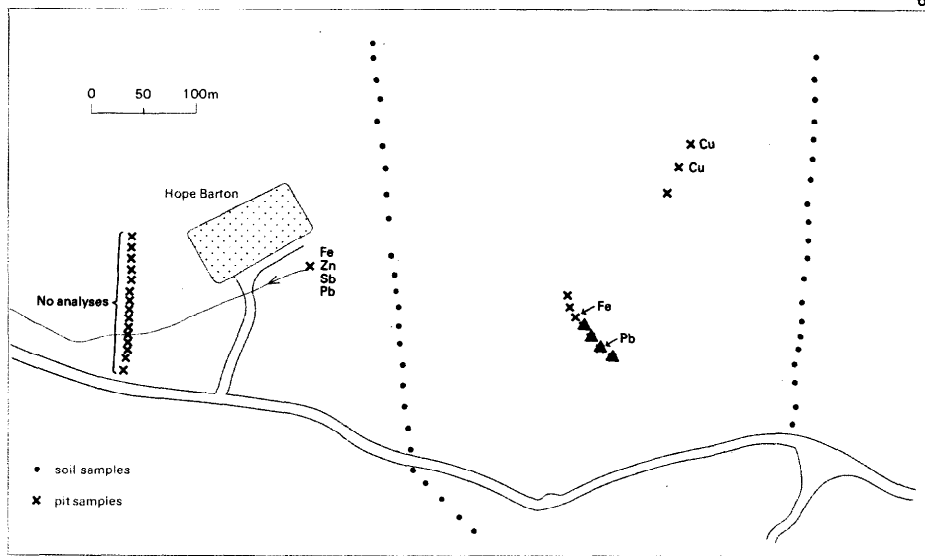
Churchill Farm

Soil samples from a reconnaissance traverse stretching from south-west of Salcombe (Figure 1), north for over 3 km across the Start Boundary, were analysed for base metals and a group of possible gold pathfinder elements. Geochemical mapping using Ti, V, Cr, Ni, Rb, Sr, Zr and Ba allowed several units to be distinguished over part of this line (Figure 31). These comprise a mafic volcanic unit (A, Figure 31), units consisting of mixed volcanic and sedimentary rocks (B, Figure 31), another unit of probable volcanic rock compositionally different from A (D, Figure 31), surrounded by mixed volcanic and sedimentary units (C, Figure 31) and a transitional unit (E, Figure 31). The volcanic unit A, which is also exposed in a new road cut at Churchill Farm, differs chemically from the unit north of Hope Barton (Figure 28), in having considerably lower Ni and Cr concentrations. In view of its evolved composition, compared with typical Start Complex igneous rocks, it is interpreted as belonging to a structural unit separate from the Start Complex *sensu stricto* (Leake et al., 1991). The boundary between this unit and the Start Complex is possibly within unit E. The identification of unit D is less certain; Cr and Ni concentrations are similar to those derived from the volcanic unit at Hope Barton, but Ti levels are considerably lower. Unit C may be displaced to the south by a fault trending north-west up the valley followed by the road. This would account for its occurrence north of Combe.

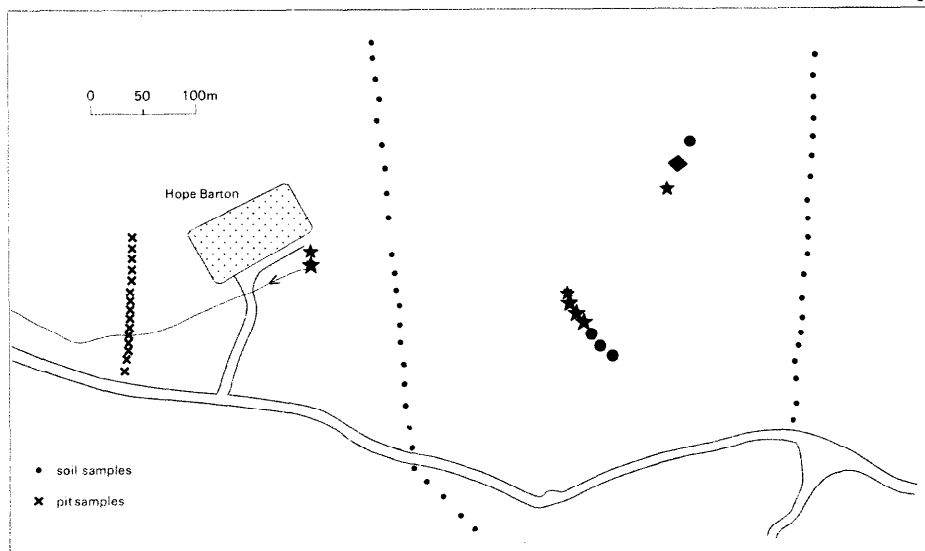
Soil samples with anomalous concentrations of Mn, Fe, Ni, Cu, Zn, As, Sb and Ba are identified in Figures 31 and 32. Most are from the area to the south of the Start Boundary, around Churchill Farm where there are anomalies of Mn, Fe, Cu, and especially Ba, As and Sb. The Cu, As and Ba anomalies extend further south than anomalies of other elements and there are also two further discrete zones of Sb anomalies, but the highest amplitude anomalies occur around Churchill Farm. Accordingly, panned pit samples were taken from this area to establish if any gold was associated with the other metal anomalies. In addition, rock samples were taken systematically from the base of a new entrance road cutting to the farm which crosses much of the area of interest.



- Gold in panned pit samples
- × < 10 ppb
 - ≥ 10 < 20 ppb
 - ≥ 20 < 110 ppb
 - ▲ ≥ 110 < 450 ppb
 - ◆ ≥ 450 < 1000 ppb (1 ppm)
 - ★ > 1 ppm < 2 ppm
 - ★ > 2 ppm
 - soil samples



- Base metal anomalies in panned pit samples
- ▲ > 3.4% Na₂O
 - Soil samples



- Tin in panned pit samples
- × not determined
 - ≤ 20 ppm
 - ◆ > 20 ≤ 40 ppm
 - ★ > 40 ≤ 80 ppm
 - ★ > 80 ppm
 - soil samples

Figure 30 Distribution of Au, Sn, Na and base-metal anomalies in panned pit samples from the Hope Barton area.

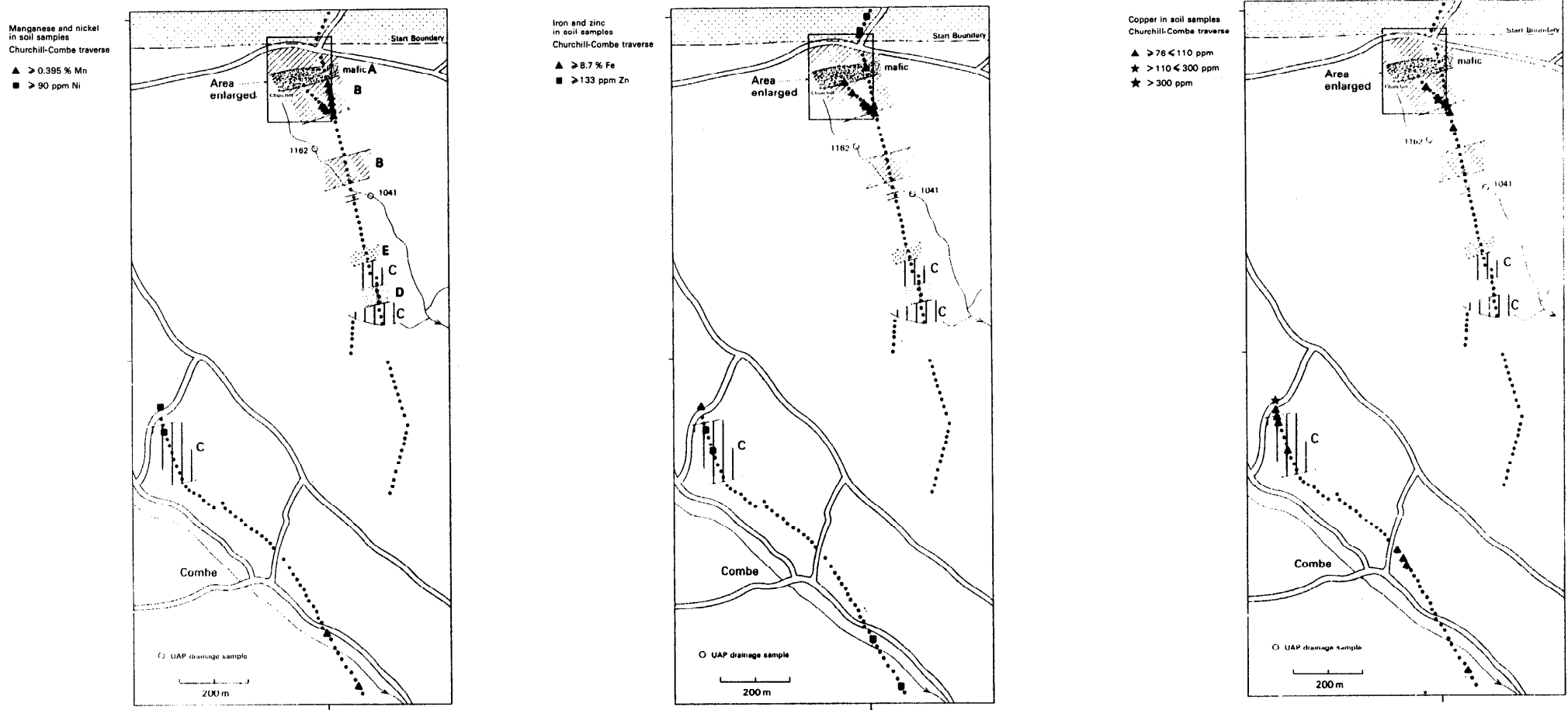


Figure 31 Distribution of Mn, Ni, Fe, Zn and Cu anomalies in soil samples from the Churchill and Combe traverses, between Salcombe and Malborough.

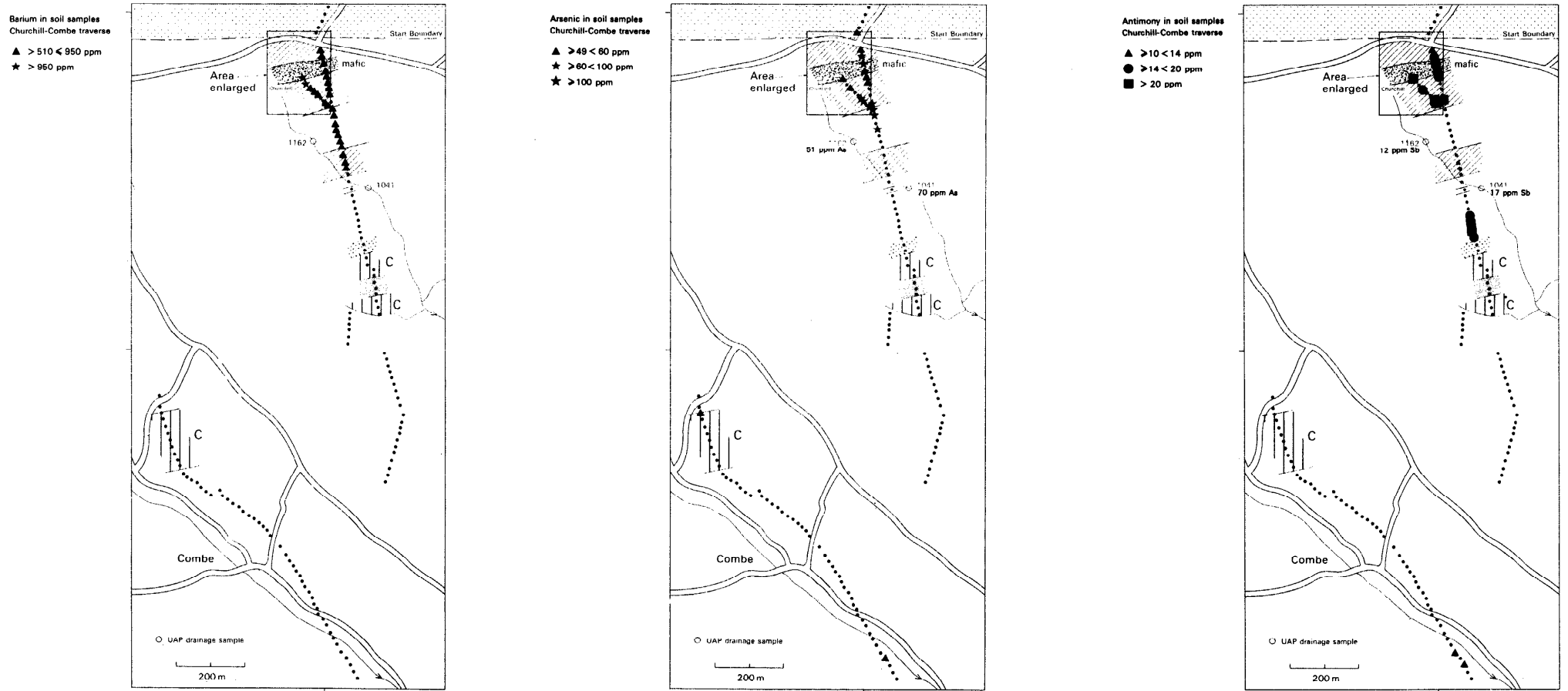


Figure 32 Distribution of Ba, As and Sb anomalies in soil samples from the Churchill and Combe traverses, between Salcombe and Malborough.

Rock samples from the cutting confirmed the soil geochemistry interpretation which indicated the presence of a mafic volcanic horizon around Churchill Farm, but showed this to consist of one unit about 30 m wide with several much thinner, but geochemically similar, horizons further to the north. The volcanic units differ chemically from the typical MORB-like Start igneous material, being relatively enriched in P and Ti, as shown in Figure 3 and in Y (29-65 ppm), Zr(143-233 ppm) and to a lesser extent in Nb (5-16ppm). The volcanic rocks are schistose and interlayered with grey micaceous schist. Three rocks from the traverse appear to have suffered some dolomitic alteration, as concentrations of Mg and Ca are much higher than in any of the other rocks.

The sites of anomalous concentrations of Au, Na, Fe, Cu, As, Sb, and Ba in both rock and panned pit samples are shown in Figures 33 and 34. Significant amounts of Au (> 290 ppb) occur in three panned pit samples, with a maximum concentration of 710 ppb. Concentrations of Au found in the analysed rock samples are much lower (maximum 31 ppb), but there is evidence for some spatial association of anomalies in each sample type (Figure 33). Concentrations of many of the other elements provide evidence that the area has been subjected to significant hydrothermal activity. Thus, both rock and panned pit samples suggest that there are areas where rocks have been albitised (maximum Na₂O, 5.64% rock, 5.65% panned pit). Similarly, high concentrations of Ba (Figure 33) in both sample types (maximum Ba 3900 ppm rock, 2000 ppm panned pit) indicate that K-feldspar alteration or possibly baryte is also present, though not exactly in the same areas as albitisation. Enrichments in As and Sb also occur in both sample types, often, but not always, in the same areas (Figures 33 and 34). Concentrations of As and Sb reach 160 ppm and 48 ppm respectively in rock, and 190 and 29 ppm respectively in panned pit samples. As and Sb-rich samples are often enriched in Ba, but the highest Ba concentrations are without corresponding enrichment in As or Sb.

A prominent zone of Fe enrichment occurs in the pits sampled immediately to the east of the farm buildings (Figure 34), coinciding approximately with a area of As and Sb anomalies. Manganese is highly enriched (3.59% MnO) in only one panned pit sample from the south of the area, but there are also small amplitude enrichments in the north of the area. Copper shows some correlation with As and is also most enriched (maximum 152 ppm in rock) in the north of the area (Figure 34). The greatest concentration of Cu in the panned pits (330 ppm) is in the south of the area where it is associated with an albite-rich sample. Concentrations of Zn and Pb are relatively low and there are only isolated anomalies in each sample type. Ag is enriched in the zone of high Fe in soil.

Though concentrations of Sn in rock are very low, four panned pit samples contain more of this element (maximum 88 ppm) than would be expected from superficial material derived by simple weathering of underlying rock. This suggests that pockets enriched in heavy minerals may occur within the overburden and this factor may account for two of the Au anomalies in the panned pit samples, which are also enriched in Sn.

