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Mineral Reconnaissance Programme

Exploration for volcanogenic mineralisation in south-west Wales

Department of Trade and Industry

MRP Report 137

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T B Colman, G E Norton, B C Chacksfield,
D C Cooper and J D Cornwell

BRITISH GEOLOGICAL SURVEY

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SUMMARY

South-west Wales has extensive and voluminous extrusive and intrusive volcanic rocks of Ordovician age interbedded with black shales and other sedimentary rocks, a sequence which has proved to contain economic base-metal deposits in other areas of the British Isles and elsewhere. No significant mineral deposits are known in the area apart from a small lead mine at Llanfyrnach which was abandoned in the last century. The Mineral Reconnaissance Programme has completed several projects in the area in the past 20 years and this report is a compilation of data collected during the programme but not previously published, together with data from additional new investigations in the Treffgarne, Crosswell and Llangynog areas.

Regional interpretations of the geophysics (gravity and aeromagnetics), lithogeochemistry and petrogenesis are presented in the report. These include the physical properties of many of the rock types and a study of the rare-earth-element (REE) contents of examples of the volcanic rocks to determine their origin and their potential for volcanogenic massive sulphide (VMS) and precious-metal mineralisation.

More detailed investigations were carried out in the Treffgarne area, following on from earlier MRP work which included the drilling of three cored boreholes. The published summary report (Brown et al., 1987) contained little data as these were in a separate unpublished dataset which was later released on open file. The current report publishes some of the results of the earlier work, including details of the drilling. No sulphides other than pyrite were found during the earlier survey but up to 8.6% Ba (as baryte) was found in rhyolite lavas and tuffs in Borehole 1 on Dudwell Mountain. This prompted further investigations, described in this report, which included additional soil geochemistry coupled with geophysical techniques not used in the earlier survey. The aim was to investigate the possibility that volcanogenic mineralisation at depths of up to 100 m may occur between the widely spaced lines of the initial survey. Geophysical methods included gravity, electromagnetic (EM) and self-potential (SP). Although no significant base-metal mineralisation was located, massive baryte and disseminated pyrite were found in a metre-wide zone of hydrothermal alteration in Rock Farm Quarry at the western end of the Roch Rhyolite Group.

Work in the Crosswell area showed anomalous levels of Ba in soil (exceeding 2000 ppm). There, coincident strike-parallel EM conductors are associated with black shales overlying volcanic rocks of the Fishguard Volcanic Group.

A regional lithogeochemical survey demonstrated that the Sealyham Volcanic Group contains acid volcanic rocks with similar intensity of alteration to that observed in the Treffgarne area; it may also be prospective for volcanogenic mineralisation.

Further work is recommended in a number of districts including the ground from Plumstone Mountain to Rock Farm Quarry in the Treffgarne area, the Crosswell locality and parts of the Sealyham Volcanic Group.

INTRODUCTION

South-west Wales is an attractive area for the discovery of volcanogenic sulphide and precious metal mineralisation based on comparisons with known producing areas in a similar geological setting, such as Parys Mountain in Anglesey, Avoca in Ireland and Buchans in Newfoundland. The area contains an Ordovician succession dominated by argillaceous sedimentary rocks interspersed with dominantly submarine volcanic rocks and cut by intrusions associated with the volcanic events. The volcanics formed within a back-arc marginal basin and include both calc-alkaline and tholeiitic magma types (Bevins et al., 1992). The volcanic rocks are associated with voluminous epiclastic sedimentary rocks, including black shales and turbidite mudstone deposits. These are often pyritic and form suitable hosts for preserving stratiform mineralisation. No significant mineralisation has been worked in the area, apart from at the Llanfyrnach lead mine, but the lack of inland exposure and extensive drift cover has made discovery of mineralisation from surface outcrop unlikely. Thus, integrated programmes of geochemistry, geophysics and surface drilling, aided by conceptual thinking, are required to explore the full mineral potential of the area.

The Mineral Reconnaissance Programme (MRP) has carried out a number of exploration projects in the area. This report contains an evaluation of the major groups of volcanic rocks based on geological reconnaissance and geochemistry, with additional detailed work over the Roch Rhyolite Group which initial studies suggested was one of the most prospective volcanic horizons.

Planning and development framework

The area has a mild climate and well-developed infrastructure, enabling year-round exploration with easy access. The coast and an area generally up to 2 to 3 km inland, together with the Preseli Mountains, are within the Pembrokeshire Coast National Park. In the Treffgarne area the National Park extends as far inland as Roch, close to the south-west limit of the survey area. Any developments within the National Park, or in adjacent areas which are visible from it, would be subject to stringent planning controls judged on the National Need and possible adverse public opinion. However the inland areas, such as Treffgarne, are of less perceived scenic value and developments would be considered within the county planning framework (Colman, 1990). Existing major developments in this part of south-west Wales include the oil refinery complexes at Milford Haven, the ferry port of Fishguard, RAF Brawdy airfield and the recently closed Trecwn armaments store, south of Fishguard. The area has a well-developed road network and access is good. The upland areas are generally open moorland with few walls or fences.

Geology

South-west Wales contains rocks ranging from Neoproterozoic to Carboniferous in age. In the north the dominant rocks are Ordovician in age whilst, in the south, Devonian and Carboniferous rocks predominate (Figure 1). The oldest rocks are the Neoproterozoic igneous intrusive and extrusive rocks of the Avalonian calc-alkaline volcanic arc complex of the St David's area and the Johnston Igneous Complex (Anderton et al., 1992). They include the Ramsey Sound Group (Pharaoh and Gibbons, 1994) and the Benton Volcanic Group which are both described later. The Coomb Volcanic Formation, a small inlier of rhyolitic lavas and breccias cropping out at Llangynog, south-west of Carmarthen, is also believed to be of Neoproterozoic age (Cope and Bevins, 1993).

