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**Gold and platinum group minerals in  
drainage between the river Erme and  
Plymouth Sound, south Devon**

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and M T Styles



Technical Report WF/90/2 (number is WF/90/003)

Mineral Resources Series

## Gold and platinum group elements in drainage between the River Erme and Plymouth Sound, south Devon

### *Cover photographs*

Front cover: The grains of gold are from a drainage sample from a site east of the River Erme: the largest are about 1 mm long.

Back cover: *Left* Single grain 1.7 mm long of platinum on gold from drainage.

*Right* Group of gold and PGE-rich grains from drainage. Electron probe surface analysis of the grains gives in percentages (clockwise from top left):

- [1] 90 Pt, 10 Hg
  - [2] 74 Pt, 12 Cu, 9 Au, 4Hg, 1 Pd
  - [3] 94 Au, 4 Pd, 2 Pt
  - [4] 79 Pt, 11 Cu, 5 Au, 4 Hg
  - [5] 87 Pt, 13 Hg
  - [6] 43 Hg, 29 Au, 28 Pd
  - [7] 92 Au, 6 Pd
  - [8] 80 Pt, 10 Cu, 7 Au
  - [9] 80 Pt, 12 Hg, 8 Pd.
- Grain 1 is 0.6 mm long.

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*This report was prepared for the Department of Trade and Industry*

*Maps and diagrams in this report use topography based on Ordnance Survey mapping*

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## SUMMARY

Significant amounts of gold have been found in drainage sediment at several localities in the area between the estuary and lower part of the River Erme and Plymouth Sound in south Devon. Gold is particularly abundant at a site about 2 km to the southwest of Holbeton where many of the grains are dendritic or otherwise extremely irregular in shape. The dendritic gold shows internal zonation of Pd abundance very similar to that seen in material within carbonate veins in limestone at Hope's Nose, Torquay. Other grains show incomplete rims rich in Pd (up to 13%) or are close to pure gold in composition. Grains with silver-rich rims are much less common than in drainage and overburden samples from east of the River Erme. Associated with the dendritic gold from southwest of Holbeton are dendritic, elongate knobby and subrounded grains rich in either Pt or Pd or both, forming around 5% of the total. Though some grains are either pure potarite (PdHg) or Au-bearing potarite without significant internal compositional variation, the majority, including all those containing a significant amount of Pt, show very complex compositional zonation. Six PGE-bearing compositional types have provisionally been recognised. The cores of grains are generally Au-rich either Au with minor contents of other metals or Au with significant Pd and Hg. Rims are generally Pt-rich, often with a significant Au or Cu content which may be recognisable as a distinct thin zone. Other compositions include Pt with a significant Hg content and a combination of roughly equal amounts of Pd, Hg, Au and Pt. Some grains show clear concentric zonation and there may be very major compositional differences between zones only a few microns thick.

Cinnabar occurs in small amounts in several drainage samples from the area but is particularly abundant (up to 2000 ppm Hg) in samples derived from an area underlain by Middle Devonian chiefly mafic volcanic rocks in the northeast of the area. The distribution of Mg, Ca, Ti, Mn, Fe, S, Ni, Cu, Zn, As, Rb, Zr, Sn, Sb, Ba, W, Pb and Bi in drainage samples is also discussed. Au concentrations show greatest positive correlation with Mn and Fe but a correlation with Sn is also significant.

## INTRODUCTION

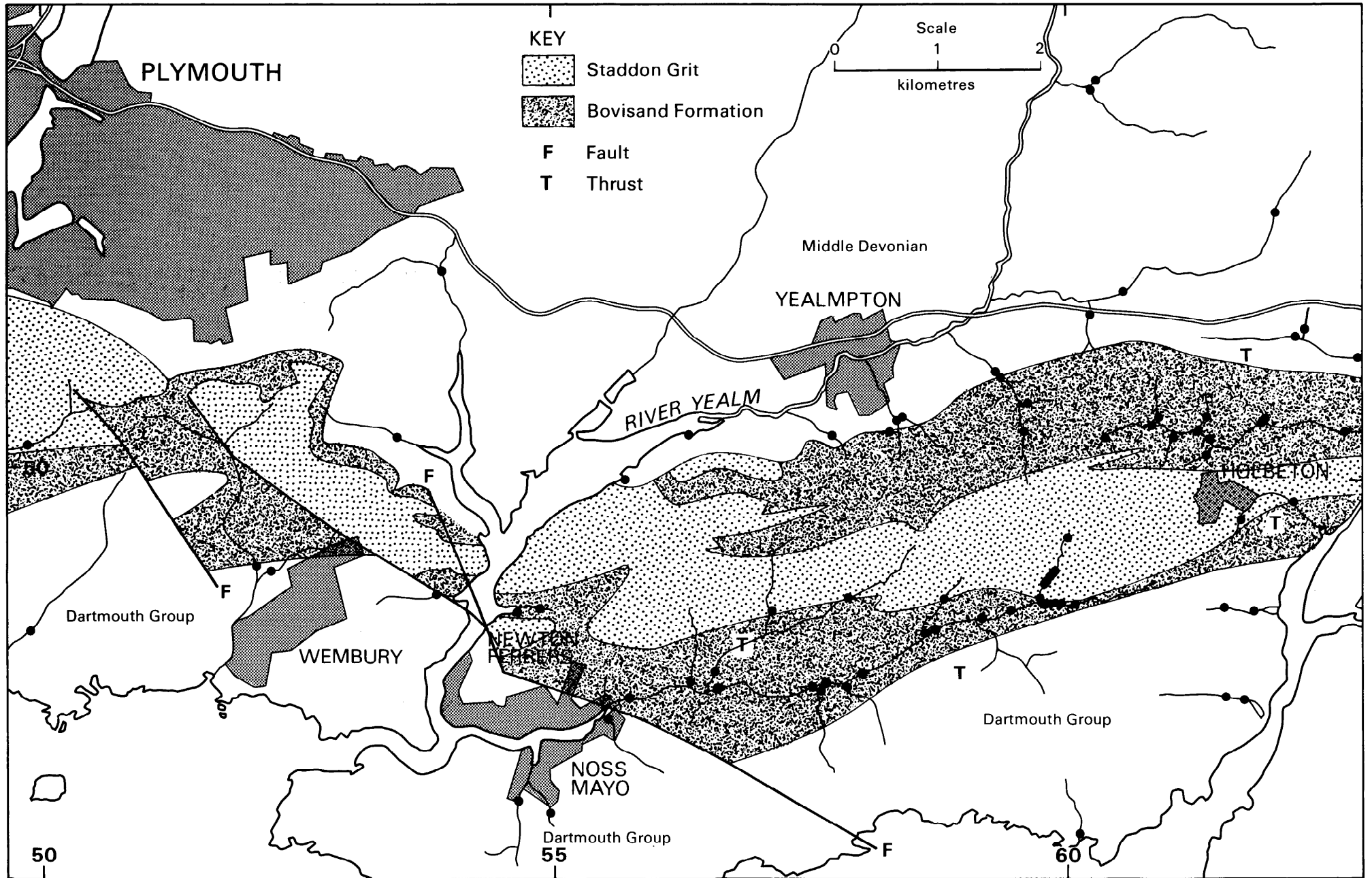
Following the discovery of significant amounts of gold in drainage samples in the area mostly underlain by Lower Devonian rocks between the lower valleys of the rivers Erme and Avon in South Devon (Leake et al., 1988) exploration was extended eastwards of the Erme valley as far as Plymouth Sound. This report describes the results of this drainage exploration and the locations of anomalous concentrations of gold and other elements. Systematic mineral exploration has not previously been carried in this area and knowledge of the area's geology and mineral potential is poor.

The gold from the area, especially from a site about 2 km to the south-west of the village of Holbeton, has a number of attributes which are unusual and of considerable interest. In particular the gold is often dendritic or otherwise intricate in shape and relatively enriched in the platinum group element (PGE) palladium. Moreover there are also grains richer in palladium and platinum, including grains of the platinum group mineral potarite (PdHg). The platinum-bearing grains, some of which have been investigated in detail, are of especial interest as they exhibit growth zonation of a type not previously described. The occurrence of these PGE-rich grains in an area dominated by sedimentary rocks, with no trace of ultramafic rocks, suggests that much remains to be learnt about the controls of PGE enrichment. Furthermore the complex internal zonation of the PGE-rich grains clearly demonstrate the mobility of Pt, Pd, Au and Hg in a low temperature environment by processes clearly not yet understood.

The results of detailed overburden sampling, ground geophysical surveys and the drilling of four boreholes in the anomalous area to the south-west of Holbeton will be described in a later report. Also included in this report will be details of gold-bearing mineralisation found in nearby coastal exposures of Lower Devonian rocks.

## PHYSIOGRAPHY

The area is topographically a plateau situated south of the Dartmoor massif and bounded by sea cliffs to the south. It is split into two peninsulas by the estuary of the River Yealm (Fig 1). The area presents a relatively level appearance, ranging in height from 140 m in the north-east of the area to around 100 m along the cliff tops in the south of the area. The drainage occupies relatively deep valleys, the lower sections of which are often tidal. The major valleys cut across the roughly east-west strike of the Devonian rocks but there is some significant strike-parallel drainage. Drainage in the Wembury peninsula is radial from the highest ground. Convex slopes into the valleys are the main landforms which do not appear to reflect any geomorphic processes except for soil creep and possibly periglacial action. Head deposits are found in the upper parts of some valleys for example, in the area north-west of Holbeton. Many of the smaller streams occupy asymmetrical valleys, a form often considered to reflect periglacial action. Terraces are not sufficiently well developed in the smaller valleys to affect the drainage sediment sampling except in the Newton stream, flowing into the sea between Newton Ferrers and Noss Mayo



**Figure 1** Geological map of the survey area and drainage sampling points

(Figure 1). The Newton stream is of particular interest because of the location of a highly anomalous site in its headwaters. It occupies a relatively broad and shallow-sided valley following the Bovisand Formation (Figure 1). At its eastern end the streams have been greatly modified by man and mill leats and drainage channels have been cut into the valley side.

#### GENERAL GEOLOGY

A general geological map of the area taken from the 1974 and 1975 editions of the 1:50 000 Geological Survey mapsheets, Ivybridge (349) and Kingsbridge and Start Point (355/356) respectively, is given in Figure 1. The area is at present being remapped at the 1:10 000 scale and the interpretation of the geology discussed below is based on a combination of the preliminary results of this work and geochemical overburden mapping and rock sampling. Within the outcrop of Lower Devonian rocks in the study area four major thrust sheets have been recognised (B.E. Leveridge, pers. comm., 1990). From south to north these comprise firstly the Dartmouth Group consisting of purple, green and pale grey slaty mudstone and siltstone containing some thick units of sandstone and quartzite and sporadic tuffs and mafic lavas. Geochemical overburden traverses and a 1.5 km rock sampling traverse along the eastern side of the Erme estuary (at the SE corner of Figure 1) suggest that separate units of two general types can be recognised within the Dartmouth Group. These are distinguished by differing proportions of arenaceous to argillaceous rock and in the composition of the interlayered volcanic material. The more shale-rich sequences contain mafic volcanic layers mostly with relatively evolved compositions (Ti, P, Y, Zr and Nb-rich). The more arenaceous sequences contain mafic volcanic rocks which are predominantly more primitive in composition (Mg, Cr and Ni-rich, Zr and Nb-poor). The significance of these differences is not yet clear but the environment of deposition of the Dartmouth Group rocks is thought to be a highly unstable rift environment containing fluviatile and playa sequences. A detailed sedimentological study of coastal exposures of the Dartmouth Group on the east side of Plymouth Sound (Smith and Humphreys, 1989) recognised three facies associations. From north to south these are interpreted as deposition in a) shallow perennial lake, b) deeper lake with unstable margins and c) a distal fluviatile environment with only subordinate lacustrine deposits.

North of the Dartmouth Group is a thrust-bounded unit of the Bovisand Formation consisting of grey slaty mudstone with thin beds of sandstone and very minor mafic tuff horizons. In the Bovisand Bay section [SX 492 502] there are also phosphatic sediments and thin limestones. Northwards this is succeeded by a further thrust unit comprising the Staddon Formation, consisting of thin to thick sandstone beds with interbeds of grey slaty mudstone, underlain to the north by the Bovisand Formation. This is followed to the north by a further thrust unit of the Staddon Formation (not shown adequately on Figure 1).

The Lower Devonian rocks are succeeded to the north by the Jennycliff Formation and other units of the Middle Devonian sequence which includes relatively thick mafic volcanic units of generally alkali basalt

composition and the local development of thick limestone units.

The structural interpretation of the area is not yet clear but some features have emerged as a result of the geological mapping (B.E. Leveridge, pers. comm. 1989). The strata dip generally southwards at moderate angles with some areas where dip increases to vertical. Units are separated by south-dipping thrusts trending between 070 and 090 degrees which are displaced by later faulting. Two directions of major faulting are prominent. The first trends between 020 and 040 degrees and is followed by the estuary of the river Erme. The second trends 290 to 310 degrees and is characteristic of dextral wrench faults which can cause major displacements of the outcrops. There may also be relatively early faults trending 090 degrees, perhaps with some transcurrent movement, which have been reactivated during subsequent regional deformation.

## **RECONNAISSANCE GEOCHEMICAL DRAINAGE SURVEY**

### **Sampling and analysis**

Following the orientation work and regional survey of the area to the east of the Erme valley (Leake et al., 1988) panned heavy mineral concentrate samples of approximately 150 ml volume were obtained from about 12 kg of minus 2mm drainage sediment at sites shown in Figure 1. In most cases after drying samples were sieved to give 3 or 4 size fractions prior to a superheavy fraction being obtained on a Mozley shaking table. Individual grains of gold and platinum metals were hand-picked from the superheavy concentrate and weighed where possible. Many were retained for examination of shape characteristics and for electron microprobe analysis (EMPA). Gold concentrations in the individual concentrate samples were obtained either from chemical analysis of 60 gm subsamples of the size fractions or from the recombined samples, to which the contribution of the previously extracted and weighed grains was added. Samples ground in a Tema swing mill with Cr steel pot were analysed chemically for Au by acid digestion followed by solvent extraction and an atomic absorption finish at Caleb Brett International, St Helens, Merseyside. This two-stage procedure of estimation of gold concentration removed the subsampling problems associated with an attempt to grind up relatively large grains of native gold. The method also allowed an estimate to be made of gold present either as inclusions in other minerals or as composite grains, which would not be visually obvious in a superheavy fraction. In addition, 12 gm powdered subsamples of either size fractions or recombined samples were analysed for Mg, P, S, Ca, Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Y, Zr, Sn, Sb, Ba, W, Hg, Pb and Bi by XRF at Nottingham University on behalf of Caleb Brett International.

### **Results**

Summary statistics of the drainage data are given in Table 1.

**Table 1** Summary statistics of drainage data

	<b>N</b>	<b>Mean</b>	<b>SD</b>	<b>Min</b>	<b>Max</b>
MgO%	74	1.48	0.59	<0.01	2.84
P <sub>2</sub> O <sub>5</sub> %	35	0.12	0.05	0.01	0.23
CaO%	74	0.57	0.61	0.13	3.90
TiO <sub>2</sub>	74	1.20	0.76	0.58	5.44
MnO%	74	0.12	0.09	0.03	0.39
Fe <sub>2</sub> O <sub>3</sub> %	74	12.81	7.50	4.20	42.51
S ppm	74	375	255	110	1484
Ni ppm	74	48	14	23	95
Cu ppm	74	92	252	5	2022
Zn ppm	74	118	89	49	515
As ppm	74	33	39	7	291
Rb ppm	72	67	19	38	118
Y ppm	33	27	13	16	85
Zr ppm	74	241	128	129	870
Sn ppm	74	1496	2788	16	13495
Sb ppm	74	11	13	<1	55
Ba ppm	74	321	108	180	830
W ppm	59	20	66	<1	412
Au ppb	74	1777	7879	<10	>47700
Hg ppm	39	63	322	<1	2006
Pb ppm	74	284	662	14	4992
Bi ppm	59	2.5	2.8	<1	12

N = number of samples; SD = standard deviation  
 Total Fe is expressed as Fe<sub>2</sub>O<sub>3</sub>

#### Multivariate statistical treatment

Principal component analysis was carried out on the data set and correlation coefficients significant at the 99% confidence limit involving metallic elements of interest are tabulated below.

**Table 2** Selected Correlation coefficients

	<b>MnO</b>	<b>Fe<sub>2</sub>O<sub>3</sub></b>	<b>S</b>	<b>Cu</b>	<b>Zn</b>	<b>As</b>	<b>Sn</b>	<b>Sb</b>	<b>Au</b>	<b>Pb</b>
CaO			0.45		0.43			0.41		
TiO <sub>2</sub>	0.34		0.33		0.58	0.33		0.39		
MnO		0.42							0.33	
Fe <sub>2</sub> O <sub>3</sub>	0.42			0.35	0.44	0.49	0.40	0.53	0.57	0.39
S					0.35					
Ni			0.32	0.34	0.64	0.65		0.58		0.34
Cu		0.35						0.34		0.87
Zn		0.44	0.35			0.53	0.36	0.69		
As		0.49			0.53			0.59		
Sn		0.40			0.36			0.30	0.33	
Sb		0.52		0.34	0.69	0.59	0.30			0.33
Au	0.33	0.57					0.33			
Pb		0.39		0.87				0.33		

The eigenvectors for the first five principal components with eigen values in excess of 1.0 are shown in Table 3.

**Table 3** Eigenvectors

	Prin1	Prin2	Prin3	Prin4	Prin5
MgO	-0.02	0.40	-0.00	0.11	0.53
CaO	0.22	0.16	-0.17	-0.29	0.49
TiO <sub>2</sub>	0.25	-0.20	-0.36	-0.16	0.13
MnO	0.14	-0.32	-0.11	0.22	0.24
Fe <sub>2</sub> O <sub>3</sub>	0.35	-0.28	0.13	0.20	0.05
S	0.22	0.12	-0.05	-0.30	0.22
Ni	0.38	0.19	-0.09	0.15	-0.07
Cu	0.23	0.11	0.57	-0.19	-0.06
Zn	0.37	0.01	-0.21	-0.11	-0.08
As	0.30	-0.06	-0.19	-0.01	-0.36
Rb	0.06	0.46	-0.08	0.30	-0.19
Zr	-0.14	-0.26	0.06	-0.46	-0.14
Sn	0.21	-0.18	0.19	0.16	-0.03
Sb	0.36	-0.03	-0.08	-0.10	-0.15
Ba	0.13	0.30	-0.02	0.22	-0.20
Au	0.07	-0.33	0.20	0.46	0.30
Pb	0.24	0.12	0.55	-0.18	0.04

The first eigenvector (Table 3) can be interpreted as reflecting the difference between the Middle and Lower Devonian rocks and their associated mineralisation. Thus this first principal component has significant positive contributions from Fe, Ni, Zn, As and Sb. These elements taken as a group are all enriched in the samples derived from the Middle Devonian rocks. The second eigenvector shows strong positive contributions from Rb, Ba and Mg and reflects the dominant presence of argillaceous rock fragments particularly those of the Dartmouth Group. It also shows a relatively high negative contribution from Au. The third eigenvector is dominated by Cu and Pb and reflects contamination of samples with metal-rich domestic rubbish. The fourth eigenvector is similar to the second except that it contains a strong positive contribution from Au. This presumably reflects the presence of Au in some samples derived from sedimentary rock catchments and the absence of any correlation between Au and volcanic rocks found in the Middle Devonian outcrop. Eigenvector 5 is perhaps the most interesting as it contains positive contributions from Au together with Mg and Ca, which suggests a correlation between gold and dolomitic carbonate. This correlation has been confirmed by systematic rock sampling of coastal exposures.

Of the 22 elements in Table 1 the distributions of all but P<sub>2</sub>O<sub>5</sub> and Y are plotted in class interval form in Figures 2 to 21. These two elements have been omitted because of a relatively small number of determinations and limited contrast. Class intervals have been chosen by analysis of the cumulative frequency plot for this data set combined



with that for the drainage samples from the area to the east of the river Erme (Leake et al., 1988). This provides a larger number of samples derived from essentially the same rocks.

### Magnesium

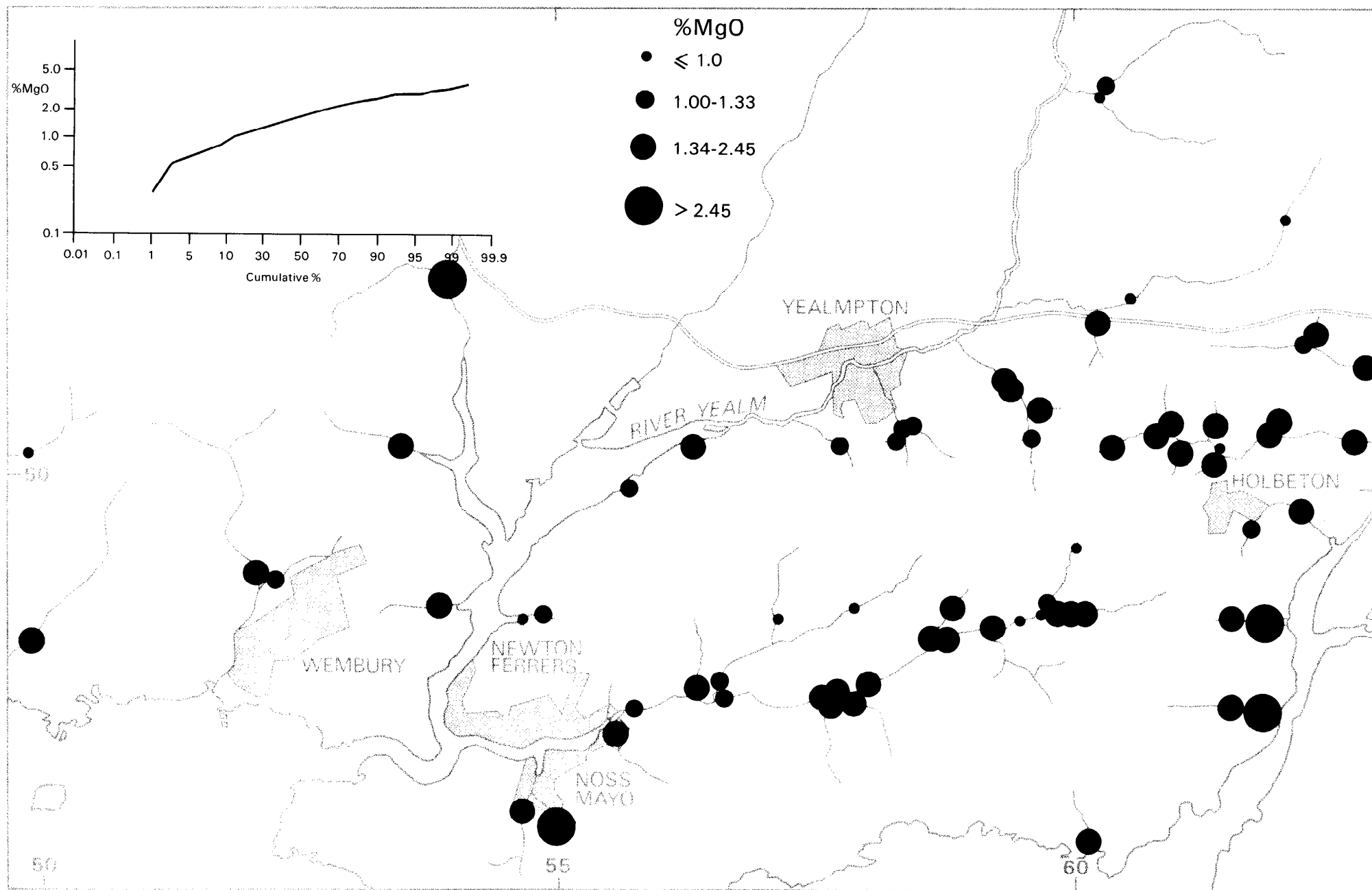
A map showing the distribution of MgO in panned concentrates is shown in Figure 2. Comparison of this with the geological map in Figure 1 shows that relative Mg depletion is associated with the outcrop of the Middle Devonian rocks and also of the outcrop of the Staddon Grit, especially between Newton Ferrers and Holbeton. Samples most enriched in Mg are derived from the Dartmouth Group but the degree of enrichment is not as pronounced as that found in samples from the southernmost part of the outcrop of the Dartmouth Group to the east of the Erme estuary (Leake et al., 1988). Concentrations of Mg are nowhere high enough to suggest that there are significant amount of ultramafic rock or even substantial amounts of basic rocks of relatively primitive composition which suboutcrop in the area.

