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Mineral Reconnaissance Programme

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MRP Report 117
Technical Report WF/92/1

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BRITISH GEOLOGICAL SURVEY

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SUMMARY

Exploration for enrichments of vanadiferous magnetite and ilmenite was carried out within the Trelan gabbro, a recently discovered component of the eastern part of the Lizard ophiolitic complex in Cornwall. Work comprised ground magnetic surveys, weathered bedrock and overburden sampling by means of a Minuteman power auger, and the drilling of four cored boreholes. In addition, limited power augering was used to assess the potential for placer concentrations of Fe-Ti oxides and other heavy minerals within the Crousa gravels, an unconsolidated deposit overlying the highest part of the Lizard.

Drilling in the vicinity of high amplitude ground magnetic anomalies near Trelan proved the existence of extensive oxide-rich gabbro containing 10-15% combined ilmenite and magnetite. Ilmenite is the predominant oxide and only rarely is magnetite more than a minor constituent. The vanadium content of the magnetite is high, commonly between 2 and 3% and reaching up to 5% V_2O_3. Texturally the oxides occur in clusters and vein-like growths suggesting that some kind of filter pressing mechanism may have caused coalescence of oxide-rich liquid prior to crystallisation. The distribution of the oxide-rich gabbro in the boreholes suggests that this process occurred only on a local scale and that coalescence did not take place to such an extent as to produce a sufficient volume of Fe-rich liquid to produce economic concentrations of oxide.

A provisional revised geological map of the eastern part of the Lizard based on geochemical mapping of the overburden samples and showing the extent of the Trelan gabbro is included in the report.

Part of the Crousa gravel, here termed the Crousa gravel *sensu stricto*, is a channel deposit a few metres wide trending east-west and up to 9 m deep. At its base there is concentration of heavy minerals but these are of exotic origin and include cassiterite and tourmaline. The channel is cut through a mass of clay-rich material which caps the highest part of the Lizard. This is now interpreted as a glacial till containing large boulders of fresh gabbro derived from the coastal outcrop of the Crousa gabbro to the east. The till is thought to have been deposited as sea ice was pushed up against the coast during a relatively early glacial event which has left little trace of its presence in the rest of Britain, due to the effects of later glaciations.

The chemistry of limited power auger sampling from the north-eastern part of the complex suggests potential for exhalative mineralisation. Siliceous sediments with anomalously high concentrations of Ba occur in close association with mafic rocks of probable volcanic origin. However, the area is structurally complex with no continuity of rock units along strike and may possibly be a melange.

INTRODUCTION

Magnetite deposits are significant sources of vanadium and those within the Bushveld Layered Complex are the most important in world terms. Major amounts of vanadium are also obtained from mixed ilmenite and magnetite (or martite) ores associated with gabbroic and anorthositic rocks. Vanadium is also enriched in magnetite-rich veins within ophiolitic gabbroic rocks eg in the Oursi region of Upper Volta (Neybergh et al., 1980). A borehole drilled within the Traboe cumulate component (Leake and Styles, 1984) of the Lizard ophiolitic complex in Cornwall (Figure 1) intersected about 3.5 m of feldspathic amphibolitised gabbro containing layers with conspicuous magnetite. Electron microprobe analyses of this magnetite revealed a high concentration of vanadium (up to 3%V_2O_5).

Overburden sampling (Smith and Leake, 1984) and aeromagnetic data (Rollin, 1986) suggested that the region in the vicinity of Trelan in the east of the complex also had potential for significant concentrations of magnetite and ilmenite. Ground magnetic traverses between Trelan and the east coast at Coverack (Rollin, 1986) indicated a discontinuous zone of strong magnetic structure. Accordingly, the area to the south and east of Trelan was selected for a detailed overburden survey and the drilling of test boreholes.

A limited investigation of the Crousa gravels was also carried out to establish if they had any potential as a placer. This was considered to be of importance because of the very high concentrations of ilmenite in drainage sediment in the area, particularly within streams draining northwards from the Lizard complex towards the Helford River. In fact, the original name of the mineral, now known as ilmenite, was given as menachanite (McGregor, 1791) to an oxide of iron and the then new metal of titanium. The original name was chosen because of the extremely high concentration of the mineral in stream sediment near the village of Manaccan, just south of the Helford River.

Detailed overburden sampling was also carried out within the apparently volcanic sequence forming the Upper Landewednack schists to follow up a relatively high copper anomaly in the reconnaissance soil survey. Since rocks of sedimentary origin were known to be exposed in the vicinity, the possibility that the overburden anomaly may reflect volcanogenic stratiform sulphide was investigated.

GENERAL GEOLOGY OF THE LIZARD COMPLEX

Investigation of the geology of the Lizard complex has had a long history. A great deal of its interpretation, especially in terms of its plate tectonic setting, still remains controversial, but some variety of ophiolitic model is now generally accepted. The two most abundant rock types within the complex are partly serpentinised peridotite and gabbro, the distribution of which, according to the mapping of Flett carried out prior to 1912, are shown in Figure 1. To the south, and probably lying structurally beneath the peridotite, are the Lower Landewednack schists. These are interbedded with metasediments of the Old Lizard Head Series at several places and are thought to be derived from metamorphosed basaltic volcanic rocks. North of the perdidotite are the Traboe hornblende schists, a sequence of metagabbros and associated pyroxenite and dunite thought to represent a

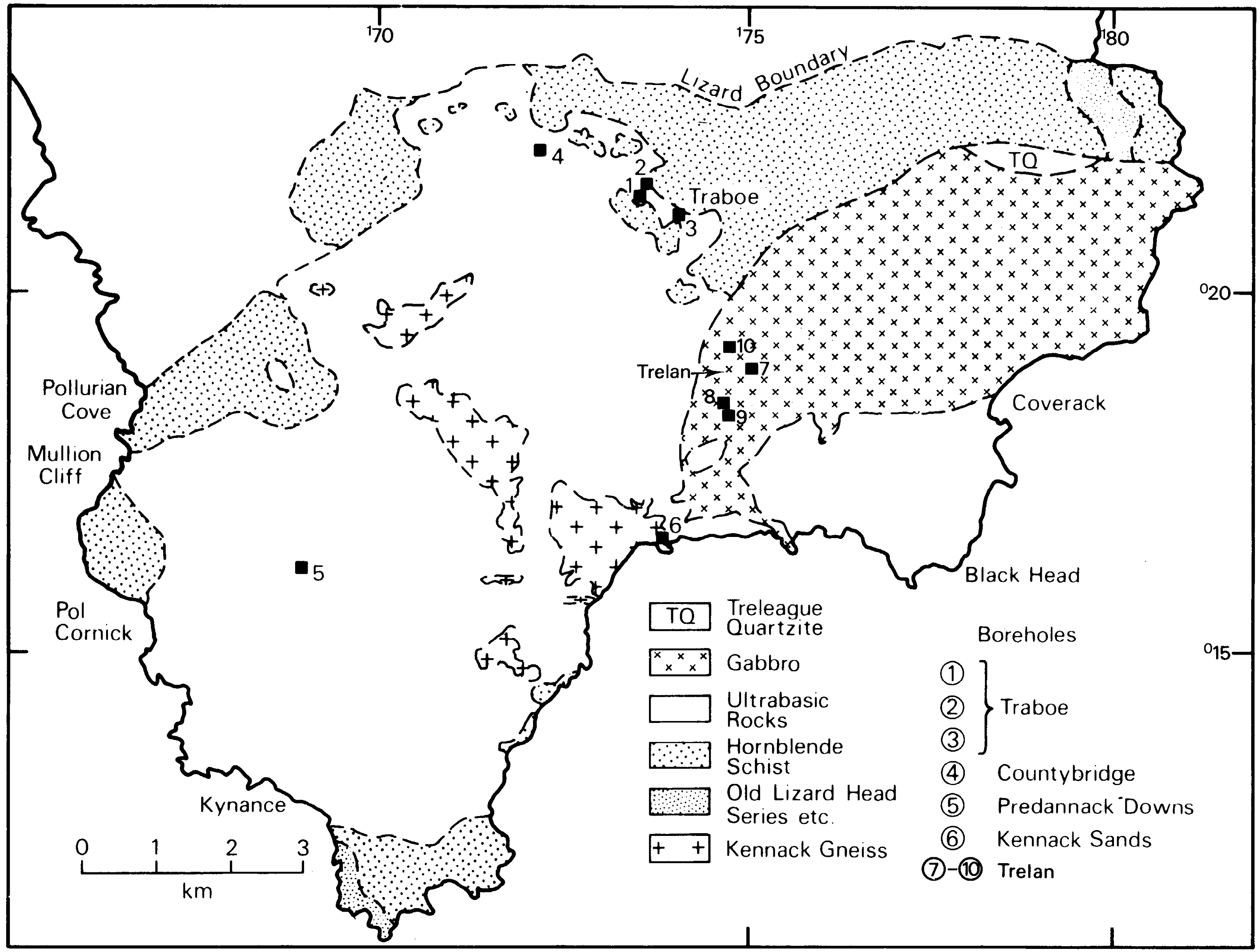


Figure 1 Simplified geological map of the Lizard after Flett (1946) with location of Traboe, Countybridge, Predannack Downs and Kennack Sands and Trelan boreholes.

metamorphosed cumulate complex (Leake and Styles, 1984) that structurally and stratigraphically overlies the mantle slab of the main peridotite.

To the north of the Crousa gabbro are a further series of metamorphosed basic rocks, known as the Upper Landewednack schists. This unit comprises a complex assemblage of metagabbros, probable metabasalts and in places metasediments, some of which are possibly of exhalative origin. The main Crousa gabbro differs from these mafic rocks in having largely an igneous texture. A further enigmatic group of rocks, the Kennack gneisses, occurs as segments interlayered with the lherzolitic peridotite in the central south-east of the complex. These rocks are now thought (Sandeman, 1988) to be composite intrusions of mixed acid and basic magmas of island arc affinities, intruded during the early phases of the emplacement of the Lizard complex into its present position. Mafic dykes are also widespread, cutting all rocks of the complex, but are particularly concentrated in a small section of the northern part of the coastal exposure of the Crousa gabbro.

The interrelationships between the various rock types, especially those to the north of the peridotite, is still uncertain. This is a direct consequence of the almost total lack of exposure inland from the coast. In the east of the complex, the Crousa gabbro overlies the largely harzburgitic peridotite, but further to the north-west this gabbro is absent and the Traboe cumulate complex overlies the ultramafic rocks. Attempts have been made to explain this in terms of a separate curved thrust sheet carrying the Crousa gabbro over the rest of the complex (Bromley, 1975) but evidence for the existence of this is not strong. The enhanced abundance of dykes in the north-east corner of the outcrop of the Crousa gabbro has been interpreted as representing the root of a sheeted dyke complex (Bromley, 1973).

The ophiolitic nature of the Lizard complex is now clearly established but whether it represents a remnant of a major oceanic basin to the south of Cornwall or oceanic crust within a small rift or even a leaky transcurrent fault remains unclear. The age of the complex is thought to be early or middle Devonian and its emplacement into its present crustal environment is considered to have taken place relatively quickly after this (Styles and Rundle, 1984; Davies, 1984).

A major problem besetting the interpretation of Lizard geology results from the lack of inland exposure. This has been compounded by the fact that the original geolgical mapping, carried out by Flett prior to 1912, was often based on the nature of boulders present in fields and protruding from the heath. It is now quite clear that the large gabbro boulders which are common around Trelan and further east and north-east are in no way related to the underlying geology. The original inland mapped boundary of the Crousa gabbro is therefore greatly in error. Attempts using geochemical overburden sampling (Smith and Leake, 1984; Shepherd, 1986) have been made to improve the mapping of the inland areas and this approach is further developed in this work.

Superficial geology

The superficial deposits of the Lizard, particularly the Crousa gravels, are very poorly understood. The widespread presence of loess, sometimes in the form of dunes, has been recognised for some time (Coombe and Frost, 1956). These deposits are most clearly recognised on the heath which has developed over the main body of peridotitic rocks, where they give rise to a distinctive soil type and associated vegetation. As a result of the MRP work the Crousa gravels *sensu stricto* are now seen as a channel deposit, several metres thick and a few tens of metres wide, running approximately east-west across the Lizard complex for at least 1 km to the west of St Keverne Beacon. Also present over a wider area around Crousa Common is kaolinite-rich material, at least 12 m thick in places, and now interpreted as a glacial till.

REGIONAL GEOPHYSICAL DATA

Bouguer gravity anomalies

Bouguer gravity anomalies on the Lizard have been interpreted using 2-D and 3-D models (Rollin, 1986) in terms of a lower tectonic sheet of hornblende schists and metasediments overlain by a mass of peridotite and gabbro. A residual anomaly maximum close to 12 mGals over the gabbro to the north of Coverack implies a body at least 1.5 km thick. From the gravity data the Landewednack hornblende schists at Lizard Point are expected to be at least 700 m thick.

Aeromagnetic anomalies

Analogue aeromagnetic data were collected over the onshore areas of the Lizard along flight lines 400 m apart and at a mean terrain clearance of 152 m (500 feet). Over the sea, data were obtained at a height of 305 m (1000 feet). These data have been digitised at BGS and interpreted with the gravity data in terms of integrated 2-D sections (Rollin, 1986). A strong aeromagnetic anomaly with a maximum over the peridotite to the south-west of Coverack appears to extend both offshore and to the north-west over the Traboe cumulate complex (Figure 2). There are also significant anomalies within the hornblende schists to the north-west of St Keverne. Some of the aeromagnetic anomalies have been investigated by ground magnetic traverses which are described below.

Airborne EM data

Coincident with the total field magnetic survey, a dual frequency EM system was flown. The results are available for inspection at BGS as fair-drawn contoured maps of the phase data at a scale of 1:25,000.

GROUND GEOPHYSICAL SURVEYS

A variety of ground geophysical surveys were carried out over the Lizard complex between 1976 and 1983 as part of the Mineral Reconnaissance Programme. The earliest surveys concentrated on the margins of the main body of ultrabasic rocks and explored for sulphide mineralisation using induced polarisation (IP) and electro-magnetic (EM) methods. The locations of the survey lines are shown in Figure 3 and the results of IP and EM traverses are available for inspection at BGS. The data show a variation in chargeability in ultrabasic rock by a factor of seven. Maximum chargeabilities occur within the Traboe cumulate complex and may be related to magnetite-rich horizons. Ground follow-up of airborne EM anomalies indentified in the 1957 dual-frequency out-of-phase results was carried out in 1978. The results of this work are also available for inspection at BGS. Most of the lines suffered from some form of cultural noise and no significant ground EM anomalies were defined.

Goonhilly-Traboe area

The orientation traverses had identified the Traboe cumulate complex as a zone of high magnetic relief and higher chargeabilities than elsewhere and so further ground surveys were carried out on traverses, the location of which are shown in Figure 4.

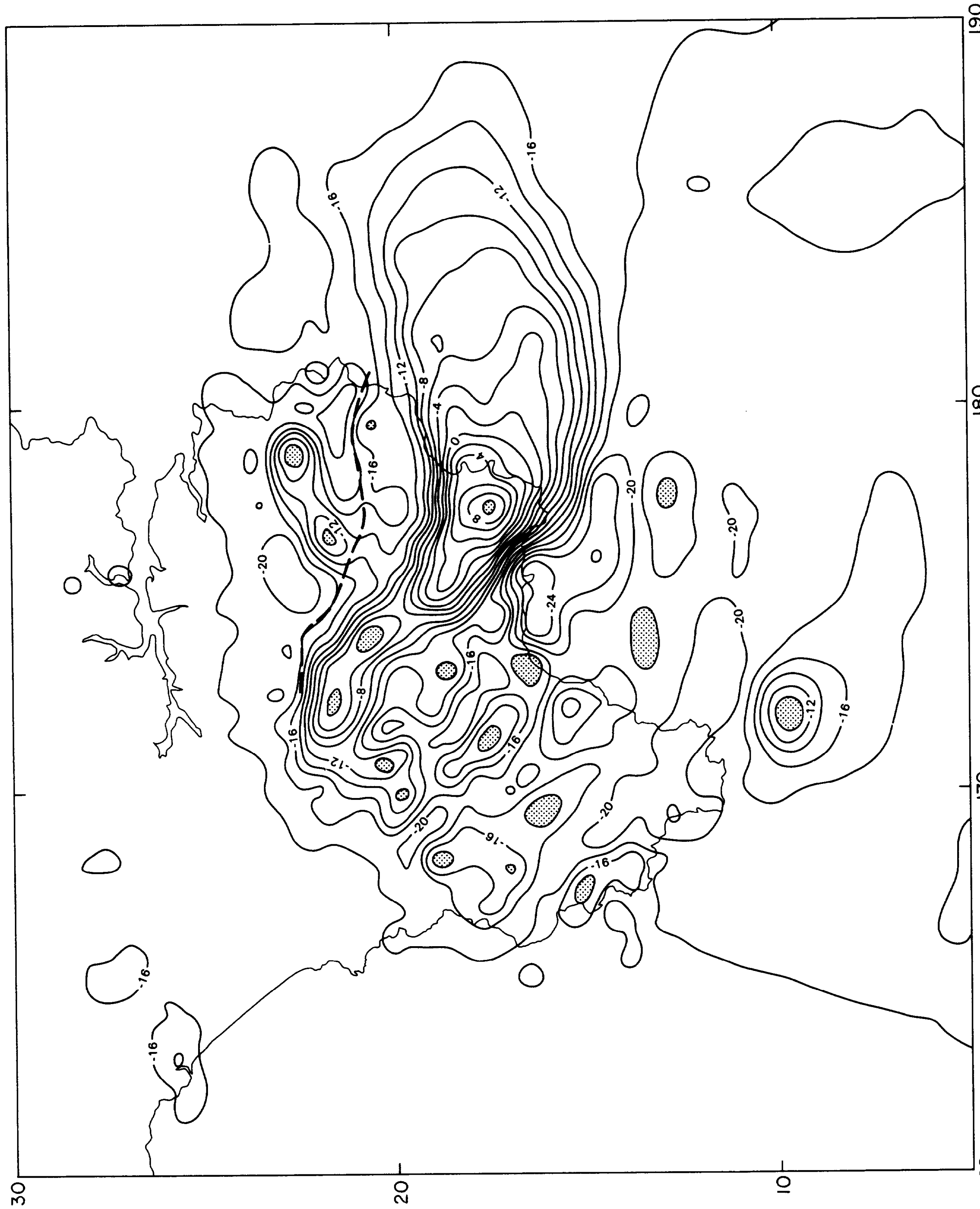


Figure 2 Aeromagnetic data over the Lizard and adjacent coastal waters. Contour values in units of 10 nT.

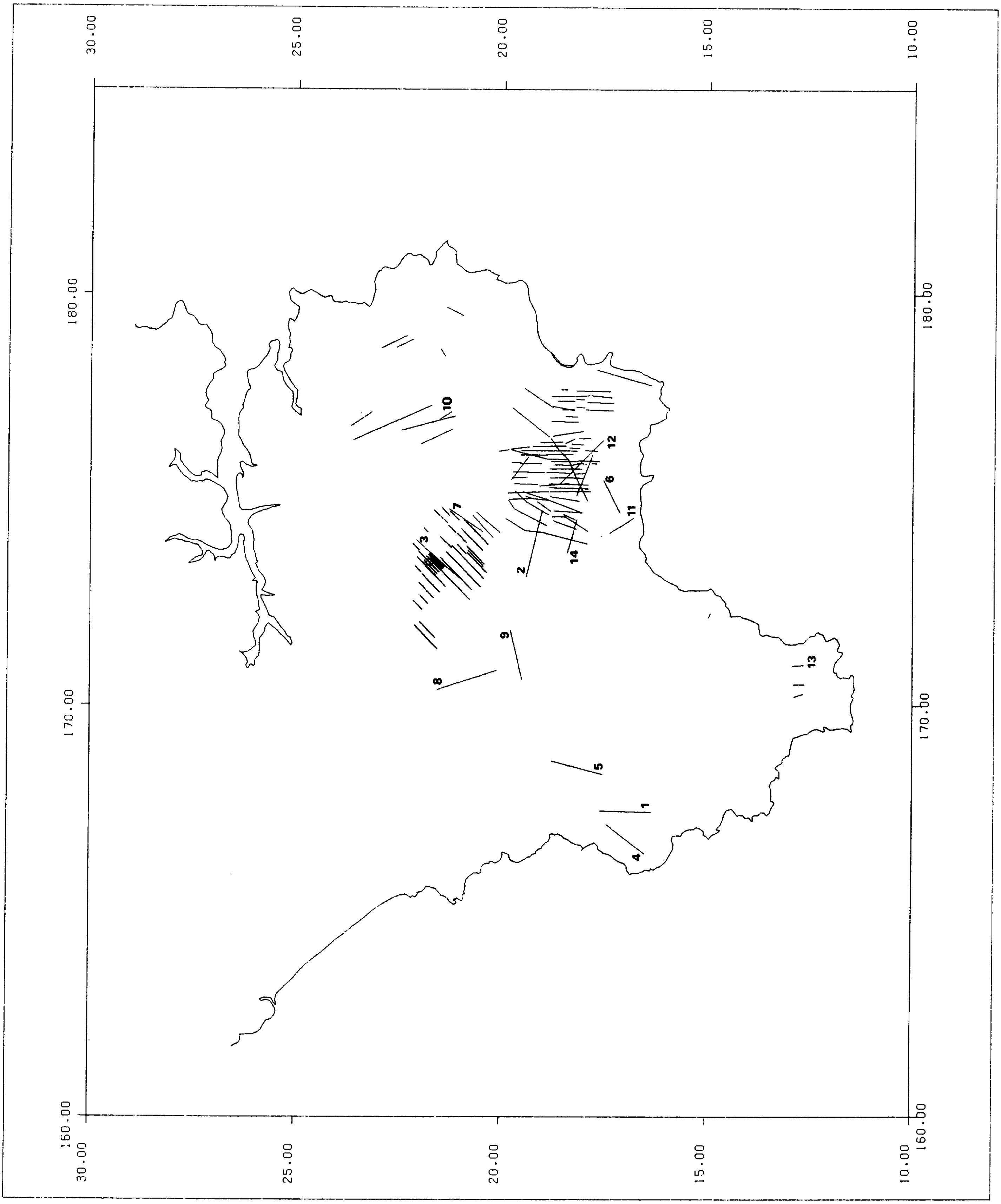


Figure 3 Location of ground geophysical survey lines Numbered lines (1-14) have dipole-dipole IP data; all other lines are for magnetic data only.

