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Mineral Reconnaissance Programme Report

No. 79

Volcanogenic and exhalative mineralisation within Devonian rocks of the South Hams district of Devon

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Volcanogenic and exhalative mineralisation within Devonian rocks of the South Hams district of Devon

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SUMMARY

Soil samples were collected from 77 reconnaissance traverses across the outcrop of the Devonian volcanic rocks in the South Hams district of Devon, between the River Yealm in the west and Totnes in the east, and were analysed for at least 15 elements including Cu, Pb, Zn, As, Sb and Ba. Several geochemical anomalies were found, the most extensive and highest amplitude of which comprise a) Ba with smaller amounts of other elements in the Burraton area, b) Ba and other elements in the Higher Ludbrook area and further north-east, c) Sb in the Ladywell area, d) As in the extreme west of the area, e) Cu in association with a diabase near Weeke and f) Zn and Pb around Willing Cross, near Rattery. Several of these anomalies appeared to follow the strike of the volcanic and associated rocks and the first three were investigated further by means of geophysical techniques and drilling. In the Burraton and Higher Ludbrook areas d. c. resistivity, IP, VLF-EM, VLF-R and some detailed gravity surveys were carried out. Around Burraton resistivity anomalies were generally coincident with soil Ba anomalies but there was no coincident gravity anomaly. In the Higher Ludbrook area a massive carbonate horizon found by drilling is responsible for a zone of high apparent resistivity, detected with the dipole-dipole array, and a residual Bouguer anomaly high; dipole-dipole IP anomalies indicate that disseminated mineralisation may be extensive, although the results of EM and resistivity surveys suggest that the massive pyrite intersected in one of the boreholes is of limited lateral extent. Limited geophysical surveys were also carried out in the vicinity of Ba anomalies around Whetcombe Cross and near Fursdon in an area of diffuse geochemical anomalies. A small amplitude IP anomaly in the Fursdon area indicates a possible zone of disseminated mineralisation.

Drilling was confined to the Burraton, Higher Ludbrook and Ladywell areas, where three, three and one holes were collared respectively. In the Higher Ludbrook area the drilling proved a sequence of massive ankeritic-carbonate/quartz rock about 25 m thick underlain by massive pyrite up to 7 m thick resting on highly altered tuffaceous volcanic rocks. This sequence is interpreted as of exhalative origin. Associated with the carbonate rock are relatively high levels of Zn, minor baryte, and veinlets containing pyrite, tetrahedrite and chalcopyrite. The carbonate rock also contains some inclusions of highly altered schistose tuff enriched in Ba, with over 5% Ba in analysed samples. In this rock, and also in similar volcanic rocks beneath the pyrite, Ba appears to be accommodated chiefly in muscovite. The massive pyrite contains interstitial quartz and ankeritic carbonate, and is lensoid in shape since it was not encountered in the third hole about 40 m away from the first. Very minor chalcopyrite is the only other sulphide identified in association with the massive pyrite. Pyrite in layers up to 0.25 m thick and as rich disseminations also occurs in the upper part of the sequence of altered volcanic rocks beneath the massive carbonate and the pyrite rock. The tuffaceous volcanics are highly altered basic rocks greatly enriched in K, and to a lesser extent Al, Mn and Ba, and depleted in Na, Mg and to some extent Fe. Minor amounts of discordant tetrahedrite, chalcopyrite and Co/Ni mineralisation also occurs in the volcanic rocks. In the Burraton area argillaceous sedimentary rocks were the dominant rock type in the drill holes but a 10 m thick volcanic horizon similar in appearance and chemistry to the Higher Ludbrook rocks was also intersected. In addition quartzite and baryte occur within a poorly-recovered 2 m thick zone which may be similar to the massive and layered baryte float seen in the vicinity. The Ladywell borehole intersected an inverted sequence of volcanic rocks similar to those from the Higher Ludbrook area. The intensity of hydrothermal alteration varied down the hole and was most intense at the stratigraphical top. Fossiliferous reef

limestone overlies the volcanic sequence, followed by tuffaceous sediment at the base of the hole. No significant antimony-bearing mineralisation was intersected and therefore the source of the high amplitude surface anomalies remains uncertain.

It is clear from both the soil geochemical survey and the drill core that the Devonian volcanic belt in South Hams is the locus of significant mineralisation and hydrothermal alteration. The extensive exhalative mineralisation and disseminated sulphide in altered volcanic rocks suggest the activity of large convective hydrothermal cells. Furthermore the geochemistry of the various types of mineralisation found suggests that significant enrichments of gold may also occur in the region.

INTRODUCTION

The belt of sedimentary and volcanic rocks which occurs to the south of the Dartmoor granite forms undulating terrain with extremely limited exposure. Very little geological work has been carried out in the area since the Geological Survey mapping of the Ivybridge sheet (No. 349), published after revision in 1912 with an accompanying memoir (Ussher, 1912). Recent work on adjacent sheets, especially Tavistock (No. 337), has shown that the geology of South-West England is characterised by thrusting and overfolding, with major tectonic units separated by low-angle discontinuities. A major flat-lying, north-facing fold has been recognised by Turner (1981) which is thought to represent an allochthonous unit introduced from the south where basin and rise facies sedimentation was developed. Hillcock (1982) describes three structural units between Buckfastleigh and Ivybridge, the lowest of which contains the Rattery volcanics and has also been thrust to the north, but no structural work has been carried out in the main belt of volcanic rocks to the south. Some recent structural work has been carried out on the coast around Torquay (Coward and McClay, 1983), where the Middle Devonian rocks are predominantly limestone rather than volcanics and shales as in the present area, and it is likely that the northward-verging thrust nappes which dominate the coastal area extend inland.

A programme of mineral exploration was carried out across the main belts of volcanic rocks in the South Hams district of Devon with the objective of locating stratabound or stratiform volcanogenic mineralisation. The area was thought to have some significant similarities with the region approximately along strike in West Germany which contains the important Meggen stratiform sulphide and baryte deposit. Evidence of the occurrence of such mineralisation within the main belt of volcanic rocks was provided by the well-defined barium anomalies in drainage samples, which followed the local strike (Jones, 1981). Accordingly, a series of 77 traverse lines across all or part of the volcanic belt were sampled with a hand auger at 20 m intervals in a reconnaissance exploration survey (Figure 1). Previous experience in the Lizard area of Cornwall (Smith and Leake, 1984) had shown that when soils are of residual origin, as seems to be the case for much of south-west England, patterns of element distribution, particularly of the more immobile elements such as titanium, can be used to provide a guide to the underlying geology in poorly exposed ground which is superior to that possible using orthodox mapping techniques. The interpretation of the significance of anomalies of such ore elements as copper was undertaken in terms of geological insight deduced from the distribution of elements which reflect differences in the underlying rock types.

In the light of this interpretative work, holes were drilled in areas where stratabound mineralisation was suspected. Multi-element chemical data were obtained on most of the drill core, and mineralogical examination and probe analyses were carried out on some samples of interest. It proved necessary to drill a series of holes in areas of interest since, although the direction of strike of the rocks could be deduced from the soil data, there was no information available as to the direction and angle of dip. The initial drill hole in each area was sited to the south of the anomaly, since all the dip directions shown on the existing geological map (sheet 349) trended to the south. This information proved to be misleading in the Burraton area, as the dip of the strata there proved to be to the north.

In some areas where geochemical anomalies were of interest, geophysical surveys were carried out prior to the drilling. The surveys comprised combinations of IP, SP, VLF-EM, VLF-R, resistivity, magnetics and detailed gravity methods and were planned initially with a view to the detection of massive baryte mineralisation and to provide structural information to help in the interpretation of the geochemical anomalies. Difficulties were caused by artificial anomalies due to buried pipes etc in several areas, but some anomalies probably related to mineralisation and variations in rock type, were detected and these are discussed below in the context of the structural interpretion of the borehole localities.

GENERAL GEOLOGY

In view of the lack of recent work on the geology of the area most of the geological descriptions and interpretations are based on borehole material, and the nature of the underlying rocks is deduced from the results of the soil sampling augmented by some reference to the original mapped boundaries. The titanium content of the soil samples has been used in the construction of the general geological map shown in Figure 2. The volcanic rocks from all the boreholes are characterised by relatively high levels of Ti (in the range 2.0 – 5.3% TiO_2) while the sedimentary rocks contain amounts up to a maximum of about 1.2% TiO_2 and frequently much less. Relatively high levels of Ti in soil also mark areas where the volcanic rocks are known to occur from the outcrop and borehole information. Similarly, low levels of Ti are characteristic of areas where the sedimentary rocks are known to suboutcrop. On examination of individual soil traverse lines, marked jumps in titanium levels are apparent from typical sedimentary levels to typical volcanic levels and the positions of these are considered to represent the suboutcrop of the contact between the two rock types. Though there may have been downhill creep of residual soils which would cause an apparent displacement of the boundary, there is little evidence to suggest that this effect is significant in most areas where the angles of slopes are gentle.

The Middle Devonian rocks which occur between the river Yealm and Totnes consist predominantly of argillaceous sediments and volcanic rocks. The sedimentary rocks intersected in the boreholes comprise grey cleaved shales with thin horizons of more silty material which seem to have undergone intense hydrothermal alteration. The volcanic rocks which are interbedded within the shales are also extremely altered but appear to be largely tuffaceous and the term schalstein has been applied to them. Ussher (1912) described the volcanics as purple, buff, brown and green schalsteins quite unfit for microscopic investigation, and noted that they had undergone shearing and were highly charged with carbonates. Some had been so altered as to be almost transformed
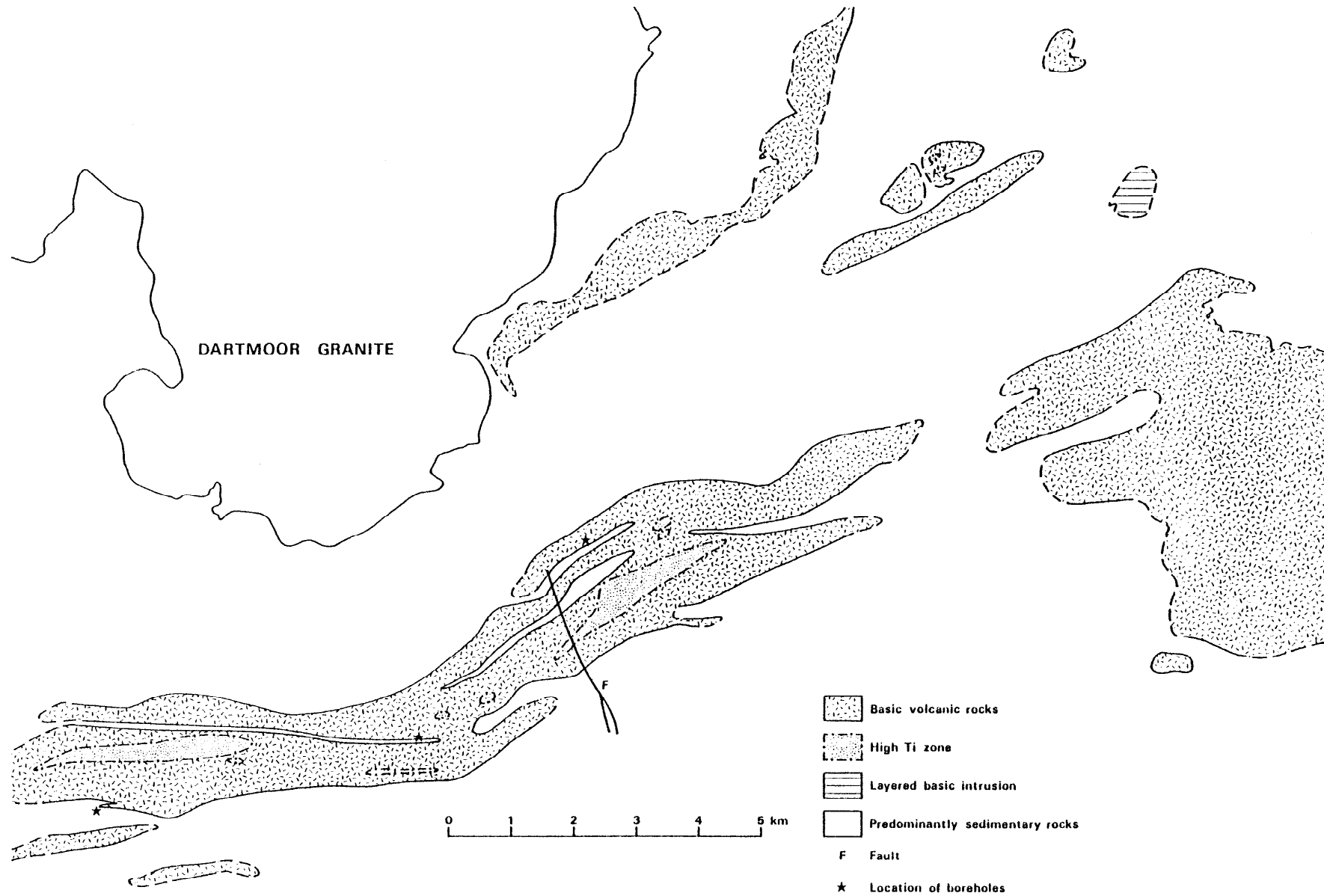
Figure 2 General geological map showing outcrop of volcanic and other igneous rocks.
Modified from Ivybridge (349) sheet of the 1:50 000 Geological Map of England in the light of
the chemistry of the reconnaissance soil samples.

into sericitic and chloritic schists.

Volcanic rocks were intersected in all three of the areas drilled but in the Burraton area only one horizon about 10 m thick was encountered. In both the Higher Ludbrook and Ladywell areas continuous sections of at least 60 and 90 m of volcanics respectively were intersected. In spite of the hydrothermal alteration the fragmental and often highly brecciated nature of the volcanics can clearly be seen. In some sections highly vesicular fragmental material is apparent. Most of the elements that have been determined in the borehole samples of volcanic rocks are clearly influenced by the variable and often intense degree of hydrothermal alteration that has occurred but the elements phosphorus and titanium are widely regarded as immobile under such conditions and therefore likely to give some indication of original composition. A plot of TiO_2 against P_2O_5 for the 105 samples of volcanic rock analysed (Figure 61) shows there is considerable overlap between the rocks from the three areas and demonstates a significant positive correlation between the two elements. Compared with the data presented by Floyd (1982) for other volcanic rocks in South West England both Ti and P contents seem relatively high which suggests that the rocks are relatively highly evolved, but lack of chemical data on other immobile elements prevents further detailed chemical comparisons. The chemical data from the boreholes strongly support the soil data in that the titanium contents of the volcanic rocks are much higher than those of the sedimentary rocks. Ussher (1912) considered that the finger-like outcrops of volcanic rocks portrayed on the Ivybridge geological sheet represented irregular outward extensions from local centres of eruption which overlap and are locally interbedded with sedimentary rocks. The outcrop pattern revealed by the titanium content of the soils (Figure 2) confirms this interpretation, with elongate lensoid volcanic zones with maximum titanium contents in the widest central parts. Furthermore, the peripheral zones, where the outcrop width is least, are also relatively low in titanium and in some cases relatively rich in calcium which may indicate that the volcanics grade into sedimentary rocks with a decreasing volcanic component or into calcareous rocks. A feature of the outcrop disposition of the volcanic rocks, which is more obvious from the geological interpretation of the soil data than the original geological map, is the tendency for the elongate volcanic zones to be arranged en-echelon. The en-echelon arrangement of volcanic fissures is of widespread occurrence and could, in this case, reflect zones of relative tension due to deep crustal dextral shear. Such an interpretation is consistent with the overall interpretation of the Hercynides as a strike-slip orogen (Badham, 1982), at least for the tectonic regime which predated the generation of northward directed nappes and thrusts.

Though thick limestones occur both to the east and to the west of the area the amount associated with the South Hams volcanic belt is minor. It is thought that reef limestones developed on volcanic masses which were elevated to near sea level. A zone about 3 m thick of what is probably reef limestone, since it contains abundant remains of colonial corals, crinoids etc, occurs below the 90 m section of volcanic rocks in the Ladywell borehole (Figure 59). Ussher (1912) describes other minor horizons of limestone often in close association with the volcanic rocks, e. g. the Hazard limestone, which also structurally underlies the volcanics.

It is extremely difficult to derive any structural interpretation of the volcanic belt from the available information. Nevertheless the existence of coralline limestone structurally below the volcanics in the Ladywell borehole would suggest that the sequence there was inverted. On the other hand volcanics overlain by massive sulphide, massive carbonate and sediment in the Higher

Ludbrook area would suggest that here the sequence was right way up. This conflicting evidence could be explained in terms of a major nappe structure, such as occurs in the Carboniferous strata to the north-west, within the Tavistock district, or alternatively as a more local flexure as portrayed by Willcock (1982) for the Rattery area.

REGIONAL GEOPHYSICS

The Bouguer gravity anomaly field in South Devon is dominated by the strong negative anomaly associated with the Dartmoor granite: across the belt of volcanic rocks in South Devon the Bouguer gravity anomaly generally increases to the south and south-east.

The aeromagnetic anomaly map (I.G.S. 1965) shows a series of elongate magnetic anomalies with local highs of about 50 nT above background. In detail these highs are located close to the mapped southern boundaries of the volcanic tuffs and schalsteins and have subdued minima to the north. An aeromagnetic anomaly of significantly greater amplitude is associated with the volcanic rocks in the valley of the River Yealm at Woodburn [SX 6057], but this is outside the area of interest of this report.

EXPLORATION

Reconnaissance soil sampling at 20 m intervals along traverse lines orientated roughly at right angles to the regional strike of the volcanic rocks was carried out in three stages. Initially 829 samples from 12 lines were collected in 1980. These were followed up in 1981 with a series of shorter lines (Figure 1) at four anomalous sites and these were used for the siting of 7 boreholes in three of these areas. In 1982 a further 2185 samples were obtained from 49 traverses to fill in between the original lines and to extend the coverage to include the volcanic zone at Rattery and also near Buckfastleigh.

After collection the soil samples were oven dried, disaggregated and then sieved to produce a minus 85 mesh BSS fraction. This was then ground further in a Fritsch Pulverisette 5, equipped with agate mortars, prior to determination of Co, Ni, Cu, Zn, Ag and Pb by atomic absorption spectrometry (A.A.S.). Subsamples of these and all the other samples were mixed with elvacite prior to Tema grinding, pelletising and analysis by X-ray fluorescence (X.R.F.). In the initial and follow-up sample batches the elements Ca, Ti, Mn, Fe, As, Sb and Ba were determined by X.R.F. and in the follow up samples Ni, Cu, Zn and Sn analyses were also obtained. In the final sample batch the additional elements V, Cr and W were determined. A small number of samples from short traverses east of Coyton, to the south-west of Ivybridge (lines 201-205, Figure 1), were analysed by Mather Research Ltd, Rothbury by an A.A.S. technique for Mn, Fe, Ni, Cu, Zn, As and Pb but these were not included in the main data set for statistical treatment and cumputer plotting because the extraction technique employed produced results which were not totally compatible with the other analytical techniques utilised. However the results were used in the production of the map showing the distribution of the main geochemical anomalies in the region (Figures 20 and 21).

Soil geochemistry

The geochemical data from the soil samples are summarised in the form of
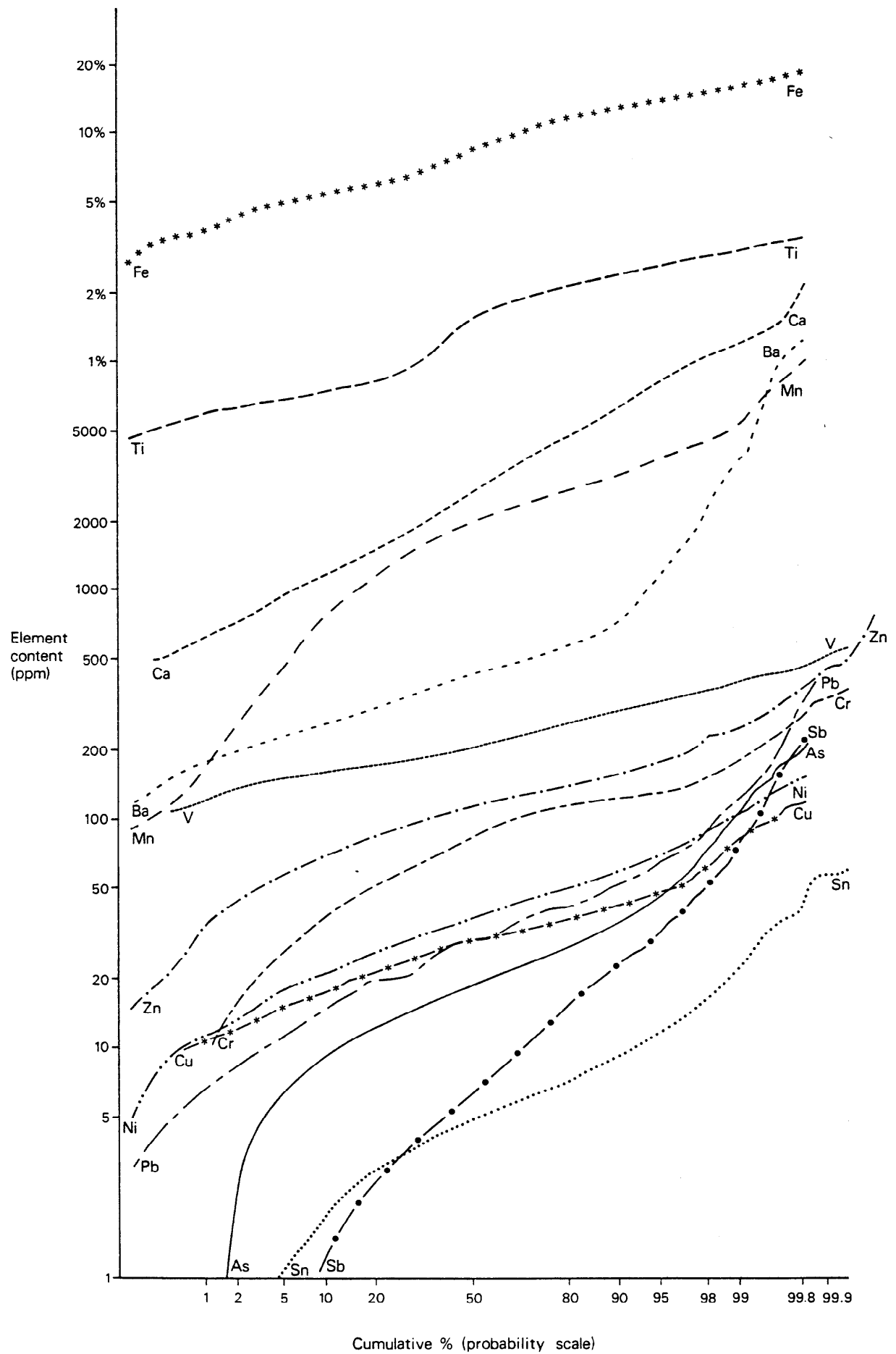
Figure 3 Cumulative frequency plot of Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Sn, Sb, Ba and Pb in soil samples.

cumulative frequency plots for each element in Figure 3. Tungsten has not been plotted because of a very limited range in concentration. Several types of distribution are apparent in the figure. Titanium shows a very well-defined bimodal distribution which corresponds to the sedimentary and volcanic rock types respectively and confirms its usefulness for geochemical mapping. Several elements show distribution patterns with sharp increases in gradient at the 90 percentile or greater. Barium is a good example of this type with the point of inflexion at around 700 ppm, above which the influence of barium in soils derived from hydrothermal mineralisation is apparent. Similar though less well defined patterns exist for Cu, Sb, As, Pb and Zn. Fe and V show populations close to lognormal but with a trace of bimodalism at roughly the same percentile level as in the titanium population. This suggests that these three elements are closely correlated in most samples but with more variation perhaps due to the influence of secondary environmental factors. The distributions of Mn and Cr are more like normal populations with a small anomalous population above the 99 and 98 percentiles respectively. Ca and Ni show distributions which are close to being lognormal.

The distribution of the elements Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Ag, Sn, Sb, Ba and Pb in soils are shown in class interval terms plotted by computer in Figures 4 to 18. The class intervals chosen for plotting are based on breaks in slope in the cumulative frequency plots either for the total data set or for smaller data sets for different subareas of the total. One group of elements comprising Ti, V and Cr shows distribution patterns which are closely related to the geology of the area, with soils derived from the volcanic rocks clearly enriched in Ti and V and depleted in Cr relative to the surrounding sedimentary rocks. The significant positive correlation between Ti and V and the negative correlation between Ti and Cr are also shown on the scatter plots of the soil data in Figure 19. The highest levels of Cr occur in samples from the area portrayed on both the Ivybridge and Torquay sheets as diabase around Week near Totnes. The soil data suggest that this body, which occurs within the sedimentary rocks, is unlike the volcanic rocks in chemistry and probably represents a layered basic intrusion.

The distribution of Fe shows a similar but less pronounced correlation with rock type, with a general enrichment over the volcanic rocks compared with the sedimentary rocks. A scatter diagram in Figure 19 also shows the significant positive correlation between Fe and Ti. The soil data suggest that some areas of volcanic rocks, especially in the extreme west of the area and around Rattery, are anomalously low in the element. It is possible that this reflects a high intensity of hydrothermal alteration as the analyses of borehole material indicate that Fe is depleted relative to Ti in the most hydrothermally altered samples, a trend which is illustrated on the scatter plot of the borehole data in Figure 56. There are also some samples with high and very high levels of Fe where the iron is probably of hydrothermal origin. This is especially likely where the Ti levels are low, such as occurs in samples from the Higher Ludbrook area as described below. Another sample from around 1 km further to the east with similar characteristics, i.e. DCS 3088, may be derived from comparable material.

Samples containing relatively high levels of calcium are to be found over both the volcanic and the sedimentary rocks. Several samples from the Burraton area show some correlation with the zone of relatively high levels of barium, though in the data as a whole there is no general positive correlation between the two elements. There is also a tendency for calcium-rich samples to occur within

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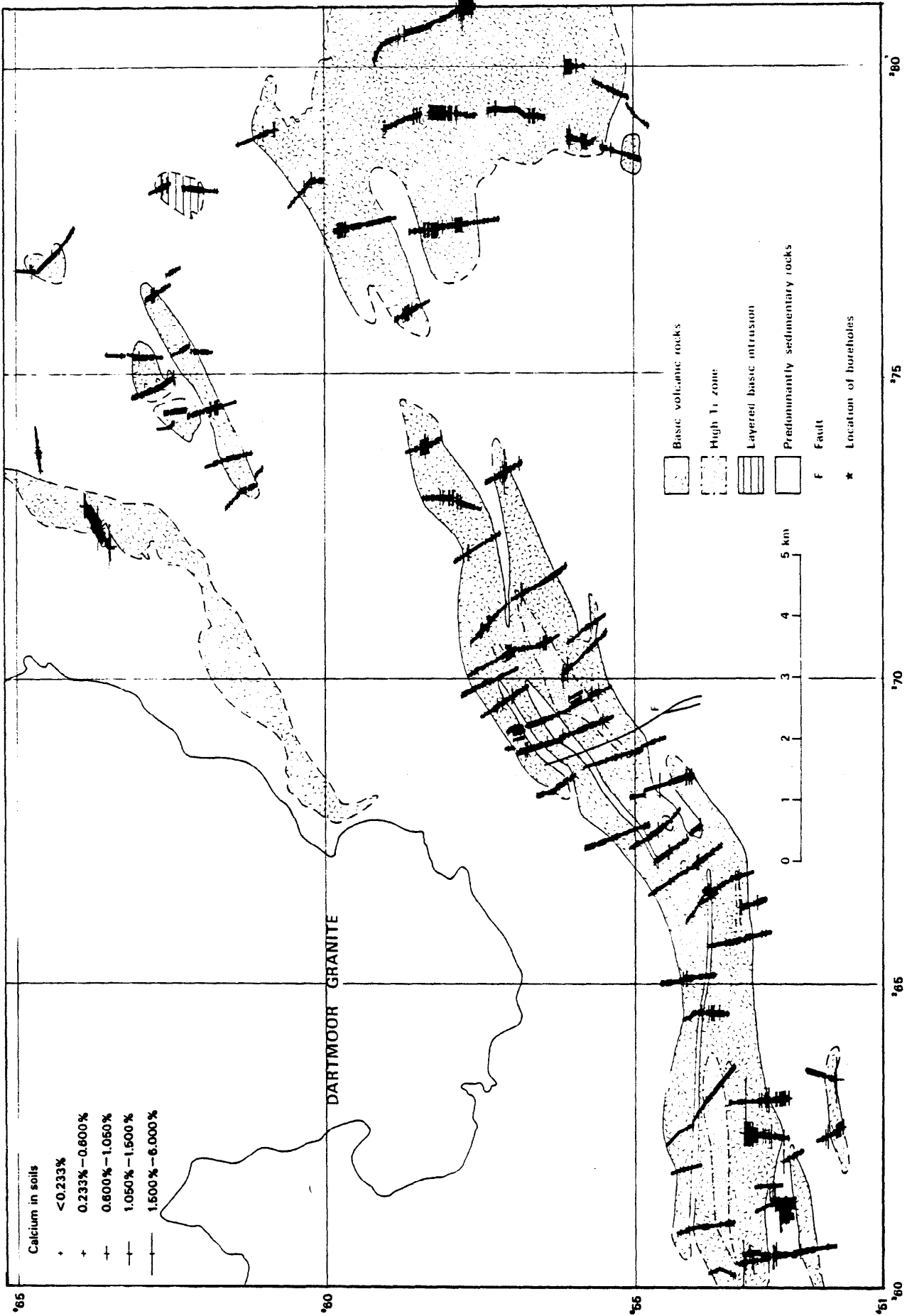
Figure 4 Distribution of Ca in reconnaissance soil samples.

Calcium in soils
- <0.233%
- 0.233%—0.600%
- 0.600%—1.050%
- 1.050%—1.500%
- 1.500%—6.000%

DARTMOOR GRANITE

Basic volcanic rocks
High Ti zone
Layered basic intrusion
Predominantly sedimentary rocks
F   Fault
★   Location of boreholes

5 km
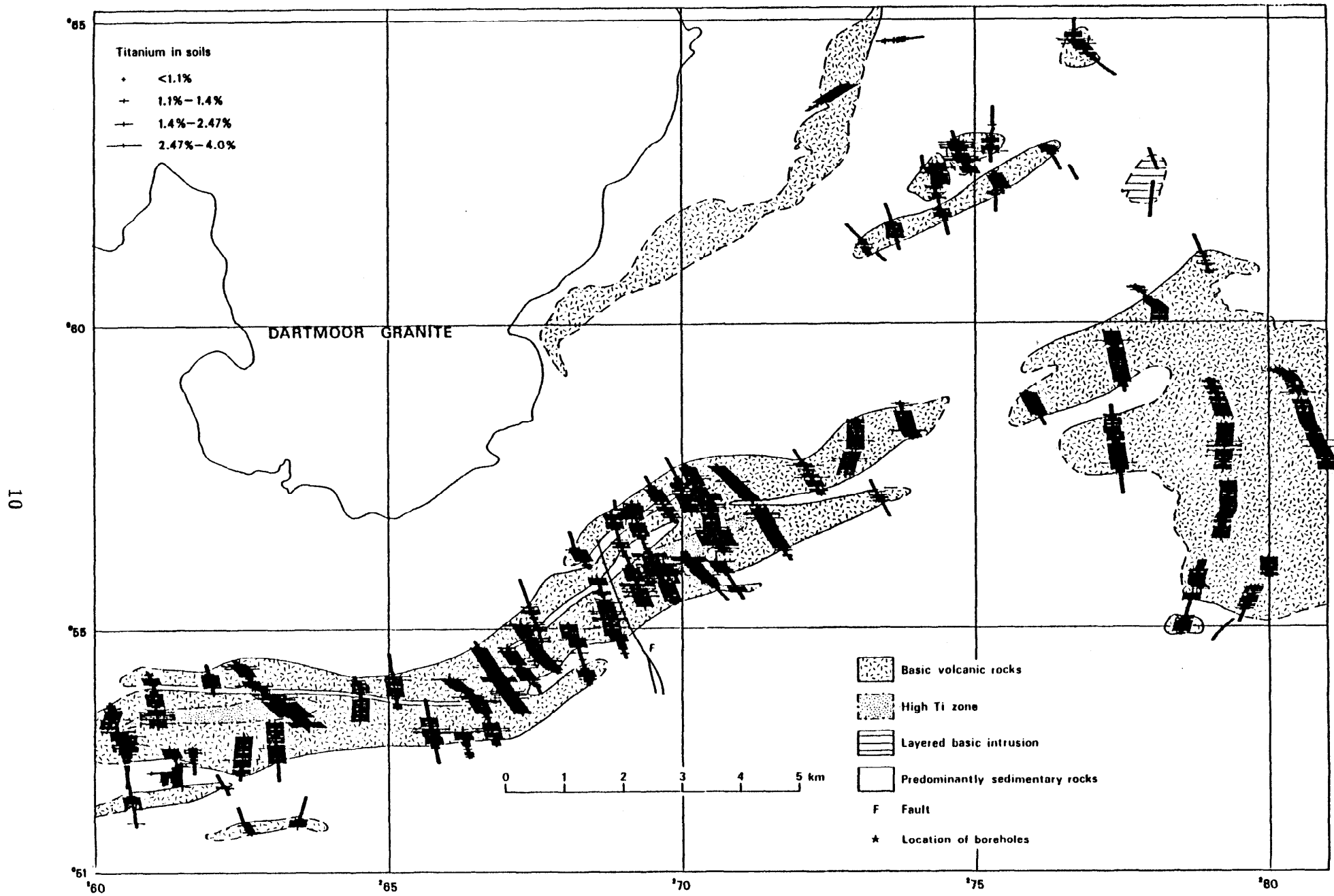
Figure 5 Distribution of Ti in reconnaissance soil samples.
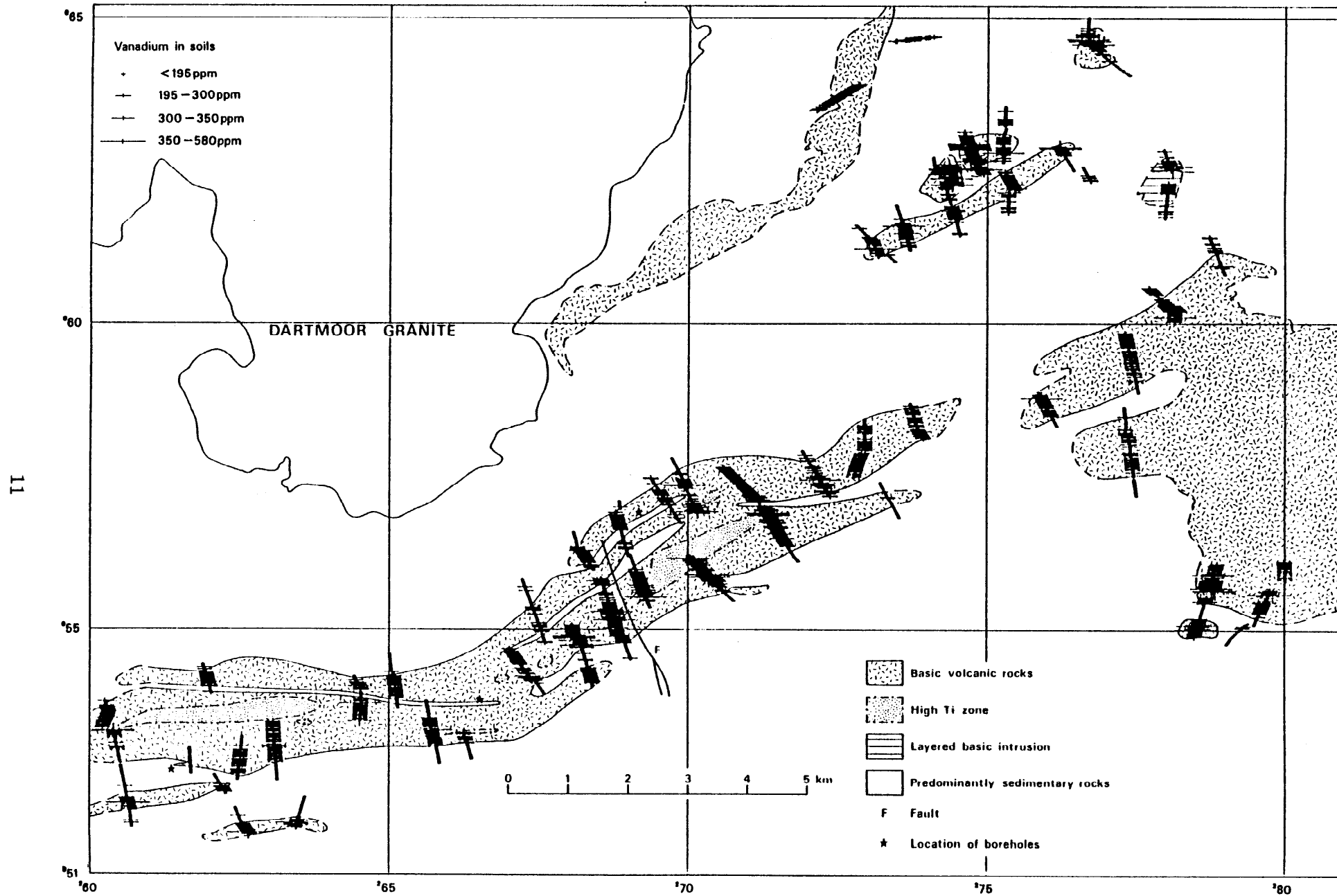
Figure 6 Distribution of V in reconnaissance soil samples.