The geochemistry of the weathered rock collected from the road cut at Churchill Farm is similar in many respects to that of mineralised material from Wadham Rocks, described above. Allowing for differences in country rock in both areas, there are rocks showing similar degrees of enrichment in Na, K+Ba, Mg+Ca, Cu, As, Sb and Au. Arsenic concentrations are very similar in the two areas, but at Churchill levels of Cu, Sb and Au do not reach the highest values found at Wadham Rocks, although Ba concentrations at Churchill are higher there is a general absence of enrichments in Pb and Zn. The chemical signature suggests that the samples from Churchill reflect similar

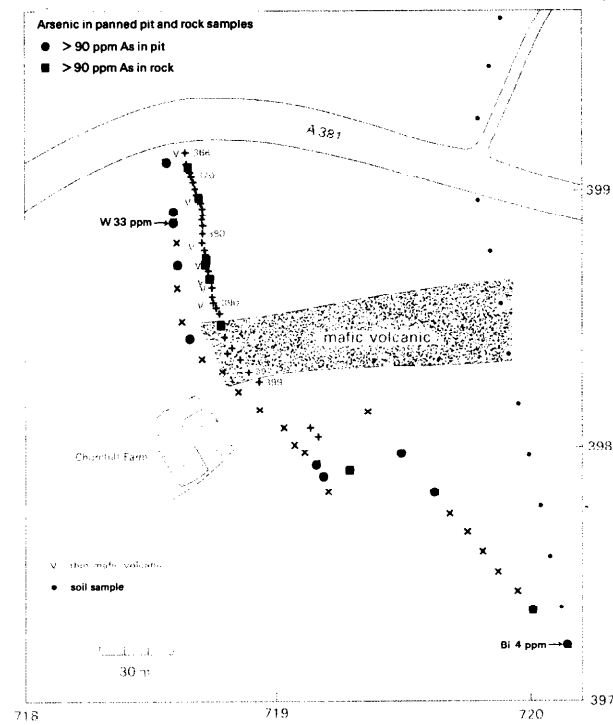
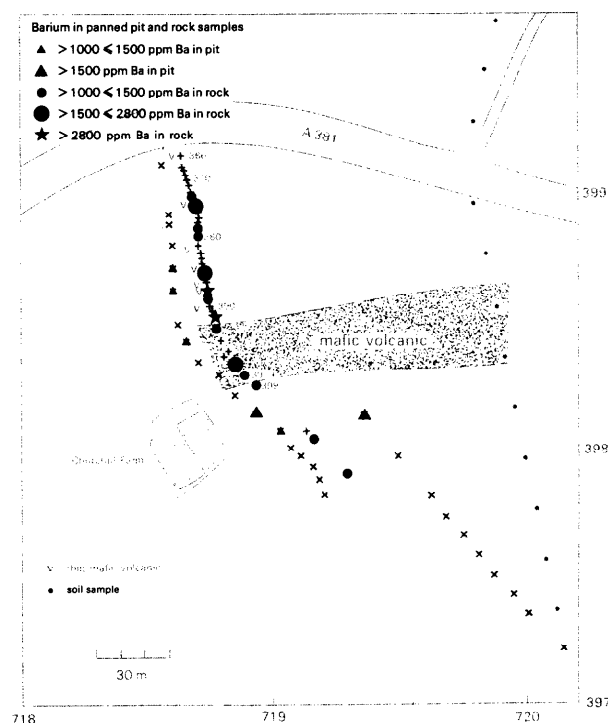
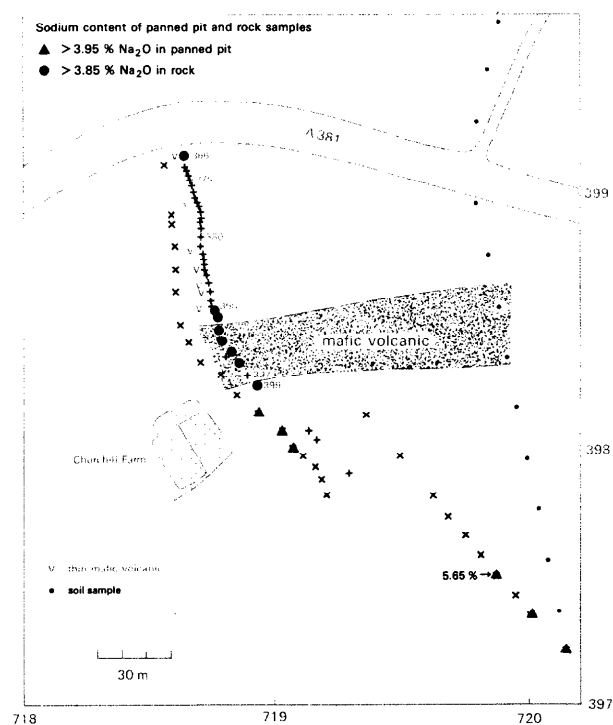
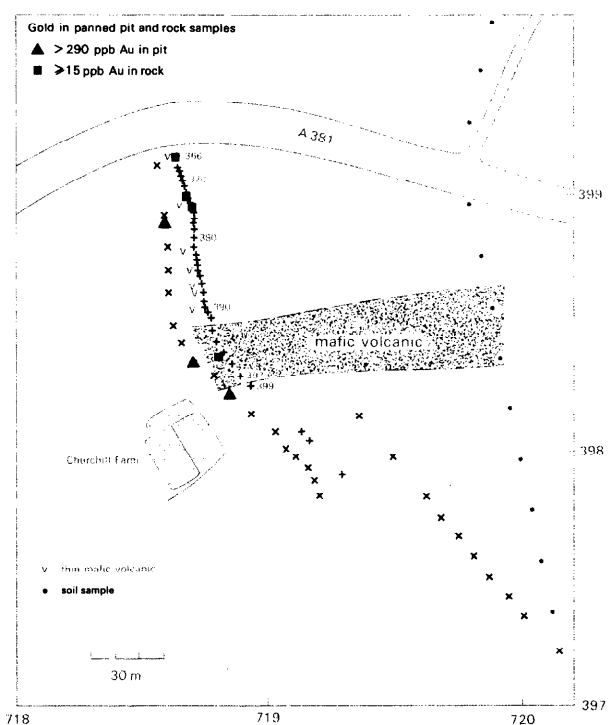


Figure 33 Distribution of Au, Na, Ba and As anomalies in panned pit and rock samples from the vicinity of the Churchill Farm.

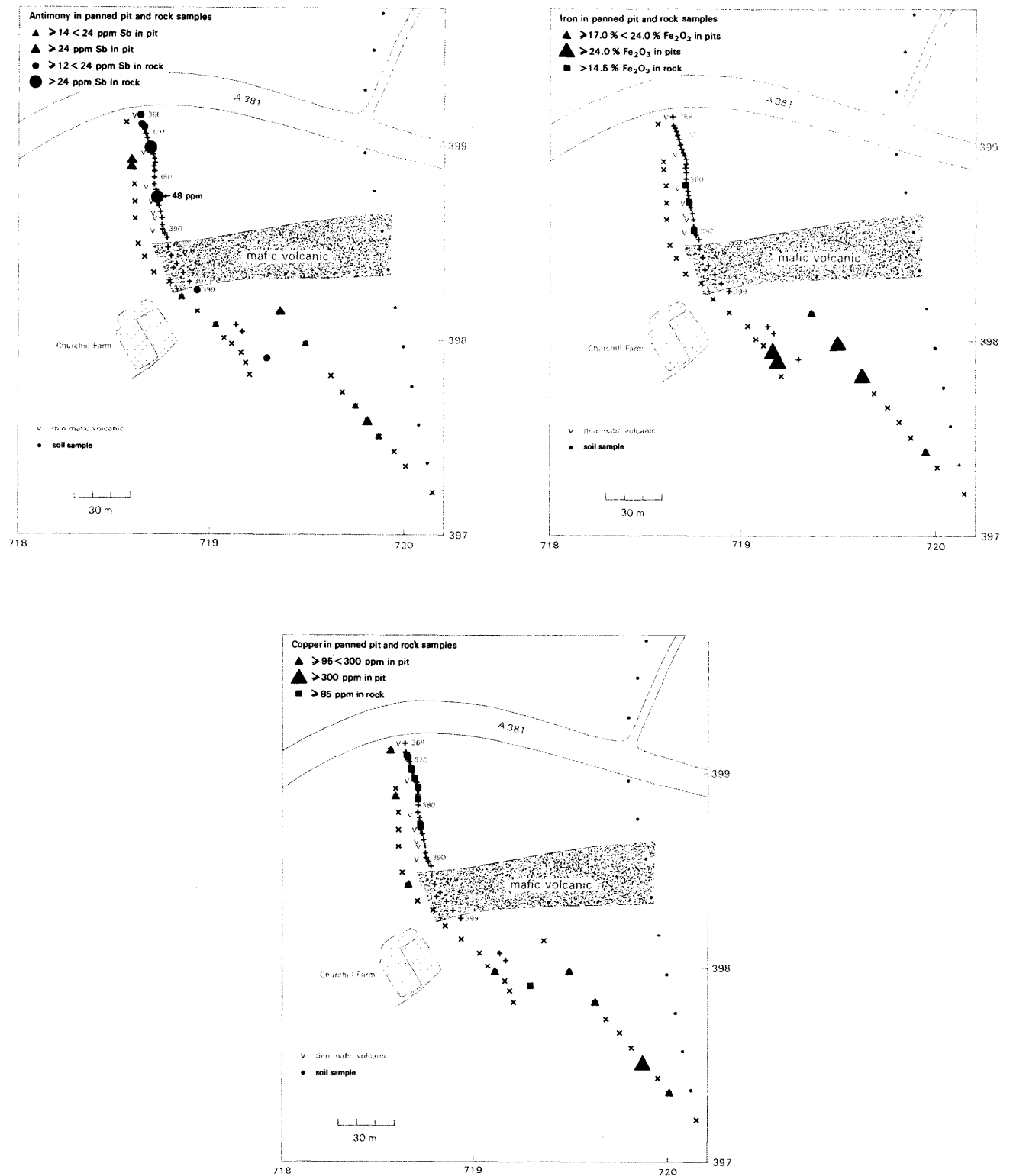


Figure 34 Distribution of Sb, Fe and Cu anomalies in panned pit and rock samples from the vicinity of Churchill Farm.

mineralisation to that observed in coastal exposure near Wadham Rocks, though perhaps at a different depth and/or intensity of hydrothermal activity. Further rock sampling in the Churchill area by means of trenching and/or drilling is required to investigate any zonation of mineralisation intensity along strike or with depth. However, the evidence of the limited sampling carried out in the area suggests that it is the site of a significant amount of hydrothermal activity.

East Prawle

A 9 km reconnaissance soil traverse was sampled northwards from the coast to the east of Prawle Point (Figure 1). Figure 35 shows the locations of anomalous concentrations of Cu, Zn, Ag, Ba and Pb in soil samples around the village of East Prawle. All of the area is within the Start Complex *sensu stricto*. Base metal anomalies are isolated and of low amplitude, as are enrichments in Ba, except in the north of the area. Concentrations of both As and Sb are low. Limited pit sampling was carried out in the areas of base metal anomalies and samples were analysed for Au and other elements. A significant concentration of Au was found only in two adjacent samples in the south of the area (Figure 35), possibly derived from an east-west structure at the base of a strong feature. One sample, derived from head at the source of the stream, contains some Sn but no Au.

Chivelstone

Around Chivelstone (Figure 1) the mid section of the 9 km long reconnaissance traverse was augmented by a another soil traverse about 1.5 km long, roughly 500m further east. Consideration of concentrations of Ti, V, Cr, Ni, Rb, Sr, Y and Zr in the soil samples allows three major contacts to be delineated. The Start Boundary can be recognised in the north of the area, south of which is a unit containing a significant amount of mafic volcanic rock. This unit can probably be correlated with volcanic unit B around Churchill Farm, and within it are units composed almost entirely of volcanic material, equivalent to unit A at Churchill. In the south of the area, a further unit can be recognised which can, with less certainty, be correlated with unit C to the south of Churchill.

Sites with anomalous concentrations of Mn, Fe, Cu, As, Sb, Ba and Pb in soil samples are shown in Figures 36-38, along with anomalies in drainage samples from the area. Six anomalous zones can be recognised across the area from north to south. Broad anomalies of As and Pb occur to the north of the Start Boundary, while Sb anomalies and isolated Mn and Fe enrichments are associated with the volcanic unit. A separate zone towards the south of the volcanic unit is marked by low amplitude Cu anomalies and an absence of Sb. South of the volcanic unit is a zone of As and Ba anomalies, with associated Sb in the east. Near Chivelstone is a well-defined anomalous zone enriched in As and Sb while in the south of the area is a zone of low amplitude Ba and Pb anomalies.

Pit sampling was carried out in all of the anomalous zones described above to establish whether gold was associated with any anomaly type. Pit samples were analysed for Au and a range of other elements as described above. Sites with anomalous concentrations of Au, Mg, Si, Mn, Cu, As, Sn, Sb and Pb are shown in Figures 38 to 40. Low to moderate amplitude Au anomalies are widespread (Figure 38), some in the vicinity of drainage anomalies. At some of the sites, Sn and/or Si (Figure 39) are also enriched, suggesting some general concentration of heavy minerals and/or detrital quartz in alluvial sediment, close to the streams, as to the west of Chivelstone. However, Au anomalies in samples upslope and south of these, without associated Sn, suggest a

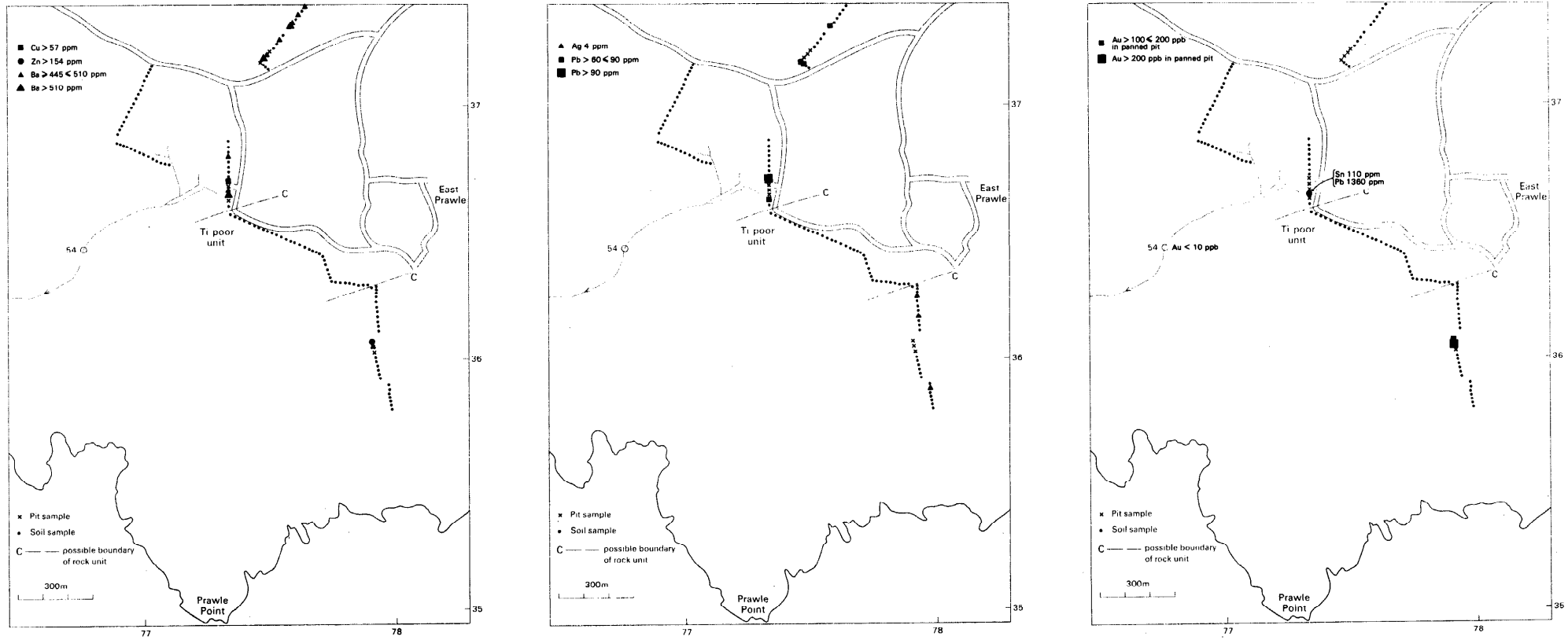
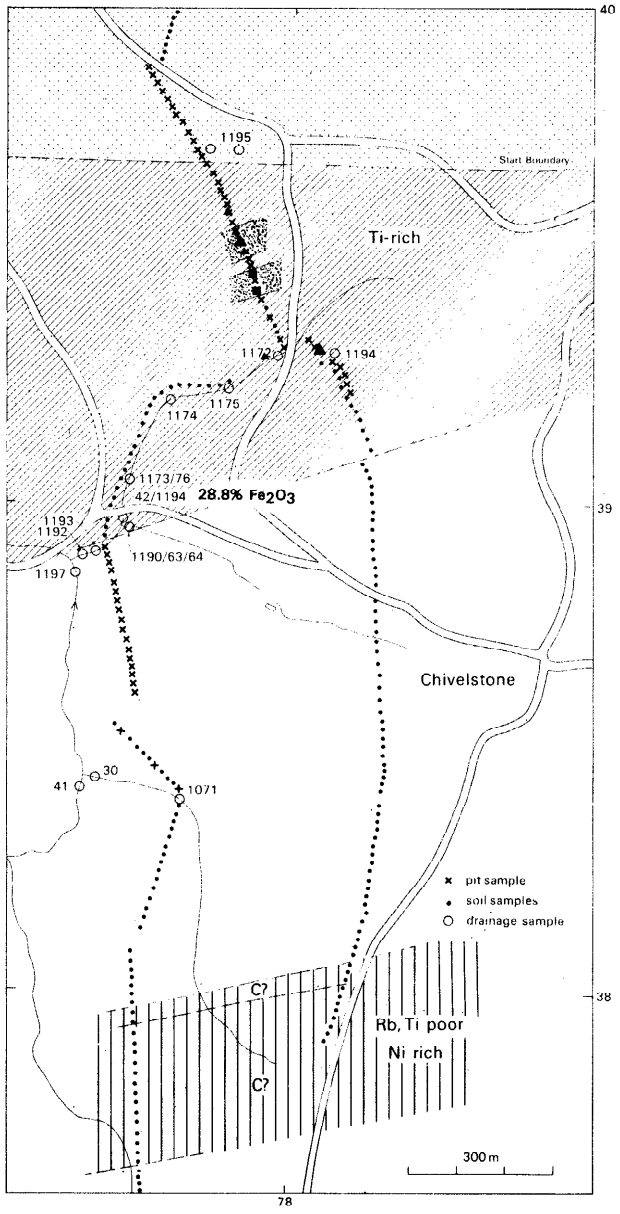
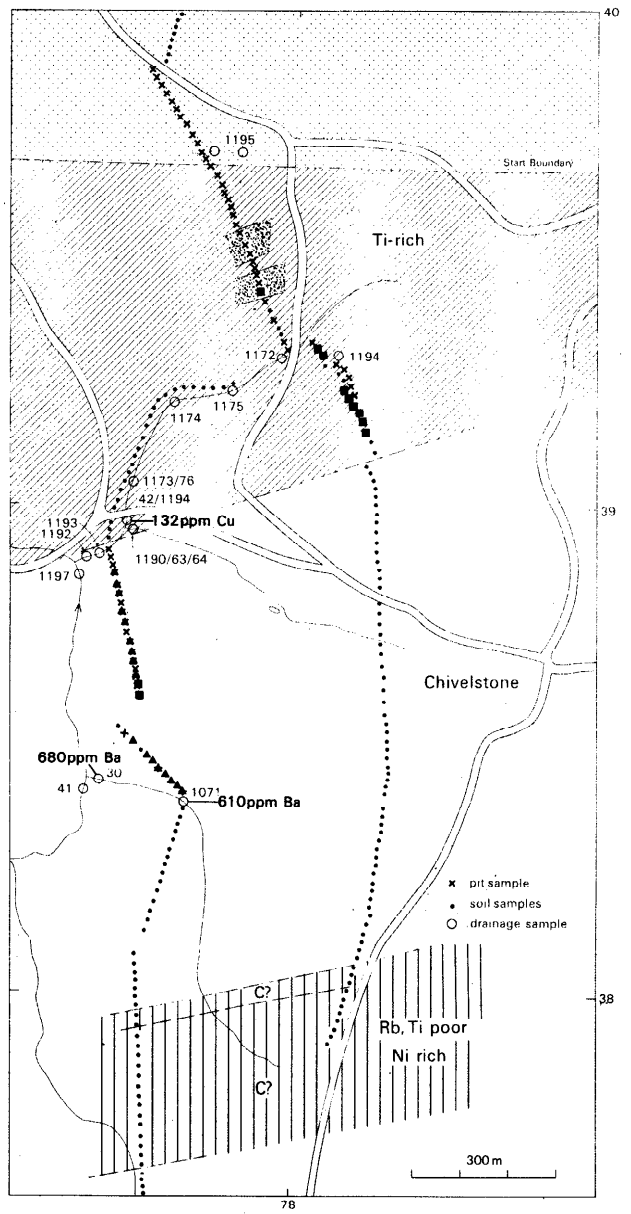