Magnetic data
Detailed ground magnetic surveys were made to try and map units within the Traboe Cumulate complex. All observations of the total field were made with a proton precession magnetometer and related to a local field base [17366 02058] near to the Goonhilly crossroads. Since the magnitude of the local anomalies of interest was of the order of 10^3 nT, corrections for diurnal change were not made.

The ground magnetic profiles (Figure 4) indicate a series of discontinuous high frequency anomalies, often difficult to trace across adjacent lines. Amplitudes commonly exceed 500 nT and occasionally exceed 1000 nT. Volume susceptibilities within the serpentinised peridotite and overlying Traboe Cumulate complex vary from less than 10^{-4} SI to over 10^{-1} SI.

A detailed grid of magnetic and IP observations was made at intervals of 10 m along lines spaced 60 m apart across the large magnetic anomaly near the centre of figure 4. The magnetic results (Figure 5a) show a complicated structure with local anomalies in excess of 2000 nT with a general north to north-west trend. With the exception of point 75N-120E all apparent resistivity maxima coincide with magnetic anomalies, though the converse is not true (Figures 5a and 5b). The data suggest, in general, that magnetite-rich rocks within the Traboe Cumulate complex could be traced across Goonhilly Downs but it would require a line spacing of around 50 m.

Induced polarisation data
Detailed magnetic and VLF traverses were supplemented by an IP profile, and a large magnetic anomaly was examined using IP with a gradient array configuration. Along line 350E, a constant separation dipole-dipole configuration was used to examine the relationships between IP, VLF and magnetic anomalies (Figure 6). In general, chargeability increases with resistivity within the Traboe Cumulate complex, as is typical for UK ultramafic rocks. Apparent resistivity maxima also approximately coincide with peaks in the total field magnetic anomaly profile. Magnetite would appear to be the main cause of the IP anomalies in the area. The detailed IP observations made across the large magnetic anomaly northwest of Traboe boreholes 1 and 3 (Figure 5b and 5c) partly support this. The apparent resistivity results show two maxima which can be traced across the grid trending roughly north-west. Chargeability patterns are somewhat different, with a maximum, above 30 msecs, close to the centre of the grid (Figure 5c).

VLF data
VLF observations along some of the lines shown in Figure 3 were made using a Geonics EM16 instrument, tuned either to NAA Maine or FUO Bordeaux. Despite interference from service installations close to the road, several VLF anomalies in the area north of the road can be related to geological conductivity structure. The manually filtered VLF profiles are available for inspection at BGS.

Trelan and Crousa Downs areas

Aeromagnetic data indicate a large anomaly extending from south-west of Coverack to north of Trelan and then westwards along the outcrop of the Traboe cumulate complex. The results of the ground magnetic traverses (Figure 7) in the area between Polcoverack and Trelan show a complex pattern of sharp anomalies in a zone trending roughly north-west to the north of Trelan and a smaller zone to the south of Trelan (Rollin, 1986). The magnitude and frequency of these anomalies are similar to those found over the Traboe cumulate complex, described above.

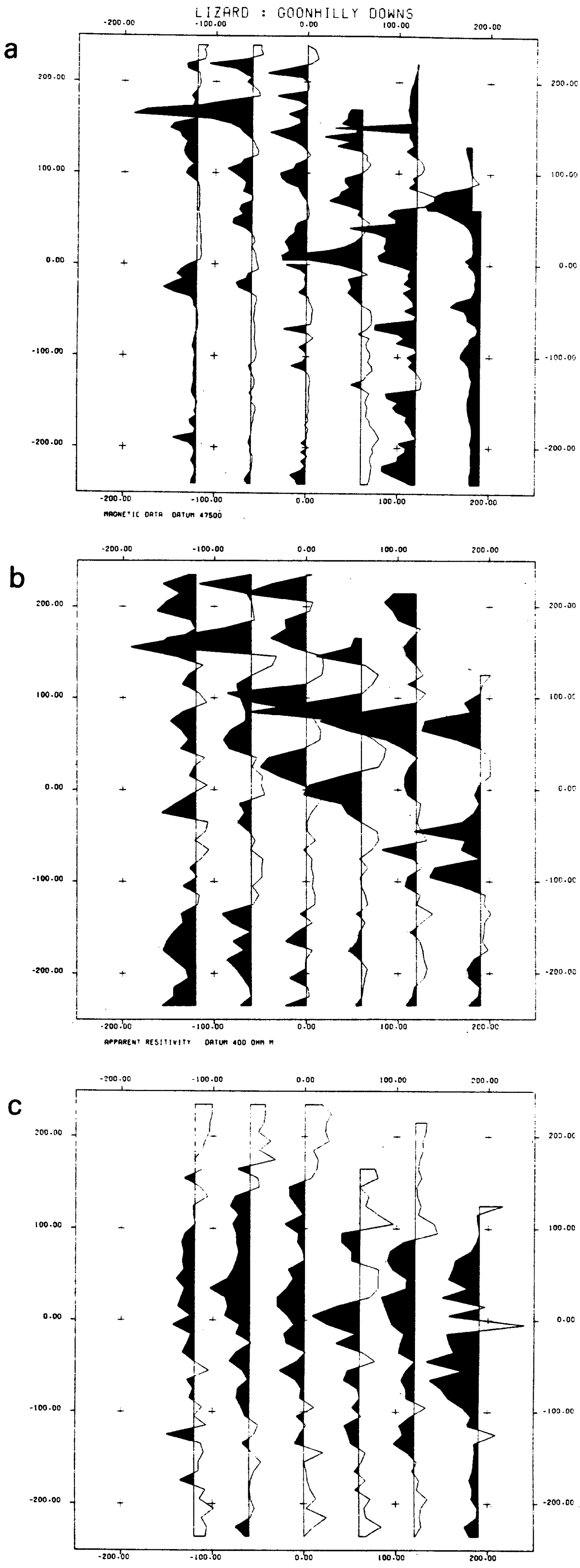


Figure 4 Ground magnetic profiles in the Goonhilly-Traboe area. The location of closely-spaced lines outlines the area of Figure 5 and the location of line 350E (Figure 6) is also given. Position of collars of Traboe boreholes also shown.

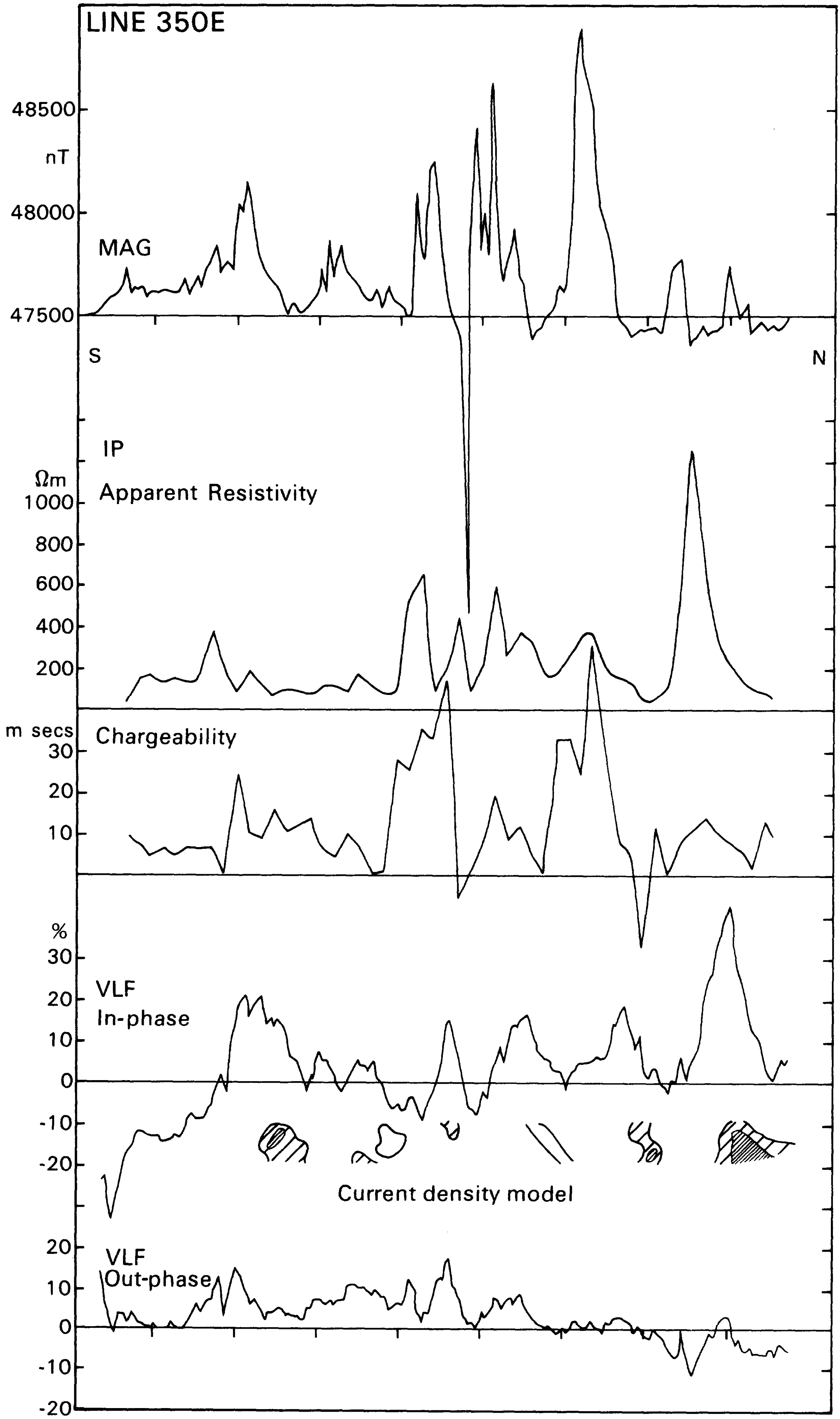


Figure 5 Detailed grid in the Goonhilly-Traboe area showing a) magnetic profiles b) apparent resistivity and c) chargeability.

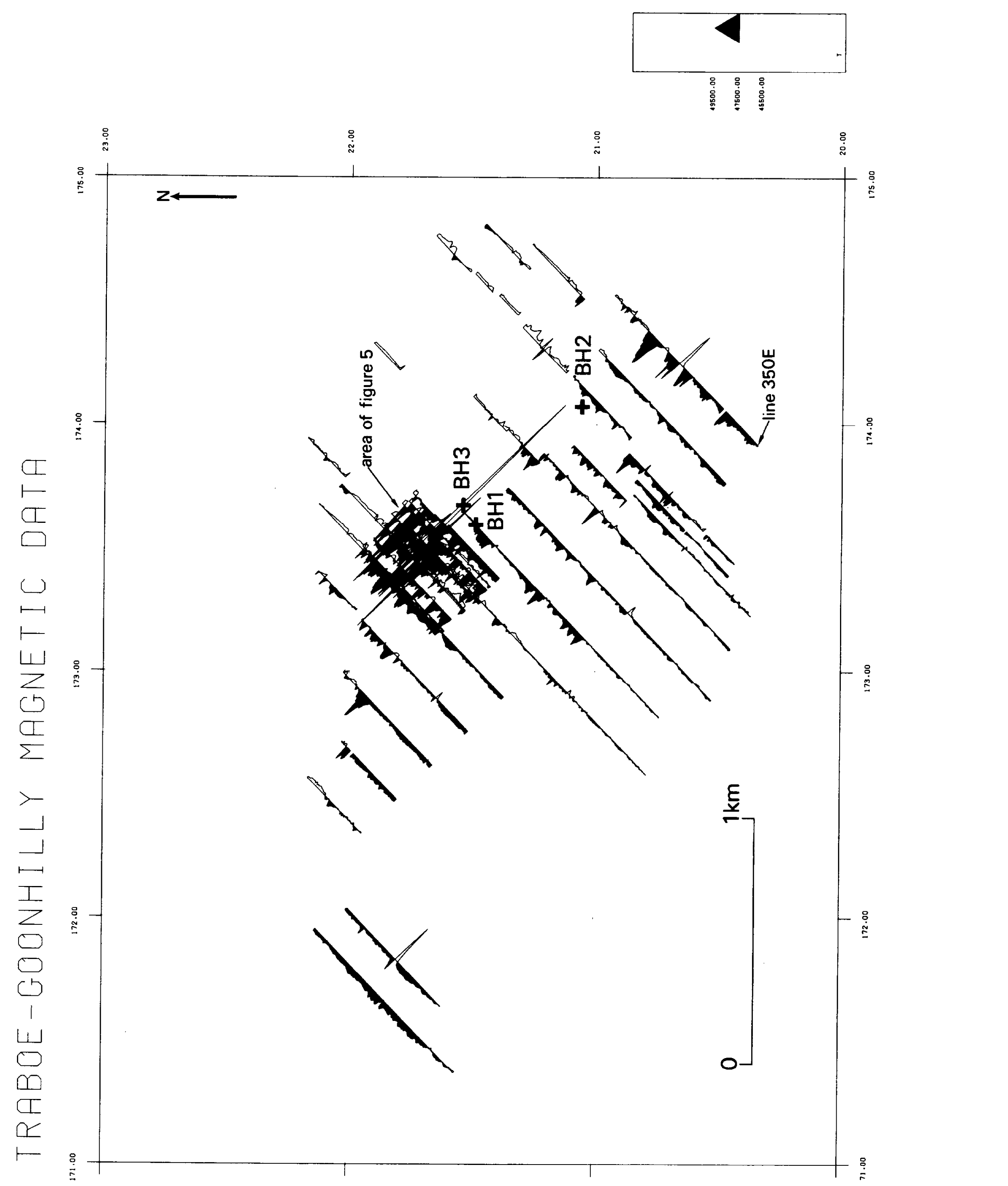


Figure 6 Comparison of magnetic, IP and VLF measurements along line 350E in the Goonhilly-Traboe grid.

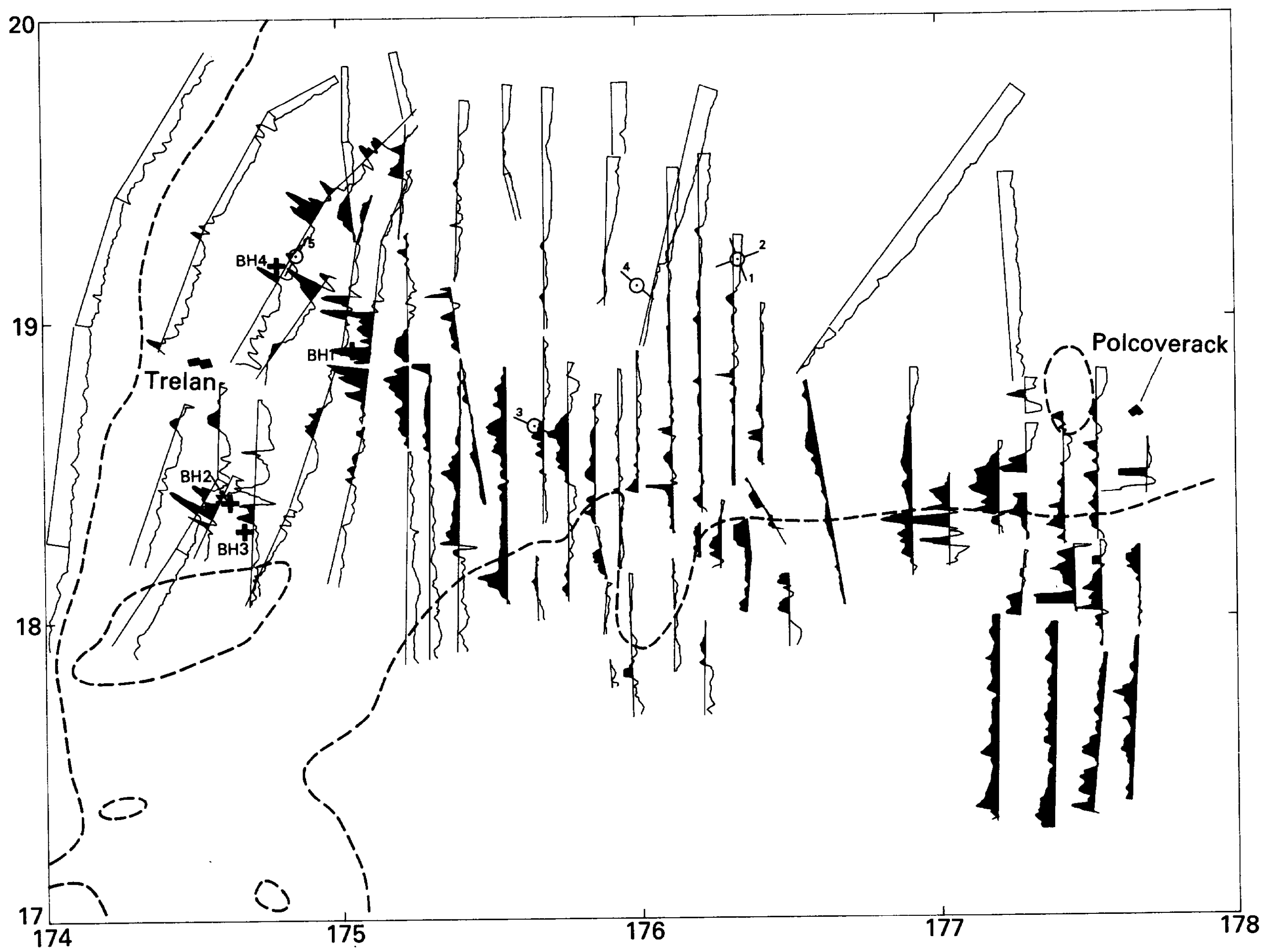


Figure 7 Ground magnetic traverses in the area between Polcoverack and Trelan superimposed on the contact of the Crousa gabbro (dashed line) according to Flett (1946). Areas shaded black have total field values greater than 47500 nT. Location of 5 Schlumberger IP-resistivity depth soundings and collars of 4 drill holes also shown.