### Calcium

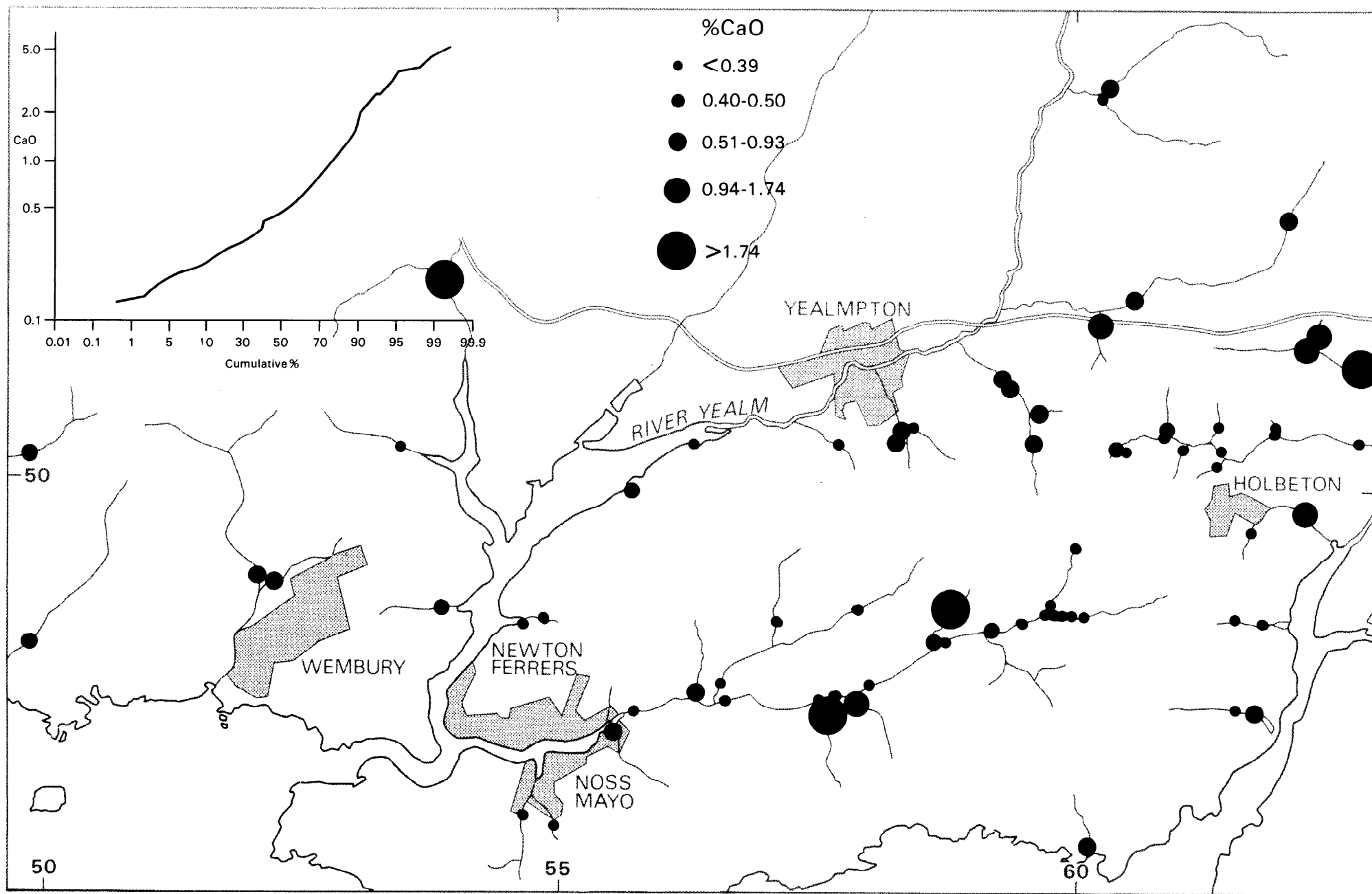
Relatively high concentrations of CaO (Figure 3) are found in samples derived from the area just south of the main road, east of Yealmpton, where a belt of Middle Devonian rocks containing mafic volcanic rocks together with some limestone is known to occur. Samples derived from the Lower Devonian rocks generally contain relatively low concentrations of Ca, but there are scattered anomalies. In some of these samples Ca shows a positive correlation with Ti and probably reflects Ca present in sphene or pyroxene and amphibole derived from mafic igneous rocks. Principal component analysis of the drainage data suggests that Au is both negatively and positively correlated with Ca in different eigenvectors (Table 3). In the latter case Ca is closely correlated with Mg which suggests a dolomitic carbonate association, which is supported by the observation of ankeritic and dolomitic carbonate in Au-rich samples from the area to the south-west of Holbeton.

### Titanium

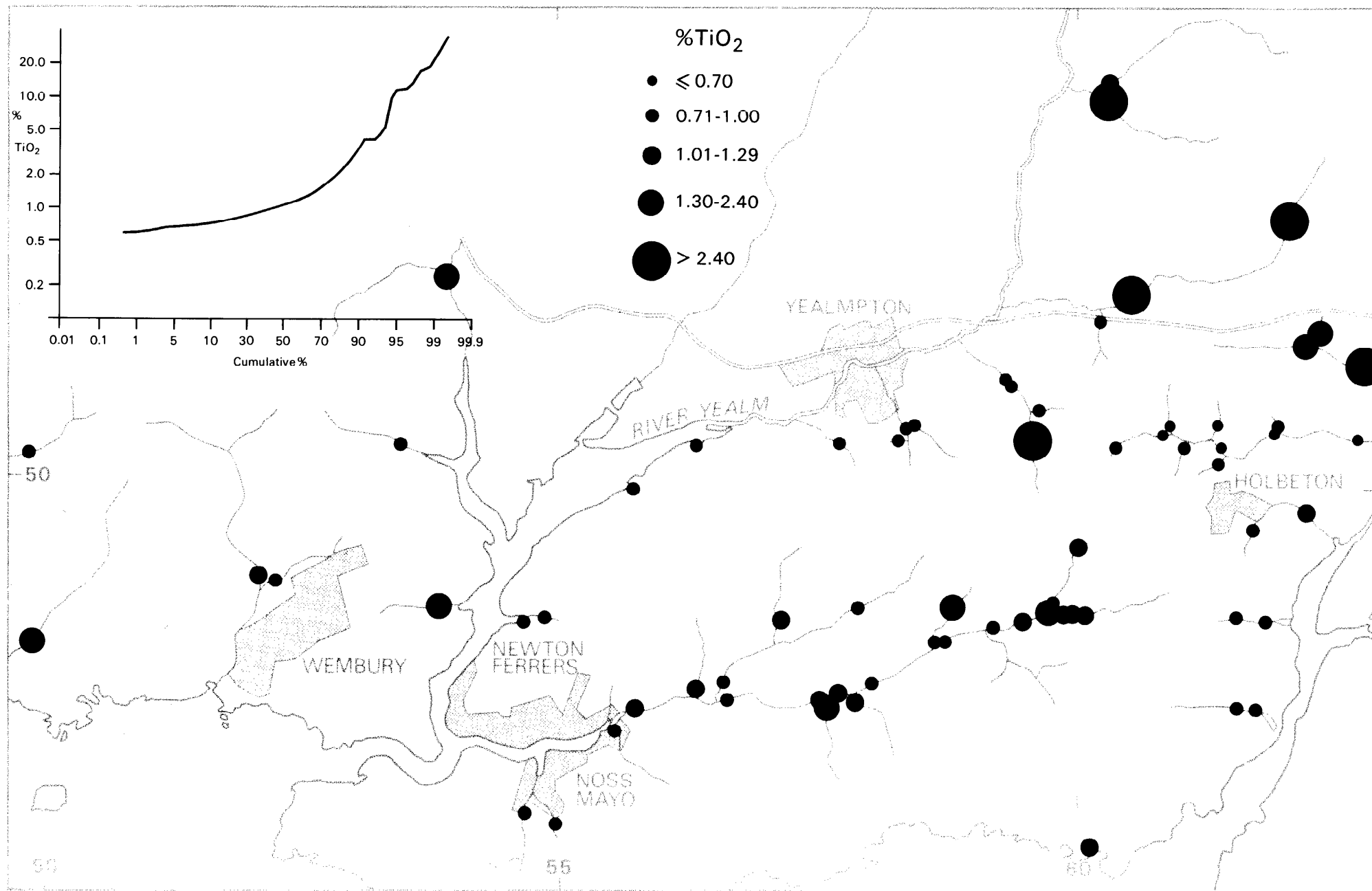
The highest concentrations of TiO<sub>2</sub> (Figure 4) are associated with the outcrop of Middle Devonian rocks in the north of the area. A sample derived from the Lower Devonian sequence to the west of Holbeton is also anomalous in Ti. No evidence of the existence of basic rocks in this area appears on the old geological map though the level of Ti in the drainage sample suggests that a significant thickness of mafic rock is likely to occur upstream of the site. Comparison of ratios of Ti to Fe, Mn and Ca in this sample and those derived from the Middle Devonian volcanic rocks further north reveals significant differences (e.g. TiO<sub>2</sub>/Fe<sub>2</sub>O<sub>3</sub> 0.41 as compared with 0.19 for a Middle Devonian sample) which suggest fundamental differences in composition of the source rocks. The ratios are more similar to those characteristic of samples derived from the greenstone bodies within the Lower Devonian rocks to the north-west of Aveton Gifford, east of the Erme (Leake et al., 1988). A slight enrichment in Ti is also characteristic of the highly Au-rich samples from south-west of Holbeton. In these samples mineralogical



**Figure 8** Distribution of magnesium in drainage panned concentrates



**Figure 3** Distribution of calcium in drainage panned concentrates



**Figure 4** Distribution of titanium in drainage panned concentrates

examination suggests that the Ti is partly in the form of oxide minerals like rutile and anatase rather than exclusively as fresh or altered ilmenite which is more typical of the mafic igneous rocks.

### Sulphur

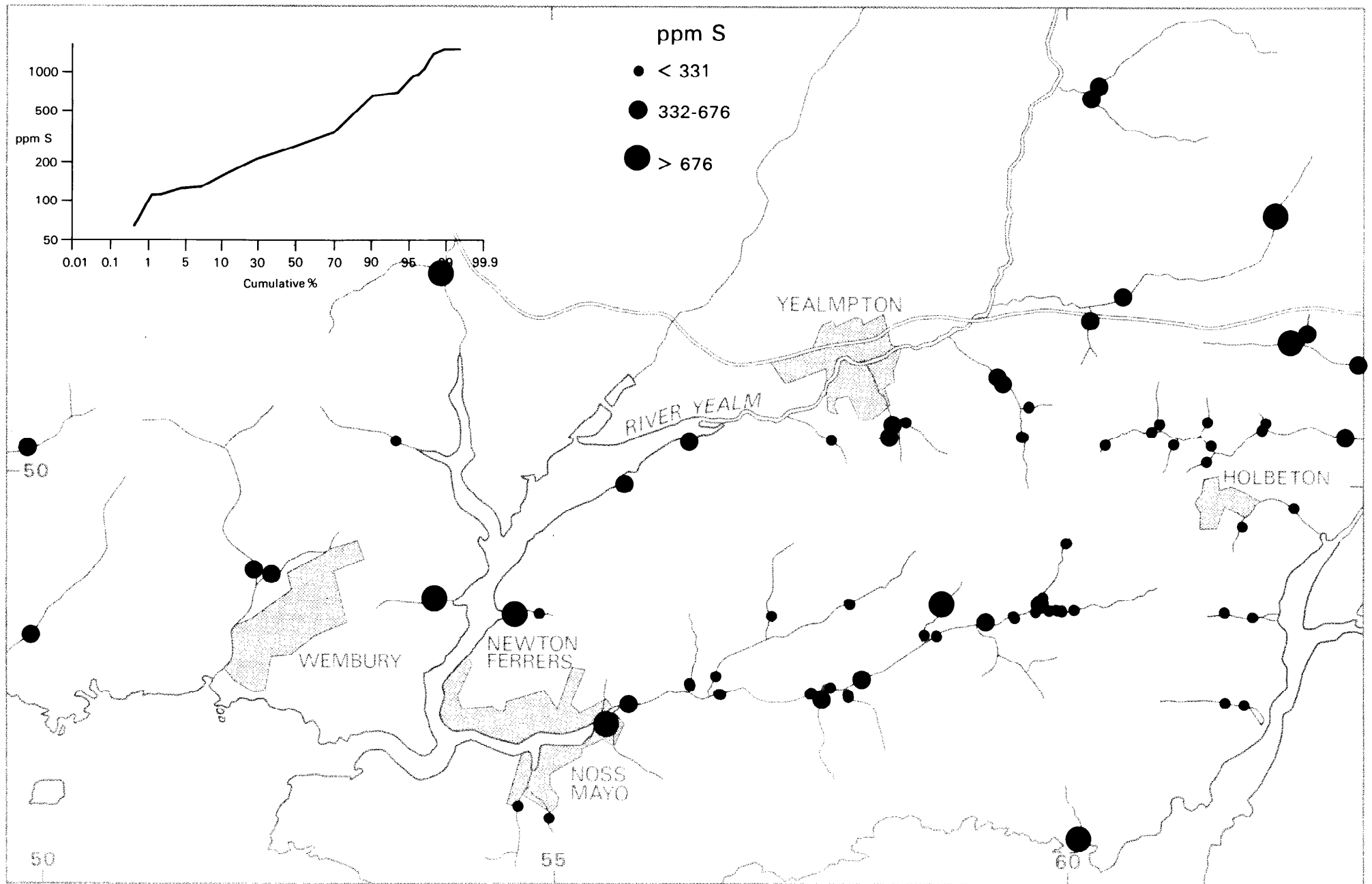
Samples derived from the Middle Devonian rocks in the north of the area are enriched in S compared with those derived from the Lower Devonian volcanic rocks (Figure 5). Borehole and coastal exposure evidence suggests that, at least for the Bovisand Formation, there is no correlation between S concentration in the drainage samples and the abundance of pyrite in the source rocks, which is commonly in the few percent range. The explanation for this lies in the deep tropical weathering that has affected the rocks of the area during past climatic regimes, probably stretching back as far as the Tertiary. Samples containing the highest S concentrations are of two types, some being associated with metal anomalies, others not. The S anomalies derived from the Middle Devonian rocks to the north-west of Yealampton are associated with metal anomalies largely of natural origin. Though samples from around Newton Ferrers, Wembury and Plymouth are contaminated with significant amounts of metal-rich domestic rubbish some may also contain metals of natural origin, especially those which have Middle Devonian rocks in their catchment. This is suggested by the analysed size fractions of the sample from the north-west of the area, near Plymouth, which shows a positive correlation between S and some of the metal levels, for example, Pb and Sb. This correlation would not be expected within metallic contaminants.

### Manganese

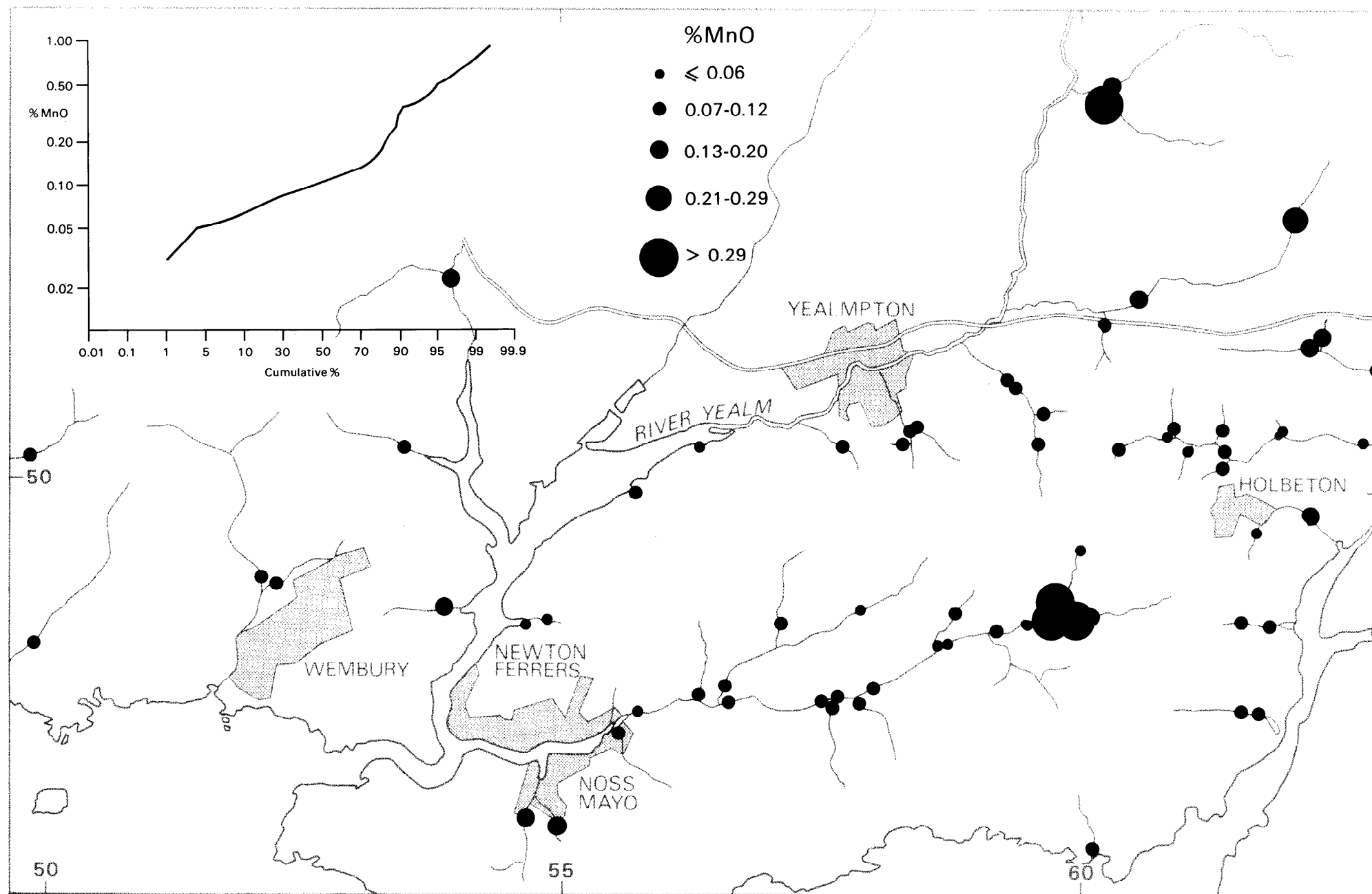
Manganese is concentrated in samples derived from the Middle Devonian rocks compared with those from the Lower Devonian rocks (Figure 6). In these samples Mn is correlated to some extent with Ti and accommodated mostly in ilmenite. Within the area of Lower Devonian rocks a clear concentration of anomalous samples occurs to the west of Holbeton in the area of high Au concentrations. Mineralogical examination of these samples indicates that the Mn is present within ankerite or ferroan dolomite type carbonate and in black oxides, probably derived from the oxidation of carbonate. Mn-rich samples are found eastwards from the confluence and the occurrence of a slightly anomalous sample to the east of Holbeton, also containing Au, suggests that the two areas may be related, perhaps derived from the same structural feature. Mn shows the second-most significant positive correlation with Au (Table 2), reflecting the samples from these two areas.

### Iron

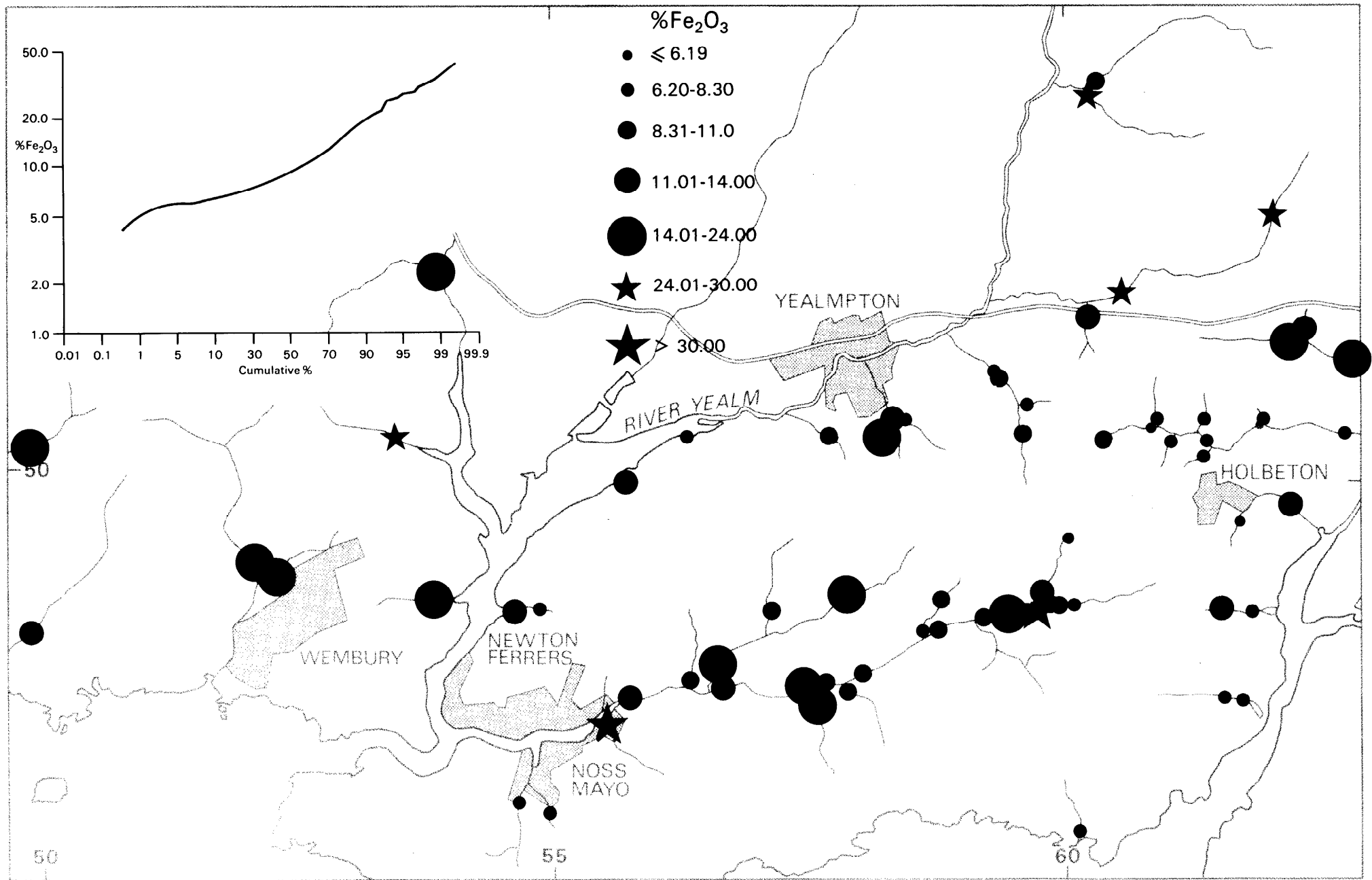
Concentrations of Fe are relatively high over the Middle Devonian rocks and highly variable over the Lower Devonian rocks (Figure 7). Within the outcrop of Lower Devonian rocks the highest levels of Fe (up to 42.5% Fe as  $\text{Fe}_2\text{O}_3$ ) are associated with the Au-rich samples from west of Holbeton. The influence of these samples results in Fe showing by far the most significant positive correlation coefficient with Au (Table 2). In these samples the Fe is present in four distinctive forms not normally found



**Figure 5** Distribution of sulphur in drainage panned concentrates



**Figure 6** Distribution of manganese in drainage panned concentrates



**Figure 7** Distribution of iron in drainage panned concentrates



except in minor amounts in concentrates from other areas. These are a) irregular unidentified hydrous iron oxide, b) radiating masses of goethite, c) siderite and d) both shiny and dull balls of iron oxide. Downstream dispersion of this material seems only to be a few hundred metres. The characteristics of other Fe-rich samples, for example at Noss Mayo and north of Wembury, appear to be different with a significant amount of Fe present in contaminants and perhaps only a minor component derived from mineralisation.