11
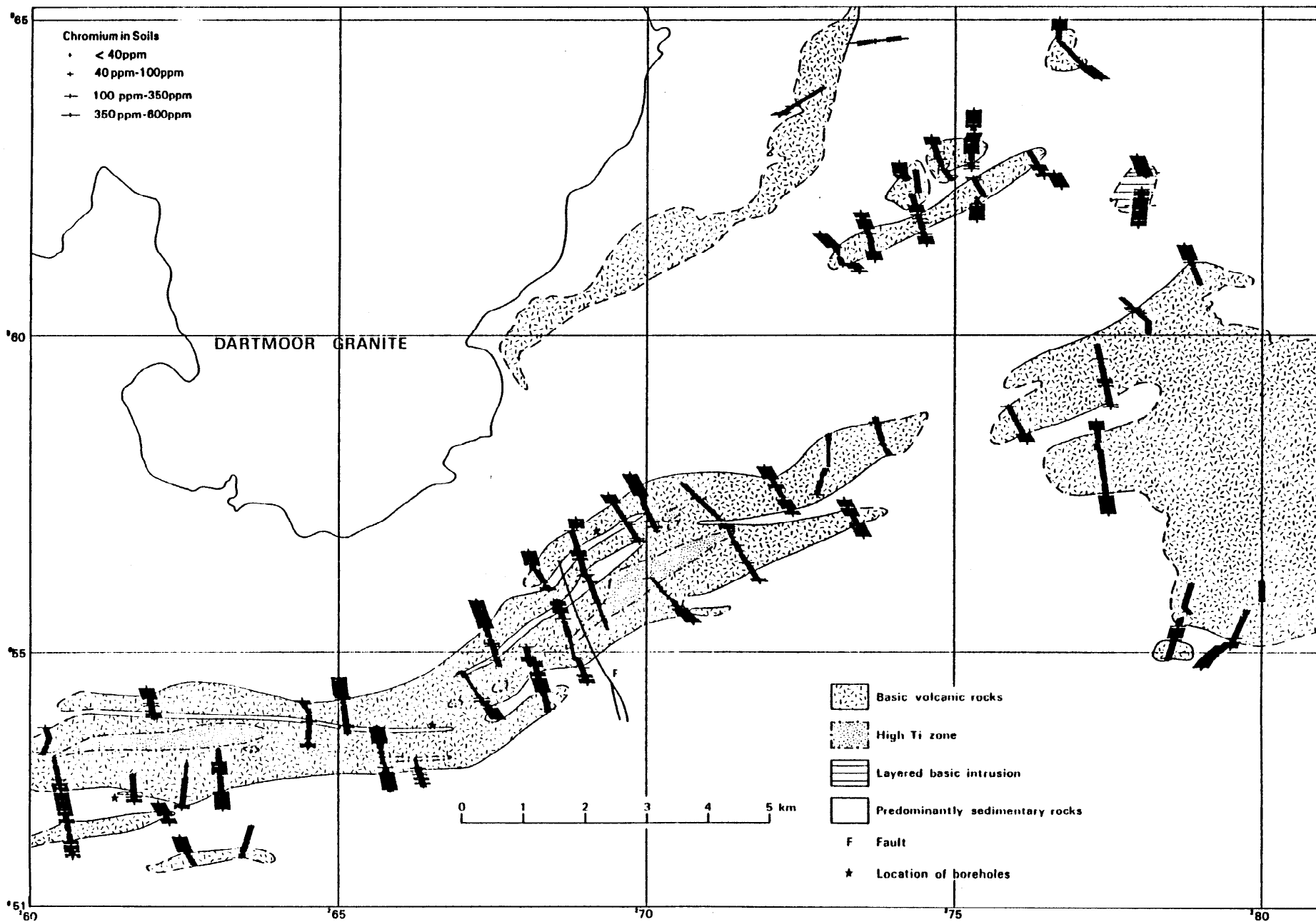
Figure 7 Distribution of Cr in reconnaissance soil samples.
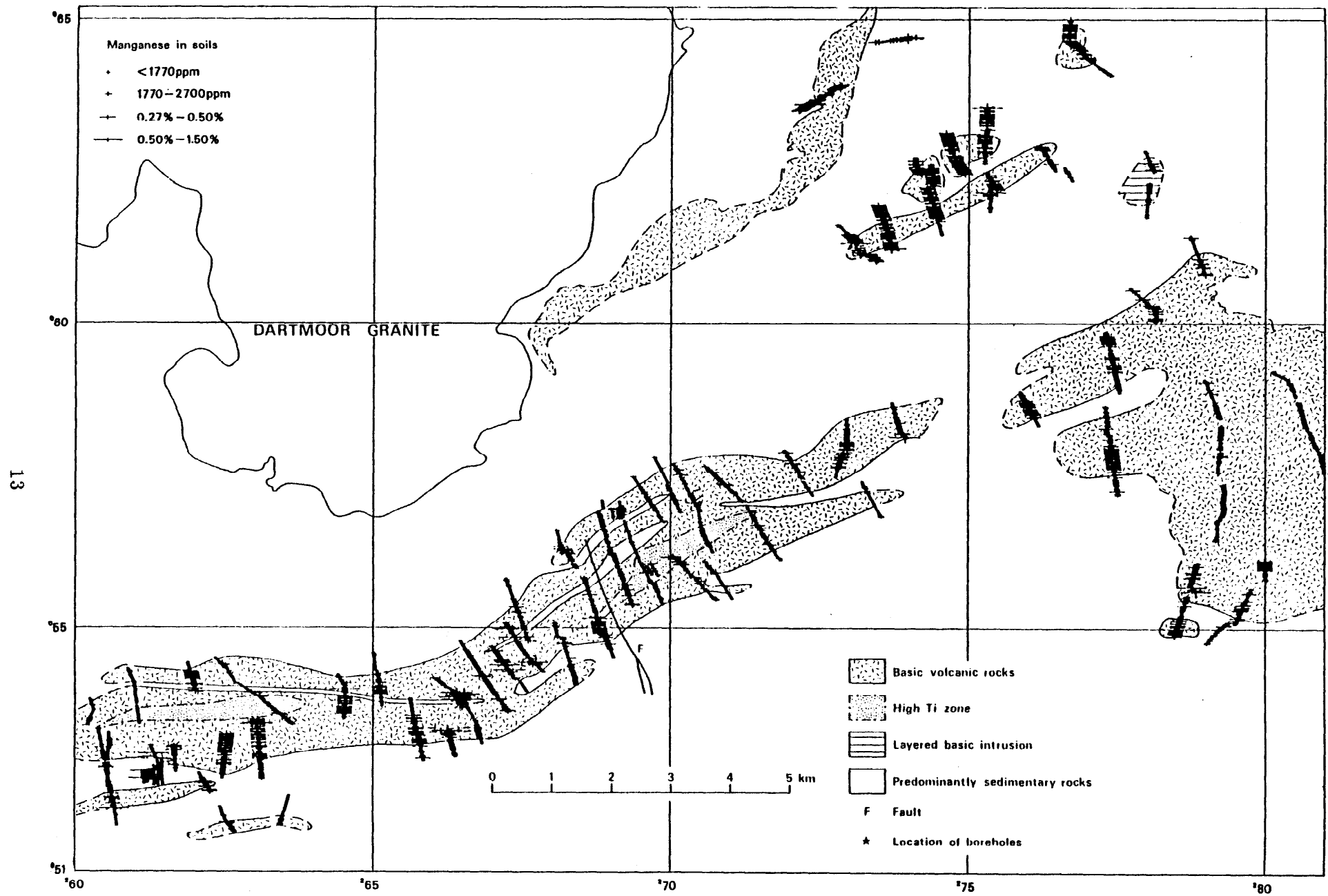
Figure 8   Distribution of Mn in reconnaissance soil samples.
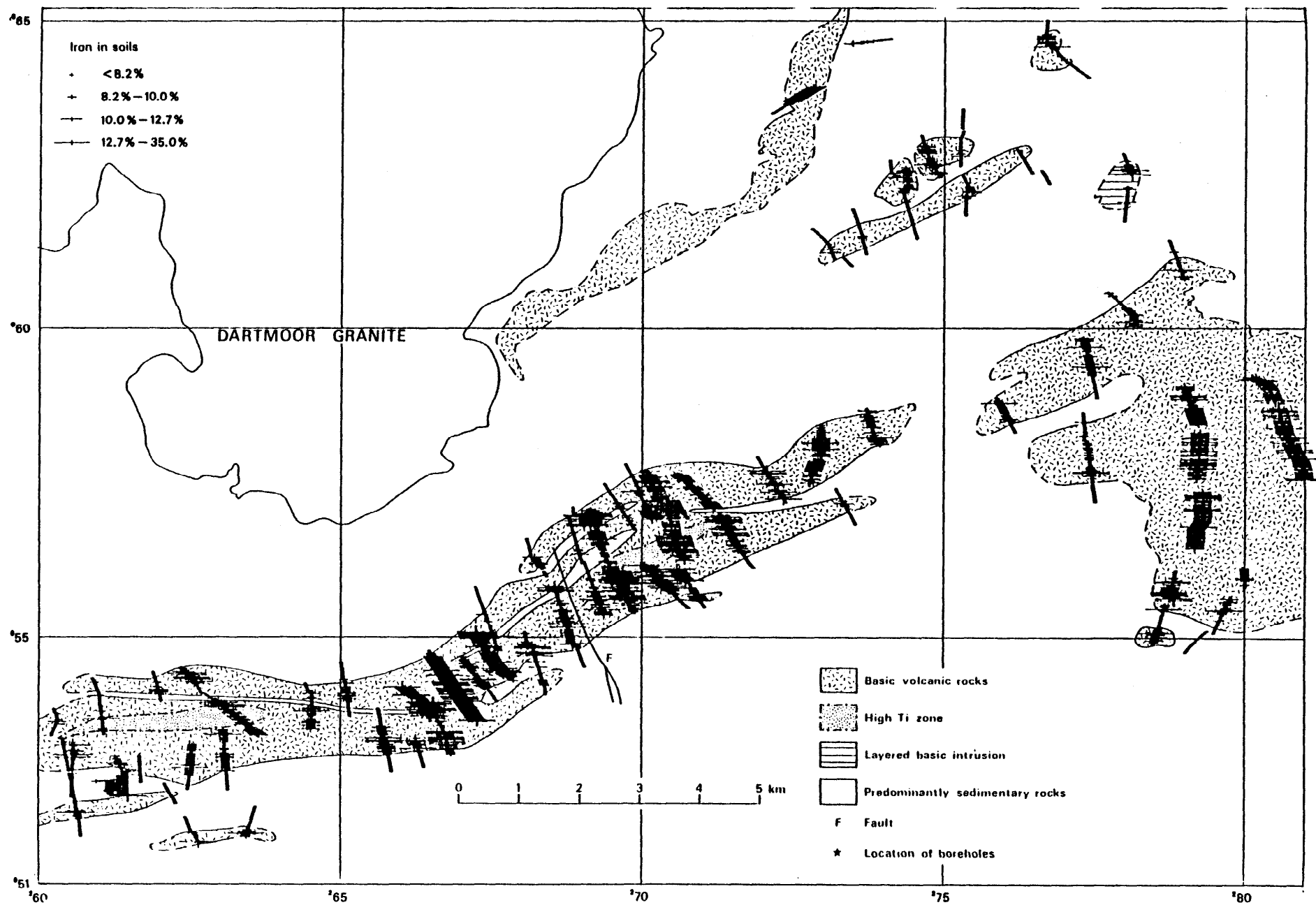
Figure 9 Distribution of Fe in reconnaissance soil samples.

Legend content within the figure:

Iron in soils
- <8.2%
- 8.2% – 10.0%
- 10.0% – 12.7%
- 12.7% – 35.0%

DARTMOOR GRANITE

Basic volcanic rocks
High Ti zone
Layered basic intrusion
Predominantly sedimentary rocks
F   Fault
★   Location of boreholes

0   1   2   3   4   5 km

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Nickel in soils

- • <65ppm
- + 65—90ppm
- —+— 90—200ppm
- —+— 200—725ppm

DARTMOOR GRANITE

Basic volcanic rocks

High Ti zone

Layered basic intrusion

Predominantly sedimentary rocks

F   Fault

★   Location of boreholes

0   1   2   3   4   5 km

Figure 10   Distribution of Ni in reconnaissance soil samples.
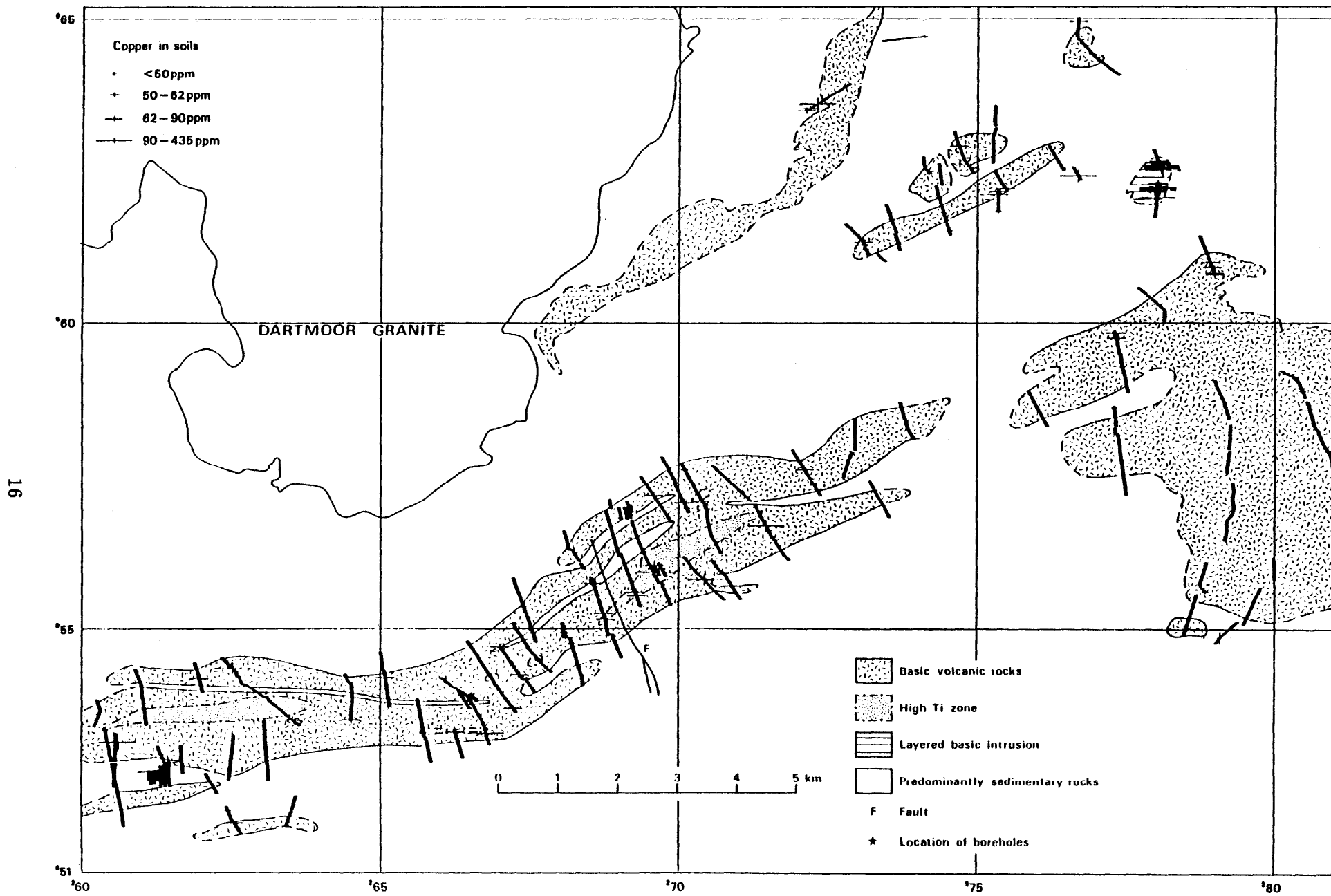
Figure 11 Distribution of Cu in reconnaissance soil samples.

Copper in soils

+ <50 ppm
+ 50 – 62 ppm
+ 62 – 90 ppm
+ 90 – 435 ppm

DARTMOOR GRANITE

Basic volcanic rocks

High Ti zone

Layered basic intrusion

Predominantly sedimentary rocks

F Fault

★ Location of boreholes

0 1 2 3 4 5 km
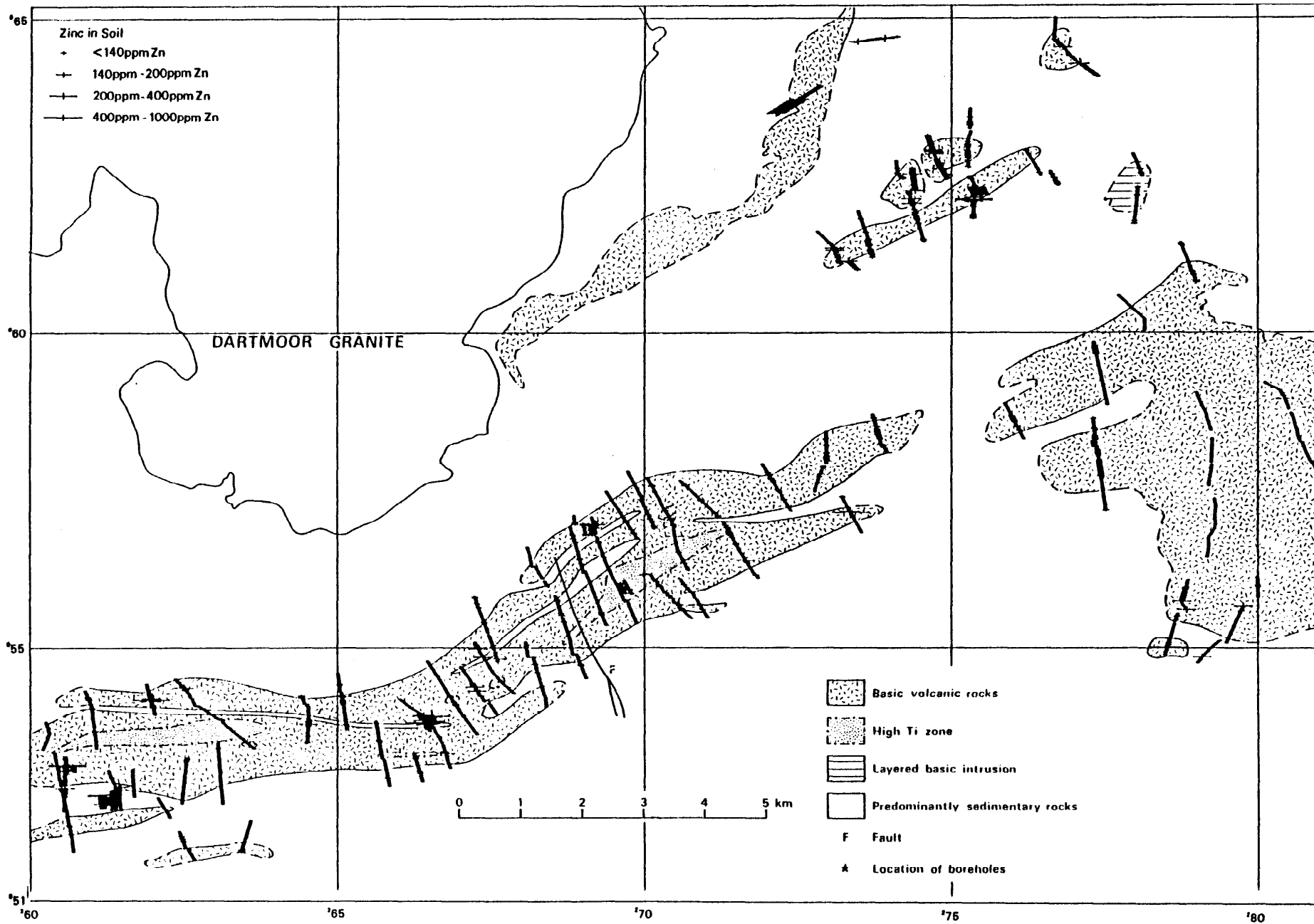
Figure 12 Distribution of Zn in reconnaissance soil samples.

Legend within figure:

Zinc in Soil
- <140ppm Zn
- 140ppm -200ppm Zn
- 200ppm-400ppm Zn
- 400ppm -1000ppm Zn

DARTMOOR GRANITE

Basic volcanic rocks

High Ti zone

Layered basic intrusion

Predominantly sedimentary rocks

F   Fault

★   Location of boreholes

0   1   2   3   4   5 km
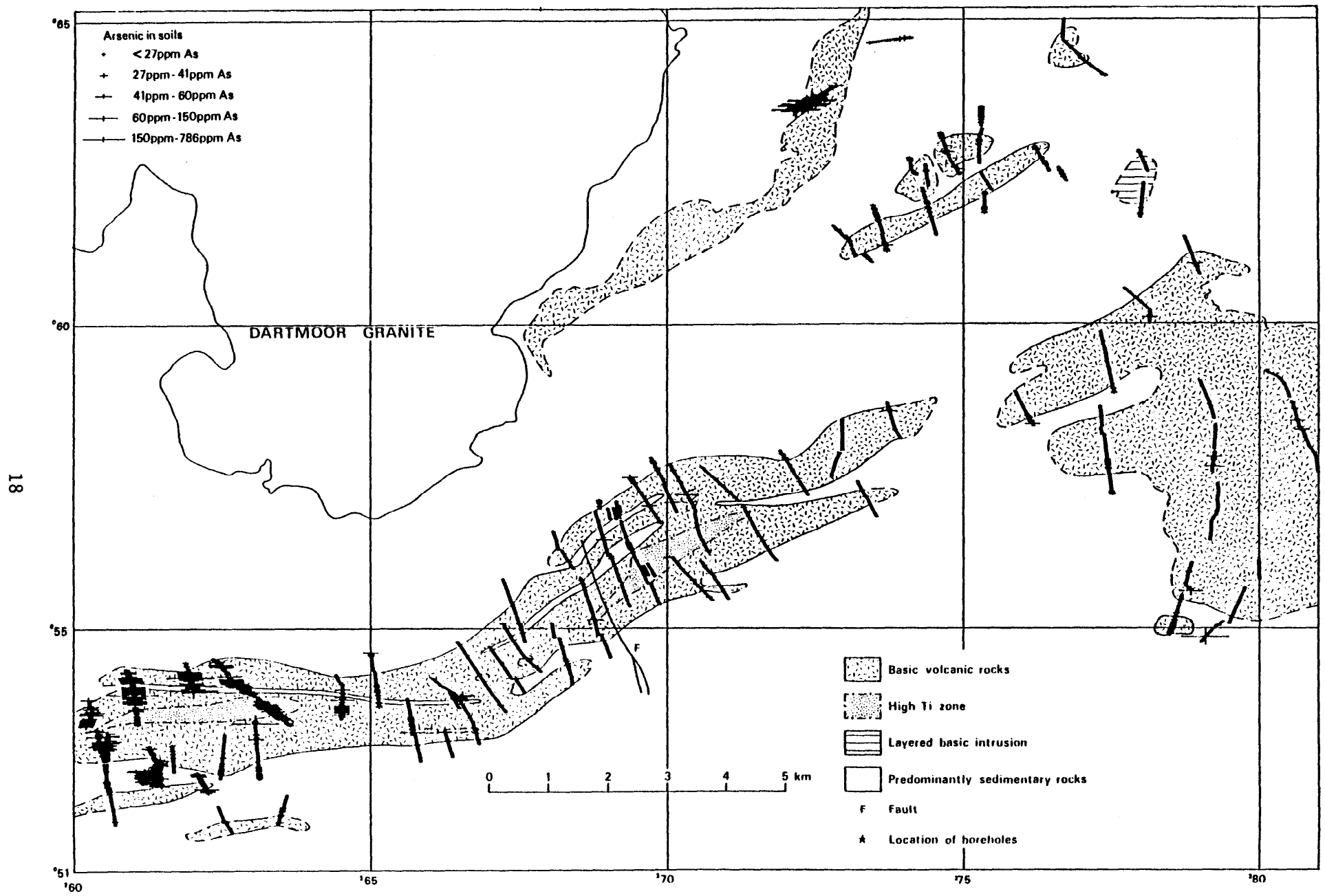
Figure 13 Distribution of As in reconnaissance soil samples.

Silver in Soil
+   <5ppm Ag
-+-   5ppm -7ppm Ag

DARTMOOR GRANITE

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Basic volcanic rocks

High Ti zone

Layered basic intrusion

Predominantly sedimentary rocks

F   Fault

★   Location of boreholes

0   1   2   3   4   5 km
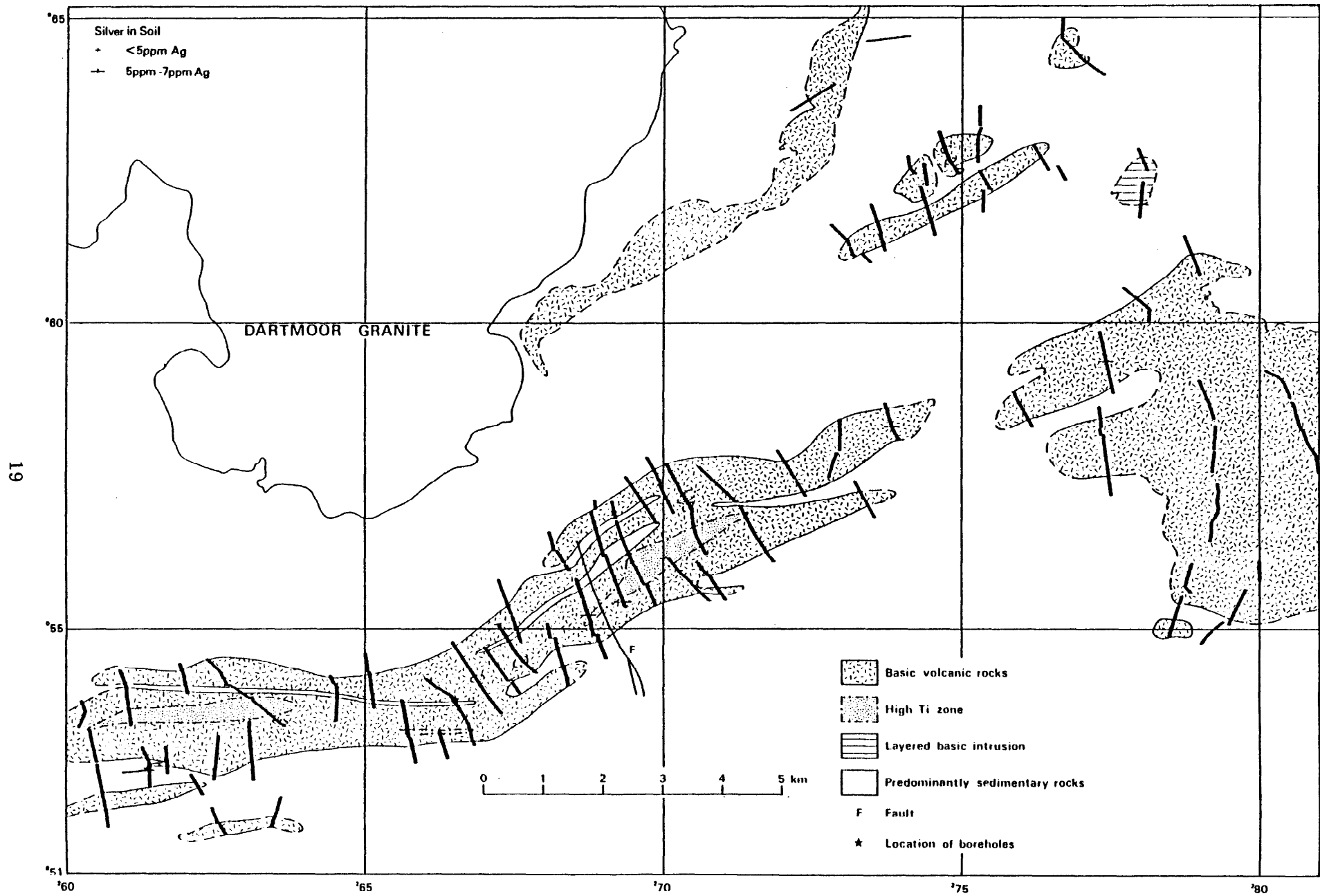
Figure 14   Distribution of Ag in reconnaissance soil samples.
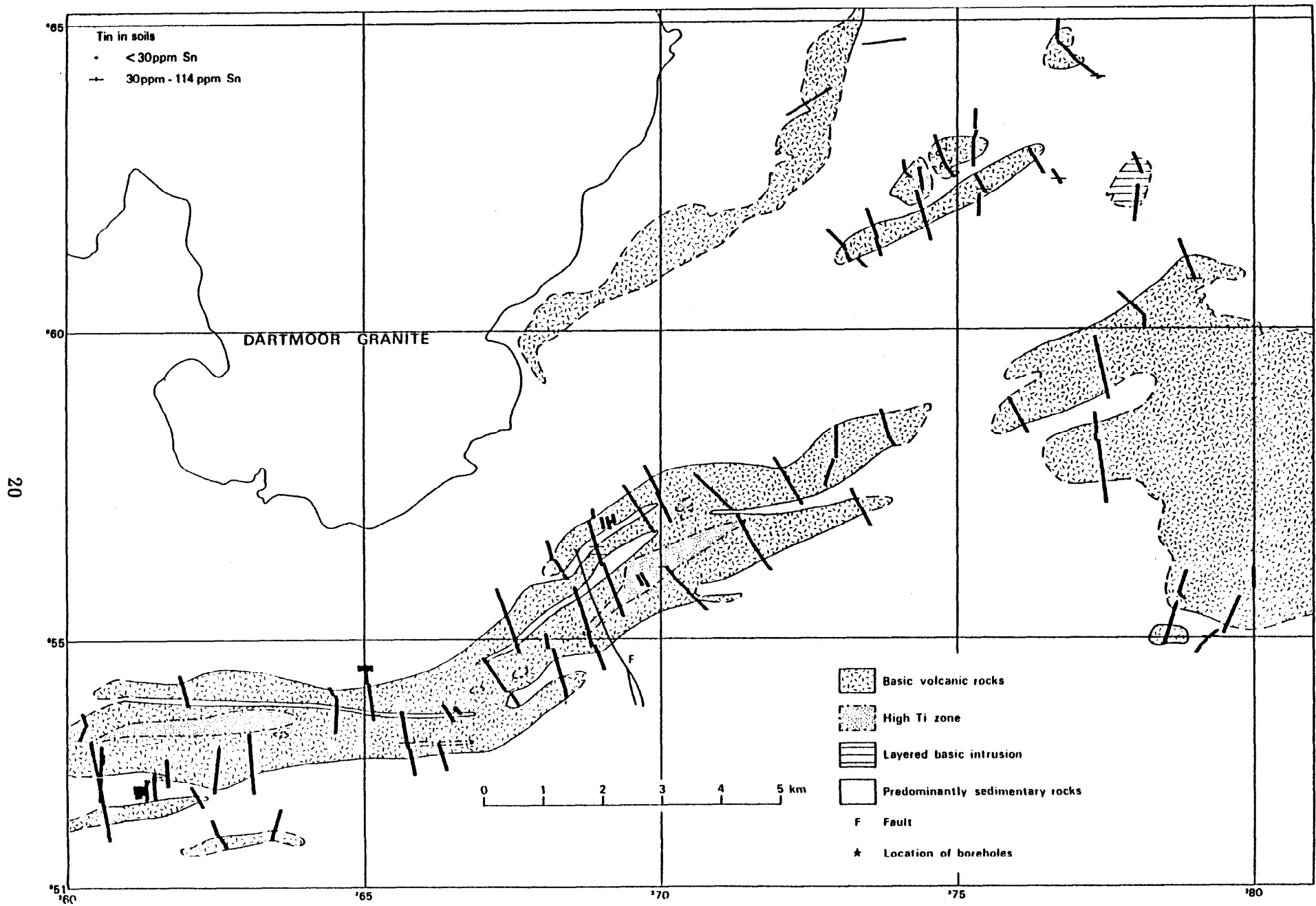
Figure 15   Distribution of Sn in reconnaissance soil samples.

Tin in soils

- · <30ppm Sn
- -·- 30ppm - 114 ppm Sn

DARTMOOR GRANITE

- Basic volcanic rocks
- High Ti zone
- Layered basic intrusion
- Predominantly sedimentary rocks
- F   Fault
- ★   Location of boreholes

0   1   2   3   4   5 km

20
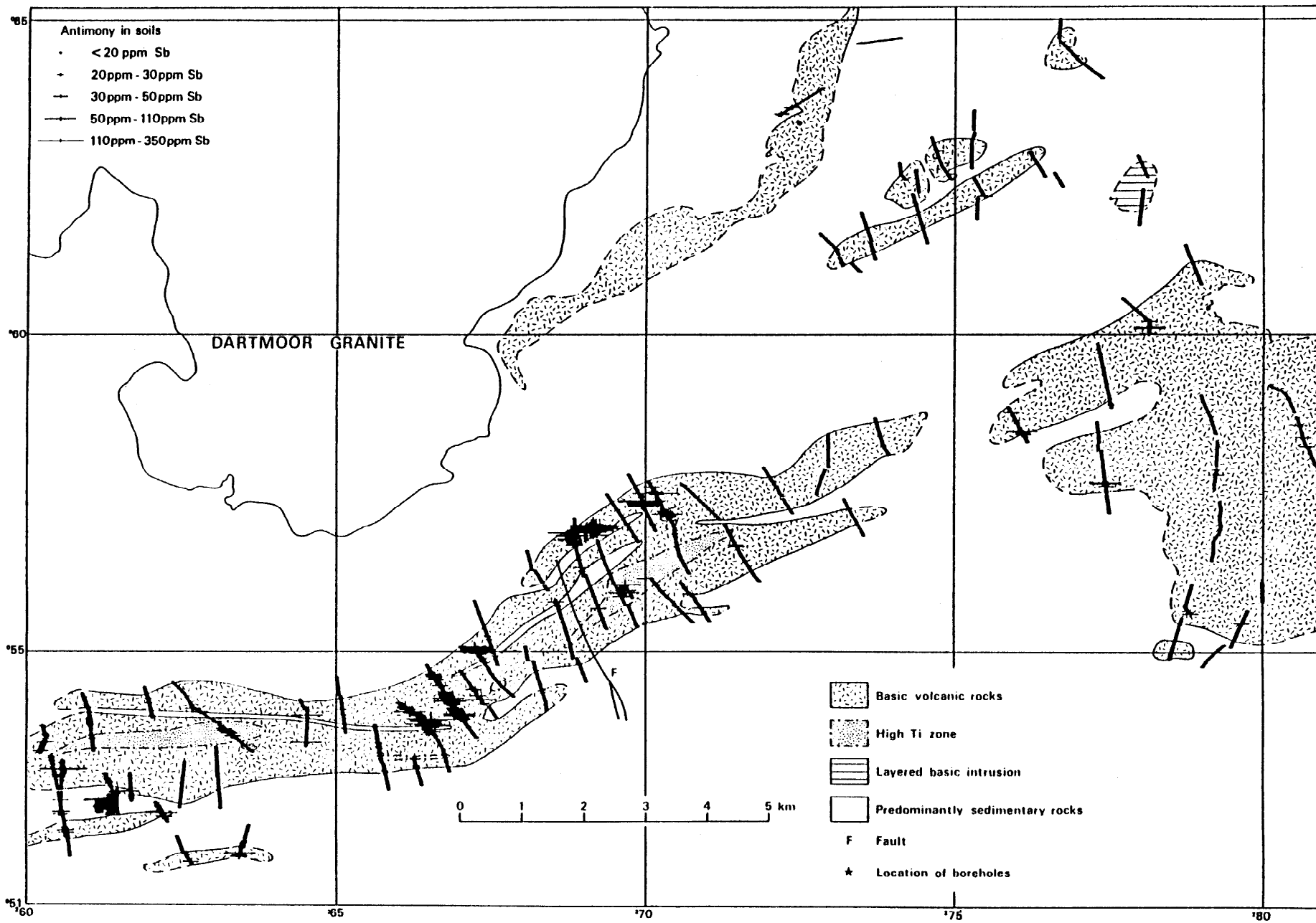
Figure 16   Distribution of Sb in reconnaissance soil samples.
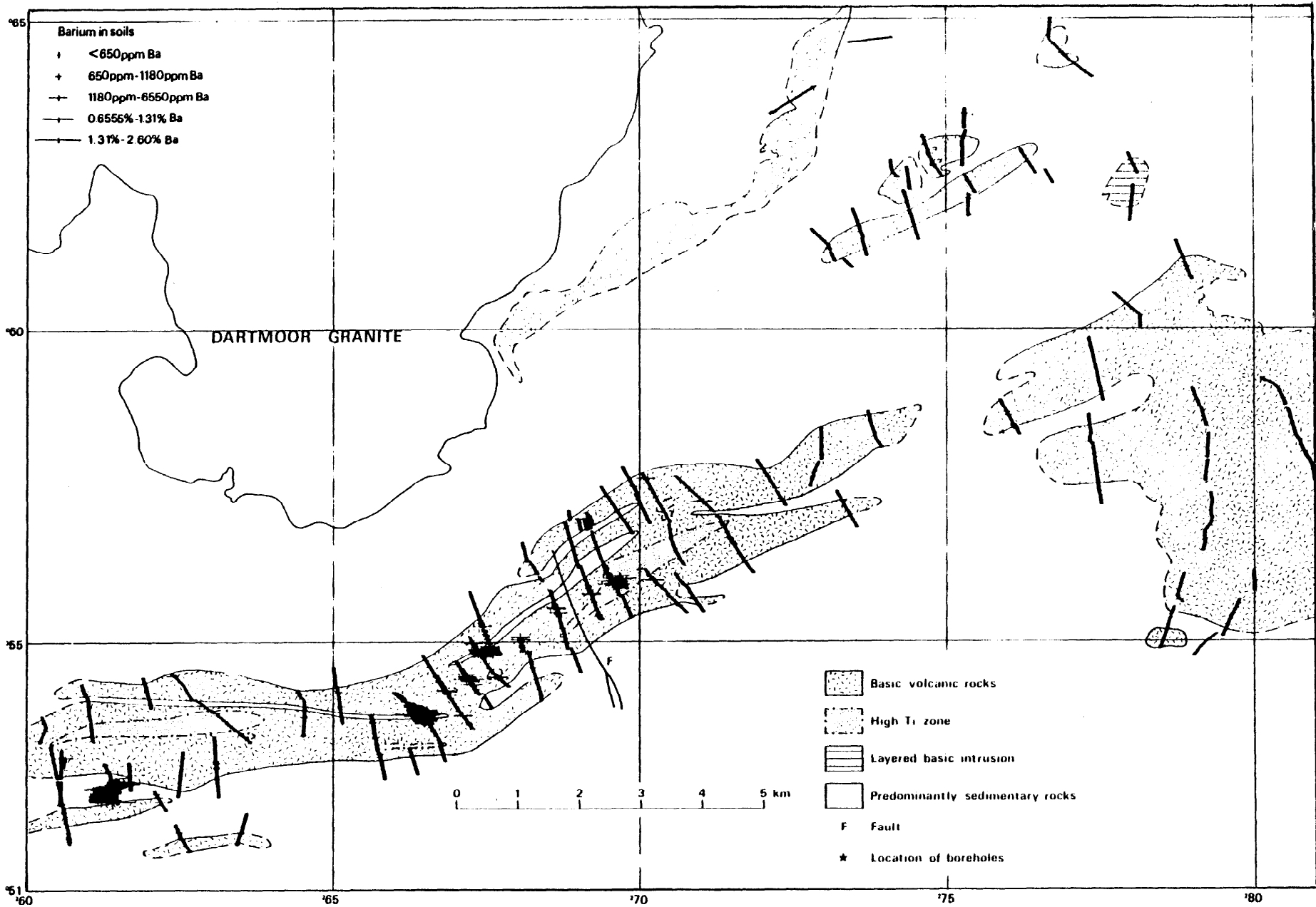
Figure 17 Distribution of Ba in reconnaissance soil samples.