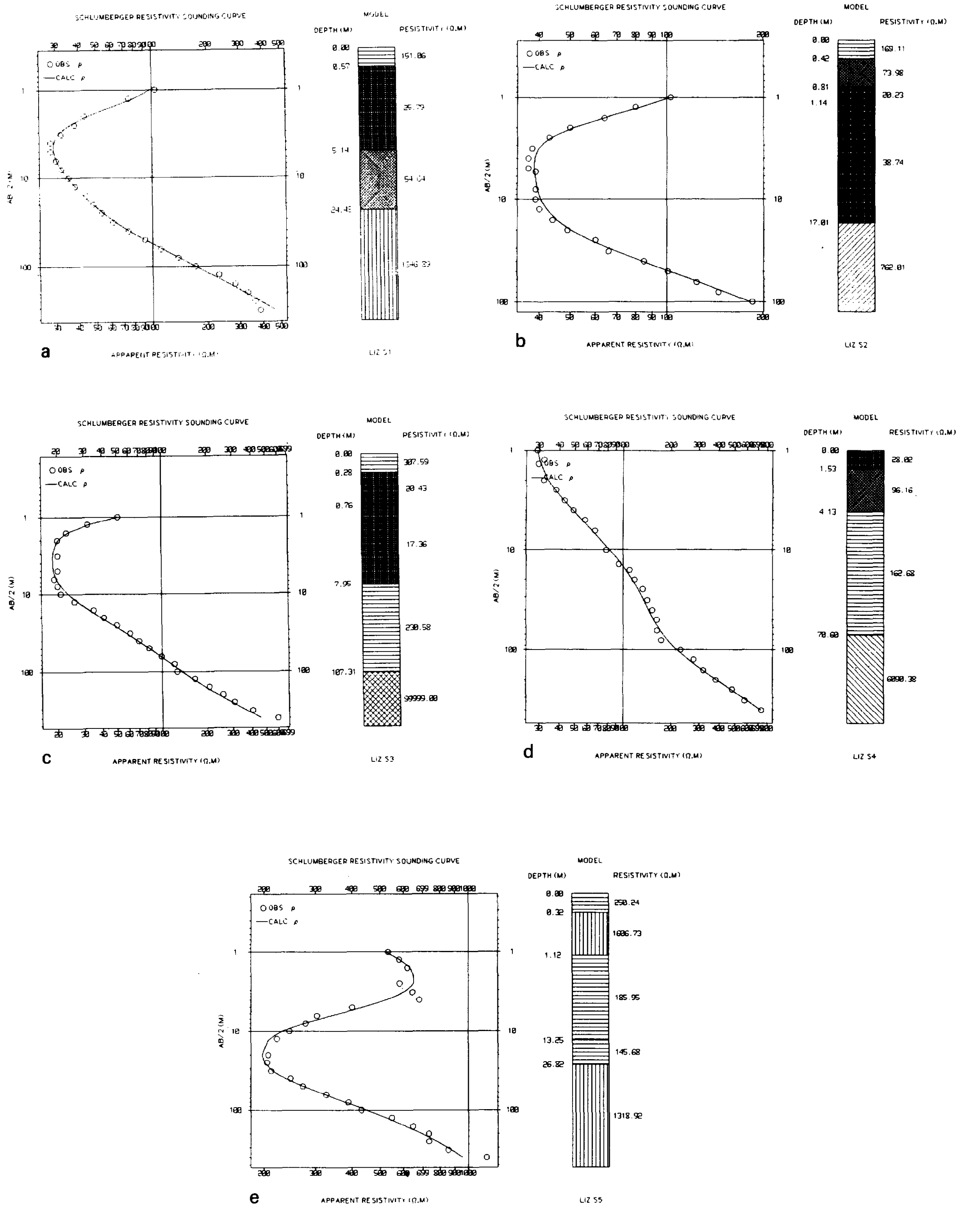


Figure 8 Schlumberger IP-resistivity depth soundings with model sections and curves. Locations as Figure 7.

Geochemical overburden sampling and drilling were planned to investigate these anomalies and in particular to see if they reflected concentrations of magnetite. Though some anomalies could be traced between adjacent lines, the general distribution pattern appears complex. Profiles north and west of Trelan indicate that this zone is not continuous with the magnetic anomalies associated with the Traboe Cumulate complex.

In addition, five IP-resistivity depth soundings were made at four sites, the locations of which are shown on Figure 7, to examine the conductivity structure in the area shown on Flett's geological map as Crousa gabbro. Soundings S1 and S2 were made at the same site and show a similar form. Interpretation of the apparent resistivity curves using an automatic inversion technique (AUTORES, Ogilvy and Lee, 1988) produce essentially similar sections (Figures 8a and 8b). A thin resistive surficial layer, less than one metre thick, overlies zones with a total thickness of about 20 m with resistivities in the 20 to 50 ohm metres range below which is resistive gabbro bedrock. The low resistivity layer is clay-rich and could either be an extension to the southwest of the kaolinite-rich superficial deposit found around the summit of Crousa Downs, the origin of which is described below, or soft, highly weathered gabbroic rock. The lower sections of soundings S3 and S4 (Figures 8c and 8d) have a similar shape and therefore interpretation, but in S4 the distinct uppermost layer is absent. The character of sounding S5 (Figure 8e) is significantly different and represents a resistive layer overlying a layer about 25 m thick with resistivity in the range 140 to 200 ohm metre. These patterns of resistivity variation may reflect interlayering of different rock types of the type seen in the boreholes described below. Chargeability measurements were also made for each sounding. The chargeability profile for sounding S4 suggests that the resistivity boundary, modelled at a depth of about 70 m, is also a major chargeability boundary.

GEOCHEMICAL EXPLORATION

Overburden sampling

A Minuteman power auger was utilised for the collection of overburden samples to provide sufficient depth of penetration in order to reach weathered bedrock and to get below superficial material of exotic origin. Samples were obtained from sites generally 20 m apart along a series of traverse lines, the locations of which are shown in Figures 11-15. The traverses were selected as far as possible, after allowing for ease of access, to cross some of the ground magnetic anomalies that had previously been detected. In the St Keverne Beacon area, the holes were more randomly sited because of access constraints. At all sites, material was taken from the base of the auger hole and also from a depth of one metre. In addition, at several sites (Figure 11) throughout the area samples were obtained at metre intervals down the profile. Profile sampling was carried out in most holes in the St Keverne Beacon area.

Sample preparation

All overburden samples were dried at 105° C and then dissagregated. Large rock fragments (>5 mm) and any vegetable matter were removed from the samples at this stage but no sieving was carried out. The entire sample was then ground in a Tema swing mill with chrome steel pot for up to 30 seconds. Orientation work (Shepherd, 1986) suggested that grinding granite chips for such a length of time produced an increase in Cr concentration between 10 and 15 ppm. After grinding about 10 gm subsamples of powder were pressed into pellets for analysis by Phillips PW1400 X-ray fluorescence spectrometer.

Chemical analysis

Chemical analyses were carried out by XRF at the Department of Geology at Nottingham University. The details of the method of analysis, calibration and standardisation are given in Shepherd (1986). Details of the results of the analysis of a number of international standards are also given (Shepherd, 1986). Data for the elements Mg, Al, Si, Ti, V, Cr, Fe, Ni, Cu, Zr and Ba are given in this report. Further elements determined in most of the overburden samples are given in Shepherd (1986).

Overburden profiles

Examples of chemical analyses of samples collected at metre intervals down auger holes, from all areas except around St Keverne Beacon, are shown in Figure 9. A number of features are clearly apparent in many examples. At several sites there is a marked enrichment in Zr in the 1 m sample compared with those from lower down the holes. This is considered to reflect admixture of the near surface soil with exotic loess which, according to Catt and Staines (1982), consists chiefly of quartz, alkali feldspar and white mica derived from glacial outwash deposits in the southern parts of the Irish Sea basin. A parallel enrichment in Ba can be accounted for in a similar way. Several sites show a distinct depletion in Mg in the near surface samples. Though this in part would reflect dilution with loess there are also some examples showing depletion of Mg without a corresponding enrichment in Zr, especially over ultramafic rocks. In these examples leaching of Mg in the surficial environment is suspected. In the profiles at sites BX 3002 and 3004 (Figure 9) there is clear evidence that much of the profile is weathered bedrock. The hole passes down from overburden dominantly of gabbroic composiiton into material clearly of ultramafic origin and then back into material of gabbroic composition. This corresponds to inclusions of ultramafic rock within gabbro of the type intersected in borehole 3 (see below).

Several of the profiled holes from the St Keverne Beacon area (examples of which are shown in Figure 10) also show the enrichment in Zr in the near surface samples, as described above. However, in many other respects they differ from those shown in Figure 9. Very conspicuous in some holes is a marked peak in Al concentrations between 2 and 5 m below surface. In addition, there is sometimes a marked break in the concentration of several elements down the hole, e.g. between 5 and 6 m in hole BX 3181 (Figure 11). The interpretation of these characteristics is discussed below.

Overburden data treatment

Maps showing the distribution of the single elements Ti, V, Cr, Fe and Cu in base of power auger hole samples are shown in Figures 11, 12, 13, 14 and 15 respectively. The results are plotted in class interval form, with classes generally derived from breaks in slope of the corresponding cumulative frequency plot. In addition, a cluster analysis procedure has been carried out so as to distinguish between different groups of samples in multicomponent space and to a produce a classification of samples that could be utilised in geochemical mapping. Prior to the use of cluster analysis, the data were standardised to give a mean of 0 and a standard deviation of 1 so as to remove the effects of varying arithmetical levels between the elements. The SAS Fastcluster procedure was adopted with a variation in the number of clusters generated at each run. The overburden samples have been classified in terms of 17 clusters. This number was chosen because it gave the most robust

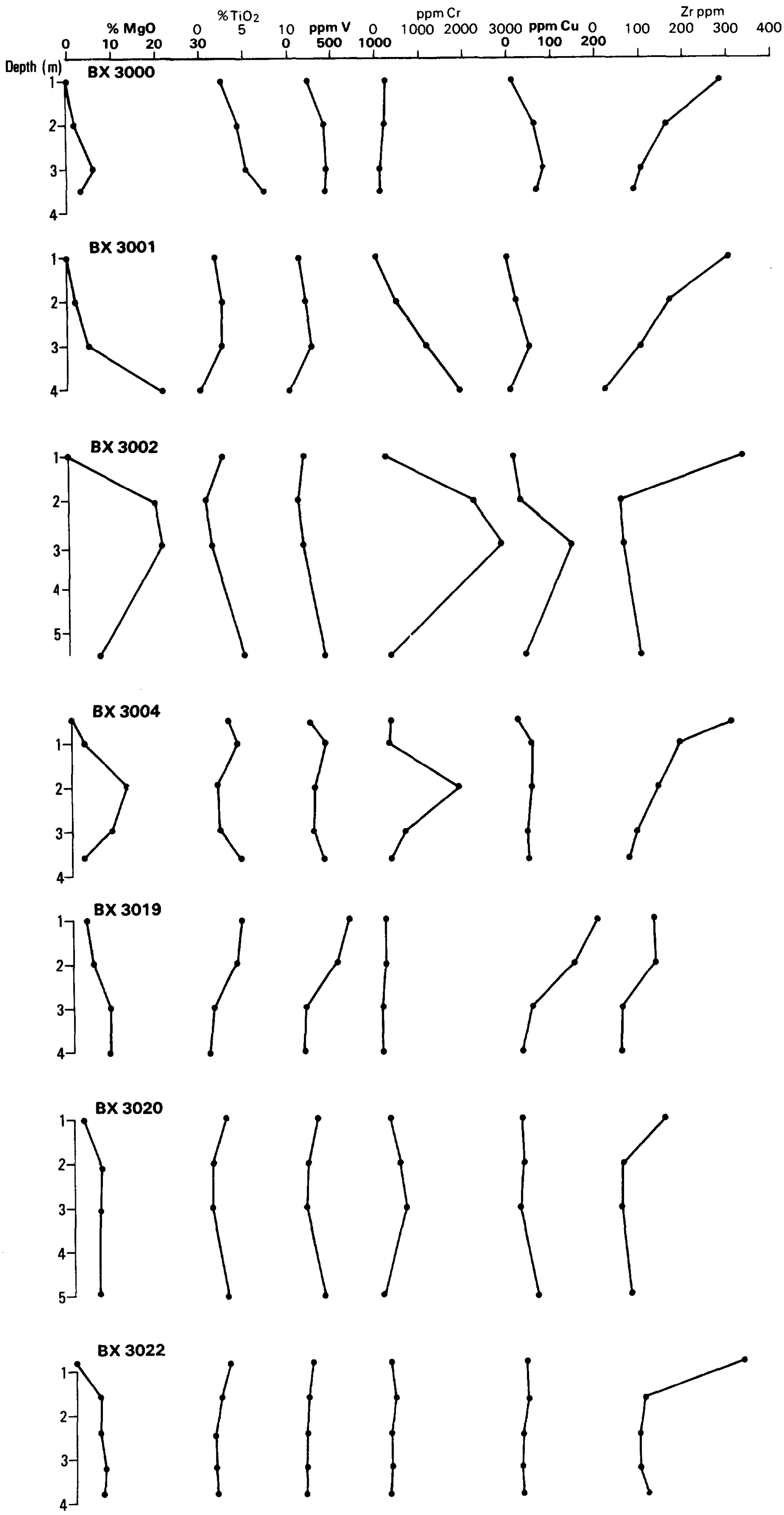


Figure 9 Concentrations of Mg, Ti, V, Cr, Cu and Zr in profiled Minuteman holes from east of Trelan. Locations on Figure 11.

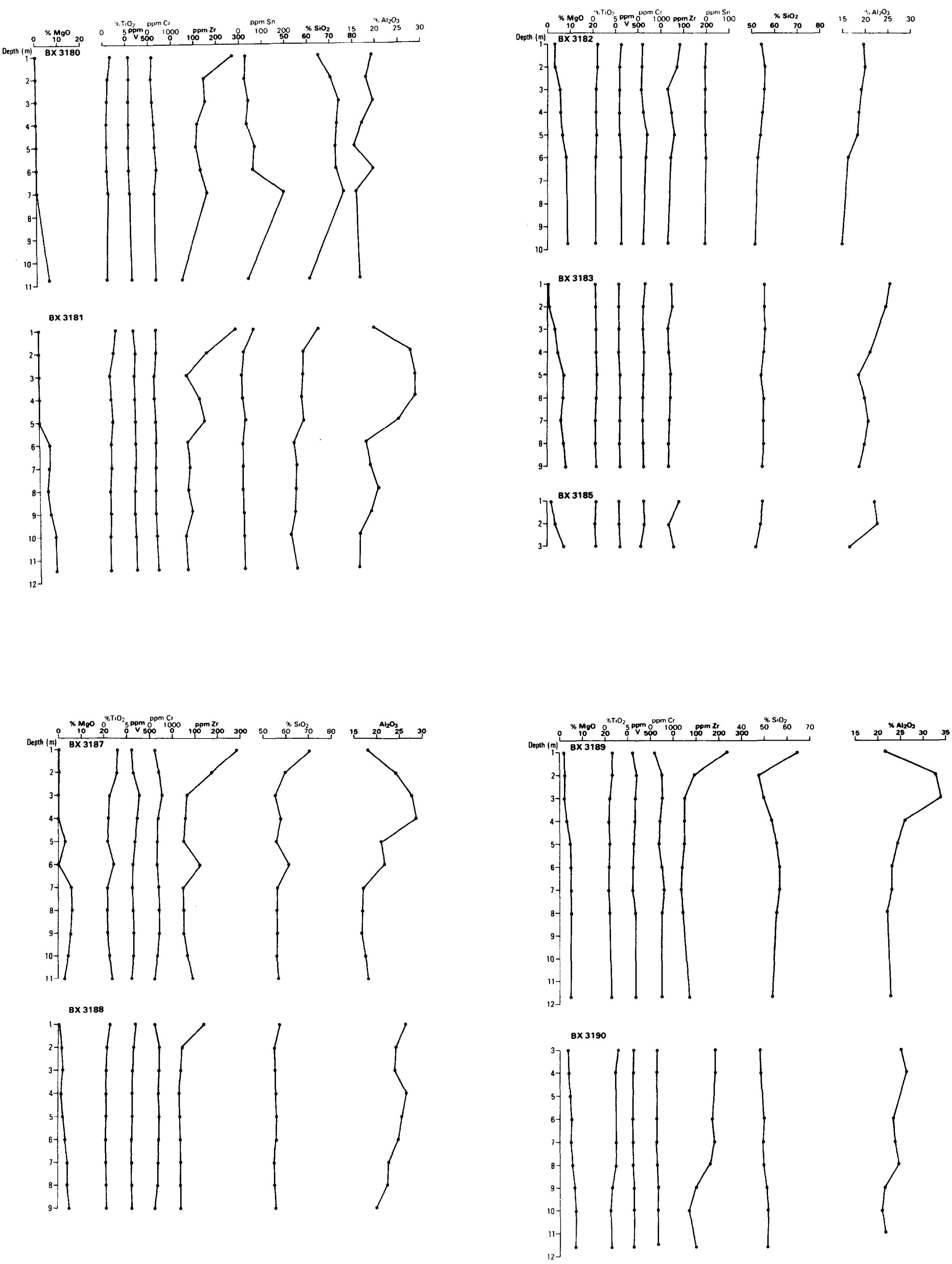


Figure 10 Concentrations of Mg, Ti, V, Cr, Sn, Si and Al in profiled Minuteman holes from around St Keverne Beacon. Locations on Figure 11.

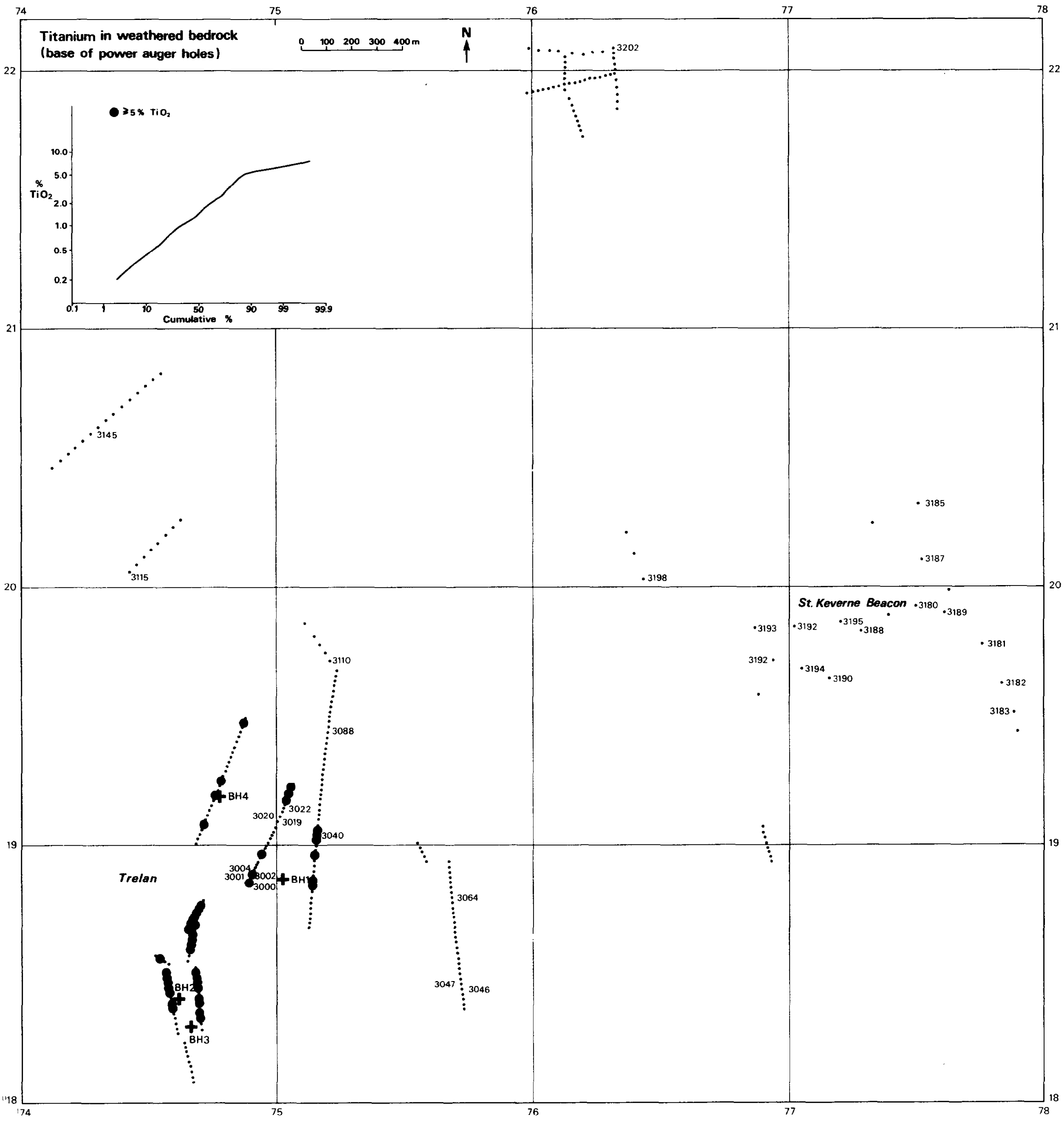


Figure 11 Distribution of Ti in samples from base of Minuteman holes. Location of profiled Minuteman holes.