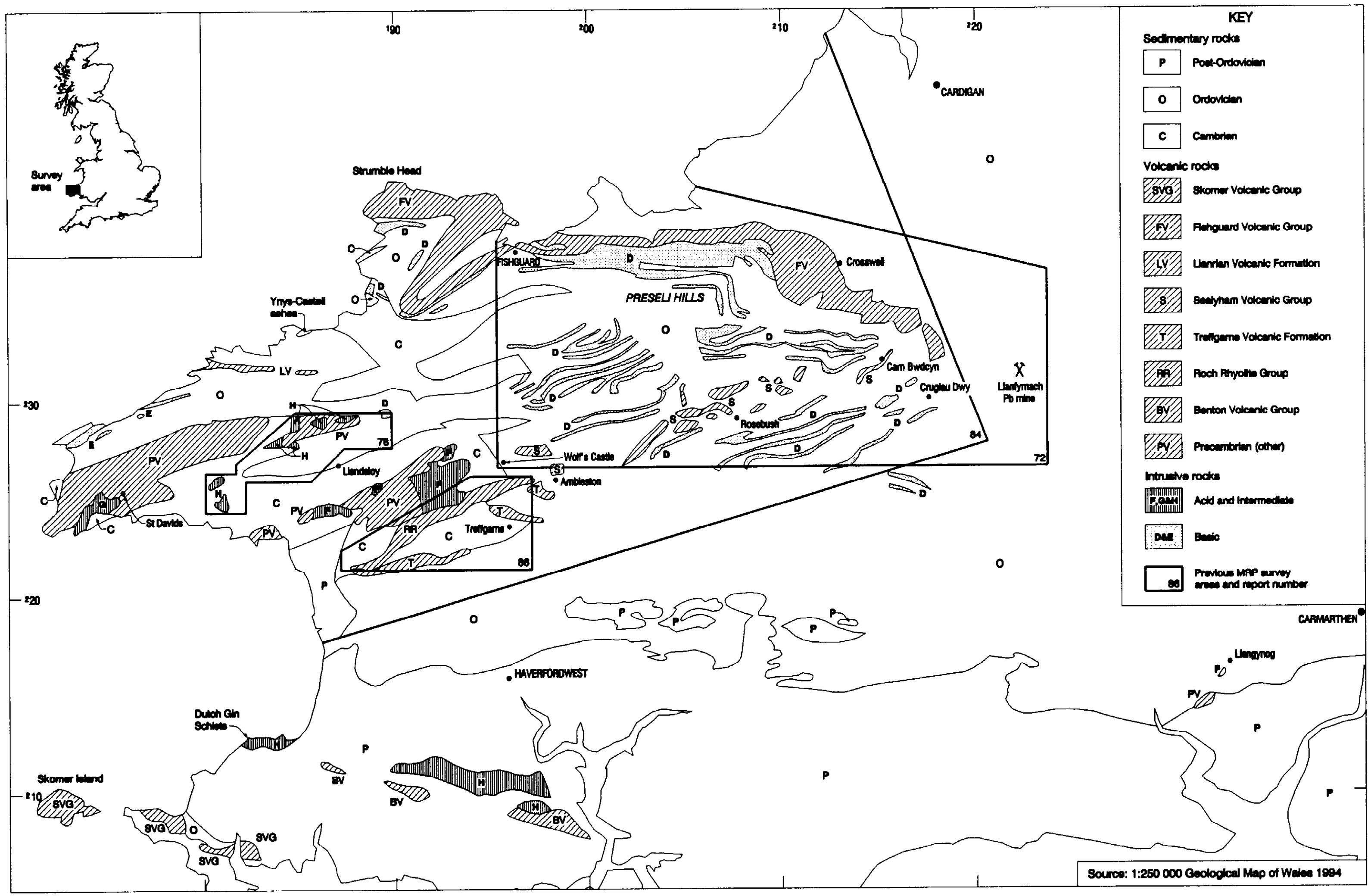

Figure 1 Generalised geology of south-west Wales showing main outcrops of Lower Palaeozoic volcanic rocks

The area lies at the southern end of the Lower Palaeozoic Welsh Basin, which developed on late Precambrian basement. The basin shows both shoreline and deeper-water Cambrian facies, ranging from basal conglomerates through sandstones to black shales with minor tuff bands, the only evidence of Cambrian volcanism in the area. The main Cambrian exposures are of the Upper Cambrian Merioneth Series. The Ordovician sequence is composed mainly of mudstones and shales, with extensive and voluminous interbedded basaltic to rhyolitic lavas and tuffs of Arenig to Llanvirn age whose composition suggests eruption in an extensional, marginal basin setting (Bevins, 1982). The individual volcanic units are described in more detail later, together with their petrogenesis and mineral potential. In the south of the area, Llandovery sedimentary rocks, together with the Skomer Volcanic Group, complete the Lower Palaeozoic sequence. Devonian siltstones and sandstones and Carboniferous limestones, sandstones and shales crop out in a belt to the south and, in the Broadhaven district, coal has been worked in a number of small pits.

Significant unconformities in the volcanosedimentary successions occur at the end of the Precambrian, Merioneth, Tremadoc, Ashgill and Silurian, within the Old Red Sandstone, and at the top of the Carboniferous. These are due to successive phases of opening and subsequent closure of mostly oceanic basins. Some workers have suggested that the tensional stage of the Welsh basin would have created a series of horst and graben structures on the margin of the basin, and would have led to differential sedimentation across the basin (Fitches and Campbell, 1987). Faults would have acted as pathways for the mobilisation of magmatic and hydrothermal fluids during the evolution of this terrain (Kokelaar, 1988). Volcanism had largely ceased by the end of the Llanvirn, and the later Ordovician sequence is composed mostly of sedimentary rocks.

The first major closure event recorded in the Lower Palaeozoic sequence is the climax of the Caledonian orogeny at the end of the Silurian. This produced several major north-east – south-west trending structures widely recognised in the Welsh Basin and on its margin. In the Pembrokeshire area, these lineaments are deflected to a mostly east–west strike direction. This area is dominated by two anticlinal axes: the east–west trending Velindre anticline with Fishguard Volcanic Group rocks along its northern limb, and the east–north-east trending Fishguard anticline. Tight, upright to gently-verging folds were created with associated axial planar cleavage. A series of major strike slip faults such as the Careg Cennen disturbance and the Church Stretton fault system seen further east is indicative of oblique closure of the Welsh Basin.