#### Nickel

The range in Ni concentrations in the drainage samples is relatively low compared with most of the other elements. Samples derived from the Middle Devonian rocks are enriched in Ni compared with those originating from the Lower Devonian rocks in general (Figure 8). The samples with the greatest Ni concentrations (from north of Wembury and at Noss Mayo) are also contaminated with a significant amount of metallic rubbish. In these samples Ni correlates closely with Fe. As some of the pyrite found within the Bovisand Formation contains significant amounts of Ni it is possible that Ni and Fe could occur naturally together in the weathering products of pyrite.

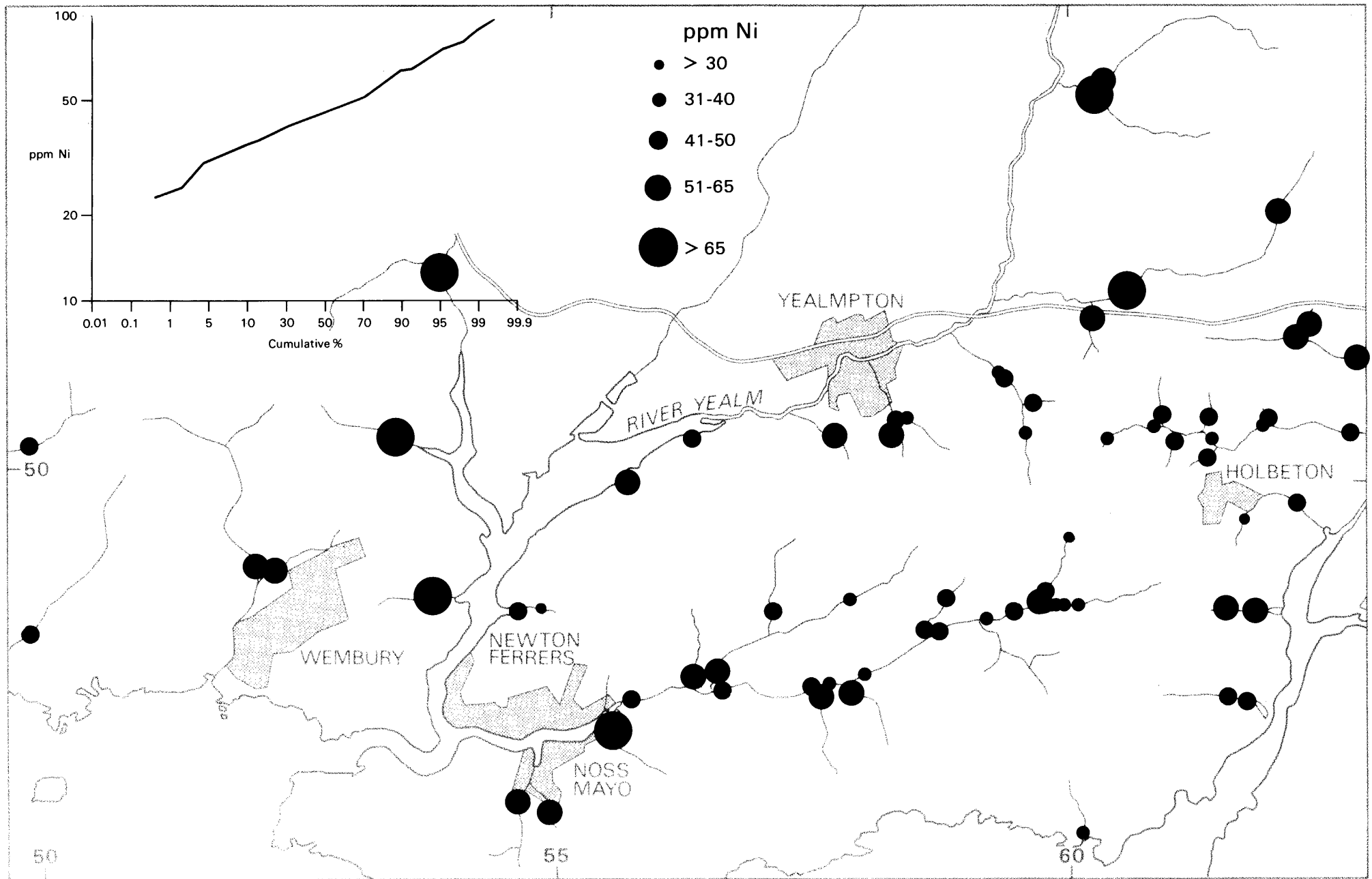
#### Copper

Several copper anomalies are found scattered throughout the area (Figure 9). A large proportion of these are due partly if not entirely to the presence of contaminants, chiefly copper wire. This applies to samples taken from south of Noss Mayo and Yealmpton. Contaminants also contribute significantly to all the Cu anomalies to the west of the River Yealm. The three anomalous samples to the south-west of Holbeton are all probably largely natural in origin as grains of chalcopyrite or other sulphides have been observed in them. This may also apply to the site east of Holbeton as no contaminants have been observed either at the site or in the sample, though contamination may be expected at such a site downstream of a village. The source of anomalies to the north and north-west of Holbeton is probably a mixture of contaminants and natural minerals as both have been observed in these samples. Principal component analysis of the data indicates that contamination is the biggest source of Cu variation in the area (eigenvector 3, Table 3).

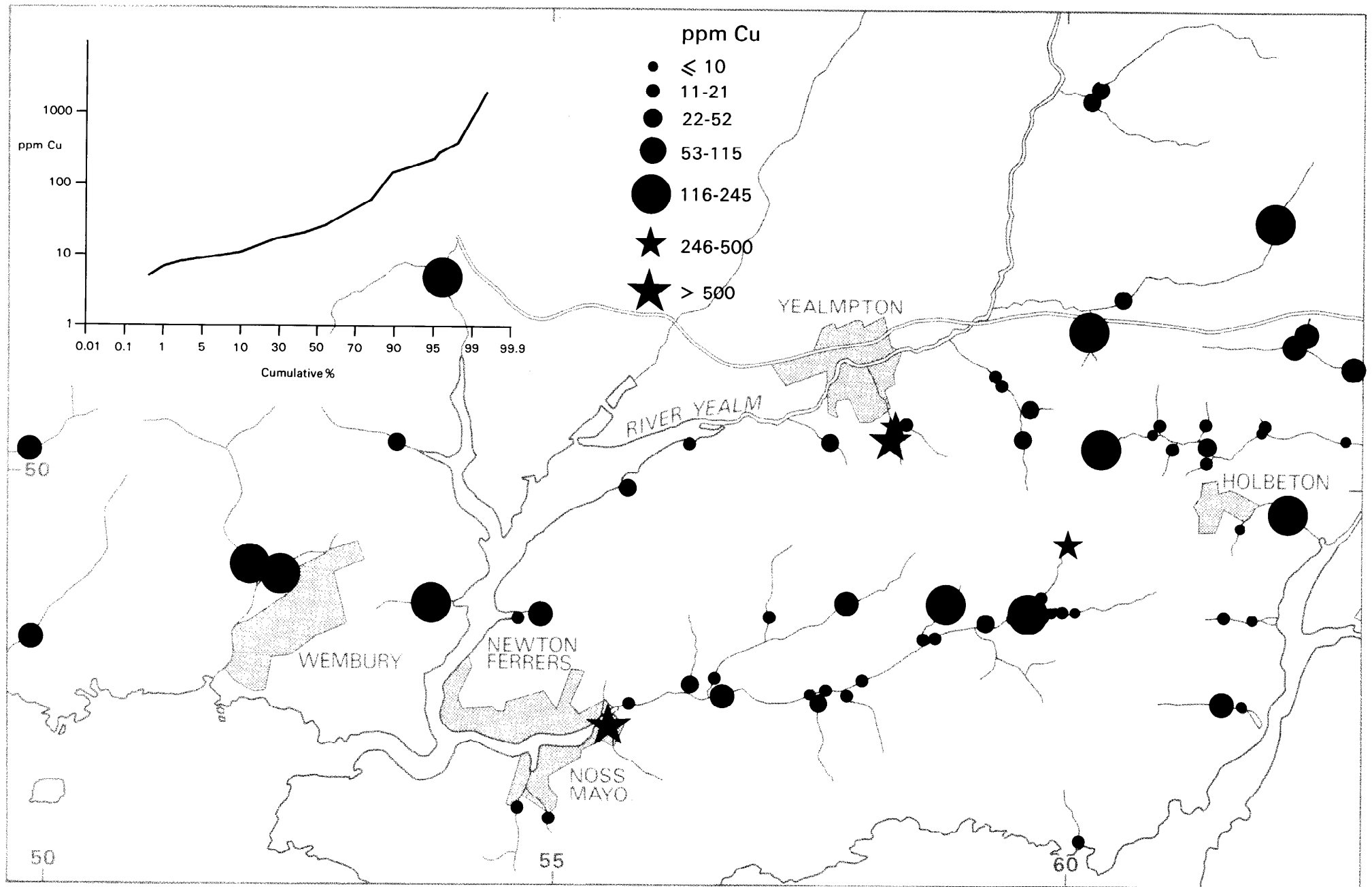
#### Zinc

Relatively low concentrations of Zn correlate generally with the outcrop of the Staddon grits (Figure 10). The highest Zn contents occur in samples derived from the Middle Devonian rocks and in these there is a correlation between Zn and Mn concentrations. This suggests that the Zn may be accommodated in carbonate-rich material, perhaps of the ferroan dolomitic type intersected in boreholes in the Higher Ludbrook

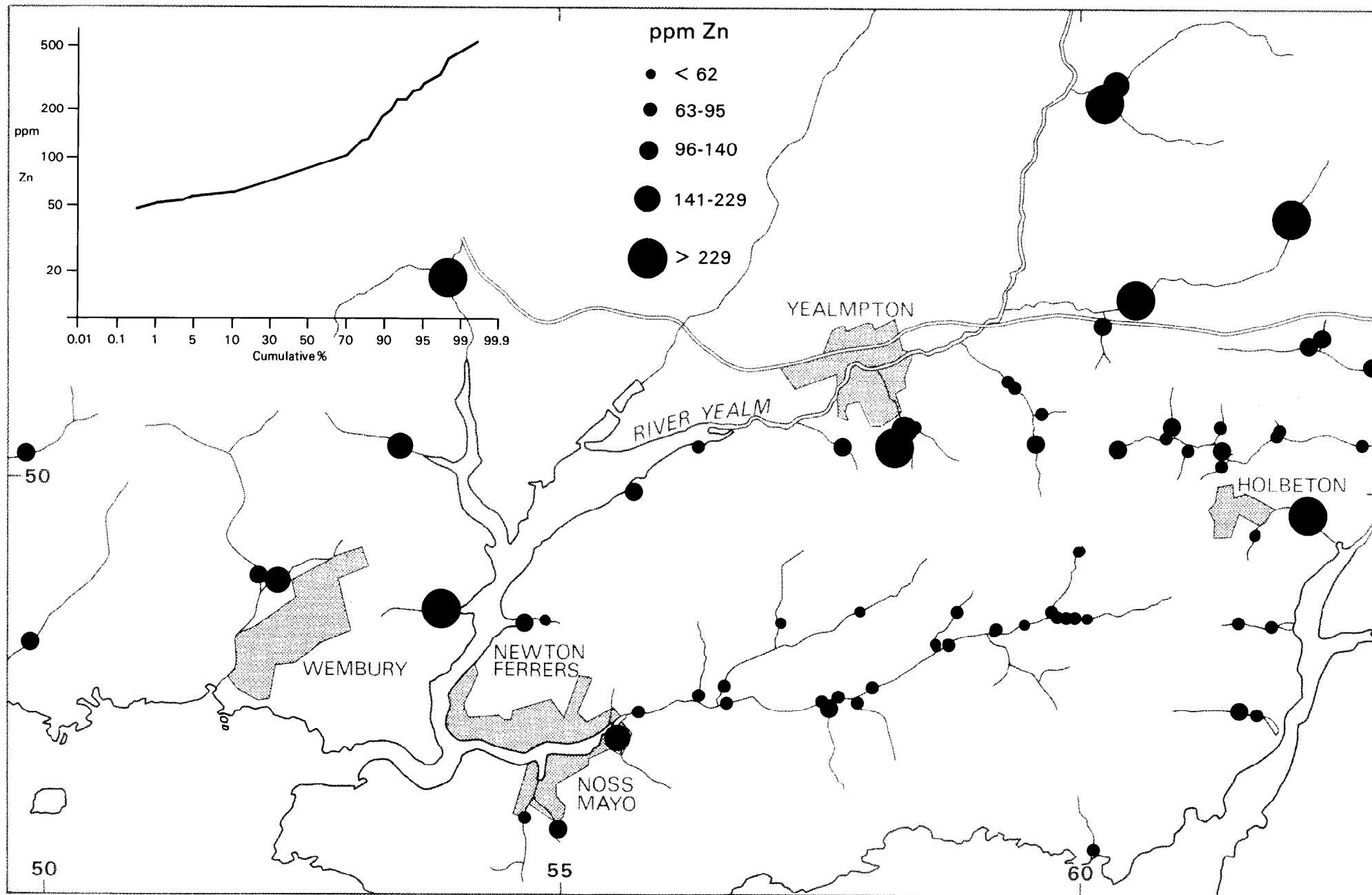
area further to the north-east (Leake et al., 1985). Elsewhere the origin of zinc anomalies is difficult to assess because many zinc-bearing contaminants are easily overlooked and the identification of sphalerite, especially in the presence of cassiterite, is difficult. However, most of the anomalies within the Lower Devonian rocks are thought to be



**Figure 8** Distribution of nickel in drainage panned concentrates



**Figure 9** Distribution of copper in drainage panned concentrates



**Figure 10** Distribution of zinc in drainage panned concentrates

derived from contaminants. The sampling site east of Holbeton is unusual in that a fine sediment fraction sample (minus 100 microns) collected at the same time as the panned concentrate is highly enriched in Zn (1170 ppm). Bias in favour of dispersion of Zn in fine sediment rather than coarse detrital material is not found at sites with typical metallic rubbish contamination. It may therefore reflect dispersion from a natural source of zinc, especially as Zn is also anomalous in the concentrate. Contamination from sewage effluent could also result in a Zn anomaly in fine sediment but this should not produce much of an anomaly in the panned concentrate. One borehole drilled in the Bovisand Formation contained widespread and locally quite abundant sphalerite though the drainage concentrate from the area is not anomalous in zinc. This could indicate that any sphalerite present in near surface rocks has largely been leached away during the intense chemical weathering phase that affected the area during the Tertiary and other times.

#### Arsenic

There is a marked contrast in As contents of the samples derived from the Middle Devonian rocks compared with the Lower Devonian rocks (Figure 11). The As enrichment in the former correlates closely with the Zn and Mn concentrations and is clearly of hydrothermal origin. Lower amplitude As anomalies also occur just south of the main road to the east of Yealmpton, where a structurally complex zone of Middle Devonian volcanic and other rocks is separated from the Lower Devonian rocks further south by major east-west faulting. The other As anomalies (south of Yealmpton, south of Noss Mayo and east of the River Yealm) are mostly at sites known to be contaminated with metallic rubbish. The high As anomaly in the sample from north-east of Wembury is perhaps more likely to be of natural origin since As correlates closely with Fe and Sb in the three size fractions analysed of this sample. No significant positive correlation between As and Au is apparent in the data (Table 2).

#### Rubidium

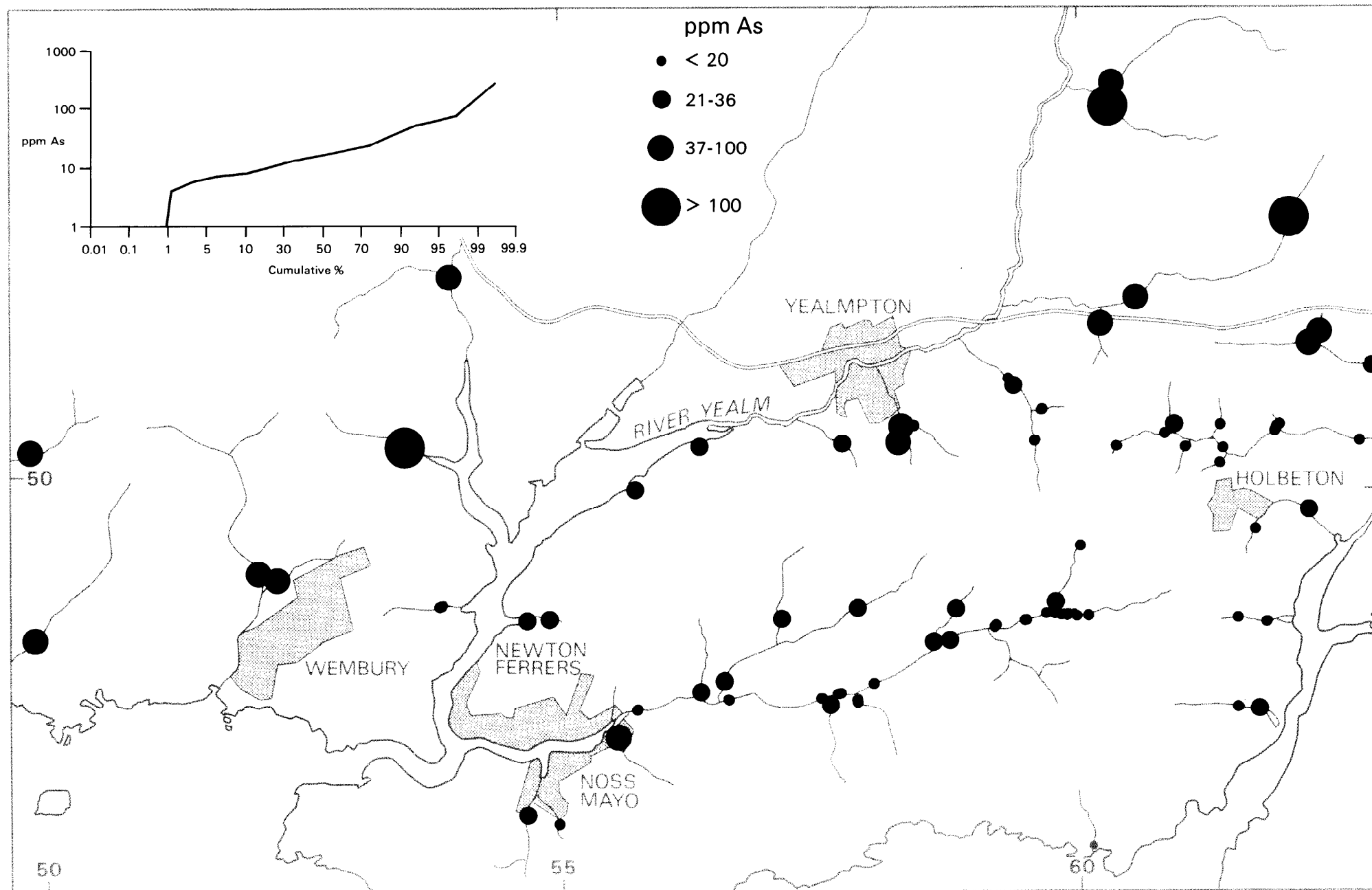
A marked depletion of Rb is apparent coinciding with the outcrop of the Staddon Formation (Figure 12). The small outcrop of Middle Devonian slates immediately south of the Yealm estuary is marked by particular enrichment in Rb. Rb does not exhibit significant positive correlation with any of the metallic elements of interest (Table 2).

#### Zirconium

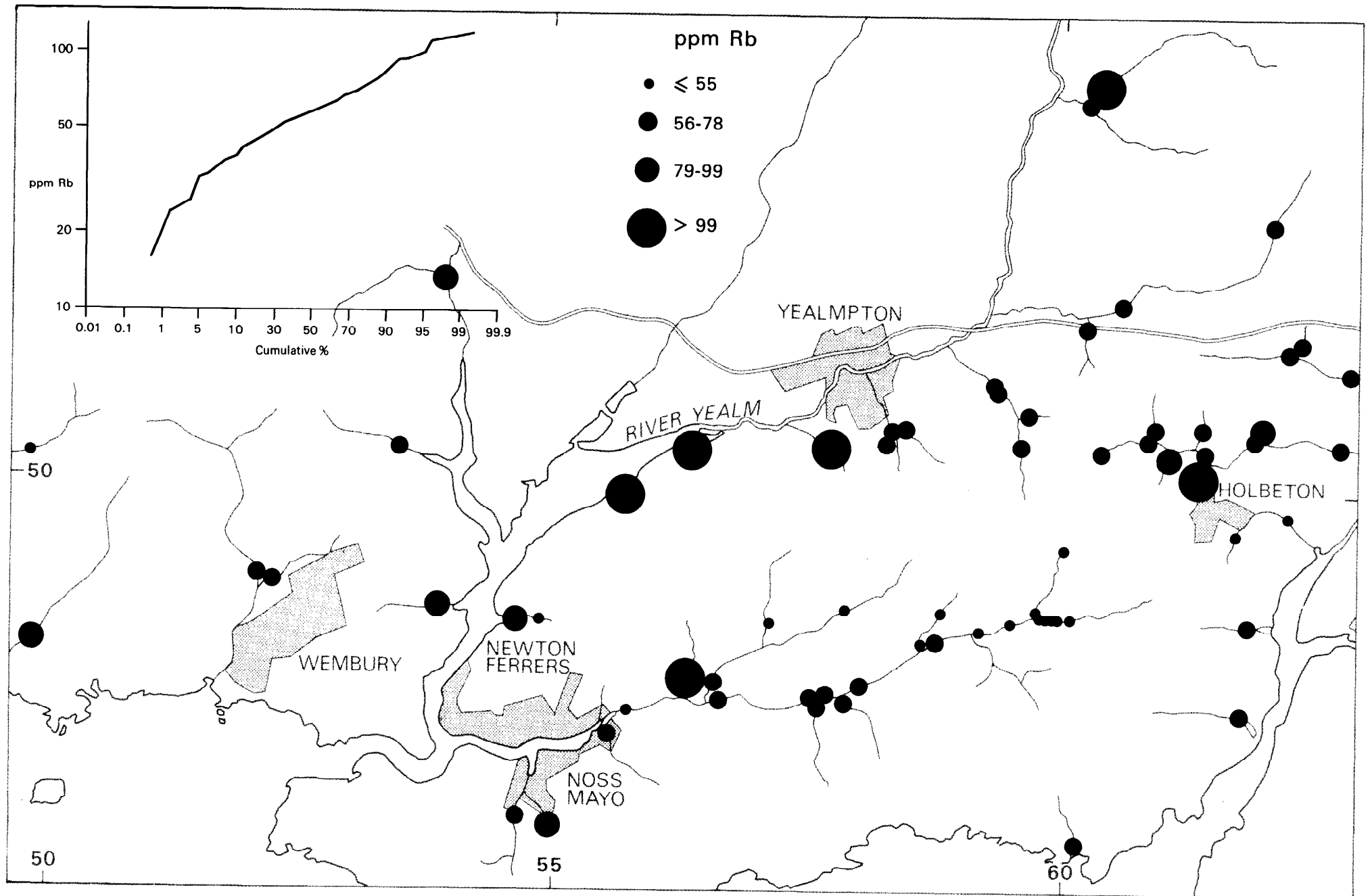
Samples showing enrichment in Zr (Figure 13) correlate with the outcrop of the Staddon Formation, which chemical analysis of rock samples showed to be arenaceous rocks relatively enriched in Zr. The drainage samples also suggest that the Middle Devonian rocks are depleted in Zr relative to the more argillaceous Lower Devonian rocks. There is no enrichment in Zr in any of the Au-rich concentrate samples.