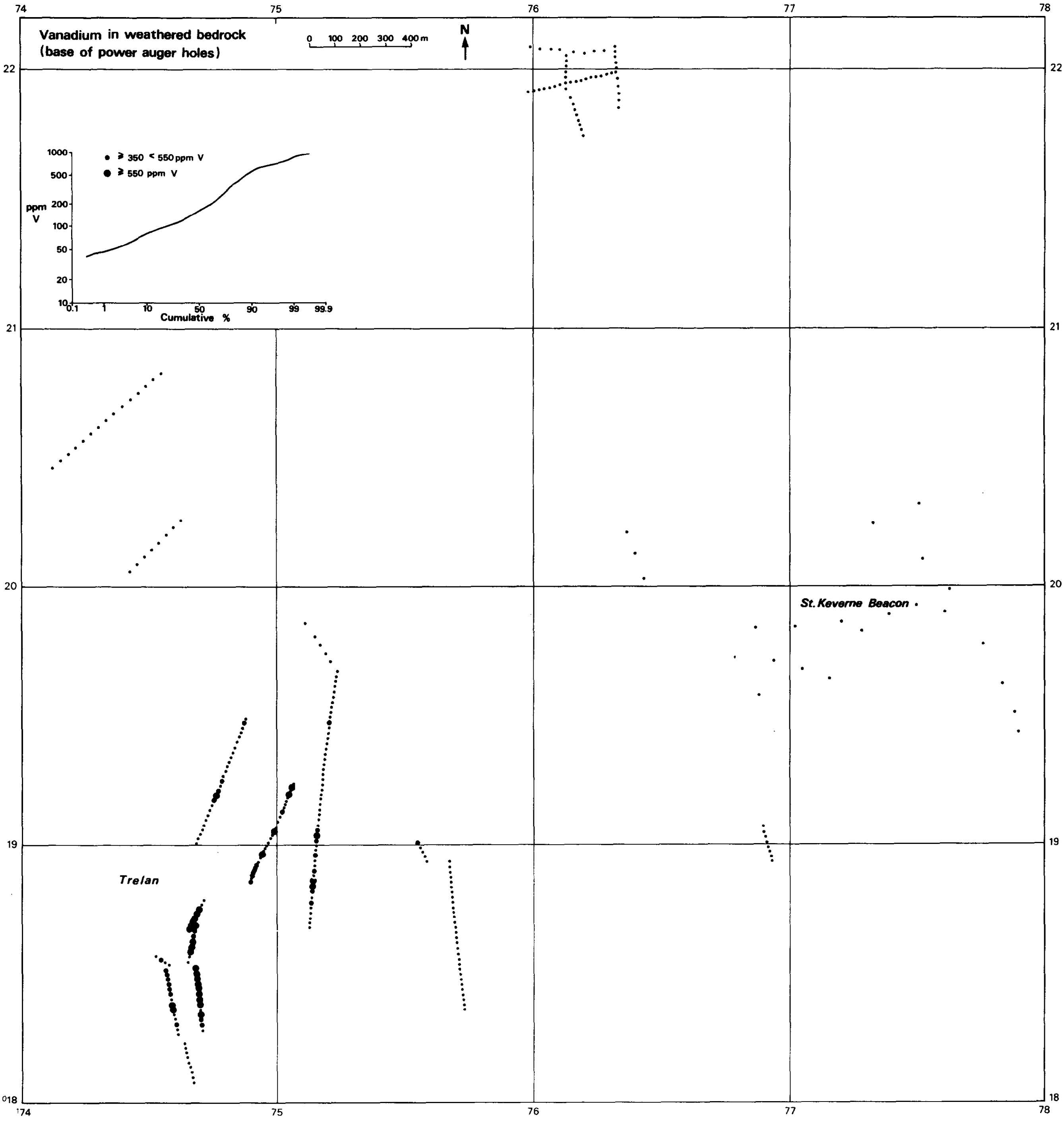


Figure 12 Distribution of V in samples from base of Minuteman holes.

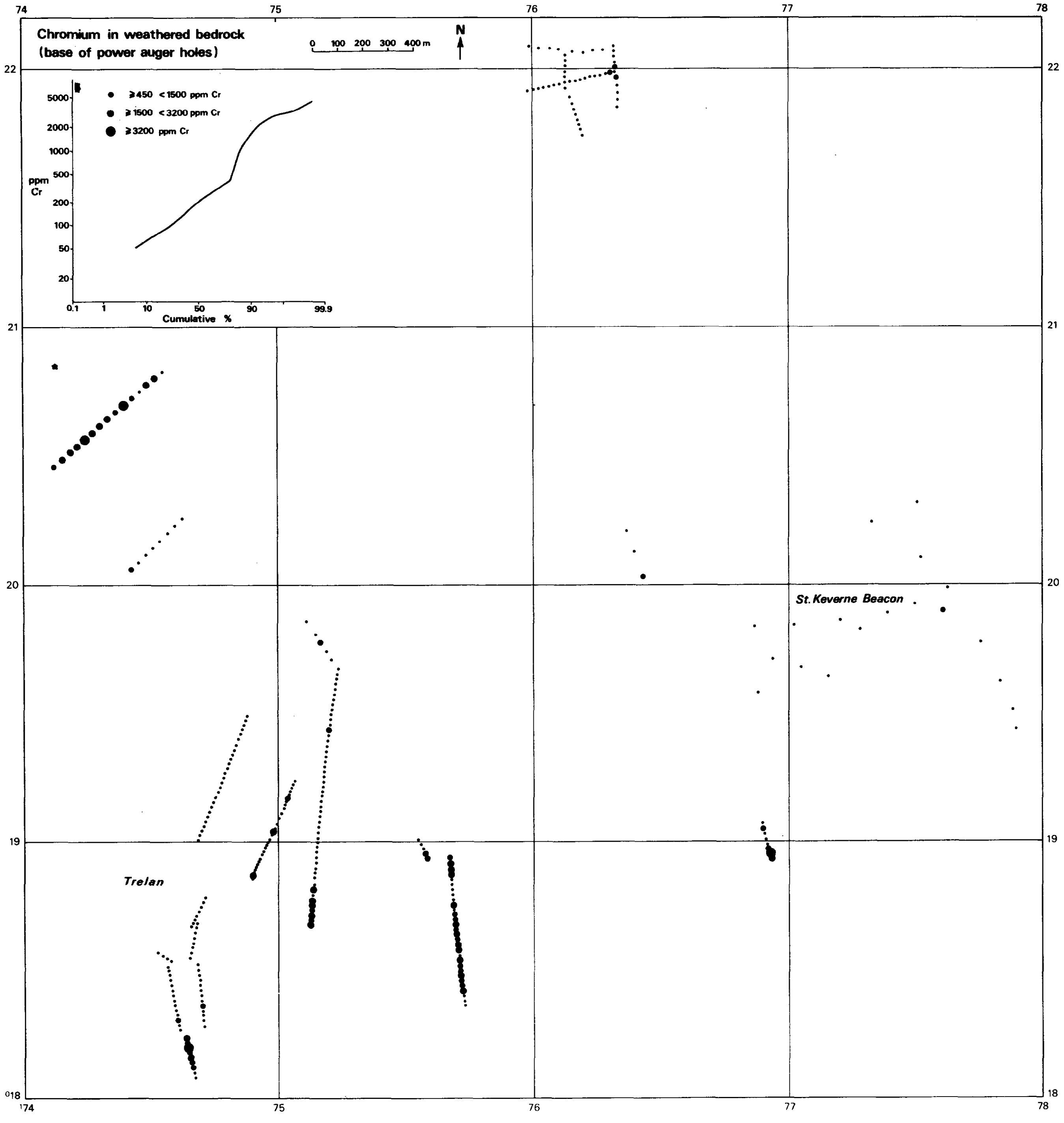


Figure 13 Distribution of Cr in samples from base of Minuteman holes.

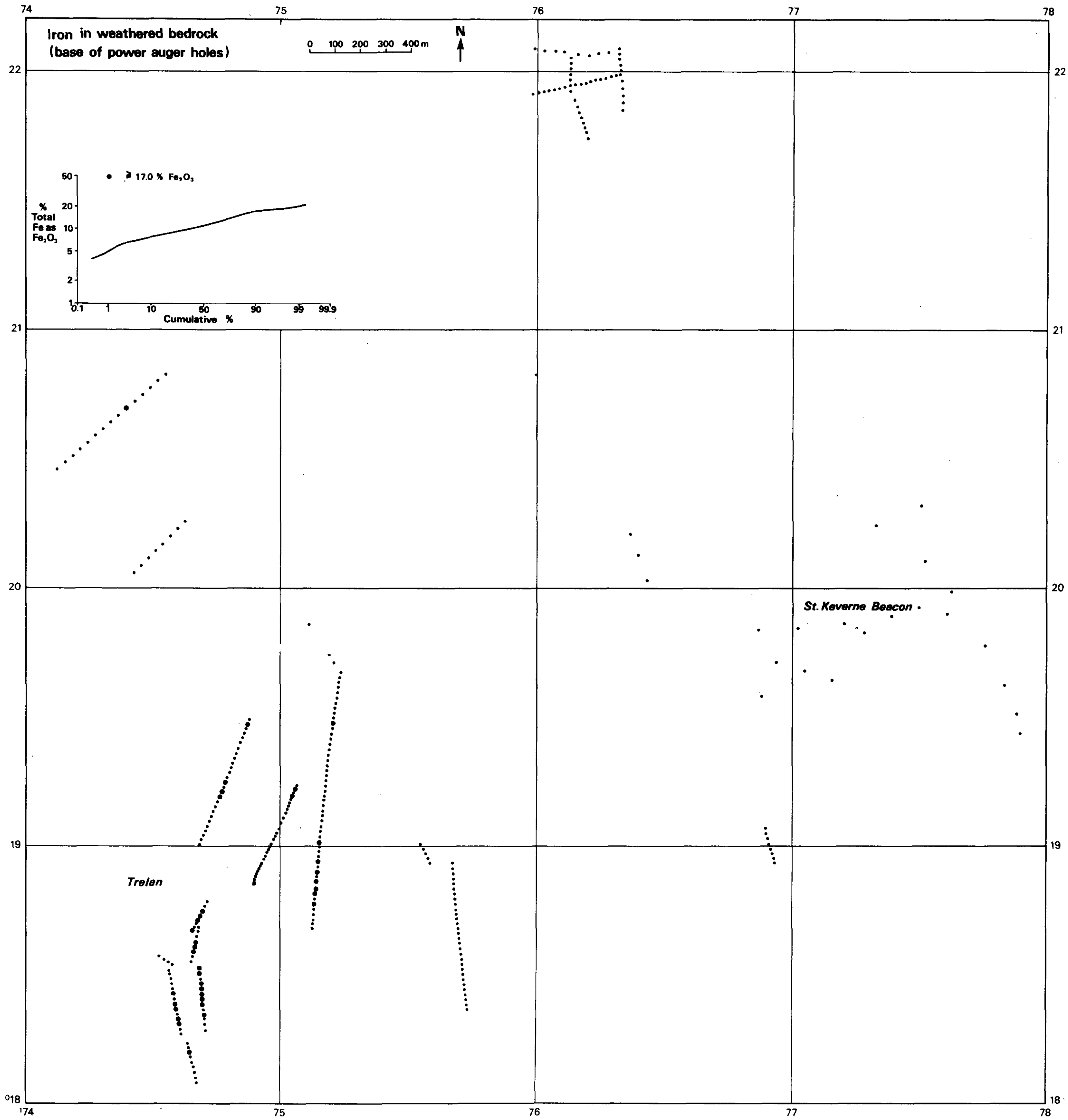


Figure 14 Distribution of Fe in samples from base of Minuteman holes.

classification, with generally clear geographical separation, and it agreed to the greatest extent with the data from the diamond drill holes. It was noticed that varying the number of clusters from 14 to 17 and the elements from 8 to 11 did not alter the classification of most samples. The mean element concentrations for each of the 17 clusters is shown in Table 1 ordered by MgO content.

Interpretation of clusters

Maps showing the distribution of basal hole samples within clusters 15, 16, 8 and 17 and within clusters 6, 3, 7, 11, 13, 5, 12 and 1 are shown in Figures 16 and 17 respectively. In addition the distribution of one metre depth samples from cluster 9 and profiles with samples from cluster 1 are shown in Figure 18. As expected, there is a close correlation between the distribution of high Ti and V (Figures 11 and 12) and the distribution of cluster 15, on the one hand, and of Cr (Figure 13) and clusters 6, 3, 7, 11 and 13, on the other. Scatter plots of all the overburden geochemical data for the element pairs Al-Mg, Cr-Mg, Ti-Si and V-Ti are shown in Figures 19 and 20. On these plots samples belonging to various clusters are highlighted so as to emphasise various chemical characteristics of the clusters.

All the clusters generated can readily be accounted for in geological terms. Clusters 2, 4 and 8 each contain only one sample, with an especially high level of Ni, Cu and Ba respectively. The 4 samples in cluster 10 are also characterised by higher concentrations of Cu than all other samples but they are also relatively rich in iron and titanium oxides and therefore represent a subgroup of clusters 14 and 15. Cluster 17 represents material of sedimentary origin which is characterised by relative enrichment in Ba. Cluster 8 is therefore a subgroup of this cluster with a greater degree of Ba enrichment. The concentrations of Ba in these samples, particularly in relation to a relatively low potassium content, suggests that there is probably a significant exhalative component in the sediments.

Clusters 9 and 1 represent material containing a major component of exotic superfical origin. Cluster 1 is the most extreme in composition and characterises only those samples from a linear zone running across the highest part of St Keverne Beacon, from west to east on line with the old gravel working south of Lanarth Gate. This represents the Crousa gravels *sensu stricto*. Samples forming cluster 9 are much more widespread but are exclusively taken from the upper metre of overburden. They are characterised by high levels of Zr and Ba relative to the other groups and are considered to reflect a significant loess and/or redistributed gravel component. There is a concentration of samples in cluster 9 in the area to the east and northeast of Trelan farms. Since these samples are roughly elongated in the direction of St Keverne Beacon, it is possible that secondary dispersion of the gravel has taken place in a relatively wide but shallow zone in this direction at some time in the past.

Five clusters represent ultamafic rocks. Cluster 3 contains the most magnesian samples and those generally richest in Cr and Ni. The interpretation of the others of this type are given in Table 1 and they reflect background ultramafic rocks mixed to varying extents with superficial material like loess, or gabbro. For some samples in cluster 6 (Figure 19), leaching of Mg and Ni may have taken place. This could have been due to hydrothermal activity as in the carbonate-altered ultramafic rocks that were intersected in one of the boreholes described below. In the core the effect of this alteration has been to deplete Mg and Ni relative to Cr. Cluster 6 samples are also significantly more Fe-rich than other samples derived from the ultramafic rocks and this probably refects hydrothermal introduction of Fe.

Table 1 Nature of Clusters - Minuteman Overburden Samples

Cl.	No.	MgO	Al_2O_3	SiO_2	TiO_2	V	Cr	Fe_2O_3	Ni	Cu	Zr	Ba	Description/interpritation
2	1	37.1	0.0	50.8	0.66	109	3145	5.33	4468	44	39	155	Most Ni-rich ultramafic rock
3	19	31.1	2.8	48.6	0.37	77	2596	10.66	2485	27	35	61	Ultramafic rock
4	1	25.9	5.5	52.7	0.46	179	3140	11.80	1889	661	33	59	Most Cu-rich ultramafic rock
7	31	24.0	7.1	47.7	1.20	144	1146	11.15	1165	38	57	43	Ultramafic rock with minor gabbro
6	6	20.3	5.8	49.7	1.13	169	3928	19.56	1812	22	96	160	Ultramafic rock with Mg leaching due to carbonate alteration (with introduction of Fe)
11	21	17.7	7.6	52.3	0.93	142	2630	14.08	2152	56	75	115	Ultramafic rock, mainly mixed with loess or gravel
13	35	11.4	11.4	51.3	1.80	234	1588	15.24	1034	43	104	115	Mixture of ultramafic and gabroic material or loess
16	136	9.0	16.2	52.6	1.02	144	342	9.92	255	30	66	91	Mg-rich gabbro poor in oxides
12	87	4.1	26.0	51.6	0.77	110	303	10.36	172	51	53	90	Clay rich glacial drift?
10	4	3.8	13.1	44.7	4.60	657	107	17.63	90	188	113	58	Oxide-rich gabbro with elevated Cu
17	11	3.3	21.4	57.0	1.26	136	188	9.25	90	29	149	705	Rocks of rich sedimentary origin (with an exhalative component)
5	126	3.3	21.8	54.3	1.65	169	277	11.16	160	33	144	139	Oxide-poor feldspathic gabbro + mafic gabbro mixed with loess or gravel
15	68	3.1	13.6	44.5	5.49	638	149	17.82	145	51	121	59	Oxide rich gabbro
14	113	3.1	16.6	50.6	3.57	357	241	14.04	149	36	162	103	Moderately oxide-rich gabbro + some oxide rich gabbro mixed with loess or gravel
8	1	1.6	19.0	61.2	1.12	108	87	7.51	38	6	178	1685	Sedimentary rock (with exhalative component)
9	48	1.1	16.6	62.2	2.46	193	219	8.91	86	23	277	212	Always near surface; gabbroic component mixed with gravel
1	12	0.5	20.7	69.8	0.79	80	219	5.65	77	23	107	144	Crousa gravel *sensu stricto*

Cl. = Cluster number

No. = Number of samples in cluster

All values quoted are mean values

V, Cr, Ni, Cu, Zr and Ba in ppm, other elements %

Clusters ordered by MgO content

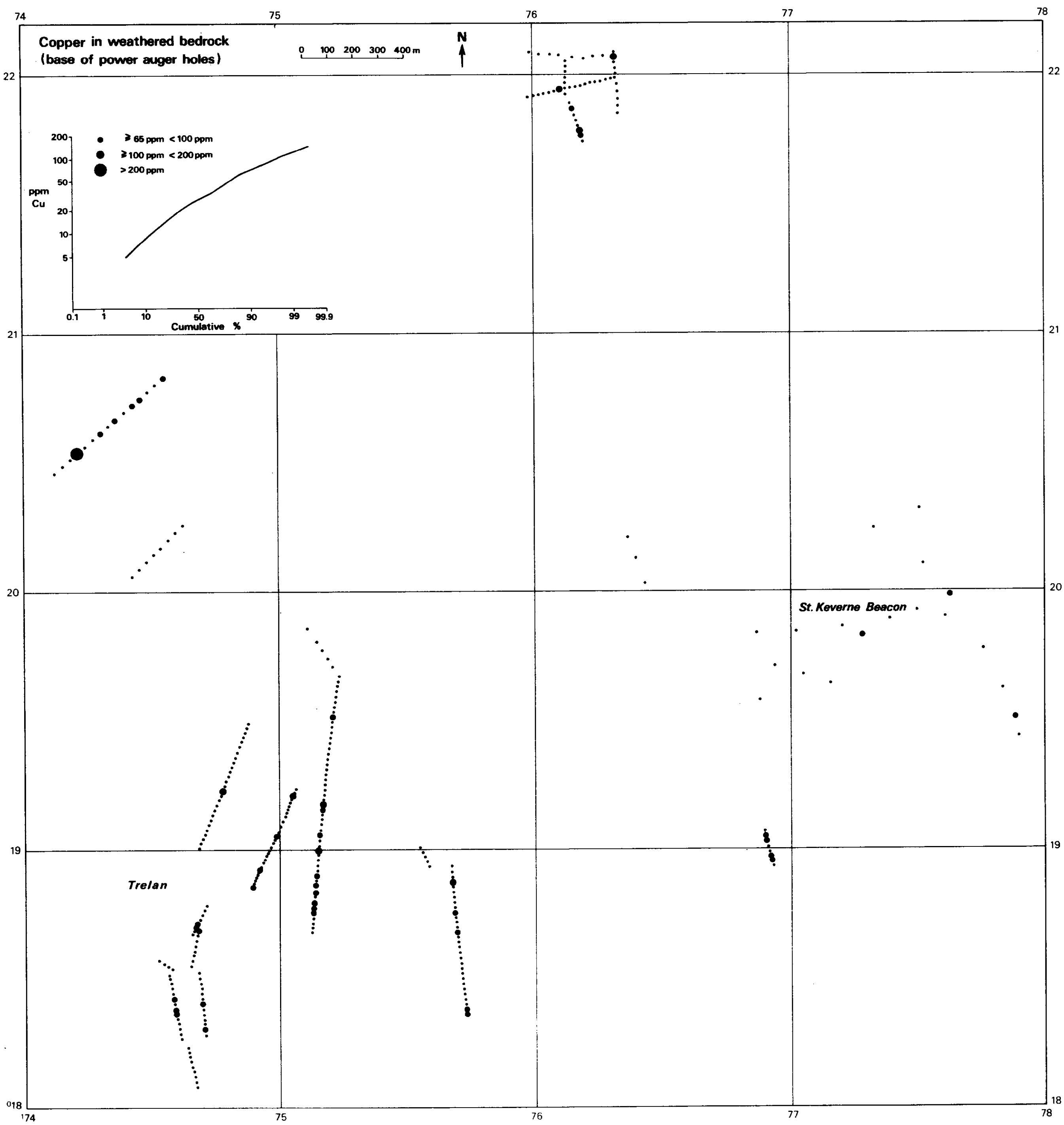


Figure 15 Distribution of Cu in samples from base of Minuteman holes.