The postulated northern boundary of major Variscan disturbance runs through the south of the area along the Johnston – Benton thrust zone (Duff and Smith, 1992), and thrusting (particularly to the south of this line) juxtaposes rocks of contrasting ages, e.g. Devonian sandstones and the Precambrian Benton Volcanic Group (Figure 1).

Mining history and previous exploration

South-west Wales does not have an extensive history of mining activity. The only mine of note is that at Llanfyrnach in the extreme east of the area (Figure 1; [SN 225 316][1]). This mine produced more than 15000 tons of argentiferous lead concentrates and minor zinc from veins in Ordovician black shales (Hall, 1971). Foster-Smith (1981) records eight minor trials for copper, lead and gold in the

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[1] National Grid Reference

area. They include workings at Ramsay Head [SM 715 235], St. Elvis [SM 812 231], and near Crymmych [SN 813 339]. There is also a reference to trials for copper and gold near Treffgarne.

The Mineral Reconnaissance Programme conducted a literature survey in the 1970s which revealed references in scientific journals to a number of sulphide (mainly pyrite) bearing localities. This prompted three exploration programmes: (i) investigations of high-level intermediate intrusions in the Llandeloy area for porphyry-style copper mineralisation (Report 78; Allen et al., 1985); (ii) a reconnaissance drainage survey of the Preseli Hills (Report 72; Cameron et al., 1984); and (iii) an examination of the sedimentary and volcanic rocks of the Roch Rhyolite Group for indications of stratabound volcanogenic base-metal mineralisation (Report 86; Brown et al., 1987). These were complemented by an airborne geophysical survey of northern Pembrokeshire (Report 84; Cornwell and Cave, 1986).

In the Llandeloy area, 12 km south-west of Fishguard, rock and soil geochemistry together with IP, VLF-EM and magnetic surveys, identified anomalous zones associated with intermediate sheeted (tonalitic and dioritic) intrusions comparable with those carrying porphyry-style copper mineralisation in the Harlech Dome (Allen at al., 1985). Locally thick unconsolidated deposits up to 20 m thick and enriched in copper hampered surface exploration. Drilling revealed pervasive hydrothermal alteration of the intrusives over an area of at least 1 km^2 with patchy low-grade copper mineralisation reaching a maximum of 0.1% Cu over 3.4 m. The style of alteration (polyphase propylitic and local potassic) and mineralisation is consistent with the deeper levels of a porphyry copper system. There is only very weak and erratic enrichment in Mo, As, Pb and Zn.

Gold was not determined at the time of the original survey but subsequently 15 samples taken from six boreholes were analysed for gold and silver. These samples, all from the more highly altered and mineralised sections and containing 47–3515 ppm Cu, revealed a pervasive low level enrichment in gold (range 5–139 ppb) and one sample containing 649 ppb gold. This sample, from borehole two, consists of altered (quartz-chlorite-epidote) quartz microdiorite carrying minor chalcopyrite (696 ppm Cu) and pyrite disseminated through the rock and coated on fractures. Overall, there is a rough positive correlation between the gold and copper contents except that the sample containing the highest concentration of copper (3515 ppm) only contains a trace of gold (24 ppb). Silver concentrations are low (0.6–1.7 ppm) but at higher levels a correlation with the gold content is evident. These results, indicating that the mineralisation at Llandeloy is gold-bearing, extends the list of similarities with the more widely known porphyry-style mineralisation in the Harlech Dome (Rice and Sharp, 1976; Allen et al., 1976).

The reconnaissance stream-sediment survey of 350 km^2 of the Preseli Hills, east of Fishguard, covered the main outcrop of the Fishguard Volcanic Group, together with associated Lower Ordovician black shales and mudstones (Cameron et al., 1984). This showed base-metal and Ba anomalies associated with, and extending from, the Llanfyrnach lead mine. The survey also showed Ba anomalies in the Crosswell area, associated with the Fishguard Volcanic Group of Llanvirn age and overlying black shales. The black shales are considered to have been deposited on the lower flanks of a submarine volcano, enhancing the potential for the formation and preservation of sulphide mineralisation.

Descriptions of abundant pyrite and traces of copper in the Nant-y-Coy Formation (Roch Rhyolite Group) around Treffgarne (Thomas and Cox, 1924) and the geological setting led to reconnaissance geochemical and geophysical studies of the area. Strong IP chargeability anomalies, accompanied by weak geochemical anomalies in overburden, were used to site three boreholes, which found extensive hydrothermal alteration and strong pyrite mineralisation with some baryte (up to 3.9% Ba over

4.5 m), but no significant base-metal sulphides (Brown et al., 1987). Alteration and mineralisation is consistent with an exhalative, volcanogenic model. The locations of the boreholes are shown in Figure 9 and lithological and geochemical plots are shown in Appendix 3. The Treffgarne area has been re-examined as part of the current project and is described below.

The helicopter-borne geophysical survey was carried out over an area of 670 km^2 extending from St. David's to the Preseli Hills (Cornwell and Cave, 1986). Magnetic, VLF-EM and radiometric data were collected over rocks ranging in age from Precambrian to Carboniferous, including the Fishguard, Sealyham and Treffgarne volcanic groups of Lower Ordovician age; some ground follow-up was also undertaken. No features solely attributable to mineralisation were found, but interpretations of a number of features could include the possibility that they were caused by mineralisation. The Crosswell area, mentioned above, showed some negative strike-parallel magnetic anomalies. These were attributed to dolerite intrusions or metamorphosed pyritic mudstone.