Figure 35 Distribution of Cu, Zn, Ba, Ag and Pb anomalies in soil samples and of Au anomalies in panned pit samples in area to west of East Prawle. Site of anomalous concentration of Sn and Pb in a panned pit sample and concentration of Au in adjacent drainage sample also shown.

Figure 36 Distribution of Mn, Fe, Ba and Cu anomalies in soil samples in traverses west of Chivelstone.

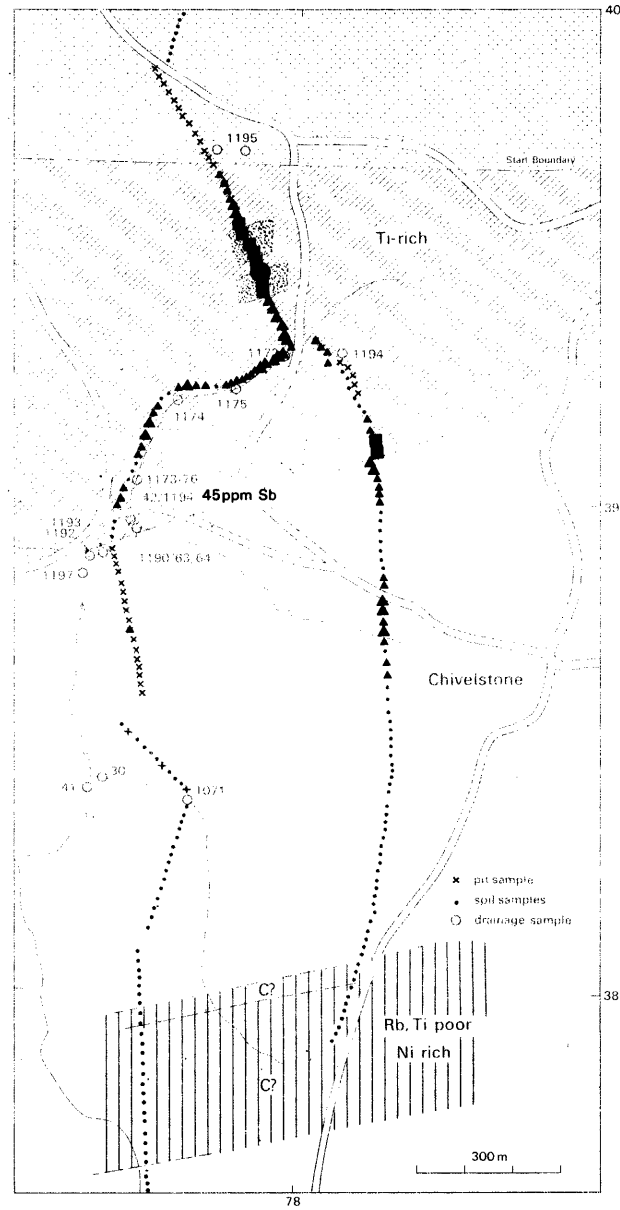


- ▲ > 3900 ≤ 6000ppm Mn in soil
- ▲ > 6000ppm Mn in soil
- > 8.7% Fe in soil

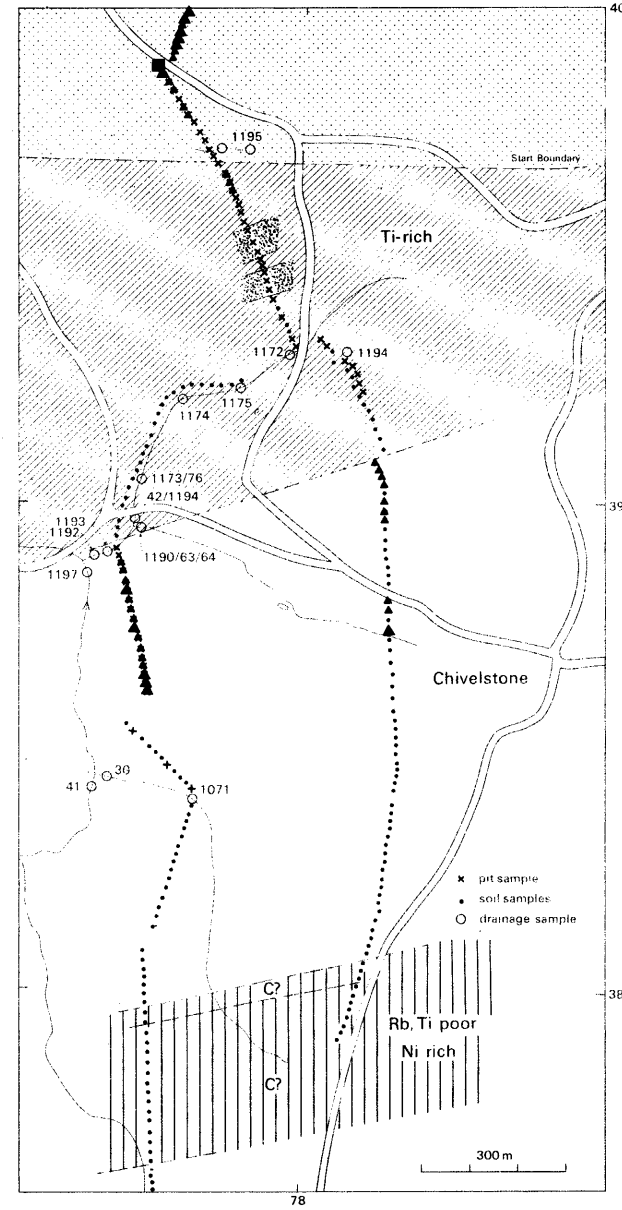


- ▲ > 510ppm Ba in soil
- > 75ppm Cu in soil

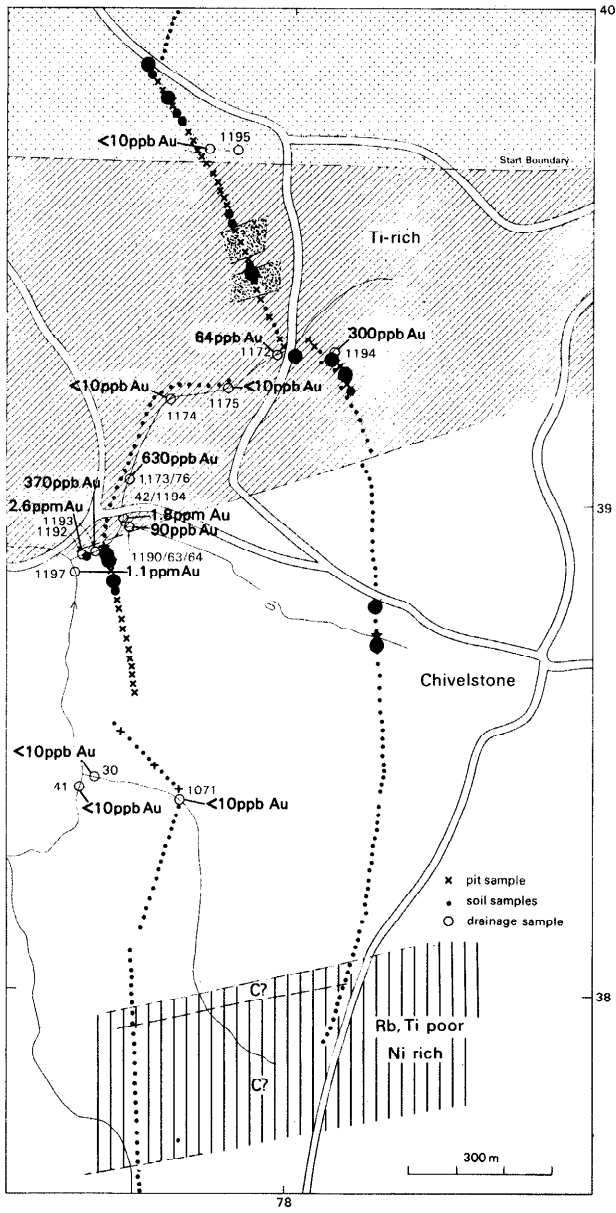
Figure 37 Distribution of Sb and As anomalies in soil samples in traverses west of Chivelstone.



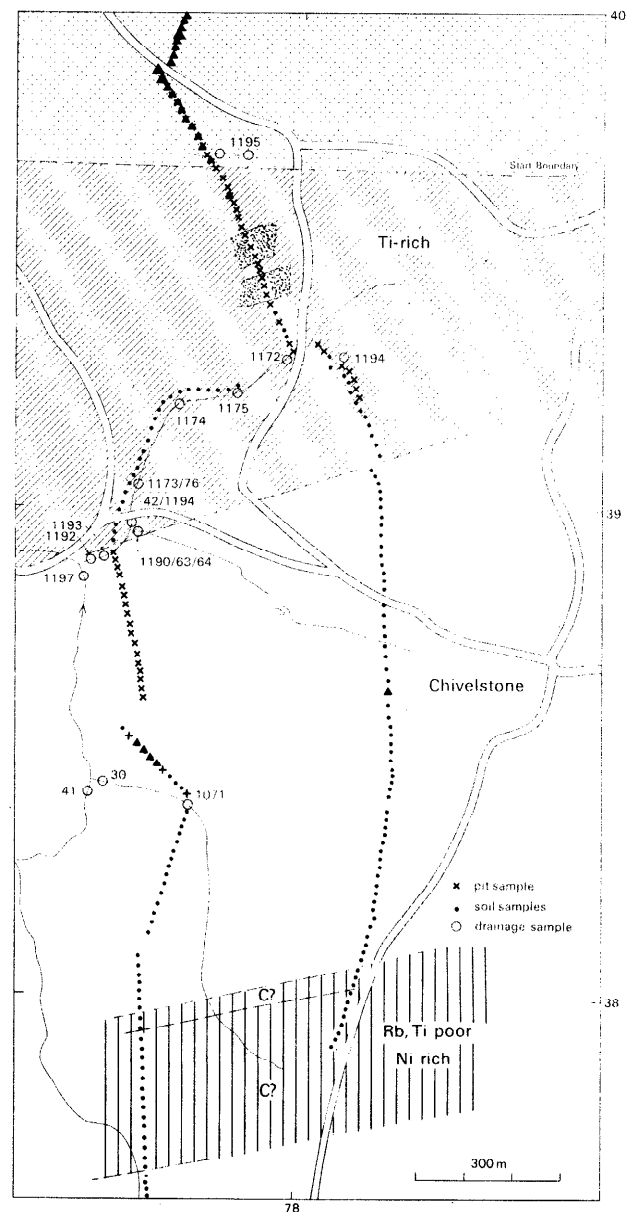
- ▲ > 10 < 14ppm Sb in soil
- ▲ > 14 < 20ppm Sb in soil
- > 20 < 30ppm Sb in soil
- > 30ppm Sb in soil



- ▲ > 48 < 60ppm As in soil
- ▲ > 60 < 100ppm As in soil
- > 100ppm As in soil



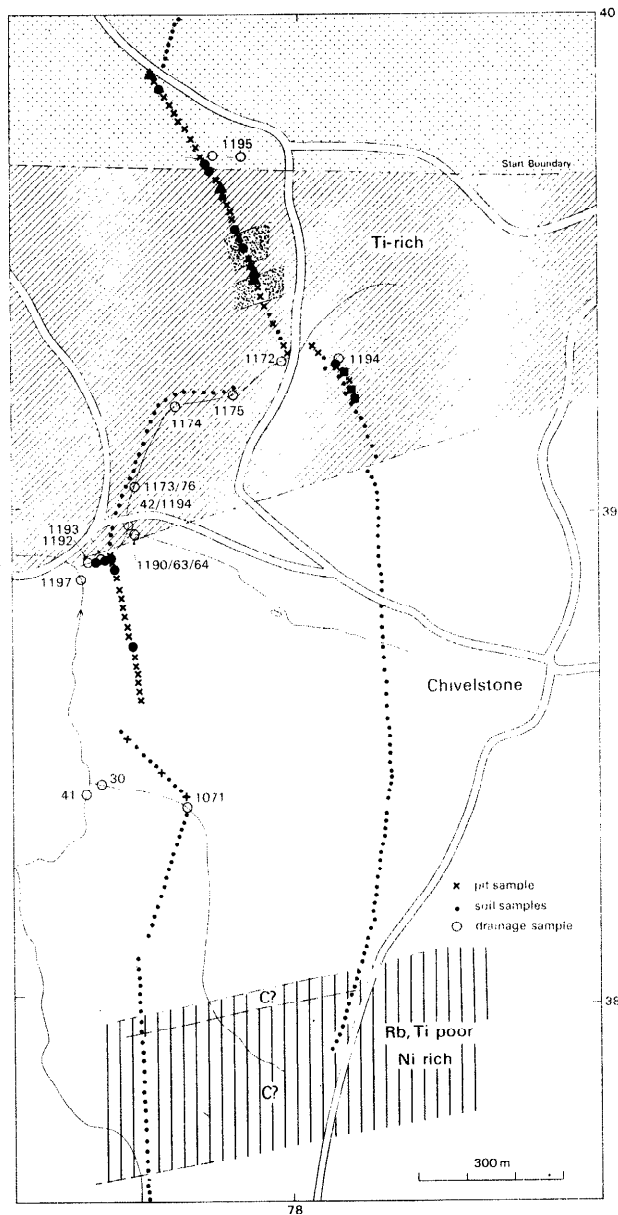
- $\geq 25 < 40$ ppb Au in panned pit
- $\geq 40 < 200$ ppb Au in panned pit
- ★ > 200 ppb in panned pit