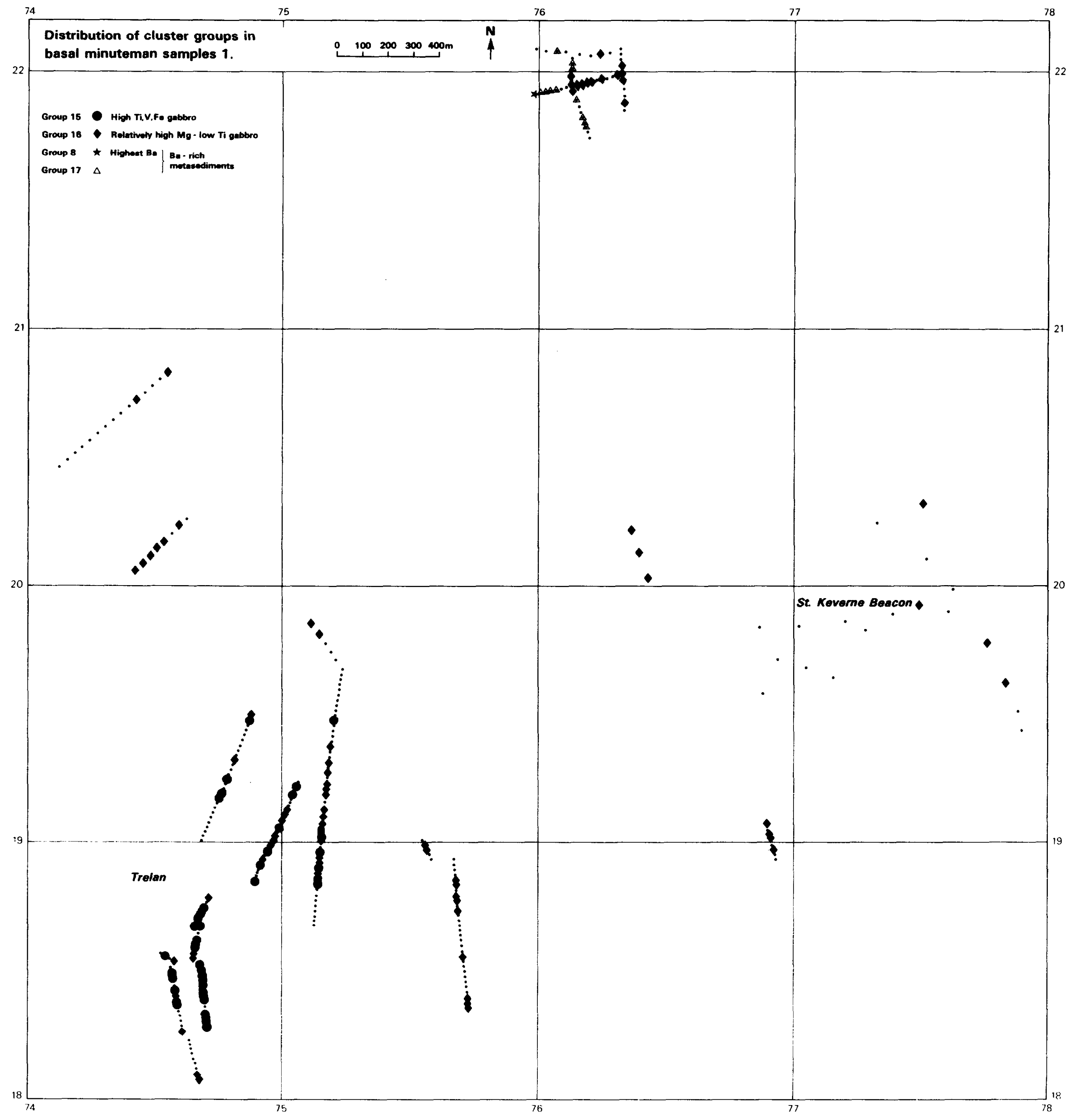


Figure 16 Distribution of cluster groups 15, 16, 8 and 17 in samples from base of Minuteman holes.

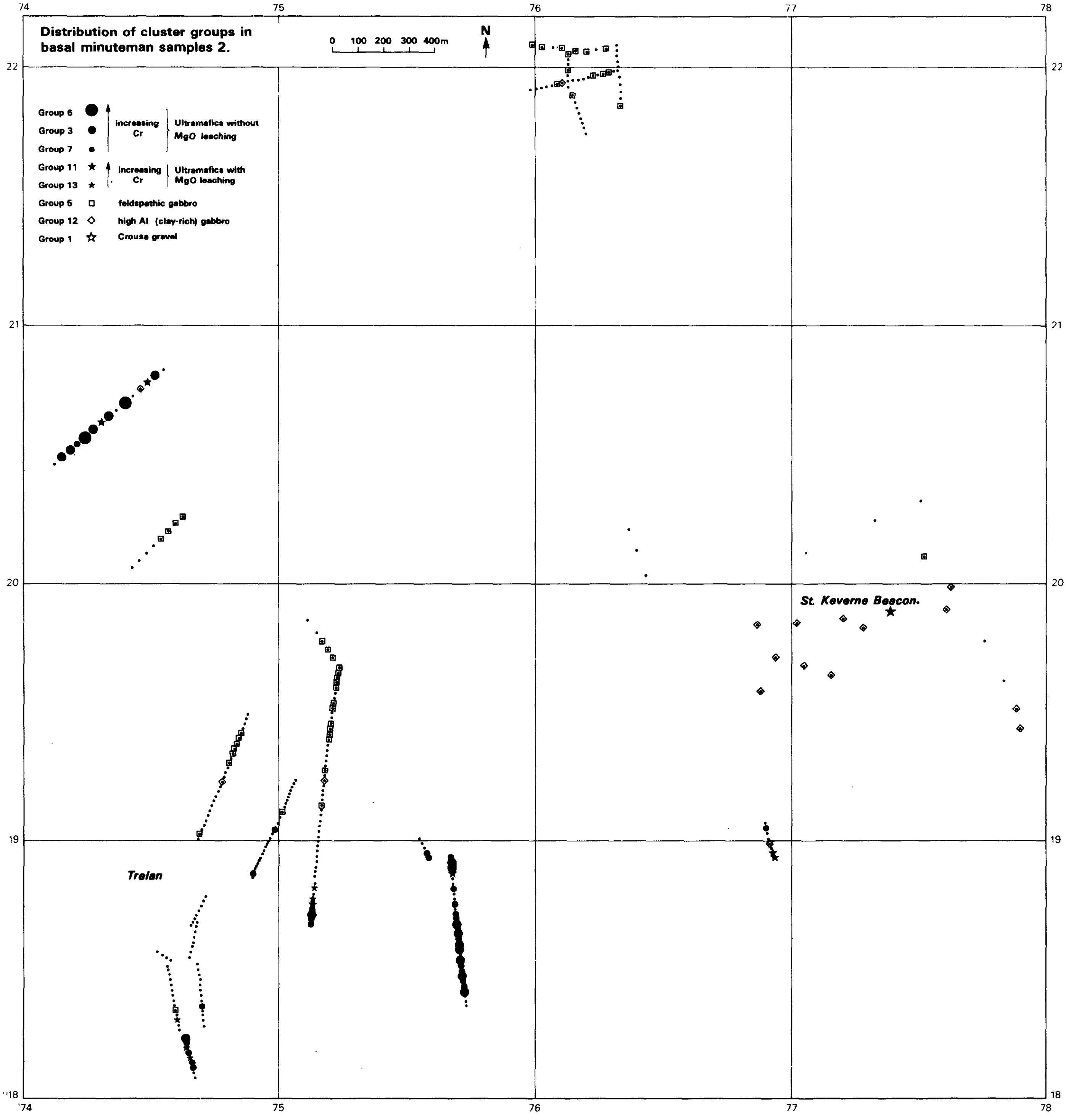


Figure 17 Distribution of cluster groups 6, 3, 7, 11, 13, 5, 12 and 1 in samples from base of Minuteman holes.

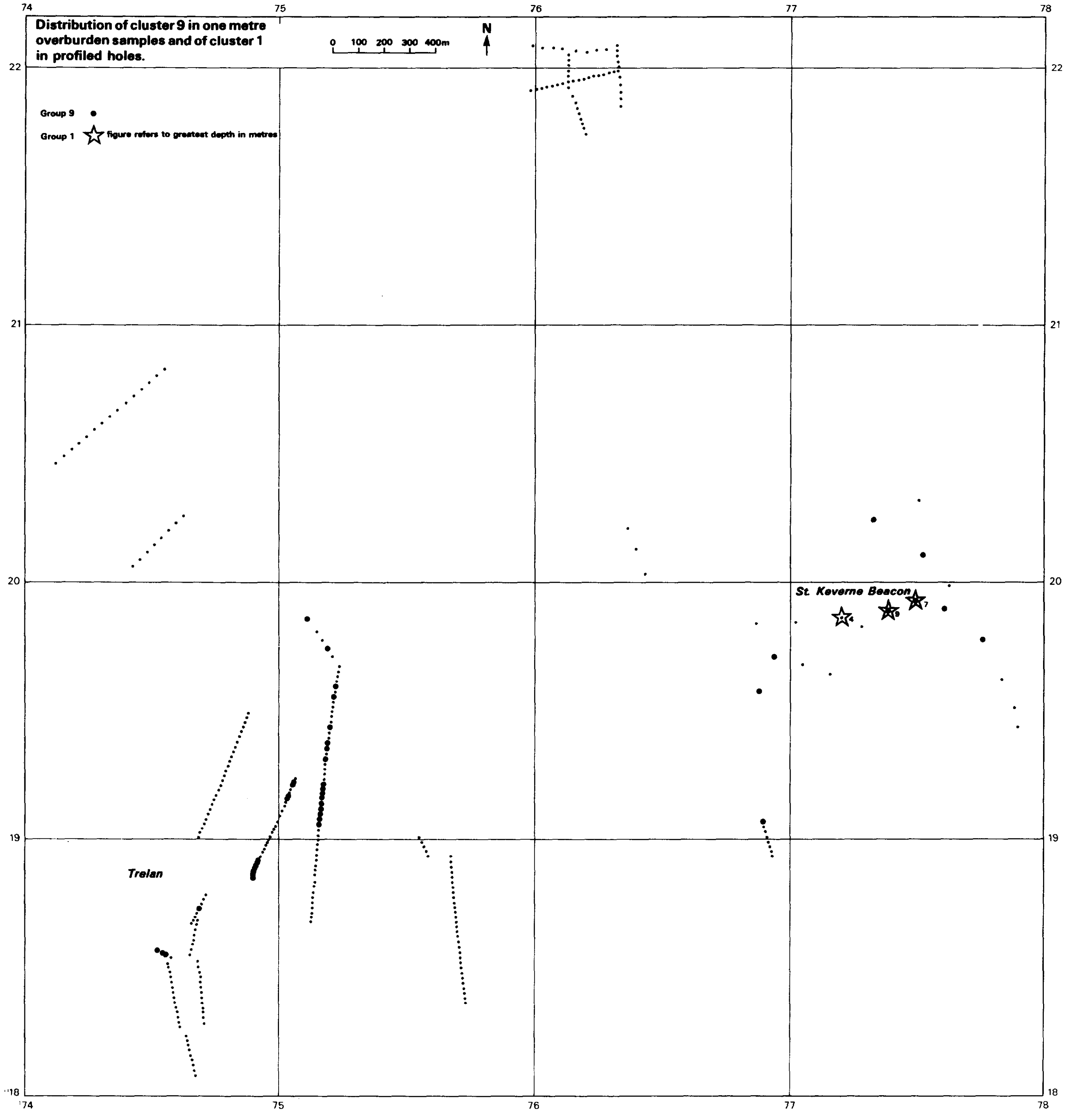


Figure 18 Distribution of cluster group 9 in one metre depth overburden samples and of cluster group 1 in profiled holes. Maximum depth in m of cluster group 1 also shown.

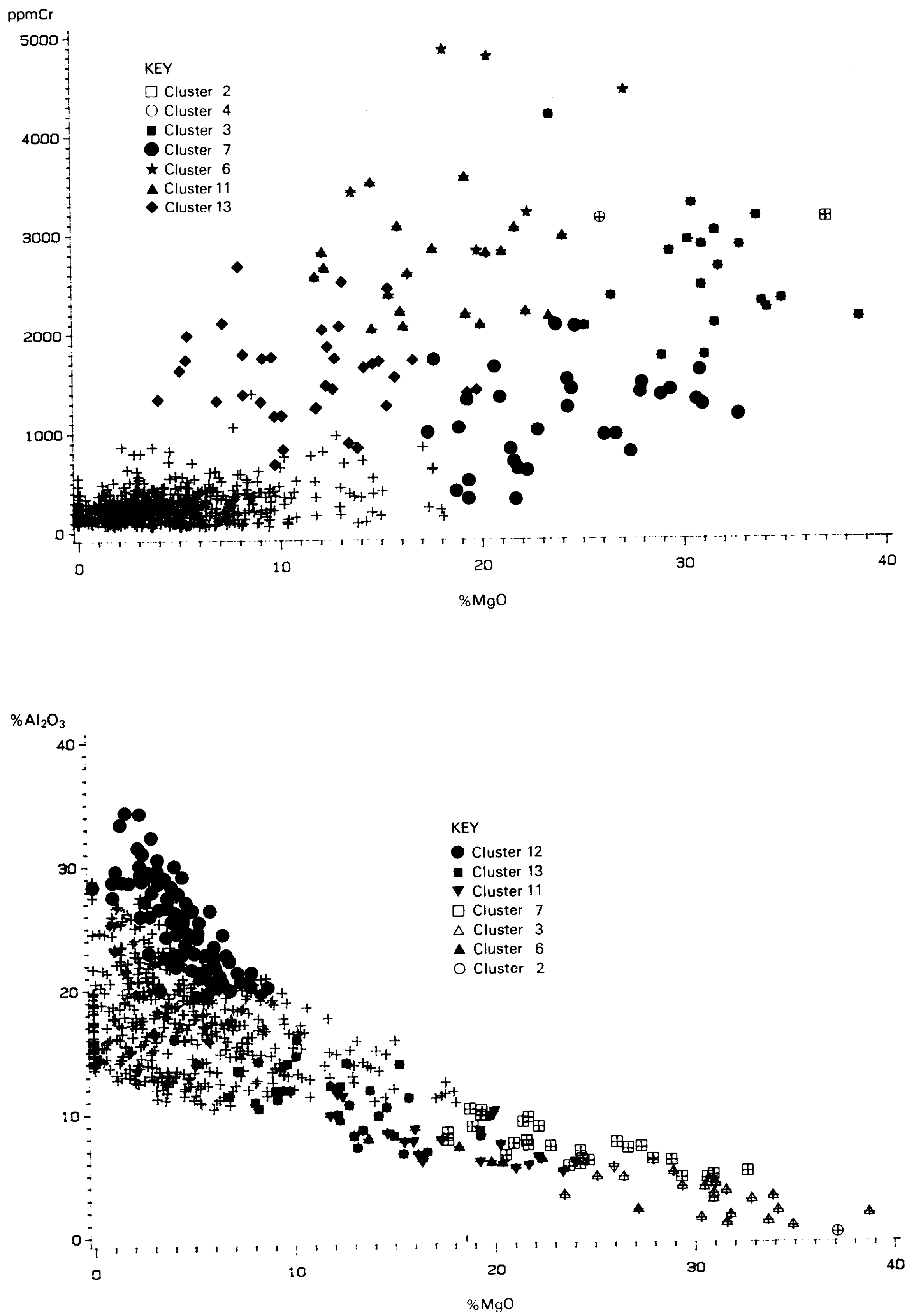


Figure 19 Plot of Al-Mg and Cr-Mg for all Minuteman samples showing identification of samples forming some of the cluster groups.

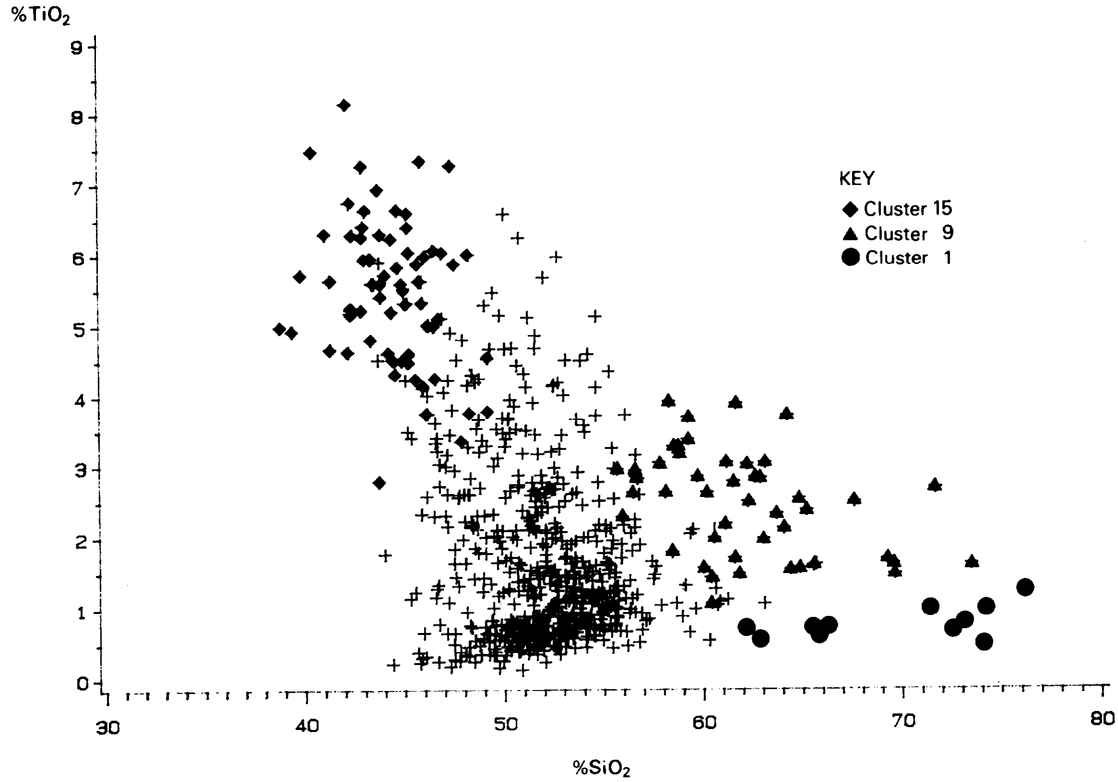
The cluster analysis picks out four groups of generally gabbroic composition which correspond compositionally to different varieties of gabbro that have been intersected in the boreholes. Group 16 represents relatively Mg-rich gabbro that is poor is oxide minerals. Cluster group 15 clearly represents the most oxide-rich gabbros while group 14 is similar but with slightly less enrichment in Ti and V and, in some cases, greater concentrations of Zr and Ba. The latter group corresponds both to the moderately oxide-rich gabbro intersected in the core and to a mixture of oxide-rich gabbro and loess. Cluster 5 can be correlated mostly with the relatively feldspathic but oxide-poor gabbro intersected in the boreholes.

Cluster 12 is the most difficult to interpret. It is characterised by relative enrichment in Al, often to extreme levels, and relative depletion in Ti and Zr. All but a few of the samples in this group are from the deep profiled holes in the St Keverne Beacon area. Several samples are very rich in clay, which is mostly kaolinitic, and this could reflect a period of intense weathering of gabbro under subtropical conditions, an event for which there is widespread evidence in Southwest England. Under such conditions, leaching of alkali elements and Ca from feldspars and of Mg from mafic minerals could have taken place leaving behind residual clay and resulting in a relative enrichment in Al. In such a process it may be anticipated that some of the more immobile elements like Ti would also tend to be enriched above the level of the unaltered gabbro. Though concentrations of Na, Mg, K and Ca can be very low in some aluminous samples there is no complementary enrichment in Ti or other relatively immobile elements like Zr and Y. In fact, the concentration of Ti and Zr is lower on average in samples from this group than in the other groups of clear gabbro compositional affinity. These factors suggest that this clay-rich material is not a residual product of the weathering of gabbro. Furthermore, the presence of a distinct break in composition in several holes, to a lower sample composition generally within cluster group 16, suggests that the clay-rich material is of exotic origin, overlying gabbro in the St Keverne Beacon area, the highest part of the Lizard peninsula. The origin of this material is further discussed below.

Origin of exotic superficial material

The relatively quartz-rich material which can be regarded as the Crousa gravel *sensu stricto*, represented by cluster 1, is compositionally very distinct. In addition to the elements utilised in the cluster analysis, some samples have been analysed for a further range of elements including Sn. In hole BX 3180 (Figure 10), Sn concentrations are also relatively high in the gravel samples, ranging from 30 ppm to 198 ppm. In addition, mineralogical examination of selected grains removed from these samples revealed several grains of tourmaline and/or quartz-tourmaline rock. Both Sn and tourmaline are not known to occur within the Lizard complex but must ultimately have been derived from the granites and their aureoles to the north and west. The deep auger holes in the St Keverne Beacon area suggest that the gravels occur as a channel deposit within the clay-rich material. In hole BX 3201 there is evidence that clay-rich material is intimately associated with typical quartz-rich gravel with a thin deposit overlying the gravel. This suggests that the origins of the gravel and the clay-rich material are closely linked. Though Sn concentrations in the few available analysed samples of clay-rich material are relatively low, a few grains of tourmaline were identified. This, together with the chemical characteristics described above, suggests that a significant proportion of the clay-rich material also originates from outside the Lizard complex.