#### Tin

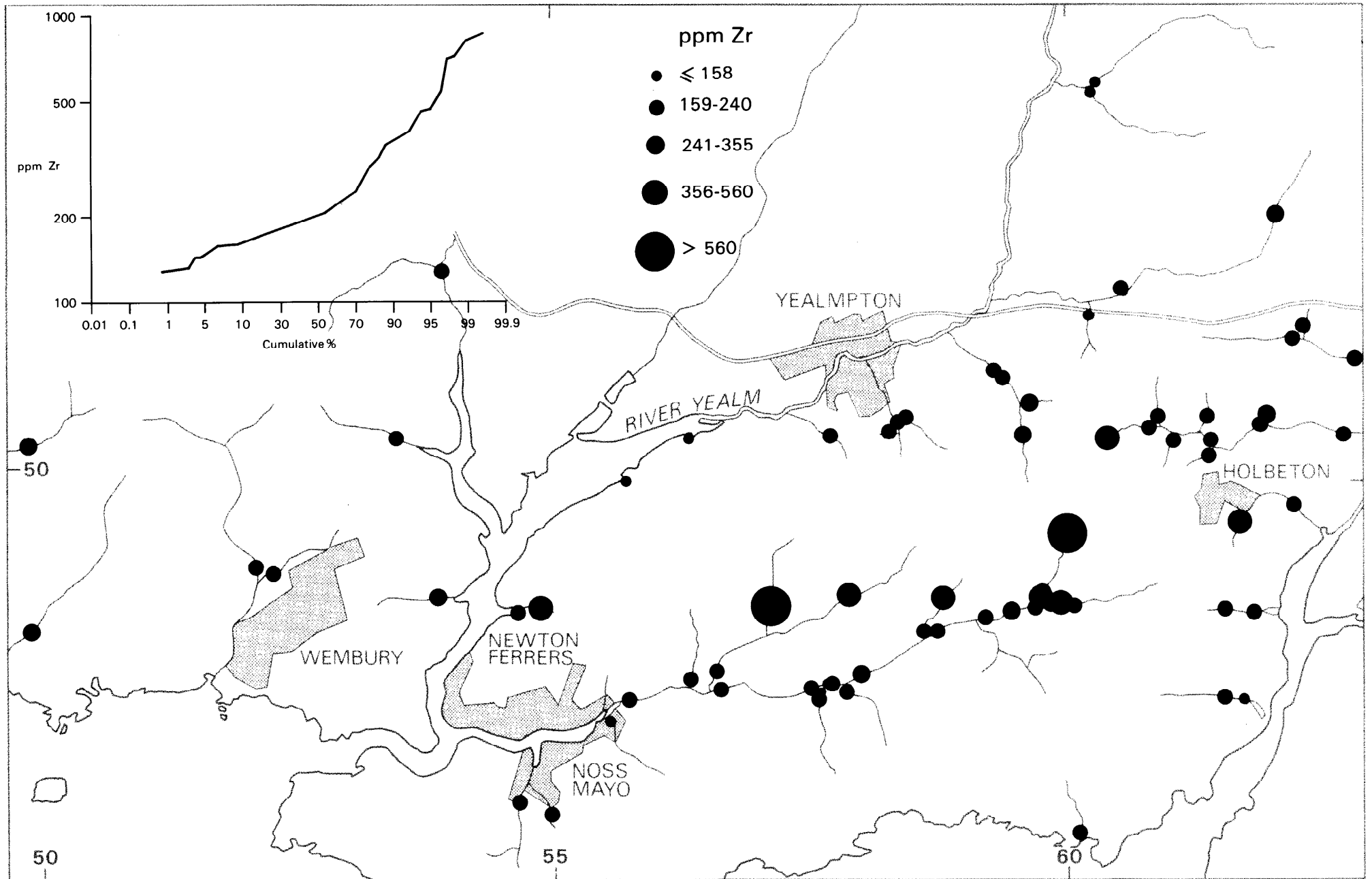
The Sn content of the panned drainage samples is extremely variable ranging from less than 10 ppm to 1.35%. The distribution of Sn anomalies



**Figure 11** Distribution of arsenic in drainage panned concentrates

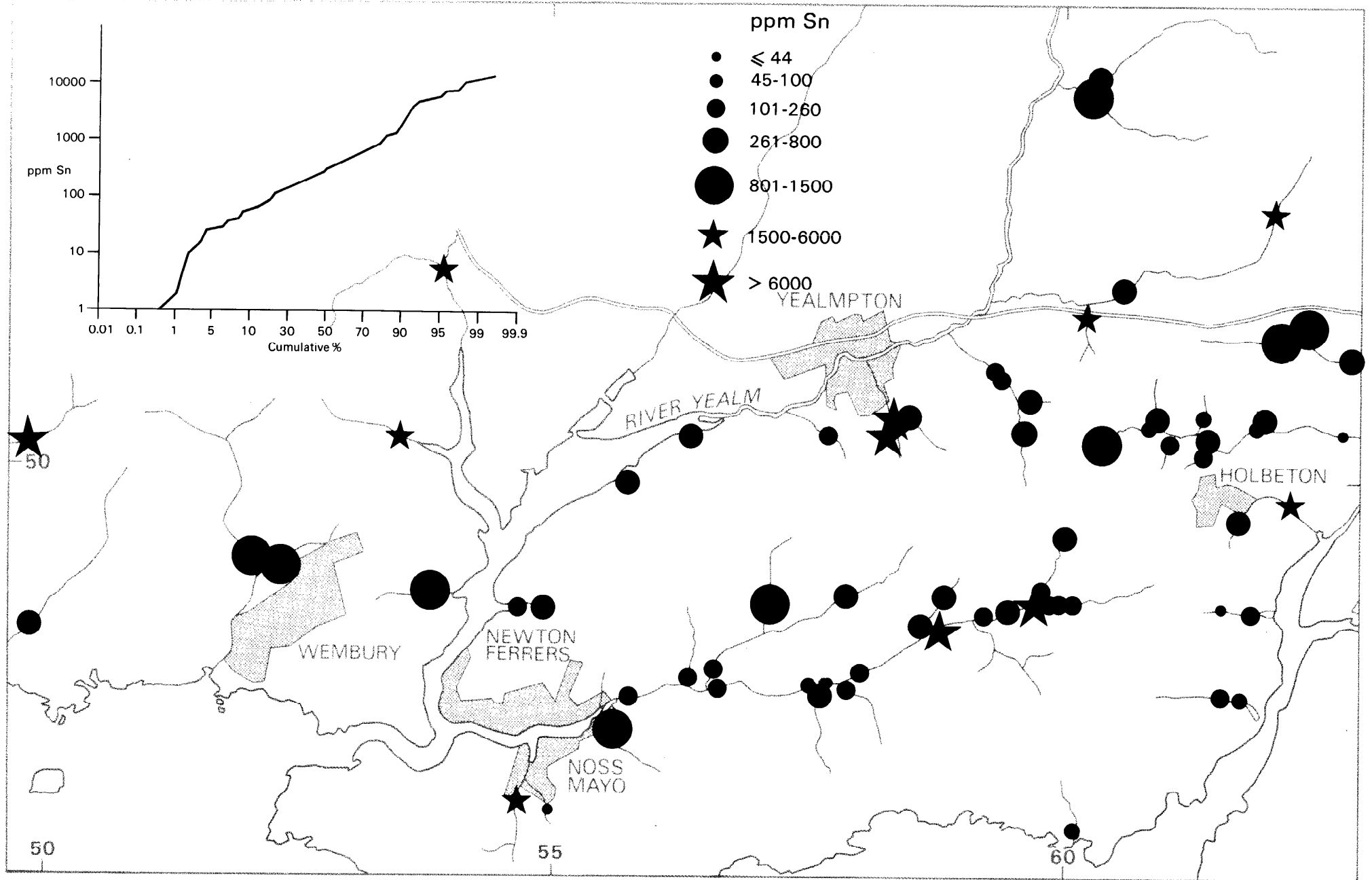


**Figure 12** Distribution of rubidium in drainage panned concentrates



**Figure 13** Distribution of zirconium in drainage panned concentrates





**Figure 14** Distribution of tin in drainage panned concentrates

(Figure 14) is complex in detail. The highest concentrations are found in two samples from south of Yealmpton. Other very high levels of Sn are found in samples from south-west of Holbeton and south of Plymouth. There are scattered anomalies of lesser magnitude all over the Middle and Lower Devonian outcrops. The vast majority of the Sn is present as cassiterite even in samples containing metallic contaminants. The size distribution of the cassiterite differs markedly in different samples. In samples containing relatively low Sn concentrations most of this is present as relatively fine material (< 0.5 mm). Two size distributions are apparent for anomalous samples. The Sn in samples from the north-west of the area shows a similar size distribution to the background samples. In contrast the Sn in samples from south-west of Holbeton is much coarser in grain size with over 60% by weight over 1 mm. The cassiterite in these samples consists of coarse rounded grains and smaller angular fragments and varies in colour from yellow to red to various shades of brown. Many grains are variegated in colour. The origin of the cassiterite in these gold-rich samples is discussed below.

#### Antimony

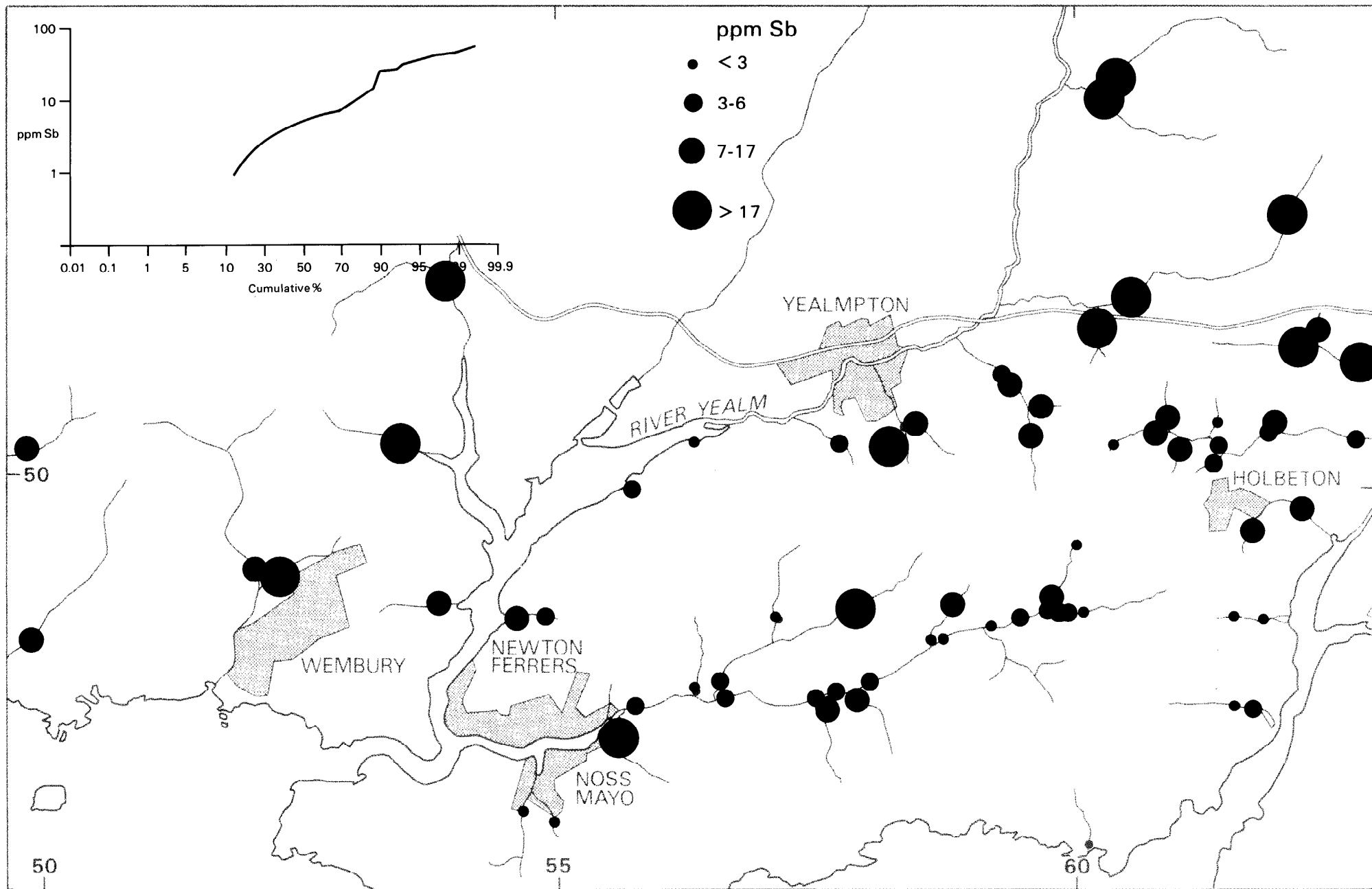
The majority of samples containing anomalous concentrations of Sb (Figure 15) are derived from the outcrop of Middle Devonian rocks on both sides of the river Yealm. This is in accordance with the previous results of exploration in the belt of Middle Devonian rocks (Leake et al., 1985) where highly anomalous concentrations of Sb were found in both overburden and core particularly in association with volcanic rocks. Generally in the samples derived from the Middle Devonian rocks Sb correlates with Fe, Cu, Zn and As (Table 2) and to a lesser extent S and Ni. Four anomalous samples are derived from the Lower Devonian rocks (Figure 15). Of these, three are from sites contaminated with metallic rubbish and enriched in a wide range of elements and showing a correlation between Sb and Pb where size fractions have been analysed. The Sb anomaly derived from the Staddon Grit west of Holbeton (Figure 15) is possibly natural in origin. A slight enrichment of Cu, As and in particular Fe is present in this sample but the concentration of Pb is relatively low.

#### Barium

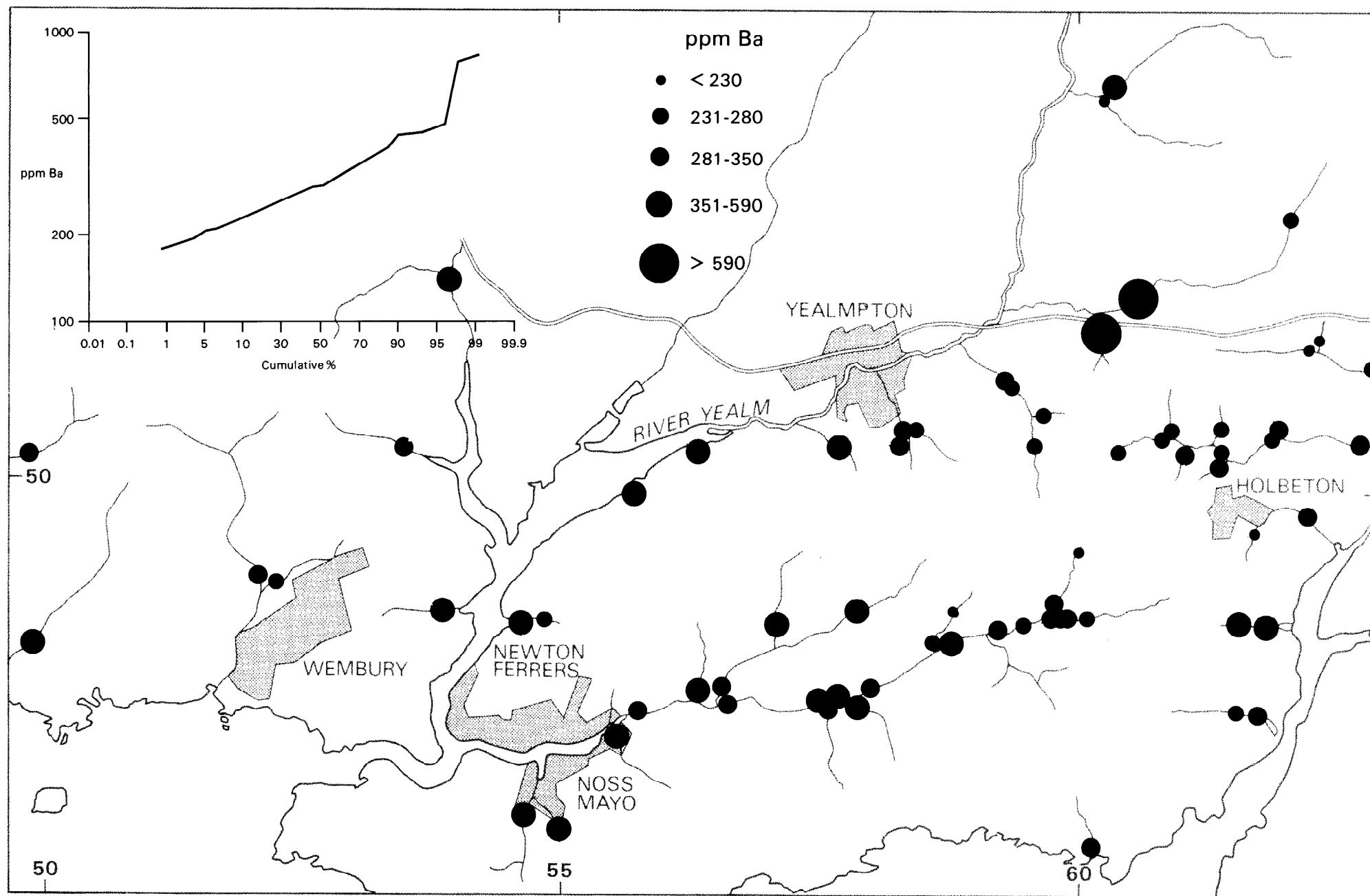
The range in Ba concentrations is relatively low. Two anomalous samples from east of Yealmpton within the outcrop of Middle Devonian rocks are conspicuous (Figure 16) and probably contain a minor amount of baryte. A boundary roughly south of Yealmpton separates relatively low Ba contents to the east from slightly higher levels to the west. The reason for this is unclear and it does not reflect the outcrop of the Staddon Formation which crosses this line.

#### Tungsten

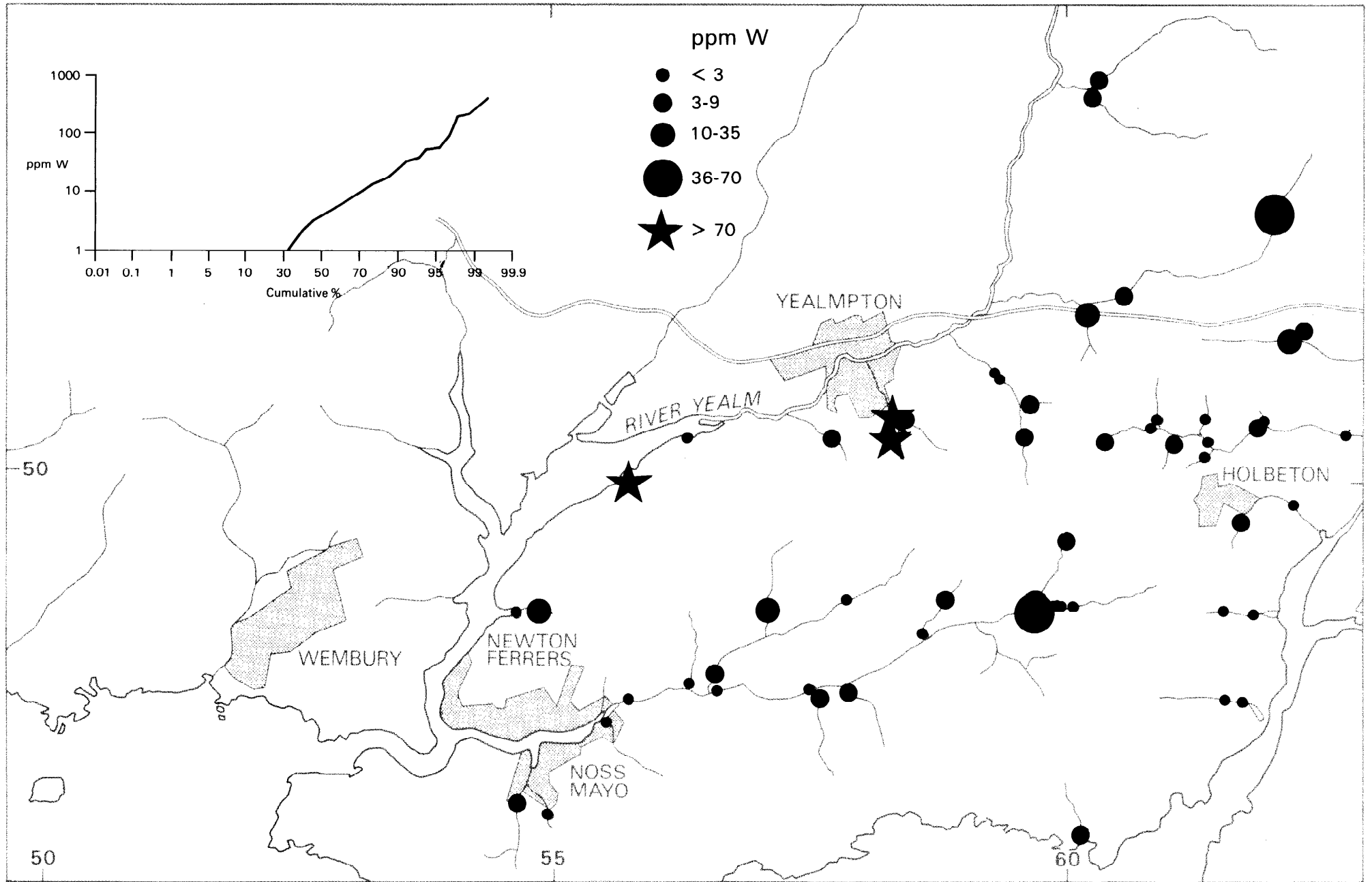
The distribution of W anomalies is shown in Figure 17 but the dataset is incomplete and in samples from west of the river Yealm W has not been determined. The origin of the three main W anomalies is not clear. Samples south of Yealmpton are also very rich in Sn but this does not apply to the sample containing the maximum W concentration (412 ppm),



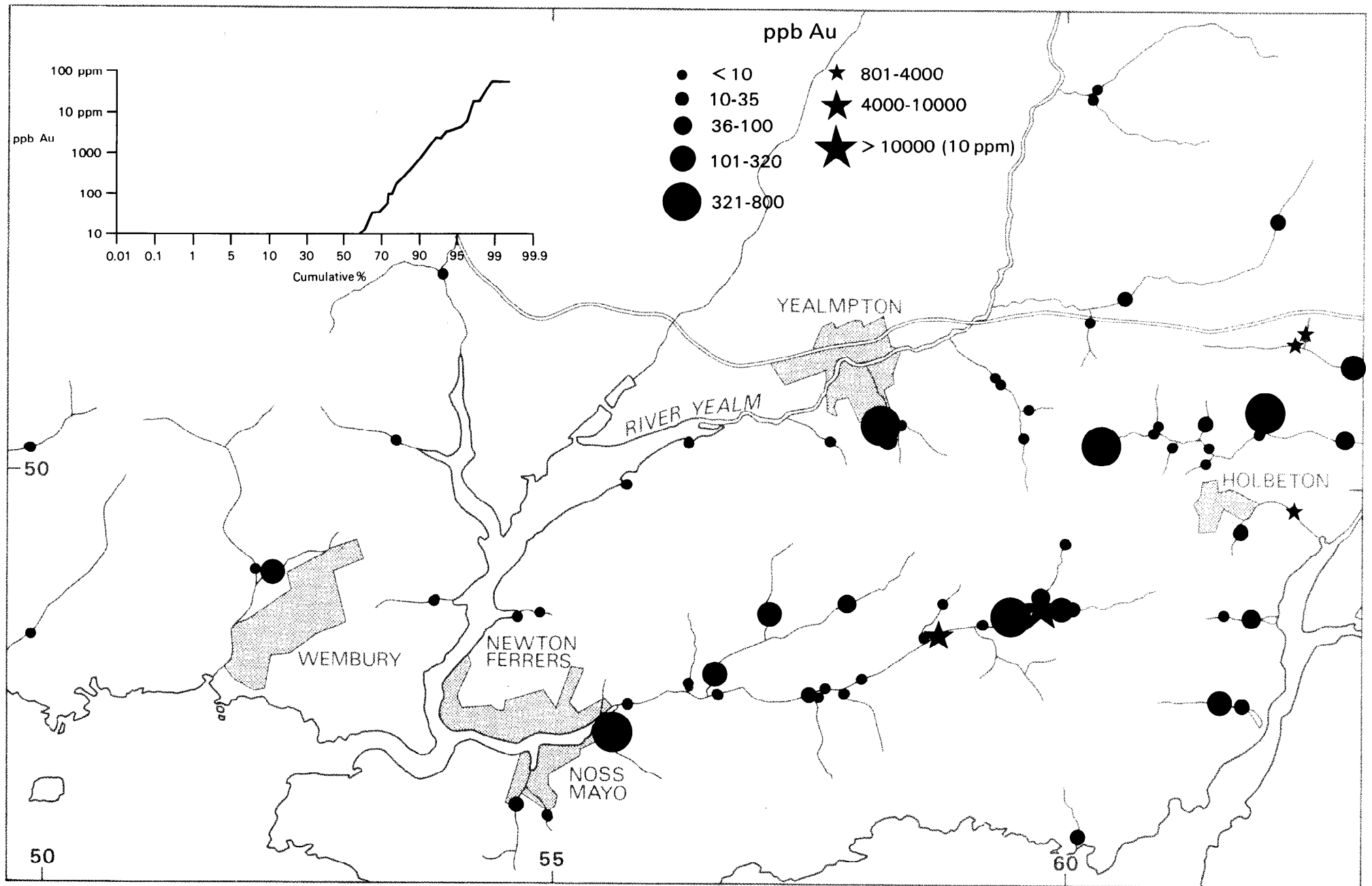
**Figure 15** Distribution of antimony in drainage panned concentrates



**Figure 16** Distribution of barium in drainage panned concentrates



**Figure 17** Distribution of tungsten in drainage panned concentrates



**Figure 18** Distribution of gold in drainage panned concentrates

from west of Yealmpton.