LITHOGEOCHEMICAL RECONNAISSANCE SURVEY

Well-exposed sections of the principal outcrops of volcanic rocks of Ordovician or uncertain age were examined briefly for indications of mineralisation and hydrothermal activity. The locations of the main groups and formations examined are indicated on Figure 1. Samples from the Pebidian Volcanic Complex (including the Ramsey Sound Group) were also collected for comparative purposes. Magnetic susceptibility (units of 10^{-3} S.I.)and radiometric measurements (total gamma count) were taken at most outcrops to aid interpretation of airborne survey data (Appendix 1).

Rock samples were collected for chemical analysis from altered or mineralised outcrops to determine or confirm the style of alteration and presence of metalliferous enrichments. In addition, some samples of typical lithologies were taken from formations that are not well described, to establish the geochemical characteristics of the volcanism. 12 g powdered sub-samples of the crushed rocks were analysed by X-ray fluorescence spectrometry (XRF) for a wide range of elements (Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Rb, Sr Y, Zr, Nb, Mo, Ba, Pb and U). Gold was determined subsequently on 15 g samples by atomic absorption spectrometry (AAS), following dissolution of the powdered rock using aqua regia and MIBK extraction from the resulting solution. Major elements were also determined in some samples by XRF on fused glass discs. All analytical data are held on the MRP geochemical database from which they can be extracted in a variety of formats to meet user requirements.

A brief description of the lithological units and sections examined is given below. The Roch Rhyolite Group at Treffgarne is excluded as its mineral potential is examined in detail later in this report. Rocks from this group contained the highest Au values recorded in the reconnaissance samples, with a maximum of 597 ppb in a sample of vein quartz in flinty rhyolite from Treffgarne Gorge [SM 959 251]. In addition, 40 samples from three boreholes drilled into the Roch Rhyolite Group to the west of Treffgarne contained up to 2594 ppb Au, with 22 samples assaying >20 ppb. It is noteworthy that the highest Au values occur in Borehole 2 and Borehole 3, the boreholes with the least degree of visible alteration and silicification.

Benton Volcanic Group

This sequence of volcanic rocks outcrops in southern Pembrokeshire (Figure 1) within an important Hercynian structure, the Johnston–Benton thrust zone (Duff and Smith, 1992). The rocks have received little attention from geologists, perhaps because of their generally poor exposure. Their outcrop, field relations and petrography are described in the coalfield memoirs of the British Geological Survey (Strahan et al., 1914; Cantrill et al., 1916), and Thorpe (1982) mentions that one analysed aphyric rhyolite (71% SiO_2) is relatively K-rich (4.8% K_2O).

The group is generally believed to be of Precambrian age and Shackleton (1975) reports K-Ar ages of 613 and 625 Ma (from Dr. S. Moorbath) which support this view. However, field relations poorly constrain their age: they are overlain unconformably by the basal conglomerate of the Llandovery Rosemarket Beds (Cantrill et al., 1916) but otherwise boundaries are thrust or fault controlled.

No succession has been elucidated, but the rocks are described as felsites, banded and spherulitic rhyolites, rhyolitic breccias and tuffs interbedded locally with more basic (andesitic) tuffs (Strahan et al., 1914; Cantrill et al., 1916). Most of the rocks are described as heavily altered, with common chloritisation, silicification and secondary iron staining. No sulphide minerals have been recorded.

During this survey all exposures described by Strahan et al. (1914) and Cantrill et al. (1916) were visited, but some no longer exist or are badly degraded. Two new exposures were found and examined. One of these, in a working quarry at Walwyn's Castle [SM 871 109], provides better exposures of these rocks than any of the natural sections. The best natural exposures are in the grounds of Benton Castle [SN 002 068]. Sections examined included: (i) Benton Castle grounds and beach section on the Daugleddau estuary; (ii) outcrops in Benton Wood [SN 000 073] and north and west of Benton Farm [SM 993 073]; (iii) in a track north-east of Great Westfield [SM 970 082] and east of the same farm; (iv) by a stream at Rosemarket [SM 956 086]; (v) near Romans Castle, by Sydney Farm Lodge gate [SM 891 106] and in a drainage cut near Tierson Farm [SM 907 097]; (vi) in Walwyn's Castle Quarry [SM 871 109]; (vii) around Rosepool [SM 861 114] and (viii) in the sunken road at Talbenny [SM 847 122]. Samples for chemical analysis were collected from all these localities except Benton Castle and Talbenny. These comprised eight rhyolites, locally silicified and quartz veined, and eight andesitic lavas and tuffs, two of which were deeply weathered.

The sections examined suggested that the proportion of tuffs, tuffites, mudstones and basic volcanic rocks in the succession is greater than indicated by previous descriptions of these rocks. This is probably due to selective sampling because the rhyolitic rocks form upstanding features and tor-like outcrops. The succession is much disrupted by faulting and may comprise a series of thrust slices. At least locally, the upward succession appears to consist of andesitic lavas and tuffs, mudstones, acid volcanic rocks with subordinate andesitic tuffs and mudstones, tuffites and mudstones. No sulphide mineralisation was seen and no evidence of alteration which might suggest such mineralisation in the vicinity. Radiometric measurements (6–12 μR/hr from basic and intermediate rocks and 11–18 μR/hr from rhyolitic lithologies) suggested no unusual concentration of radioactive minerals. Predictably low magnetic-susceptibility values were associated with the rhyolites (<0.01–0.68), but that some andesitic lavas were appreciably magnetic. The most magnetic measurements (maximum 12.3) came from a porphyritic andesite in Walwyn's Castle Quarry containing the highest Ti (1.19%), Fe (10.57%) and Zn (136 ppm) levels recorded in the group, suggesting the presence of appreciable amounts of Fe-oxides. However, the chemical analyses of rock samples indicated an absence of any base-metal enrichments above levels typical of these lithologies. A silicified rhyolite from west of Benton Farm containing low levels of transition metals and Sr is possibly enriched in Rb (201 ppm) and Ba (860 ppm), but Au is low (<10 ppb). On the basis of these results it was therefore concluded that no further work was merited on this group.