The original interpretation of the Crousa gravels *sensu lato*, by Flett (1946), was that they were deposited on a marine platform during the Pliocene. This was based on clear evidence for their exotic origin from the minerals present, the similarity with other gravel deposits in Cornwall,



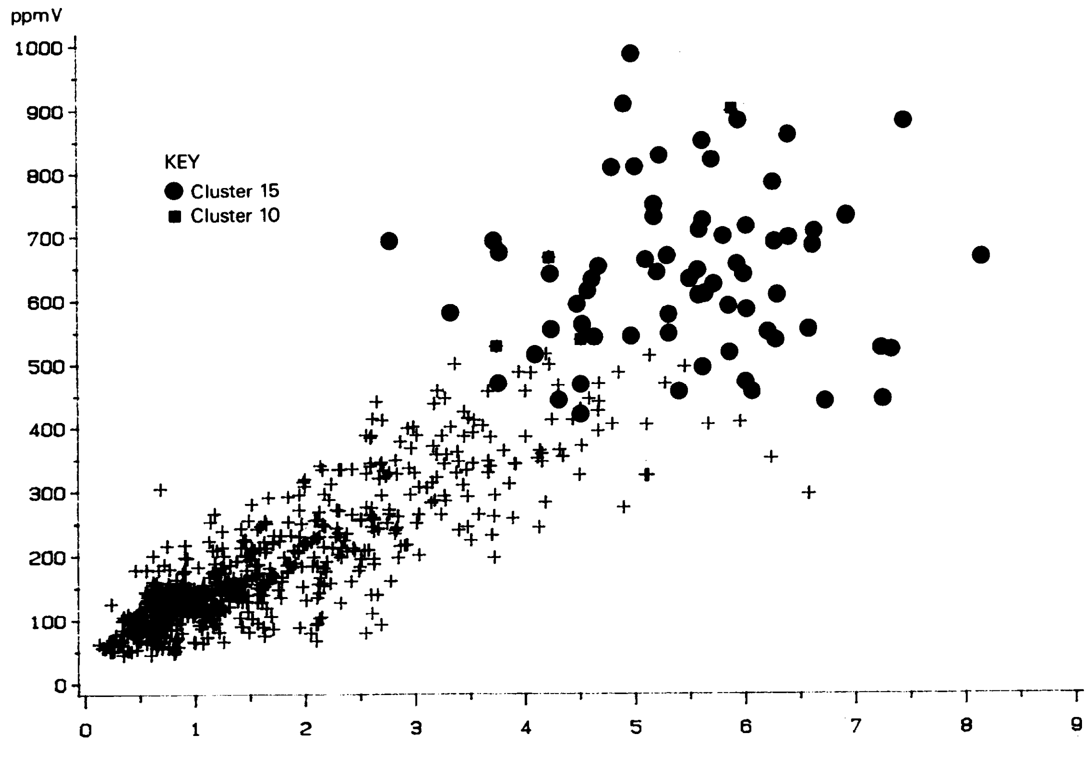


Figure 20 Plot of Ti-Si and V-Ti for all Minuteman samples showing identification of samples forming some of cluster groups.

including those from St Erth which have fossil evidence for Pliocene age, and the correlation of their height above sea level with a Pliocene platform. The important association between the clay-rich material and the very large boulders of fresh gabbro, which are very abundant in some areas, does not seem to have been recognised by the previous geological mapping. Several drainage ditches show quite conclusively that rounded boulders of hard fresh gabbro are embedded within the clay-rich material which the auger holes and resistivity soundings show can be several metres thick. These boulders have no connection with the underlying rock, which, in some cases, can be shown to be gabbro of entirely different composition or even ultramafic rock. Moreover, in all cases the underlying rock is deeply weathered and soft. The interpretation of the boulders as of residual origin is therefore untenable. Rock of very similar appearance does, however, occur along the present coast north of Coverack.

The most reasonable explanation of large exotic boulders within a clay-rich matrix is a glacial till. Further evidence of this is provided by the size analysis of Crousa gravel material carried out by Shepherd (1986). This shows a particle size distribution similar to glacial till and quite different from either stream or beach sediment. The Crousa gravel *sensu lato* is, accordingly, thought to originate as sediment from the sea-bed to the east of the present coast line which was pushed up onto the Lizard plateau together with boulders of gabbro from the exposed coast at the base of a sheet of sea ice. The gravel *sensu stricto* which occurs in one major channel deposit cut into the till can be intrepreted as a fluvial sub-ice meltwater channel deposit. The date of the glacial episode during which this occurred is not clear but the presence of loess overlying the gravels (Staines in Shepherd, 1986) which is considered to be late Devensian in age (Wintle, 1981) suggests a relatively early glacial event. This intrepretation is consistent with the suggestions made by Kellaway et al. (1975) that the English Channel had been subjected to one or more relatively early glaciations.

Geochemical overburden mapping

A proper understanding of the geology of the inland parts of the Lizard, where exposure is lacking, is essential for assessment of any mineral potential. A number of conclusions can be made from the results of the power auger sampling programme which are of importance in this respect. A provisional geological map of the area covered by the survey, constructed from the results of this work together with data reported previously (Smith and Leake, 1984; Leake and Styles, 1984; Shepherd, 1986; Shepherd et al., 1987), is given in Figure 21. Because of the unequal coverage of the area with minuteman sampling, this map is sketchy and requires further work to fill in gaps before boundary lines can be drawn over the whole area with confidence. Nevertheless, several geological units can be recognised and some conclusions relating to these are described below.

The position of the contact, in the area to the east of Trelan, between predominantly ultramafic rocks and gabbroic rocks to the north, at about 800 m north of the contact shown in the old survey geological map (Figure 1), confirms the previous intrepretation on the basis of soil geochemistry (Smith and Leake, 1984). However, the contact is not a straight line but appears to have been displaced by faulting. The restriction of the oxide-rich Trelan gabbro type generally to the area south, east and northeast of Trelan also confirms previous results (Smith and Leake, 1984), though a contact between the oxide-rich gabbro sequence and an oxide-poor feldpathic gabbroic unit, running approximately east-west, can also be recognised about 400 m north of Trelan. Compositionally this appears different from the gabbro underlying the St Keverne Beacon area, which is correlated with the Crousa gabbro *sensu stricto*. The geometrical relationship between

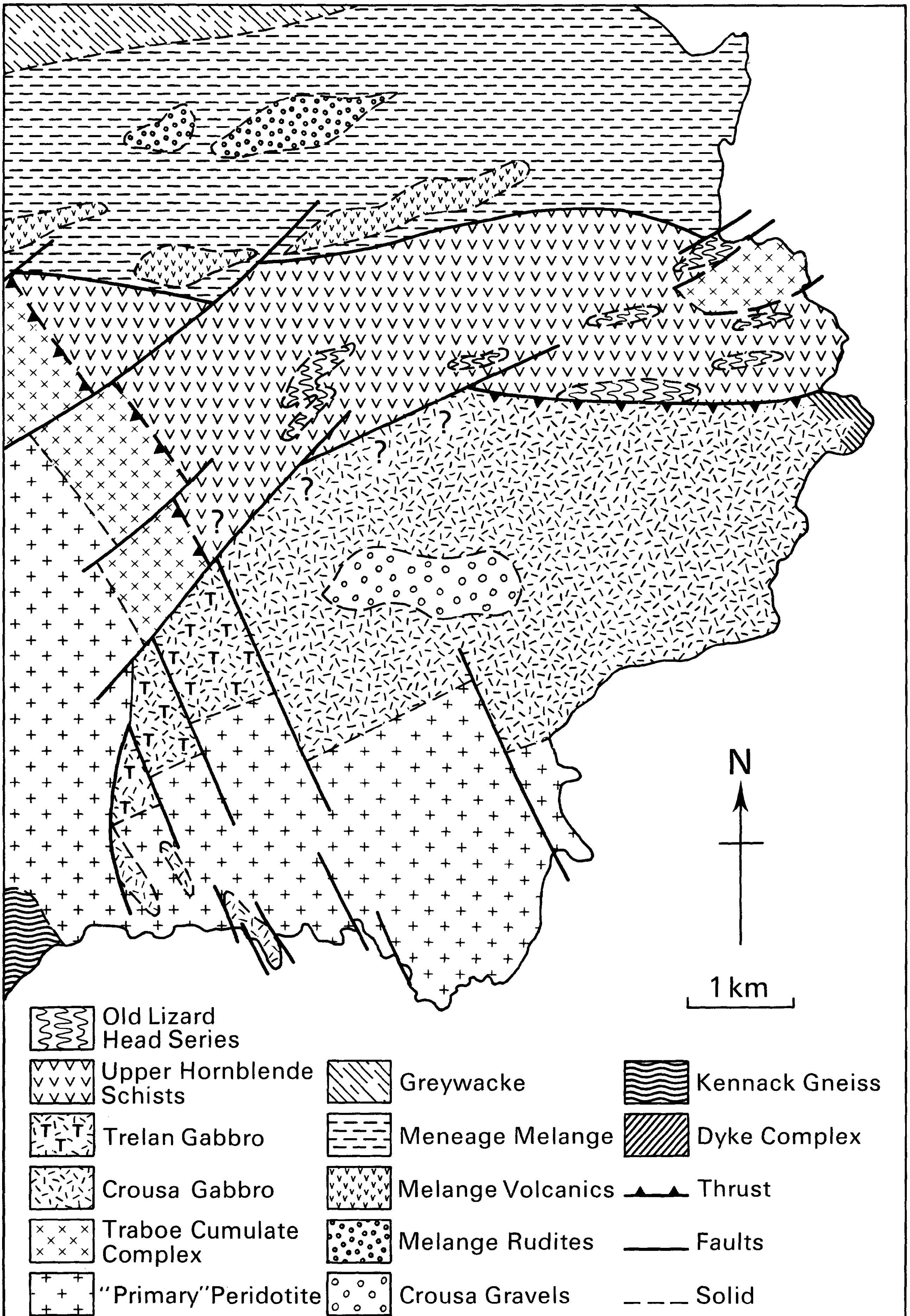


Figure 21 Provisional geological map of eastern part of the Lizard complex.

these two units is not yet known. There appear to be slight compositional differences recognisable from the minuteman survey between the ultramafic rocks of the Traboe cumulate complex and the ultramafic rocks from south and south-east of Trelan and this is discussed further below with respect to the borehole material. There is gabbroic material interlayered with the ultramafic rocks but compositionally this appears to be only of the oxide-poor, relatively Mg-rich type. The presence of a major break between the Traboe cumulate complex and a generally gabbroic sequence along strike is clearly apparent. Though compositionally this gabbroic sequence resembles the relatively oxide-poor feldpathic gabbro to the north of Trelan mentioned above, the examination of fragments shows that it consists of amphibolitic rocks. Further north, the presence of rocks of sedimentary origin shown on the original survey map is confirmed. The minuteman samples suggest that the metasedimentary rocks extend further north-east than shown on the map and are interlayered in a complex manner with rocks of mafic composition.

THE DIAMOND DRILL HOLES

Four diamond drill holes were collared to intersect different parts of the Trelan gabbro and more particularly those areas showing the greatest concentrations of vanadium in near surface material. Though sites were close to magnetic anomalies, difficulties of access did not allow exact siting of holes at localities with the maximum amplitude of magnetic field. Nevertheless, it is considered likely that the drill holes provide a respresentative section through the Trelan gabbroic rocks and into ultramafic rocks beneath. The sites of the holes from which core was recovered are shown on Figures 7 and 18. Other holes were drilled but technical problems caused loss of the drill string and prevented any recovery of core. Borehole 2 is relatively short for the same reason.

Geochemistry of drill core

Sampling and analysis

Half core samples were taken for analysis from most of the drill core. After crushing in a jaw crusher, subsamples were ground in a Tema swing mill with a steel pot. After grinding, about 10 g subsamples of powder were pressed into pellets and analysed by Philips PW1400 X-ray fluoresence spectrometer for major elements and S, V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr and Pb.

Data treatment

Chemical analyses for each hole are shown graphically together with summary logs in Figures 22-25. Multivariate statistical procedures were also utilised on the diamond drill hole data both singly and in combination with the minuteman data. Comparisons have also been made with chemical analyses of other rocks of the Lizard complex. For the purposes of multivariate statistical analysis the chemical data were split into two classes, ultramafic rocks and gabbroic rocks. Cluster analysis of the type applied to the overburden data was used to classify a combined data set of gabbroic rocks from the boreholes and 60 samples collected by A Shepherd from systematic traverses within the Crousa gabbro in the West of England quarry, Dean Point quarry and Coverack shore section (Shepherd, 1986). Direct comparison of data sets is possible since both sets of sample were analysed on the same machine at Nottingham University using the same method of analysis.

Chemistry of the gabbroic rocks

Though the gabbroic rocks can be divided readily into oxide-rich and oxide-poor types on the basis of petrography and chemistry, multivariate statistical techniques are required to investigate less obvious chemical differences. Cluster analysis was carried out by means of the SAS Fastcluster procedure using different numbers of clusters, after standardisation of the data. Most of the groups were found to be robust with little change as the number of clusters changed. The mean element concentrations for all the clusters in a 14 cluster classification of the data are given in Table 2, ordered by TiO_2. The minor and single sample clusters reflect hydrothermal effects or extreme compositions.

Three varieties of both oxide-rich and oxide-poor gabbro were separated by the cluster analysis viz. clusters 3, 9 and 14 and 2, 8 and 13 respectively. For the oxide-rich gabbros, cluster 3 differs from the others in being generally richer in Na relative to Al and especially richer in P, Y and Zr (Table 2). The majority of the samples forming cluster 3 belong to distinct units at the base of borehole 1 and borehole 4. The relative enrichment in K shown by some gabbro samples is thought to represent secondary hydrothermal introduction in the vicinity of major shear zones or thrusts. Below the main gabbro/ultramafic contact in borehole 3 the relatively magnesian cluster 9 is the predominant gabbro type. No examples of the oxide-rich gabbro types are present in the Crousa gabbro data set.

Cluster 13 includes samples from both the Trelan boreholes and the Crousa gabbro but these can be distinguished in terms of several elements. The Crousa gabbro group is distinctly poorer in Na and richer in Ca than the Trelan samples. It is also richer in Mg and poorer in Ti and V (Figure 26) and with a lower V/Ti ratio than the Trelan samples. Phosphorous concentrations are relatively high in the Crousa gabbro samples, especially in relation to the amount of Fe and Ti oxides. Cluster 8, with one exception, is made up of samples of the Crousa gabbro.

The vanadium content of the oxide-rich gabbros is quite variable. Ilmenite concentrations reach about 15% by weight over about 2.3 m towards the top of borehole 4 and here magnetite concentrations appear to be low. Magnetite concentrations are higher at the bottom of borehole 4 and also within borehole 3 but even in these sections ilmenite is predominant. The considerable range in Ti/Fe ratios within the oxide-rich gabbros is shown in Figure 26. There are indications of two trends in the plot of V against Fe (Figure 26), the lower line being made up of samples from boreholes 2 and 3. Higher V/Fe ratios are found in the oxide-rich samples from boreholes 1 and 4, together with a 5 m thick section in borehole 3. Since boreholes 1 and 4 intersect a higher level in the Traboe gabbroic rocks than boreholes 2 and 3, it is possible that some fractionation towards V enrichment occurs upwards in the complex.

Petrography of drill core

Borehole 1

This borehole consists almost entirely of medium to coarse-grained gabbro. The grain size, shown particularly by plagioclase, varies from around 3 mm to over 1 cm. The proportion of felsic to mafic minerals varies somewhat but is typically around 35% mafic minerals. In hand specimen, however, there appears to be a much greater variation in mineral proportions but this is largely due to secondary processes. Fresh plagioclase in these and most other Lizard gabbros is a very dark

Table 2 Nature of Samples - Borehole and Outcrop Gabbroic Rocks

Cl.	No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V	Cr	MnO	Fe_2O_3	Ni	Sr	Y	Zr	Description
3	25	3.13	5.85	10.45	46.95	0.31	0.42	8.80	5.35	801	58	0.21	17.25	38	205	42	131	Oxide -rich Gabbro
14	71	2.82	7.29	11.33	46.77	0.11	0.51	9.91	4.82	643	104	0.17	15.24	81	247	25	93	Oxide-rich Gabbro
9	14	2.04	12.16	11.17	45.62	0.10	1.34	6.18	4.37	557	79	0.19	15.25	79	171	24	87	Oxide-rich Gabbro
5	1	1.07	25.04	7.37	40.87	0.60	0.15	5.16	4.38	521	173	0.34	16.54	321	59	54	182	Very Mafic Gabbro
1	3	0.95	24.09	8.08	41.87	0.05	0.08	6.97	3.69	464	74	0.27	14.02	144	50	20	61	Amphibolitic Gabbro
11	1	0.94	19.22	7.32	45.74	0.16	0.11	10.46	2.57	456	337	0.16	13.14	452	32	29	75	Largely Pyroxenite
10	1	1.25	15.52	9.44	44.38	1.11	0.67	9.78	3.43	449	189	0.25	13.88	185	112	62	71	Mafic Gabbro
6	1	2.38	7.41	12.47	46.79	0.54	0.29	9.73	2.49	377	322	0.18	12.18	80	219	64	598	Extreme differentiate Crousa Gabbro
7	1	0.94	7.80	8.77	44.17	0.05	4.50	13.03	3.20	358	984	0.18	12.23	290	86	18	69	Very altered Gabbro
2	37	3.34	7.52	13.45	51.33	0.12	0.52	9.74	1.80	276	85	0.16	9.68	75	344	24	74	Feldspathic Gabbro
8	14	2.67	8.55	13.19	47.18	0.36	0.40	10.14	2.02	237	179	0.16	9.97	109	262	39	152	More differentiated Crousa Gabbro
12	3	2.33	11.88	13.05	48.93	0.23	3.33	5.78	1.69	228	282	0.12	9.43	187	189	27	141	Very altered Gabbro
13	72	2.75	9.74	13.66	48.48	0.09	0.33	10.08	1.08	183	371	0.14	8.38	131	257	17	52	Mixed Crousa Gabbro and Feldspathic Trelan Gabbro
4	2	1.38	14.99	8.58	39.69	0.14	1.03	18.18	1.22	151	191	0.22	8.69	168	142	28	74	Pyroxenitic Rock

Cl. = Cluster number

No. = Number of samples in cluster

All values for clusters with >1 sample are means

V, Cr, Ni, Sr, Y and Zr in ppm, all other elements in %

Clusters ordered by V content

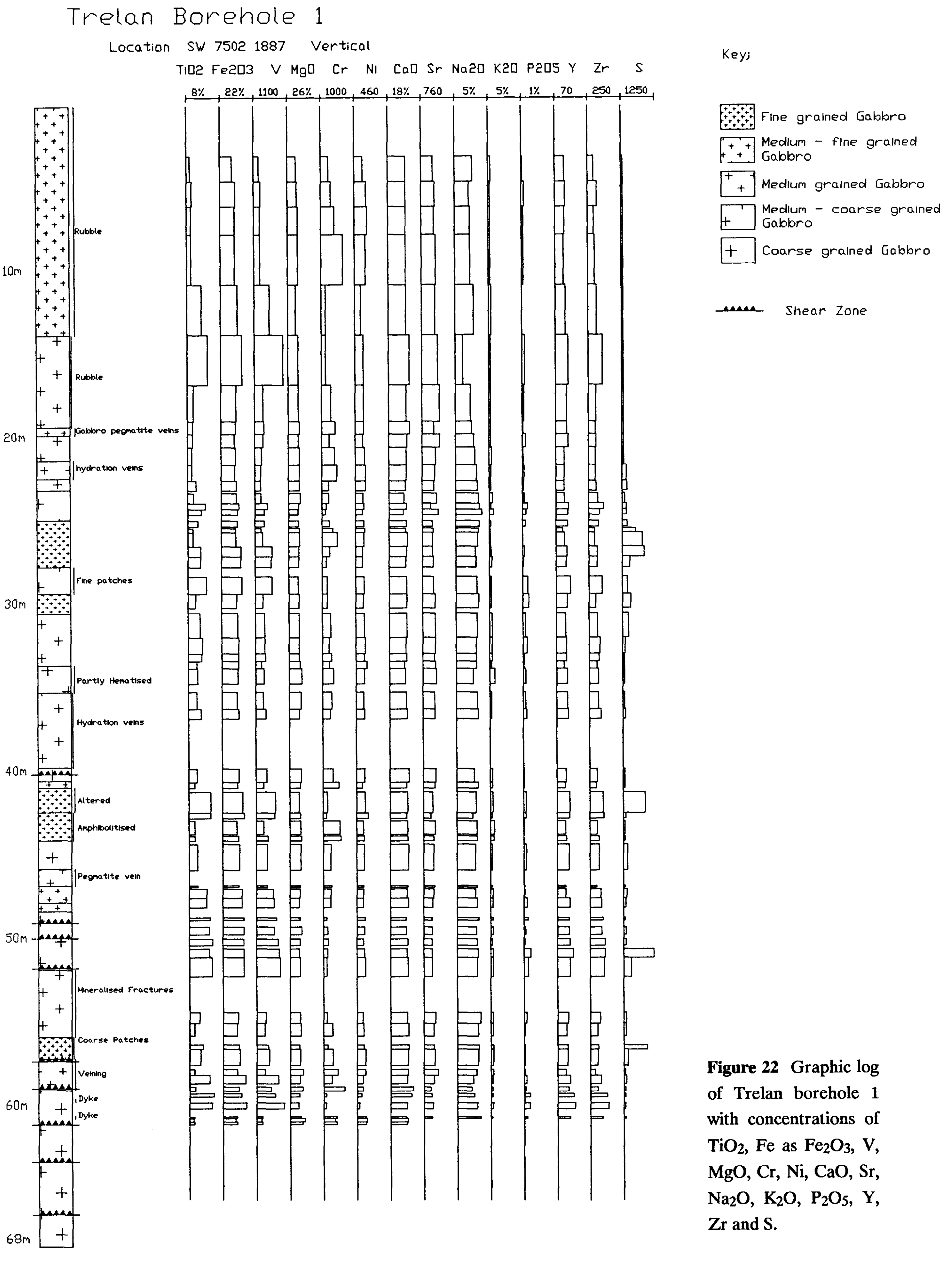


Figure 22 Graphic log of Trelan borehole 1 with concentrations of TiO_2, Fe as Fe_2O_3, V, MgO, Cr, Ni, CaO, Sr, Na_2O, K_2O, P_2O_5, Y, Zr and S.

purple colour, probably due to a relatively high iron content, and, in consequence, a fresh gabbro appears almost black in colour and superficially similar to ultramafic rocks. Only when the plagioclase has been saussuritised and turned white do the rocks take on the more typical gabbro appearance. Visual estimation of the plagioclase abundance is only simple in the extensively hydrated gabbros.