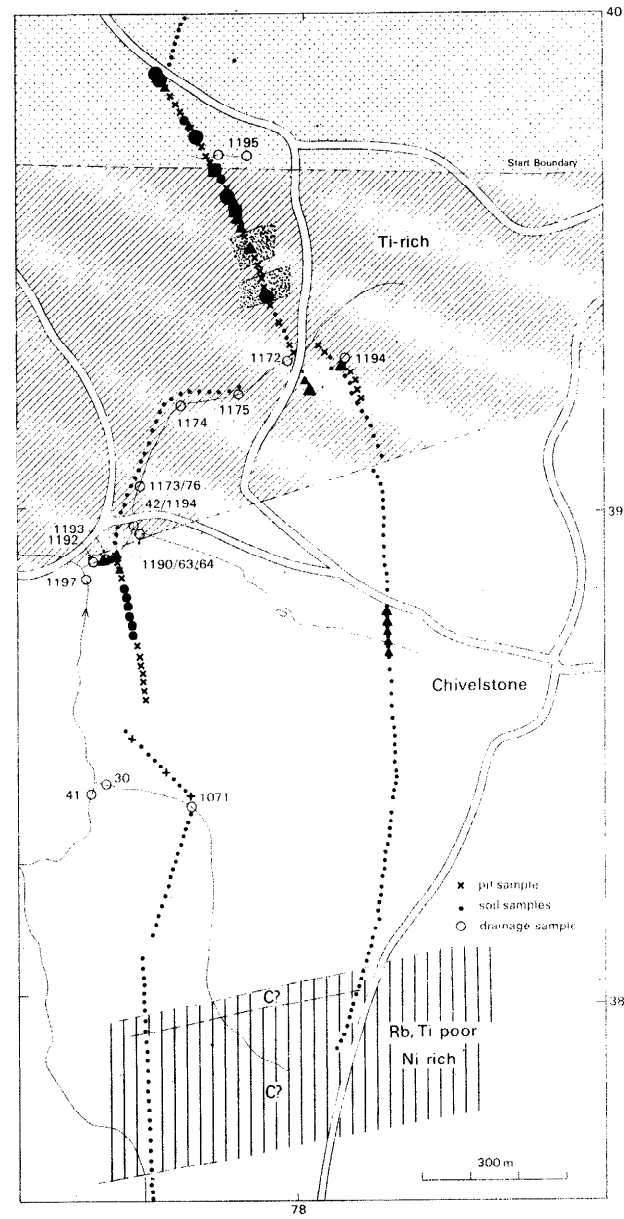
- ▲ $> 90 \leq 175$ ppm Pb in soil
- ▲ > 175 ppm Pb in soil

Figure 38 Distribution of Pb anomalies in soil samples and Au anomalies in panned pit samples from the traverse west of Chivelstone. Concentrations of Au in panned drainage samples also shown.

Figure 39 Distribution of anomalous concentrations of MgO, Ni, MnO, SiO₂, Sn and As in panned pit samples from traverses west of Chivelstone.

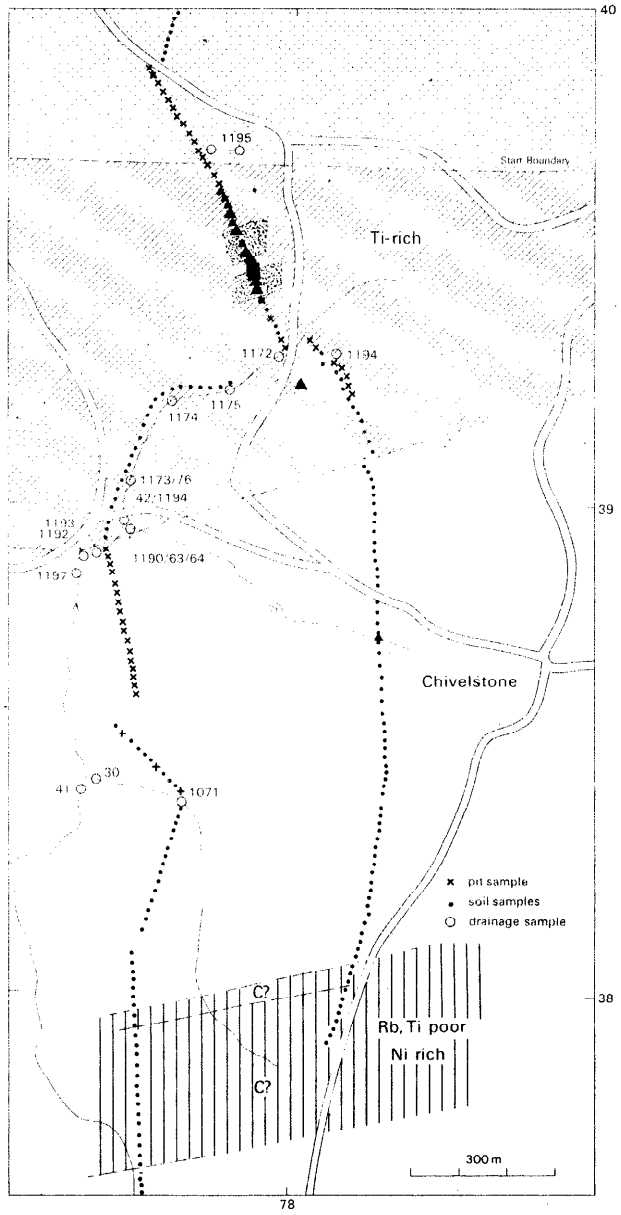


- > 4.0% MgO (> 95ppm Ni) in panned pit
- ▲ > 0.38 < 0.57% MnO in panned pit
- ▲ > 0.57% MnO in panned pit
- > 69% SiO₂ in panned pit

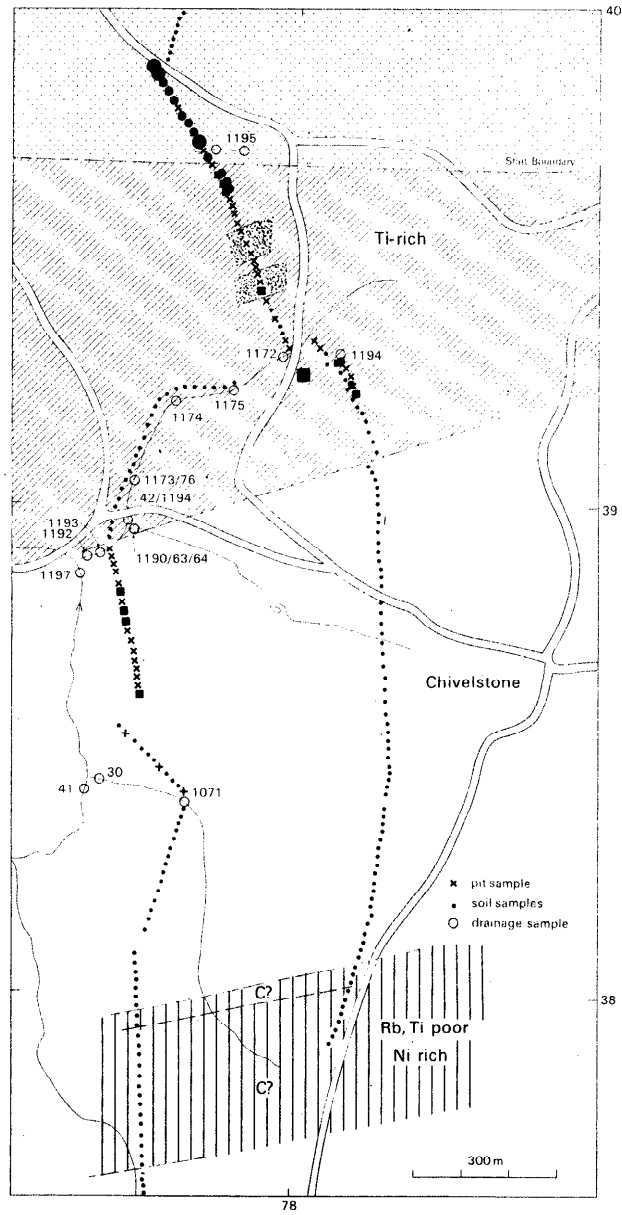


- ▲ > 14 < 30ppm Sn in panned pit
- ▲ > 30 < 70ppm Sn in panned pit
- ▲ > 70 < 140ppm Sn in panned pit
- > 140ppm Sn in panned pit
- > 75 < 130ppm As in panned pit
- > 130ppm As in panned pit

Figure 40 Distribution of anomalous concentrations of Sb, Cu and Pb in panned pit samples from traverses west of Chivelstone.



- ▲ $\geq 13 < 22$ ppm Sb in panned pit
- ▲ $\geq 22 < 60$ ppm Sb in panned pit
- ≥ 60 ppm Sb in panned pit



- $\geq 85 < 200$ ppm Cu in panned pit
- ≥ 200 ppm Pb in panned pit
- $\geq 80 < 200$ ppm Pb in panned pit
- ≥ 200 ppm Pb in panned pit

source in bedrock, possibly trending roughly eastwards towards Chivelstone. At Chivelstone, some upgrading may have taken place in the valley in view of the low but significant quantity of Sn present. Low amplitude Au anomalies are associated with the distinct zone within the volcanic unit which is enriched in Cu (Figure 36). As Mg is also enriched in the pit samples from this zone (Figure 39), it is likely that an igneous unit, compositionally different from the main sequence, is present. Just north of this, the Au anomaly is associated with enrichments in Sn and Si, suggesting a source from alluvial sediment. Within the main body of volcanic material, Au is associated with the maximum Sb anomaly (133-155 ppm, Figure 40), together with Fe and Mn (Figure 39). North of this, a low amplitude Au anomaly is associated with a zone of enrichment in Sn and Si. The Start Boundary is also marked here by considerable enrichment in Sn and Si, probably originally accumulated in a fissure along the fault, but in this case without associated Au. In the north of the area, Au anomalies are associated with the zone of anomalous As and Pb (Figures 39 and 40), but without Sn.

The types of anomaly occurring around, and to the north of, Chivelstone differ from those at Churchill Farm. No zone of albitisation and enrichment in Ba, in association with As and Sb, can be recognised at Chivelstone. Rather, there appear to be several weakly mineralised zones or structures where Au accompanies a range of different elements in both sedimentary and igneous rocks.

Frogmore

Overburden sampling carried out at the northern end of the 9 km long reconnaissance traverse and on a parallel line around 1 km further east is shown in Figure 41. The anomalies in soil and pit samples are summarised on this map as they are generally more isolated than in sampling further to the south. Pit sampling was carried out around some of the base metal anomalies. Five contacts can be recognised on the basis of changes in abundances of several elements and these are shown with the geochemical signature of the units they separate in Figure 41. In the north of the area, the argillaceous unit with relatively high concentrations of Rb appears to die out to the west. The biggest concentration of base metal anomalies is in the extreme west of the area but elsewhere anomalies are isolated. Concentrations of Sb do not exceed 13 ppm, except at Frogmore, and As levels are also relatively low throughout the area. Pit samples north of Frogmore contain anomalous concentrations of Au. The northernmost sample is derived from alluvial sediment, associated with the present stream, and is enriched in Si and Sn as well as Au. The source of the gold in the southernmost pit is not so clear. The site is well above the present stream but still within the broad valley running from the north. Several elements are enriched in the soil samples but not in the corresponding pit samples, suggesting possible contamination of near surface soil from some previous human activity. Concentrations of Sn, Si and other elements suggest that there has been no general upgrading of heavy minerals to account for the gold anomaly, which may therefore reflect gold-bearing mineralisation. Drainage samples indicate that there are additional sources of gold upstream to the north, as far as Sherford and beyond, and also east of Frogmore.

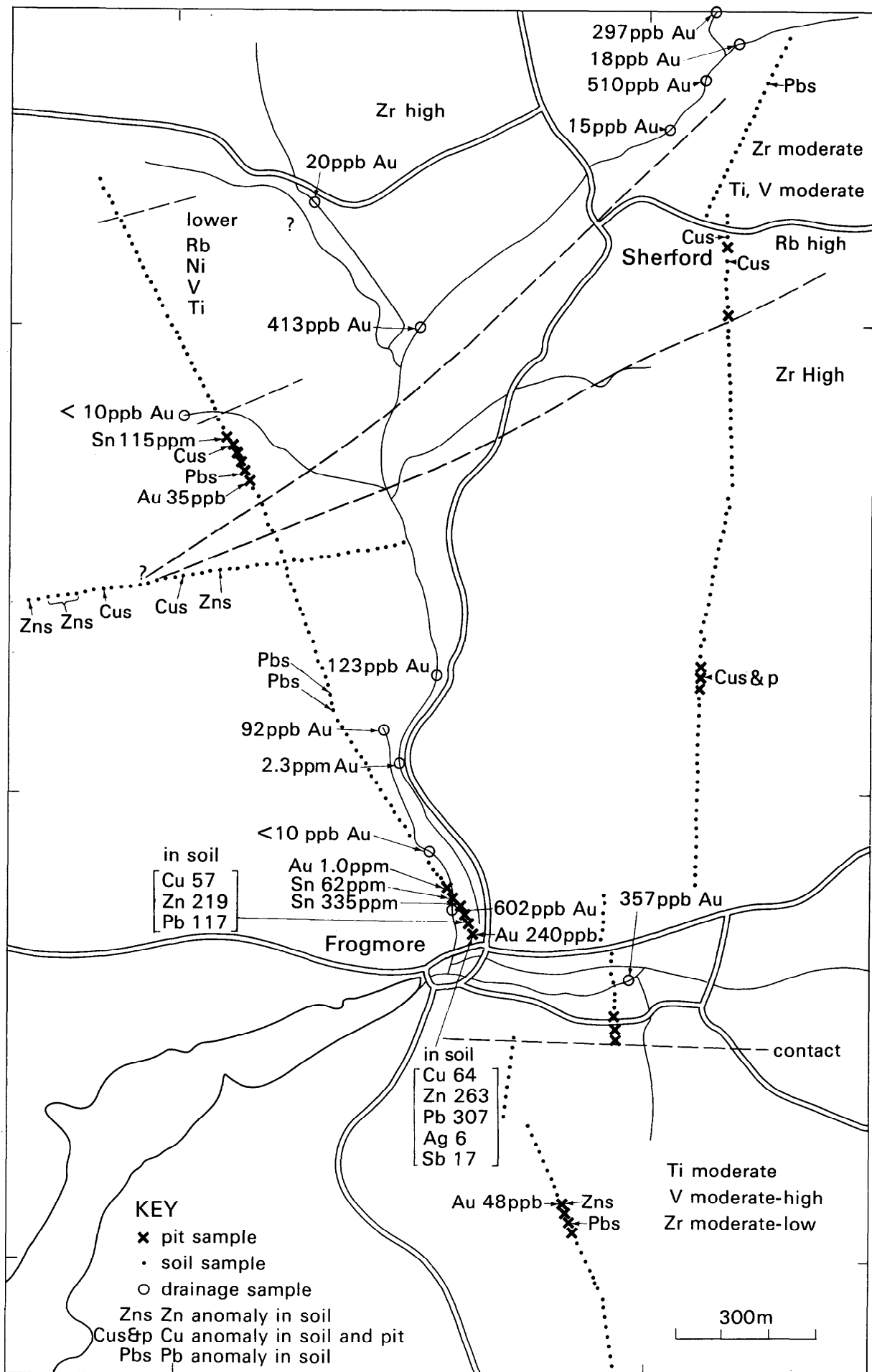


Figure 41 Distribution of Cu, Zn, Pb anomalies in soil and panned pit samples and of Au, Sn, Ag and Sb in panned pit samples from Frogmore - Sherford area. Rock unit boundaries deduced from concentration of Rb, Ni, V, Ti and Zr in soil samples also shown. Concentrations of Au in panned drainage samples also included.

GEOPHYSICAL SURVEYS NEAR BROWNSTONE FARM

Geophysical surveys were used to help in elucidating the structure in the area around the anomalous confluence to the south of Brownstone Farm [²⁵⁹⁷0495], and to identify any conductive source of metal anomalies in the near surface environment. The results of similar geophysical surveys carried out at Whympton Farm are available from BGS as a data package.

Methods

Geophysical mapping, based largely on the electromagnetic properties of differing lithological formations, can be effective in defining geological structure in areas of poor exposure. In lowland Britain, these methods are hindered by land access restrictions due to farming operations and by significant interference from cultural noise due to power lines, pipes and wire fences. Nevertheless, manual filtering of obvious cultural noise often permits the main elements of geological structure to be mapped across land with little or no exposure.

The Scintrex Integrated Geophysical System-2 (IGS-2) facilitates a rapid survey of a target area by simultaneous digital recording of several geophysical parameters. At Whympton Farm significant variation in resistivity had been identified using the M-VLF and E-VLF survey options (magnetic and electric field Very Low Frequency surveys) and a similar procedure was adopted at Brownstone Farm. Lines were surveyed with a tape and compass on a magnetic bearing 340° (grid 335°) and caned at 25 m intervals, the orientation being constrained by the direction to a suitable VLF transmitting station (GBR 16.0 kHz), and are shown in Figure 42. All IGS-2 observations were made at intervals of 12.5 m. Total Field magnetic data were also obtained at a ground clearance of about 2.0 m using a back-mounted bottle connected to the IGS-2 module. Such observations are less accurate than a pole-mounted system, use of which is impractical when simultaneously recording M-VLF and E-VLF data. Daily observations were tied to field bases at 00-400E and 100S-1100E; the total field intensity at both stations was close to 47640 nT. Two lines of time-domain induced polarisation were also surveyed, using the Schlumberger array, to provide rapid appraisal of the potential for sulphide mineralisation.