Dutch Gin schists
These quartzose metasedimentary rocks which crop out on the west coast of southern Pembrokeshire and to the west of the Benton Volcanic Group (Figure 1) appear to be closely associated with the late Precambrian Johnston Complex of intermediate to acid intrusions (Patchett and Jocelyn, 1979; Thorpe 1970, 1982). They have been interpreted as greenschist facies metasediments (Claxton, 1963) and foliated and mylonitised rocks from the Johnston Complex (Baker et al., 1968).

Three analysed rocks (RPR 221–223) from the coastal section at Dutch Gin [SM 818 126] revealed an acid (SiO_2 68–75%) and sodic (Na_2O 4.6–5.9%) composition, consistent with the interpretation of Baker et al. (1968). There were no indications of metalliferous enrichments.

Coomb Volcanic Formation

These rocks occur as small inliers within an area about 5 km by 0.5 km centred 8 km south-west of Carmarthen. They consist of rhyolitic and andesitic lavas, breccias and tuffs, with minor basic volcanics and a small intrusion at Lambstone [SN 336 160]. They were described by Cantrill and Thomas (1906) and later by Strahan et al. (1909), who ascribed an Ordovician (Arenig) age to them, based on the occurrence of similar tuffs in the Arenig succession elsewhere in the district; the observed contacts being everywhere faulted or unconformable. Strahan et al. (op. cit.) admit the possibility that they may belong to "some much older group of rocks not visible elsewhere in the neighbourhood". However, Cope (1977) and Cope and Bevins (1993) place the Coomb Volcanic Formation in the late Precambrian on the basis of the discovery of medusoid fossils of Ediacaran age in volcaniclastic siltstones interbedded with basalt lavas above the 400 m thick rhyolite succession. No radiometric dates are available for the igneous rocks of the inlier.

Interest was aroused in the area from descriptions in Cope (1982) who mentions an abundance of small pyrite cubes in Precambrian rhyolite at Allt-y-Crug [SN 3626 1565] and Strahan et al. (1909) who describe pyrite in the "diabase" exposed in the road east of Pentrenewydd Farm [SN 3232 1370]; the latter exposure is no longer visible. These sulphide occurrences and the descriptions of thick rhyolites and rhyolite breccias around Castell Cogan [SN 3270 1400] were considered worthy of investigation for volcanogenic mineralisation. Thirteen rock samples from all the major igneous lithologies, of which five were analysed for major elements, and 16 soil samples on two short lines were collected during a brief visit. No sulphides other than pyrite were seen. A rhyolite sample from a forestry road at Castell Cogan [SN 3255 1415] contained a 2 cm lens of massive pyrite.

Major element analyses of six samples show that the rhyolites contain around 78% SiO_2, the andesites around 58% SiO_2 and the single, very weathered and carbonated basalt sample 50% SiO_2. A plot of the 'Igneous Spectrum' (Hughes, 1973) shows there is some Na enrichment in half of the samples but that there is no evidence for extensive hydrothermal alteration. A soil-sample traverse across the rhyolites in the Castell Cogan area showed no anomalous values in the elements analysed (Ba, Cu, Ni, Pb and Zn by XRF). Another traverse over the dolerite with reported pyrite at Pentrenewydd also showed no anomalous values. The rhyolite at Allt-y-Crug contained about 1% pyrite but showed only low base-metal values. Four samples from the area were analysed for Au but contained only 1–2 ppb Au.

In spite of the presence of thick acid volcanic rocks, including rhyolitic breccias, the area does not appear to have significant potential for the discovery of base-metal mineralisation. There is no evidence of extensive hydrothermal alteration, no sulphides other than pyrite have been seen and no elevated base-metal values have been found in the limited sampling of rocks and soils. However, no geophysical exploration has been carried out. The currently exposed area is very small but the intense faulting may conceal extensions to the volcanics.

Table 1 Selected partial analyses of altered and mineralised rocks collected during the geological reconnaissance

Number	*282*	*293*	*331*	*337*	*343*	*349*	*387*	*394*	*398*
Ti (%)	0.35	0.59	0.39	0.17	0.35	0.27	0.14	0.19	1.37
Fe (%)	3.26	6.38	3.99	1.08	4.13	25.99	1.56	2.16	15.44
Mn (%)	0.18	0.61	0.13	0.07	0.10	0.02	0.06	0.01	0.81
Ca (%)	1.81	0.34	6.12	0.22	0.41	2.91	0.04	<0.01	1.71
V	93	102	80	<2	<2	90	10	<2	340
Cr	45	66	50	10	10	40	30	10	10
Co	17	25	14	1	4	6	2	2	62
Ni	30	46	28	<2	<2	63	<2	2	5
Cu	148	30	30	<2	<2	60	<2	2	7
Zn	55	83	73	394	152	66	40	5	120
As	<2	22	4	1	2	82	<2	10	11
Rb	9	128	19	31	73	17	9	94	20
Sr	338	103	453	67	64	95	72	11	86
Y	21	32	20	27	66	40	69	146	56
Zr	189	175	185	200	402	62	342	754	174
Nb	7	15	4	6	17	7	14	34	6
Mo	<1	1	<1	<1	<1	5	<1	3	<3
Au (ppb)	<10	60	28	14	11	<10	17	<10	<10
Ba	138	309	360	650	720	220	40	2173	110
Pb	15	26	6	38	8	82	2	7	15
U	1	1	<1	1	2	6	2	4	3

282: Porphyritic andesite, Treffgarne Volcanic Formation, Little Treffgarne Wood [SM 963 236]
293: Dark grey, cleaved ashy mudstone, Spittal Member, Spittal Brook [SM 971 239]
331: Brecciated, pyritic, silicified dacite, Sealyham Volcanic Group, Garn Turne Rocks [SM 979 272]
337: Rhyolite, Sealyham Volcanic Group, Goetty Mountain [SN 069 291]
343: Flow-banded, altered (pyritic) rhyolite, Sealyham Volcanic Group, Carn Bwdcyn [SN 155 326]
349: Pyritic tuffite, Llanrian Volcanic Formation; Abereiddi Bay [SM 796 311]
387: Silicified rhyolitic tuff, Ynys Castell ashes, Abercastle [SM 850 338]
394: Highly altered acid volcanic rock, Fishguard Volcanic Group, Abergwaun [SM 962 378]
398: Pyritic, gossanous feldspathic tuff, Fishguard Volcanic Group, Abergwaun [SM 962 376]