Barium in soils

‚	<650ppm Ba
+	650ppm-1180ppm Ba
—+—	1180ppm-6550ppm Ba
—+—	0.6555%-1.31% Ba
—+—	1.31%-2.60% Ba

DARTMOOR GRANITE

Basic volcanic rocks

High Ti zone

Layered basic intrusion

Predominantly sedimentary rocks

F   Fault

★   Location of boreholes

0 1 2 3 4 5 km
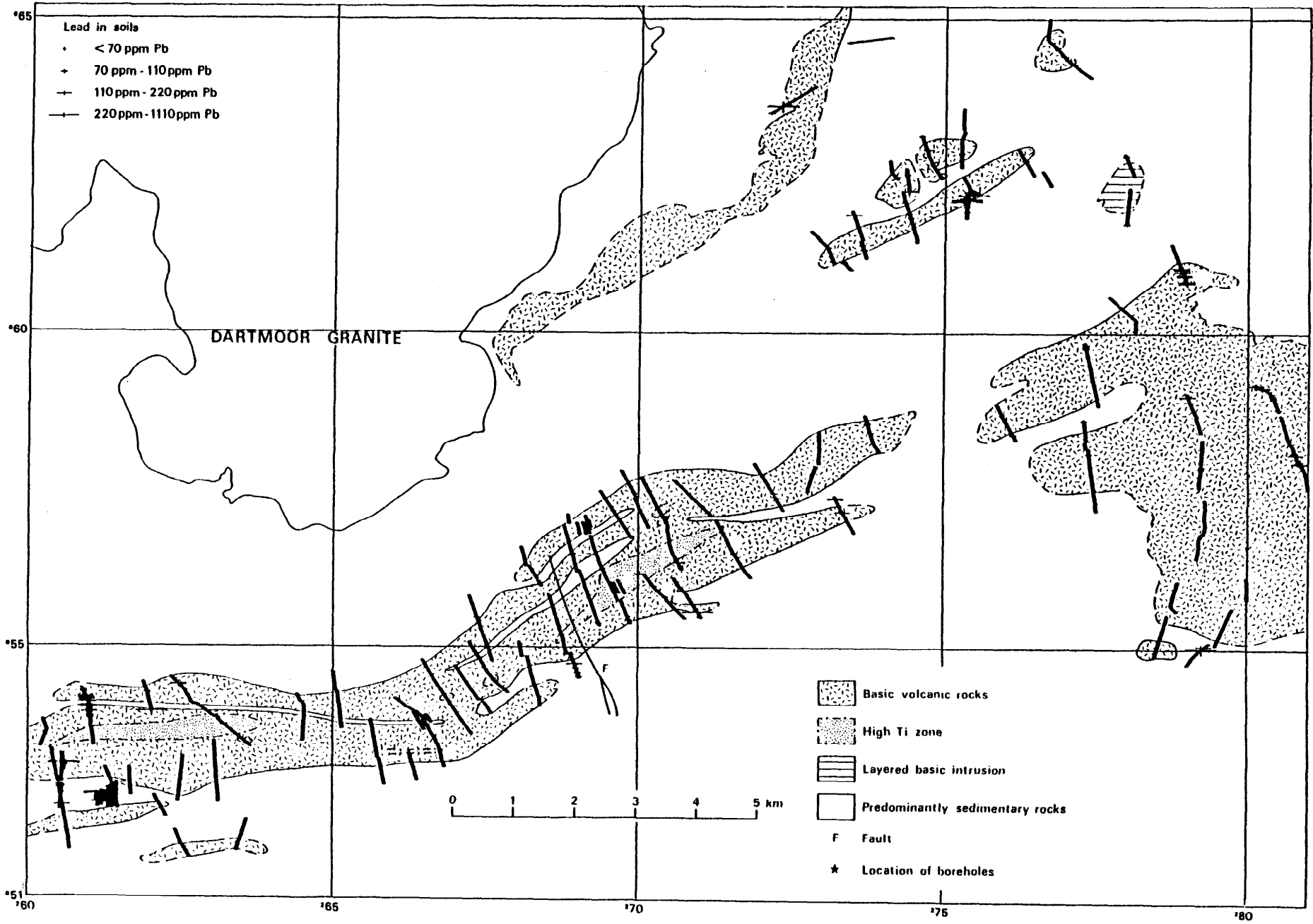
Figure 18 Distribution of Pb in reconnaissance soil samples.
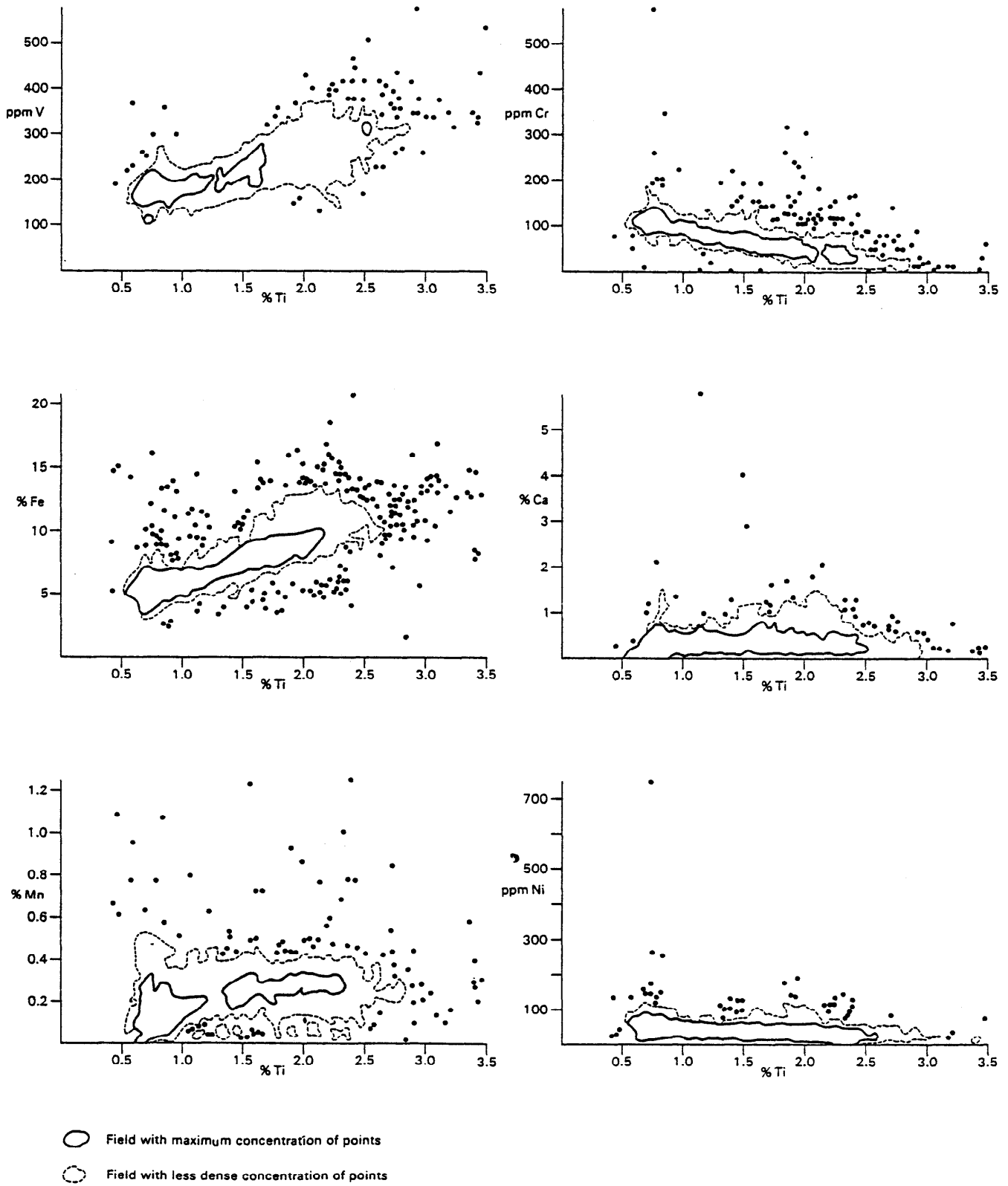
Figure 19 Relationship between Ti and V, Fe, Mn, Cr, Ca and Ni in soil samples.

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relatively narrow zones of volcanic rock which appear to lens out along strike into the sedimentary rocks. These samples may reflect the presence of thin limestones at these localities. There is no significant correlation between levels of calcium and the ore elements, except in the area to the west of Dean Prior, where the samples are also rich in As and to a lesser extent Sb.

The lack of a significant positive correlation between Mn and Ti is apparent in the scatter plot in Figure 19. There are samples with relatively high Mn contents in areas underlain by both volcanic and sedimentary rocks. The map plot of Mn in soils indicates that the sediments and some of the volcanic rocks to the north of Rattery are in general relatively rich in Mn and there is a tendency for the rocks from the main belt of volcanics to be richer in Mn in the west than elsewhere. The boreholes also suggest a similar relationship since the thin volcanic horizon intersected in the Burraton area is significantly richer in Mn than the volcanic rocks from either the Ludbrook or Ladywell areas. The maximum level of Mn in soil (2.56%) occurs in a sample from the Higher Ludbrook area which is probably derived from the exhalative ankeritic carbonate, a rock generally enriched in Mn, with levels typically in the range 0.5 to 0.86% MnO. Other relatively Mn-rich soil samples to the ENE of Higher Ludbrook suggest that similar exhalative carbonate may suboutcrop further along strike. Manganese-rich samples from west of Dean Prior are also anomalous in a number of ore elements, especially As and Pb. The most Ni-rich samples (maximum level 723 ppm Ni) are associated with the body of diabase at Week. These levels, in association with the high levels of Cr, indicate that the diabase is probably a layered basic intrusion with some olivine-rich horizons, and quite distinct from the basic volcanics. In the Dean Prior area the Ni-rich samples are also enriched in As or Cu, As and Pb, which suggests that the element is a component of the mineralisation in the area.

Tin levels in soil are generally low compared with many other parts of South West England and there is a tendency for levels in soils derived from the sedimentary rocks to be higher than those in soils derived from the volcanic rocks. The only concentration of relatively anomalous samples is near Penquit to the south-east of Ivybridge. Though the geological map does not show river gravel intersected by the traverse line it is recorded nearby and could perhaps by extended upslope to intersect the line. Since this gravel is derived to a large extent from the Dartmoor granite it is likely to be relatively rich in tin. A few single samples with relatively high tin contents are scattered elsewhere throughout the area. Some of these can probably be related to the occurrence of alluvium while for others there is no readily available explanation.

Metallic element anomalies

Details of the main anomalies of metallic and other elements which are thought to reflect mineralisation are summarised in Table 1. The locations of these anomalies are plotted in Figures 20 and 21.

There are very few samples with Ag contents above 4ppm and those that exist are isolated and scattered. There is no apparent correlation between the Ag contents and anomalies in other ore elements, which suggests that the analytical method used is not sensitive enough to pick out meaningful variation within the soil samples.

Samples containing the highest levels of Ba are concentrated in three areas. The Burraton area, where a soil grid was sampled and boreholes drilled, is described

Table 1 Ore Metal Anomalies in Soils

Anomaly	Location	Elements	Number of Anomalous Samples	Host rock	Mineralisation Type
Burraton	SE of Burraton	Ba	Grid	Sedimentary	Stratiform
1	N of Wilburton Farm	Cu, Zn, Pb, Sb (As, Ba)	3 major 5 minor (Zn)	Volcanic	Vein? Old workings present?
2&3	Coyton-West Worthele	As, Zn, Pb	Broad anomalies of low amplitude on adjacent lines	Mostly volcanic, few at volcanic/ sediment interface	Dissemination? Stratabound?
4	W of Weeke	Cu, As (Co)	Narrow low amplitude anomaly on 3 adjacent lines	Volcanic	?
Higher Ludbrook	E of Higher Ludbrook Farm	Zn, Ba, Sb, As, Mn, Fe	Grid	Volcanic/ sediment interface	Stratiform Exhalative
NE of Higher Ludbrook	Along strike from Higher Ludbrook	Ba, Sb (Mn, Fe)	Broad Sb and narrow Ba anomaly on line 117. Ba anomalies up to 12 samples further E	Volcanics with ?thin sedimentary horizons	? Similar to Higher Ludbrook
Z	E of Bowcombe	Sb, Fe (Mn)	7	Volcanics	? Similar to Ladywell
5	SE of Kitterford Cross	Ba, (Sb, Cu)	Small grid	Volcanics	? Veins or dissemination
Ladywell	NW of Ladywell Farm	Sb, Fe	Grid	Volcanics	Stratabound
6	SW of North Huish	Cu	2	Volcanics	?
Y	N of Langford Barton	Sb	4 on line 22 3 & 5 on line 125	Volcanics + volcanic/ sediment interface	Stratabound as Ladywell
7	NE of North Huish	Cu	2	Volcanics	?
8	NE of Dipford	Zn	2	Volcanics distal environment	?
9	S of Higher Washbourne	Cu, As, Ni (Zn)	1	Sediment	?
X	WNW of Key's Englebourne	Sb (Fe)	2	Volcanic	?
W	SE of Dorsely Barton	Sb (Fe)	2	Volcanic	?
10	S of Copland NW of Totnes	Pb (Cu)	3 groups of 2	Volcanic	?
11	N & S of Weeke	Cu (Ni, Cr)	2 groups of 6 on line 37, 10 on line 36	Layered basic intrusion	Disseminated?
12	Around Willing Cross	Zn, Pb, Cu (As, Sb)	11	Volcanic + volcanic/ sediment interface	Disseminated ?stratabound
13	W of Dean Prior	As, Zn, Pb, Cu, Sb	14 and 5	Sedimentary	?disseminated
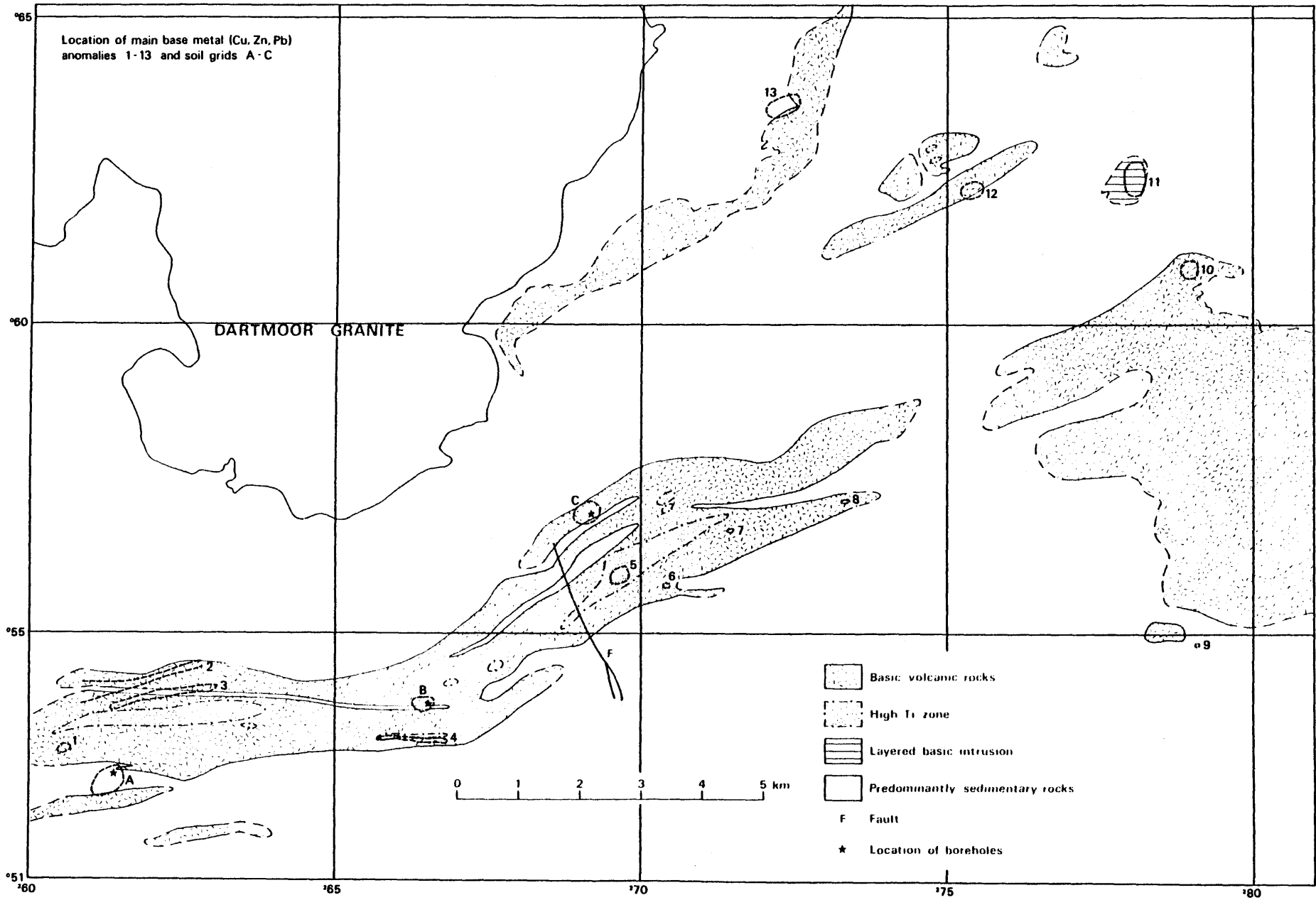
Figure 20   Location of main Cu, Zn and Pb soil anomalies and of soil grids.
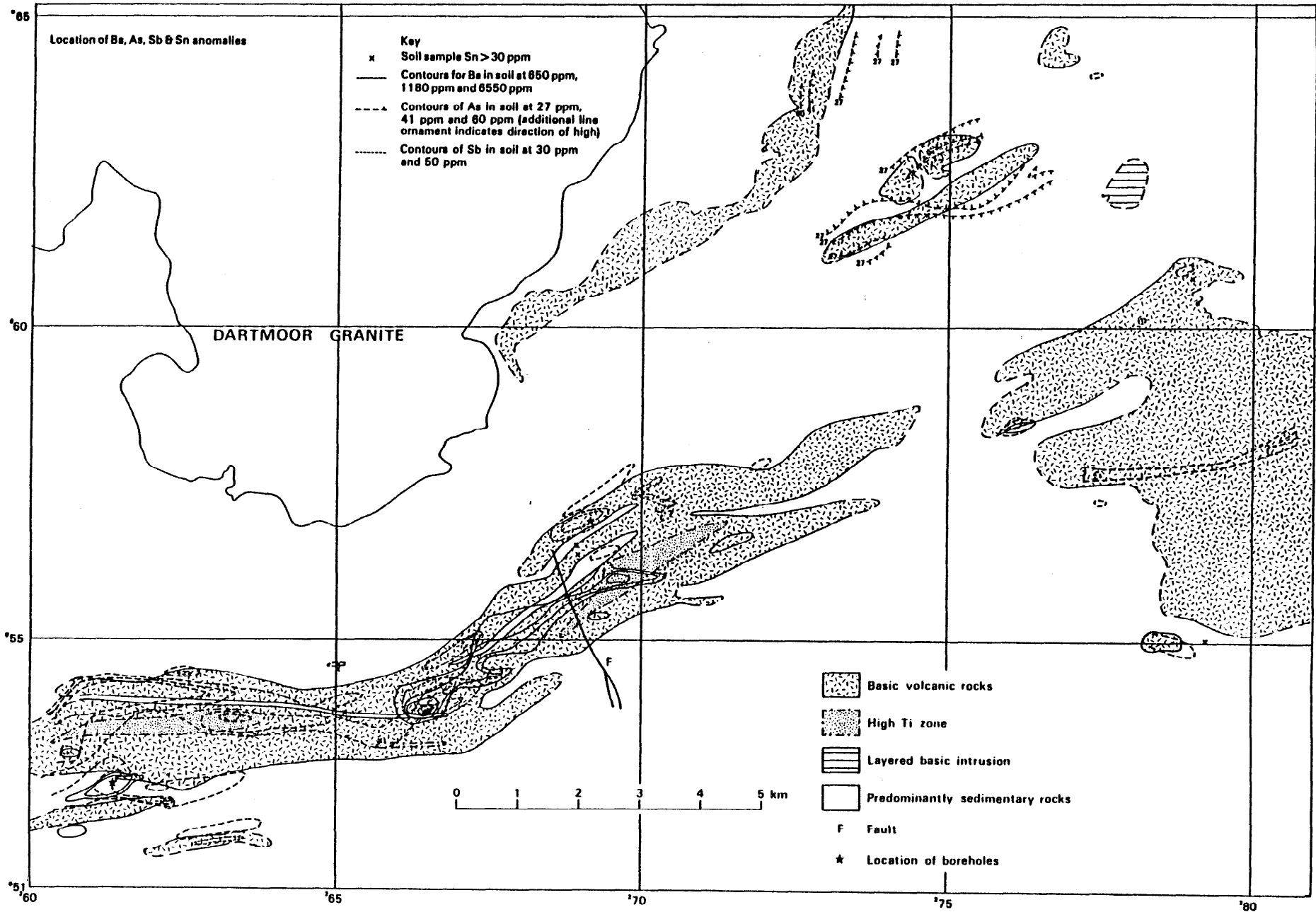
Figure 21 Location of Ba, As, Sb and Sn anomalies in reconnaissance soil samples. Ba, As and Sb anomalies are shown in contoured form.
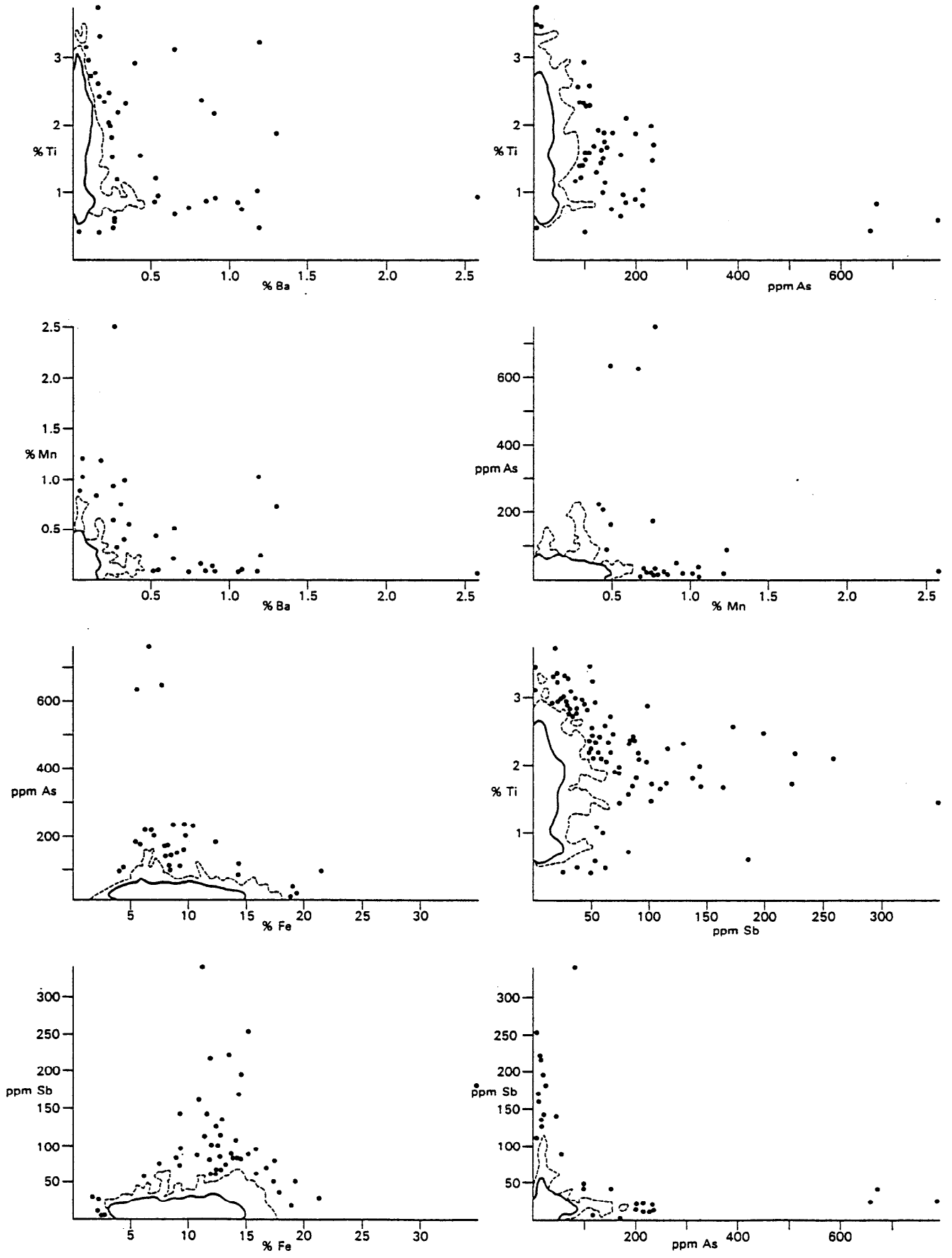
Figure 22 Relationship between the element pairs Ti-Ba, Mn-Ba, As-Fe, Sb-Fe, Ti-As, As-Mn, Ti-Sb and Sb-As in soil samples.
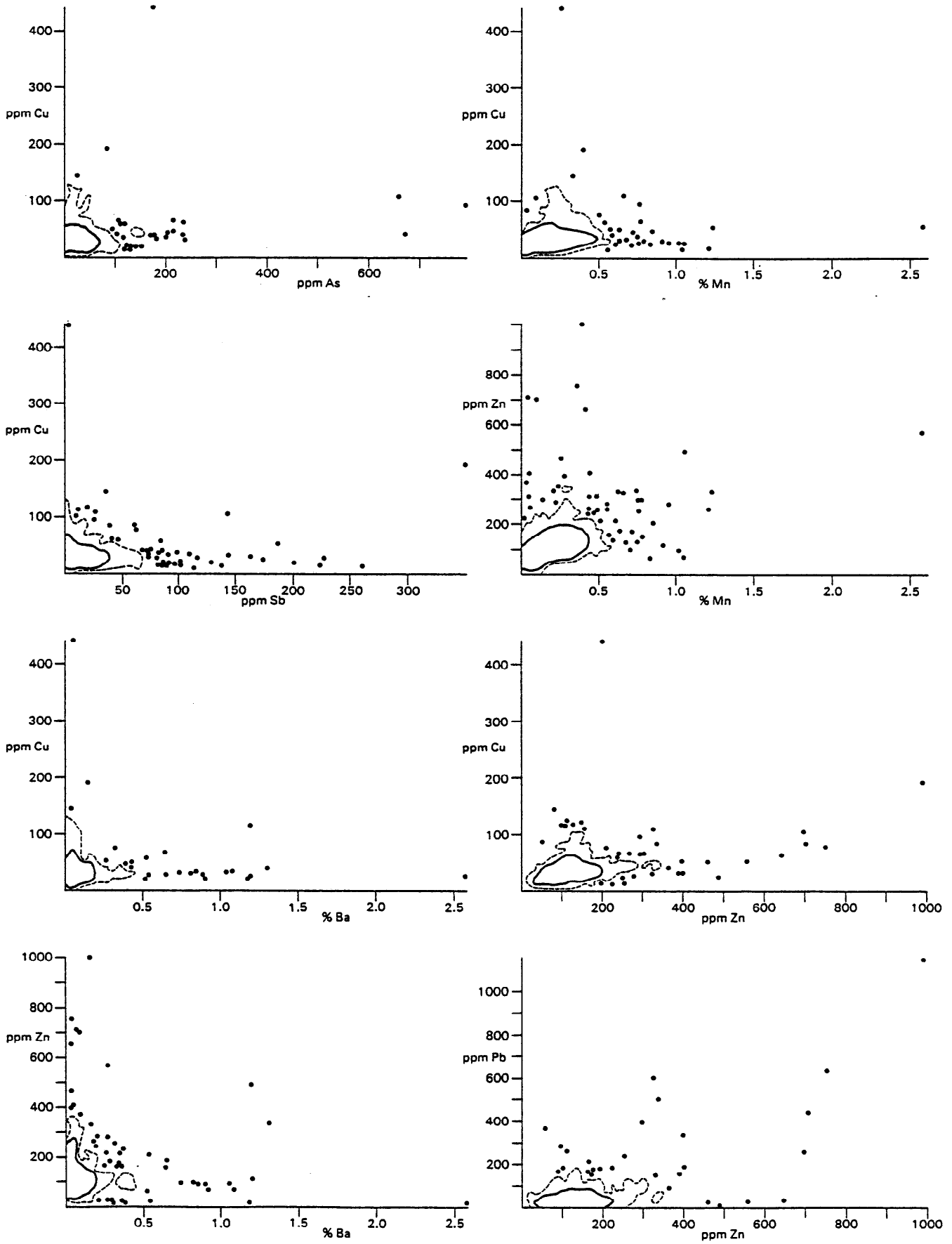
Figure 23 Relationship between element pairs Cu-As, Cu-Sb, Cu-Ba, Zn-Ba, Cu-Mn, Zn-Mn, Cu-Zn and Pb-Zn in soil samples.

in detail below. In this area massive baryte float occurs at surface. The Ludbrook area is also described in detail below and here the borehole data indicate that the barium associated with the exhalative mineralisation is present in muscovite for the most part and baryte is absent. A string of anomalies occurs in a zone extending to the north-east from Higher Ludbrook and these are represented in contoured form in Figure 21. There are only isolated anomalies elswhere in the area. A plot of Ba against Ti in the soils (Figure 22) shows the majority of Ba-rich samples to be relatively Ti-poor, signifying that enrichment in the element is associated with sedimentary rocks or exhalative material. There are also a few samples, especially from south-east of Kitterford Cross, where Ba enrichment is associated with high Ti levels indicative of volcanic rocks. Some degree of positive correlation is apparent between Mn and Ba in a few Mn-rich samples (Figure 22) which probably reflects their occurrence together in carbonate rock of exhalative origin. On the other hand most of the higher Ba anomalies are not associated with Mn and therefore probably reflect the presence of baryte as at Burraton. There is little evidence of any significant positive corelation between Ba and As, Sb, Zn or Pb but some correlation with Cu is apparent.

Relatively high levels of As are concentrated in two areas; in the extreme west of the area and to the west of Dean Prior. There is also general As enrichment in soils derived from the volcanic rocks south-west of Ivybridge and the higher anomalies tend to be broad. This is confirmed by the extra data obtained but not plotted. The majority of these samples are clearly derived from the volcanic rocks but there are also several samples with low Ti levels, which suggests that sedimentary rocks between the volcanics are also enriched in the element. There are also some anomalies within the Burraton grid and relatively high levels of As occur in some sedimentary rocks from the boreholes. To the west of Dean Prior the elevated As is associated particularly with Pb and Cu and to a lesser extent Zn. Some positive correlation between As and Mn is apparent (Figure 22) but As is not associated with the most Mn-rich samples, which are mostly derived from the exhalative carbonate at Higher Ludbrook.

The general levels of Sb in soils, especially over the main volcanic belt, is high when compared with typical background levels, and the area must be regarded as an Sb-rich province. The most prominent Sb anomalies occur in the Ladywell area and are discussed below. They are associated with relatively high levels of Ti in the soil which indicates the presence of volcanic rocks and this has been confirmed by the borehole at Ladywell. Similar anomalies on soil line 22 occur about 800 m to the ENE of the Ladywell grid and also further east but the intervening line (21) is not anomalous. A series of anomalies occurs in volcanic rocks on line 118 near Bowcombe. These may be similar to the Ladywell anomalies though their amplitude is less. The plot of Sb against Ti (Figure 22) shows that there is a good corelation between Sb and the occurrence of volcanic rocks. Though a positive correlation between Sb and Fe is apparent in some samples (Figure 22), Sb lacks significant correlation with other ore elements.

The most obvious Cu anomalies are associated with the diabase now interpreted as a layered basic body. Plots of Cu against other elements in Figure 23 show that slight enhancement of As and Zn accompanies the highest Cu value. In general there is little indication of correlation between Cu and As in the soil data, but in some samples slight correlation exists between Cu and Sb, Zn and perhaps Mn. The few samples which demonstrate a positive correlation between Cu and Ba are derived from the volcanic belt south-east of Kitterford Cross. Cu is associated with other ore element anomalies west of Dean Prior (line 49), and near Rattery (line 42) as shown in Figure 24. South of Higher Lubdrook Cu

anomalies occur in the volcanic rocks which are relatively Ti-rich. Other soils with relatively high Cu contents are scattered throughout the volcanic belt.

The most prominent Zn anomalies occur around Willing Cross near Rattery on line 42. Here a sharply defined Zn anomaly (Figure 24) correlates with Pb and to some extent Cu in volcanic rocks not far from their southern contact with the sedimentary rocks and there is a broader low-amplitude anomaly further north. On the soil line to the west of Dean Prior Zn shows only a broad low-amplitude anomaly, unlike the other elements mentioned above. Zn is enriched in some soils from the Higher Ludbrook area. In the area to the south and south-west of Ivybridge there are a series of Zn anomalies associated loosely with the zone of As enrichment. Most occur on the lines analysed by Mather and not plotted, but some are present on line 6 which is plotted in Figure 1. The Ti levels in these samples are relatively low for the volcanic class and they may reflect volcanic rocks interbedded with some sedimentary layers or tuffaceous rocks with a significant sediment component. This sort of material may be expected to occur distally from the main eruptive centres. The anomaly on line 27 to the north-east of Dipford, with which Pb is associated, also has a relatively low Ti level and occurs in a distal volcanic sequence. Other anomalies are scattered and comprise single samples.

There is a moderately good correlation between Pb and Zn anomalies as described above (Figure 24). In the area south and south-west of Ivybridge some anomalies correlate with Zn, others with As and others with neither, but in general they are not sharp or of high amplitude. The anomaly to the south-east of Harbertonford on line 33 is associated with the maximum Sn anomaly, a combination of elements which suggests contamination of human origin. Several moderate amplitude anomalies occur on line 35 in conjunction with a slight enrichment in Cu in an area where Ti levels in soil suggest that volcanic rocks alternate with sediments at the northern edge of the major mass of volcanics centred on Ashprington.

Geophysical surveys.

The initial geophysical survey was based on galvanic resistivity, VLF-EM and VLF-R methods since pure baryte has a high resistivity (ca. 5×10^{12} ohm/m) compared with about 500 ohm/m for the argillaceous rocks of South Devon. Huntek Mk III equipment used for the galvanic resistivity survey was also utilised to make induced polarisation (IP) measurements; delay time and basic integration period were 120ms and 60ms respectively. The VLF technique, using world-wide military transmitters, is primarily an exploration technique for conductive targets but resistivity contrasts can be located and usually give an in-phase peak with a cusp in the quadrature (out of phase) component at the boundary. Resistive baryte-rich zones within conductive shales have been located in the Scottish Dalradian (Coats et al., 1978) using the in-phase data. An inverted gradient filter identifies the resistive zones within a conductive formation. The radiohm (VLF-R) is more suited to resistive targets and the apparent resistivity of the earth (ρa) is determined from the complex surface impedence (Ex/Hy) of the incident VLF wave where Ex is the horizontal electric field and Hy the horizontal magnetic field. Signals from VLF transmitters at Rugby (GBR) and Maine (NAA) were used; operating frequencies are 16 kHz and 17.8kHz respectively.

In addition to the electrical surveys some gravity surveying was carried out as pure baryte has a density of 4.5 g/cm^3 compared with a mean value of 2.7 g/cm^3 for crustal rock, giving a maximum density contrast of 1.8 g/cm^3. This should
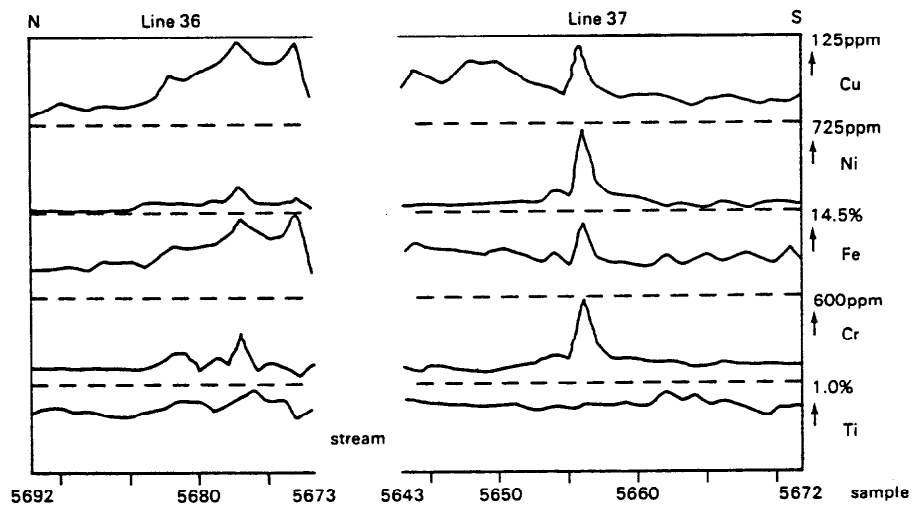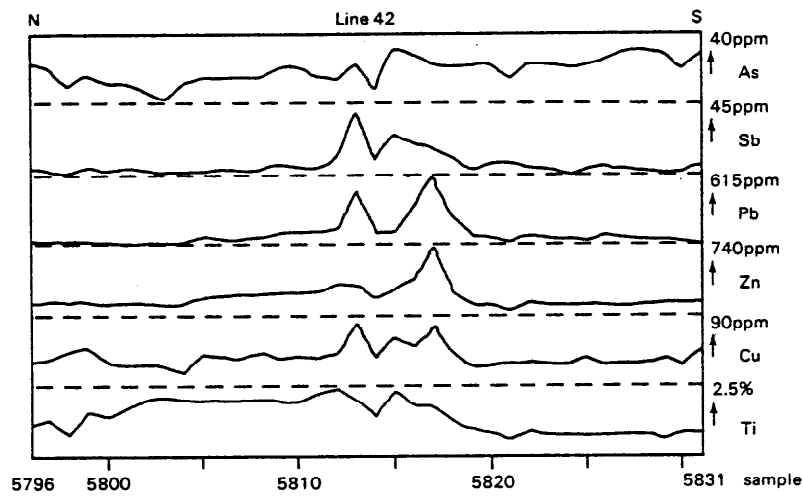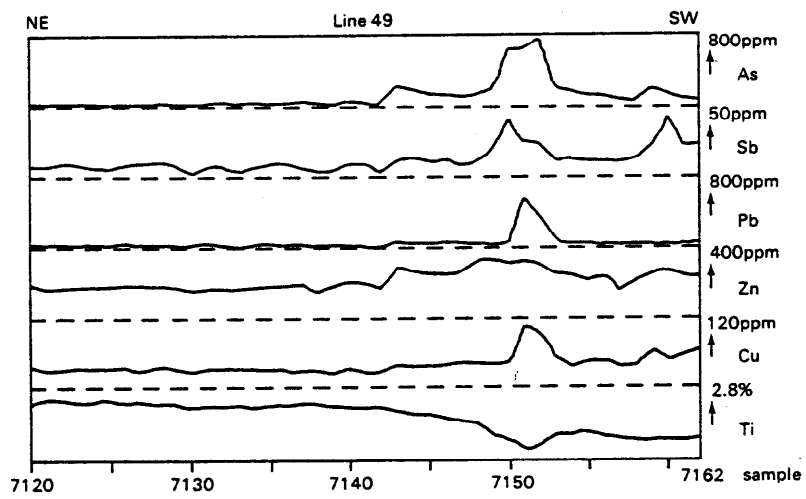
Figure 24 Transect plots of As, Sb, Pb, Zn, Cu and Ti levels in reconnaissance soil lines 49 and 42 and of Cu, Ni, Fe, Cr and Ti in lines 36 and 37.

ensure that significant quantities of baryte close to the surface would easily
be detected. This applies especially in areas where relief is subdued, as it is
in South Devon. In theory a 15m wide vertical prism of pure baryte of infinite
length, depth 75m and a top surface 1m below below ground level would produce a
maximum anomaly of 1.08 mGal. Factors which reduce the magnitude of the anomaly
include impurities, especially quartz (density 2.56 gm/cm^3), thickness of
overburden (5m to top of body reduces anomaly to 0.88mGal) and thinning and/or
shallowing of the body.

At a later stage in the work, various geophysical techniques were tested over
the massive pyrite that had been intersected in the borehole at Higher Ludbrook.
In addition limited geophysical surveys were carried out in the Fursdon area, to
the east of Coyton, in the region of the As, Zn and Pb anomalies in soil.

Burraton.

Further work was carried out in the Burraton area since high levels of Ba (up to
2.6% Ba) occur in reconnaissance soil samples with a trend parallel to the
deduced strike. The work comprised detailed soil sampling on a grid, geophysical
surveys and drilling. A few small pits were dug in the region of the original
anomalies and these showed higher levels of Ba (up to 4.9% Ba) in sieved
material and also fragments of massive baryte. Further fragments and boulders of
massive baryte and baryte and quartz were visible in the hedge near the
anomalous zone. In some of these fragments the baryte seemed to be very
fine-grained with a chert-like texture, while others showed layering with minor
amounts of quartz.

The soil grid was sampled in the same way as the reconnaissance samples and is
shown in Figure 25. It shows that Ba is enriched in the soil in an ovoid zone at
least 400m long and up to 120m wide. The zone trends at about 55 degrees, which
is subparallel to the regional strike. The maximum Ba anomalies occur in the
north of this zone with a trend nearer to 65 degrees and there is a very
sharp-cut off to the north but a more gradual one to the south. This sort of
asymmetric anomaly could be the result of downhill creep or alternatively may
indicate stratabound mineralisation with low grade disseminated Ba on one side
of a stratiform enrichment and essentially barren material on the other. The
nature of the source of the isolated but intense Ba anomaly at the south of the
grid is unclear since it does not occur on adjacent lines. The analyses of other
elements from the soil samples indicates that the Ba anomaly occurs in
sedimentary rocks. This was confirmed by the drilling, which showed the main
outcrop of volcanic rocks to lie to the north, with a thinner belt of volcanic
rocks in the south.

The location of lines along which geophysical surveys were carried out in the
Burraton area is also shown in Figure 25. Apparent resistivities are plotted in
Figure 26 and show a background of 200-300 ohm/m for the argillaceous rocks. A
resistive zone with apparrent resistivities up to 2000 ohm/m crosses the area
trending at 55 degrees, which is roughly parallel to the soil barium anomalies.
The maximum apparent resistivities (at 310S 100W) are coincident with the
maximum soil Ba anomaly, which also suggests that the two are correlated.
Asymmetry of the resistivity profiles suggests a southerly dip of the cause of
the anomaly. The resistive zone appears to be deflected southwards on line 100E.
This is consistent with the soil data, which indicate that the contact between
sediments and volcanics is also shifted to the south in the same general area.

Figure 25   Ba levels in soil in Burraton area.