Gravity observations were also made along these two lines, at intervals of 25 m (175N-350S on line 600E). An additional 18 gravity observations were also made at OS bench marks and spot heights on the OS plans SX 5948, 5949, 6048 and 6049. All gravity observations were made using a La Coste and Romberg gravity meter 280. All stations have been connected to the National Gravity Reference Net 1973 (NGRN73) and reduced at a density of 2.70 Mgm⁻³. Innermost zone terrain corrections out to 390 m (Hammer Zone E) have been made using zone charts and 1:10,000 maps. Terrain corrections for a 5x5 km square surrounding the BNG km square containing each station have been made using a Digital Terrain Model (DTM) of the area, based on mean elevations within squares of side length 250 m. Outer zone terrain corrections, up to 21 km from each station were made using the BGS heights databank of mean elevations with BNG 1 km squares.

Results

Total field magnetic data

The total field data are plotted in Figure 43 relative to a datum at 47630 nT. Areas shaded in black have values above this. All data have been corrected for diurnal change. Some cultural noise from

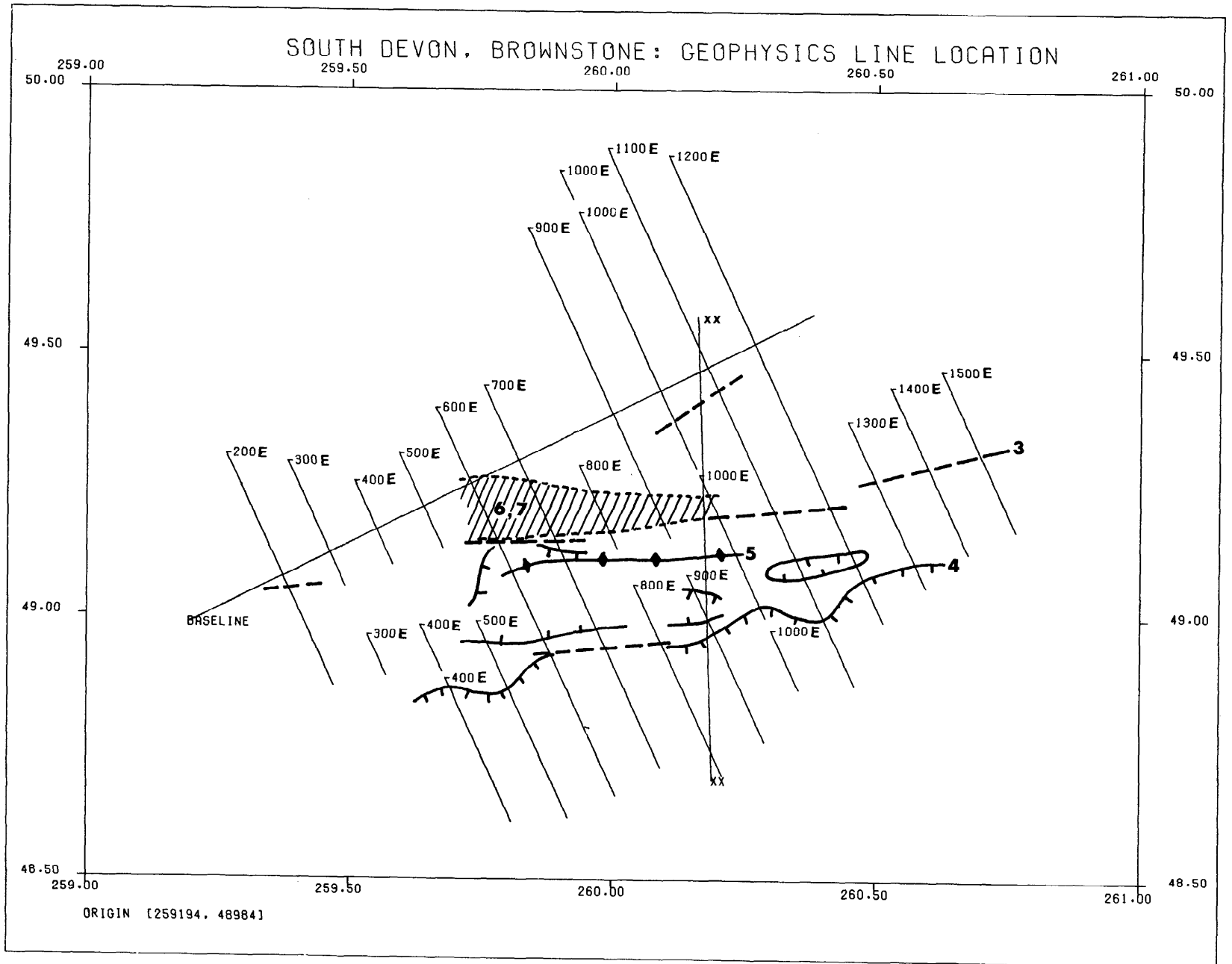


Figure 42 Location of geophysical survey lines and summary of more important features of geophysical data as lineations. Numbers refer to different data sets, i.e., 3 to VLF-EM in-phase data, 4 to VLF resistivity data, 5 to IP resistivity, 6 to IP chargeability and 7 to Bouguer gravity data.

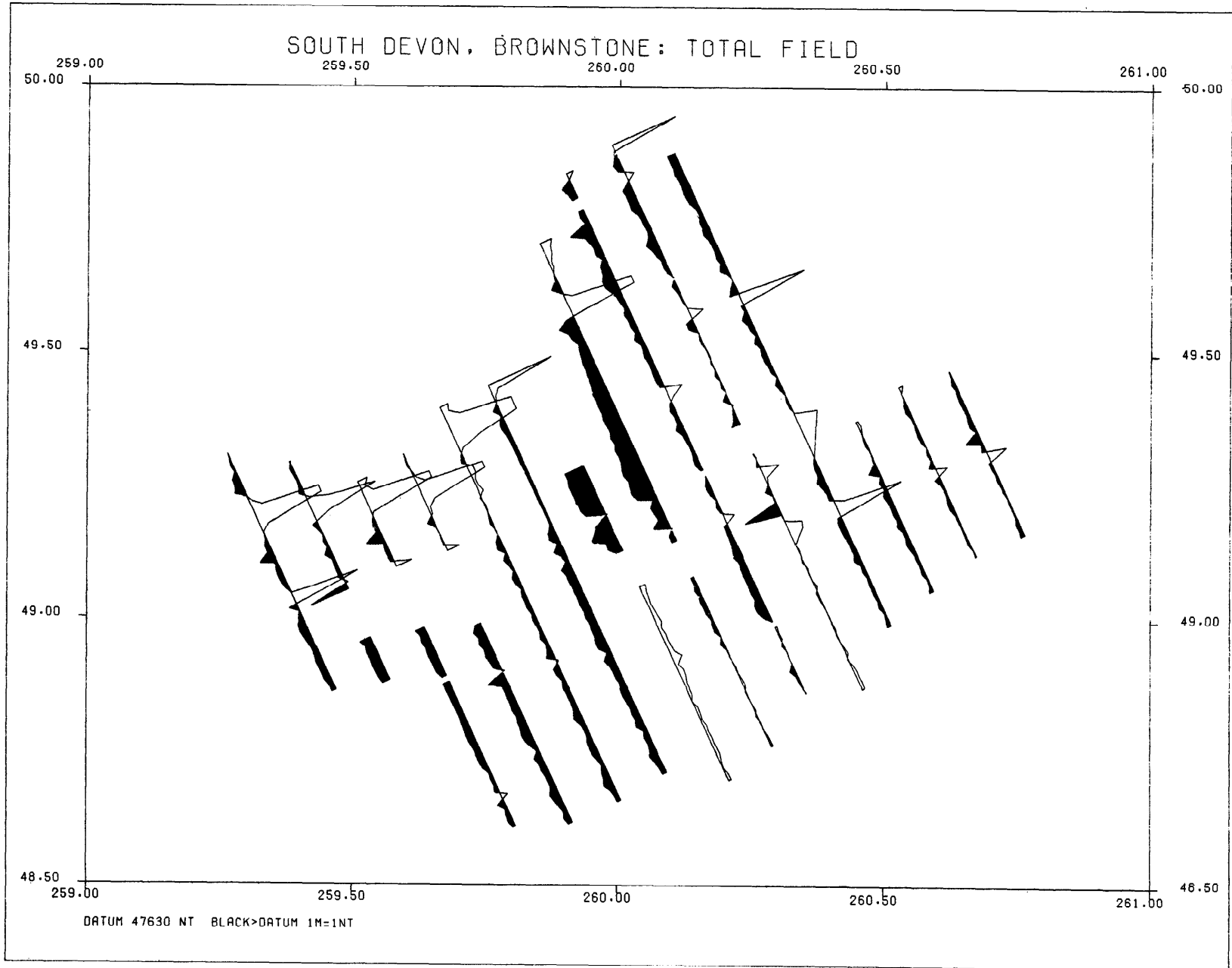
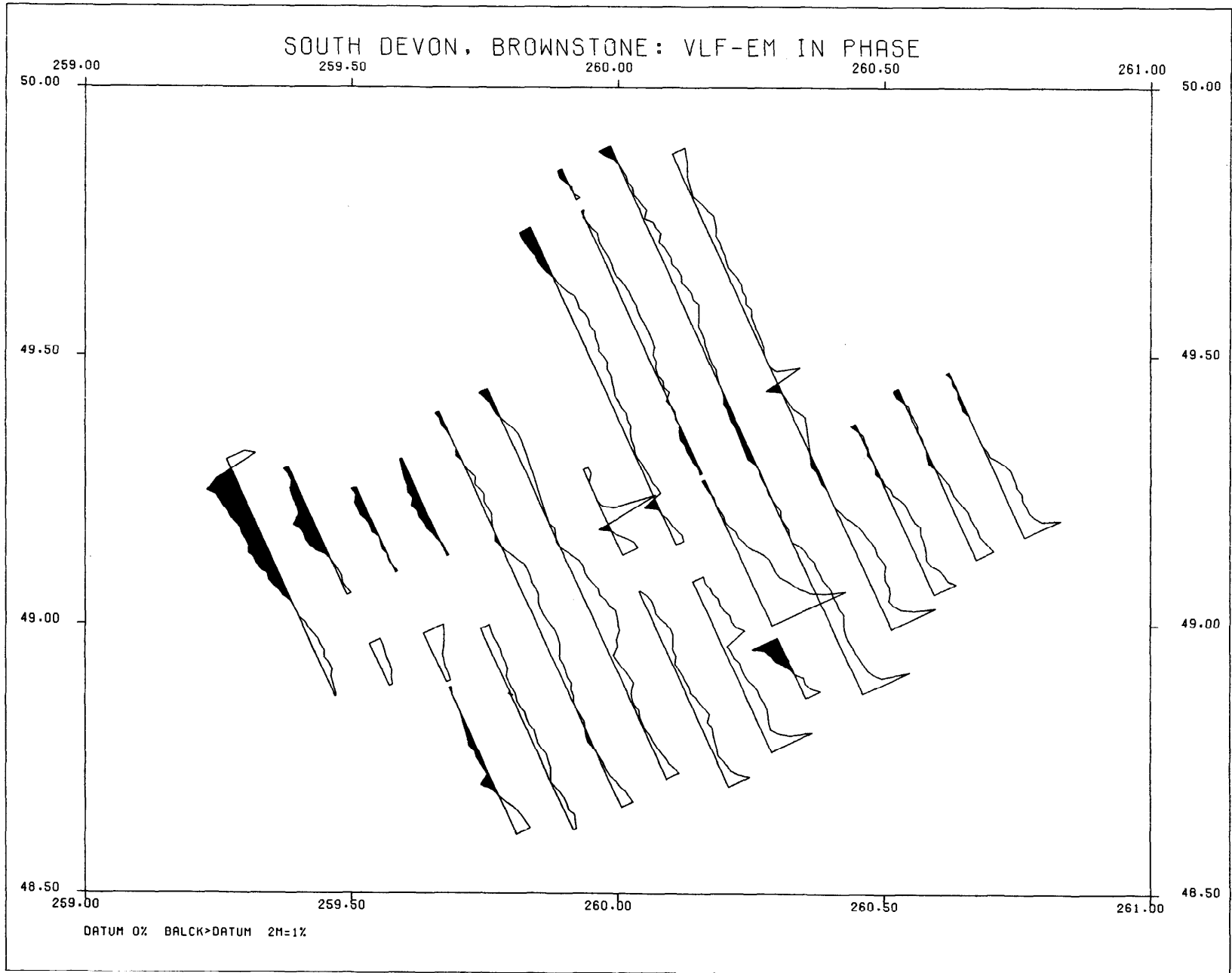


Figure 43 Total magnetic field data plotted relative to a datum at 47630 nT such that areas shaded in black have values above this.

Figure 44 In-phase M-VLF observations plotted so that areas shaded in black have a positive in-phase VLF component.



power lines and fences has been filtered from the data by truncating values less than 47580 nT. Apart from the obvious anomaly associated with the track to Brownstone Farm, the main feature of interest is a linear anomaly observed on lines east of 800E, with amplitudes up to 100 nT (line 1100E). This feature is mostly due to wire fencing, and on line 600E the magnetic profile shows no significant anomalies.

M-VLF data

The in-phase M-VLF observations are shown in Figure 44, where areas shaded black have a positive in-phase VLF component. Interference from wire fencing is evident at the southern ends of lines east of 700E and on line 1000E. A clear anomaly extends across all the eastern lines and is associated with a major change in lithology. Continuous mapping of the anomaly across the area is limited by lack of data from the wooded enclosures, but the boundary probably extends across all the grid. The basic anomaly pattern can be identified on line 200E.

E-VLF data

The inductive apparent resistivity data are shown in Figure 45, plotted relative to a datum of 200 ohm metres. Areas shaded black have resistivities above 200 ohm m. Over most of the northern part of the grid, apparent resistivities are close to or less than 100 ohm m; to the south, values exceed 500 ohm m. Maximum values occur on lines 700E and 800E. Correlation of resistive zones across adjacent lines is not clear, but there do appear to be at least two zones of higher resistivity within the Dartmouth Slate Group. Some correlation in the southern resistive zone can be seen across lines 700-1000E.

Induced polarisation data

Schlumberger array apparent resistivity and chargeability data for lines 600E and XX are shown in Figure 46. For IP resistivity the data are plotted relative to a datum of 300 ohm m; for IP chargeability the datum is 10 msec. Apparent resistivities generally increase to the south but with a local resistivity minimum just south of the baseline, in the low-lying area close to the stream confluence. Chargeabilities are all below 20 msec but do reach maxima in the zone 0-100S on 600E. On line XX, running approximately north-south through the baseline at 1075E, apparent resistivities are much higher, over 800 ohm m. Resistivity appears to increase gradually between 200 and 400S and then sharply further to the south onto the Dartmouth Slate Group.

Gravity data

The new data are compatible with existing regional data and have been plotted as points and profiles in Figure 47. Two regional stations, reoccupied in the present survey, gave repeat Bouguer gravity anomalies within 0.10 mGal of the original survey. The general pattern shows a decrease to the north and north-east. This is only in part due to the Dartmoor Granite, since the background field away from the granite is about 15 mGal. Some of the increase to the south, indicated in Figure 47, might be due to shallow basement structure.