## Gold

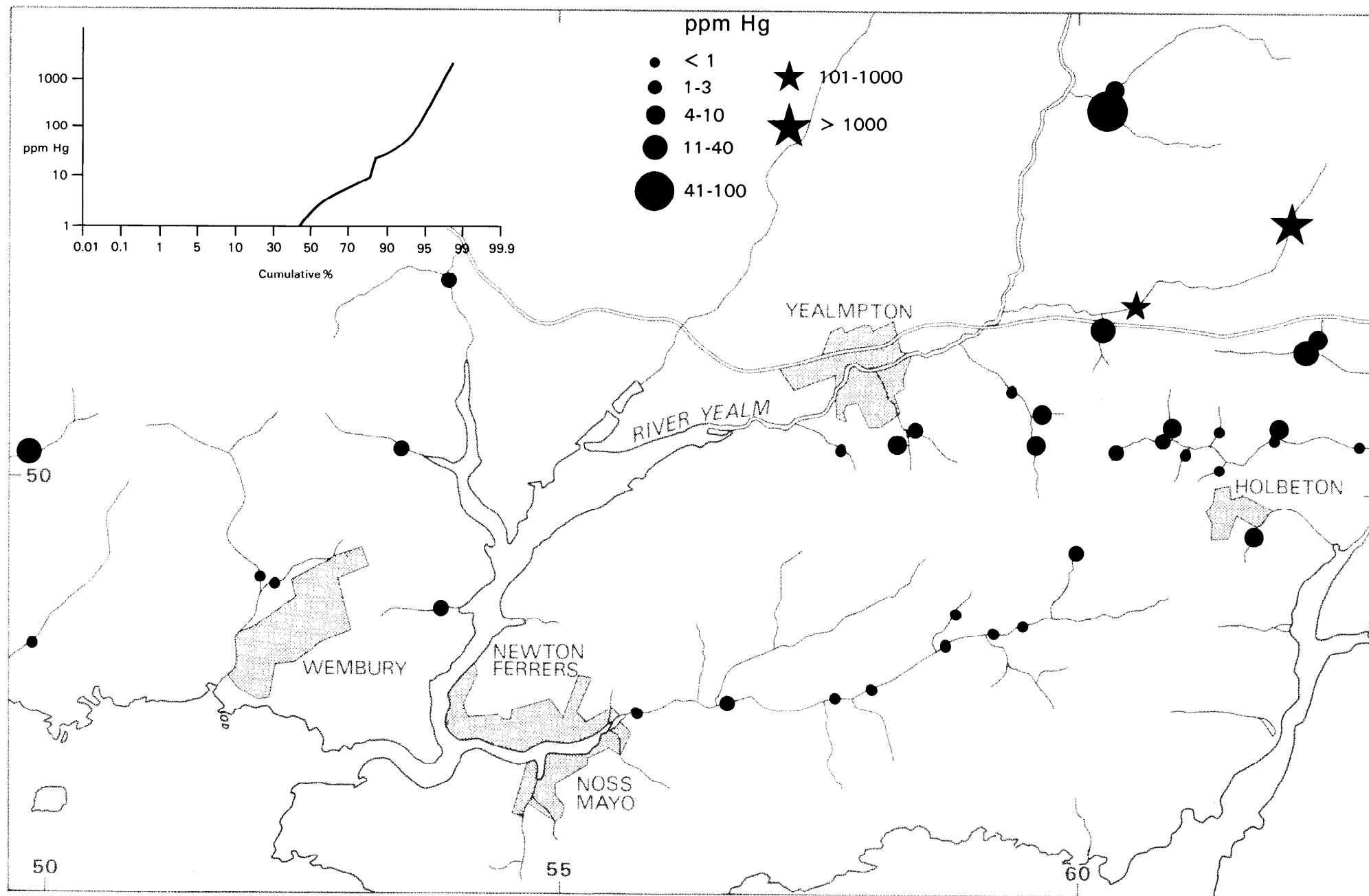
The distribution of gold in the drainage panned concentrates is shown in Figure 18. The maximum concentration of Au (47.8 ppm) is an underestimate as the sample analysed after removal of the visible grains contained more than the maximum detection limit of the analytical method (10 ppm). The nature of the gold from the most anomalous site to the south-west of Holbeton at [SX 59719 49167], on Brownstone Farm, is described in detail below. At this site samples are also enriched in Fe, Mn and Sn, which results in positive correlation coefficients between Au and these elements (Table 2). Enrichment in Ti, W, Cu, Pb and Bi occurs to a smaller extent. The detailed mineralogy of these samples, including the grains rich in PGE which are also present, is described below. This site has been the location of follow-up overburden sampling, geophysical surveys and drilling.

Significant amounts of gold occur in the area at a minimum of six other localities in the area (Figure 18). The sample from east of Holbeton is almost certainly related in origin to the main anomaly south-west of Holbeton as it contains distinctive dendritic grains of similar shape. Lower amplitude anomalous sites occur in the extreme east of the area, south of the main road east of Yealmpton where the bedrock is Middle Devonian volcanic and sedimentary rocks. Fe and Sn enrichment are less pronounced in these samples but anomalous concentrations of As and Sb are present. No dendritic or other intricate shaped grains of gold have been found from this locality. Limited overburden sampling in the area showed minor amounts of Au to be present in samples derived both from mafic volcanic rocks and from argillaceous sediments. Overburden samples derived from both rock types are enriched to a small extent in As while Sb is particularly enriched in the volcanic material though neither element shows any close correlation with Au. Volcanic-derived samples are also enriched in Fe some of which is in the form of the fibrous goethite found in Au-rich samples from south-west of Holbeton. Minor amounts of cinnabar occur in the overburden samples.

South and south-west of the above are two further anomalous sites of less amplitude where Au is present without Fe enrichment or particularly anomalous Sn concentrations. At both of these sites geological mapping has suggested the presence of significant amounts of gold. Gold in the other two sites (south of Yealmpton and south of Noss Mayo) is accompanied by a wide range of other metallic elements, some of which originate from contamination. This makes the presence of any associated minerals of natural origin difficult to establish.

## Mercury

Only about half of the samples have been analysed for Hg. The element was not determined prior to the visual observation of abundant cinnabar in concentrates from the north-east of the area. Small amounts of cinnabar have been observed in the gold-rich samples from south-west of Holbeton though the abundance of Hg was not determined in these samples. Cinnabar is clearly greatly enriched in material derived from the Middle



**Figure 19** Distribution of mercury in drainage panned concentrates



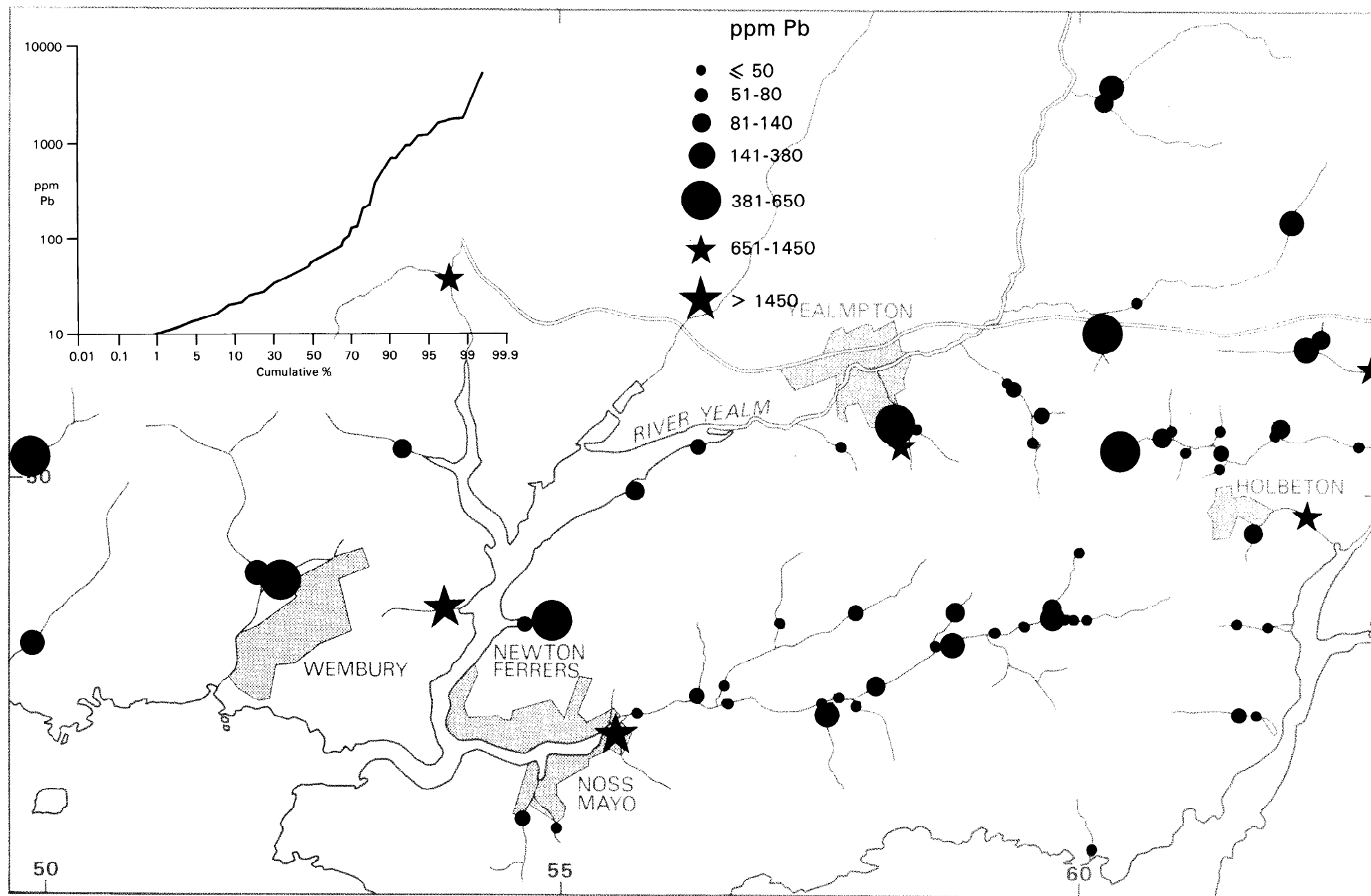
Devonian rocks compared with the Lower Devonian rocks. (Figure 19). The distribution of the higher Hg anomalies (Maximum 2006 ppm) suggests that volcanic rocks are more likely to be the source, in this area, than the sediments. In the anomalous sample from the north-west of the area (the catchment of which is mostly in the Staddon Formation) some of the Hg is present as globules of native mercury, though whether this is of artificial origin is not clear. The element Hg is not included in the principal component analysis of the data but visual inspection of the results does not show any positive correlation between Hg and Au.

#### Lead

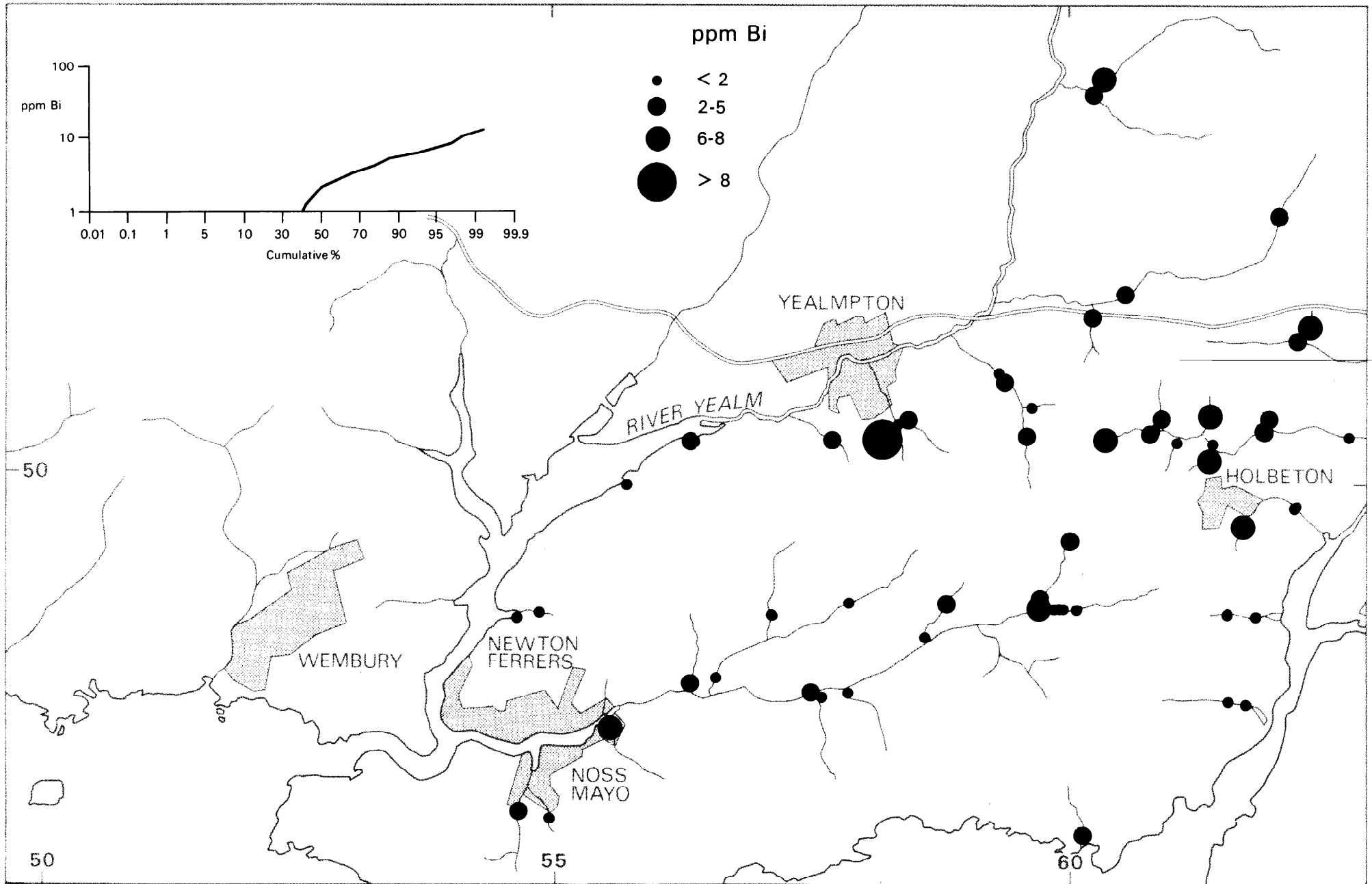
The majority of Pb in anomalous amounts in drainage samples throughout the area (Figure 20) originates as contaminants. Lead metal either as shot or sheet and lead glass have been identified in several samples. In the absence of detailed mineralogical examination to locate the form of Pb in anomalous samples, something of the likely source can be deduced from the nature of associated element enrichments and in particular the size distribution of Pb in the drainage sample. Natural Pb minerals are frequently easily broken down mechanically so that natural Pb anomalies occur over a wide grain size spectrum. Contaminants such as lead shot are not easily broken down. Therefore anomalies originating from this type of material are characterised by the Pb being overwhelmingly present in the coarser fractions. The Pb in the anomalous sample from south-east of Noss Mayo is both relatively coarse-grained and associated with a wide range of other metals which suggests that it is mostly, if not entirely, derived from contaminants. Similarly the relative coarse-grained nature of the Pb in the two anomalous samples from north of Newton Ferrers suggests contaminant origin. The anomalous sample from south of Plymouth (Figure 20) may contain material of natural origin since much more of Pb is relatively fine-grained. In addition there is some correlation between Pb, Sb, S and As in the size fraction analyses which may indicate the presence of sulphosalt minerals or their weathering products. A small amount of galena occurs in the gold-rich samples from south-west of Holbeton but this is much subordinate to lead metal plate and lead-rich glass contaminants. A significant amount of fine-grained Pb is present at the anomalous site to the east of Holbeton which suggests that there may be some material of natural origin or contamination with sewage-derived material as well as the common detrital grains. A moderate Pb anomaly is present in soil near the site of the drainage anomaly to the north-west of Holbeton which suggests that the source of this Pb is natural.

#### Bismuth

Samples from west of the River Yealm have not been analysed for Bi. Maximum concentrations of Bi (up to 12 ppm) occur in the sample south of Yealmpton (Figure 21) which is rich in several metallic elements and in one of the Au-rich samples from south-west of Holbeton. The form of the Bi in the latter sample is not known.



**Figure 20** Distribution of lead in drainage panned concentrates



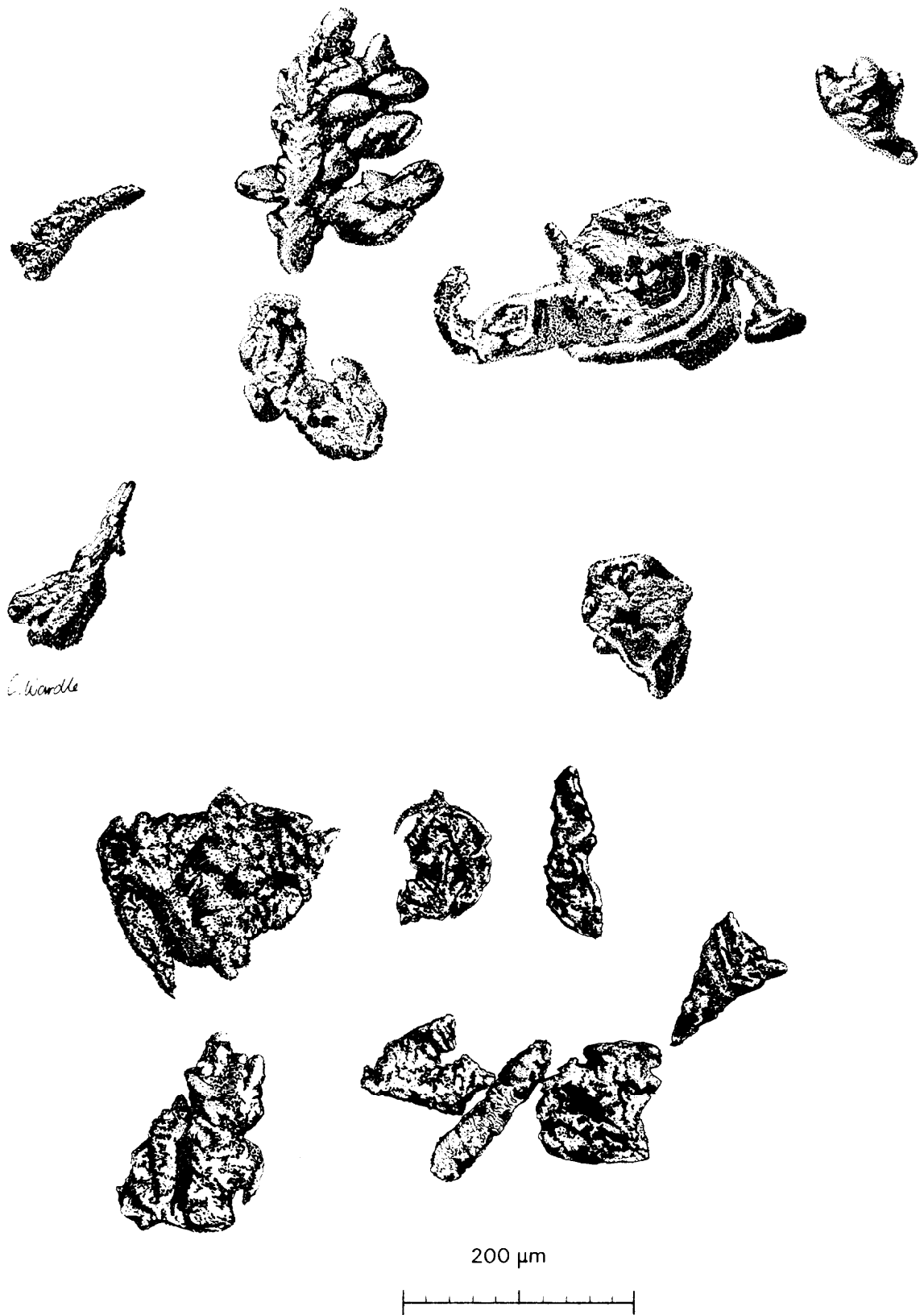
**Figure 21** Distribution of bismuth in drainage panned concentrates