35
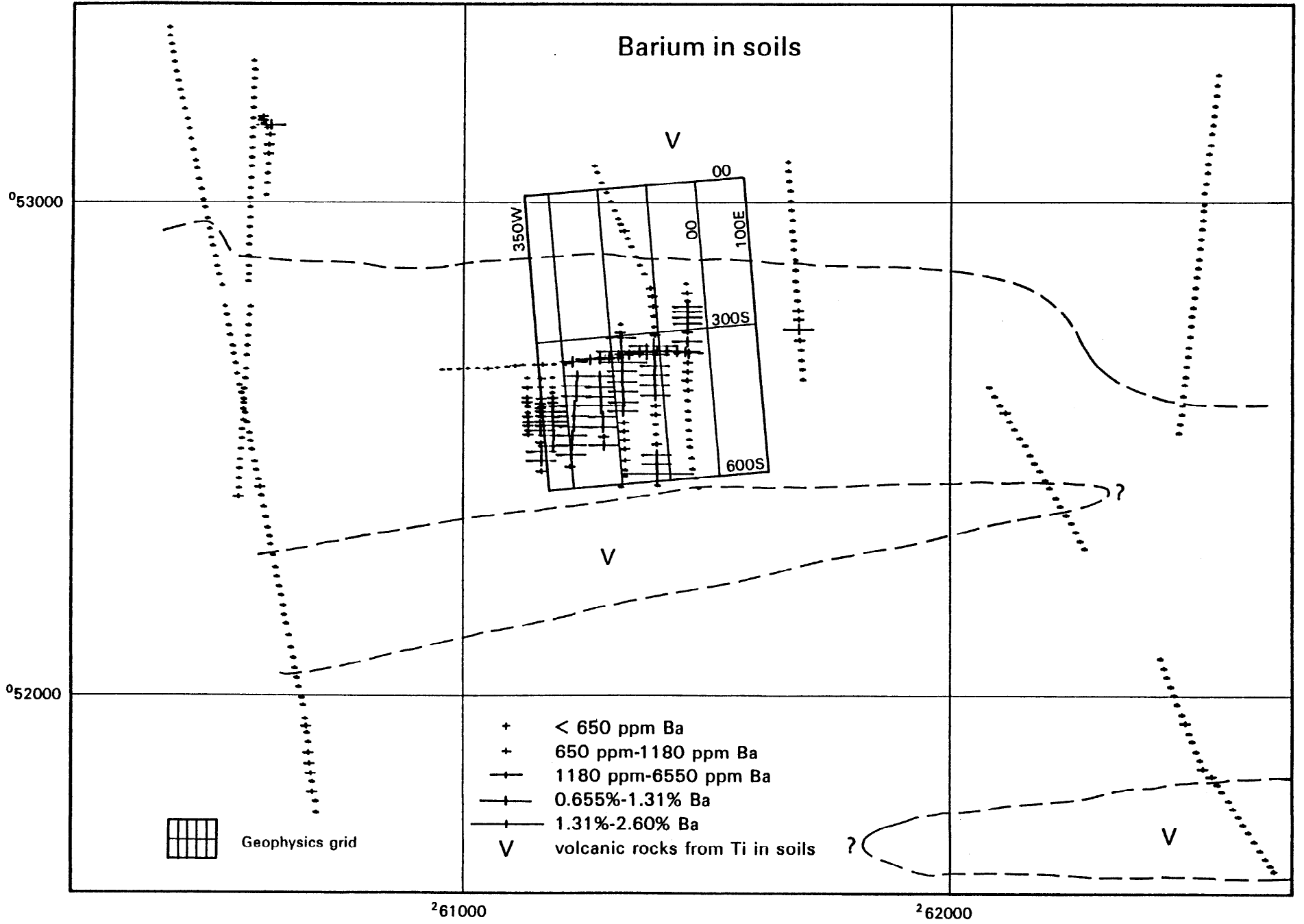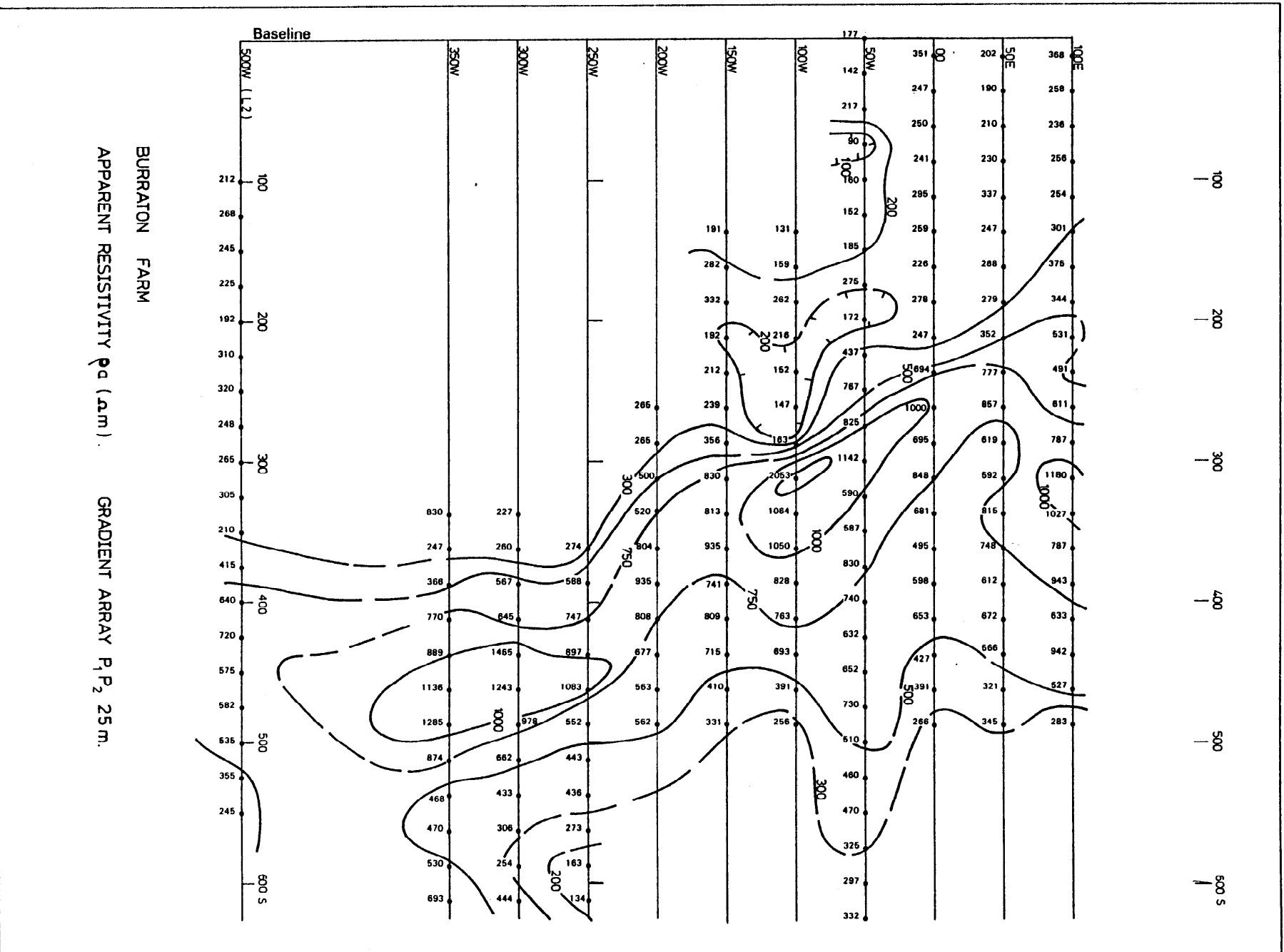
Figure 26 Plot of apparent resistivity in Burraton area.

BURRATON FARM

APPARENT RESISTIVITY ρa (Ωm).   GRADIENT ARRAY P₁P₂ 25m.

36
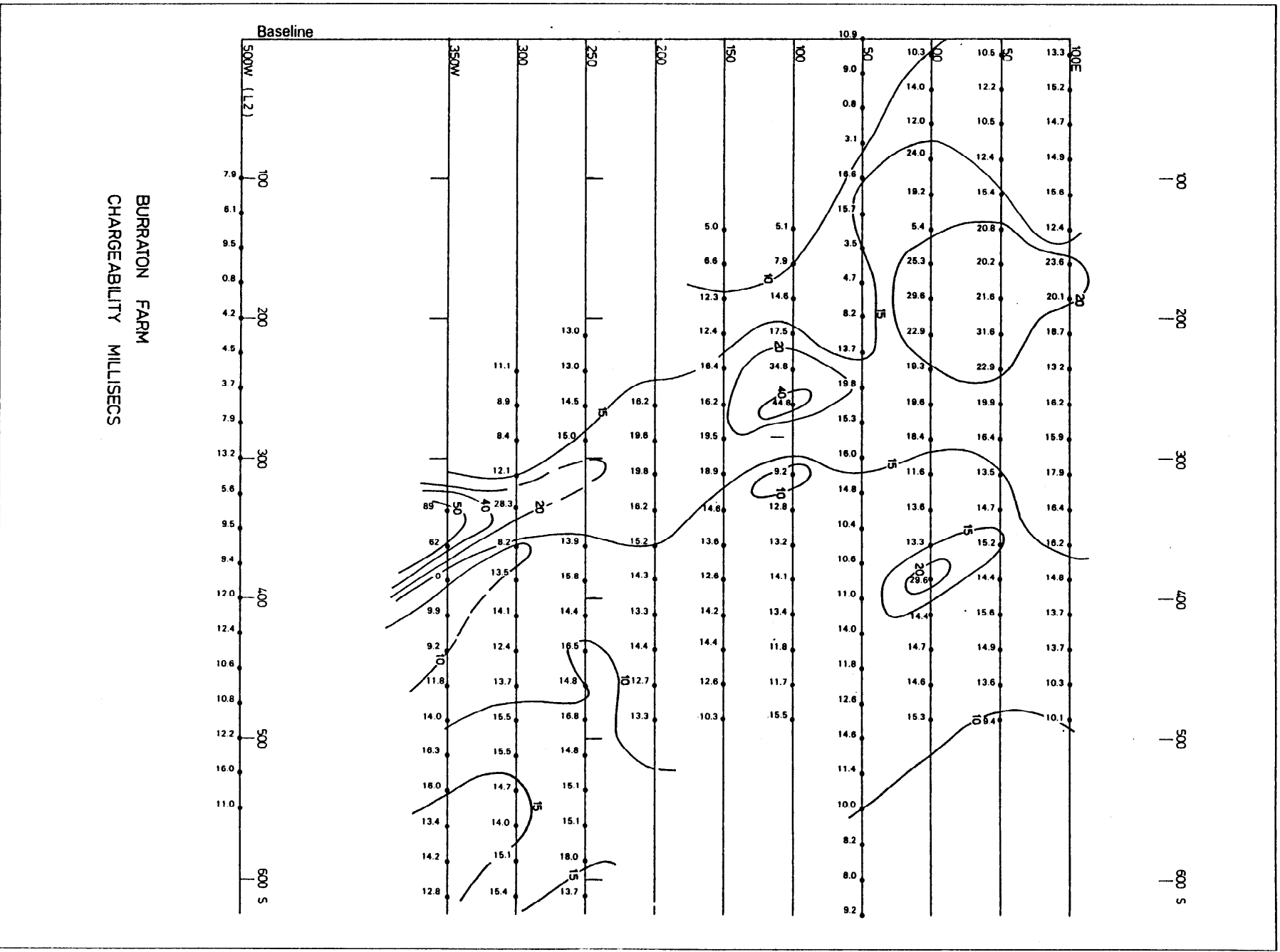
Figure 27 Plot of chargeability in Burraton area.

37
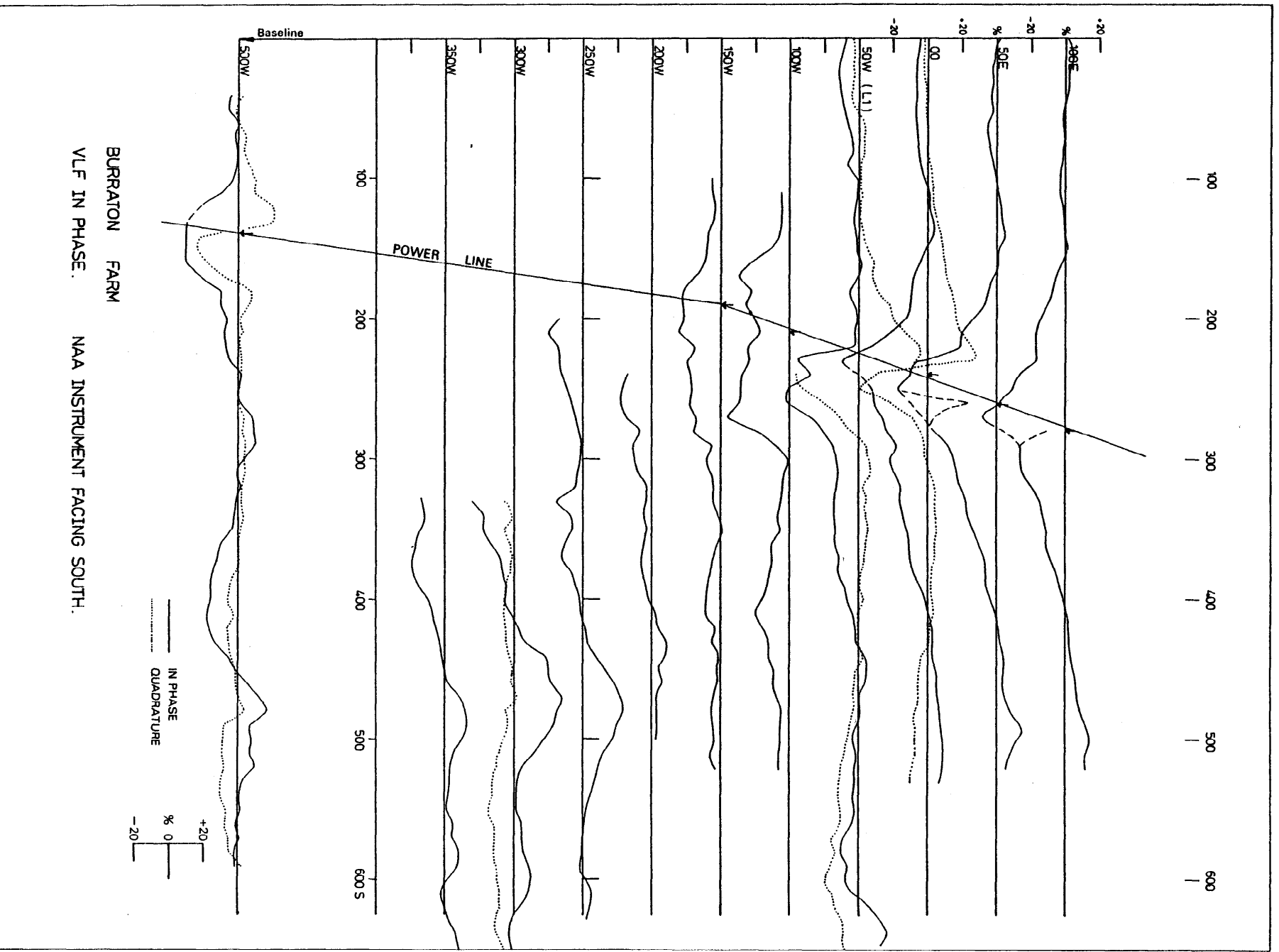
Figure 28 VLF-EM profiles, Burraton area.

BURRATON FARM

VLF IN PHASE.   NAA INSTRUMENT FACING SOUTH.

Baseline

POWER LINE

500W
350W
300W
250W
200W
150W
100W
50W (L1)
00
50E
100E

IN PHASE
QUADRATURE

+20
%   0
−20

·20
·20
%
·20
%
·20

100   200   300   400   500   600

38
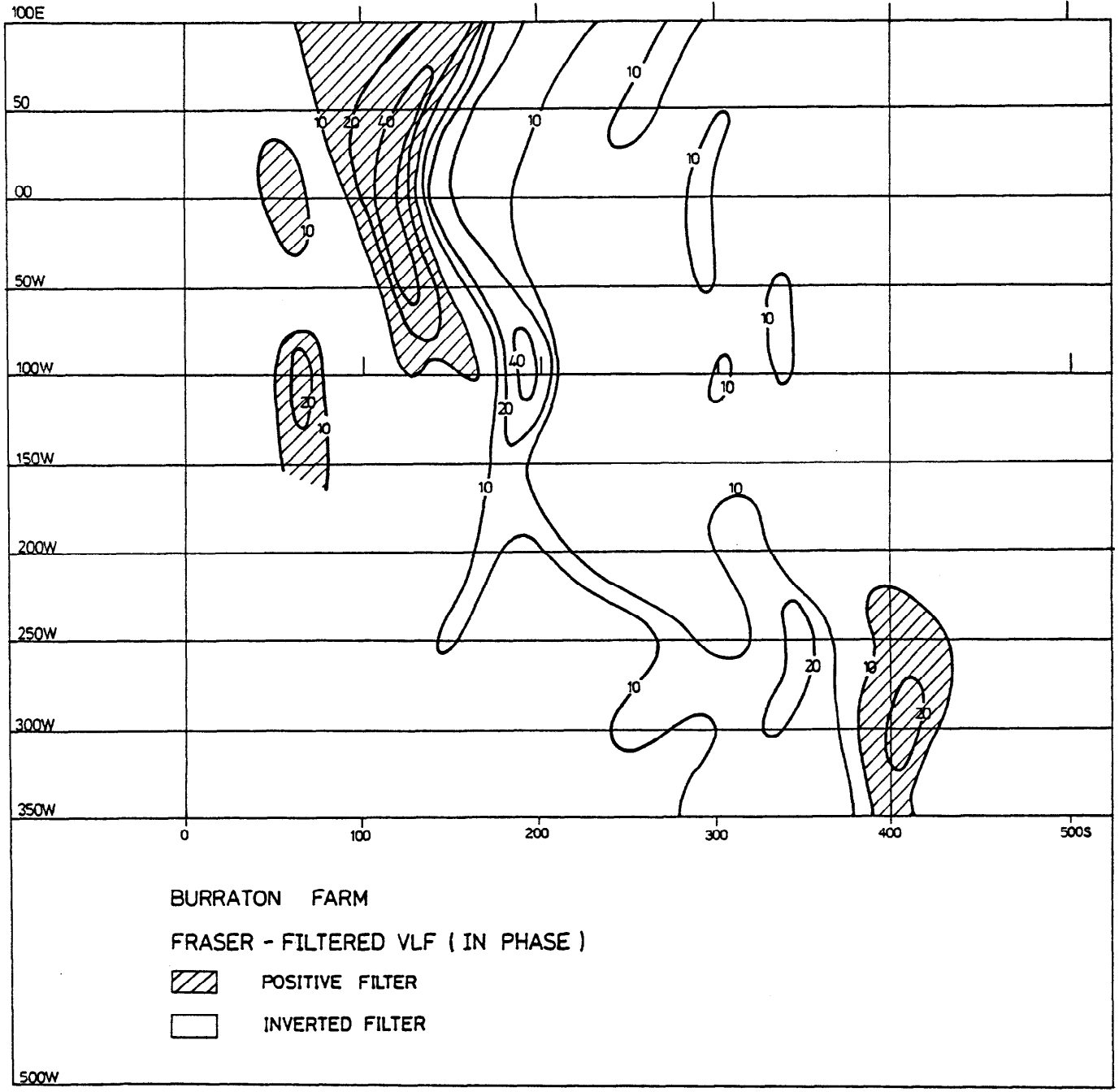
Figure 29 Plot of Fraser-filtered VLF values, Burraton area.
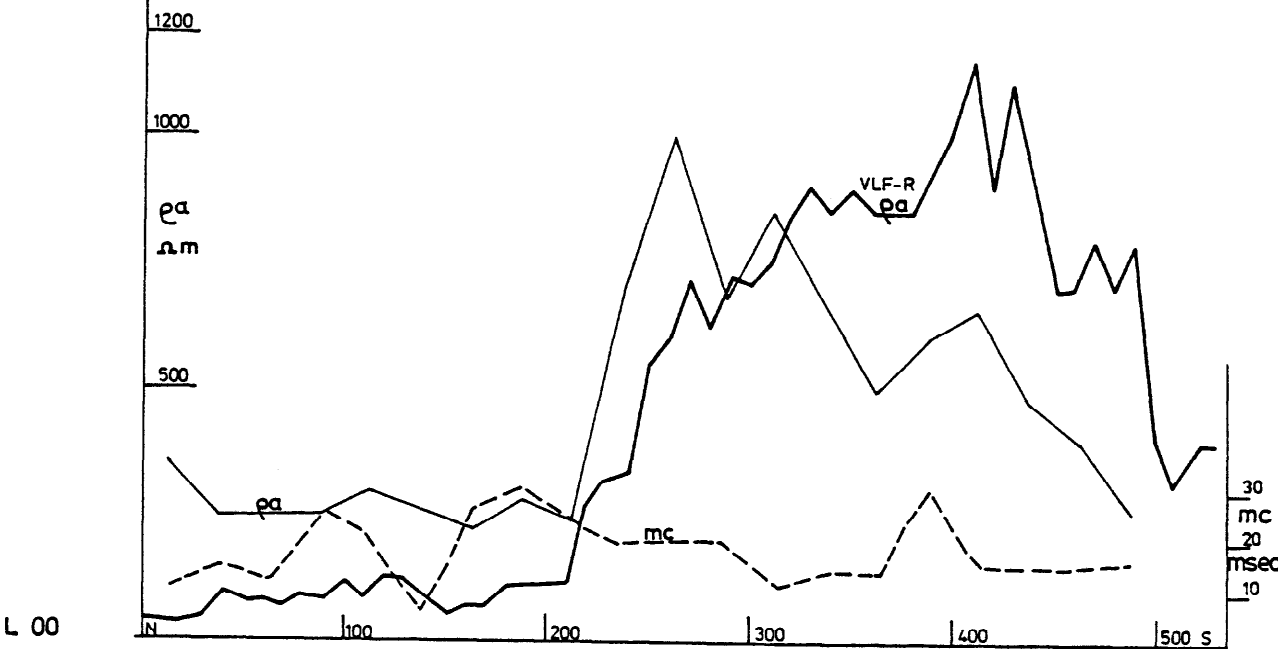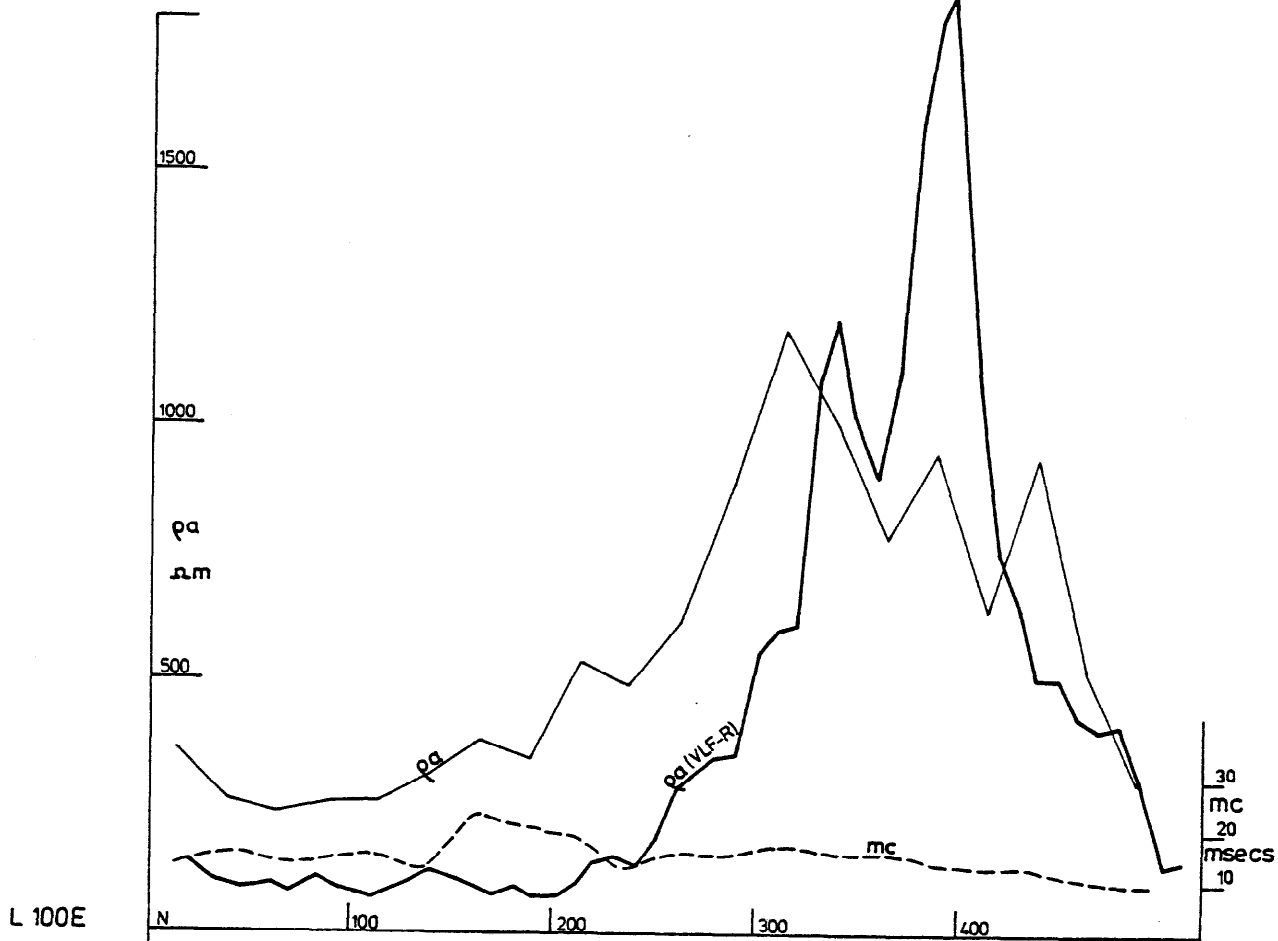
Figure 30 VLF-R, galvanic resistivity and chargeability profiles for lines 0 and 100E, Burraton area.

40
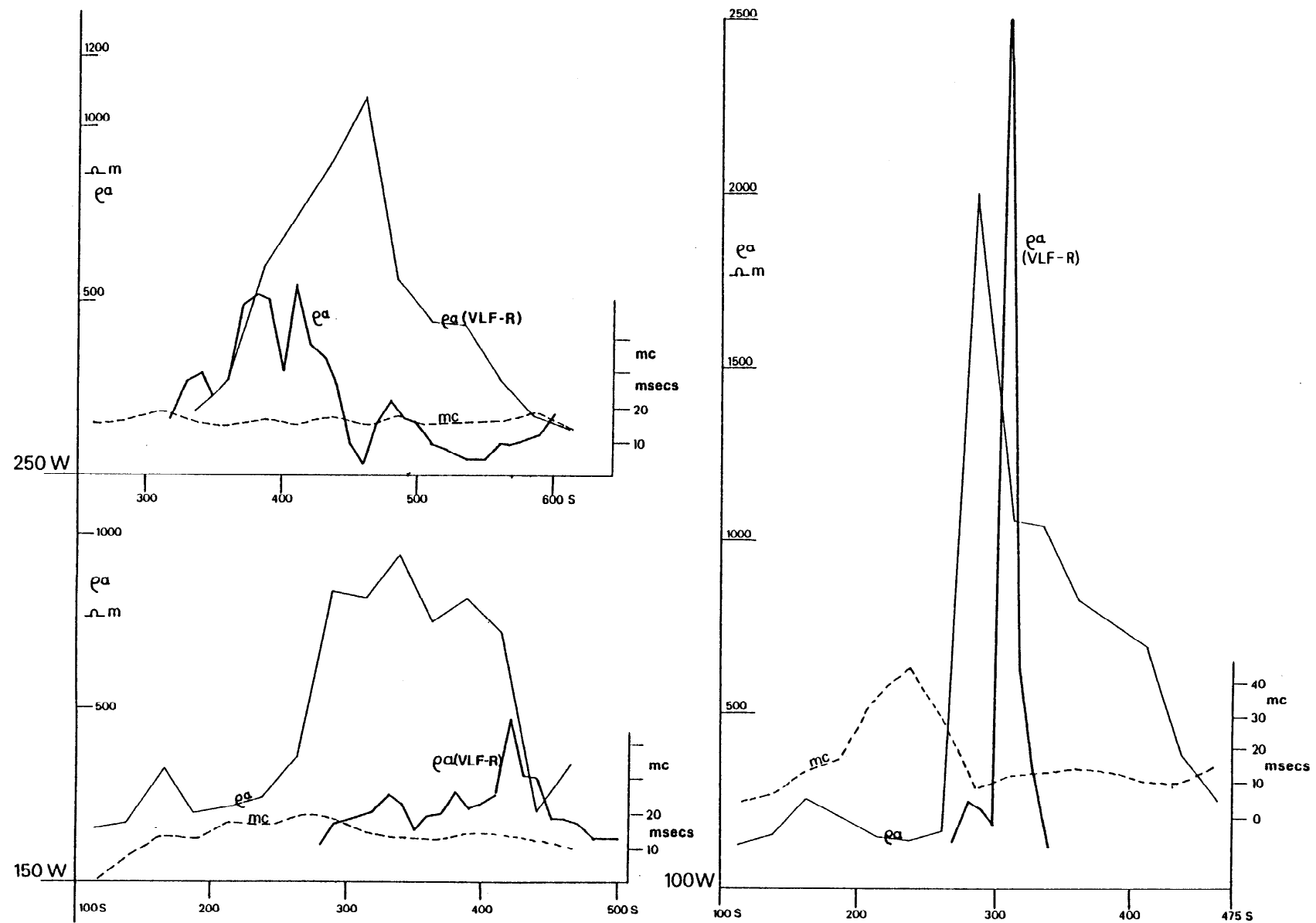
Figure 31 VLF-R, galvanic resistivity and chargeability profiles for lines 100, 150 and 250W, Burraton area.

BURRATON FARM

GRAVITY TRAVERSES

INCOMPLETE BOUGUER GRAVITY ANOMALIES

VALUES IN MGALS $\rho = 2.70$

NGRN 73 IGF 67
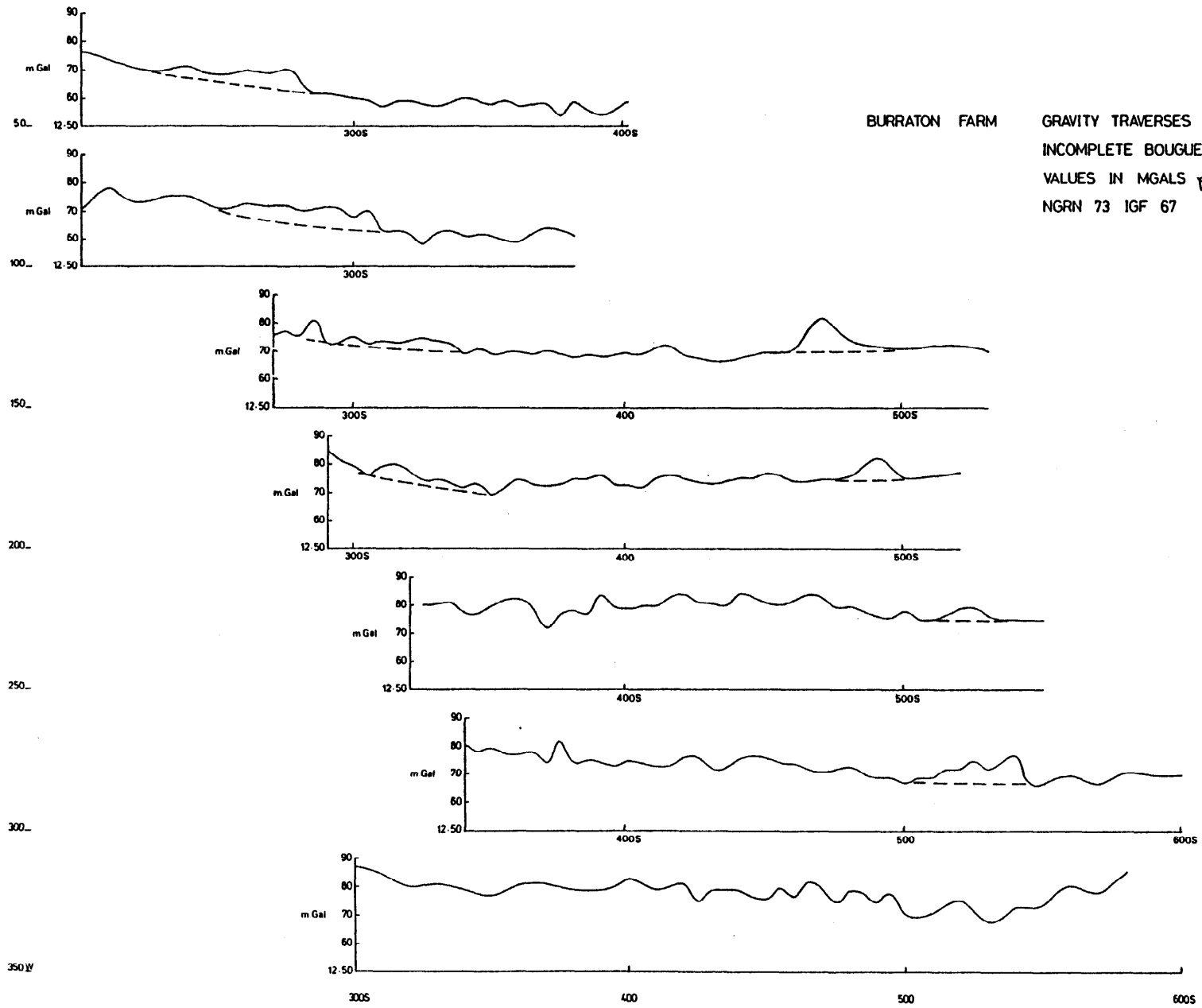
Figure 32 Detailed gravity traverses, Burraton area.

Table 2 Density Measurements on Ba-rich rocks from South Devon

Sample Number	Description	Grain Density	% Porosity	Void Ratio (e)	Dry Density	Saturated Density g/cc	Average Saturated Density
A01	Aberfeldy	4.038	0.312	0.003	4.026	4.029	4.029
B01 a	South Devon	3.284	0.722	0.0073	3.260	3.267	3.543
B01 b	"	3.714	3.876	0.0373	3.858	3.820	
B02 a	"	4.128	0.420	0.004	4.111	4.115	4.023
B02 b	"	3.944	0.409	0.004	3.928	3.932	
B03 a	"	2.954	1.074	0.0101	2.922	2.933	2.919
B03 b	"	2.939	1.812	0.0184	2.886	2.904	
B04 a	"	3.176	1.215	0.0123	3.138	3.150	2.988
B04 b	"	2.848	1.221	0.0124	2.813	2.825	
B05 a	"	3.566	1.642	0.016	3.625	3.069	
B05 b	"	3.337	1.756	0.0179	3.279	3.296	3.242
B05 c	"	2.859	2.080	0.021	2.800	2.820	
B06 a	"	2.932	2.000	0.0204	2.873	2.893	2.884
B06 b	"	2.914	1.989	0.0203	2.856	2.876	
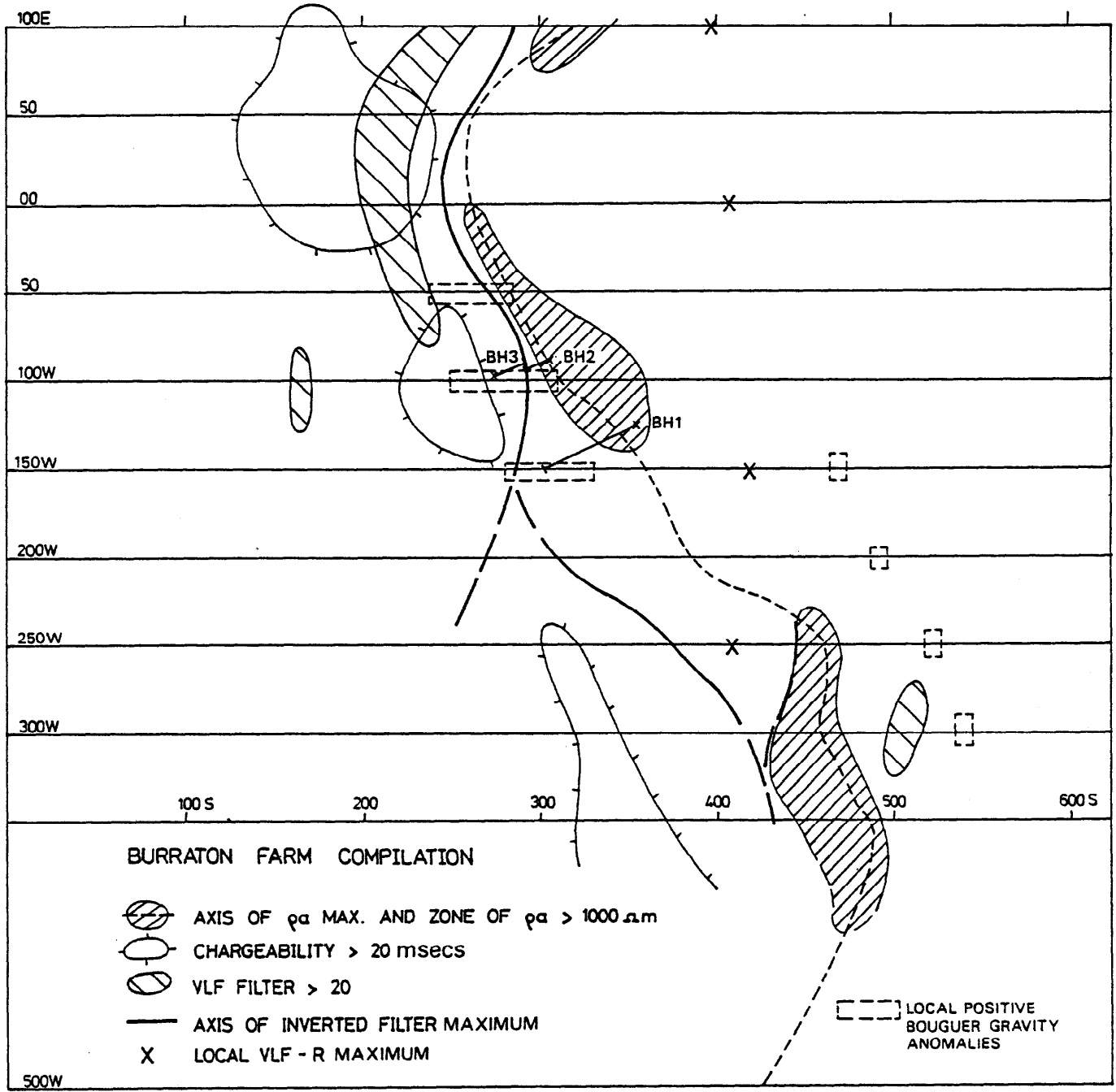
Figure 33 Compilation of geophysical results for Burraton area.

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Chargeabilities are generally low (< 15msecs) but a significant positive anomaly extends across the area (Figure 27) with a trend of about 60 degrees which is parallel to the resistive zone. Localised maxima in excess of 40 msecs occur at 260 S on line 100W and 350 S on line 350 W.

The VLF-EM results are plotted in Figure 28 which shows a distinct in-phase anomaly on all lines east of 150W complicated by the presence of a power line (PL on Figure 28). The responses on lines 100W and 150W suggest that another anomaly, probably of natural origin, occurs south of the power line. In addition a positive in-phase anomaly occurs on lines 250-500W at about 475m S. The main features of the normal and inverted Fraser filtered values are shown in Figure 29. A large normal filtered anomaly on lines east of 100W indicates a conductive structure which is approximately in the zone of higher chargeabilities. A distinct inverted filter anomaly extends across all lines and marks approximately the position of an apparent resistivity boundary.

VLF-R observations were made along lines 100E, 0, 100W, 150W and 250W using both NAA Maine (17.8 kHz) and GBR England (16 kHz). The apparent resistivities are compared with the galvanic resistivities for lines 0 and 100E in Figure 30. On both lines the VLF-R profiles show a strong resistivity anomaly, the position of which compares well with that on the galvanic profiles, though the amplitude is increased and the maximum value shifted to the south. The VLF-R observations on the more western lines (Figure 31) were all made using GBR. This transmitter is not directly along strike and this probably accounted for the subdued response on lines 150 and 250W. The high apparent resistivity (2700 ohm/m) observed at 310S line 100W indicates a very resistive formation close to the surface and correlates with the presence of baryte-quartz float. The reduction of amplitude on lines 150 and 250W may be due to thickening of a more conductive layer above the resistive horizon.

The detailed gravity traverses in the Burraton area, in Figure 32, show no clear traceable anomaly across the grid. Only on lines 50 to 200W are there any indications of residual anomalies in excess of 0.10 mGal. Table 2 gives the measured density of 7 samples of float material thought to contain baryte. The results range from 2.88 to 4.02 g/cm^3 which suggests that the baryte is closely associated with quartz. The lack of a substantial positive anomaly in spite of the presence of some high density material at surface may be the result of a combination of low thickness and shallow dip.

A compilation of the geophysical results from the Burraton grid is shown in Figure 33. The boundary of the resistive zone is well mapped by the inverse Fraser filtering of the VLF in phase data. Although the VLF-R anomalies often exceed those of the galvanic resistivity methods, attenuation of the anomaly by local overburden irregularities is probably more severe.

Higher Ludbrook.

Two additional soil lines were sampled on either side of the reconnaissance line to the south-east of Higher Ludbrook farm where anomalies of Ba, Sb and Zn were apparent. Maps showing the distribution of Zn, Sb and Ba in this area are shown in Figures 34 to 36. These show a complex anomalous zone within what appeared to be sedimentary rocks, on the basis of the Ti levels in the soil samples, with typical volcanic rocks both to the north and south. One sample was highly anomalous with over 34.9% Fe and 2.57% Mn in addition to 0.265% Ba, 186 ppm Sb and 567 ppm Zn, and this is now known to be derived almost entirely from the massive exhalative ankeritic carbonate that was intersected in the boreholes.

Barium seems to be richer towards the west with a maximum of 1.31% Ba and a wider anomalous zone while Zn reaches 495 ppm but Sb only 52 ppm. Geophysical surveys were also carried out in the same general area as the soil lines; the results of these surveys are discussed below. Drilling targets were selected on the basis of a stratabound model of the mineralisation but it was only possible to cover a small part of the potential zone of interest since access was limited to one small field in the anomalous zone.