Treffgarne Volcanic Formation

The Treffgarne (or Trefgarn) Volcanic Formation (Traynor, 1988) comprises a succession of basaltic andesites, andesites and volcaniclastic sedimentary rocks of very early Ordovician age. Traynor (1988) divides the succession into a lower volcanic member composed of andesitic lavas and an upper Spittal Member containing gravity-flow deposits of andesitic and rhyolitic material. The precise age of the volcanism is uncertain. The base of the succession is faulted against the Upper Cambrian Treffgarne Bridge Beds and at the top faulting again separates Spittal Member rocks from tidal sandstones and mudstones of the Arenig Blaencediw Formation, whose original relationship to the Spittal Member may have been an erosional surface. Treffgarne-type clasts are present in the Lower Arenig (Moridunian) Ogof Hen Formation of the St. David's area (Traynor, 1988).

Chemical analyses show the lavas to have a calc-alkaline signature (Bevins et al., 1992). Petrographic and geochemical similarities with the Rhobell Volcanic Group (Kokelaar, 1979; Bevins et al., 1984) suggest a similar age, and formation in a volcanic-arc tectonic setting.

The rocks are only well exposed in road cuttings and old quarries by the A40 trunk road as it passes through Treffgarne Gorge [SM 960 240]. Other exposures are found around Mount Pleasant Farm [SM 956 242] and Wolfsdale [SM 927 213]. Examination of these exposures provided no evidence of substantial hydrothermal alteration or mineralisation associated with these rocks. Chemical analyses largely supported this conclusion. However, a porphyritic andesite from the south end of the quarry exposures by the A40 road [SM 960 237] contained a weak gold enrichment (12 ppb) and a similar rock (RPR 282) from an old quarry in Little Treffgarne Wood [SM 963 236] contained a high level of Cu (148 ppm; Table 1). Magnetic susceptibility (0.10–0.40) and radiometric (5–11 µR/hr) values were low.

Sealyham Volcanic Group

This group comprises rhyolitic and trachytic lavas and tuffs of early Llanvirn age which form a series of isolated outcrops on the southern side of the Preseli Hills (Part, 1922; Evans, 1945) and in the type area to the north of Wolf's Castle (Thomas and Cox, 1924). Due to an absence of coastal sections or other good exposures this is one of the least known groups of volcanic rocks in Wales. They comprise a succession of rhyolitic and dacitic lavas and tuffs. The rhyolitic lavas are characterised by micro-phenocrysts of plagioclase and the dacitic rocks by amphibole pseudomorphs (Bevins et al., 1992). According to Evans (1945) the volcanic succession on the southern flanks of the Preseli Hills thins from about 80 m in the west to 30 m in the east but, if so, it must thicken again into the type area where Thomas and Cox (1924) estimated a minimum thickness of about 200 m. This estimate accords more closely with geophysical data which suggests c. 500 m of acid rocks at Rosebush [SN 075 295].

Rhyolitic lithologies yield low (0.09–0.26) magnetic susceptibility readings and radiometric values in the range 10–15 µR/hr, except for silicified rocks which yield much lower values. Intermediate rocks, predictably, produce slightly higher magnetic susceptibility (0.11–0.91) and lower (5–12 µR/hr) radiometric values.

The volcanic rocks have a calc-alkaline character (Bevins et al., 1992); these authors also note a similarity between the geochemistry of the Sealyham Volcanic Group and the Treffgarne Volcanic Formation, with both groups giving similar Ce_n/Yb_n ratios. Duff and Smith (1992) suggest that they are approximately coeval with, and related genetically to, the acid volcanic rocks of Ramsey Island, termed the Aber Mawr Formation (Kokelaar et al., 1985), but the work of Bevins et al. (1992) indicates that the Aber Mawr Formation rocks have a tholeiitic character.

A large number of outcrops and sections of the Sealyham Volcanic Group were visited, including: (i) the well-exposed sections each side of the Afon Anghof between Wolf's Castle [SM 958 268] and Rock Wood, north of Sealyham Bridge [SM 971 283]; (ii) outcrop and float blocks in the fields around Brynhyfryd [SM 965 270] and Brookfield [SM 968 270]; (iii) the tor-like outcrop forming Garn Turne Rocks [SM 979 272]; (iv) float blocks and poor, deeply weathered outcrops at Rinaston [SM 983 260]; (v) tor-like outcrops at Ambleston [SN 008 258]; (vi) substantial exposures by the dam of Rosebush Reservoir [SN 062 292] and in the gorge below; (vii) quarries on Goetty Mountain to the east of the reservoir [SN 069 291]; (viii) float on the hillside at Eithbed-fach [SN 083 293]; (ix) outcrops on the hillside at Banc Du, New Inn [SN 063 306]; (x) tor-like outcrop at Carn Afr [SN 093 302]; (xi) Craig y Cwm quarry [SN 096 312]; (xii) float on the hillside at Waen Clyn Coch [SN 106 312] and (xiii) the line of outcrops and float on the south-east side of the Preseli Hills, principally between Caermeini Isaf [SN 142 312], Carn Ty-cwta [SN 146 316] and Carn Bwdcyn [SN 155 326]. Analysed samples were collected from all these localities except Eithbed-fach, Banc Du and Caermeini Isaf.