The profile data are plotted relative to a line datum of 16.5 mGal; areas shaded black have Bouguer gravity values above this. Along line 600E, the Bouguer gravity anomaly increases from 16.20 to 17.0 mGal southwards, but a clear local positive anomaly occurs around 50S, with anomaly values about 0.5 mGal above the regional trend. This anomaly is roughly coincident with the chargeability maximum on line 600E. On line XX, complete Bouguer gravity values increase to the south from about 15.5 mGal to 17.3 mGal. A slight positive anomaly appears to occur between 300

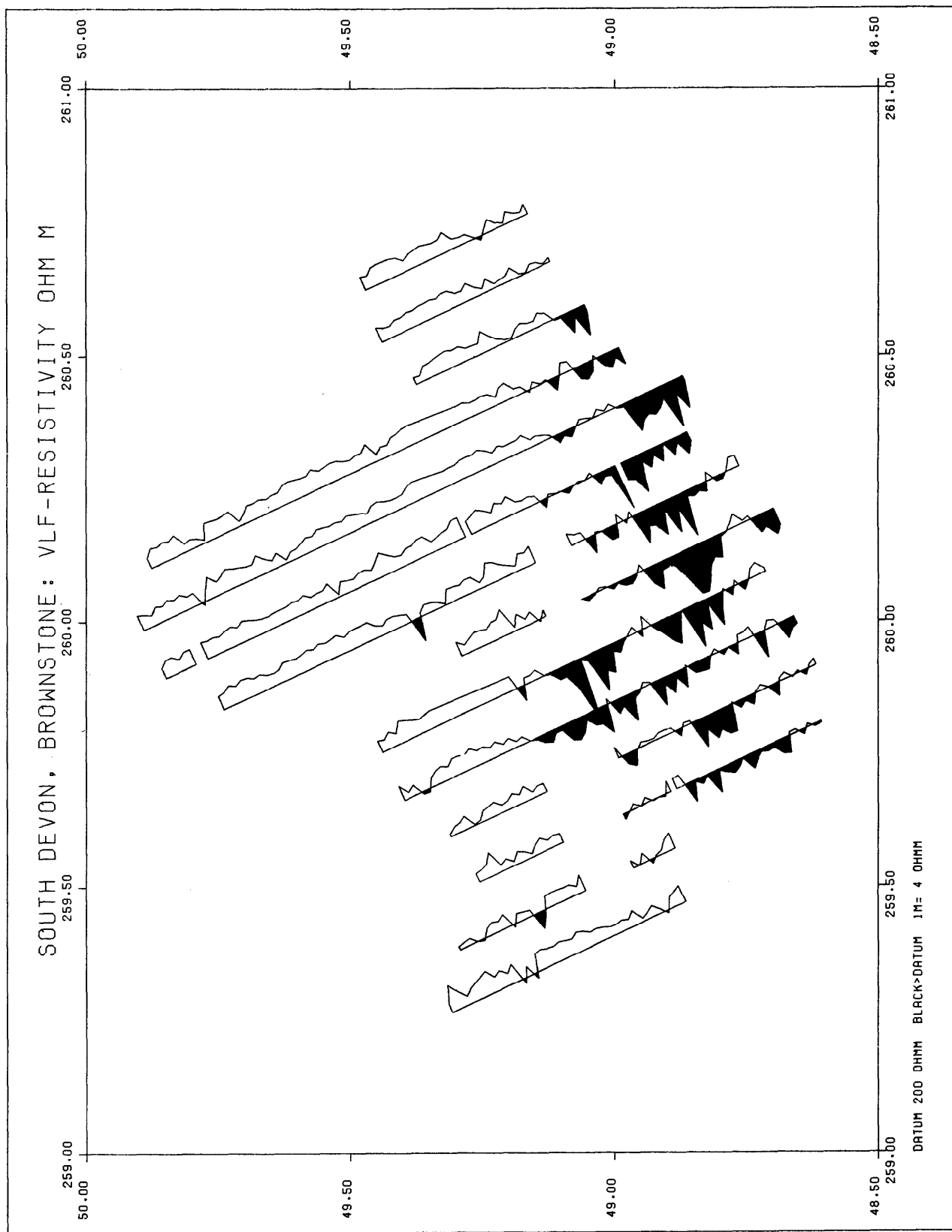


Figure 45 Inductive apparent resistivity data plotted relative to a datum of 200 ohm metres such that areas shaded black have resistivities above 200 ohm m.

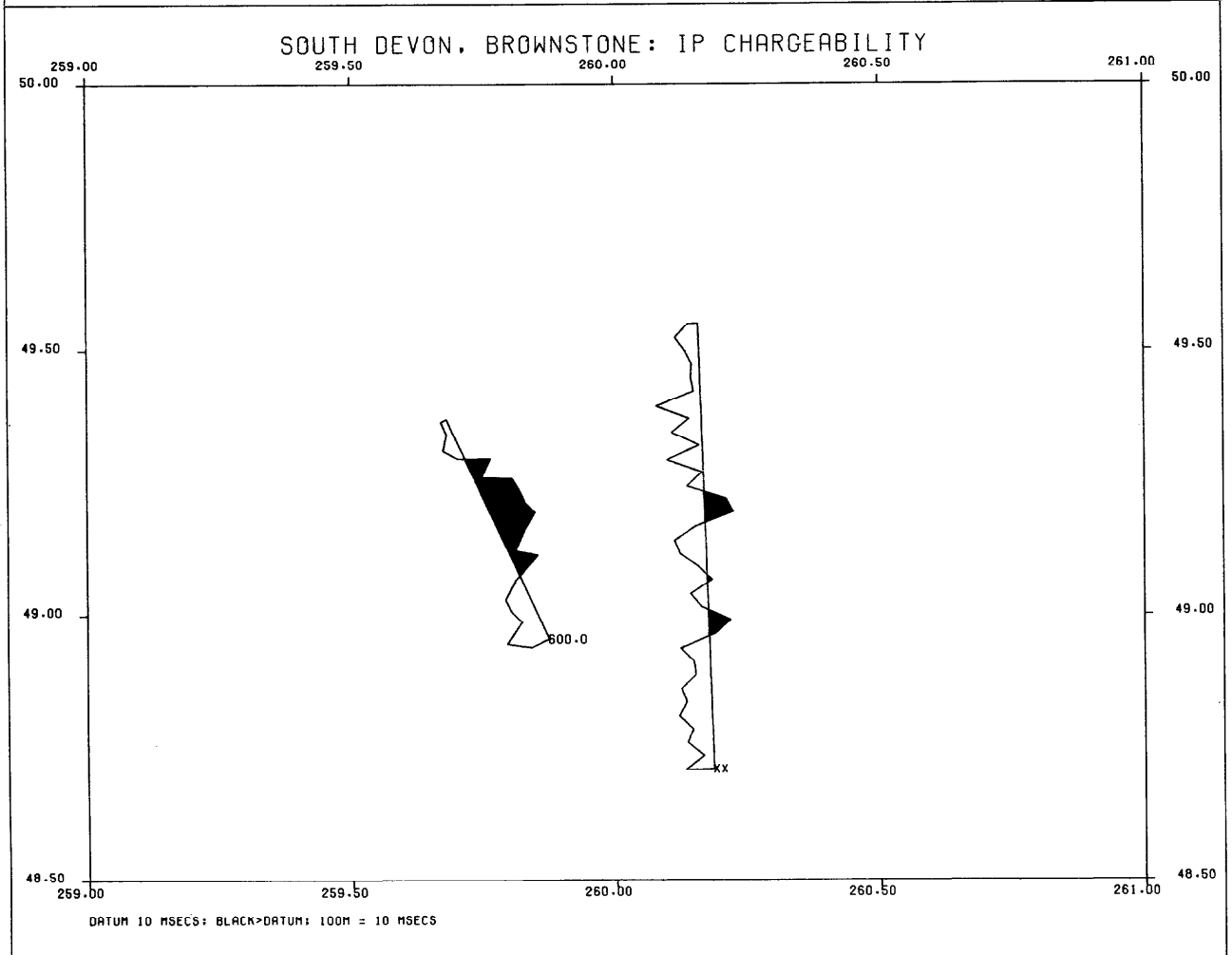
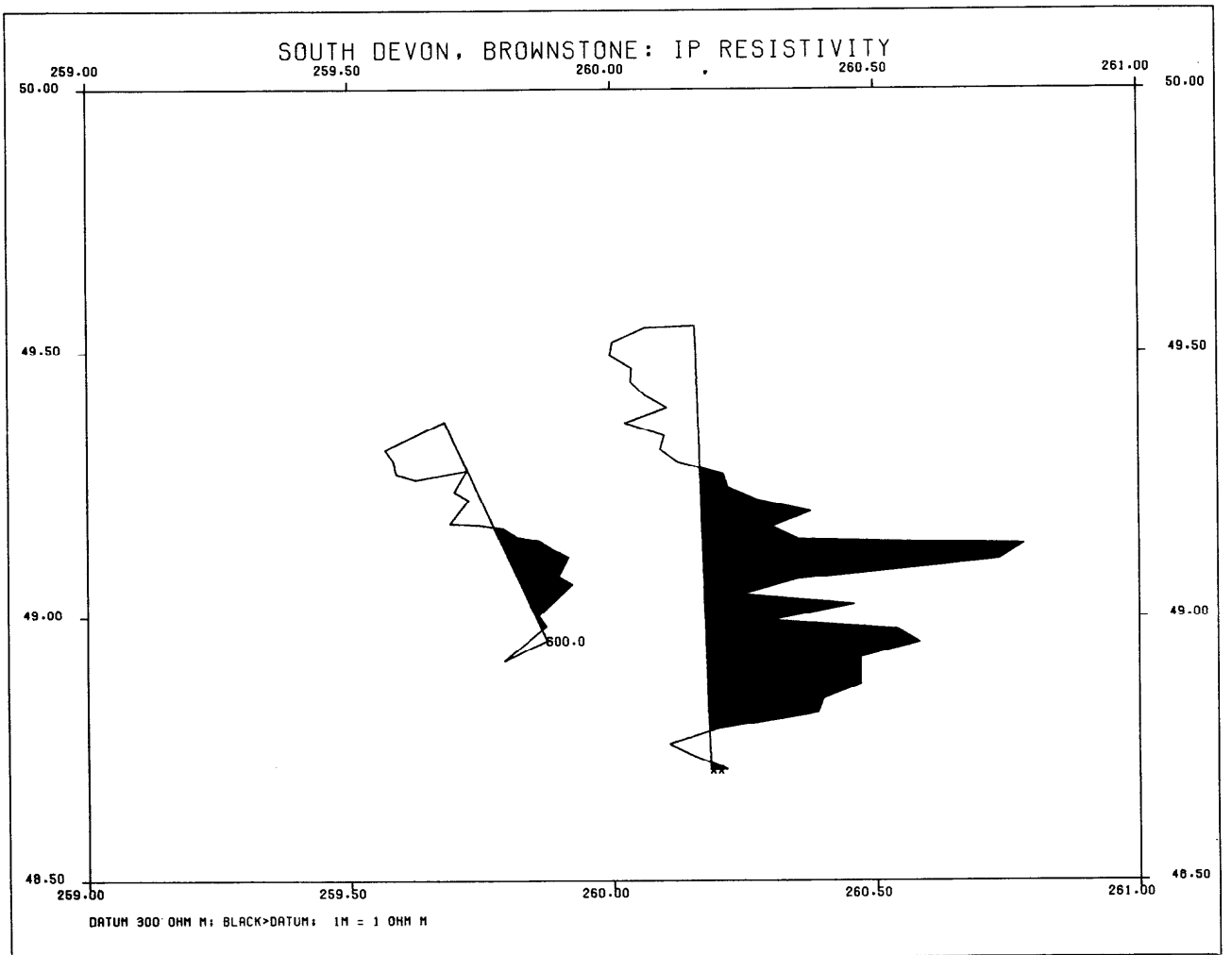


Figure 46 Schlumberger array apparent resistivity and chargeability data plotted relative to a datum of 300 ohm m and 10 msec respectively.

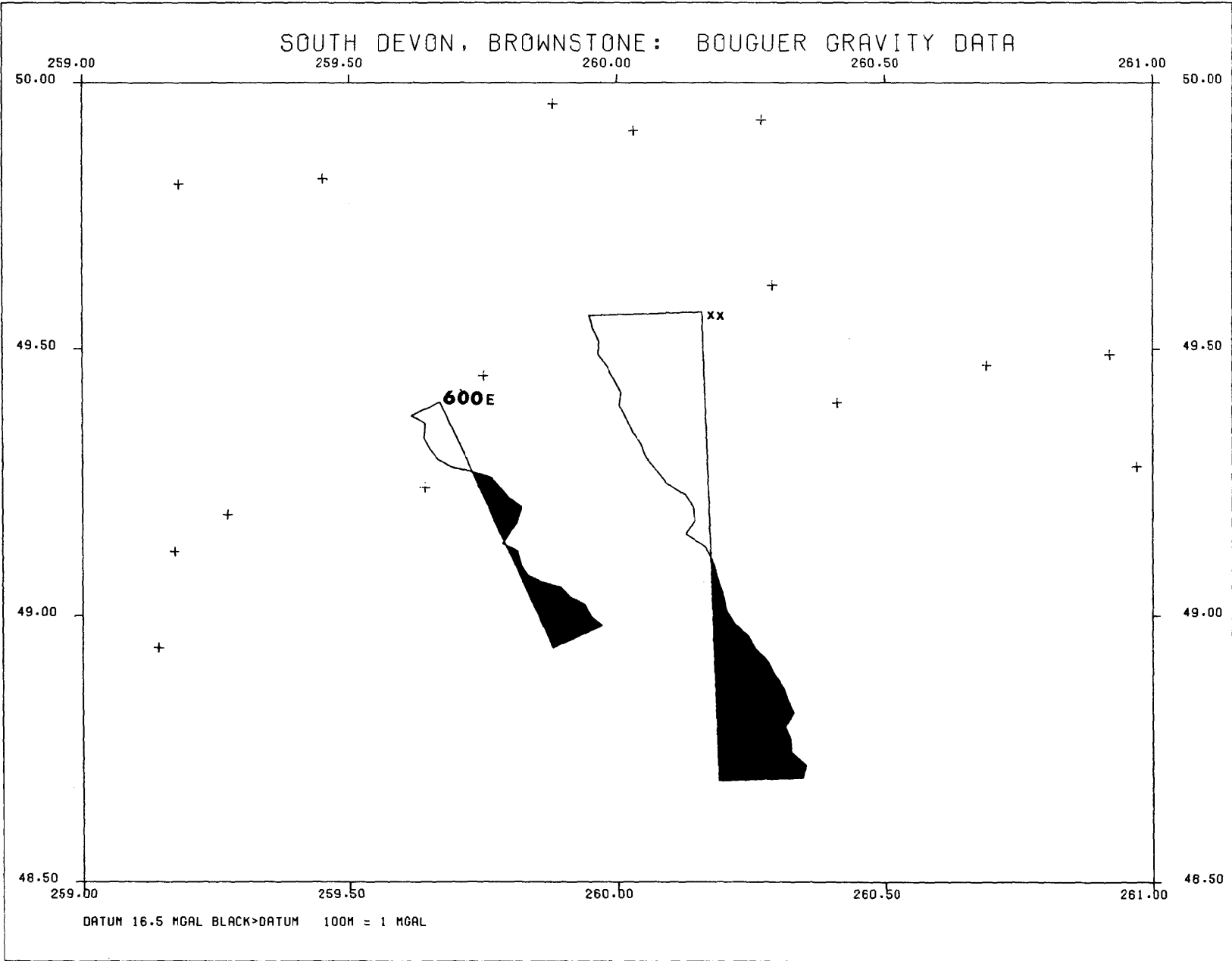


Figure 47 Bouguer gravity data plotted relative to a datum of 16.5 mGal such that areas shaded black have Bouguer gravity values above this.

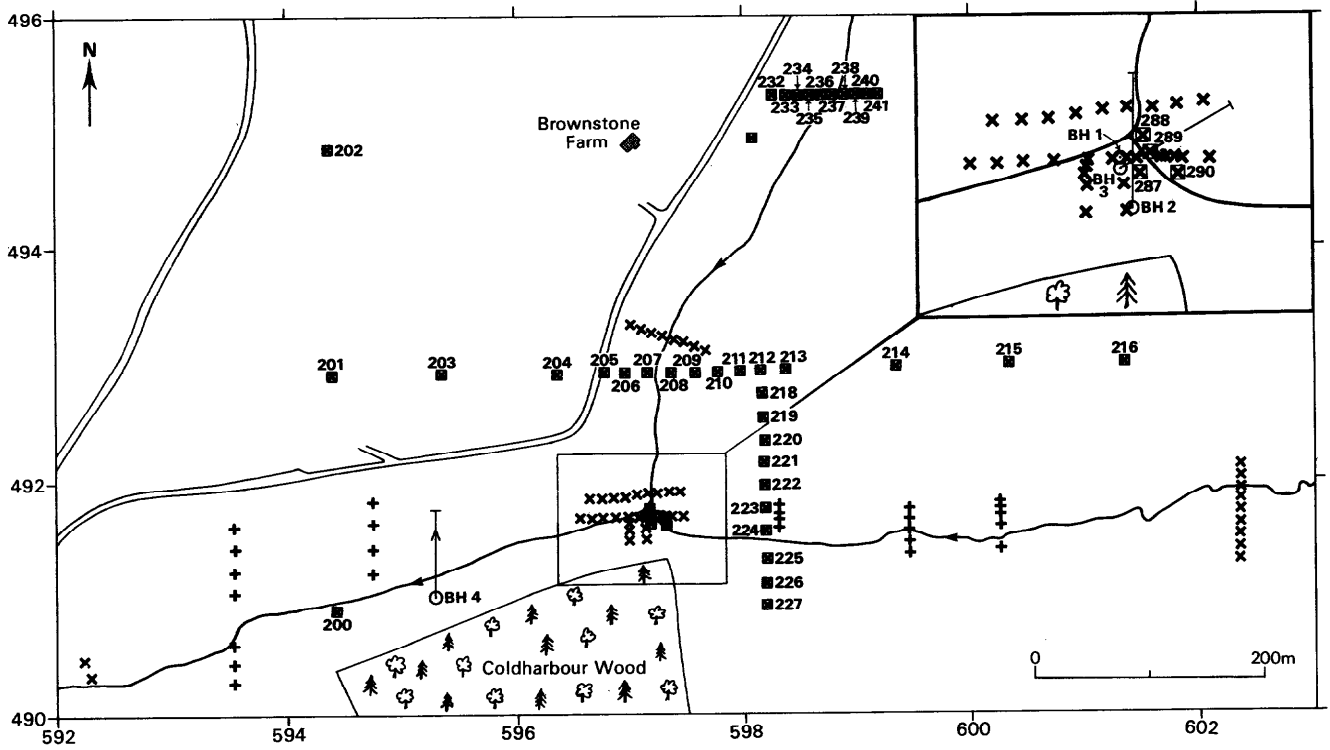


Figure 48 Collars and horizontal projections of four boreholes south of Brownstone Farm. Location and numbers of soil pits also given.

and 500S but it is not as clear as on line 600E. Station 425S which has a Bouguer gravity anomaly about 0.13 mGal below the trend looks erroneous, but no error is apparent in the leveling or in the terrain correction profile. The relative Bouguer gravity anomaly at about 400S correlates well with a slight chargeability maximum (Figure 46).