## SHAPE AND SIZE OF GOLD GRAINS

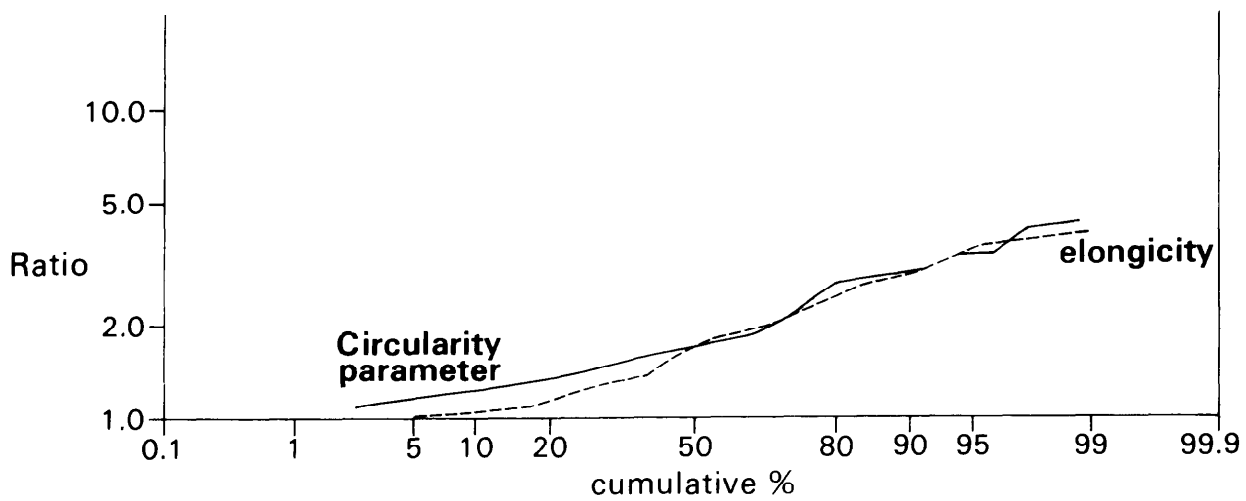
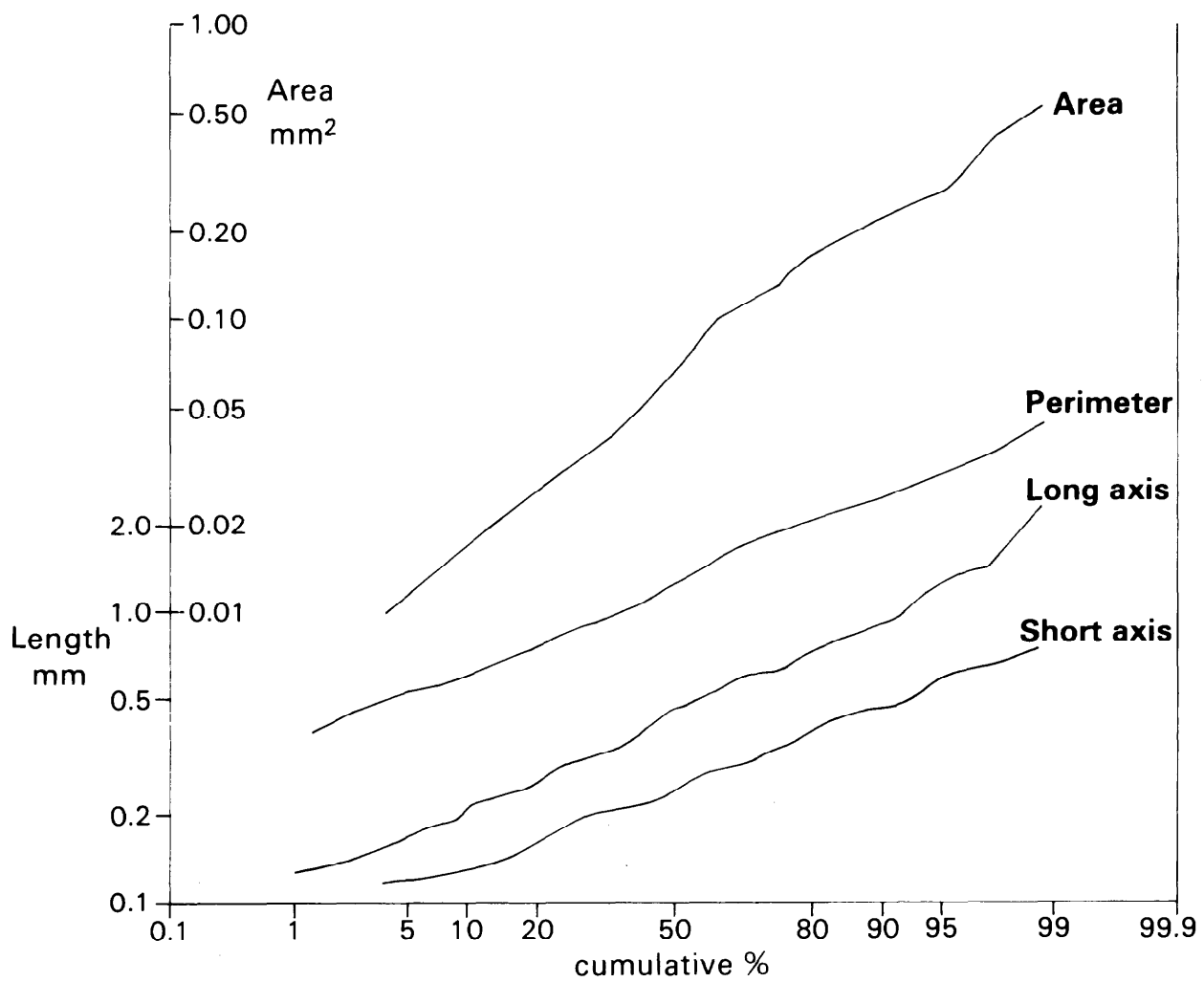
The shape of 139 grains of gold from the site at [SX 59719 49167], to the south-west of Holbeton, have been classified qualitatively into 9 shape forms. In addition the size and shape of 80 grains from the same site have been investigated quantitatively after digitising the grain outlines using Autocad on a Compaq 286 PC. A selection of 15 grains from the site have been drawn from photographs and are shown in Figure 22. Dendritic and frond-shaped grains are very distinctive types from the locality and form about 18 % of the total. There are also a few grains with wire-like projections which may be distorted examples of dendrites, and in addition there are grains showing bending of dendrites due to rolling. In all broad dendritic types make up about 36% of the total. Plate-like forms comprise a second major category of shapes forming about 25% of the whole. A few grains (5%) are transitional between fronds and plates with most of the space between the fronds filled in. About 11% of the grains are relatively small and dodecahedral or subrounded in shape and there are also a few grains composed of multiples of these. Grains with a more irregular shape, either elongate or more compact, make up the remaining 23%.

Size and shape parameters of the measured grains are plotted in cumulative frequency form in Figure 23. Possible breaks in slope on the short axis and perimeter plots between the 20 and 30 percentiles and in the area at about the 60 percentile may reflect different grain populations. The plot of elongicity suggests a break at around the 40 percentile while the plot of circularity (perimeter squared /  $4\pi$  x area, a dimensionless number the greater the value above a minimum of 1, representing a circle, the more irregular-shaped the grain (J.S. Coates pers. comm., 1990)) shows a break in slope between the 60 and 70 percentile. The above breaks in shape parameters coincide roughly with the percentage of subspherical and plate-like grains and the percentage of dendritic and wire-like forms respectively. The third dimension is not considered in these measurements which means that not all shape characteristics are defined and there is possible overlap in types considered in only two dimensions. Nevertheless valuable quantification of gold grains dimensions is possible and this can be used to compare different sites in the same area or the gold of different areas.

Accordingly measurements of size and shape have been made for comparative purposes of grains from two anomalous sites to the east of the Erme (Leake et al., 1988). A number of size and shape parameters are compared for the three locations in Table 4.



**Figure 22** Shape of 15 gold grains from site at [SX 59719 49167] (drawn from photographs)



**Figure 25** Cumulative frequency plots of size and shape parameters of 80 grains of gold from site at [SX 59719 49167]. Elongicity = Longest dimension/Middle dimension. Circularity = Perimeter squared/ $4\pi \times$  area.

**Table 4** Summary statistics of size and shape of gold grains from 3 sites

Location	A	B	C
No of grains	70	78	80
Short axis mean mm	0.255	0.173	0.290
Short axis min mm	0.070	0.060	0.120
Short axis max mm	0.570	0.530	0.800
Long axis mean mm	0.349	0.242	0.526
Long axis min mm	0.080	0.070	0.130
Long axis max mm	0.970	0.690	2.240
Long/Short mean	1.291	1.323	1.586
Long/Short min	1.000	1.000	1.000
Long/Short max	3.471	2.773	4.386
Perimeter mean mm	1.015	0.713	1.511
Perimeter min mm	0.250	0.220	0.390
Perimeter max mm	2.610	2.200	6.300
Area mean mm <sup>2</sup>	0.075	0.032	0.113
Area min mm <sup>2</sup>	0.003	0.003	0.010
Area max mm <sup>2</sup>	0.290	0.270	1.130
Circularity mean	1.346	1.569	1.975
Circularity min	0.917	0.716	1.089
Circularity max	2.235	3.899	4.266

Locations A and B from area east of Erme (Leake et al., 1988)  
 Location C anomalous site at [SX 59719 49167]

Major differences between the three locations, in both size distribution and shape, are apparent from Table 4. The grains from south-west of Holbeton are larger, more elongated and more irregular in outline than those grains from the other two sites. These differences are clearly of significance in assessing the history of grain growth in both primary and secondary environments together with distance of subsequent mechanical transport. An assesment of the relationship between grain parameters and differences in internal chemistry which in turn reflect the environment of crystallisation is particularly important. With such information it may be possible to establish empirical exploration criteria for recognising the significance of gold anomalies in drainage using relatively easily measured size and shape parameters.

#### **PLATINUM GROUP ELEMENT-RICH GRAINS**

Between 5% and 10% of the precious metal grains from the anomalous locality at [SX 59719 49162] are either platinum group element-rich gold or a platinum group mineral. These grains are generally silver-grey to dark grey in colour and exhibit either a wide range of spectacular elongate dendritic or prismatic shapes or more irregular subrounded forms. A number of these grains are illustrated on the back cover of the report. The The platinum group mineral potarite (PdHg) grains are usually subrounded though one spectacular three pronged grain has been found.

## COMPOSITION OF PRECIOUS METAL GRAINS

The composition of gold and PGE-rich grains has been determined by electron probe microanalysis. A combination of point analyses on the outer surface of rough grains and on polished sections through grains, together with microchemical mapping of complete or parts of polished sections have been used.

### Microchemical mapping

Microchemical mapping has been carried out using a Cameca SX50 automated microprobe. Digital beam scans were made producing a matrix of 256x256 points, the spacing of which varied according to the size of the grain. In the examples given the area covered is between 60 and 100 micrometres square. The data at each point are uncorrected X-ray counts and the colour contouring has been roughly calibrated by means of point analyses. Data to provide maps for the elements Au, Pt, Ag, Pd, Hg and Cu were collected. Microchemical mapping is the best way of demonstrating complex chemical variation within grains, especially where there are major changes in chemistry over distances of only a few micrometres as demonstrated below. Each map is equivalent to over 65,000 individual point analyses. The hazards of attempting to characterise the chemical variation within such grains by means of a small number of point analyses are clearly evident.

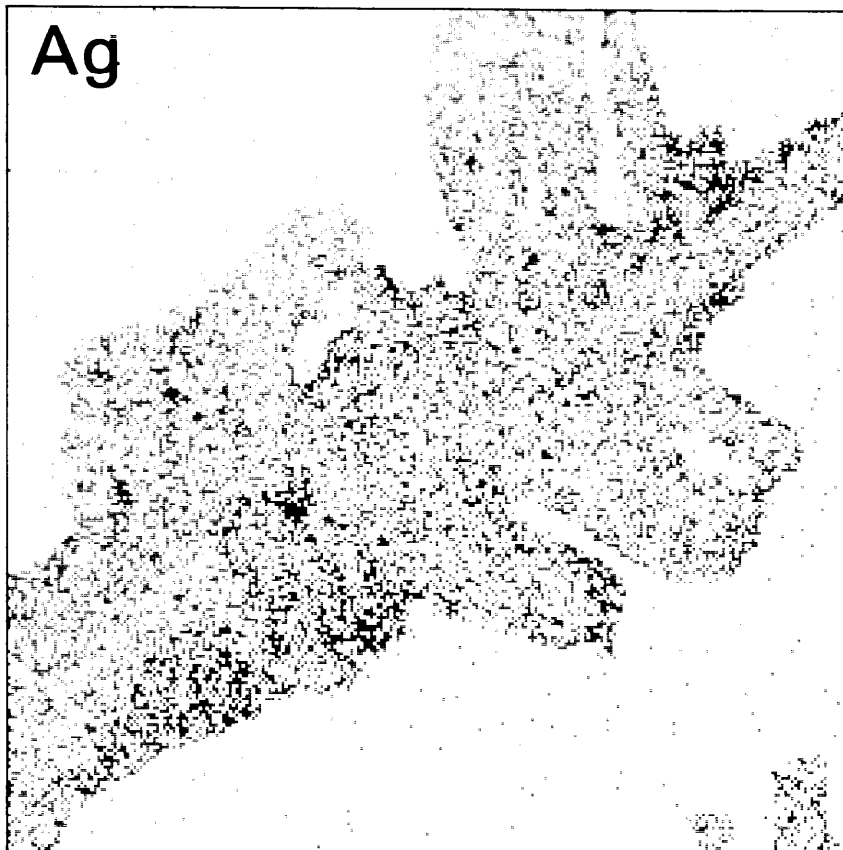
### Gold-dominant grains

Compositional variation within four grains of gold from the anomalous locality at [SX 59719 49167] was mapped as described above. Images of two of these grains are shown in Figures 24 and 25. The Pd image of the dendritic grain (Figure 24) shows striking compositional variations with a central Pd-poor spine and distinct rims and peripheral patches showing relative Pd-enrichment, picking out the internal growth structure of the grain. In contrast the Ag image of the same grain shows little internal variation except for slight Ag-enrichment in a few relatively Pd-rich peripheral patches. A second grain, shaped like a shoe in section (Figure 25), shows a pronounced but partial rim of Pd-enriched gold and a chevron of Pd-enrichment towards one end. The corresponding Ag image shows no internal structure. A further grain, not illustrated, show assymetrical compositional variation, with areas of Pd enrichment to one side superimposed upon which is a thinner zone also enriched in Ag. A fourth grains shows a total lack of compositional variation and is almost pure Au. The maps clearly demonstrate a complex and dynamic history of gold grain growth with the suggestion that grain composition may show a pattern of change with time from nearly pure Au to Au+Pd to Au+Pd+Ag.

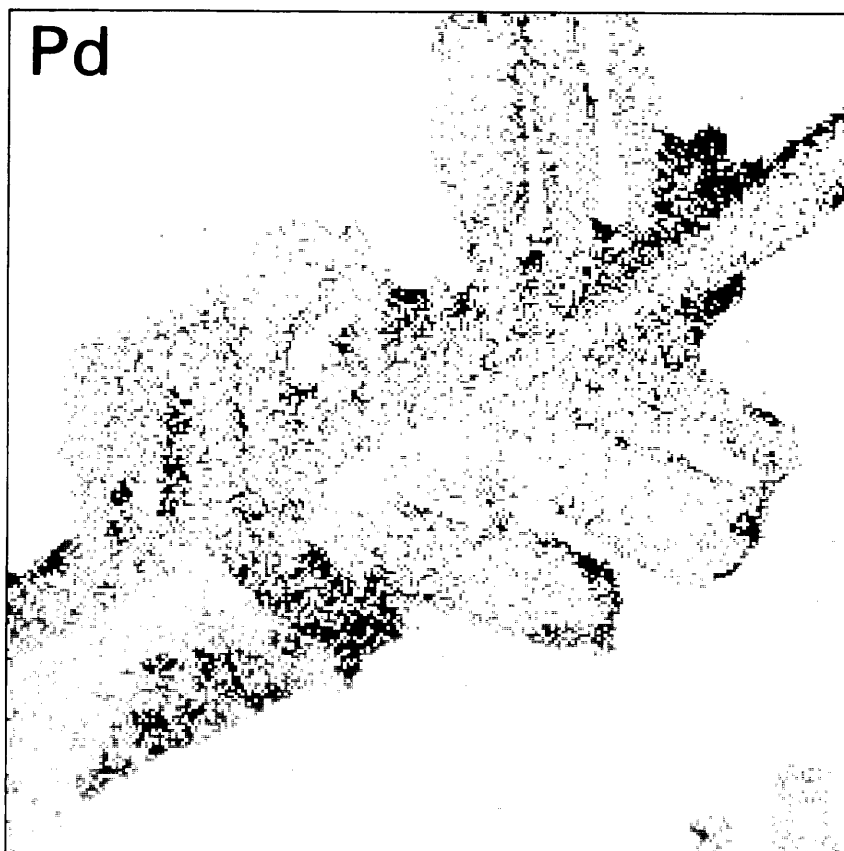
### Platinum group element-rich grains

Microchemical mapping of five grains rich in PGE has been carried out. One grain with an overall composition close to ideal potarite (PdHg) showed little evidence of internal compositional variation with a composition close to Pd35%Hg65%. In contrast four grains containing significant amounts of platinum showed an enormous range in internal composition. Element maps of three of these grains are given in plates

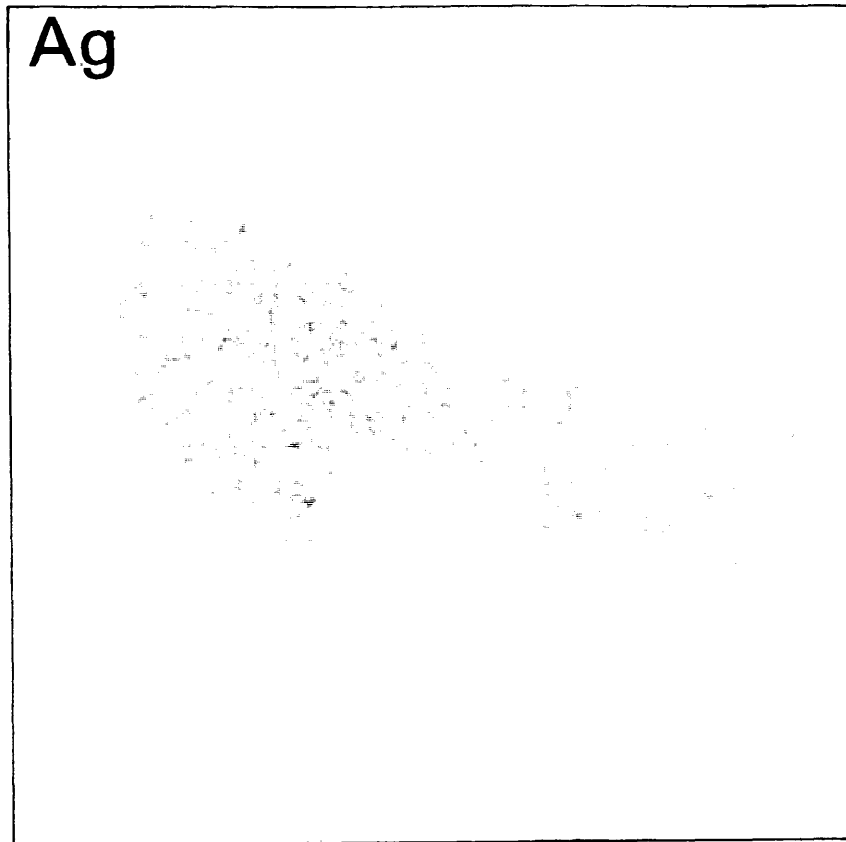




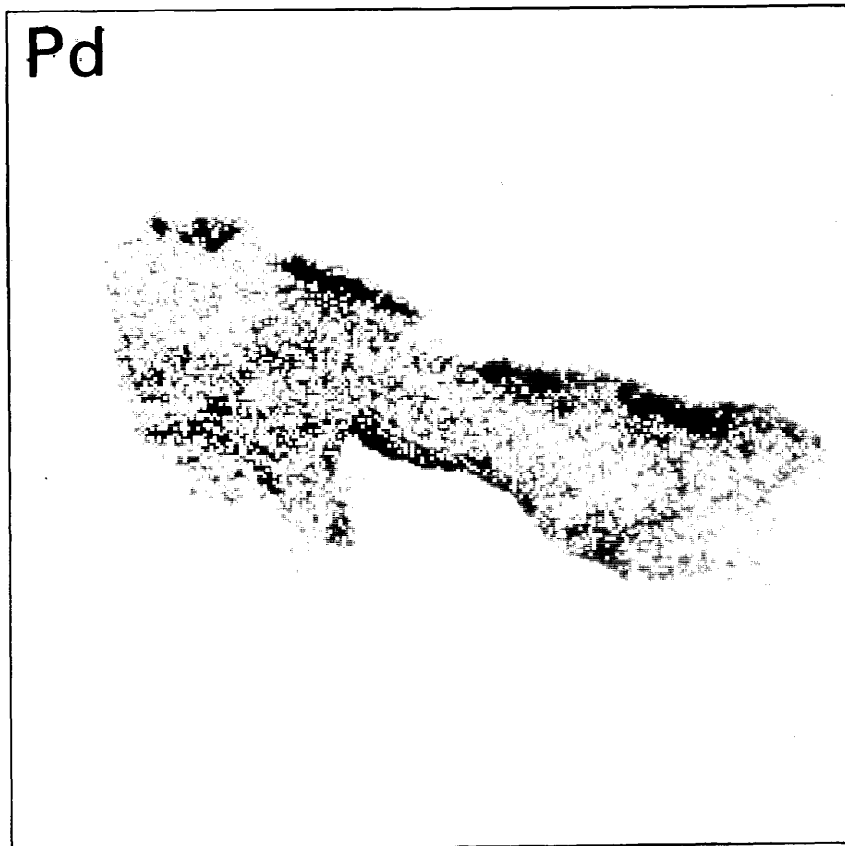
100 microns



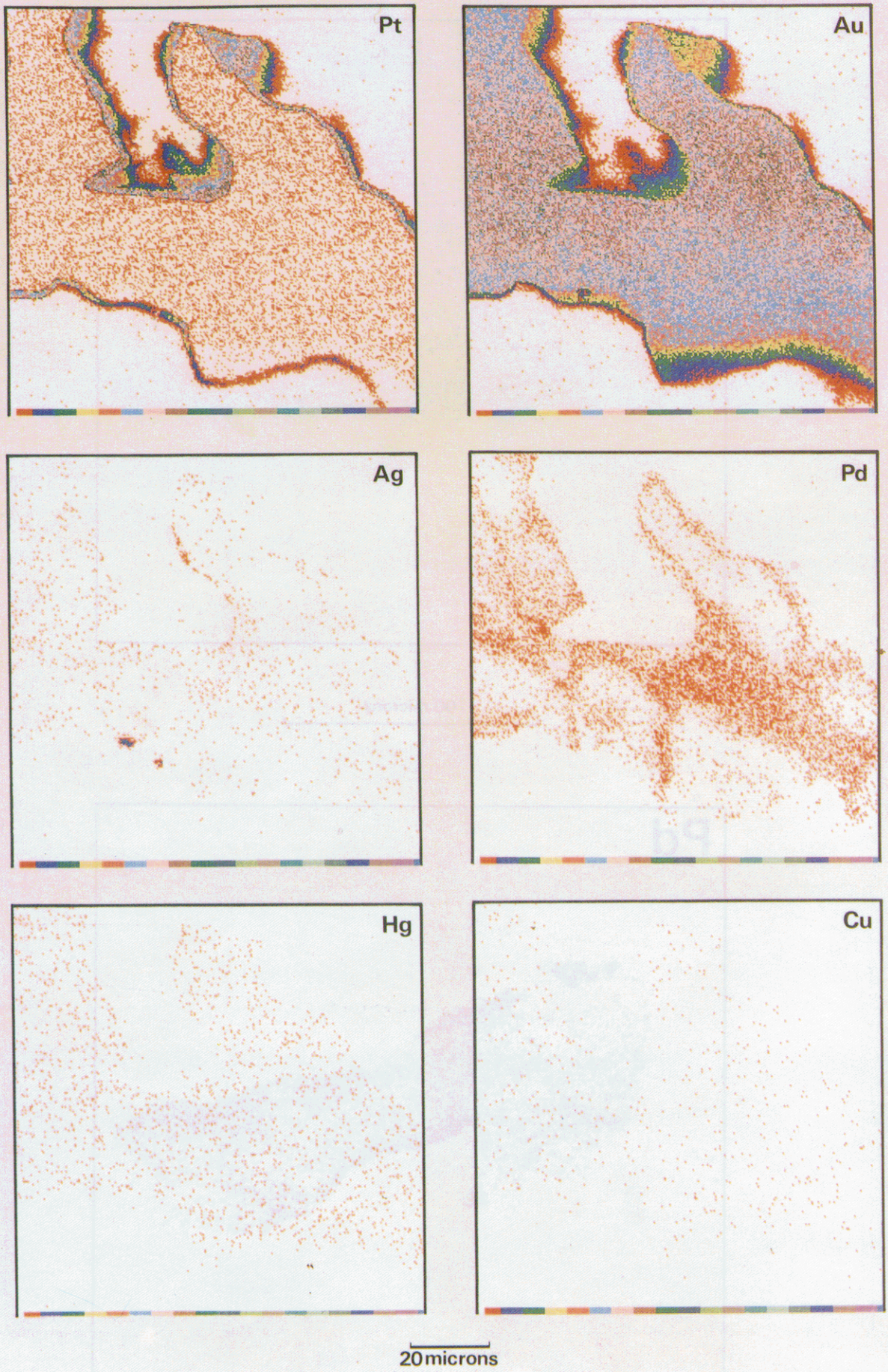
**Figure 24** Microchemical map showing Ag and Pd distribution in a dendritic gold grain from drainage at [SX 59719 49167]. Concentrations range up to about 1% for Ag and 4% for Pd.