The geophysical survey lines are shown in Figure 1 (in pocket): solid lines indicate the positions of the initial traverses while dashed lines indicate further traverses conducted after the drilling. Discussion is confined to the southeastern half of the survey area; the northwestern half is only sparsely covered and additional measurements would be required before any structure could adequately be delineated.

Figure 37 shows the results of gradient array IP and resistivity measurements in the vicinity of the boreholes. A very weak chargeability high with an E-W trend, which crosses line 50E at about 200S, may be related to the sulphide mineralisation intersected in BH 1. The chargeability peak centred at about 150S on line 100E is almost certainly due to a buried pipe.

Information on resistivity variations is provided by the gradient array and also by VLF-EM and VLF-R data (Figure 38). The gradient array shows a zone of lower resistivity centred just south of 200S on line 50E. To the south of this is an arcuate resistivity boundary with higher resistivity values to the south. In addition a high resistivity zone crosses the grid at approximately 100S and values are also higher at the northern end of line 150E. The apparent resistivities decrease towards the northern ends of the remaining lines.

There is a good correlation between the conductor axes defined by downward inflections in the VLF-EM in-phase data and resistivity minima on the VLF-R profiles. The two best defined axes are indicated on the VLF-R plot in Figure 38 and have been superimposed on the gradient array plot in Figure 37. There is a reasonable agreement between the southern conductor axis and the principal gradient array low resistivity zone while a somewhat weaker correlation exists in the case of the northern axis. As neither of the conductors is associated with anomalous chargeability values it is unlikely that they reflect sulphide-rich mineralisation. The most likely cause of the southern feature is a zone of relatively conductive argillaceous rocks of the type intersected in the upper part of BH1 and BH2 (Figure 57). The northern conductor may be due to similar rocks or perhaps to a belt of fractured rocks associated with a fault.

There is no clear indication of the massive pyrite mineralisation in the resistivity or VLF-EM data. This is surprising considering the highly conductive nature of the mineralisation, as revealed by tests on core samples. Apparent resistivity values measured by gradient array and VLF-R methods are in excess of 100 ohm/m in the vicinity of the mineralisation and this implies a skin depth of greater than 40m for the VLF-EM method at the GBR frequency of 16 kHz. The mineralisation was intersected at 35m below ground level and presumably extends at least a short distance above this, which means that it should lie within the depth of exploration. If the conductive zone extended along strike, significant current channelling would be expected, giving rise to an identifiable VLF-EM response. The most likely explanation for the lack of geophysical response is that the massive sulphide is a lens of limited lateral extent, which is also suggested from the results of BH 3 where no massive sulphide was intersected. The only VLF-EM anomaly in the zone of interest is a small inflection at 195S on
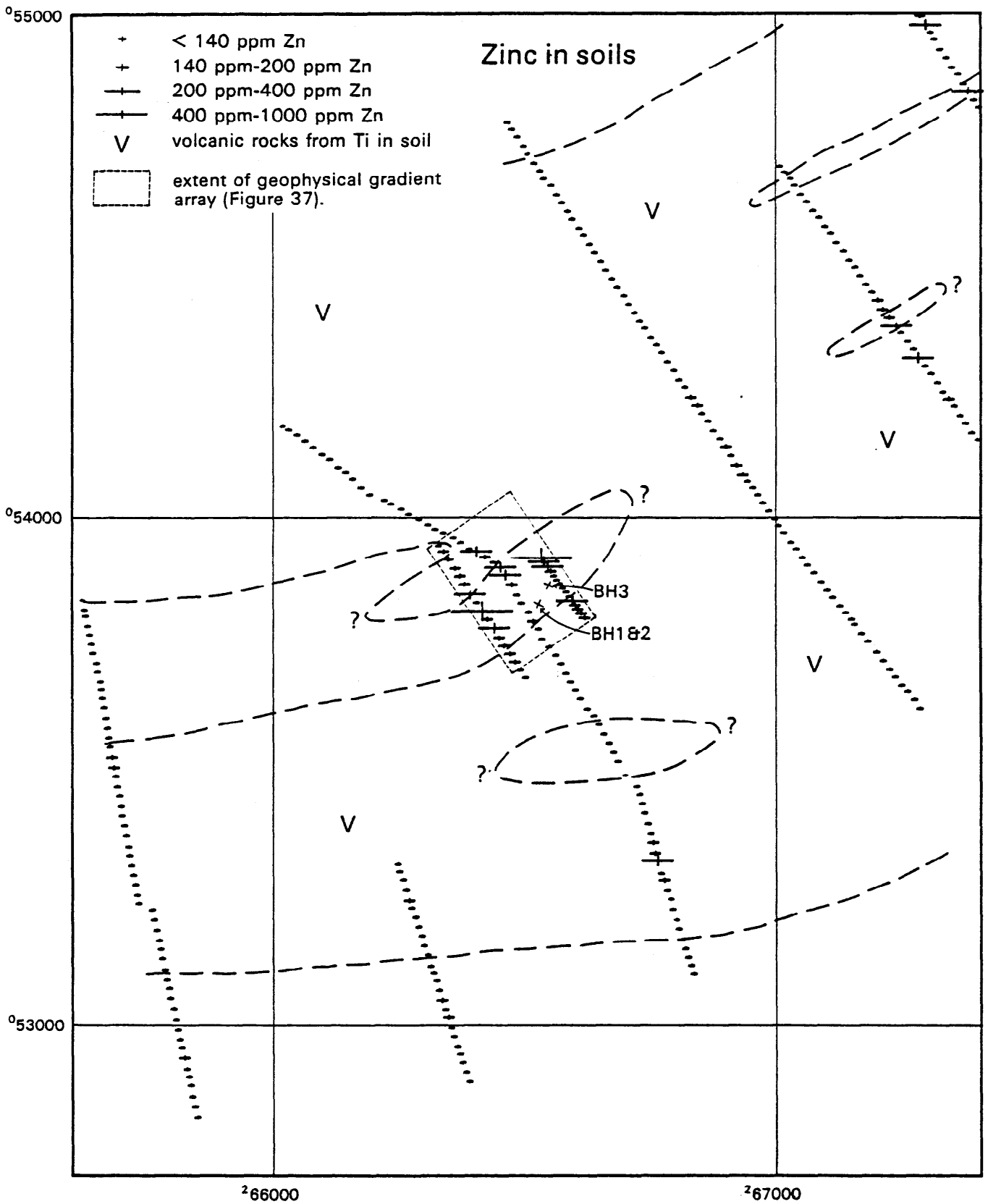
Figure 34 Zn levels in soil, Higher Ludbrook area.

47
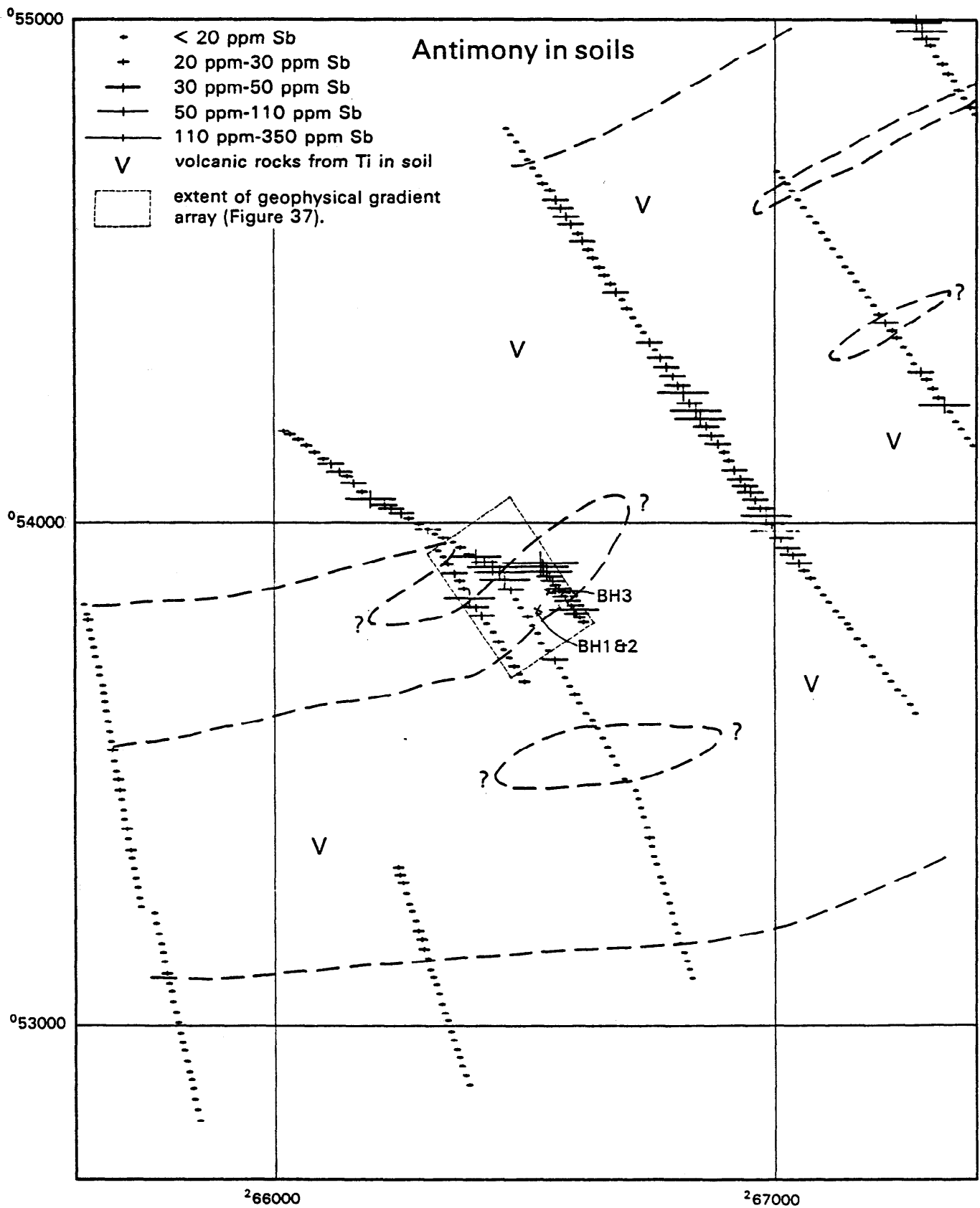
Figure 35 Sb levels in soil, Higher Ludbrook area.
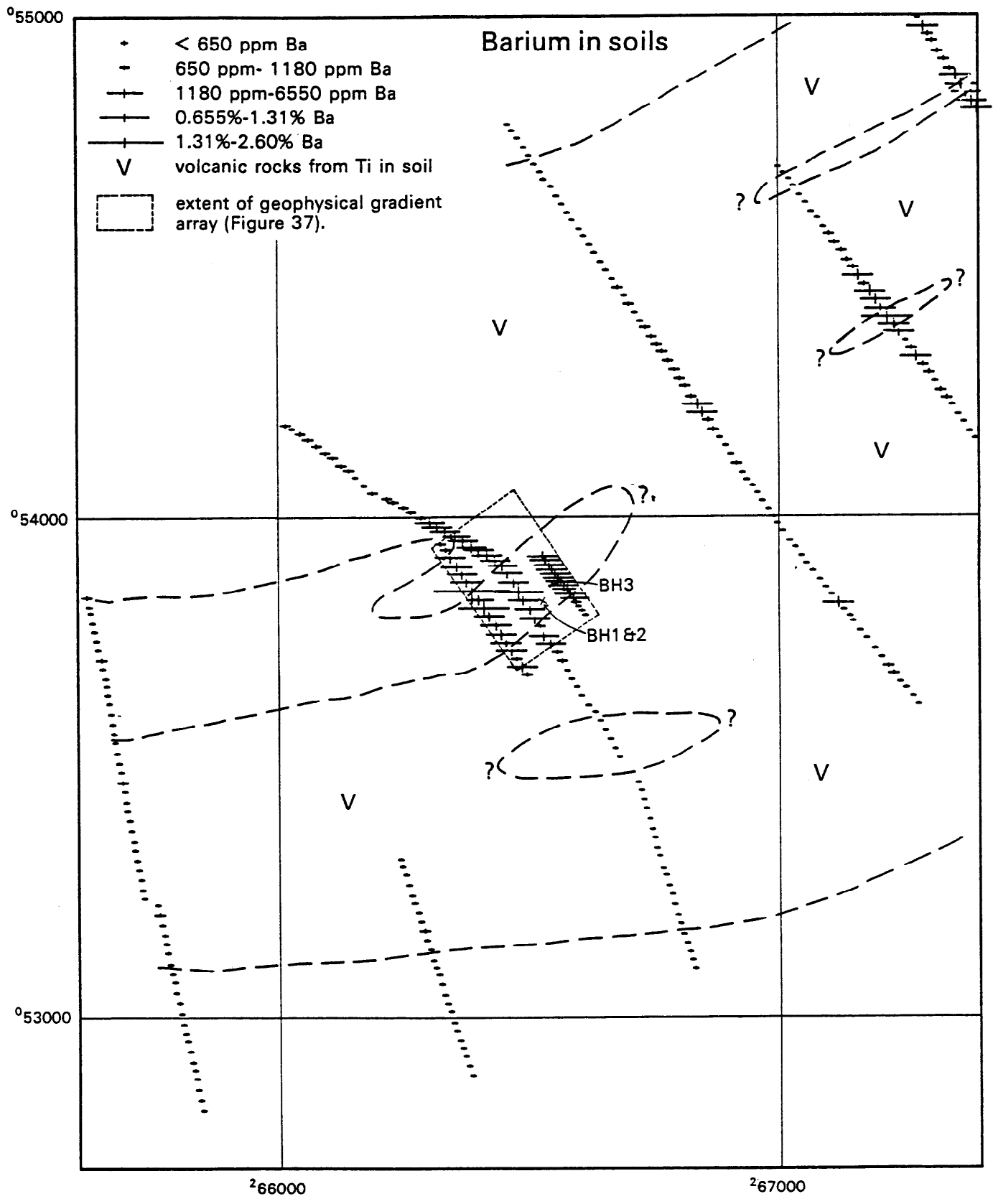
Figure 36 Ba levels in soil, Higher Ludbrook area.

line 50E, and this has too short a wavelength to be caused by the observed mineralisation. The sharp anomaly at 125S on line 100E is due to a buried pipe.

Detailed gravity traverses were conducted along lines 00 and 50E (Figure 39). When a likely regional effect is removed, the traverses show an E-W trending twin-lobed residual Bouger anomaly high with maximum amplitude of 0.2 to 0.4 mGal. The lobes are centred at 100S and 180S on line 00 and at 120S and 190S on line 50E. BH 1 was drilled on the southern lobe of the high (relative positions shown in the apparent resistivity map in Figure 37). The massive sulphide intersected in this borehole is very dense (5 samples from BH 1 have a mean density of 3.69 g/cm^3), but it is not likely that this is the principal cause of the high, in view of the observed electrical and electromagnetic responses. Samples of the massive carbonate and tuff from BH 1 also have fairly high densities of 2.87 g/cm^3 (9 samples) and 2.83 g/cm^3 (7 samples) respectively, and it appears likely that these rocks are the main cause of the higher residual Bouger anomalies, although further measurements of the densities of neighbouring rocks are required to confirm this. The massive carbonate is believed to be the major contributor, since there is a good correlation between the broad gravity feature (embracing both northern and southern lobes) and a zone of low Ti in soils (see page 47). The source of the residual Bouger anomaly low, which divides the broad high, is unclear; possible explanations are that it is due to low density sediments or to a zone of increased alteration associated with a fault.

The massive carbonate is likely to be relatively electrically resistive. The gradient array and VLF-R data do indicate higher apparent resistivities over the northern lobe of the Bouguer anomaly high but the effect of the southern lobe is indistinct, probably because of the influence of overlying conductive sediments.

Following drilling, additional electromagnetic measurements were made along a line at 90E using the Crone Pulse EM (PEM) system, with a receiver separation of 60m, and the SIROTEM Transient EM (TEM) system, with a 40m square coincident loop configuration. Details of the PEM and TEM methods are given in Ogilvy (1982). No indication of a buried conductor was found by either method in the vicinity of the known mineralisation, supporting the conclusion that the massive sulphide body is of limited extent.

Although the massive mineralisation may be local, it is possible that disseminated mineralisation is extensive and may be detectable by IP surveys but not by resistivity or EM methods. The gradient array gives very poor depth discrimination, so to obtain a clearer idea of variations of electrical properties with depth, additional dipole-dipole traverses were conducted. A dipole length of 40m was used and lines at 100W, 90E, 250E and 380E were covered (Figures 40 to 43 respectively).

On line 90E the chargeability data are disrupted by a burried pipe, which crosses the line 117S, and may also be influenced by a fence at 139S (Figure 40). The mineralised zone, at approximately 190S, lies on the southern flank of the disturbance caused by man-made structures. There is some evidence of a genuine slight northward increase in chargeability in the undisturbed measurements immediately to the south of this, but it would be unwise to draw firm conclusions from the available data. The resistivity data for this traverse are more enlightening. An apparent resistivity high centred at 240S at the n=5 level is probably due to the massive carbonate. The relatively low resistivity values at the n=2 and 3 levels in this vicinity are perhaps due to the overlying

CHARGEABILITY (msecs)   APPARENT RESISTIVITY (Ω m)

├───■───⊙   BOREHOLE WITH SULPHIDES

─·──────   VLF CONDUCTOR AXIS (SEE FIGURE 38)

[======]   EXTENT OF RESIDUAL BOUGUER ANOMALY
           HIGHS ON TRAVERSES 00 AND 50E (SEE FIGURE 39)
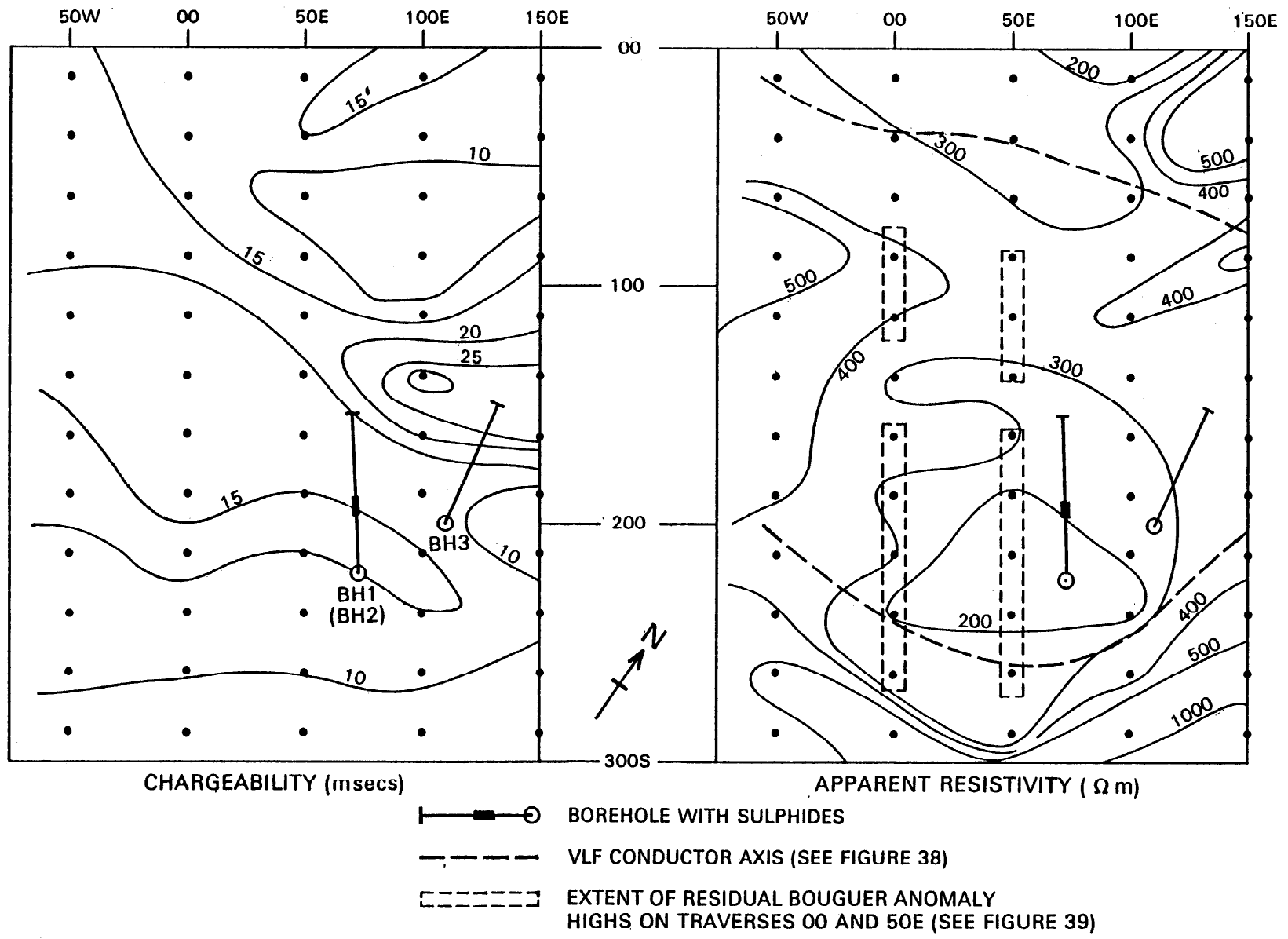
Figure 37   Chargeability and apparent resistivity for gradient array IP survey, Higher Ludbrook area.
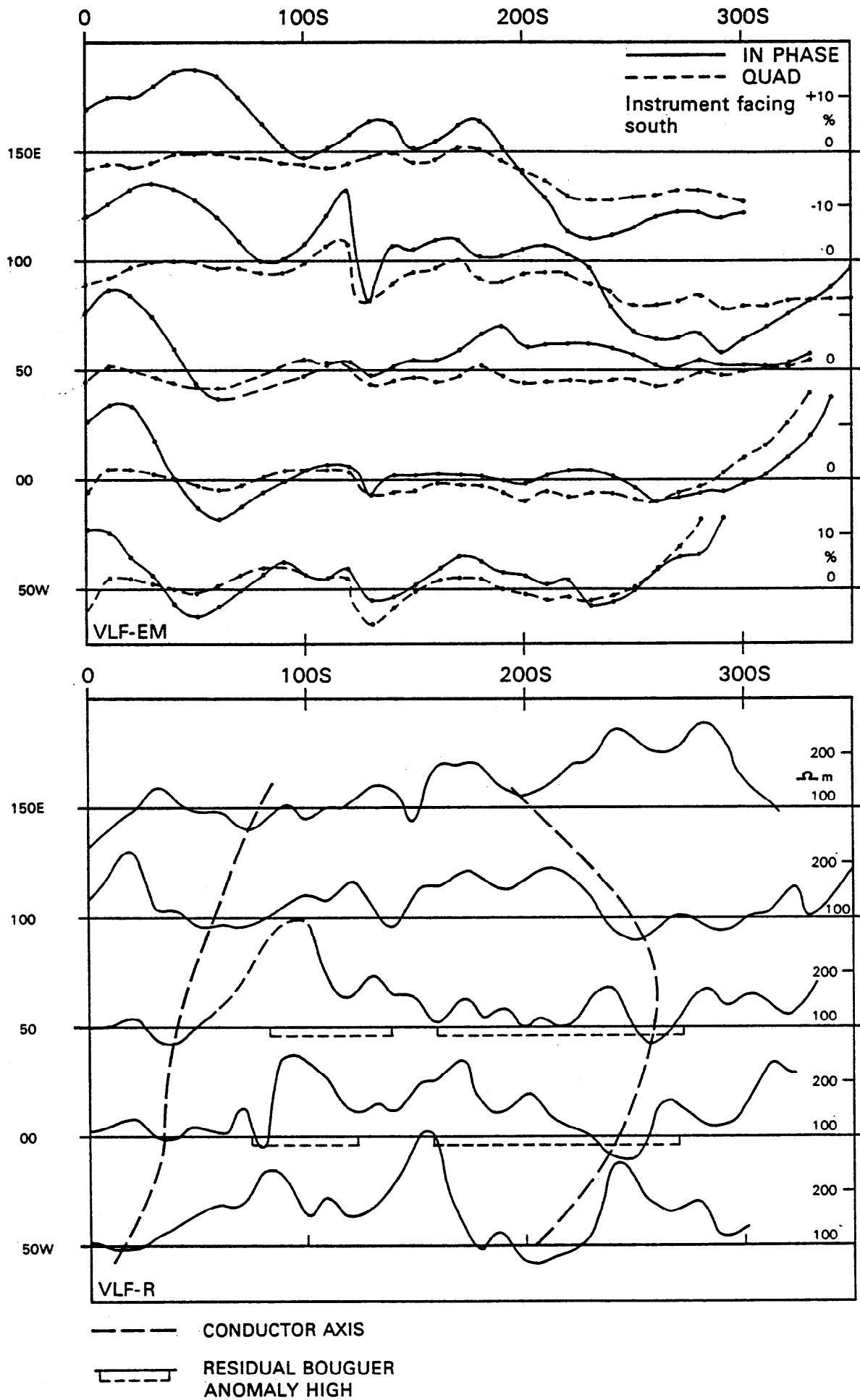
Figure 38 Profiles of VLF–EM and VLF–R results, Higher Ludbrook area.

52
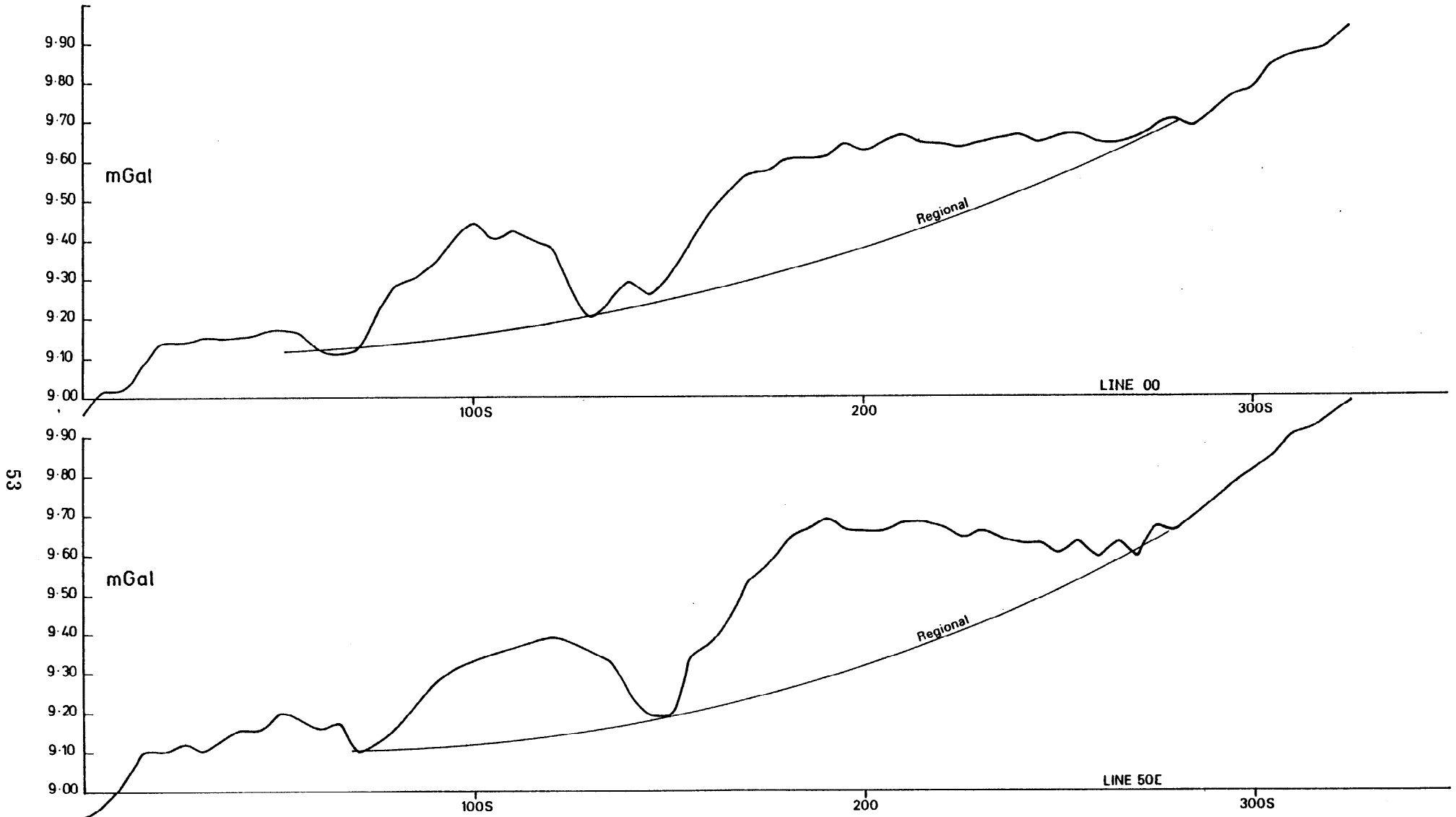
HIGHER LUDBROOK   GRAVITY TRAVERSES: BOUGUER ANOMALIES
VALUES IN MGALS, NGRN 73, $\rho = 2.70$

Figure 39 Detailed gravity traverses in Higher Ludbrook area.

LINE 90E
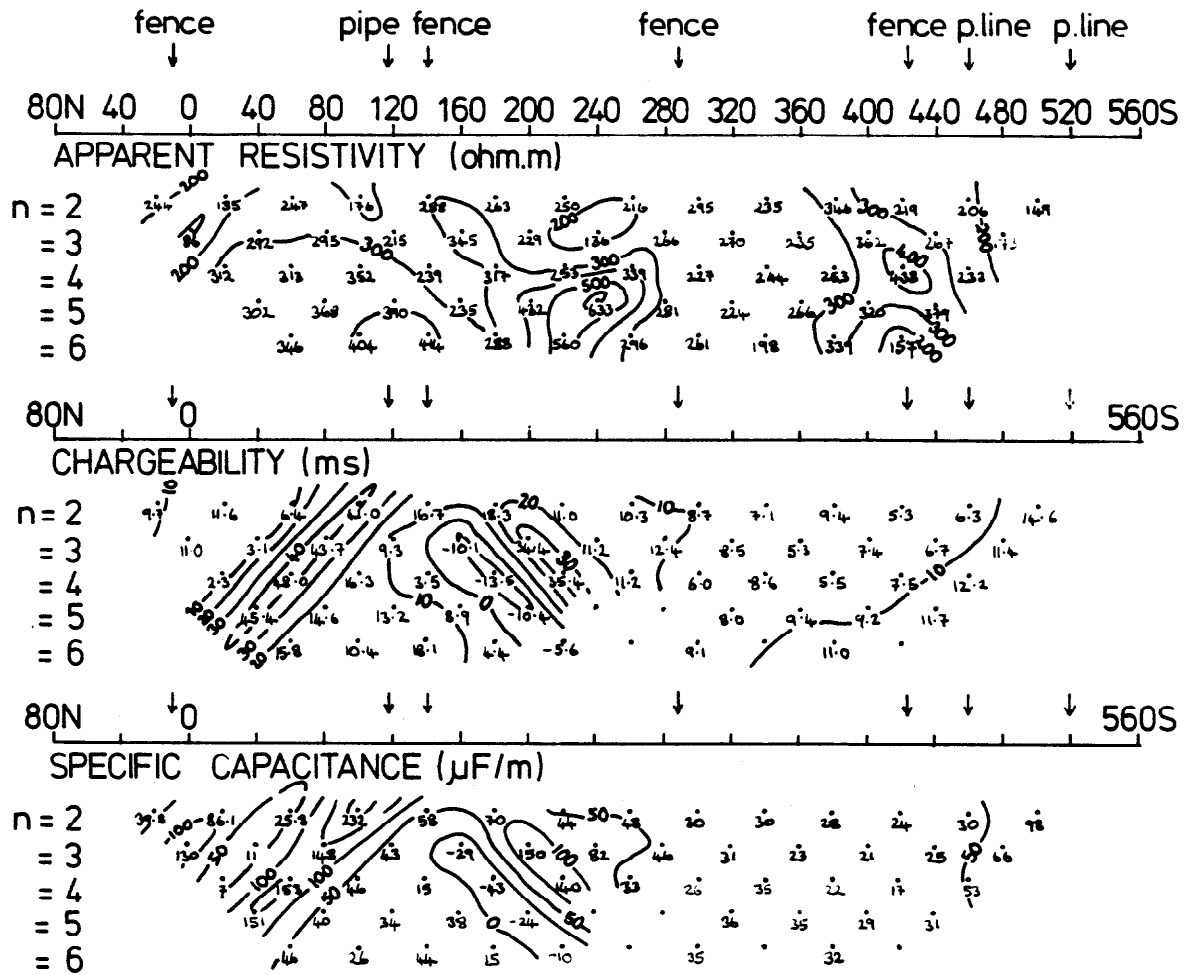
Figure 40 Dipole-dipole data for line 90E, Higher Ludbrook area.

LINE 100 W

fence   power line +fence   fence
↓   ↓   ↓

120N 30 40   0   40 80 120 160 200 240 280 320 360 400 440 480 520 560S

APPARENT RESISTIVITY (ohm.m)

n = 2
  = 3
  = 4
  = 5
  = 6

120N   560S

CHARGEABILITY (ms)

n = 2
  = 3
  = 4
  = 5
  = 6

120N   560S

SPECIFIC CAPACITANCE (µF/m)

n = 2
  = 3
  = 4
  = 5
  = 6
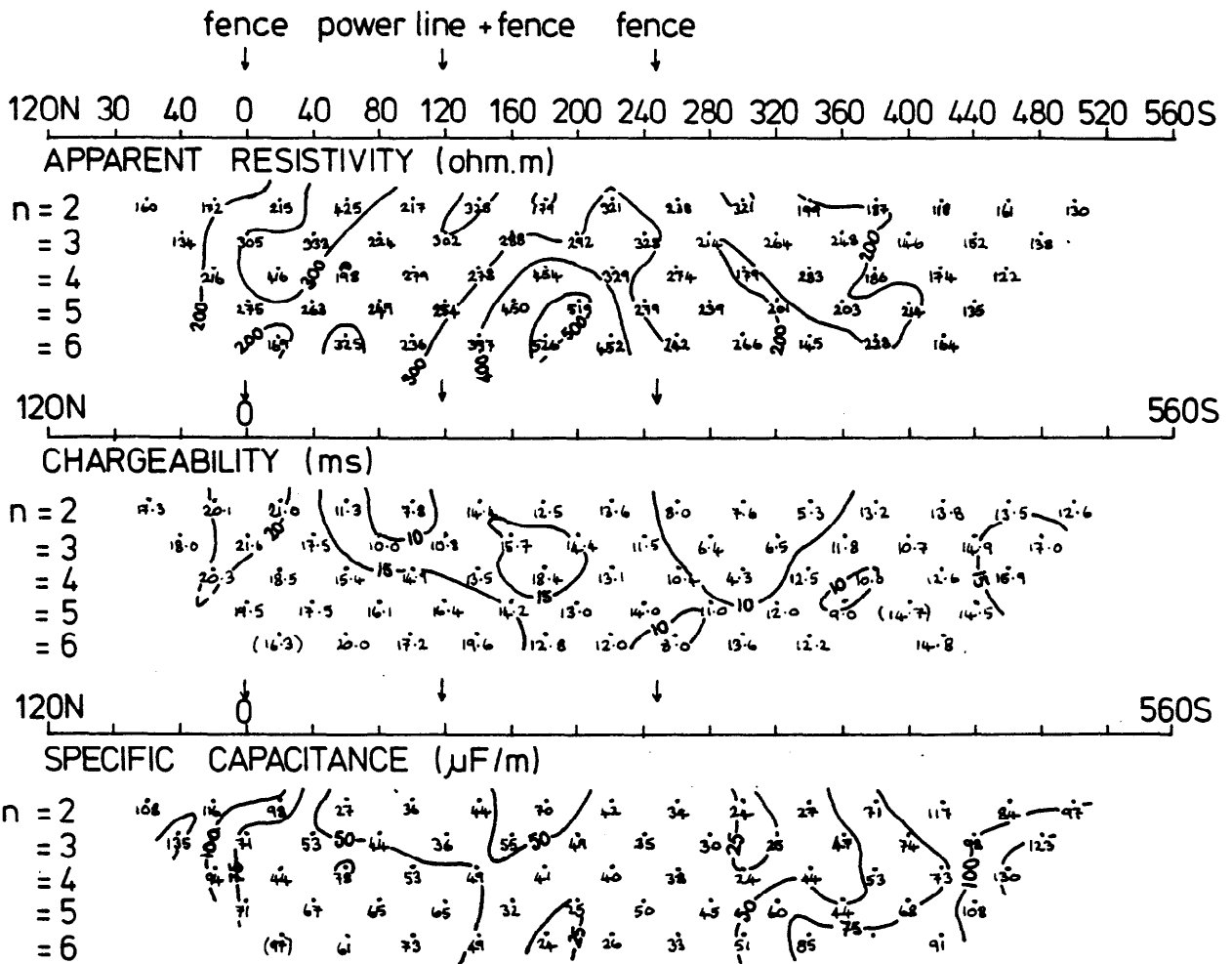
Figure 41   Dipole–dipole data for line 100W, Higher Ludbrook area.

55
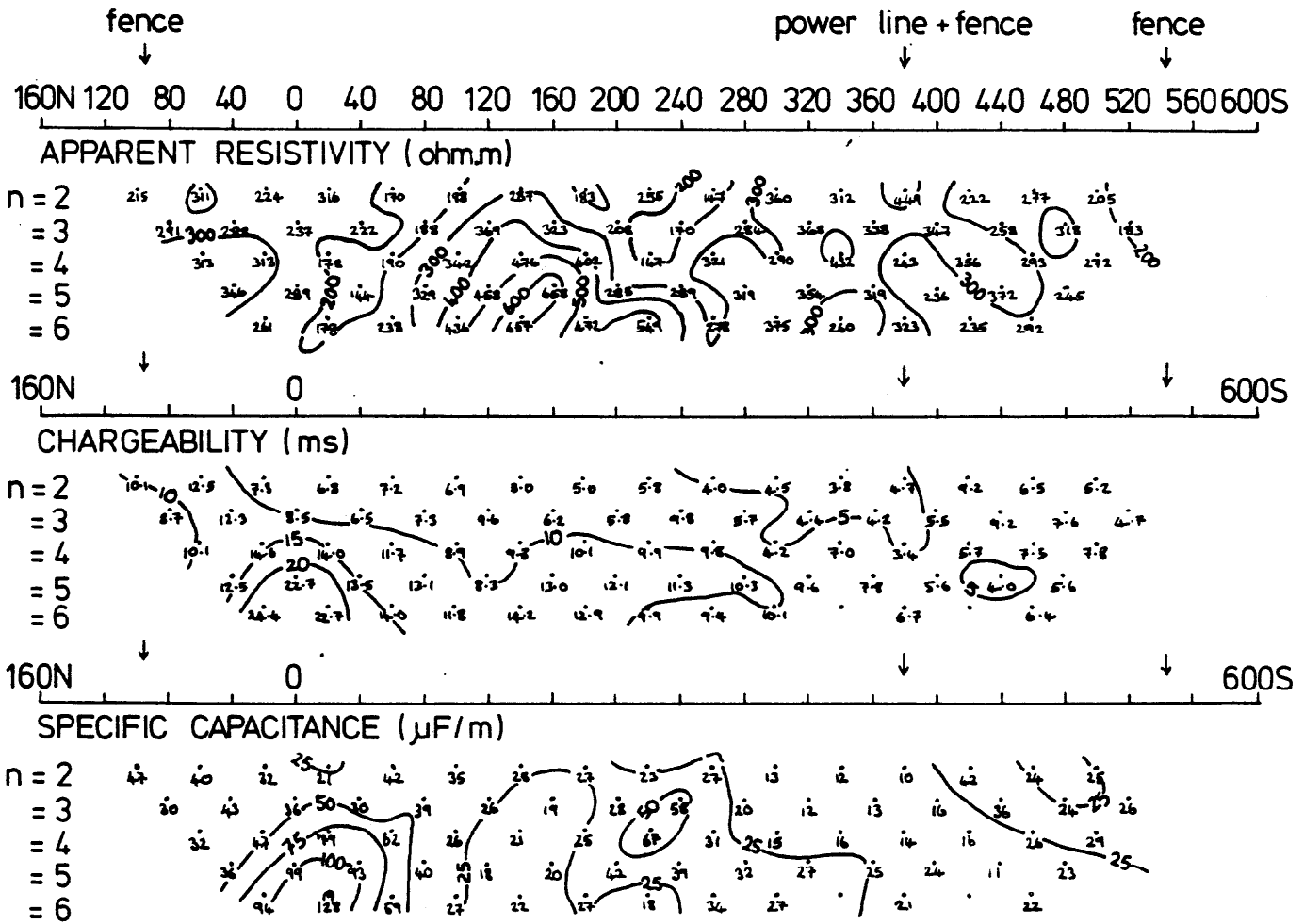
LINE   250 E

Figure 42   Dipole–dipole data for line 250E, Higher Ludbrook area.