Geological interpretation

Some of the important features of the geophysical data are summarised in Figure 42 as lineations, annotated to indicate source data. The VLF-EM data have indentified a significant geological boundary across the area, roughly coincident with the boundary between the Dartmouth Slates and Meadfoot beds on the published geological map. Within the Meadfoot Group there are high resistivity zones which may coincide with arenaceous units. A distinct positive gravity anomaly of about 0.5 mGal occurs on line 600E in the zone 0-100S and centred over a local galvanic resistivity low and chargeability high. A continuation of this feature to the east, immediately north of a feature in the VLF-EM data, is suggested from gravity and chargeability results on line XX. This may reflect a zone of enrichment in pyrite in argillaceous rocks, fragments of which were recovered from power auger holes along an east-west zone around the confluence.

DRILLING NEAR BROWNSTONE FARM

Four holes were drilled on Brownstone Farm, the collars and projections of which are shown on Figure 48 in relation to the soil samples. The first hole was sited to establish the direction and angle of dip and of cleavage in the rocks. Borehole 2 was sited to intersect at depth the east-west trending zone which, from the overburden sampling, was deduced to be the main control of gold distribution. Borehole 3 was sited roughly at right angles to this in order to intersect any north and north-north-east trending mineralised structures that may occur. Borehole 4 was sited about 200 m to the east in order to intersect the east-west zone of interest away from the possible structural complexities around the confluence.

Most of the core was split in half, and sampling intervals were chosen on the basis of lithology and degree of alteration. Samples were analysed for major elements and a range of trace elements by XRF, using the same laboratory and methods as for the rock samples described above. Similarly, Au determinations were made on about 50% of the core by the method described above.

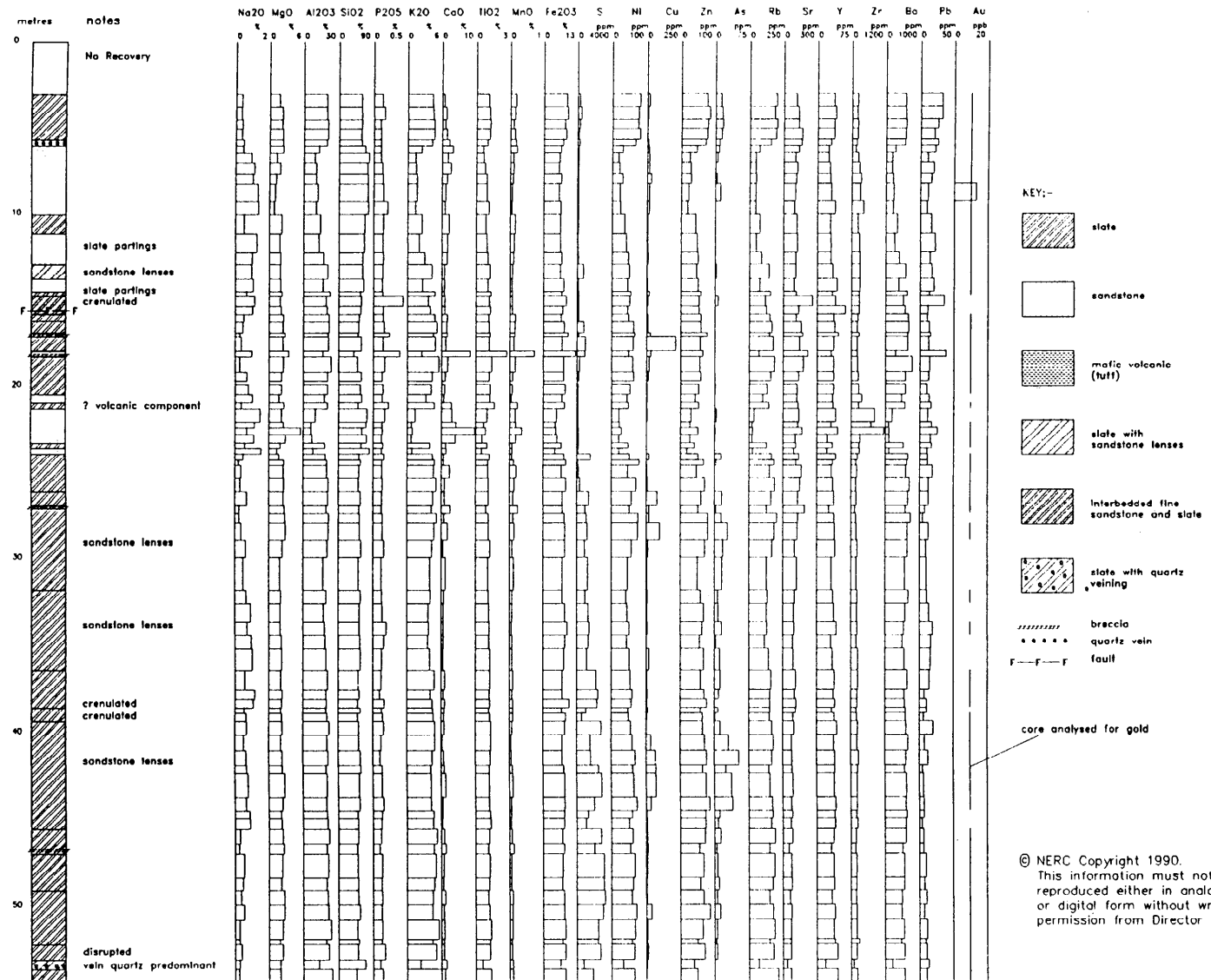
Borehole 1

This hole was drilled vertically at the edge of the presumed east-west mineralised zone and a graphic section is shown in Figure 49 together with plots of major and trace element contents. It intersected an alternation of slate and feldspathic sandstone, passing into dark grey slate below 24 m and a mafic volcanic horizon 0.25 m thick. Measured dip was highly variable, indicating that the sequence was flexured, but averaged 45° to the south. Parts of the section were brecciated and the presence of a fault was deduced because of a sudden rapid change in dip. A possible load cast together with graded bedding suggested that the sequence was right way up. Pyrite is present in the slate below about 26 m depth but mostly absent above.

Lenoid vein quartz, sometimes with minor carbonate, is widespread and in many cases contains marginal green chlorite. The maximum width of vein quartz intersected is 0.4 m but most was much thinner than this. Of particular interest are zones within vein quartz lenses with euhedral carbonate

Brownstone BH 1
 Location, SX 5971 4917 Inclusion, Vertical
 Depth, 54.35m

Figure 49 Graphic lithological and chemical log of Brownstone borehole 1.



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rhombs and voids. Carbonate veining and disseminations also occur within some sandstone units. Chemically, the carbonate is enriched in Ca, Mg, Mn and Fe and is, therefore, largely ferroan dolomite or ankerite. Grains of carbonate were extracted from the drill sludge and, after mounting on a slide and coating, were analysed for Ca, Mg, Fe and Mn on an electron microprobe. Of 19 grains analysed, 8 could be classified as ankerite, 5 as ferroan dolomite, 3 as dolomite, 2 as calcite and 1 as siderite. The maximum content of manganese obtained was 4.0% MnO in a ferroan dolomite.

Concentrations of base metals are generally low in the core, but slight enrichments in Cu (maximum 215 ppm) occur in some sections of the slate. Discrete grains of chalcopyrite have been identified as the main Cu-bearing mineral. Discrete zones of enrichment in As (maximum 53 ppm) are also present in the slate, mostly following the zones enriched in Cu (Figure 49). No significant concentration of Au was found by analysis in any of the samples from this hole.

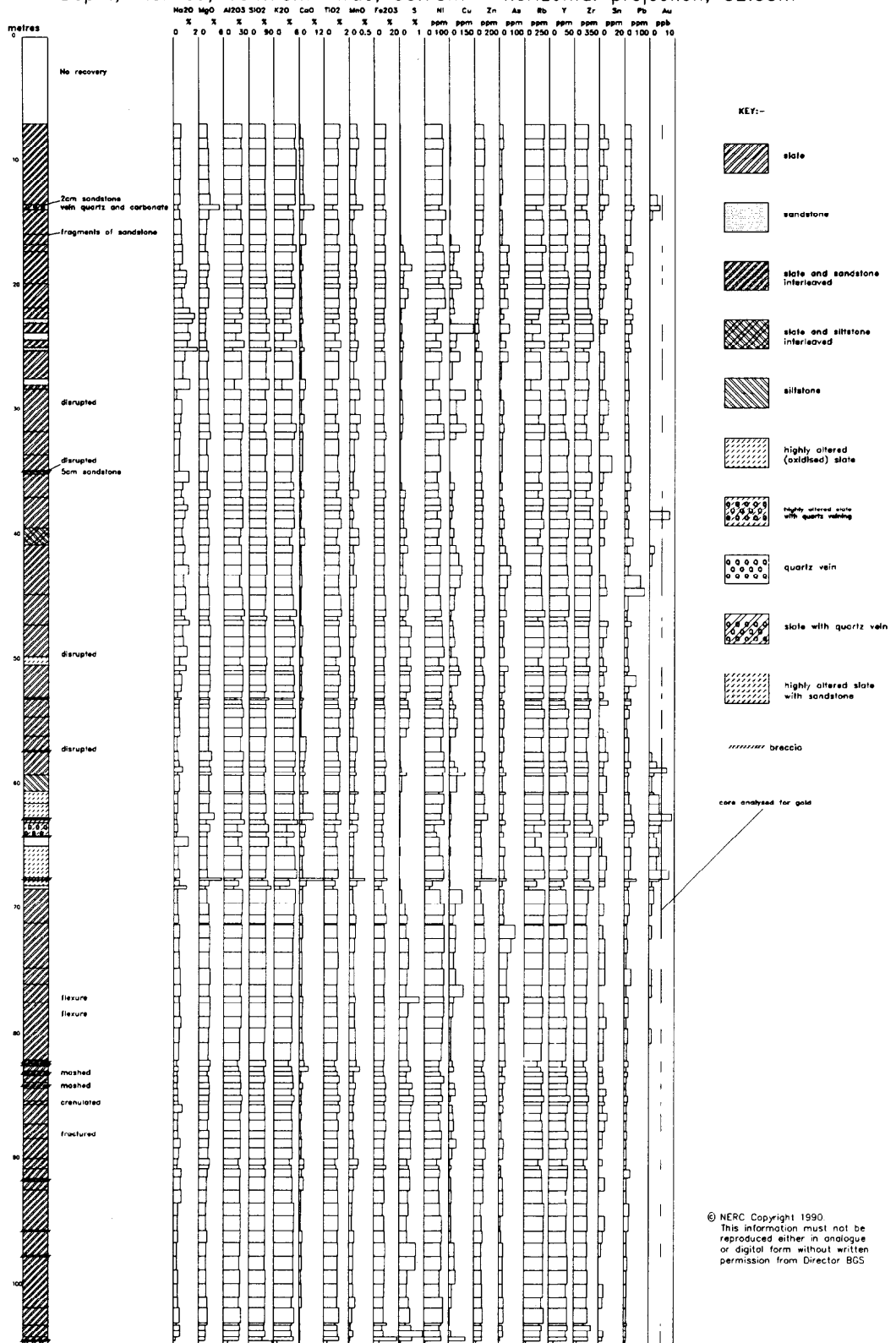
Borehole 2

This hole was drilled northwards, at an inclination of 60°, from a position south of borehole 1, in order to be roughly perpendicular to bedding and to intersect the presumed east-west mineralised zone at depth. A graphic log of the hole, together with plots of contents of major and trace elements, is shown in Figure 50. The hole intersected mostly slates, with minor feldspathic sandstone horizons near the top. The amount of sandstone is much less than in borehole 1 and because of this, and the absence of the thin mafic volcanic horizon, correlation between the two holes is difficult. This may be accounted for if the disrupted and altered zone around 34 m down the hole represents a fault. The slates are well cleaved and also show a second crenulation cleavage, but appear more deformed below 47 m down the hole. Disseminated pyrite is present in the slates below 16.6 m inclined depth and particularly conspicuous towards the base of the hole where concentrations reach several percent by volume.

Between 60.5 and 68.1 m inclined depth is a zone of alteration, brecciation and carbonate veining which is most likely the downward extension (55 m below surface) of the east-west mineralised zone. Assuming a vertical or near vertical trace, it correlates with the surface expression of the zone and is about 4 m true width. Within the zone, pyrite is absent and the slate is fragmented, brecciated and oxidised with red, pinkish, pale yellow green and brown colours predominant. Within some of the brecciated zones are masses of dolomitic carbonate, slightly enriched in Mn (maximum 0.31% MnO).

Elsewhere in the core, veining is conspicuous, with at least five separate types or generations being discernible. Earliest is strained, layer-parallel quartz, sometimes with relatively coarse carbonate. This is cut by thinner veins of quartz accompanied by feldspar, which in one section has been shown by probe examination to be albite. Later irregular, thin, cross-cutting carbonate veins which tend to follow grain boundaries and wider, more persistent, carbonate veins, some showing ferruginous alteration, are also present. In addition, Fe-rich chlorite veinlets and lenses (30.3-31.3% FeO by probe analysis in one section), often accompanied by carbonate and quartz, are also present. In several sections, there are carbonate-filled vugs at the intersections of fine, anastomosing veinlets cutting the strained quartz. The vugs are commonly fringed by a generation of unstrained quartz which has grown over the original strained quartz and are filled with brownish carbonate with a central void. These vuggy veinlets are present throughout most of the hole.

Brownstone BH 2
 Location, SX 5972 4917 Azimuth, 0° Inclusion, 60°
 Depth, inclined, 104.70m true, 90.75m horizontal projection, 52.35m



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Figure 50 Graphic lithological and chemical log of Brownstone borehole 2.

As in borehole 1, the pyritiferous slate contains zones showing slight enrichment in Cu (maximum 140 ppm) and As (maximum 63 ppm) but, unlike borehole 1, there are also zones showing minor enrichment in Pb (maximum 80 ppm). In one probe section, minor chalcopyrite, tennantite, bornite and chalcocite were located in thin carbonate veining within pyritiferous slate. Concentrations of Au in the core are generally very low, but a zone of slight enrichment is associated with the altered zone.

Borehole 3

Borehole 3 was sited near borehole 1 and oriented to intersect any structures trending roughly north-south through the area around the confluence and also to intersect, obliquely, the presumed east-west trending mineralised zone at depth. A graphic log of the hole together with plots of major and trace element contents are shown in Figure 51. The hole initially intersected slate with sandstone horizons and a thin mafic volcanic unit as in borehole 1. Disseminated pyrite is conspicuous in the slate below 16.9 m inclined depth but between 30.6 and 43.3 m, pyrite is absent and the rocks are generally altered and oxidised. This zone is vertically beneath the surface trace of the presumed mineralised zone. Within the zone, some of the rock is brecciated and impregnated with dolomitic carbonate as in borehole 2. Below 43.3 m inclined depth, similar alteration is patchy and associated with brecciated slate, while below 49.6 m pyritiferous slate is predominant. Between 58.5 m and 65.2 m is another altered zone below which the sedimentary sequence changes abruptly into one containing much more arenaceous material (Figure 51). As this sequence is completely different to that found in the lower part of borehole 2, it is necessary to postulate a fault trending between north and north-north-east, with a significant downthrow to the east, which displaces the Staddon Grit Formation to the south.

Much of the pyritiferous slate in borehole 3 is relatively enriched in Cu, to a greater extent than in boreholes 1 and 2. Thus the concentration of Cu is frequently in the range 100-250 ppm and reaches a maximum of 400 ppm. Concentrations of As are only slightly higher in borehole 3 than the other two, with a maximum of 69 ppm. Three samples from the altered zone contain more Au than in any sample in boreholes 1 and 2, reaching a maximum of 380 ppb. No metallic elements are enriched in any of these samples. Elsewhere, Au levels are similar to those found in the other two holes. As no discrete gold was found in a section from the core carrying the most Au by analysis, it has not been possible to establish whether any particular type of carbonate veining is associated with the gold. A wide range of carbonate types from almost pure dolomite to ferroan dolomite with 13.5% FeO is present, but it does appear that the relatively late and clear carbonate is dolomite rather than ferroan dolomite. In two sections from this hole, balls of iron oxide are present in the dolomite veins. Compositionally, these balls appear to be goethite with between 64.4 and 81.5 % Fe as FeO and small amounts of silica and alumina. The reason for their presence in carbonate veins is enigmatic, but it may be of importance as a general correlation between the presence in drainage of gold and iron oxide balls, some magnetic and others nonmagnetic, has been observed throughout South Devon.