In thin section the plagioclase laths generally have small interstitial augite grains giving an intersertal texture but in some samples the augites are larger forming a subophitic texture. Serpentine pseudomorphs, possibly replacing olivine, are present in a few sections. Small amounts of apatite, biotite and a brown kaersutitic amphibole are present in some samples. The brown amphibole tends to occur around the edges of and sometimes partially replacing augite and is itself partly altered to green hornblende. A reaction between augite and a late stage Ti-rich magmatic residue is thought to account for the brown amphibole. The biotite probably formed at the same time and in a similar manner, showing that the fluids are hydrous.

Oxide minerals are the principal accessory minerals in the gabbros and reach up to 15% in some types. Ilmenite is generally much more abundant than magnetite and often occurs in clusters of grains and vein-like aggregates and is described in more detail below. Magnetite usually occurs as relatively small grains together with the ilmenite aggregates but in a few samples it occurs as large single grains. The ilmenite usually contains very fine exsolution lamellae of hematite, and magnetite always contains coarse exsolved ilmenite. Small amounts of chalcopyrite and pyrite are found in close association with the oxides in some samples.

All samples show varying degrees of secondary alteration ranging from late/post magmatic high-temperature hydration and deformation to later low-temperature hydrothermal alteration. Plagioclase shows a progression from slight turbidity and recrystallisation to complete saussuritisation with the formation of dark granular aggregates in thin section. Clinopyroxenes always show some alteration to a green hornblende. This varies from a few small patches in essentially fresh pyroxene, through extensive rims around grains, to a complete replacement of the pyroxene. The grain size and colour of the hornblende depends on the stage of alteration. Generally hornblendes formed early and at high temperature are coarser and darker green than those formed later which are paler and finer-grained, sometimes forming felted mats. The ilmenites do not seem to have been greatly affected by the alteration processes and sphene and other alteration products are rare. In contrast, the magnetite is often greatly affected by alteration, with magnetite extensively or completely altered to goethite, leaving virtually fresh lamellae of ilmenite in the characteristic exsolution texture. Several rocks have minor late cross-cutting veins of carbonate and less commonly prehnite.

Most of the gabbros are coarse-grained but within these there are widespread patches and vein-like bodies of pegmatitic gabbro. These probably reflect local enrichment in volatiles during crystallisation that promote rapid grain growth. No correlation between these grain-size variations and composition are apparent. Horizons of finer-grained gabbro were also present in several parts. These tend to be relatively thin with a maximum thickness of a few metres, often occurring in the vicinity of distinct shear zones. Thin sections show that they have a granular texture which is associated with high temperature recrystallisation rather than the typical igneous texture. It is thought that these rocks represent a response to less intense deformation than the severe grain size reduction seen in the shear zones and mylonites.

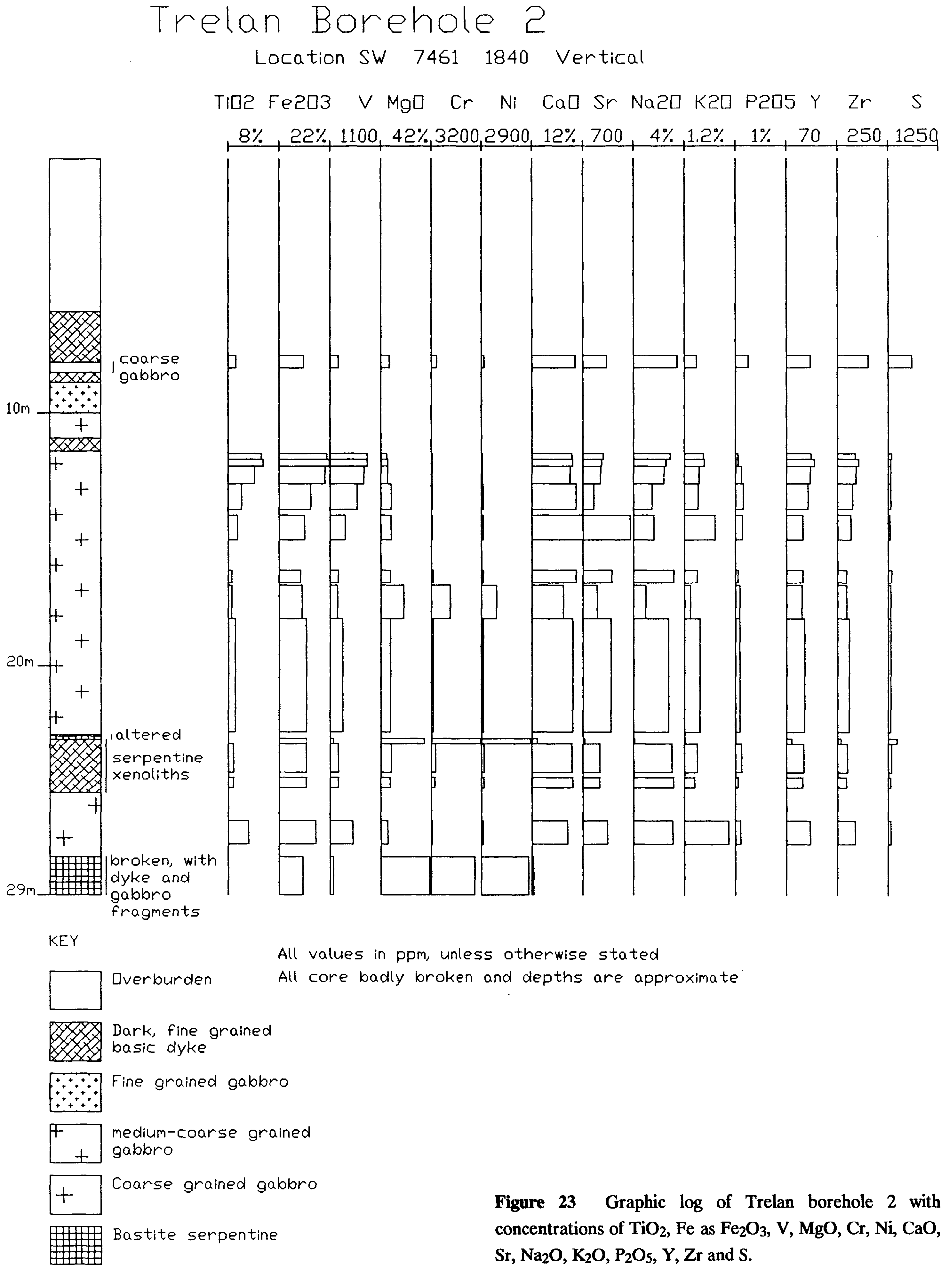


Figure 23 Graphic log of Trelan borehole 2 with concentrations of TiO_2, Fe as Fe_2O_3, V, MgO, Cr, Ni, CaO, Sr, Na_2O, K_2O, P_2O_5, Y, Zr and S.

Borehole 2
Borehole 2 is composed almost entirely of coarse-grained gabbro, similar to that found in borehole 1. Apart from dykes described below, there are also two horizons of highly altered bastite serpentinite.

Borehole 3
The upper part of this borehole consists largely of coarse-grained gabbros, similar to those in borehole 1, with several zones of fine granular rocks, some of which are clearly associated with shear zones. In the section between 55 and 65 m the rocks are extremely altered with extensive carbonate impregnation and carbonate veining. The original rock type can usually be determined but little other information gained. The zone represents a tectonic contact between gabbros and a sequence in which ultramafic rocks predominate. No metallic mineralisation is associated with the carbonate.

Several distinct rock types occur in a section around a major shear zone near 90 m. These include gabbro mylonites, similar to those in borehole 1, and distinctive ultrabasic rocks. The ultrabasic rocks are extensively altered to amphibole but numerous relict patches show that the original rock was a granular clinopyroxenite very similar to those from the Traboe boreholes (Leake and Styles, 1984). Also present in this zone are amphibolitised granular gabbros containing brown as well as the typical green amphiboles, characteristics again typical of rocks from the Traboe area and contrasting with gabbros from the rest of the Trelan boreholes where brown amphiboles are only seen in the coarse gabbros.

The lower part of the boreholes consists largely of the typical 'bastite serpentinite'. This is a variably serpentinised peridotite of the variety harzburgite consisting of large orthopyroxene crystals up to 5 mm in size, now partly or completely altered to bastite (platy lizardite serpentine) in a matrix of fine serpentine. The original fabric of the olivine is clearly shown in the serpentinite but no olivine relics have been found in these samples.

Close to the base of the hole at 111.7 m there are 1-2 cm white veins cutting the peridotite. Thin section shows that they are veins of clinopyroxenite that are now largely altered to amphibole. The peridotite adjacent to the veins contains large clinopyroxenes as well as the normal orthopyroxene making this a lherzolite rather than a harzburgite though it is possible that this is a consequence of local metasomatism associated with the pyroxenite veining.

Borehole 4
Borehole 4 is composed entirely of medium to coarse-grained gabbros showing features very similar to those described above. The abundance of Fe-Ti oxides is marked in several horizons in this borehole, particularly near the bottom.

Dykes
The basic dykes found in the lower part of borehole 1 (Figure 22) consist of microphenocrysts of plagioclase in a fine dark matrix containing conspicuous oxide mineral grains. Both the plagioclase and the matrix are very altered such that matrix constituents cannot readily be identified. In the least altered parts a subophitic or variolitic texture can be seen and an amphibole can be identified in the groundmass. Larger phenocrysts or xenocrysts up to 2 mm are also sparsely present. Veins of

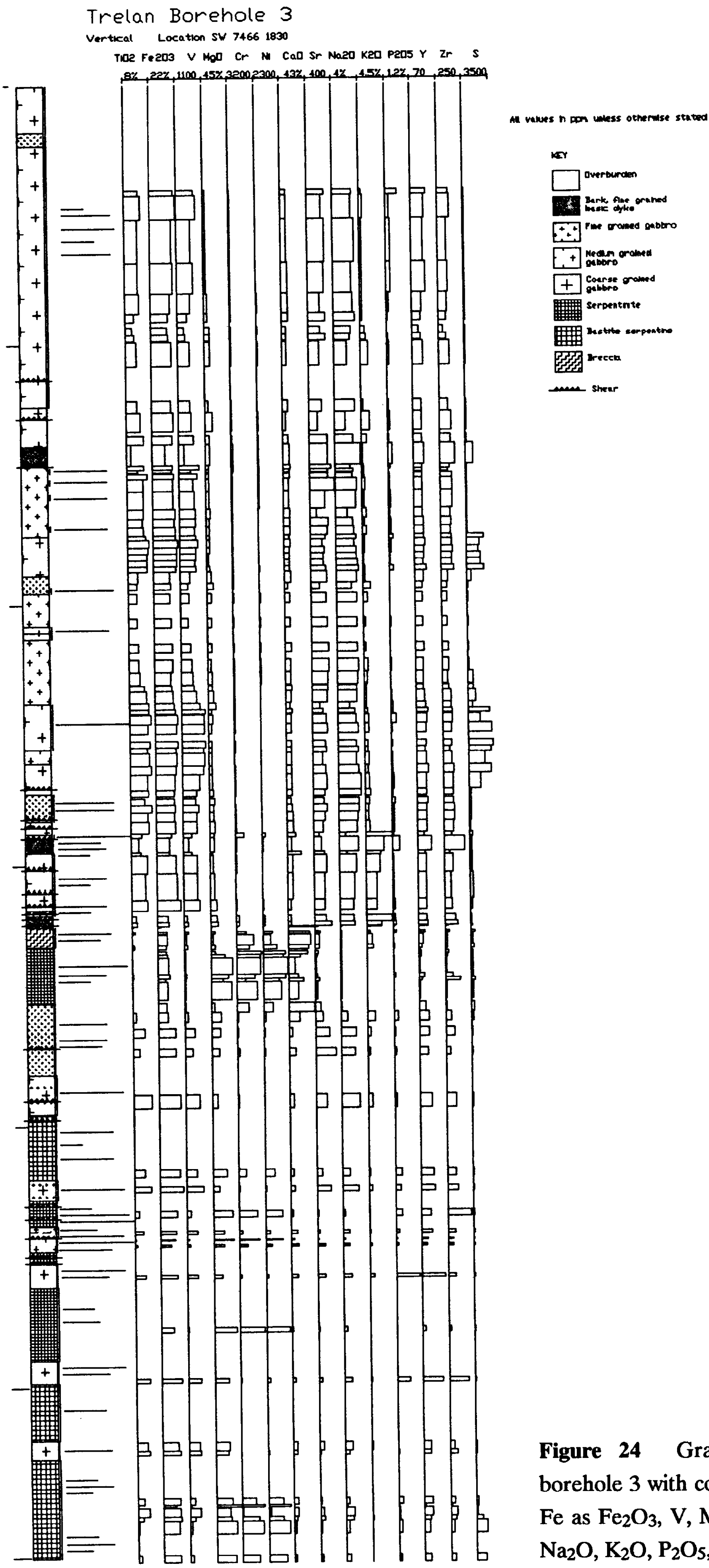


Figure 24 Graphic log of Trelan borehole 3 with concentrations of TiO_2, Fe as Fe_2O_3, V, MgO, Cr, Ni, CaO, Sr, Na_2O, K_2O, P_2O_5, Y, Zr and S.

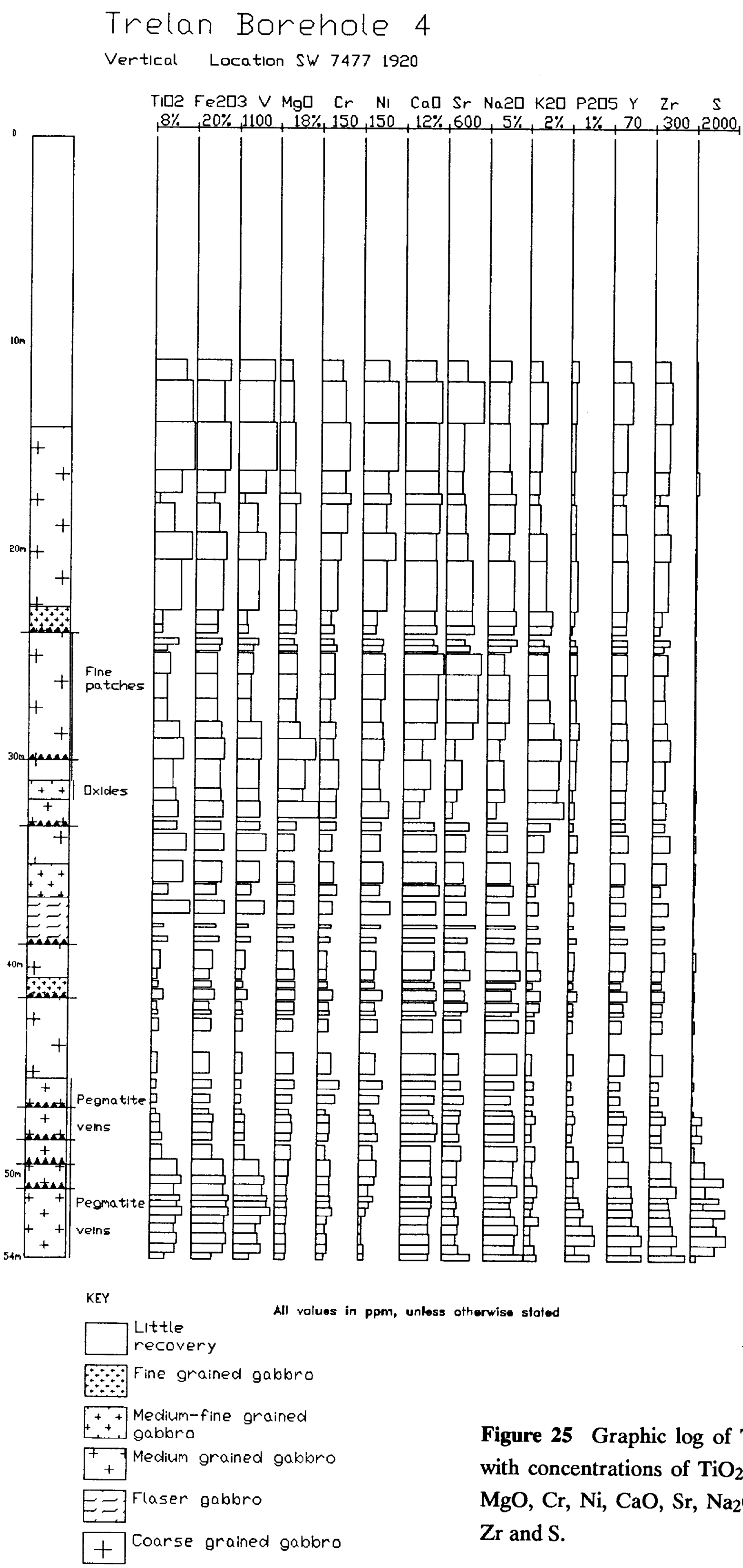


Figure 25 Graphic log of Trelan borehole 4 with concentrations of TiO_2, Fe as Fe_2O_3, V, MgO, Cr, Ni, CaO, Sr, Na_2O, K_2O, P_2O_5, Y, Zr and S.