LINE 380 E
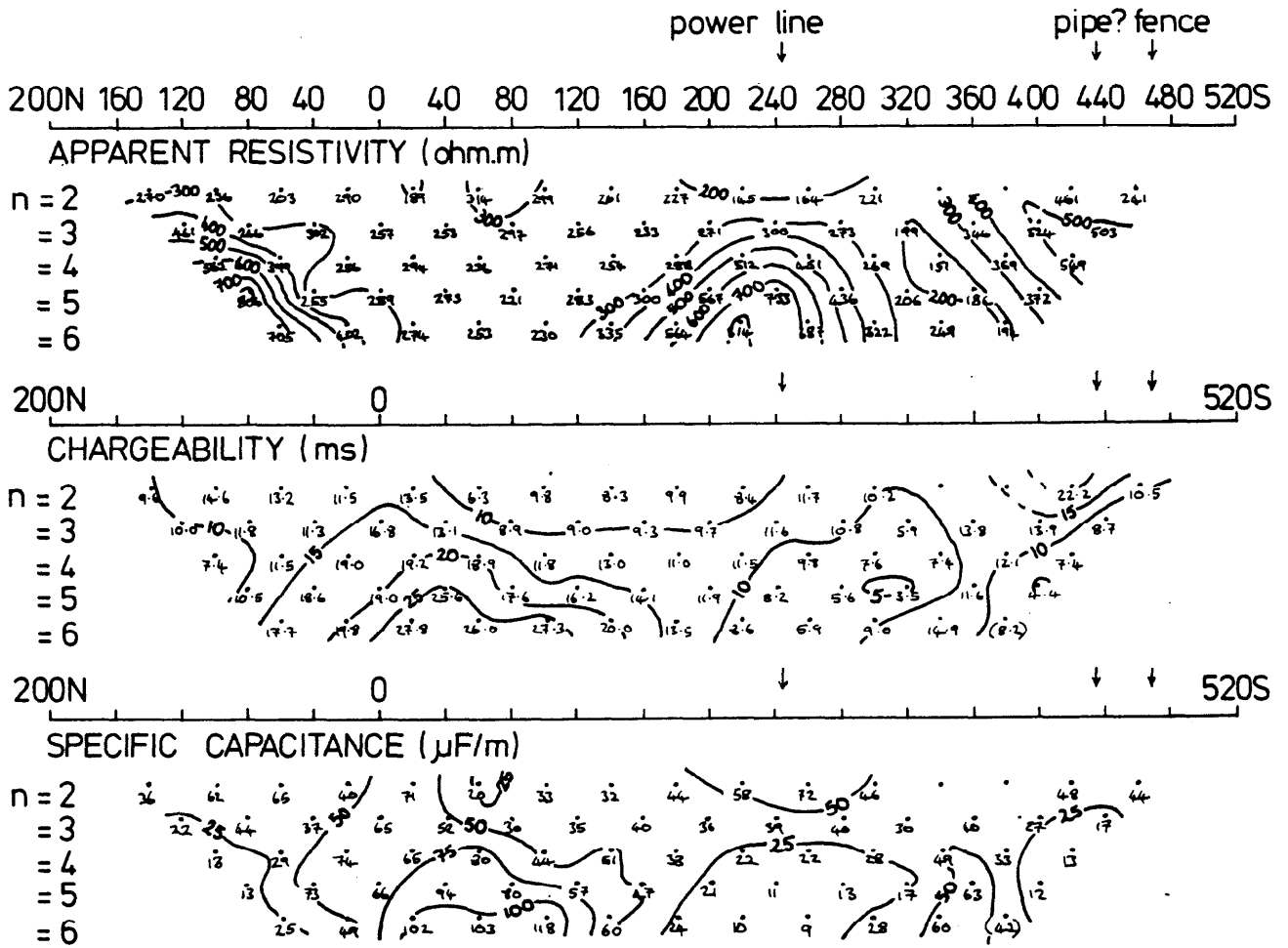
Figure 43   Dipole–dipole data for line 380E, Higher Ludbrook area.

conductive argillaceous sediments. A near-surface conductor is indicated between 40S and 80S; this has also been identified on the VLF traverses (Figure 38). At 400S there is evidence of a zone of moderately resistive rocks of unknown lithology.

Line 100W (Figure 41) lies to the SW of the gradient array grid. A resistive zone centred at 190S at the n=5 and 6 levels is probably the massive carbonate. The higher chargeabilities found at the northern end of this line appear to have a near surface cause and may be due to clay minerals in the weathered layer. The higher chargeabilities can be traced to the northern end of line 50W of the gradient array and perhaps further eastward, underlying the spurious peak on lines 100E and 150E. A small chargeability high centred at 180S at the n=4 level may indicate sulphide mineralisation, as its position just to the north of the massive carbonate is analogous to that of the known mineralisation. This anomaly lies along the trend of an axis of slightly higher chargeability which crosses the gradient array at around 200S (Figure 37). The correlation of this feature with mineralisation is in some doubt, however, as it passes slightly to the south of the known occurrence and apparently cuts across geological strike at the east side of the gradient array (this feature retains its E-W orientation while resistivity information indicates that the rocks swing to a more northerly strike).

The resistivity high at 100-240S on line 250E (Figure 42) is also probably due to the massive carbonate, while a chargeability high centred at 0S may be due to sulphide mineralisation. Similar resistivity and chargeability features are centred at 220S and 60S respectively on line 380E (Figure 43); in this case the chargeability anomaly is somewhat more pronounced. A further resistive zone is indicated at the north end of line 380E.

If the chargeability highs on lines 250E and 380E reflect mineralisation, this is likely to be mostly disseminated in form as there is no strong conductive response,though further discrete lenses of massive sulphide are possible. The zone of high chargeability appears to diverge from the resistive carbonate zone towards the east : the separation increases from 140m on line 250E to 180m on line 380E.

The resistivity data from the dipole-dipole traverses at the n=5 dipole separation is contoured in Figure 44. The high resistivity zone associated with the massive carbonate is clearly defined and correlates well with the southern lobe of the residual Bouguer anomaly high. The carbonate horizon is disrupted by folding or faulting at around 250E. Similar changes in trend can be identified in the available ground magnetic data (not shown).

The fact that the principal resistivity and chargeability anomalies are only evident at the wider dipole separations is probably a reflection of the deep weathering in this area. From the dipole-dipole data it is estimated, using the method of Edwards (1977) that significant weathering typically extends down to depths of 40m to 50m. It is therefore clear that use of the dipole-dipole array is greatly to be preferred over the gradient array since it has the ability to delineate variations in electrical properties beneath the weathered layer.

Ladywell.

The soil-sample traverse lines around the Sb anomalies discovered on the reconnaissance soil survey to the northwest of Ladywell are shown in Figure 45.

58
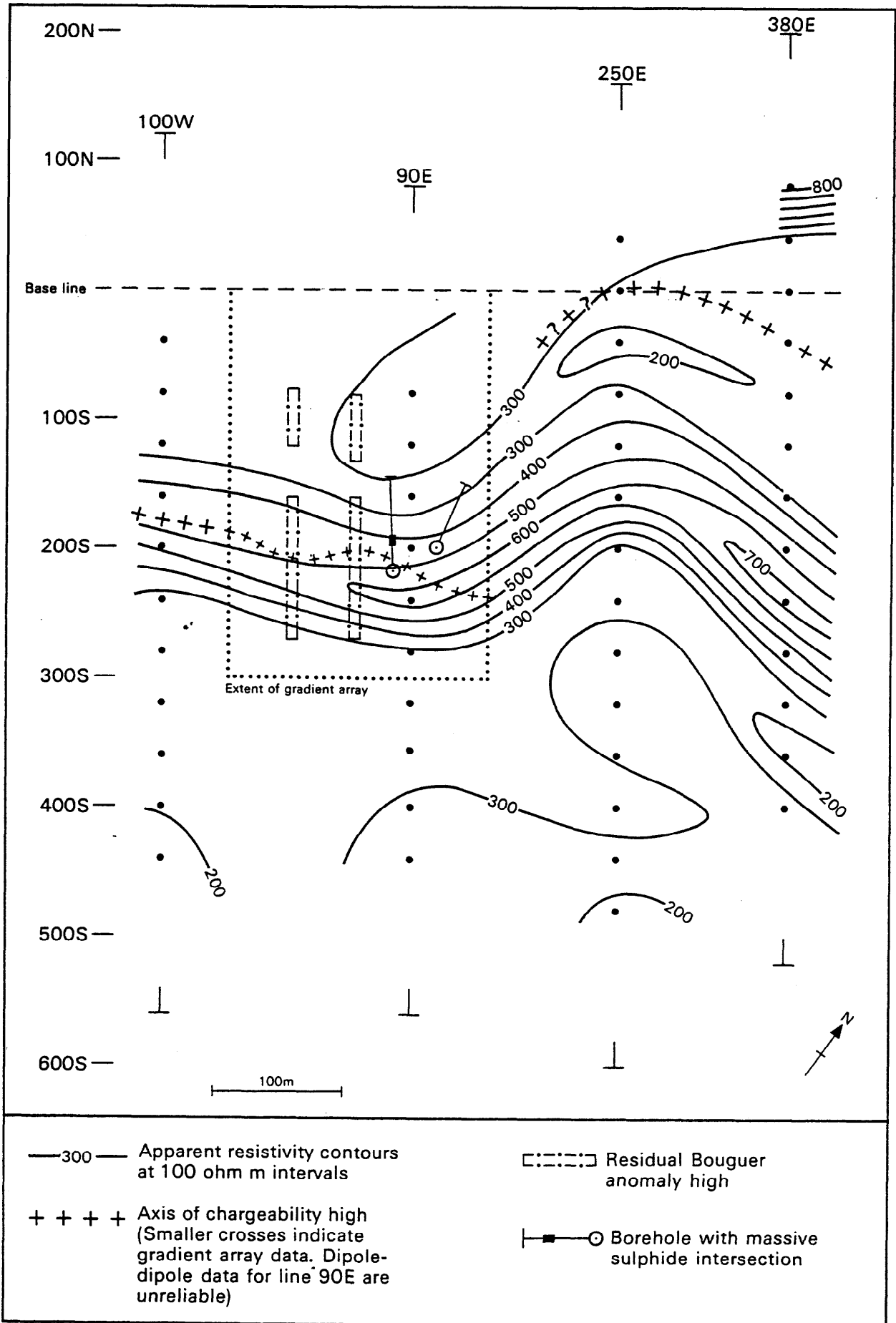
Figure 44 Contour map of dipole–dipole data for the Higher Ludbrook area: n=5 (dipole centre separation = 200 m).

This shows an anomalous zone up to 140 m broad which trends parallel to the local strike of the rocks. No other elements except Fe are associated with Sb and according to the soil data all anomalies occur within the volcanic rocks. The maximum level of Sb in these samples is 226 ppm but this increased to 464 ppm in a sample from the base of a shallow pit. Around 40 m north of the anomalous zone the soil data indicate that there is a sharp contact between volcanic rocks and sedimentary rocks which then extend for a considerable distance further to the north. Some 80 m south of the anomalous zone the soil data suggest that there may a relatively thin zone of sedimentary rocks with volcanics again further to the south. Similar anomalies also occur further to the northeast but separated from the Ladywell zone by a line with no anomalies (Figure 16). Furthermore some 3 km to the south of Ladywell, on the line east of Bowcombe, there are other similar Sb anomalies.

No geophysical work was carried out in this area.

Whetcombe Cross.

Two further soil lines were sampled in the vicinity of Ba anomalies around Whetcombe Cross, to the south of Ladywell and to the southeast of Kitterford Cross. These showed moderate amplitude Ba anomalies to be persistent across the three lines with a trend approximately parallel to the regional strike. Furthermore the area was marked by several Sb anomalies (Figure 45) though only half of these corresponded to Ba anomalies. A few Cu anomalies also occur in the area which is the only one to show a positive correlation between Cu and Ba (Figure 22). The soil data also indicate that the rocks underlying the grid are all volcanic with no indication of other types.

Geophysical surveys were also carried out in the area (Figure 1 under the heading Ladywell), and results are plotted in Figure 46. The apparent resistivity results range from 300 ohm/m to over 1800 ohm/m, but the site of the main Ba anomaly in soil is close to a resistivity minimum. A ridge of high apparent resistivity extends across the grid between 100 and 135S though this does not appear to be related to any of the soil anomalies. Chargeabilities are generally between 15 and 30 msecs with no obvious feature of interest. VLF-EM results showed no features of interest and are not plotted. VLF-R results indicate anomalously high resistivity on lines 100E and 150E at 115S which correlates with the other resistivity results.

Both the geochemical and geophysical data indicate that the source of the anomalies in this region differs from that at Higher Ludbrook and there is no stratiform mineralisation. Stockwork or disseminated root zone mineralisation may be a possible explanation.

Fursdon.

A limited geophysical survey was carried out to the southeast of Fursdon over an area of diffuse geochemical anomalies. The gradient array IP technique was used, and contour maps of apparent resistivity, chargeability and specific capacitance are shown in Figures 47 to 49.

The apparent resistivity map shows a distinct gradient at approximately 200S which may mark the contact between two contrasting rock types. The position of this does not correlate with the boundary between volcanics and slates to the north as indicated by the Ti in soil levels. A higher resistivity zone of unknown origin also appears in the northwest corner of the grid.

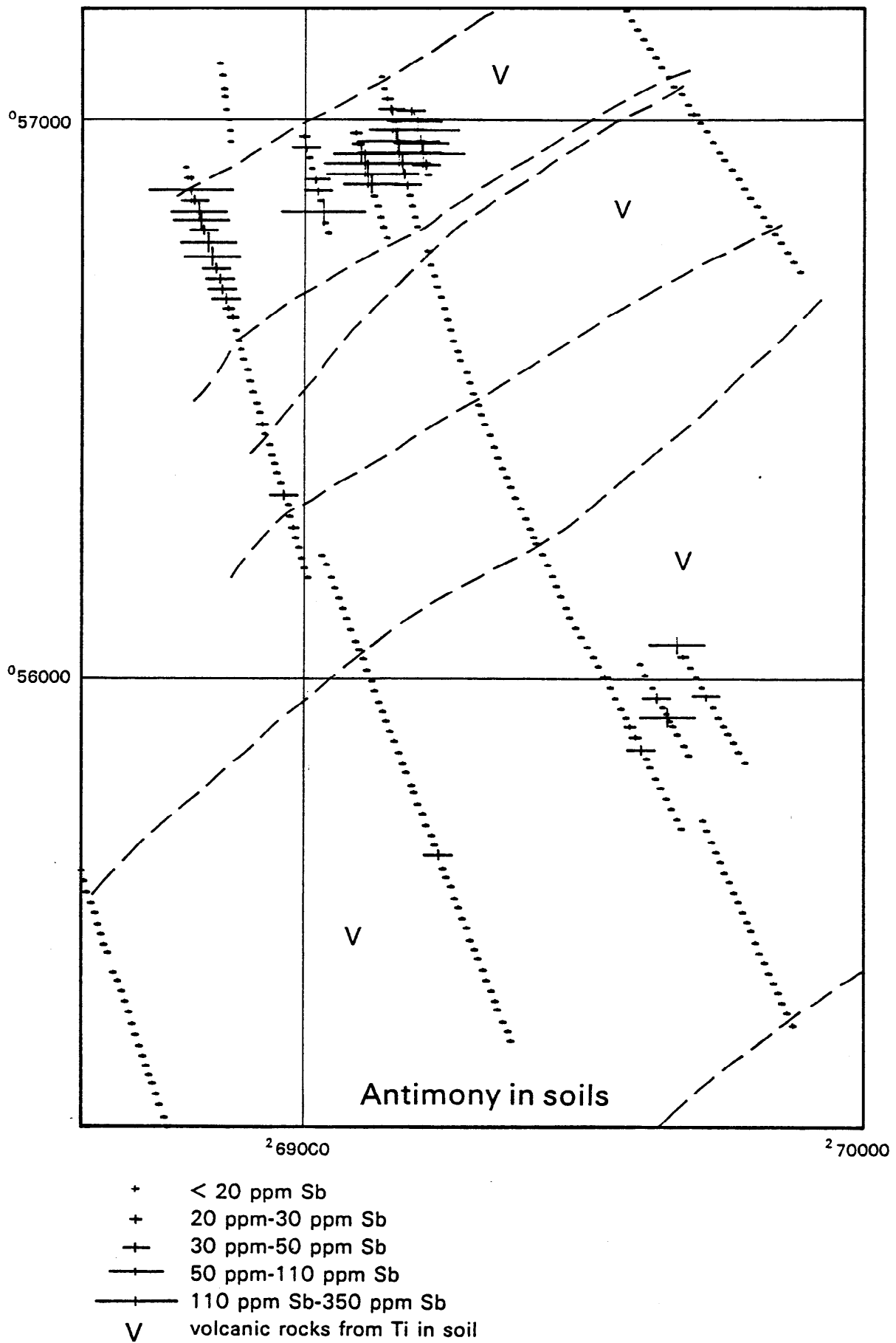**Figure 45** Antimony levels in soils, Ladywell area.
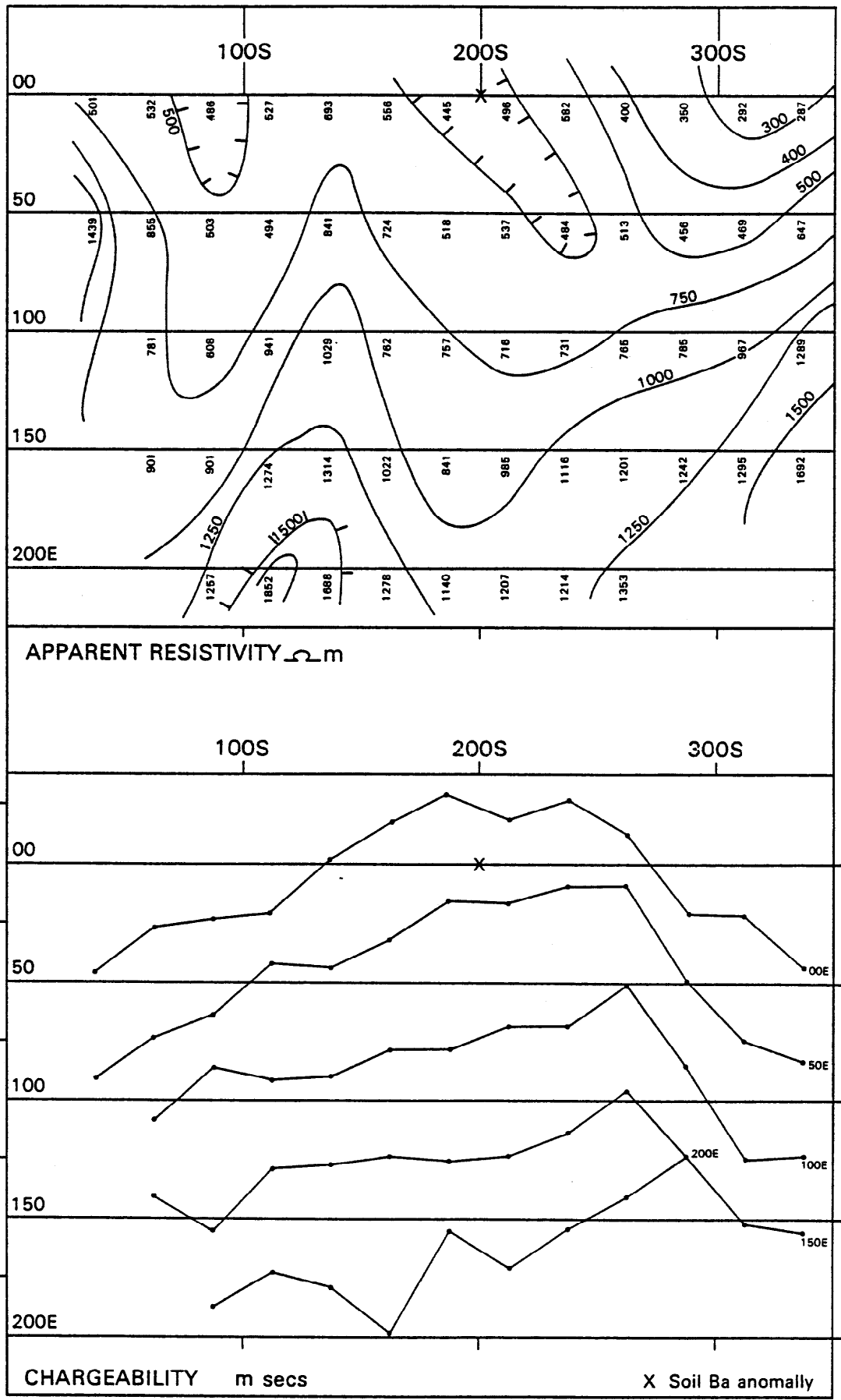
61

Figure 46 IP results from Whetcombe Cross area.

FURSDON GRADIENT ARRAY
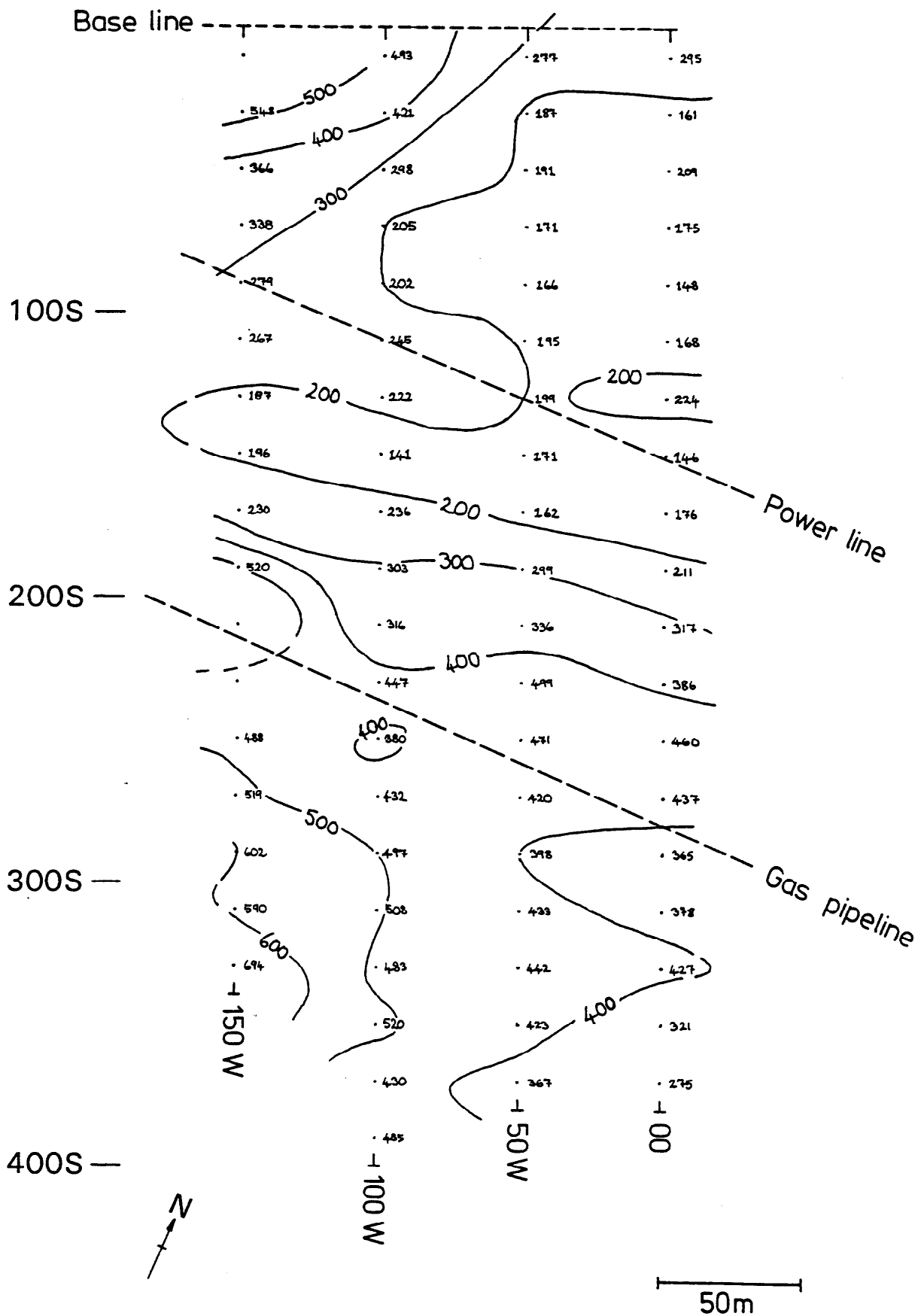## APPARENT RESISTIVITY (ohm·m)

Base line

Figure 47   Gradient array apparent resistivity, Fursdon area.
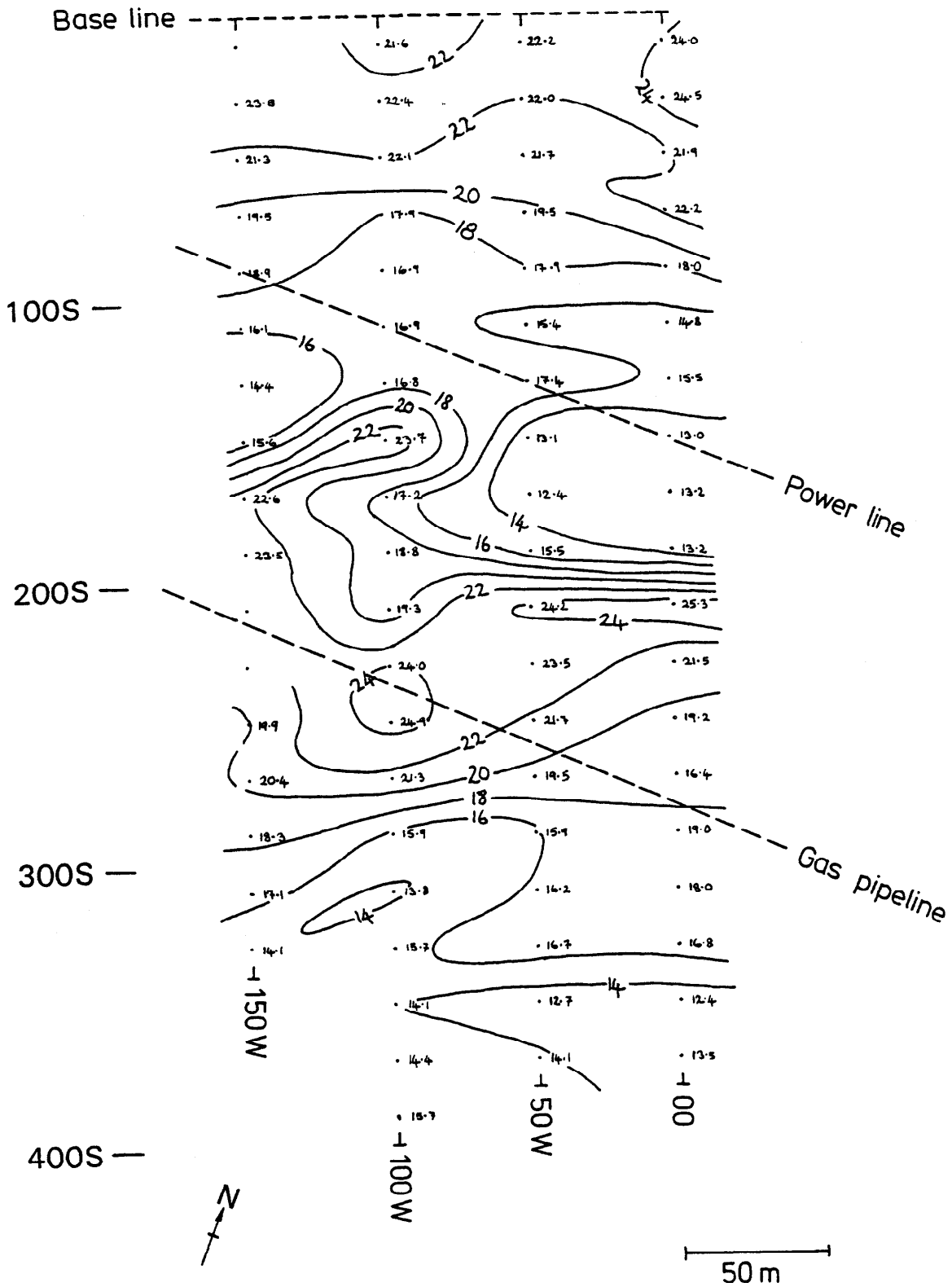
FURSDON GRADIENT ARRAY
CHARGEABILITY (ms)

Figure 48 Gradient array chargeability, Fursdon area.
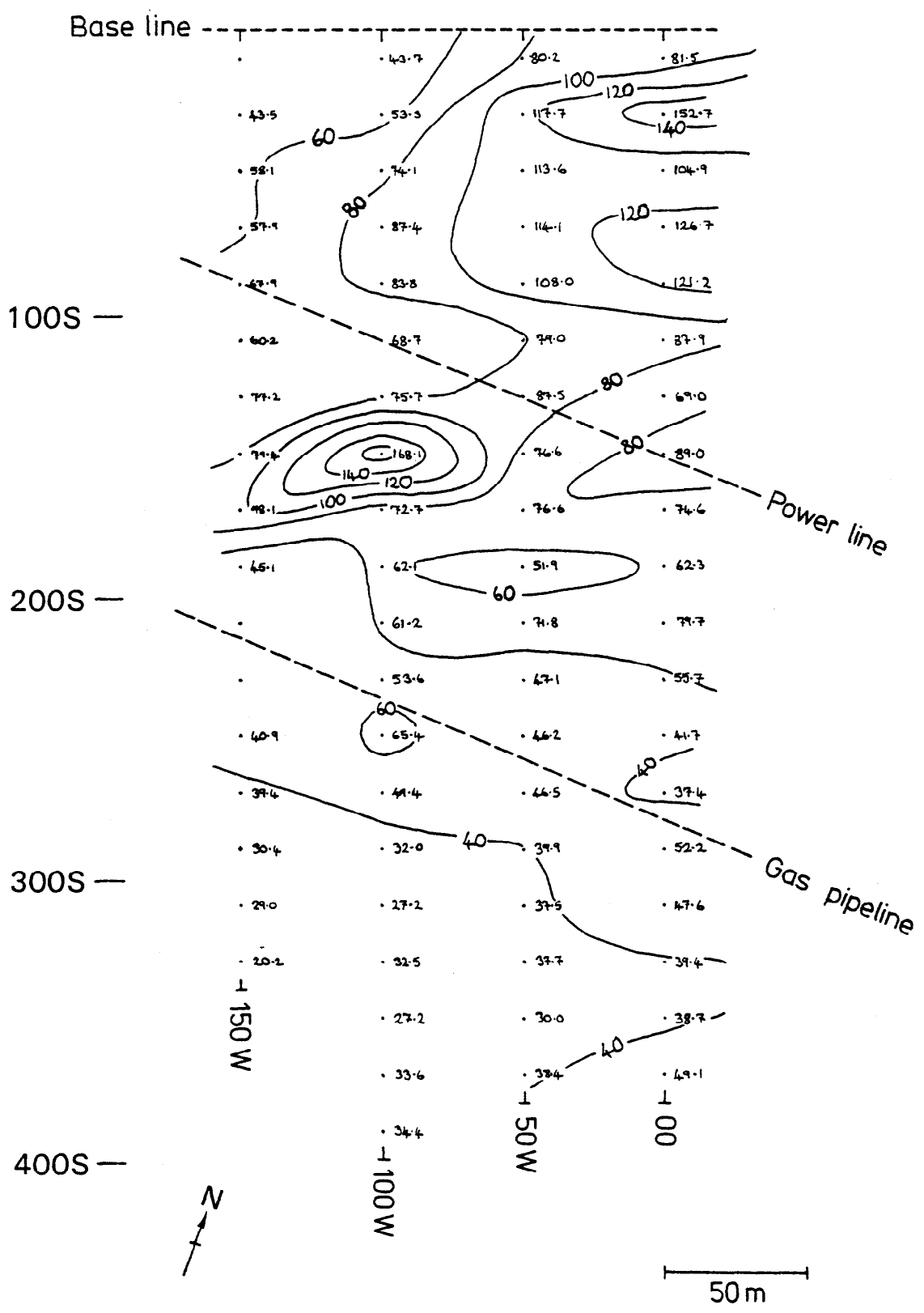
64

Figure 49 Gradient array specific capacitance, Fursdon area.

A zone of higher chargeability, which occurs just south of 200S, correlates in general both in position and trend with the diffuse anomalous zone of As in soils shown in Figure 21. The chargeability values are not particularly high and the anomalous zone does not show up clearly on the specific capacitance map, which would however tend to compensate for a genuine correlation between disseminated mineralisation and a more resistive host rock. A gas main interfered with readings on line 150W, but it is too far away from the main high chargeability zone further to the east to be the cause of this. The narrow lobe of higher chargeability on line 100W is due to a buried water pipe. Higher chargeabilities and specific capacitances are found at the northern end of the two easternmost lines where, on the basis of the geochemical data, the sedimentary rocks are thought to outcrop.

THE DRILL HOLES.

Burraton.

Three holes were drilled in the Burraton area, the locations of which are shown in Figure 53. The first hole was sited on the southern side of the anomaly which, on the basis of the available evidence, was assumed to originate from stratabound mineralisation with a dip towards the south. The Geological Survey map of Ivybridge area (Sheet 349) showed dip arrows in the area to be uniformly in this direction. The log of this borehole together with the chemical analyses of split core samples are shown graphically in Figure 50. Argillaceous sedimentary rocks were dominant throughout the hole, with some horizons of more silty material, and a cleavage was well developed in the finer grained rocks. Weathering seemed to be pronounced down to a depth of about 14 m. In addition one horizon of volcanic rock about 10 m thick was intersected. This consisted of buff schistose tuff containing manganoan siderite in veins and lenses. Chemically the volcanic rock is basaltic with relatively high levels of Ti and P (up to 4.56% TiO_2 and 0.75% P_2O_5), elements which are thought to be little effected by processes of hydrothermal alteration. The rock has undergone intense hydrothermal alteration leading to enrichment in K, Al and probably Mn and Fe, with up to 5.56% K_2O, 21.45% Al_2O_3, 0.68% MnO and 16.88% Fe as Fe_2O_3. In parallel with these enrichments are depletions in Na, Mg and Ca to levels as low as 0.26% Na_2O, 0.54% MgO and 0.78% CaO. Higher levels of Ca and Mg in several samples reflect introduced carbonate. No significant amounts of sulphide mineralisation were encountered in this borehole but minor disseminations of pyrite are widespread. Arsenic is relatively enriched in parts of the volcanic horizon, reaching a maximum of 97 ppm, and sparse amounts of tetrahedrite and a (Co,Ni,Fe) sulph-arsenide phase, probably related to cobaltite, were identified with the aid of the electron microprobe. Barium is enriched in the last three samples from the hole but since sulphur levels are low, only 69 ppm S to 3674 ppm Ba in one sample, it cannot be present in the form of baryte and is most likely to be as Ba-rich muscovite.

The second hole (Figure 51) was sited nearer to the maximum soil anomaly. It intersected only sedimentary rocks, chiefly of argillaceous type. Little evidence of mineralisation was apparent except for mild enrichment in Ba at the top of the hole and an elevated level of Sb (115 ppm) in an altered red-stained horizon. In general the composition of the sedimentary rocks seemed similar to those in the upper part of the first borehole.

Borehole 3 (Figure 52) was sited to the north of the maximum soil anomaly and drilled in the opposite direction to borehole 2. This hole proved somewhat difficult to drill because its direction was close to that of the well-developed
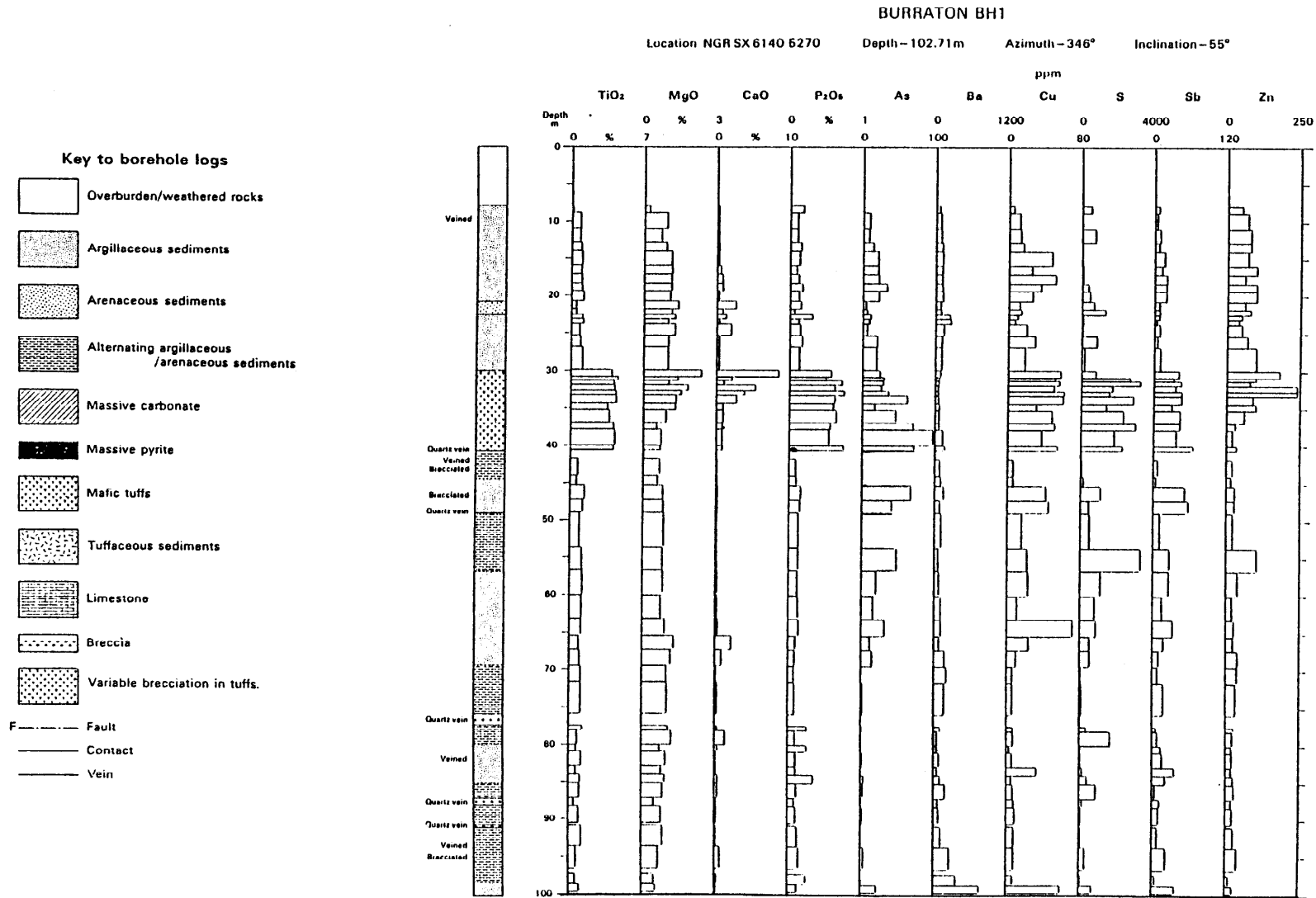
Figure 50 Graphic log of Burraton borehole 1 including chemical analyses. Key to all borehole logs attached.