Borehole 4

Borehole 4 was drilled in the same direction as borehole 2 but about 200 m to the west, away from the structurally complex zone around the stream confluence. It was sited to intersect the east-west mineralised zone at depth. Some uncertainty existed as to the location of the mineralised zone

Brownstone BH 3

Location, SX 5971 4917 Azimuth, 60° Inclination, 60°

Depth, inclined, 97.55m true, 84.48m horizontal projection, 48.78m

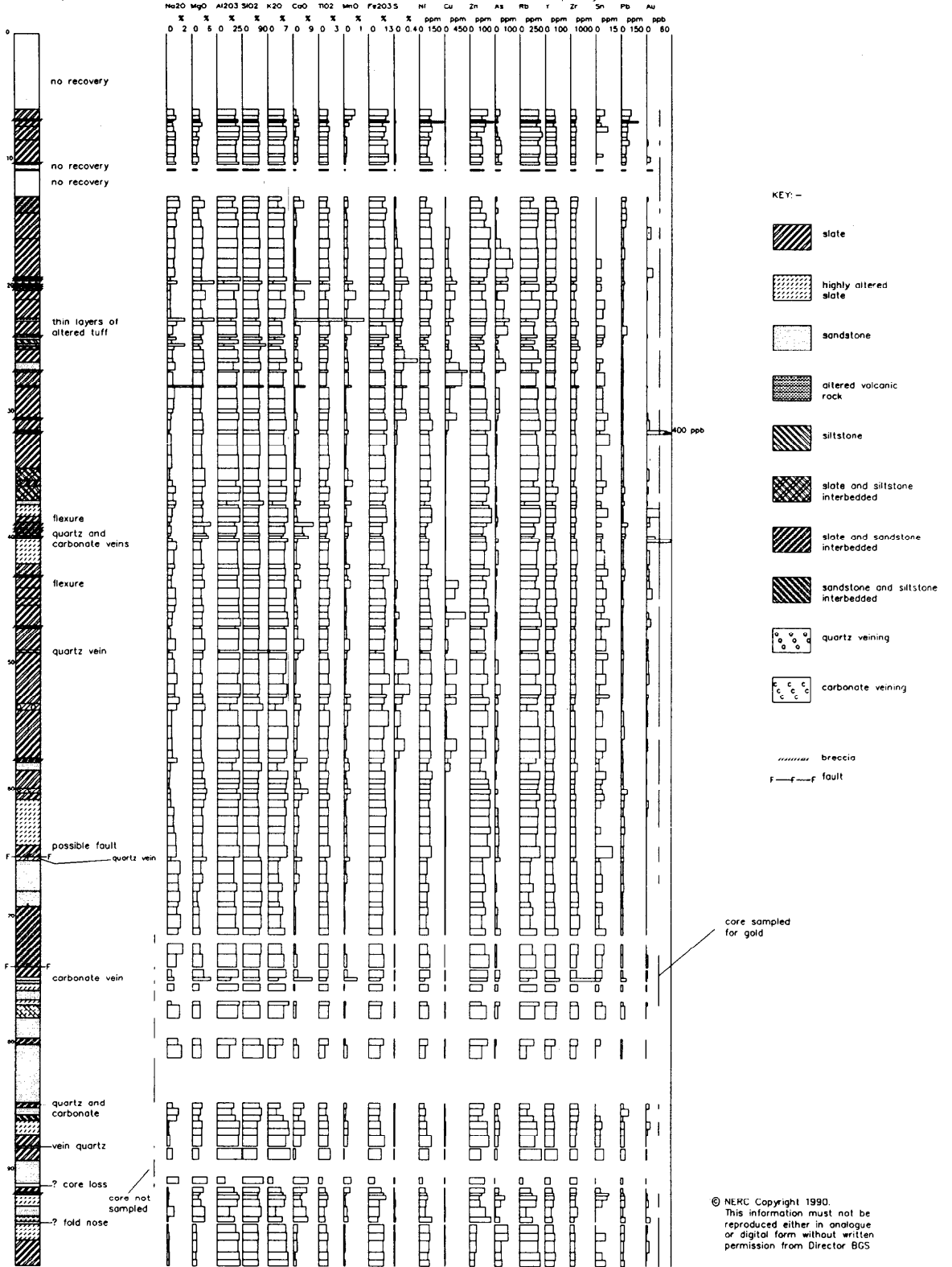


Figure 51 Graphic lithological and chemical log of Brownstone borehole 3.

Brownstone BH 4
 Location SX 5933 4911 Azimuth 0° Inclination 55°
 Depth, inclined, 131.70m true, 107.88m horizontal projection 77.54m

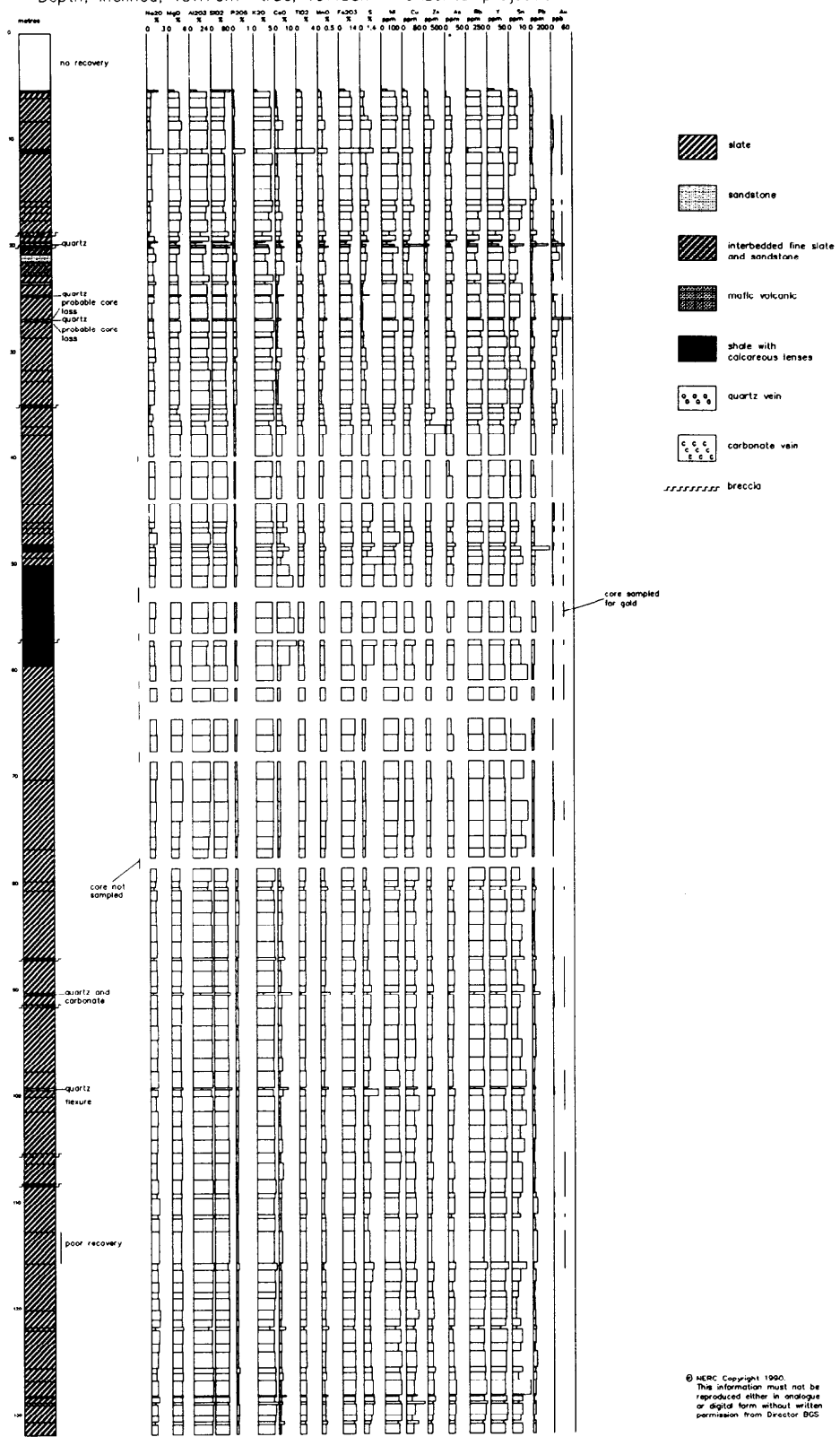


Figure 52 Graphic lithological and chemical log of Brownstone borehole 4

as overburden sampling in the vicinity was at a lower density than around the confluence. The graphic log of the hole and plots of concentrations of major and trace elements is shown in Figure 52. The hole intersected slate with minor sandstone near the top, together with the mafic volcanic horizon which provides a very good marker and allows correlation of borehole 4 with boreholes 1 and 3. Virtually the entire core consists of pyritiferous slate and no highly altered zone, such as occurs in boreholes 2 and 3, was intersected. Two samples of the slate from near the top of the hole were subjected to palynological investigation. One of these yielded rare spores which suggested an early Devonian age, but not older than Siegenian. Between 37.0 m and 59.5 m (especially between 50.0 and 59.5 m), the slate contains many calcareous lenses and layers with concentrations of calcium reaching a maximum of 9.0% CaO. This material was not intersected in any of the other holes.

Though the largest amounts of pyrite are found in parts of borehole 4, compared with the other boreholes, the concentrations of Cu and As are much lower, with maxima of 49 ppm and 27 ppm respectively. On the other hand, zinc is generally more enriched in borehole 4, reaching a maximum of 465 ppm. Lead is also relatively enriched in parts of the core (maximum 170 ppm) but does not follow Zn closely. Minor amounts of base metal sulphide mineralisation are widespread in the core. Between 22.7 m and 31.7 m, there are at least two quartz+carbonate veins containing aggregates of millerite with pyrite, chalcopyrite and galena. Thin carbonate veinlets and vuggy veins are common and frequently contain isolated crystals of pyrite, chalcopyrite, sphalerite and galena. Within the slate, there are also many fracture planes coated with kaolinite, carbonate, including siderite, and euhedral sphalerite, galena and pyrite. Gold concentrations, determined by analysis, are highest towards the top of the hole, between 19.5 and 30.5 m, where vein quartz and carbonate is both most abundant and in the thickest veins, reaching a maximum of 54 ppb within a 20 cm section of quartz-carbonate vein containing millerite. Below 50 m inclined depth Au concentrations are very low. Nowhere did the hole intersect any oxidised rock similar to that found in the other boreholes.

Fluid inclusions

Samples of veins from the Brownstone boreholes, especially those containing the vuggy material, were examined for fluid inclusions at BGS by T Shepherd. The strained and deformed quartz veins did not contain any inclusions suitable for study. On the other hand, many of the vugs were found to be lined with a generation of clear unstrained quartz which had overgrown the main vein quartz and sometimes contained suitable inclusions. Two types of fluid inclusion were found in the quartz overgrowths: two-phase liquid plus vapour inclusions and liquid only inclusions which appear to be a necked down variety of the former. The two-phase inclusions are ovoid or irregular, with long axes perpendicular to the boundary between the overgrowth and the pre-existing quartz and in some cases they are arranged in trails parallel to this boundary, along possible growth zones. Measurements on the inclusions show them mostly to contain an aqueous fluid with salinity between 1 and 5 wt% NaCl, entrapped at a temperature between 150 and 210 °C.

Interpretation of Brownstone mineralisation

A possible model can be put forward to account for the variety of mineralisation and metal enrichments that occur in bedrock at the southern edge of Brownstone Farm. The drilling did not encounter sufficient gold to prove conclusively the source of the anomalies in the overburden at

surface, but there is enough information from the area and the region as a whole to provide an interpretive framework.

The volcanic unit intersected in three of the holes is geochemically coherent and similar compositionally to some of the volcanic rocks from the Erme estuary and also from the North Start unit. There is no evidence of a primary association of mineralisation with this unit and it is chemically different from the highly evolved volcanics from the Erme estuary which do carry gold. The slate, which is the predominant rock type at Brownstone, is all pyritiferous but there is no evidence of an original general association of gold with this rock. Superimposed on the general abundance of pyrite are geochemical enrichments in Cu and As, which are particularly marked in borehole 3 but absent from borehole 4. The source of these elements is not clear but it is probably relatively early, ie pre-deformation, and may be related to a hydrothermal system similar to that responsible for the mineralisation at Wadham Rocks.

After the deformation of the Devonian sequence and its emplacement as part of the stack of thrust sheets transported from the south, the whole area was subjected to further hydrothermal activity by low salinity aqueous solutions which attacked quartz veins and deposited dolomite and minor amounts of sphalerite and galena to the west of the confluence. The whole sequence seems to have been subjected to this activity as small vuggy veins are present right through the core. There may also have been emplacement of some thicker quartz+carbonate veins carrying minor gold during this phase of activity.

Subsequently, there was further brittle deformation, and linear zones of deformed rock were subjected to oxidation from solutions derived from overlying Permian rocks, which penetrated considerable distances down into fractured Devonian rocks. These solutions were low temperature but saline and highly oxidising and caused clay alteration of the sedimentary rocks and deposition of some dolomitic carbonate. The Pd-rich gold in dendritic forms and the potarite and other complex Pd and Pt-bearing grains, found within the overburden and weathered rock within the east-west trending zone around the confluence, are thought to be derived from these solutions. Deposition occurred where the oxidising solutions reacted with the underlying reactive pyritic rocks with a sharp change in redox potential (Leake et al., 1991). Following removal of overlying Permian rocks by erosion, the soft and altered mineralised zone was preferentially eroded and residual material rich in precious metals may have accumulated near surface, perhaps within cracks within the weathered rock. Some modification of the original precious metal grains may have taken place at this stage, with corrosion and redeposition of gold and other elements, but in many cases the dendritic and other delicately shaped grains retained their original form.

ECONOMIC POTENTIAL OF SOUTH DEVON FOR GOLD MINERALISATION

The results described in this report indicate that there are two main contrasting varieties of precious metal mineralisation which have potential economic significance. The earlier phase of polymetallic mineralisation with geochemical characteristics similar to epithermal mineralisation probably occurs in at least four localities. These areas are (a) Wadham Rocks, (b) Churchill Farm, (c) east of Chivelstone and (d) the area around and to the west of the old Loddiswell mine. The mineralisation and hydrothermal alteration at Wadham Rocks extends for over 700 m and is generally up to 10 m wide. The soil and rock sampling at Churchill suggests that hydrothermal

alteration and mineralisation are present within a zone at least 300 m wide and of unknown extent along strike, suggesting that a much bigger centre of hydrothermal activity may exist. Further work is required to trace the extent of this mineralisation, as sampling has been confined to the vicinity of the initial reconnaissance soil line. Information as to the vertical extent of the mineralisation and zonation in precious metal content is lacking, and drilling is required to obtain mineralised material beneath the surface weathered zone. The drainage data suggest that a centre of polymetallic mineralisation may exist to the east of Chivelstone, connected with which a structure, probably carrying gold, runs through Chivelstone and further to the west. It is probable that mineralisation of the type found at Brownstone may follow this same structure. Further work is required to locate any centre west of Chivelstone and to assess its dimensions and the intensity of mineralisation. The drainage data also indicate that an elongate area to the west of the Loddiswell mine may be a centre of polymetallic mineralisation, but no overburden sampling to confirm this has so far been carried out.

Most of the precious metal mineralisation, however, belongs to a later phase of activity. It is apparent that all, or almost all, the gold grains which are so widespread throughout south Devon are derived from zones within the Devonian rocks that have been altered by oxidising saline solutions derived from the Permo-Triassic. This can be stated with some confidence because of chemical constraints on the transport and deposition both of the Au, Pd, Hg, Pt, Cu and Ag which make up the grains and also the selenide inclusions (Leake et al., 1991). Furthermore, similar Pd-bearing gold and gold containing selenide inclusions has been found in material derived from Permian rocks. Accordingly, the mineralisation in south Devon is likely to be locally rich, but possibly of limited vertical extent, and is also likely to increase in intensity as the original Permian surface is approached. Areas of greatest mineral potential are therefore likely to be where major structures within favourable reactive rocks, such as pyritiferous slates or limestones, pass beneath Permian strata. In these areas the Permian unconformity and structures within its basement are likely to be the most favourable environments.

It is not clear to what extent pre-existing enrichments of Au in the underlying rocks may influence the precious metal content of the mineralisation derived from the Permian saline solutions. Oxidative alteration of the large amounts of potentially mineralised Devonian volcanic and other rocks that may have been eroded and deposited within the Permian sedimentary sequences could have provided a substantial source of many metals. However, the widespread occurrence of gold in drainage from south Devon, in areas with no evidence of earlier mineralisation, suggests that the main source of precious metals may have been within the Permian itself, perhaps in association with volcanism.

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