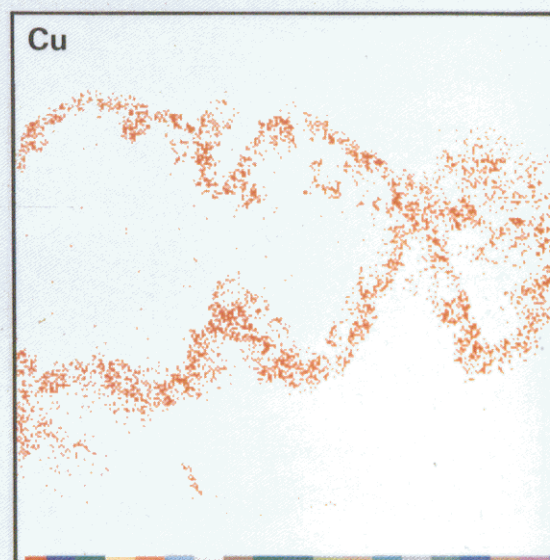
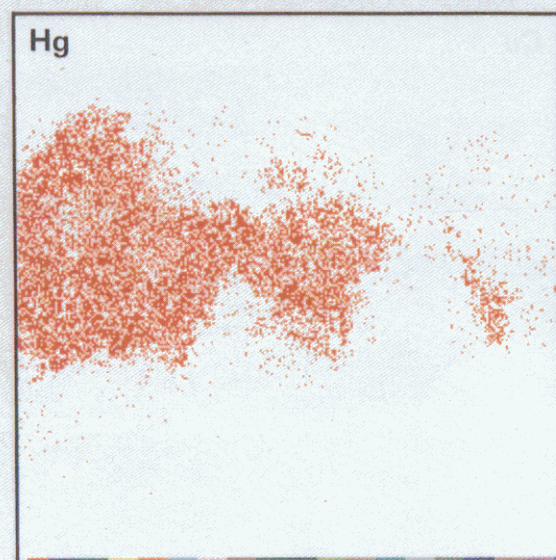
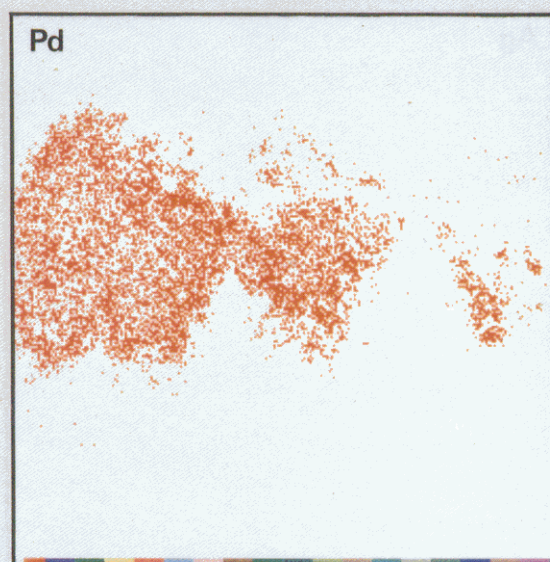
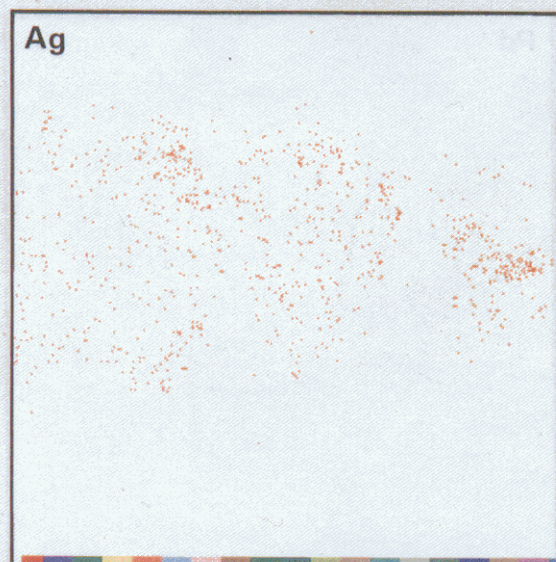
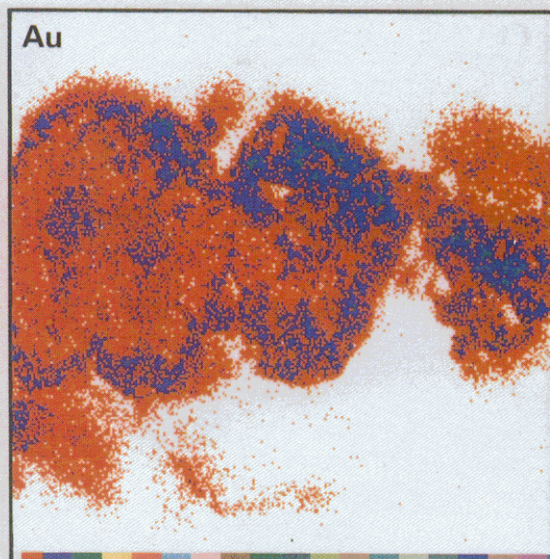
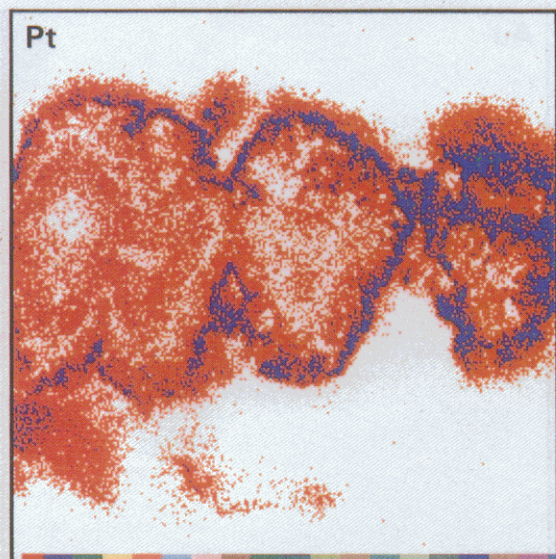
100 microns



**Figure 25** Microchemical map showing distribution of Ag and Pd in a shoe-shaped gold grain from drainage at [SX 59719 49167]. Concentration range as Fig. 24

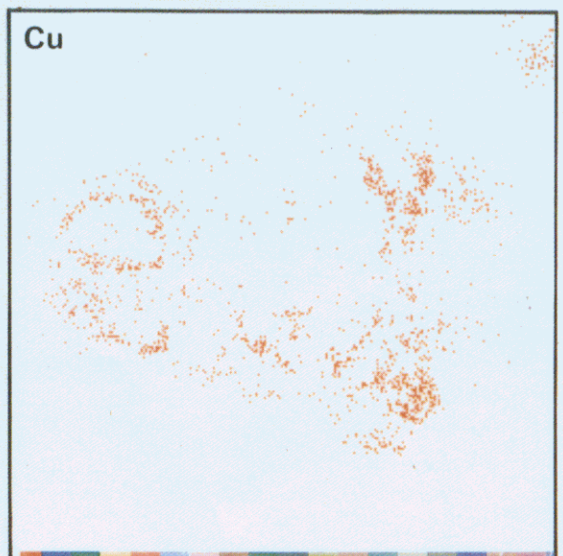
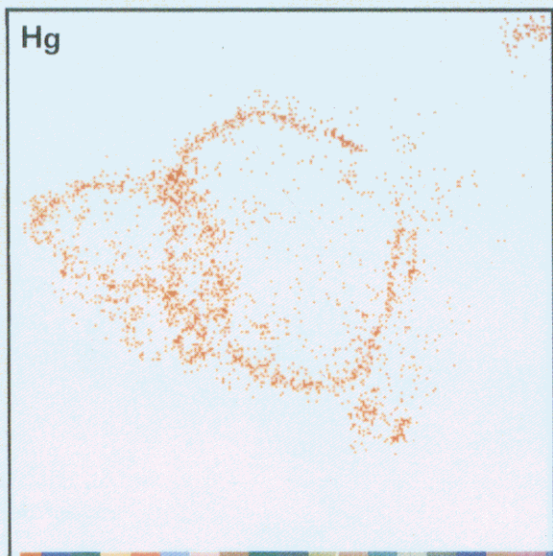
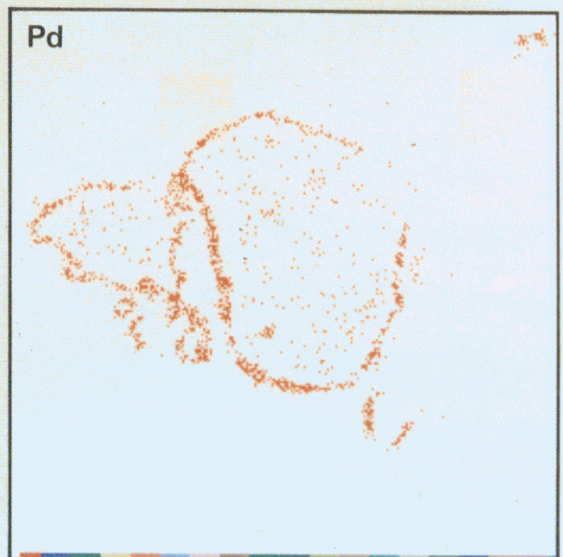
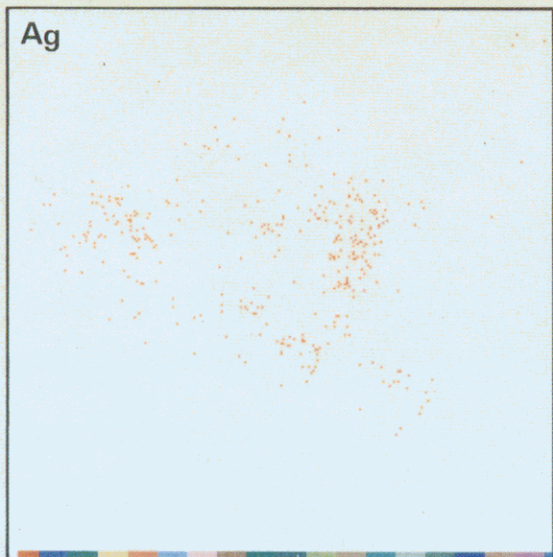
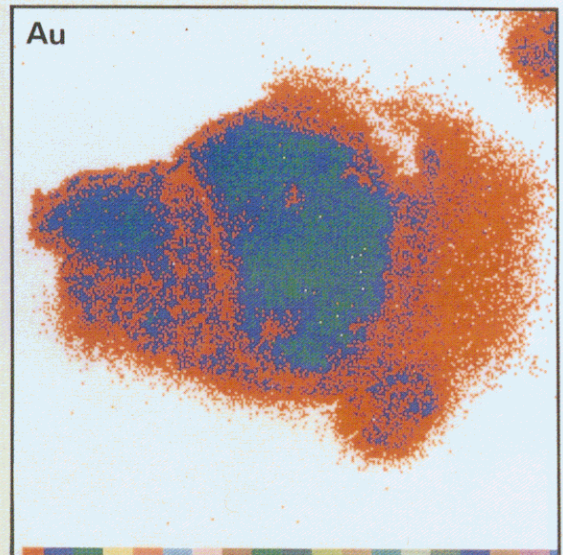
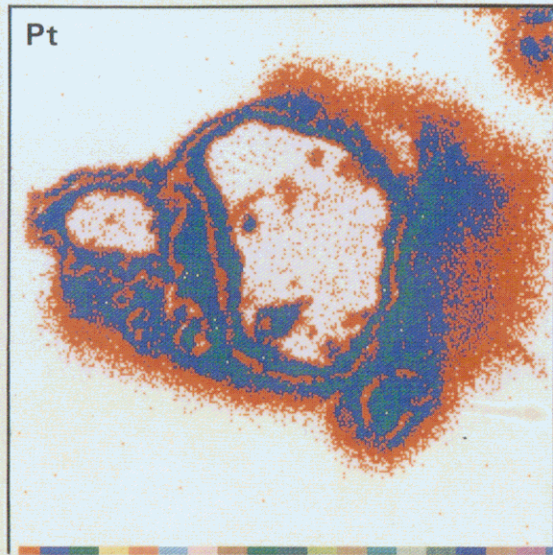


**Plate 1** Microchemical maps showing the distribution of Pt, Au, Ag, Pd, Hg and Cu in grain B10. The colour scale is roughly proportional to concentration from white (zero) increasing to the right. Pt and Au show colours up to brown or the second green which is equivalent to around 80 weight%



20 microns

**Plate 2** Microchemical maps showing the distribution of Pt, Au, Ag, Pd, Hg and Cu in grain B1. The colour scale ranges up to yellow which is equivalent to around 80 weight%.



20microns

**Plate 3** Microchemical maps showing the distribution of Au, Ag, Pt, Cu, Hg and Pd in grain 6A. The colour scale is the same as in plate 2

1,2 and 3.

In general the grains consist of a core of nearly pure Au or a Au+Pd alloy around which there are a wide range of overgrowths. Grain B10, plate 1, has a core of gold containing about 2% Hg, evenly distributed, and Pd, up to 5%, showing a patchy distribution inversely related to a slight enrichment in Ag. A very prominent feature of the grain is the thin (around 2 micrometres) platinum-rich rim, appearing somewhat thicker on the upper edge as the grain is dipping into the section towards the upper right corner. The composition of the rim is roughly Pt80%Au20%. The contact with the gold core is absolutely sharp and shows no gradation over a distance of less than 1 micrometre. A linescan along line 60 of the map, approximately 100 micrometres long (Figure 26), clearly shows the thin rim and sharp boundaries. On other parts of this grain the thin Pt-rich rim has detached from the main part of the grain, showing that it is a thin veneer.

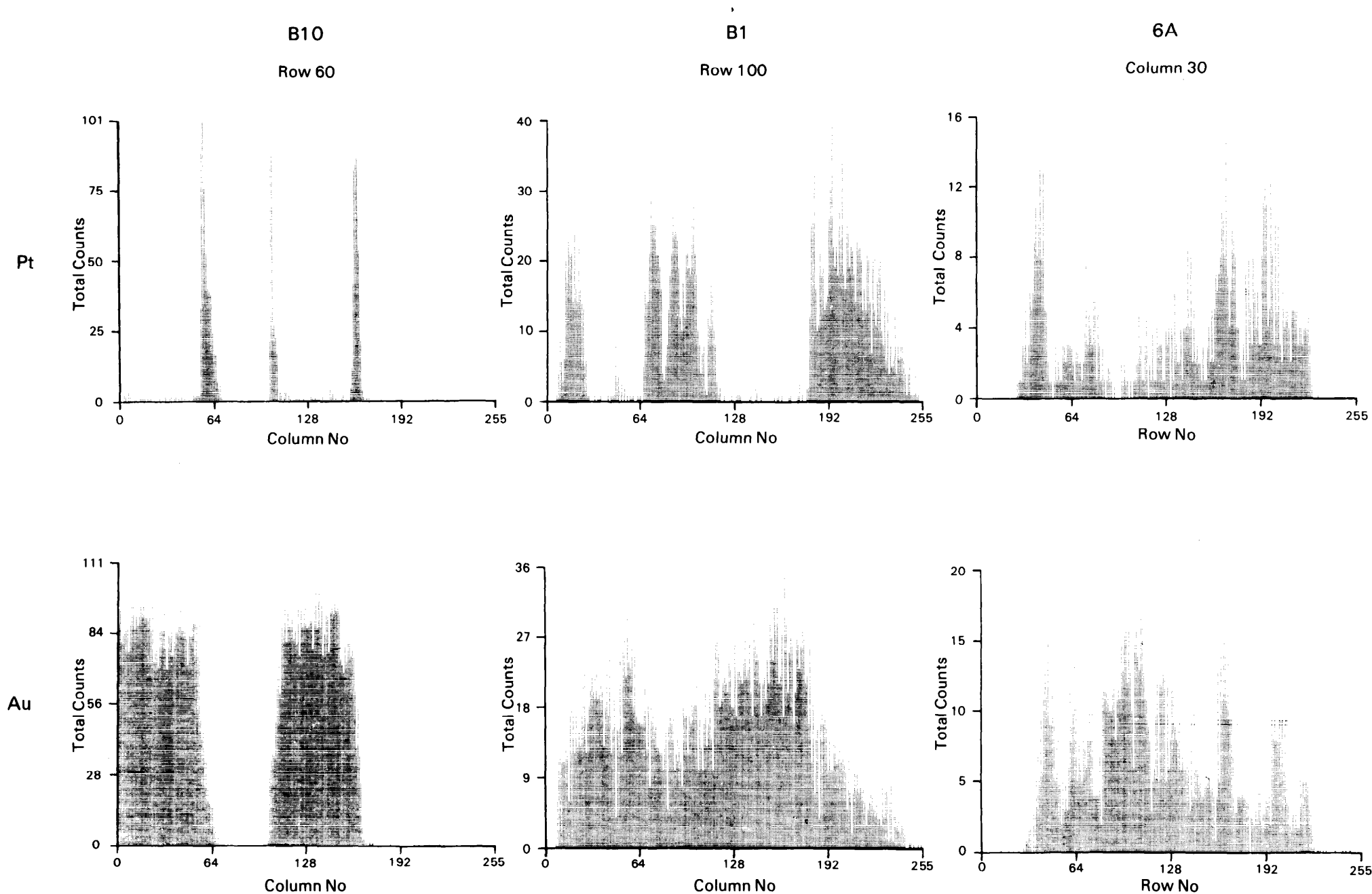
Grain B1, plate 2, shows a different range of compositional features. The core of this grain is Au with up to 5% of Pd and Ag, with an indication of an antipathetic relationship between Pd and Ag enrichment. Around the core is a complex zonal compositional pattern. The innermost zone is composed of a Pt+Au alloy with minor Cu, followed by a very narrow zone of Pd+Hg and then a broader zone of the Pt+Au alloy. The inner zones are very thin and satisfactory analyses have not yet been obtained but the data available suggests that the Pt-rich zone is probably around Pt80%Au20% and the Pd-rich zone is around Hg45%Pd30%Au20%. The line profile for Pt along line 100 (Figure 26) shows these zones very clearly; at the left only the inner Pt zone is recorded but in between the two parts of the grain there are four distinct peaks and at the right a sharp peak for the inner zone and a broad peak for the outer zone.

Grain 6A is a large grain and it is thought that the polishing has barely exposed the core of the grain. A marked zonation is again apparent with a central Au+Pd+Hg alloy, composition around Au30%Pd20%Hg40%Pt5%. Platinum is much enriched around the edge of the grain which has a composition around Pt70%Au15%Cu15%. There are also distinct zones of less intense Pt-enrichment within the Pd-rich part which can also be seen in the line profile along column 30 of the image (Figure 26).

### **Quantitative analysis**

#### **Gold-rich grains**

The composition of a number of gold grains from the anomalous area to the south-west of Holbeton has been determined using a Cambridge Instruments Microscan 5 X-ray microanalyser fitted with a LINK Systems energy-dispersive analyser. The limits of detection by weight for this method range from around 0.2% for Cu to around 1.0% for Pt in a gold matrix. Some analyses were also made using a Cameca SX50 with a wavelength dispersive system where the limit of detection is, usually, no worse than 0.2%. Initially analyses were made on the surface of rough grains mounted on double-sided Sellotape and then grains were embedded



**Figure 26** Line profiles from microchemical maps (256 × 256 points) of platinum element-rich grains B10, B1 and 6A (plates 103). Concentrations are shown as uncorrected X-ray counts from each point. For all profiles the highest point on the peaks is equivalent to around 90 weight% for Pt or Au.

in epoxy resin and a flat polished surface produced. The electron beam, focussed to around 2 micrometres in diameter, penetrates to depth of around 1 micrometre so that only a very small volume is analysed. Determinations of Au, Pd, Ag, Pt, Cu, Hg and Fe were made at up to 11 points per grain.