BURRATON BH2

Location NGR – SX 6136 5265   Depth – 39.01 m   Azimuth – 335°   Inclination – 65°

Figure 51   Graphic log of Burraton borehole 2 including chemical analyses.

cleavage present particularly in the argillaceous rocks. It intersected sedimentary rocks but in the upper part of the hole these were more quartzitic than other sedimentary rocks encountered and below this was a section about 5 m long containing baryte and quartz, which was very poorly recovered. Chemical analyses showed that the quartzitic sediments were enriched in Ba. In the top three samples high levels of barium were not accompanied by an elevation of sulphur content in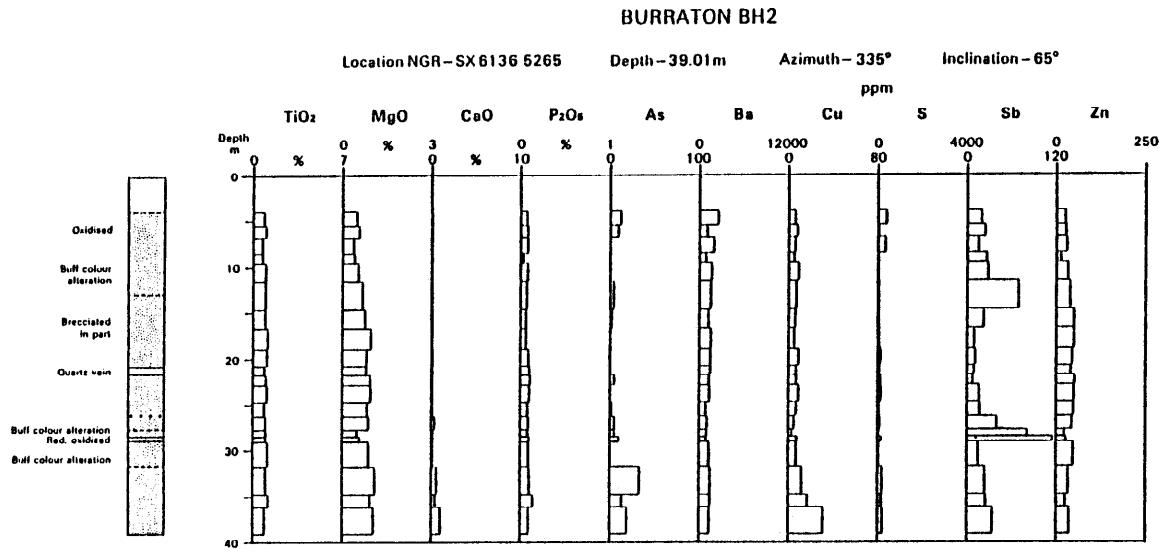dicating that the barium was not present as baryte. In the two samples below, in contrast, the Ba enrichment was accompanied by sulphur to the level of 0.32% against around 1% Ba. In the absence of significant sulphide in this material it is concluded that the Ba is present mostly as baryte, though traces of Ba were detected in K-mica and Fe hydroxide by the electron microprobe. Below this there are fragments of quartz and some baryte but because of poor recovery no analyses have been obtained. The rocks beneath this zone are argillaceous sediments similar to those from the other two boreholes and do not show any enrichment in Ba. Some elevation of Sb levels is found towards the base of this hole, as in borehole 2. In none of the holes is there evidence of the existence of anything other than minor veining and it therefore can be concluded that the Ba anomalies in soil are not due to the presence of steeply-dipping vein structures.

Figure 53 shows a structural interpretation of the boreholes based on the angles of dip measured from the core and correlations of similar material between the holes. In this interpretation the beds are seen to be nearly horizontal, with a significant dip to the north in the vicinity of the maximum soil anomalies, perhaps the result of a relatively local flexure. The soil anomaly is seen to correspond to the projected outcrop of the stratiform zone containing baryte and quartz which, though poorly recovered, is probably similar to the material seen as float at the surface. The low angle of dip of the strata, probably chiefly to the south, would account for the relatively wide anomalous zone in the soil grid.

Higher Ludbrook.

Three boreholes were drilled to the east of Higher Ludbrook farm within the zone of soil anomalies. The first hole was sited to the south of the soil anomalies on the assumption that they were stratabound with a southerly dip. The log and chemical data from the first hole are shown graphically in Figure 54. Argillaceous sedimentary rocks were intersected initially though they were poorly recovered. This confirmed the prediction from the soil data that this area was not underlain by the volcanic rocks. Below this a highly distinctive red limonitic rock was intersected which consisted mostly of oxidised carbonate and some quartz. This horizon, which is about 25m thick, is massive without visible layering, and, although it is mostly red in colour, there are also zones where the colour is orange or yellow or, especially towards the base of the intersection, pale pink. This pink material probably represents the original unoxidised carbonate and tends to have a saccharoidal texture with some interstitial quartz. According to the chemical analyses of this rock the proportions of Ca, Mg, Mn and Fe suggest that the carbonate is an ankerite with Mg/Fe of around 1.6. Probe analyses of the red coloured variety show that the material consists of ferroan dolomite containing fine-grained disseminated iron oxides, which is consistent with original ankerite partly oxidised. Clear ankerite occurs in veinlets with quartz and calcite and sometimes rosettes of a problematical micaceous mineral. Optically this mineral resembles a colourless chlorite but probe examination showed the presence of only Al and Si. An approximate calculation of composition was close to the obscure phase called donbassite ($Si_5Al_8O_{22}.7H_2O$) and X.R.D. examination confirmed the possibility of
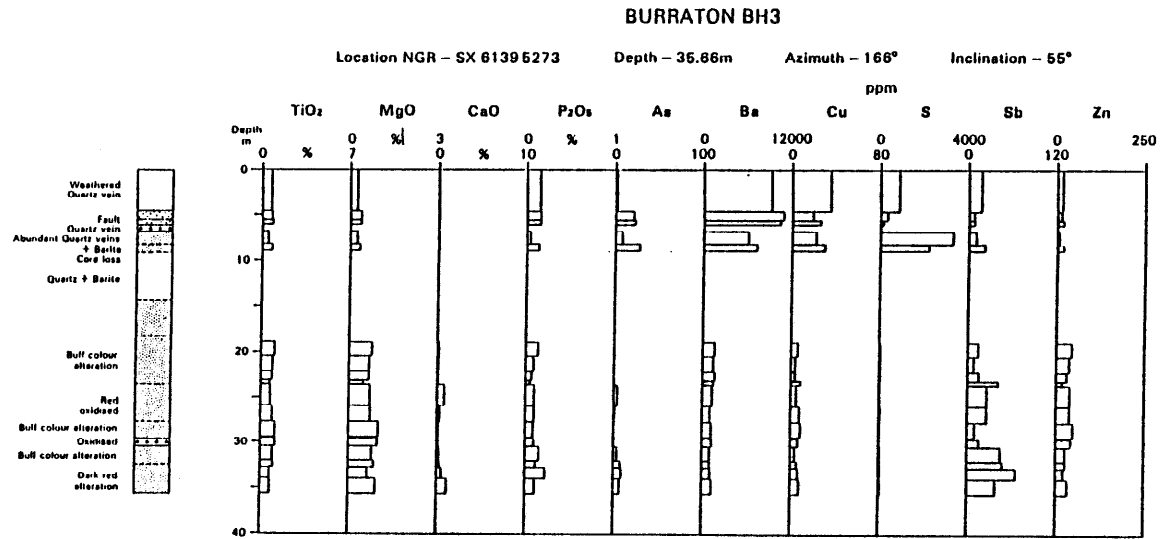
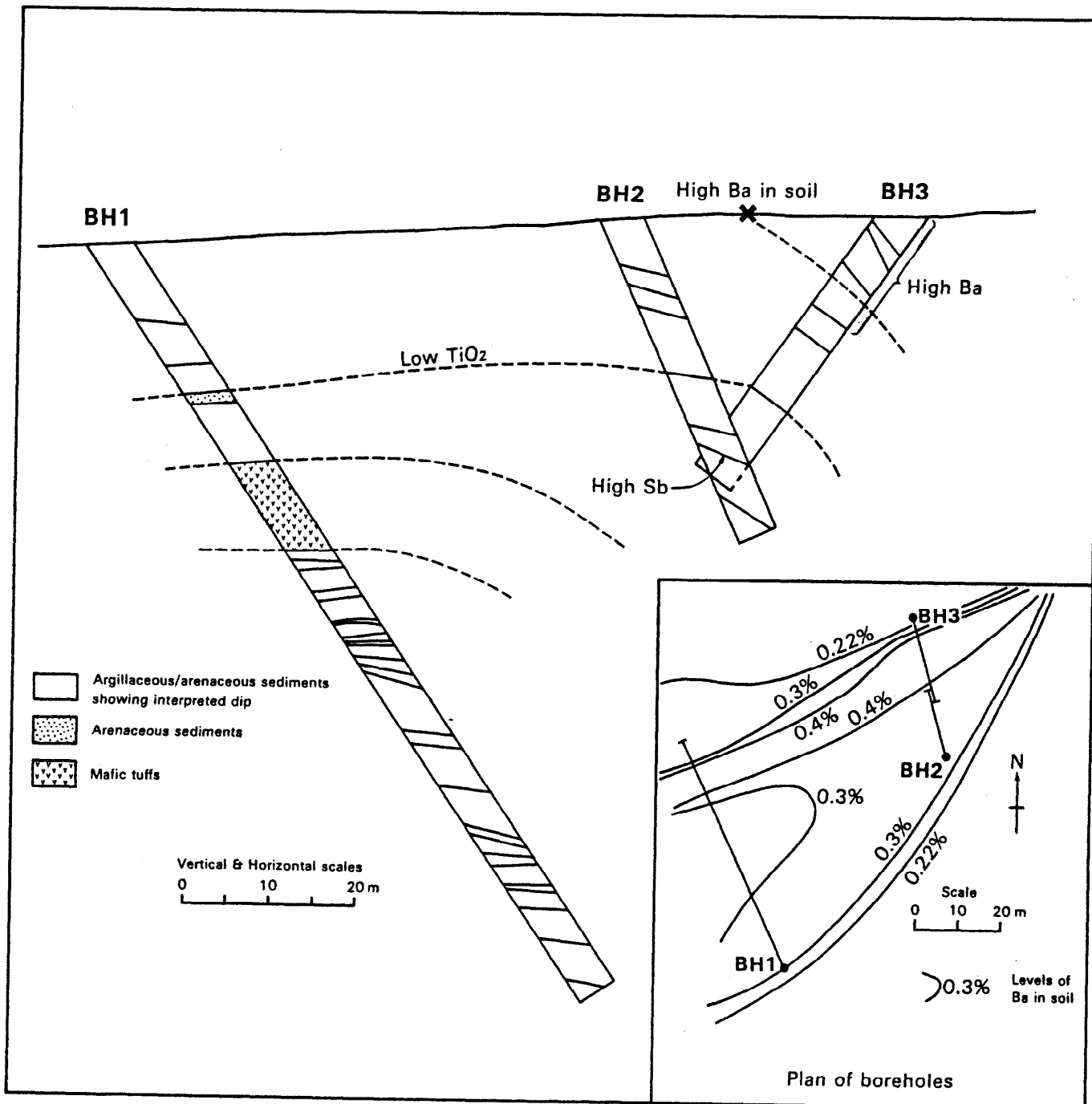**Figure 52** Graphic log of Burraton borehole 3 including chemical analyses.

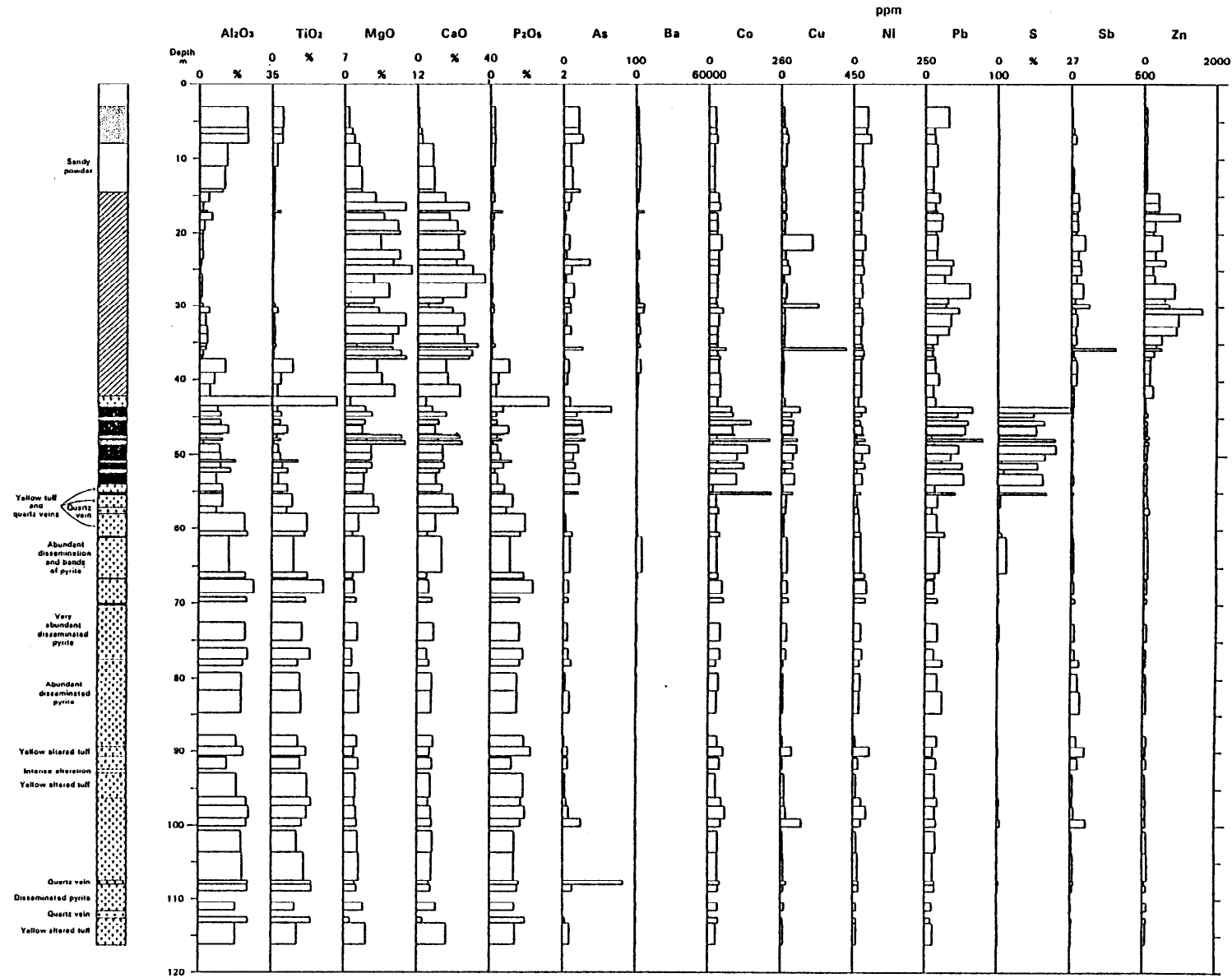**Figure 53** Structural interpretation of Burraton boreholes.

Figure 54   Graphic log of Higher Ludbrook borehole 1 including chemical analyses.

this mineral but also suggested the structurally very similar Li-chlorite, cookeite ($LiAl_4(Si_3Al)O_{10}(OH)_8$). Since Li cannot be detected on the electron microprobe this is the most likely possibility though other light elements like N (as NH_4) could also be present. Within this carbonate Zn levels are generally elevated, reaching 1600 ppm over 0.8m, with a mean level of 580 ppm over 22 m. The zinc is not present as sulphide, as in most of the samples sulphur levels are low, typically around 100 ppm. The zinc is therefore probably dispersed in the carbonate. Barium is also enriched in the rock but in a more irregular manner. Levels reach 0.65% (and again sulphur levels are low, down to only 30 ppm). In most of the Ba-rich samples there are inclusions of highly altered schistose rock within which the Ba probably resides as barium-rich muscovite. Only in one sample is an enrichment in Ba accompanied by a corresponding one in sulphur, and in this baryte has been identified in a lens within the carbonate, though a trace of baryte was also identified by electron probe in another sample. Three samples contain elevated levels of Cu and Sb. In a sample of the fresh pink carbonate containing 403 ppm Cu and 305 ppm Sb over 0.3 m a veinlet with pyrite, tetrahedrite and chalcopyrite intergrown together has been observed. Probe analyses show that the tetrahedrite contains a few percent mercury but no detectable silver. In addition there are also a few included grains of carollite, a Cu-rich member of the linnaeite group ($Cu(Co,Ni)_2S_4$) within the tetrahedrite. In the other two samples, which are of the red oxidised carbonate, the copper occurs as malachite and azurite and the antimony probably as a pink mineral which may be kermesite.

Below the carbonate is a thin horizon or lens of pale grey, highly-altered tuff containing conspicuous fine pyrite and several white carbonate-quartz veins. Sericitic mica, quartz, the problematical micaceous phase, siderite, ankerite, Fe-oxides and some grains of Mn-oxide were identified in this material. Opaque minerals consist of disseminated rutile and tetrahedrite, chalcopyrite and sphalerite in association with siderite veinlets. It is similar in composition to the volcanic rock from the Burraton borehole but with somewhat higher levels of Ti and P. Levels of K and Al are high due to the presence of sericite, which must have developed as a result of intense hydrothermal alteration by the fluids which deposited the massive ankerite.

Massive pyrite underlies this thin volcanic rock. In general it is coarsely or finely crystalline, with cubic forms well developed, while layering seems to be absent. Overgrowths have developed on earlier euhedra which have undergone fracture and brecciation. Quartz and carbonate are the main interstitial minerals. The carbonate is ankerite or ferroan dolomite and contains minor Mn. Sheaves of the problematical micaceous mineral are conspicuous and occasional opaque stringers (possibly carbonaceous) are filled with tiny rutile grains. Within the sulphide there are irregular veins and lenses of quartz and a pale yellowish carbonate which on the basis of the chemical data seems similar in composition to the massive carbonate overlying it. A trace of chalcopyrite is the only other sulphide mineral that has been identified in the sulphide rock and this is consistent with the chemical analyses which give 114 ppm as the maximum Cu level and 223 ppm as the maximum Co level. Both Zn and Pb levels are also relatively low but Pb is enriched in the sulphide compared with all other material intersected.

In borehole 1 the intersection length of material with massive pyrite dominant was 11.9 m but layers and lenses of highly altered mafic tuff increased in abundance and thickness towards the base of this zone, with individual layers reaching up to 0.6 m in length. Estimation of the true thickness of the massive

pyrite zone is difficult but it may be about 7 m based on the structural interpretion of the boreholes. Below the massive sulphide is a pale-coloured, highly-altered tuff but further thin horizons of massive pyrite up to 0.25 m thick also occur and disseminated pyrite is conspicuous in places. The amount of disseminated pyrite is highly variable but in general there seems to be an overall decrease down the hole, though it is still present in small amounts near the base. The composition of the tuff seems fairly uniform and it is all relatively rich in Ti and P, elements which are thought to be little influenced by the sort of hydrothermal alteration that has affected the rocks. All samples have high but variable amounts of Al and K and low levels of Na and Mg, due presumably to the intense hydrothermal alteration that they have suffered. Some indication of bedding is apparent in most of the rock, which is relatively fine-grained, but brecciated material occurs near the contact with the massive sulphide and is relatively rich in Ba. Otherwise the tuffs are not enriched in Ba or Zn. Copper reaches 127 ppm in association with 109 ppm Sb in a zone enriched in disseminated pyrite. Sb shows some enrichment with levels between 42 and 99 ppm in one 14m section of core, compared with levels up to 27 ppm elswhere.

The second borehole at Higher Ludbrook (Figure 55) was sited at the same place as the first hole but was drilled almost vertically in order to provide structural information. It initially intersected sedimentary rocks which, though poorly recovered, are more quartzitic than those in the first hole. Following these are argillaceous rocks more similar to those in borehole 1. These sedimentary rocks are anomalously rich in Ba with levels up to 1.32% Ba but low sulphur contents. Beneath the sedimentary rocks is the massive red-coloured carbonate, similar in appearance and composition to that in borehole 1. There are also included lenses of highly altered tuffaceous schistose rock. An analysis of this material shows it to be similar to the mafic tuffs below the sulphide in borehole 1 with relatively high levels of Al and K signifying extreme alteration. Furthermore the rock is highly enriched in Ba, with over 5% of the element. Since there is only 16 ppm S present the Ba is most likely present as Ba-rich muscovite. Other lenses of similar material occur further down the hole, which was terminated in the carbonate because of drilling problems and lack of recovery.

The third borehole was drilled about 40m away from the other two, which was as far away as it was possible to go within the small field to which access had been given. The graphical presentation of the log and chemical data is shown in Figure 56. Very little except fragmentary quartz was recovered from the first 15.4m of the hole and it is not known whether sedimentary rocks are present though this is likely on the basis of the soil data. Beneath this poorly recovered zone was the reddish oxidised carbonate similar in texture and chemistry to the material in the other two holes. As in borehole 2 small amounts of highly altered tuffaceous rocks occurred as inclusions. At the base of this section there was a transition into finely-layered and bleached tuff with no indication of massive pyrite. Just beneath this transition zone a layer of pale highly altered tuff with a 3 m long intersection showed relatively high levels of Co, Cu, Ni and Sb (maxima of 252, 447, 201 and 430 ppm respectively) together with elevated levels of sulphur and a slight enrichment in As. These elements are present as stringers and segregations of grey minerals including tetrahedrite with some pyrite. Below this zone is altered tuffaceous rock similar to that found in borehole 1 though the amount of disseminated pyrite appears less. Disseminated pyrite only becomes conspicuous towards the base of the hole.

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LUDBROOK BH2

Location NGR SX 6651 5385   Depth-48.26m   Azimuth-328°   Inclination-80°
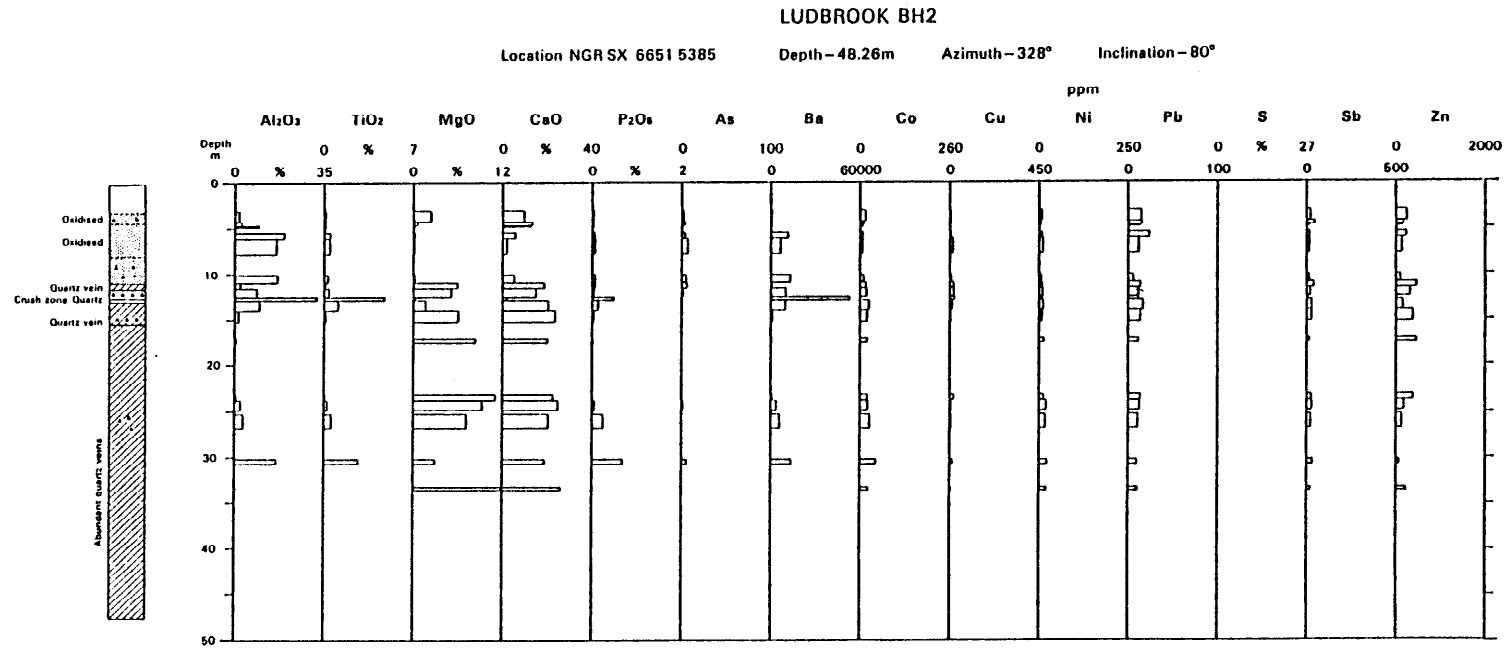
Figure 55   Graphic log of Higher Ludbrook borehole 2 including chemical analyses.

LUDBROOK BH3

Location NGR SX 6654 5387   Depth—93.87m   Azimuth—351°   Inclination—55°

ppm

| Al₂O₃ | TiO₂ | MgO | CaO | P₂O₅ | As | Ba | Co | Cu | Ni | Pb | S | Sb | Zn |

Depth m

Quartz debris

Quartz vein
Quartz vein

Quartz vein

Quartz vein

Quartz vein

Yellow/white altered tuff
White altered tuff

Quartz vein
Quartz vein
Quartz vein
Quartz veining

Yellow altered tuff
Intense alteration

Yellow altered tuff

Quartz vein
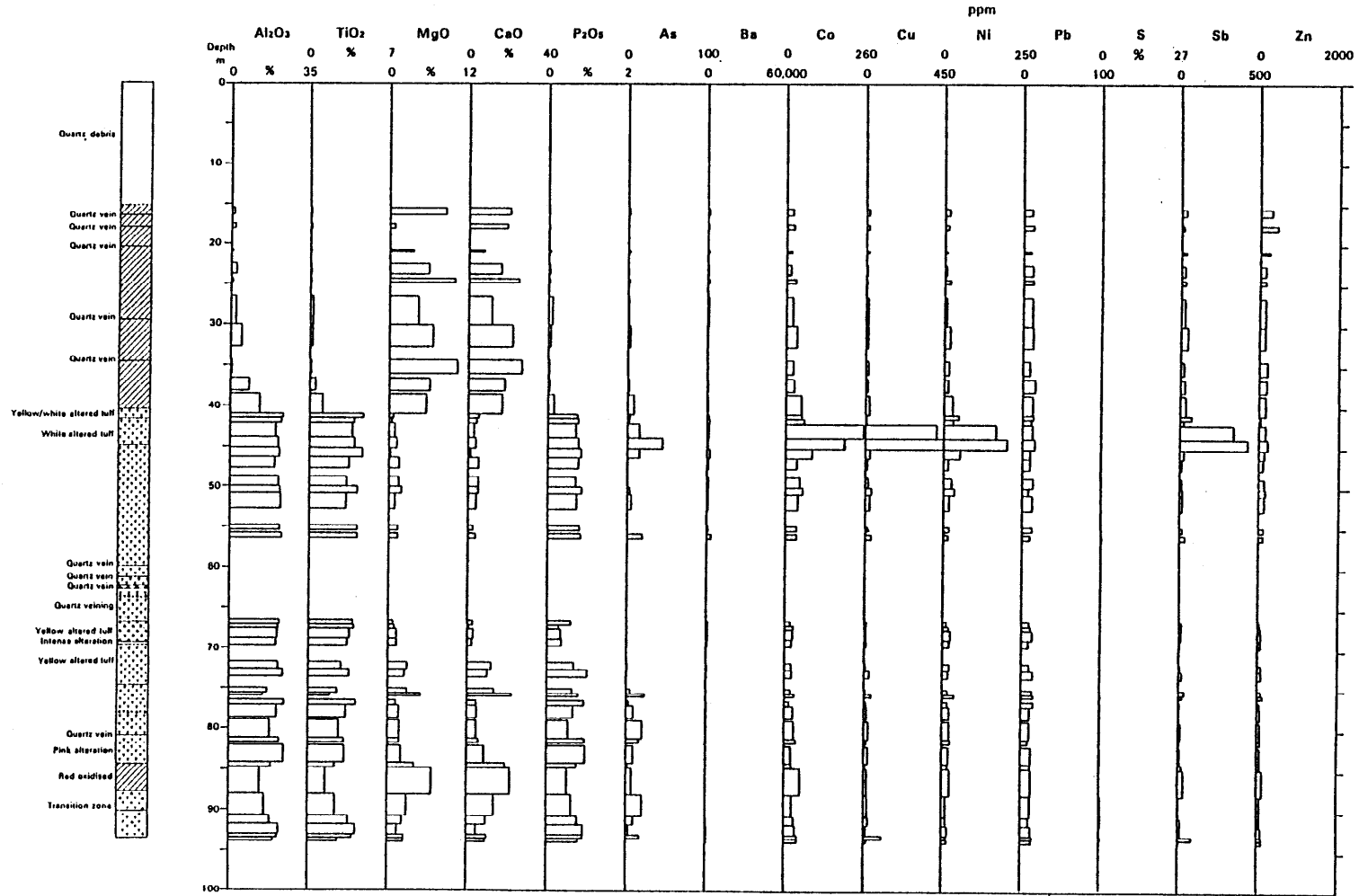Pink alteration

Red oxidised

Transition zone

Figure 56 Graphic log of Higher Ludbrook borehole 3 including chemical analyses.

A structural interpretation of the Higher Ludbrook boreholes is shown in Figure 57, which is based on relative intersections of the various rocks, angles of dip measured on the core and information from the soil data. Borehole 3 is sited approximately along strike from the other two and its position is projected into a north-south plane through boreholes 1 and 2 in Figure 57. Correlation between the boreholes is clear except for the massive pyrite which is absent in borehole 3. The computed dips seem variable to the south, which suggests that local flexuring of the rocks may exist. The apparent discordance between relatively high angle dips computed from the core and the shallower dip of the geometry of the contact between the sedimentary rocks and the massive carbonate may also suggest folding, although it is also possible that low angle faulting may have been active along this contact zone. In contrast there seems little evidence for such movement between the carbonate and sulphide or volcanics. It is therefore probable that the apparent lensing out of the sulphide between boreholes 1 and 3 represents original configuration due to variations in depositional geometry. Both the presence of a possible low angle thrust above the carbonate and the lensoid nature of the sulphide may explain the absence of the significant EM response that should be expected from the amount of sulphide encounted in the first borehole.

Ladywell.

One borehole was drilled in the Ladywell area to investigate the source of the antimony anomalies in soils and it was sited to the south of the anomalous zone on the assumption that the mineralisation was stratabound with a dip to the south. Lack of time prevented the drilling of a further hole in another direction to confirm the source of the anomalies and its structural setting. The log and chemical data are plotted graphically in Figure 58. The hole intersected volcanic rocks which were schistose and tuffaceous as in the other areas. These were generally green in colour with significant chlorite of the Fe-rich brunsvigite type, often in sheaves parallel to the cleavage trace, and bleached sericitic rocks were absent, though chlorite is often interleaved with stringers of siderite and calcite. Lenticular clasts up to 5 mm in length with relict volcanic textures occur in some zones with a matrix composed of albite, ankerite and occasional quartz, the albite laths imparting a herringbone texture to the rocks. Rutile is the main disseminated opaque mineral present, though traces of bornite, chalcopyrite and tetrahedrite were observed in one sample. Probe analyses show that, in contrast to the Higher Ludbrook rocks, the carbonate is Mn-free which also applies to the chlorite. Irregular to ovoid vesicles filled with carbonate occurred in some zones while brecciation was conspicuous in others. Small irregular veins of quartz and carbonate were common, some with small clusters of the problematical micaceous phase, but these did not contain any significant amount of sulphide. Below 80 m down the hole pale bleached material, similar in appearance to the volcanic rocks from the other two areas, was intersected. Chemically this rock differed from the greener volcanics in having less Na and Mg and more Al, Ca and K, and some sections contained disseminated pyrite. Some horizons of chloritic tuff occurred but they were subordinate to the bleached material in the lower part of the core. Compared with the volcanic rocks from the other holes, those from Ladywell contained more Na and Mg and less Al, K and Ba, though Ti and P levels, elements generally considered to be immobile in hydrothermal alteration, were broadly similar. Ore minerals appeared inconspicuous in most of the volcanic rocks and Sb levels were low compared with material from Higher Ludbrook. One red altered zone contained an elevated level of Sb (94 ppm) without associated Cu, and possible stibnite was identified in segregations in one section of core.
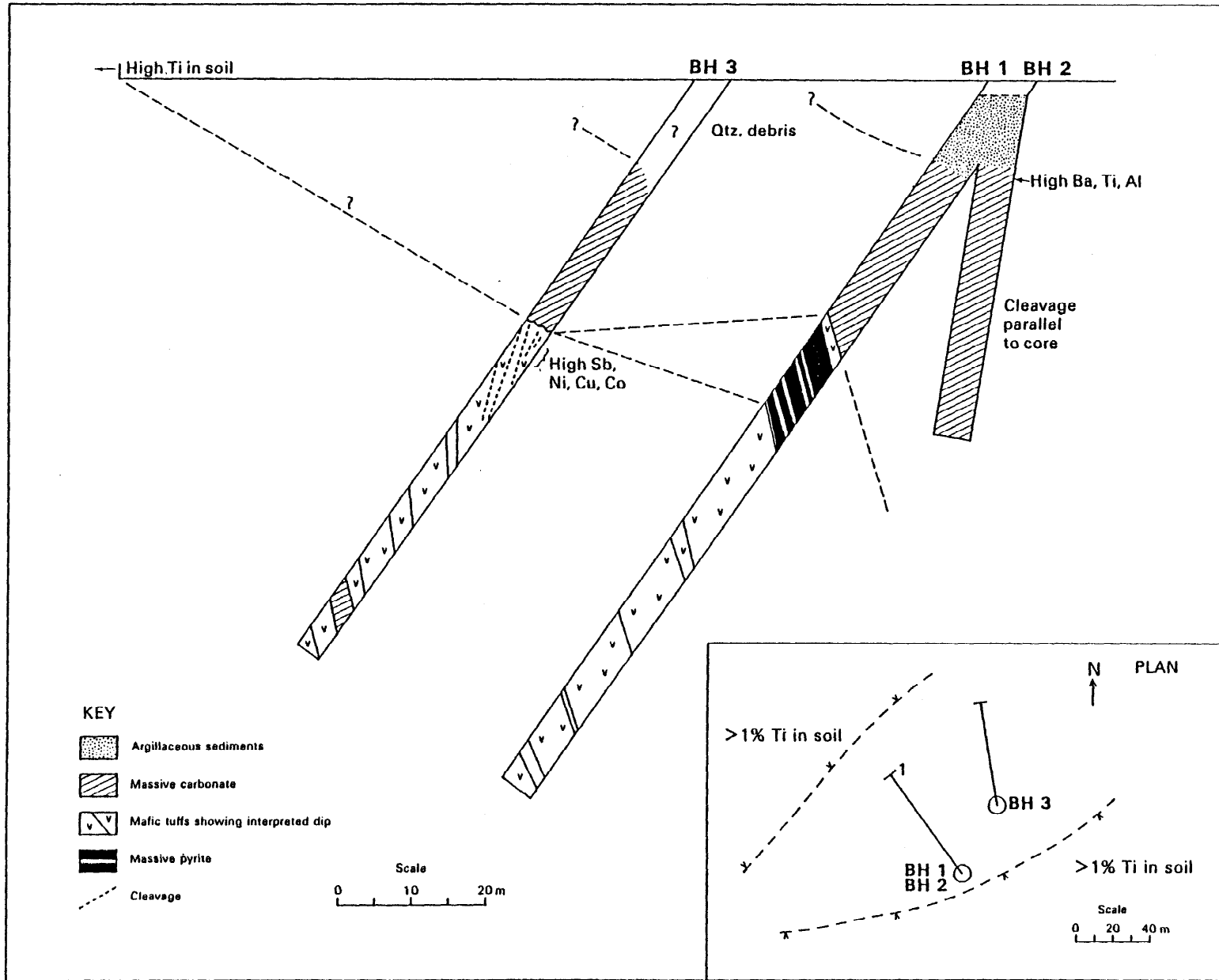
Figure 57 Structural interpretation of Higher Ludbrook boreholes. Borehole 3, although roughly along strike from borehole 1, is projected into the plane of boreholes 1 and 2.
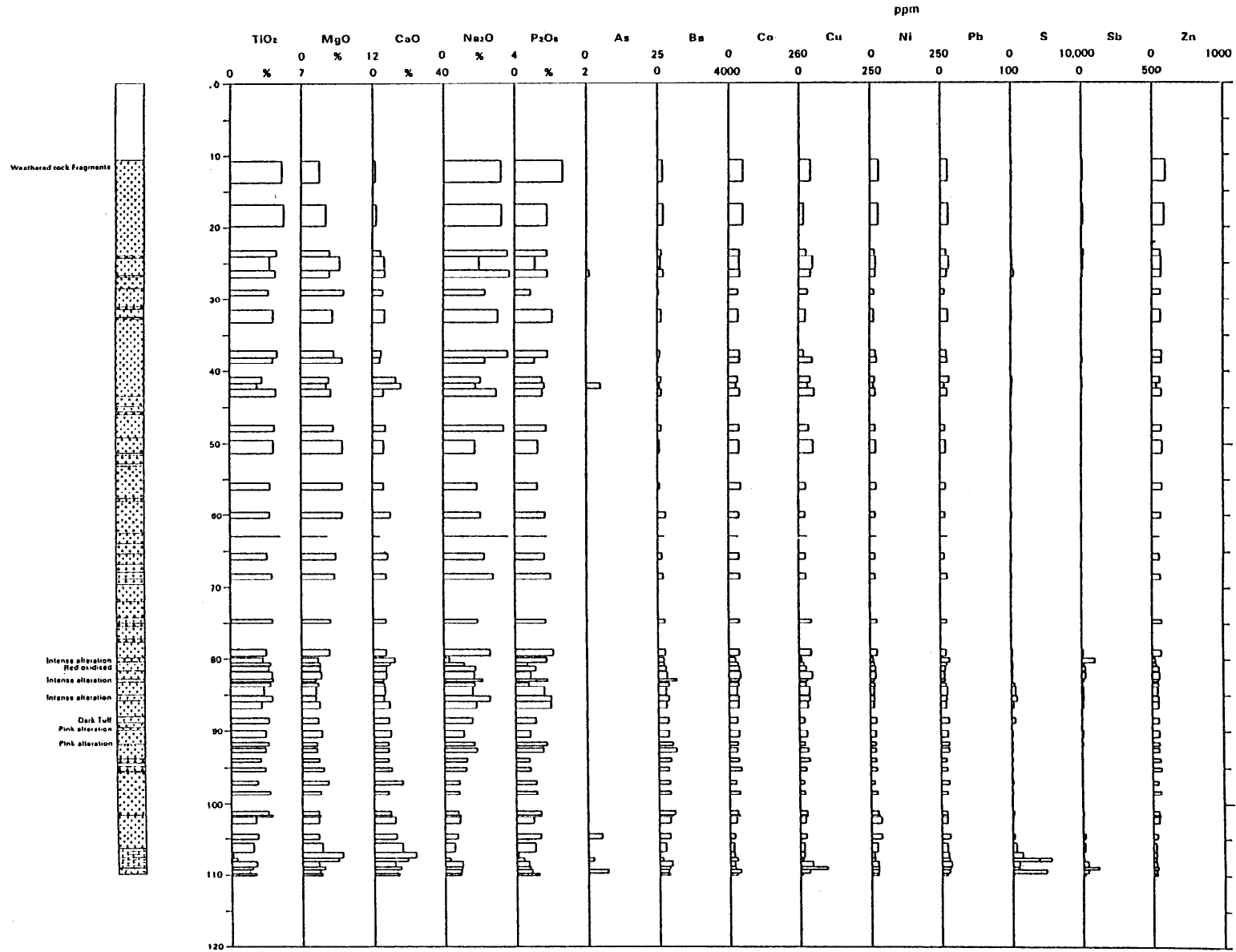
Figure 58 Graphic log of Ladywell borehole including chemical analyses.

At the base of the hole the volcanic rocks are more veined and brecciated and they grade into limestone which contains fossils of corals and other reef animals. Below this again is a bedded tuffaceous sediment containing included fragments of fossiliferous limestone. A thin horizon of black limestone is followed by further tuffaceous sediment, some of which shows fine bedding and slump structures, to the base of the hole. Ankerite, the problematical micaceous mineral, sericite, quartz and rutile were identified as the main minerals present in this tuffaceous rock. The rutile is concentrated in parallel stringers and associated with swarms of tiny pyrite grains. Some of the tuffaceous material below the limestone is highly brecciated and contains a minor amount of tetrahedrite in thin stringers, which accounts for the relatively high level of Cu and Sb in an analysed sample of this material. Fine pyrite is conspicuous in some of the layered tuff in the same section. A plane rich in possible stibnite was also present in a poorly recovered section of the tuff above the limestone.

A structural interpretation of the borehole is shown in Figure 59. This is necessarily speculative since it is based on only one hole and its core intersections. Nevertheless the transition from a massive volcanic sequence into limestone containing shallow water reef fossils strongly suggests that the sequence encounted in the borehole is overturned.