In the Afon Anghof section intermittent overgrown exposures of interbedded, dominantly acid, volcanic rocks and mudstones, suggesting sub-aqueous eruption, revealed few indications of mineralisation. The cleaved mudstones have been worked extensively for slate about 0.5 km north of Wolf's Castle [SM 959 274]. In the vicinity of the principal working (a flooded quarry) both the mudstones and the acid volcanic rocks locally contain disseminated pyrite. Chemical analyses did not detect any metalliferous enrichments in these rocks, which often showed evidence of shearing at the junctions between mudstone/acid volcanics. North of Sealyham Bridge silicified acid volcanic rocks carrying disseminated and, locally, veinlet pyrite and quartz veins are exposed [SM 969 281] but chemical analyses did not reveal any accompanying metalliferous enrichments. Further upstream outcrops at Sealyham Rocks [SM 969 283] were found to contain quartz-veined and silicified acid volcanic rocks. Chemical analysis of this rock revealed slightly enhanced levels of Zn (87 ppm) and Pb (56 ppm). Subaqueous eruption of the Sealyham lavas and associated hydrothermal activity probably produced the brecciation and silicification, although the degree of alteration is not as intense as that occurring in parts of the Roch Rhyolite Group (see later section).

Around Brynhyfryd [SM 965 270] and Brookfield [SM 968 270] large numbers of blocks occur at surface, some of which are probably little moved from source. They are principally composed of variably altered (silicified), brecciated, acid volcanic rocks cut by locally intense quartz veining, as described by Thomas and Cox (1924). Small amounts of disseminated pyrite, in places forming aggregates on planar surfaces, was the only sulphide mineral seen. These rocks may persist to Garn Turne Rocks [SM 979 272] where similar lithologies, but less quartz-veined, are exposed. Chemical analyses revealed no metalliferous enrichment of these altered rocks except for a small amount of Au (28 ppb) in the sample (RPR 331) from Garn Turne Rocks (Table 1).

By comparison, the rocks exposed at Ambleston (grey-green porphyritic acid lavas) are little altered and, not surprisingly, no metalliferous enrichments were recorded. At Rinaston [SM 983 260] little exposure could be found but float suggests that the volcanic rocks here are dominantly intermediate in composition and may include one or more intrusions.

At Rosebush Reservoir large exposures of porphyritic lavas (keratophyric) appear little altered, and no metal enrichments were recorded in the sample taken here. However, samples (RPR 337, 338) taken from the porphyritic grey-green flinty lavas exposed in quarries to the east, on Goetty Mountain [SN 069 291], contained minor base-metal enrichments and a trace of Au (Table 1).

At Eithbed-fach [SN 083 293] terraced features rise up the hillside but little exposure was found. The features suggest interbedded mudstones and volcanic rocks. Float blocks indicate the presence of volcanic breccias, locally silicified and quartz-veined. Similar lithologies outcrop on the hillside at Banc Du, north of New Inn [SN 063 306] but here there is little quartz veining. The principal outcrop at Carn Afr [SN 093 302] consists of massive, grey-green weakly porphyritic lavas and thin tuffs. Beyond the western end of the main outcrop there are numerous float blocks of fine-grained, acid volcanic rocks carrying abundant disseminated pyrite. Analysed samples from outcrop and float did not contain any metal enrichments. Exposures of the volcanic succession in Craig y Cwm quarry [SN 096 312] are poor and disturbed by faulting and/or basic intrusions. No sulphide mineralisation was seen except for minor disseminated pyrite. A variety of acid to intermediate lavas and tuffs are present as float on the hillside at Waen Clyn Coch [SN 106 312]. Some appear to be silicified and also contain disseminated sulphide, but chemical analysis confirmed that only pyrite is present.

On the south-east side of the Preseli Hills, exposures and features formed by the volcanic rocks occur on the hillsides to the north-east of Caermeini Isaf [SN 142 312]. At Carn Ty-cwta [SN 146 316] porphyritic acid lavas and tuffs, sometimes flow-banded, show little evidence of alteration. Similar rocks are exposed at Carn Bwdcyn [SN 155 326], but locally here the rocks appear altered (silicified with loss of phenocrysts) and contain pyrite, both disseminated and as aggregates crystals. An analysed sample of this rock (RPR 343; Table 1) contained slight enrichments of Zn (152 ppm) and Au (11 ppb) compared with the unaltered rocks nearby.

Radiometric and magnetic susceptibility measurements were taken at all the principal outcrops examined. The rocks are all weakly magnetic (0.07–0.63) and yielded total gamma readings typical of, or lower than, those usually associated with acid volcanic rocks (5–15 μR/hr), reflecting the sodic composition. Unusually the lowest and highest readings were in rhyolitic rocks. The low values may be caused by alteration (silicification) or leaching/deep weathering of tors.

Fishguard Volcanic Group

Rocks of this group outcrop on the north coast of Pembrokeshire around Fishguard and form the promontory of Strumble Head to the west, where they are best exposed. They may be traced inland to the east of Fishguard, through the Preseli Hills, for about 30 km (Figure 1). The volcanic succession has its greatest development in the Strumble Head area. It thins eastward, although geophysical evidence points to a considerable thickness of acid lavas at Crosswell.

This group has been the subject of more publications than any other volcanic rocks of south-west Wales, notably Cowper Reed (1895), Evans (1945), Thomas and Thomas (1955), Bevins and Roach (1979), Lowman and Bloxam (1981), Bevins (1982) and Bevins et al. (1989). The early papers concentrated on describing in some detail the lithologies and their petrography, whilst those published in the 1980s provided information on the geochemistry of the rocks and environment of eruption and deposition. The group has also formed a substantial part of recent papers on the mineralogy, geochemistry and petrogenesis of Ordovician volcanic rocks in south-west Wales (Bevins et al., 1984, 1991, 1992; Thorpe et al., 1991).

The entire volcanic sequence was erupted sub-aqueously as a succession of acid to basic lavas and volcaniclastic deposits. The volcanic centre is believed to have been in the vicinity of Fishguard, and graptolite-bearing shales within the succession date the volcanism to upper Llanvirn in age. In the Fishguard area the rocks have been divided into three formations:

3. Goodwick Volcanic Formation: principally rhyolitic lavas and tuffs with bedded basaltic tuffs and, near the top of the succession, basalts intruded into wet silicic tuffs and tuffites.

2. Strumble Head Volcanic Formation: dominated by massive and pillowed basaltic lavas.

1. Porth Maen Melyn Volcanic Formation: rhyolitic and rhyodacitic lavas, debris-flow breccias and tuffs (bedded and massive).