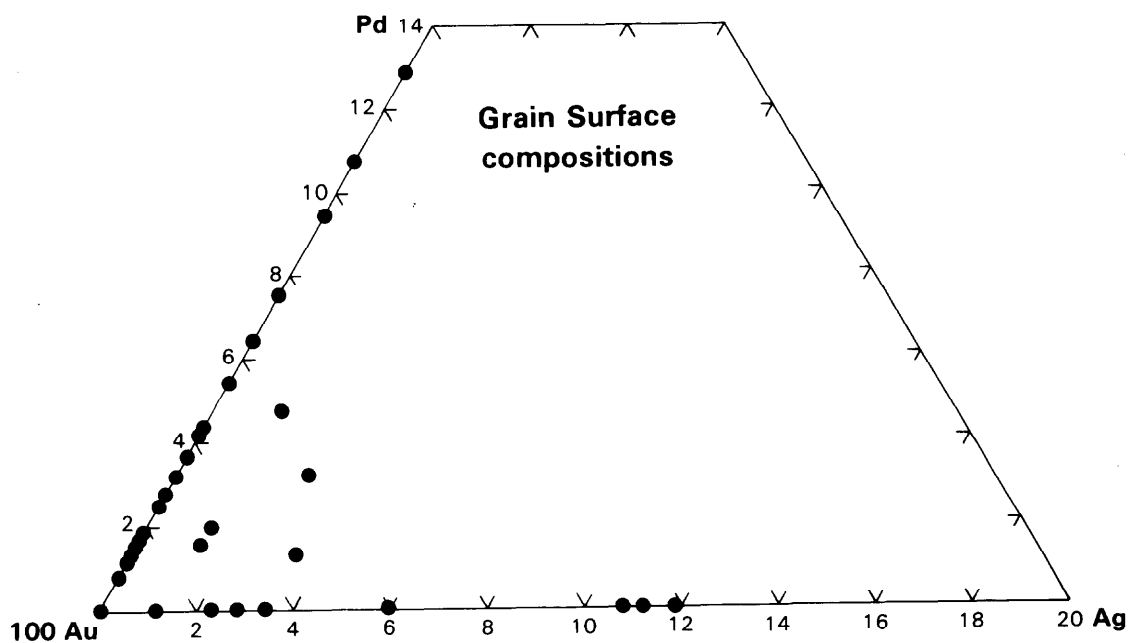
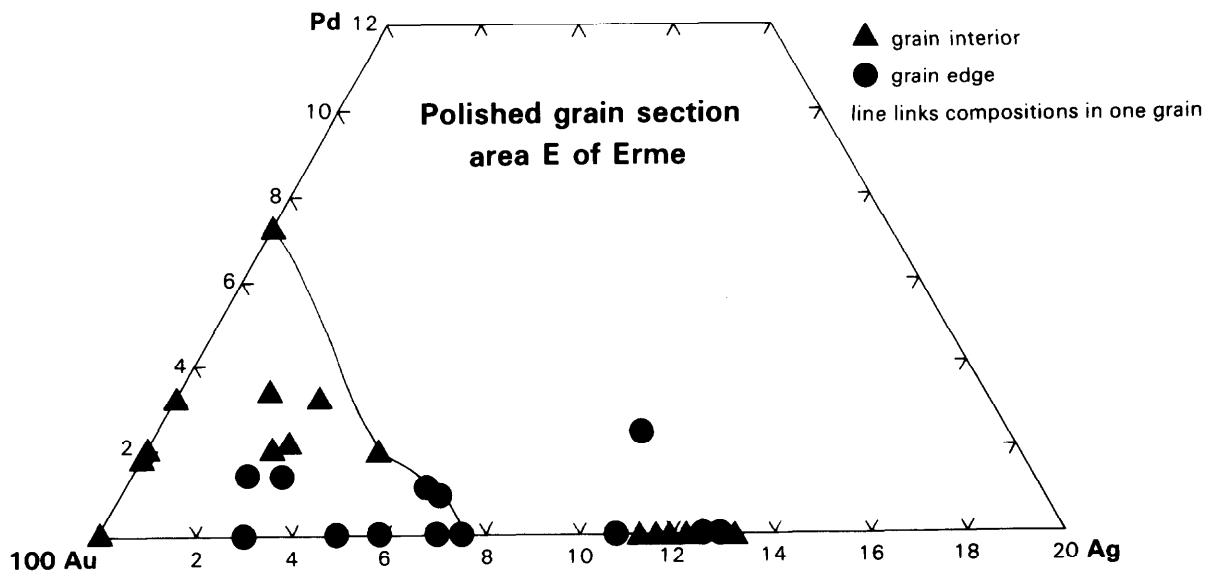
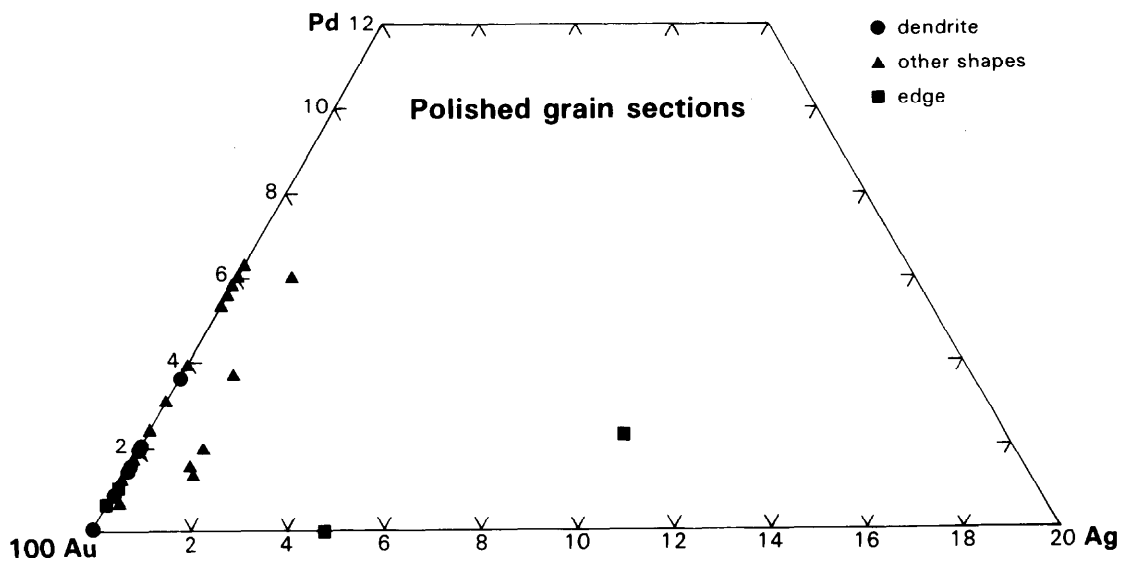
The results of these analyses are shown in Figure 27, expressed in terms of the proportions of Au, Pd and Ag. Analyses of the polished grains show that most compositions are close to the Au-Pd tie line with a significant amount of Ag only in a few edge compositions. Analyses of grain surfaces show much the same pattern though, as would be expected, there is a greater proportion with enhanced Ag content. In addition to the elements in the plot Cu was detected up to 0.8%, Hg up to 2.4% in polished grains and up to 16% in surface analyses, Pt up to 3.5%, Fe to 5% and Bi to 3% in some grains. For comparative purposes compositions obtained from polished grain mounts of gold from an anomalous site to the east of the river Erme (B in Table 4) are also included in Figure 27. At this locality relatively Ag-rich compositions are much more apparent both for grain edges and also in grain interiors. This indicates that the differences in gold grain shape and size between the two areas is matched by differences in composition.

#### Platinum group element-rich grains

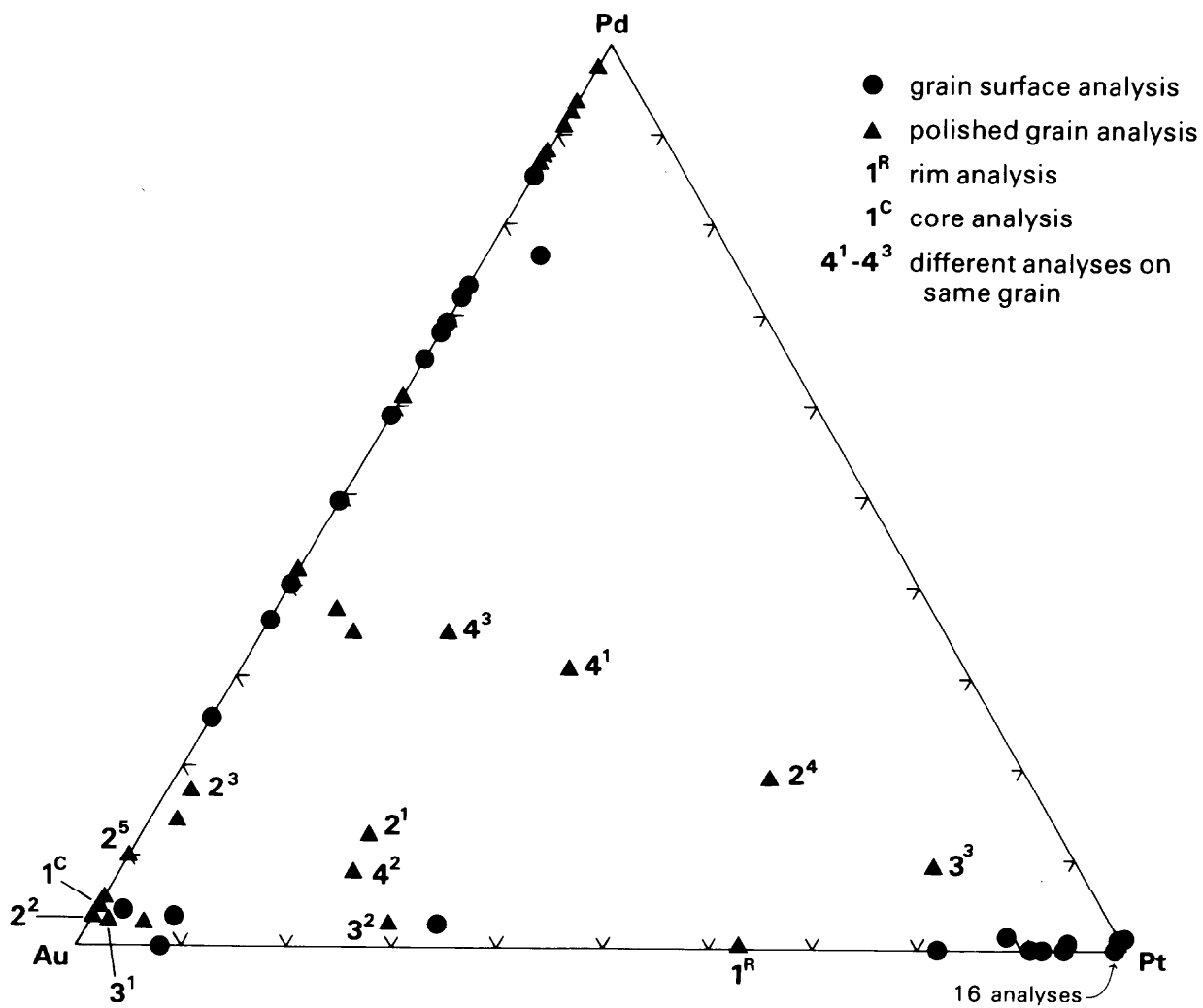
Platinum group elements occur in two distinct forms in the precious metal grains from the anomalous area. Both Pt and Pd+Hg occur as overgrowths on gold grains. Pt occurs usually with minor Cu both as broad overgrowths and very thin zones including a thin outer veneer without associated Cu. Pd occurs in association with Au in the centre of grains and also in overgrowths where it is closely associated with Hg. Attempts to analyse these thin zones within the gold grains always gives much higher Au and in some cases Pt than in the analyses of discrete potarite grains. Since the zones may be less than 1 micrometre in thickness it may not be possible to obtain a quantitative analysis given a minimum beam diameter of at least 1 micrometre which will therefore include some of the adjacent zone. It is not therefore clear whether the composition of the thin Pd-rich zone is essentially pure potarite or not.

The composition of a number of spots on the surface of several platinum-coated grains has been determined using a LINK energy dispersive analyser on a Cambridge Instruments Microscan 5 x-ray microanalyser. Concentrations of Au, Ag, Pd, Pt, Hg, Cu and Fe were determined for these spots and the results are plotted in terms of a Au-Pd-Pt triangular diagram in Figure 28. In addition spots have been analysed on 12 polished grain mounts and the results of these are also shown in Figure 28. Though a wide range of compositions is apparent on Figure 28 a pattern of compositional grouping can be recognised especially if compositions are also plotted on the Pd-Pt-Hg triangular diagram shown in Figure 29. Six compositional types can tentatively be recognised. Type 1 consists predominantly of Pt with a small Au and Hg content and sometimes up to 12.7% Cu. Type 2 consists of Pt+Hg with minor Au and Pd. Type 3 is loose grouping with Au as the dominant constituent with Hg, Pt and Pd in roughly equal quantities. Type 4

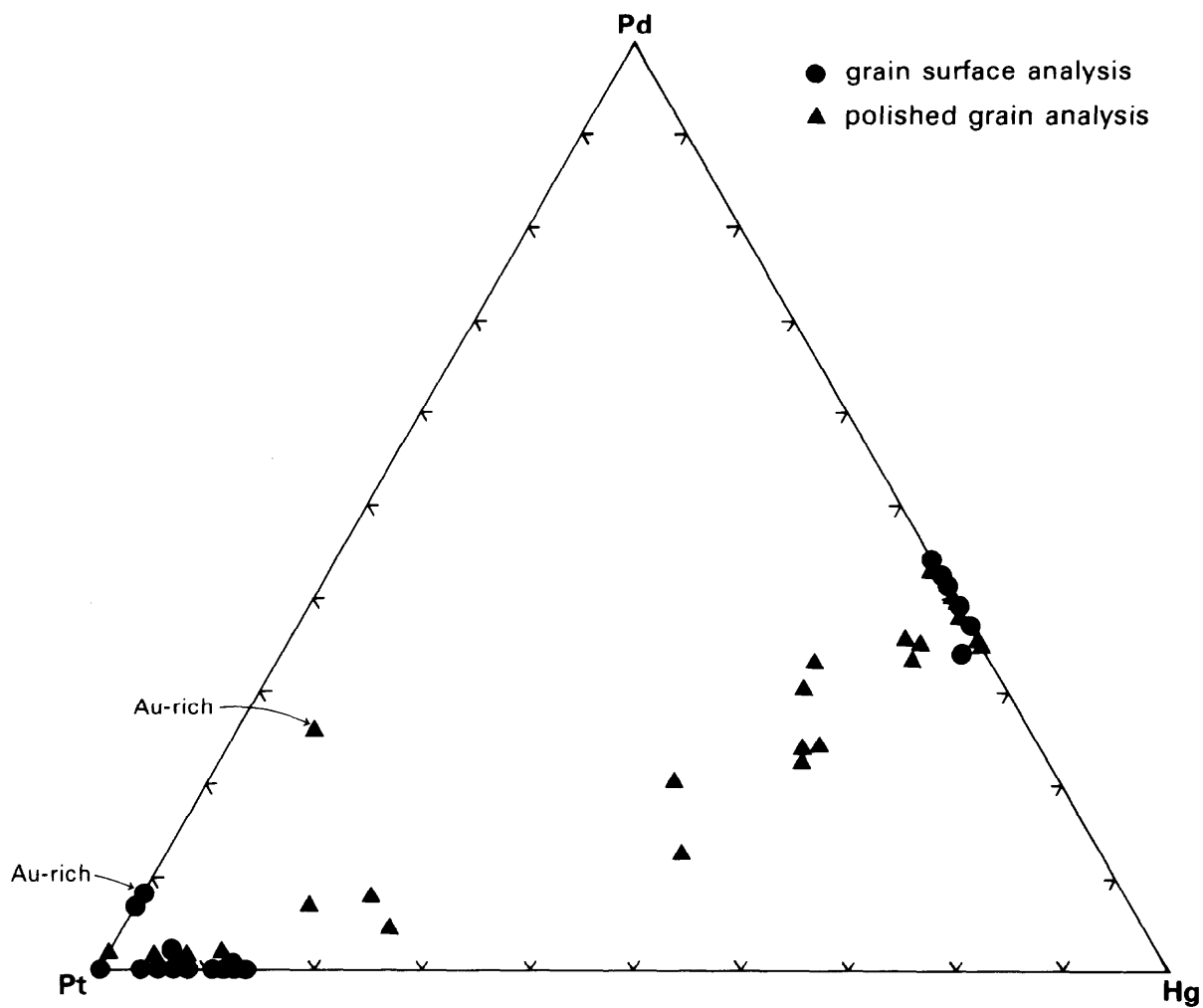




**Figure 27** Compositions of  $2\mu\text{m}$  spots on gold grain surfaces and on polished gold grain mounts expressed in terms of the proportion of Au, Pd and Ag. The diagrams are portions of the Au-Pd-Ag triangular diagram near to the 100% Au apex. Compositions of gold grains from an anomalous drainage site to the east of the Erme estuary are also included.



**Figure 28** Compositions of  $2\ \mu\text{m}$  spots on platinum element-rich grain surfaces and on polished mounts of the same or additional grains expressed in terms of the proportions of Au, Pd and Pt. Analyses from some zoned grains are numbered, superscripts generally increase outwards from core towards rim except for grains 2 and 4, where 2/2 and 4/2 are closer to the centre.



**Figure 29** Composition of  $2\ \mu\text{m}$  spots on platinum element-rich grain surfaces and on polished mounts of the same and addition grains expressed in terms of the proportions of Pt, Pd and Hg

consists of roughly equal proportions of Pd, Hg and Au and less Pt. Type 5 consists of Pd and Hg with variable but usually relatively high Au. Type 6 consists of Pd and Hg with minor Au and corresponds to the mineral potarite. In addition there are also associated compositions of Au with minor Pt, Pd and Hg. The ratio of Pd to Hg is roughly constant throughout the range of compositional types.

**OTHER MINERALS IN PRECIOUS METAL-RICH CONCENTRATE AT [SX 59719 49162]**

The mineralogy of the PGE-bearing drainage samples has been investigated in some detail. Other minerals identified are given in three concentration classes in Table 5 below.

**Table 5** Other minerals identified in sample from [SX 59719 49162]

Rare	Moderate	Common
cinnabar	siderite	pyrite
arsenopyrite	ankerite	cassiterite
cuprite	pyroxene	rutile
galena	amphibole	zircon
chalcocite	fibrous goethite	leucoxene
chalcopyrite		Fe-oxide balls
tourmaline		chlorite
magnetite		irregular goethite
anatase		
chromite		
malachite		

**ORIGIN OF PRECIOUS METAL GRAINS**

The conclusions as to the origin of the gold and PGM grains presented here are preliminary as, at the time of writing, not all data on the borehole material, either chemical or mineralogical, are available. The results of the detailed exploration carried out to try and trace the source of the precious metals, involving geophysical surveys, soil sampling, deep overburden sampling using a Minuteman power auger and diamond drilling of four holes, will form the content of a subsequent report.

The most striking feature of the gold grains from the site at [SX 59719 49162] is the frequent presence of dendritic and other intricate-shaped grains. These shapes cannot survive any significant transport in drainage as any thin projections would rapidly be rolled over the main body of the grain. The number of grains showing any evidence of rolling is very small. From this it can be deduced that the gold in the drainage sediment at this site is very close to its point of origin. Deep overburden sampling confirms this fact as several dendritic grains have been recovered from a number of sites along a zone trending roughly east-west through the anomalous drainage site. Some gold also occurs, although in lesser amounts, in drainage sediment and to a small extent in overburden in the valley occupied by the stream draining from the

north.

The deep overburden sampling indicates that in the valleys to the north and to the west of the confluence there is a layer of alluvium close to the stream which is generally less than one metre thick. This alluvium is related to the present drainage system and contains a significant amount of material derived from the rocks to the north. Beneath this layer and extending over a greater part of the east-west valley is overburden containing many of the minerals in Table 5 including rounded cassiterite and delicate fibrous goethite. The thickness of this material is variable but commonly sufficiently thin for most of the power auger holes to have penetrated into weathered bedrock. Gold occurs in the overburden but also in weathered bedrock which contains no significant cassiterite. A feature of the panned overburden samples, in general, is that they contain much less Sn relative to Au than the drainage samples. Furthermore Au correlates more strongly in the complete overburden dataset with Mn, S and Cu than with Sn. The presence of the cassiterite in the overburden and its possible relationship with gold therefore remains a difficult question. No evidence of the presence of any significant amount of cassiterite has so far been found in the borehole core from the area, although most of the other minerals present in the anomalous drainage samples do occur in the core.

The boreholes will be described in detail in the subsequent report but a few features are included here. The boreholes were orientated firstly to intersect the rock underlying the east-west zone of anomalies in overburden and secondly to intersect any structure which may follow the trend of the valley to the north. The rocks intersected were overwhelmingly sedimentary with only one thin horizon of a highly altered mafic volcanic unit which is probably a tuff. Most of the sedimentary rock is grey shale, often pyritiferous. Within this sequence there is abundant veining of several varieties and relative ages. The most conspicuous veining is tension gash fillings of carbonate with or without quartz. In many cases the carbonate occurs as euhedral rhombs which project into voids. Associated with the carbonate there are scattered grains of euhedral sulphides, mostly pyrite, chalcopyrite and possibly gold. Significant amounts of sphalerite and to a lesser extent galena also occur in one of the holes. There is also more pervasive carbonate alteration and oxidation associated with a near vertical structure running approximately east-west and roughly coincident with the zone of maximum Au anomalies in overburden. Whether this carries gold is not yet known. Gold has, however, been found by analysis at concentrations up to 400 ppb in nearby coastal exposures of slates and mafic volcanic rocks within an east-west trending zone containing much veining, some of which is of euhedral rhomb carbonate.

The precious metal grains could have crystallised into their present forms within at least three different environments. Available evidence does not allow a definite choice between them but a number of observations can be made. Firstly precious metals could have been introduced from outside the area along with the cassiterite and then recrystallised within the overburden during a previous climatic regime. As the area is on a valley floor it is possible that at some time in the past a marsh was present. Organic acids produced by vegetation decay

could have been responsible for the dissolution of precious metals, their local transport and recrystallisation into the grains now found. It is also possible that gold and other metals could have been transported into fissures within the weathered bedrock beneath the overburden. Pyrite, siderite and magnetite balls occur in both drainage and overburden samples from the area. Bacterial action has been proposed to account for the pyrite framboids and siderite spherules that have been found in a number of tin placers in Cornwall (Hosking and Camm, 1980). As these authors also describe similar framboids from both weathered and unweathered parts of mineral veins, it is apparent that other processes may be active in their formation. Spheres of pyrite occur within vein carbonate in the boreholes from the present area though they are relatively rare. A strong association between precious metals, including platinum, and organic matter has been clearly demonstrated in the Zechstein copper deposits of Poland (Kucha, 1982) within a thin organic-rich black shale horizon. In addition native platinum has been observed in pyrobitumen locally associated with sphalerite in New York (Parnell, 1988)

The precious metal grains may be more associated with residual overburden or locally-derived head and therefore with the local bedrock. A second possible environment of formation of the grains is the zone of supergene enrichment associated with chemical weathering in a previous climatic regime. In this environment it is likely that precious metals were transported chemically in solutions resulting from the breakdown of pyrite during the intense tropical weathering that is thought to have affected the area (Leake et al., 1989). Deposition of the grains would occur at the water-table where there was a significant decrease in Eh. There may also have been some lateral migration of solutions towards the valley floor. There is a marked contrast between the depth of weathering in the valley floor which is commonly only a few metres and the more elevated land where boreholes (Leake et al., 1988) have shown pyrite not to be preserved above 40 metres below surface. The valley floor could have more recently been eroded below the original base of the oxidation zone leading to some residual concentration of the precious metal grains in a thin overburden layer. The zoned platinum group element-rich grains are particularly important as they provide constraints on fluid chemistry as solutions must have been capable of transporting Pt and Pd as well as Au, Ag, Hg and Cu. Though acid saline waters are found in lateritic terraines, derived in part from the weathering of pyrite (Mann, 1984) and which are capable of transporting Au, it is unlikely that they would be extreme enough in composition to transport Pt as chloride complexes (Plimer and Williams, 1988). Where carbonate is present along with pyrite, as in the present area, lateritic weathering could produce near neutral solutions containing the thiosulphate ion (Mann, 1985) which is also capable of transporting Au, Pd and Pt (Plimer and Williams, 1988).

A third possibility is that the precious metal grains originated within veins in the bedrock. Subsequently there may have been little change in their chemistry during their residence in the residual overburden derived from the veins. The drill holes have intersected a large number of veinlets and lenses partially filled with euhedral rhomb carbonate with sufficient space for intricate grains of precious metals to have

crystallised. Microchemical mapping of dendritic gold from carbonate veins within limestone at Hopes Nose show Pd and Ag enrichment in rims very similar to that shown in Figures 24 and 25. These similarities are so great as to suggest that the grains from the two areas originated in a similar manner.

It is also possible that the precious metal grains have multiple origins and that different environments and solution chemistries were of importance at different times. A complete description of the results of the overburden sampling and core drilling and discussion of the origin and significance of the gold and PGEs will appear in the subsequent report.

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