ROCK CHEMISTRY

A total of 20 elements were determined in 272 samples from the borehole cores by X.R.F. at Nottingham University. The data are summarised in cumulative frequency form in Figure 60. Some elements show similar distribution patterns in core and soil samples while for other elements there are significant differences between the two. Ti shows an upper population of similar shape in both sample types, which clearly represents the volcanic rocks. Ba distribution in both sample types shows an upper anomalous population with a similar gradient. The distributions of Fe, Ni, Sb and Cu are also quite similar in the two sample types. Ca distributions are different, probably due to the influence of the relatively large number of samples of carbonate rock in the core and also the tendency for Ca to be leached from surface material. The distinct upper population of Mn in the core is also a reflection of the carbonate samples. As distributions are also rather different, with generally higher levels in the soil samples, which suggests that the boreholes are not representative of the area as far as As is concerned. Similar criteria also apply to Pb. The small anomalous Zn population in soils is also not apparent in the core data.

Various element pairs in the analysed samples of the borehole cores are plotted in Figures 61 to 64. Figure 61 demonstrates the generally high levels of Ti and P in the volcanic rocks and also the significant positive corelation of Ti, P and Fe regardless of locality or degree of hydrothermal alteration suffered. Also shown is the significant negative correlation between K and both Mg and Na due to increasing intensity of sericitic alteration. The material from the upper section of the Ladywell borehole clearly shows the least alteration and the highest levels of Na and Mg. Figure 62 demonstrates a positive correlation between Mn and Co in the lower part of their ranges but shows higher levels of Mn to be confined to the carbonate and of Co to be largely confined to the massive pyrite. Separate trends in the sedimentary and volcanic rocks are apparent in the Ni-Co plot which also separates the distinct multielement mineralisation found in the Higher Ludbrook boreholes from the massive pyrite. This same separation is also apparent in the Co-S and Fe-Co plots in Figure 62.
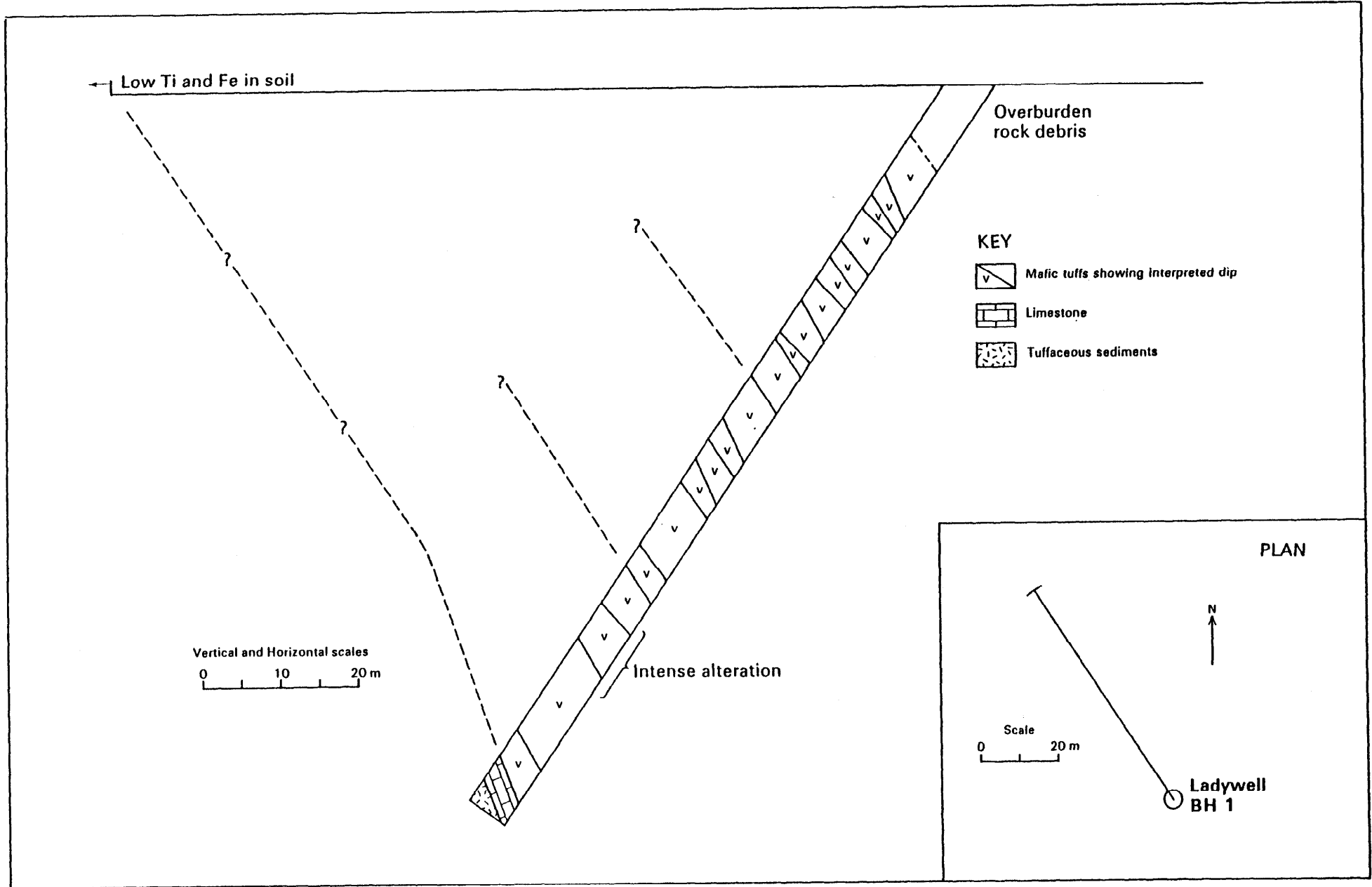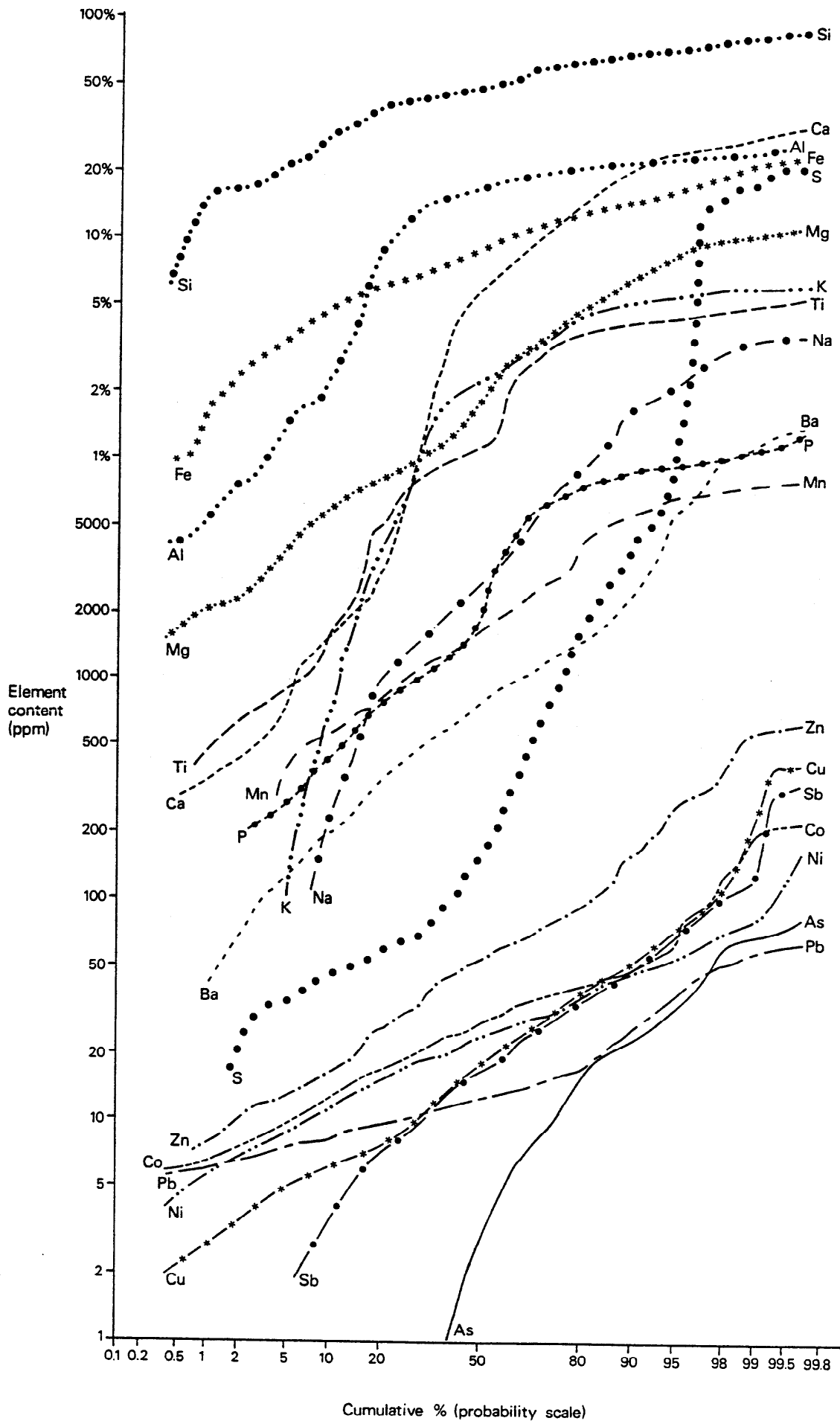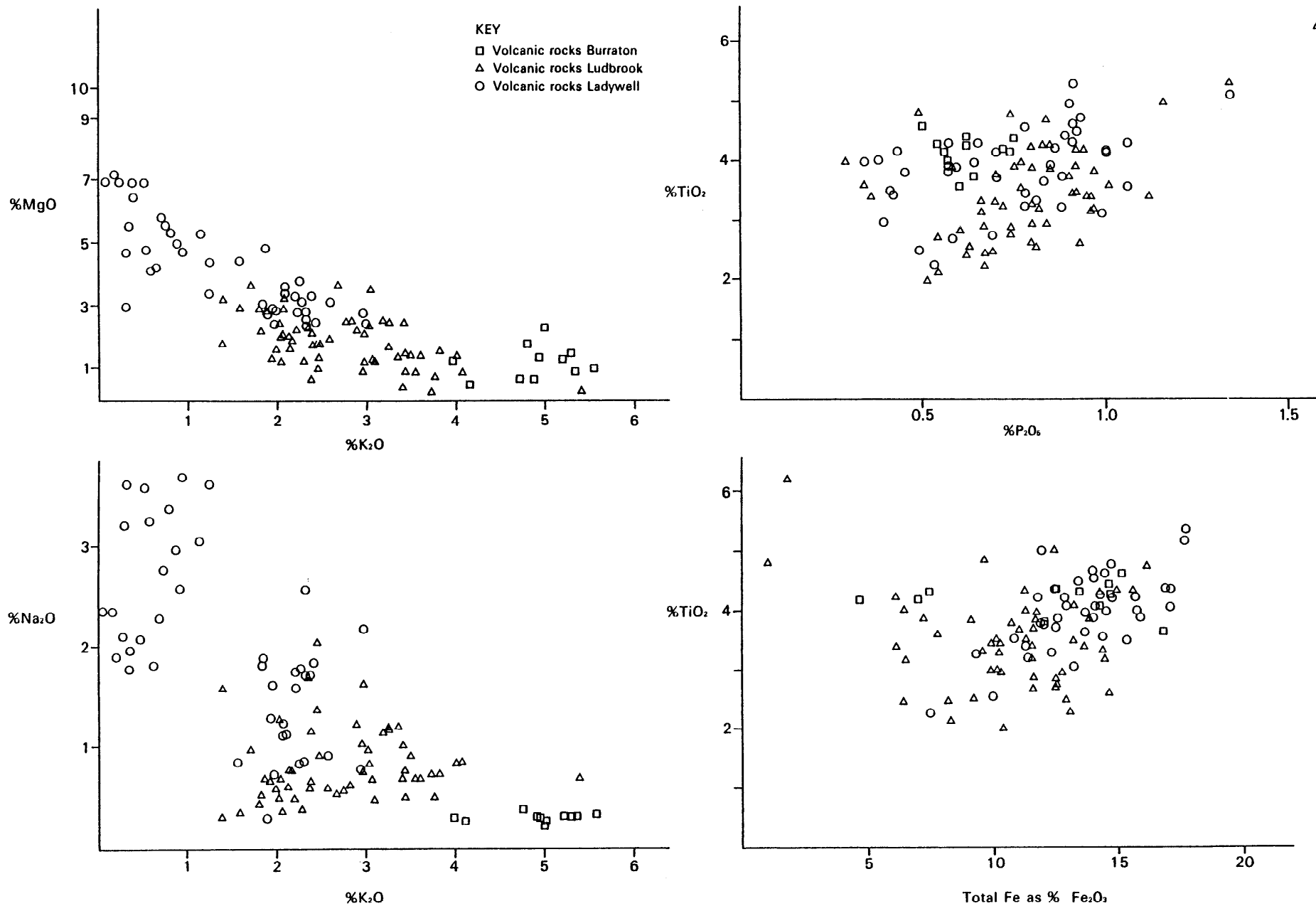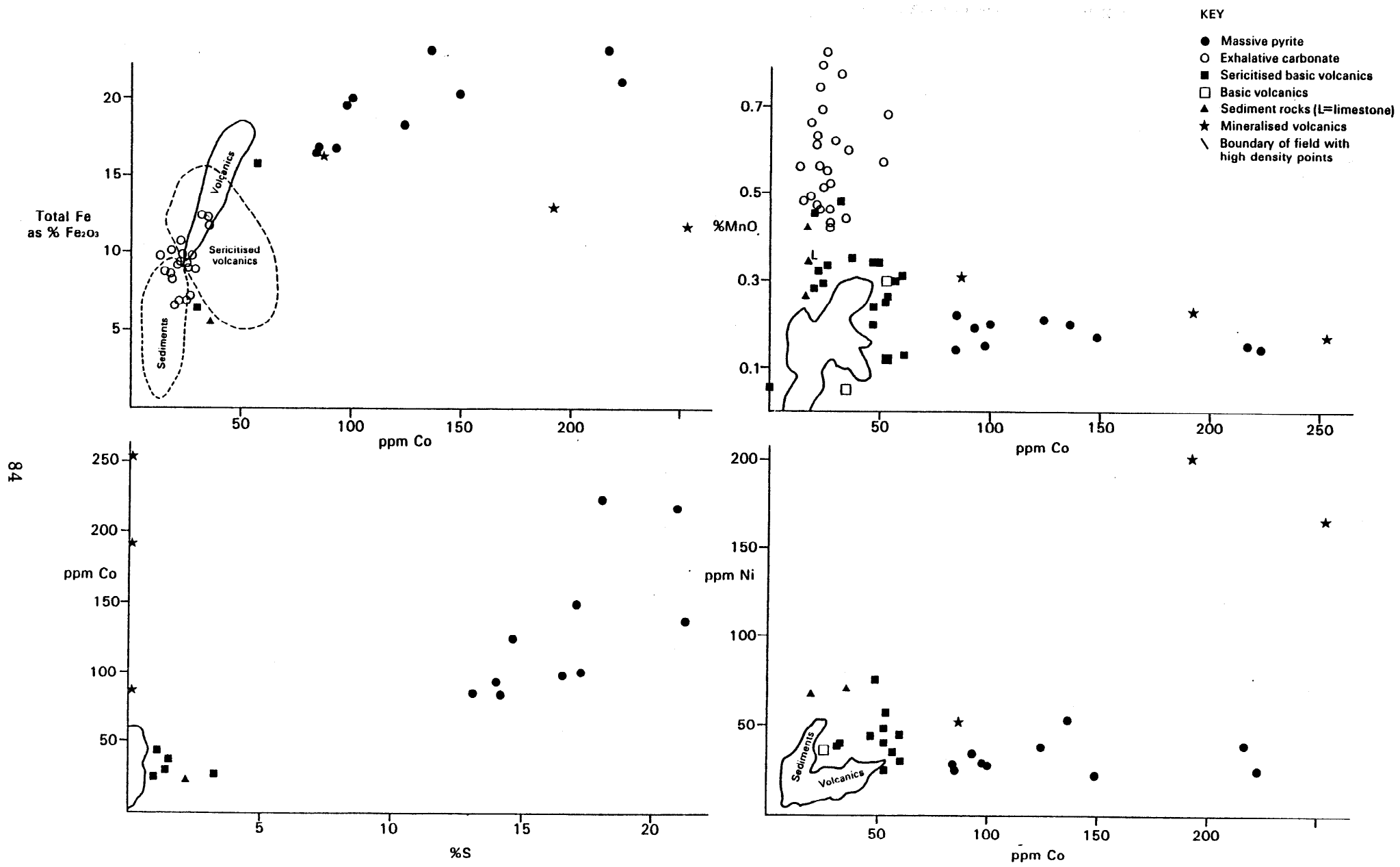
Figure 59 Structural interpretation of Ladywell borehole.

Figure 60 Cumulative frequency plot of Na, Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe, Co, Ni, Cu, Zn, As, Sb, Ba and Pb in borehole samples.

Figure 61 Relationship between the element pairs MgO-K$_2$O, Na$_2$O-K$_2$O, TiO$_2$-P$_2$O$_5$, TiO$_2$-Total Fe as Fe$_2$O$_3$ in borehole samples.
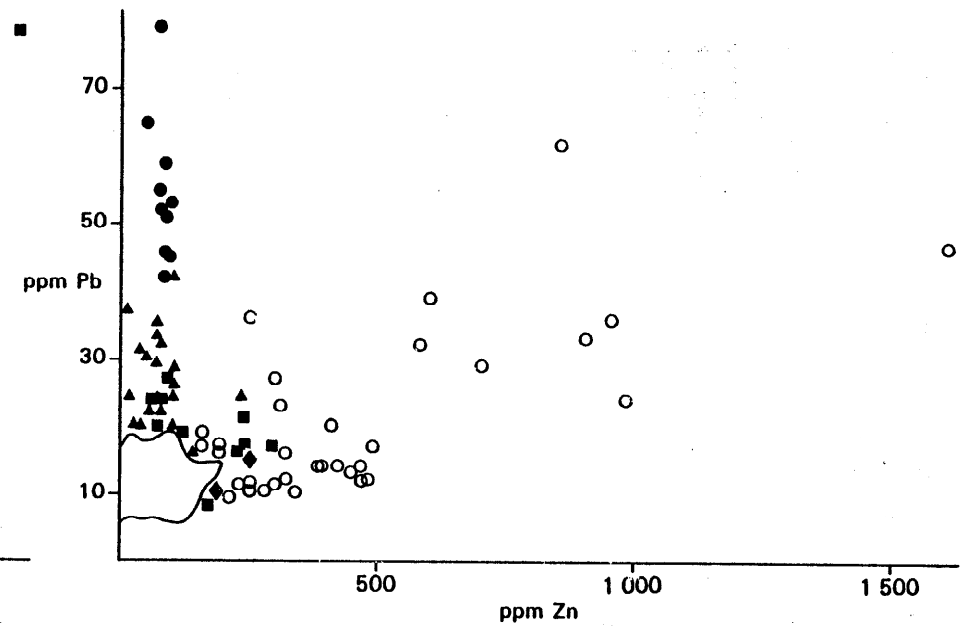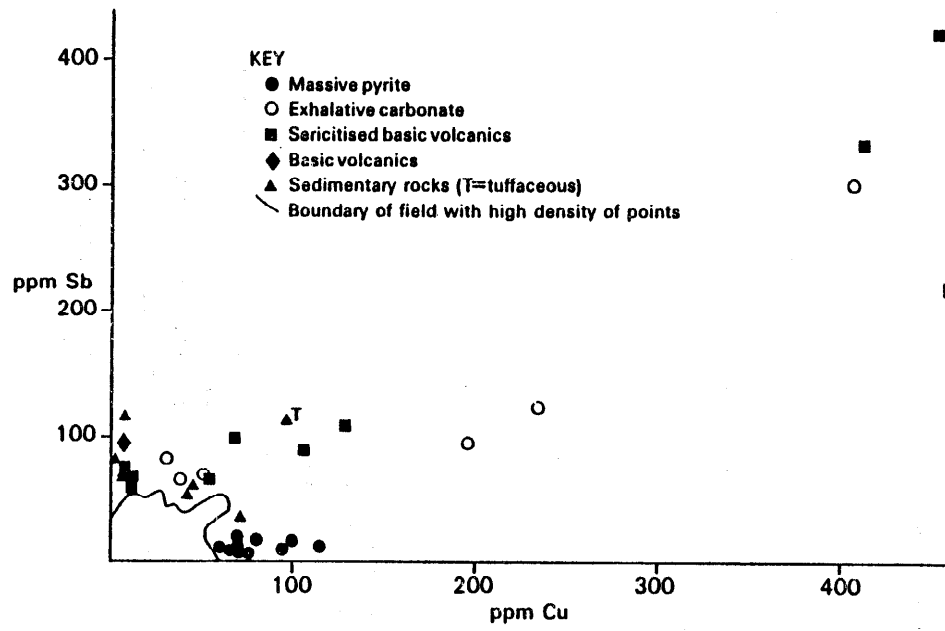
Figure 62 Relationship between the element pairs Total Fe as Fe_2O_3-Co, Co-S, MnO-Co and Ni-Co in borehole samples.
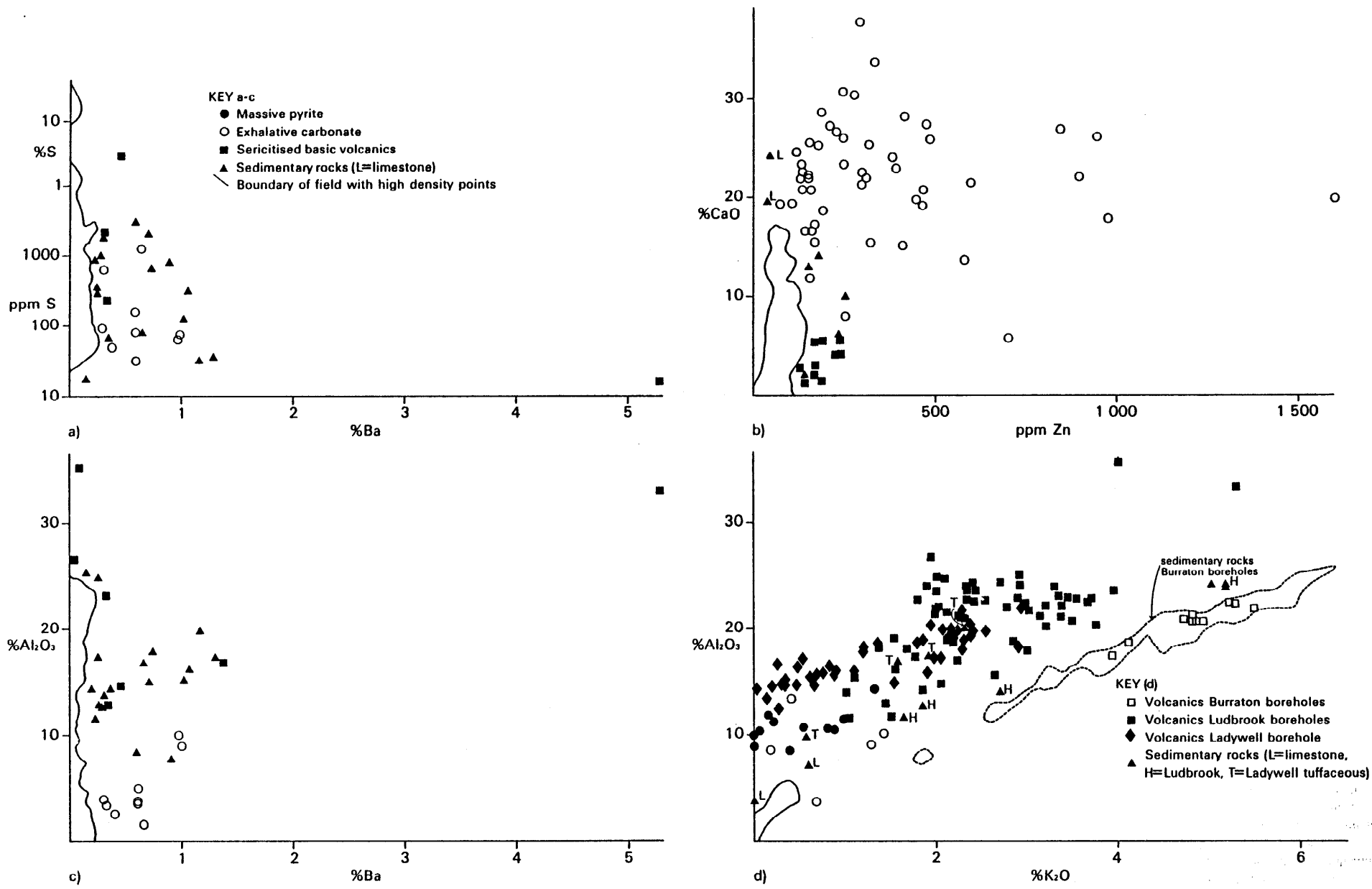
Figure 63 Relationship between the element pairs S-Ba, Al2O3-Ba, CaO-Zn and Al2O3-K2O in borehole samples.
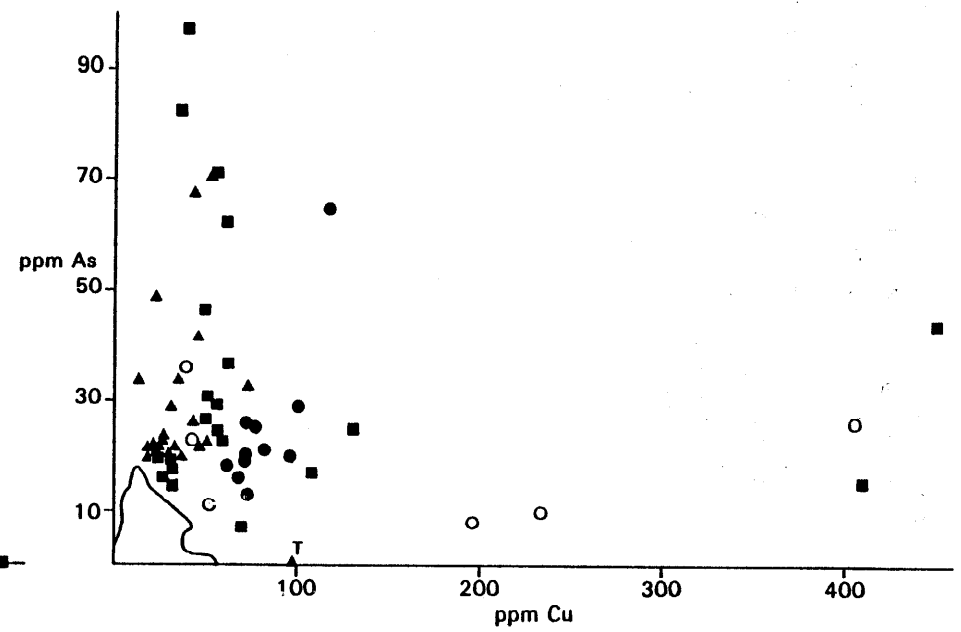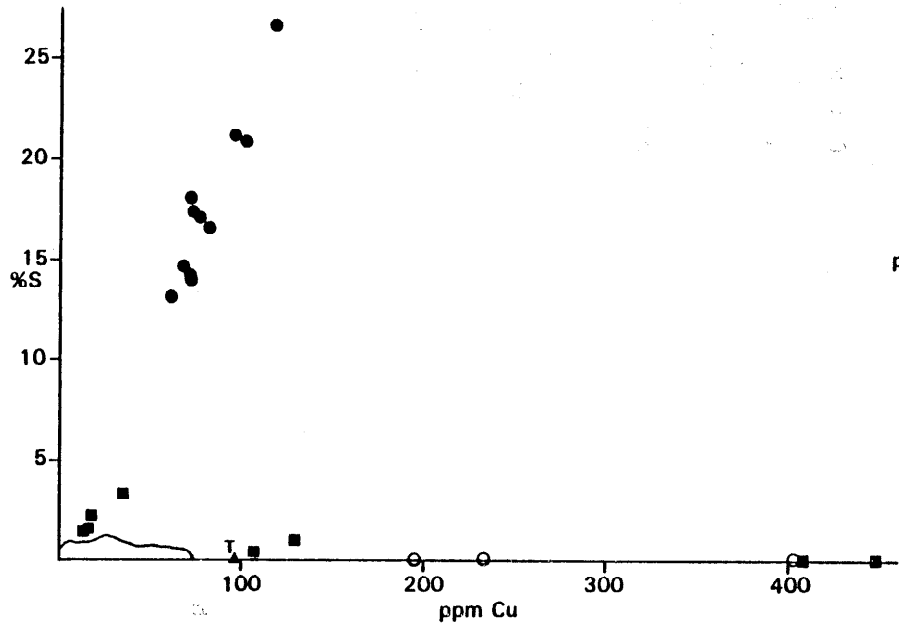
Figure 64   Relationship between the element pairs Sb-Cu, S-Cu, Pb-Zn and As-Cu in borehole samples.

The latter plot also demonstrates the tendency for Fe levels in the altered volcanics to be depleted relative to the fresher volcanics and the much higher levels in the massive sulphide compared with the carbonate.

Figure 63 demonstrates that in most cases Ba enrichment is not accompanied by corresponding enrichment in S. Only in a few cases, most of which are from a small section of the Burraton borehole 3, are levels of Ba and S consistent with the presence of baryte. Ba in fact shows a positive correlation with Al and K (Figure 63), which suggests that all three elements occur largely in sericite or perhaps even feldspar, as is the case around the Aberfeldy stratiform baryte deposit (Fortey and Beddoe-Stephens, 1982). The Ca-Zn plot in the same figure demonstrates the association of elevated Zn levels with the massive carbonate but shows an absence of any direct correlation between the two elements.

Figure 64 indicates that some positive correlation between Zn and Pb levels occurs, particularly in the carbonate, but is absent in many of the sedimentary rocks and the massive pyrite which are both relatively depleted in Zn. A plot of Cu against S in the same figure shows that within the massive pyrite there is a good positive corelation between the two elements. The same diagram also demonstrates the presence of sulphur-poor Cu mineralisation in both the altered volcanics and the massive carbonate. In these samples there is a close correlation between Cu and Sb but not with As. A slight degree of positive correlation may exist between Cu and As in the massive pyrite but there is none between Cu and Sb in this material.

INTERPRETATION OF THE MINERALISATION

The exhalative mineralisation.

The mineralisation intersected in the Higher Ludbrook boreholes is clearly of exhalative origin. The amount of ankerite rock in the area is substantial, with a probable thickness of up to at least 25m and a strike length possibly of hundreds of metres. The relationship of the massive pyrite to the carbonate is, on available evidence, uncertain. It could either be of minor importance and confined to a local centre of exhalation or alternatively it may be more extensive elsewhere as a larger exhalative centre is approached. The presence of irregular lenses of highly altered volcanic material within the carbonate rock and the absence of fine layering suggests that it was not deposited in a quiet basin and may have undergone some slumping. This may indicate that it was originally deposited in a positive structure which then suffered some slumping due to its instability as it grew. The geochemical soil data indicate that material similar to that at Higher Ludbrook may occur along strike to the ENE, either as part of a continuous zone or as separate lensoid bodies. This and the thickness of carbonate at Higher Ludbrook would suggest that a relatively large exhalative system was present.

The massive pyrite encounted in BH 1 is absent from borehole 3 and therefore probably lenses out between the two which are about 40m apart. The pyrite is mostly coarsely crystalline without evidence of layering which, together with the presence of some inclusions of volcanic material as in the case of the carbonate, would suggest that it cannot have been deposited in a stable third-order basin. Rather there may have been slumping away from source. On the other hand the presence of several thin pyrite layers beneath the main horizon in borehole 1 and the conspicuous disseminated pyrite suggests that its location is close to an exhalative centre, though the type of stockwork mineralisation that may be expected at such a site does not appear to be present. It is

therefore concluded that the Higher Ludbrook site is probably near to but not at an exhalative centre and the change from pyrite to carbonate deposition is due to a fall in temperature away from the emanative centre and possibly also the consumption of available reduced sulphur.

Though the massive pyrite does not appear to contain a significant amount of other sulphide minerals there is evidence, from chemical analyses of both it and the massive carbonate, of other elements in the ore solutions. A general elevation of Ba in the carbonate rock, and especially in the inclusions of volcanic material within the carbonate, suggests that barium-rich solutions passed through the exhalative deposits. In the inclusions the Ba is present probably as Ba-rich muscovite, formed by replacement of original volcanic constituents. The general absence of baryte in the Higher Ludbrook area suggests that sulphate was not available at the site to precipitate baryte and the barium was dispersed further away from the exhalative centre, perhaps to be precipitated in more distal basins. Alternatively the baryte, such as occurs at Burraton, may have originated from separate centres to that at Higher Ludbrook.

Zinc is also enriched in the carbonate rock but does not occur as sulphide. This suggests that zinc was present in the solutions that deposited the carbonate but that sphalerite was not deposited in any signicicant amount in the Higher Ludbrook area, possibly because of the absence of sulphur. It is not clear whether zinc levels in the ore solutions were generally low, which would make significant concentrations of sphalerite, even at favourable depositional sites, unlikely, or whether deposition of sphalerite occurred at a higher-temperature, more proximal site than the Higher Ludbrook locality. Similar criteria should also apply to copper though this element may also be expected to occur in stockwork zones within the volcanic rocks beneath exhalative centres. It is perhaps significant that at the Rammelsberg ore deposit, which is of broadly comparable age and occurs within a similar tectonic regime to the South Devon area, there are carbonate-rich beds which are generally similar in composition to the Higher Ludbrook carbonate and they also show enrichment in Ba and Zn. These carbonate-rich beds are present within the same general horizon as the ore deposit but further to the north-west of the main Rammelsberg orebodies. This suggests that ore fluids may have had similar compositions and evolutionary paths in the two areas.

The chemical data indicate that the volcanic rocks are highly altered in the Higher Ludbrook area to depths of at least 50m. Compared with the least altered material in the Ladywell borehole, the Higher Ludbrook volcanics are highly enriched in K and to a lesser extent in Al, Mn and Ba. They are also highly depleted in Na, Mg and to a lesser extent Fe. The type of alteration typical of hanging-walls of many massive sulphide deposits involves an enrichment of Mg rather than its depletion, though the associated rocks are usually relatively acid igneous rocks. Strong enrichment in K is often associated with the stockwork zone of Kuroko type deposits, while sericite is also enriched in the material above the ore. In some ophiolitic massive sulphide deposits Mg is depleted in stockwork zones where pyrite has formed at the expense of chlorite, and this is possibly the case at Higher Ludbrook. It is possible however that the more Mg-rich chloritic alteration of the volcanics could be present nearer the exhalative centre. If true, such a relationship could be useful in further exploration of the area.

In general there appears to be less Cu present in the volcanic rocks from the Higher Ludbrook area than in the Ladywell material, with average levels of 19 and 33ppm Cu respectively. Both these figures are relatively low for basaltic

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rocks and may give an indication of substantial leaching of the element in the altered volcanics. If this is the case it would suggest that redeposition of Cu in exhalative hydrothermal systems could have occurred.

Other mineralisation.

An association of Cu, Sb, Co, Ni, As and trace Hg in the form of tetrahedrite with associated chalcopyrite and cobalt/nickel minerals like carollite is widespread in minor amounts in the boreholes. Its occurrence in both volcanic rocks and the massive carbonate in the Higher Ludbrook area, sometimes in clearly discordant veinlets, indicates that it must postdate the exhalative mineralisation, but little else can be deduced about its origin or controls. Unfortunately too little of the stibnite mineralisation was recovered from the Ladywell borehole to establish its nature or to give a clear picture of the cause of the soil anomalies in the area. It is quite clear from both the boreholes and the soil results that the Devonian volcanic belt in the South Hams district is anomalously rich in Sb and possibly other associated elements over a wide area. In this respect it has clear parallels with the similar volcanic belt in the Wadebridge area with which there is also an association of Sb in the form of sulphosalt minerals and stibnite. Further work is required to establish the significance of this association and whether precious metals are associated with it.
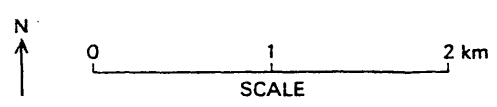
ACKNOWLEDGEMENTS

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FIGURE 1   LOCATION OF GEOCHEMICAL AND GEOPHYSICAL SURVEYS

LADYWELL

LUDBROOK

BURRATON
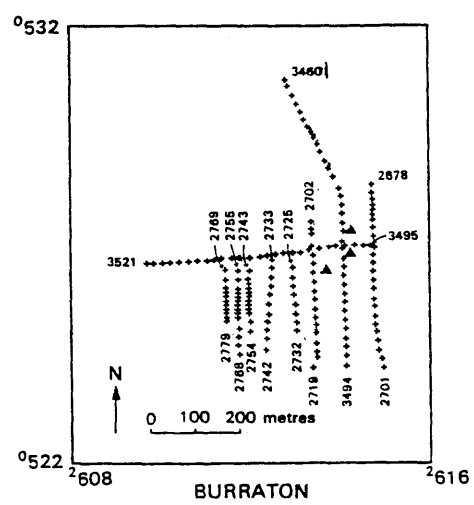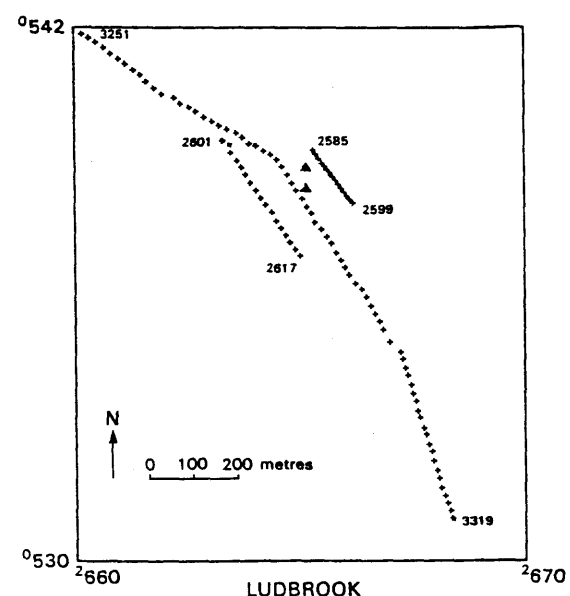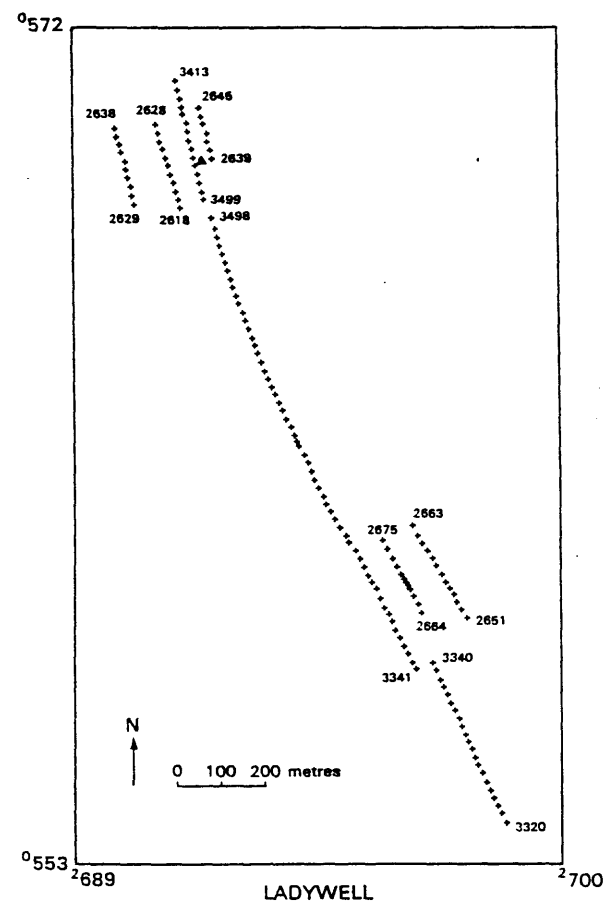
KEY TO MAIN MAP

5533 33 5501   SOIL TRAVERSE LINES
▲   BOREHOLE
A 385   ROAD
- - - -   RAILWAY
River Avon   RIVER
COTT   BUILT-UP AREA

KEY TO GEOCHEMICAL DIAGRAMS
•   Soil sample
▲   Borehole

SCALE

BUCKFASTLEIGH
STAVERTON
DARTINGTON
RATTERY
COTT
TOTNES
SOUTH BRENT
River Avon
HARBERTON
DIPTFORD
HARBERTONFORD
IVYBRIDGE
UGBOROUGH
LADYWELL
SEE INSETS
FURSDON
SEE INSETS
BURRATON
SEE INSETS
LUDBROOK
SEE INSETS
ERMINGTON
MODBURY

LUDBROOK GEOPHYSICS TRAVERSES

BURRATON GEOPHYSICS TRAVERSES

LADYWELL GEOPHYSICS TRAVERSES

FURSDON GEOPHYSICS TRAVERSES

LOCATION OF SURVEY AREA