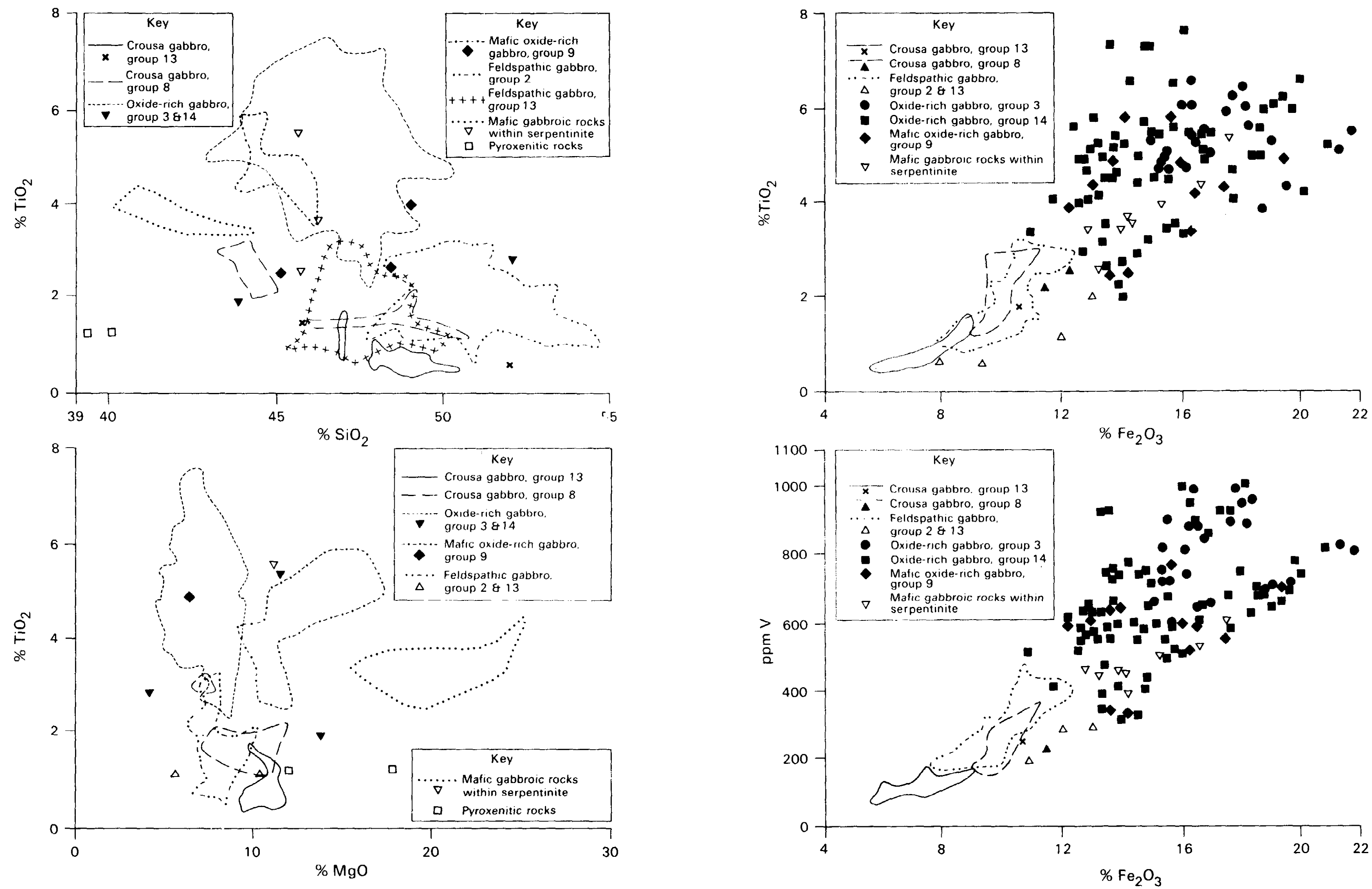


Figure 26 Scatter plots of element pairs TiO_2-SiO_2, TiO_2-MgO, TiO_2-Fe_2O_3 and V-Fe_2O_3 in Trelan core samples showing fields occupied by various cluster groups.

carbonate and prehnite, of the type found in the gabbros, also cut the dykes. The basic dykes in the top of borehole 2 (Figure 23) are much less altered than those in borehole 1. A sample from 11 m consists of plagioclase laths (100-150 microns) in a subophitic intergrowth with green hornblende after clinopyroxene containing a few remnants of the origin mineral. Scattered small grains of ilmenite are also present. One of the dykes in borehole 2 contains xenoliths of serpentinite.

Mode of occurrence of Fe-Ti oxides

The Fe-Ti oxide minerals ilmenite and magnetite occur in all the gabbroic rocks but with a considerable range in modal abundance from < 1% to > 10%. When the proportion is low they tend to occur as isolated scattered grains as is typical in most gabbros but when the proportion is high their mode of occurrence is different and of particular interest.

The rocks with abundant opaque oxides usually have ilmenite as the dominant phase and only rarely is magnetite other than a minor constituent. Abundant oxides usually occur in medium to coare-grained gabbro in grains similar in size to other minerals, i.e. 1-3 mm. The textures of these gabbros shows that they crystallised as a framework of plagioclase and augite with interstices filled with ilmenite, lesser magnetite and minor apatite and biotite. The distribution of ilmenite is not, however, random, as might be expected from simple *in situ* crystallisation, but often occurs in clusters or vein-like growths. Only a few samples contain ilmenite with holly-leaf type textures which might be attributed to *in situ* crystallisation. These features suggest that some kind of filter-pressing mechanism might have caused the coalescence of ilmenite and magnetite-rich liquid prior to crystallisation. The ilmenites almost invariably have narrow reaction coronas around their margins, particularly where they are in contact with clinopyroxene. The coronas are composed of hornblende and suggest that there has been some reaction between iron-rich liquid and previously-formed silicates. The presence of apatite and biotite along with the ilmenite suggests that these are also differentiates of the gabbroic melts. The mode of occurrence and pattern of distibution of these aggregates suggest that they may have formed as pockets of differentiated Fe-rich liquid that have accumulated ilmenite and magnetite and, due to external stresses, have undergone localised injection into surrounding gabbros to form the vein-like masses now seen.

Mineral chemistry

Eighteen polished thin sections of the gabbroic rocks were selected for electron microprobe study to determine the compositions of the oxide minerals and to compare the composition of silicate minerals with those found in the Crousa gabbro.

Clinopyroxene

Analyses of clinopyroxene showed all to be augites with little variation in composition in samples from boreholes 1-3 and the upper part of borehole 4 (Figure 28). They show a narrow range of Mg-Fe variation which indicates a limited amount of fractionation of the magmas. A much greater range of Ca variation was found which is largely a temperature effect due to some reequilibration during the slow cooling of a plutonic body. A few of the oxide-rich samples from the lower part of borehole 4 had, in addition to clinopyroxene of typical composition, much more Fe-rich compositions showing that locally there had been fractionation to more Fe enrichment. The data for clinopyroxene compositions from the Crousa gabbro from Kirby (1978) are also plotted in Figure 28. There is no overlap in composition between the two, which indicates that the Crousa and

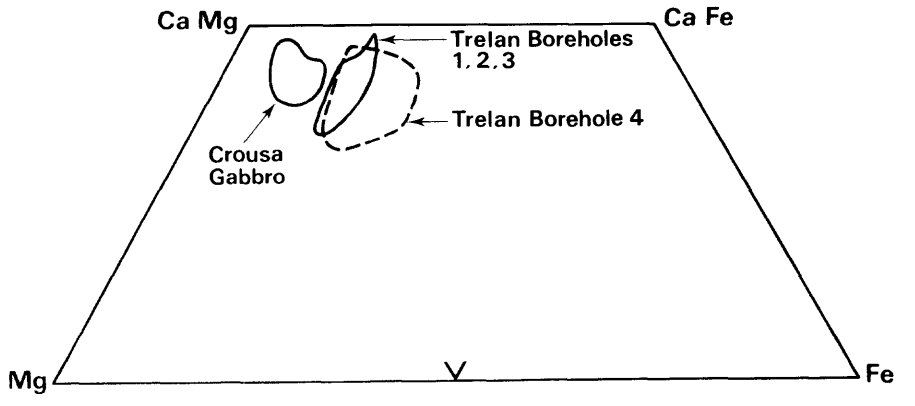


Figure 27 Clinopyroxene compositional fields from Trelan boreholes compared with those from Crousa gabbro (data from Kirby, 1978) plotted on part of Ca-Mg-Fe triangular diagram.

Trelan gabbros are separate bodies. The Crousa gabbro pyroxenes are more magnesian and therefore presumably more primitive, while the Trelan gabbros, if related to the Crousa gabbro, are derived from a more fractionated source. The Fe-rich pyroxenes from borehole 4 possibly show a continuation of this fractionation trend.

Plagioclase

Interpretation of the plagioclase analyses is complicated by alteration to more albitic compositions due to hydrothermal alteration. In all samples from the boreholes it is assumed that the apparently fresh grains giving the most calcic compositions represent the original magmatic plagioclase. The probe analyses indicate that the original composition of plagioclase was in the range An30-40 with a few compositions up to An50. The data from Kirby (1978) show that plagioclase from the Crousa gabbro ranges from An50-70 in composition while Shepherd (1986) found the range An50-56 in similar material. As with the clinopyroxene, there is no overlap in plagioclase composition between the Trelan and Crousa gabbros and a more primitive origin is indicated for the latter. The only exceptions to this were a few more fractioned gabbros from the Crousa gabbro in Dean quarry in which a plagioclase composition of An32-35 was found by Shepherd (1986). In bulk chemistry these rocks show significant differences from the Trelan rocks, as described above.

Ilmenite and magnetite

Analyses of ilmenites and magnetites are shown in Tables 3 and 4 and the patterns that emerge are typical of gabbros. The ilmenites typically contain around 0.5% V_2O_3 by weight while in the magnetites the vanadium content is much higher, often 2-3% and sometimes up to 5% V_2O_3. Most of the vanadium in the oxide-rich gabbros is therefore accomodated in the ilmenite and for very high levels of V to be reached a high magnetite content is required. The magnetites normally have coarse exsolution of ilmenite and probe analyses of the magnetite between lamellae with a fine electon beam (2-3 micron) give a low Ti content of up to about 2%, though prior to exsolution the original Ti content of the magnetite would have been much higher.

ECONOMIC POTENTIAL OF THE LIZARD

Ilmenite and magnetite in gabbro

A substantial amount of oxide-rich gabbro (defined as containing more than about 4% TiO_2) was intersected in the Trelan holes, comprising 26% of borehole 1, 64% of borehole 3 above the contact with ultramafic rocks and 54% of borehole 4. However, the concentrations of magnetite and ilmenite do not reach levels sufficiently high to be comparable to economic deposits of magmatic ilmenite within anorthosite-gabbro-ferrodiorite massifs, which contain at least 18% TiO_2 (Force, 1991). The textural evidence of the operation of a filter pressing mechanism on a Fe and Ti-rich differentiate suggests that the potential for greater concentrations of oxide exists in the area. However, the distribution of the oxide-rich fraction in the boreholes suggests that the process operated only on a local scale and that it is unlikely to have developed sufficiently for the coalescence of a large volume of residual Fe-rich liquid. Though it proved impracticable to site any of the holes directly on the peak of a magnetic anomaly, it is considered probable that the range in oxide content of the rock intersected in the holes is typical of the area in general. This is likely as the range of concentrations of Ti and V in the core is similar to the range found in the power augering sampling. The greatest concentration of ilmenite (7.6%TiO_2 over 2.3 m) occurs at the top of borehole 4, which is furthest north and considered to be at a higher level in the complex than the other holes.

Table 3 Chemical analyses of ilmenites

Trelan Boreholes 1 and 2

TiO_2	50.07	51.12	51.95	44.54	52.83	50.77	49.50	53.04
V_2O_3	0.53	0.29	0.50	0.26	0.00	0.33	0.00	0.00
FeO	47.37	47.42	46.32	51.78	45.43	46.18	47.50	44.19
MnO	0.62	0.81	0.69	0.91	1.12	0.89	1.23	0.68
MgO	0.54	0.64	0.76	0.63	0.23	0.39	0.00	0.37
Total	99.12	100.28	100.22	98.11	99.61	98.56	98.24	98.28

Number of ions on the basis of 6 oxygens

Ti	1.933	1.946	1.967	1.789	2.007	1.963	1.939	2.031
V^{3+}	0.022	0.012	0.020	0.011	0.000	0.014	0.000	0.000
Fe^{2+}	2.034	2.007	1.950	2.313	1.920	1.985	2.068	1.881
Mn	0.027	0.035	0.029	0.041	0.048	0.039	0.054	0.029
Mg	0.041	0.048	0.057	0.050	0.017	0.030	0.000	0.028
Total	4.056	4.048	4.023	4.205	3.993	4.030	4.061	3.969

Trelan boreholes 3 and 4

TiO_2	50.58	51.65	50.99	51.60	53.16	52.54	51.80	52.20
V_2O_3	0.52	0.00	0.48	0.37	0.64	0.77	0.42	1.10
FeO	46.15	47.14	45.89	45.29	46.30	45.58	47.32	47.45
MnO	0.89	0.76	0.91	0.80	1.04	0.77	0.86	0.73
MgO	0.91	0.48	0.57	0.63	0.63	0.97	0.37	0.33
Total	99.04	100.02	98.84	98.69	101.77	100.63	100.76	101.80

Number of ions on the basis of 6 oxygens

Ti	1.944	1.967	1.962	1.981	1.978	1.973	1.960	1.953
V^{3+}	0.021	0.000	0.020	0.015	0.025	0.031	0.017	0.044
Fe^{2+}	1.973	1.997	1.964	1.933	1.916	1.903	1.991	1.974
Mn	0.039	0.033	0.039	0.035	0.043	0.033	0.036	0.031
Mg	0.069	0.036	0.043	0.048	0.047	0.072	0.028	0.024
Total	4.045	4.033	4.028	4.012	4.009	4.012	4.032	4.025

Table 4 Chemical analyses of magnetites Trelan Boreholes 1 and 2

TiO_2	1.11	0.94	0.69	0.93	0.47	4.41	1.43	2.00
Al_2O_3	0.65	1.17	2.42	2.21	0.56	1.47	1.09	1.57
Cr_2O_3	0.00	1.04	0.42	0.00	0.00	0.00	0.00	0.00
V_2O_3	1.85	3.64	3.66	2.46	2.29	1.63	3.13	2.32
Fe_2O_3*	64.09	58.42	57.02	58.88	63.49	55.55	58.77	58.32
FeO*	30.66	32.78	34.50	33.46	29.97	33.33	33.53	32.17
MnO	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00
MgO	0.24	0.64	0.34	0.33	0.71	0.45	0.20	0.73
Total	98.59	98.63	99.06	98.25	97.49	97.02	98.15	97.12

Number of ions on the basis of 32 oxygens

Al	0.238	0.960	1.891	1.837	0.546	1.148	0.921	1.320
Ti	0.258	0.494	0.346	0.491	0.292	2.201	0.768	1.071
Cr	0.000	0.574	0.220	0.000	0.000	0.000	0.000	0.000
V^{3+}	0.458	2.036	1.949	1.391	1.511	0.864	1.794	1.326
Fe^{3+}	14.929	11.771	11.452	12.119	13.561	11.090	12.267	11.885
Fe^{2+}	7.936	7.338	7.699	7.651	7.111	7.394	7.778	7.284
Mn	0.000	0.000	0.000	0.000	0.000	0.103	0.000	0.000
Mg	0.109	0.663	0.340	0.345	0.877	0.448	0.213	0.777
Total cats	23.929	23.835	23.898	23.835	23.898	23.248	23.741	23.663
Total 3+	15.883	15.835	15.858	15.838	15.910	15.303	15.750	15.602
Total 2+	8.045	8.001	8.039	7.997	7.988	7.945	7.991	8.062

Trelan boreholes 3 and 4

TiO_2	1.21	1.30	0.72	1.26	0.64	1.10	1.87	2.17
Al_2O_3	1.00	0.87	1.23	0.77	1.68	1.16	1.57	1.89
Cr_2O_3	0.00	0.00	0.38	0.00	0.00	0.00	0.00	0.00
V_2O_3	2.99	3.23	2.19	1.81	4.71	3.95	1.56	1.52
Fe_2O_3*	62.58	58.48	60.76	61.70	58.75	58.60	60.34	59.54
FeO*	30.46	32.81	31.98	32.34	29.88	31.51	34.73	34.41
MnO	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00
MgO	0.28	0.26	0.48	0.32	1.31	0.83	0.00	0.23
Total	98.51	96.94	97.74	98.20	97.22	97.15	100.08	99.74

Number of ions on the basis of 32 oxygens

Al	0.362	0.753	1.101	0.703	1.419	0.984	1.308	1.537
Ti	0.280	0.715	0.412	0.732	0.342	0.597	0.993	1.127
Cr	0.000	0.000	0.230	0.000	0.000	0.000	0.000	0.000
V^{3+}	0.740	1.897	1.327	1.119	2.700	2.287	0.883	0.841
Fe^{3+}	14.531	12.391	12.781	13.177	11.422	11.921	12.493	12.114
Fe^{2+}	7.861	7.724	7.474	7.673	6.453	7.122	7.988	7.778
Mn	0.000	0.000	0.000	0.000	0.151	0.000	0.000	0.000
Mg	0.128	0.285	0.543	0.365	1.401	0.897	0.000	0.232
Total cats	23.903	23.765	23.868	23.769	23.887	23.807	23.665	23.627
Total 3+	15.913	15.755	15.851	15.730	15.882	15.788	15.677	15.618
Total 2+	7.989	8.009	8.017	8.038	8.005	8.019	7.988	8.009

Magnetite, though often highly vanadiferous, appears to be much less abundant than ilmenite in the Trelan gabbros. Concentrations of Fe are highest in borehole 2 and at the top of borehole 3. Maximum vanadium concentrations in the core reach 0.17% V_2O_5 and in borehole 4, 13.2% of the core contains between 0.16 and 0.17% V_2O_5. There is no further enhanced concentration of oxide or vanadiferous magnetite in association with the zone at the bottom of borehole 4, which exhibits Fe enrichment in pyroxenes. Furthermore, sections showing relative enrichment in apatite, a mineral often found in magnetite-rich rock, in the bottoms of boreholes 1 and 4 are depleted in oxide minerals relative to adjacent material. There may be additional concentrations of magnetite which give rise to the narrow high amplitude magnetic anomalies, but these would have to be very localised and of limited extent. There is no evidence of enrichment of vanadium in the near surface rock due to weathering or alteration processes or of its depletion due to the transformation of magnetite into goethite, a mineral unable to accomodate as much vanadium as magnetite.

The upper part of the Traboe cumulate complex (Leake and Styles, 1984), if preserved, may have greater potential for significant concentrations of magnetite and perhaps ilmenite. This may be concluded from the presence of thin but very magnetite-rich layers in the Traboe borehole 3 within what is probably at a relatively low level in the gabbroic part of the complex. This rock has more potential for cumulate enrichments of magnetite, of the sort which occurs in the Bushveld complex, than the Trelan gabbro. The full extent of the subcrop of the Traboe cumulate complex and its northern contact are not yet known, as the area is intensively farmed and there are no exposures.

Other mineralisation

Precious metals

Concentrations of Pt, Pd, Rh and Au have been determined by fire assay followed by ICP-MS at Acme Analytical Laboratories in Vancouver, Canada in 84 10 g subsamples of all rock types within the Trelan boreholes, including oxide-rich, carbonate-rich and sulphide-bearing rocks. In all these samples, concentrations of these elements were at background levels (1-6 ppb Pt, 2-7 ppb Pd, 2-4 ppb Rh and 1-4 ppb Au). Analyses of 11 samples from the lower part of Traboe borehole 3 (Leake and Styles, 1984) gave somewhat higher concentrations of Pd (up to 21 ppb). A significantly higher concentration of precious metals (Pt 50 ppb, Pd 93 ppb and Au 28 ppb) was found in a sample of gossan, a few cm thick, derived from Ni and Cu-rich sulphide from near the northern boundary of the Lizard complex at Porthallow. The gossan appears to be structurally controlled, trending roughly east-west and parallel to boundary faulting in coastal exposures at Porthallow.

Placer concentrations of Fe-Ti oxides and other minerals

The Crousa gravel *sensu stricto* does not have any potential as a source of Fe-Ti oxides, as it was derived from material exotic to the Lizard. However, cassiterite does occur, with Sn concentrations up to 198 ppm measured in a sample from its base, but volumetrically the amount present is likely to be low.

The area to the south of Trelan does have some potential as an ilmenite resource because of the deeply weathered and soft nature of the top few metres of rock. In the core drilling it proved impossible to recover core from above about 8 m depth, while power augering in 57 holes in oxide-rich material penetrated on average to 3.8 m. This soft weathered rock can be considered as an ilmenite resource in its own right, especially if some residual concentration of oxide has occurred. It may also have been a significant source of relatively coarse-grained ilmenite which was dispersed during a previous climatic regime in drainage and hence into estuarine sediment surrounding the Lizard to the north and east .

The presence of other sources of ilmenite in rock and residual or transported overburden in the northern part of the Lizard is also possible in view of the abundance of the mineral in the streams draining north into the Helford River and the presence of a watershed between there and the Trelan area.

Volcanogenic mineralisation

The geochemistry of the limited Minuteman sampling in the north of the area suggests some potential for exhalative or sea-floor mineralisation. The data suggest that sedimentary rocks are intimately interlayered with mafic igneous rocks. As the chemistry of the sediments is unusual, with high concentrations of Ba, particularly in relation to K in siliceous sediment, it is possible that the sequence represents volcanic rocks and sea-floor sediment containing a significant chemical component. Stratiform concentrations of Cu-rich sulphide are possible in such an environment. Structurally this area appears very complex with rapid alternation of igneous and sedimentary rocks and no continuity along strike, probably due to tectonic interleaving in an imbricate zone. It is unlikely that more than minor amounts of sulphide would be traceable in such a complex geological environment.

ACKNOWLEDGEMENTS

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