The Strumble Head Volcanic Formation is restricted to the Fishguard–Strumble Head area. To the east, into the Preseli Hills, there is an increase in mass-flow deposits, including sub-aqueous, often welded, pyroclastic flows, and the whole succession is dominated by acid volcanism, notably thick rhyolitic flows and domes.

The volcanic pile is cut by numerous high-level coeval intrusions, dominantly of dolerite and gabbro but also including diorites, microgranites and microtonalites. The bimodal volcanism has tholeiitic affinities and Bevins (1982) believed that the observed compositional variations were produced by low-pressure fractional crystallisation of a parental tholeiitic magma. More recently it has been suggested that calc-alkaline and tholeiitic magmas were both available simultaneously for eruption in this region, in part because rocks from the Porth Maen Melyn area have calc-alkaline affinities (Bevins et al., 1991, 1992). The complex is believed to have formed in an extensional (marginal basin) setting, probably controlled by graben or half-graben fault structures (Bevins, 1982; Kokelaar et al., 1984).

Coastal sections were examined from Pwll Deri [SM 892 384] to Pwll Arian [SM 885 403], Strumble Head [SM 898 414] to Aber Felin [SM 928 400], Pant y Dwr [SM 935 403] to Fishguard Harbour [SM 953 394], and both sides of the inlet of Lower Fishguard Old Harbour (Abergwaun) from Saddle Point [SM 957 377] to east of Castle Point [SM 962 378]. Low tide conditions are required to aid access to many sections.

At Pwll Deri [SM 892 384], beneath the base of the Fishguard Volcanic Group, the back of the bay is cut in soft mudstones of the Penmaen Dewi Shale Formation (Cox, 1930; Bevins and Roach, 1982) and on both headlands intermediate and basic intrusions are exposed. The highly deformed mudstone succession in the bay was found to contain tuffites and acid tuff horizons which are locally intensely altered and pyritic. Chemical analyses of three of these acid volcanic units (RPR 388–390) indicated low levels of most metals, but one sample contained an appreciable amount of As (129 ppm).

The rhyolitic and rhyodacitic rocks of the Porth Maen Melyn Volcanic Formation were examined in the type section [SM 888 393] and inland south of Caerlem [SM 902 396] where there is a tor-like outcrop of rhyolitic agglomerate which may represent the site of a volcanic pipe (Thomas and Thomas, 1955). Apart from localised quartz veining, silicification and minor pyrite, little evidence of hydrothermal activity was seen in the limited accessible coastal exposures or inland. This contrasts with the Abergwaun section (see below). The rocks are not magnetic (0.07–0.22).

The Strumble Head Volcanic Formation was examined in coastal sections from north of Porth Maen Melyn to Pwll Arian [SM 885 403], east of Strumble Head, and on the west side of Abergwaun [SM 958 386]. Spectacular outcrops of pillowed and massive basaltic lavas characterise these sections; silicic rocks and mudstones are also present. The basaltic lavas are frequently strongly magnetic (0.37–74.3) with the highest values recorded on the west side of Abergwaun. Epidote-quartz veins, quartz veins, silicified rocks and disseminated pyrite are present locally, particularly close to faults and shear zones, but there is little evidence of substantial hydrothermal activity except for the effects of lava-seawater interaction. Two samples of silicified basalt, one containing pyrite and the other sheared (RPR 391, 392) and a silicified mudstone (RPR 395) were analysed. Except for a moderately high level of Ba (1290 ppm) in the mudstone, no metal enrichments were revealed, and levels of elements concentrated in basic rocks are rather low in the basalts, due to the silicification.

The Goodwick Volcanic Formation was examined in the extensive exposures between Fishguard Harbour and Maen Jaspis [SM 940 405] and on both sides of Abergwaun. The rocks in the northern section (Maen Jaspis to Pen Anglas) appear little altered except for local silicification and minor quartz veining but to the south, around Goodwick and particularly in Abergwaun, the rocks appear to become more altered locally and to contain more disseminated pyrite.

The section exposed on the east side of Abergwaun has been mapped in detail by Lowman and Bloxam (1981), who recorded a succession dominated by vitric and lapilli tuffs interrupted by a dolerite intrusion and overlain at Castle Point by the unfossiliferous calcareous and arenaceous flags. These sedimentary rocks, called the Castle Point Beds are believed to be of Llandeilo age (Cox, 1930). The massive and pillowed basaltic lavas of the Strumble Head Volcanic Formation, present on the west side of the bay, appear to be absent in this section. Some of the tuff units are distinctly pyritic, for example "the dark pyritous rhyolitic ash" of Thomas and Thomas (1955). Most of the tuff and mudstone units contain disseminated pyrite and rocks are locally altered, particularly in the vicinity of faults in the upper part of the succession where they are decomposed to a mixture of quartz, clay and secondary iron minerals. Silicification and quartz veining are also found locally. At the north margin of a dolerite intrusion there is a 4 m wide gossanous unit, the "pyritous coarse feldspar sands" of Thomas and Thomas (1955). This is probably a deeply weathered pyritic tuff. Chemical analyses of this rock (RPR 398) confirmed its highly ferruginous nature but revealed no other metal enrichments except for high background levels of V and Zn (Table 1). Likewise, analysed samples of altered and pyritic tuffs from this section contained no base-metal enrichments, though one highly altered acid volcanic rock from near the top of the succession (RPR 394) contained 0.2% Ba and high levels of Y and Zr (Table 1). To the east of Castle Point, high cliffs are composed of acid volcanic rocks cut by dolerite intrusions that are only accessible at a few points and were therefore not examined in detail.

The section on the west side of Abergwaun also contains acid volcanic rocks of both the Porth Maen Melyn and Goodwick volcanic formations which are locally altered and rich in finely disseminated sulphide. An analysed sample of one of the most sulphidic tuffs (RPR 397) contained no obvious metal enrichments except for high background levels of Fe (6 %) and Zn (128 ppm). Basic lavas, some pillowed, and tuffs of the Strumble Head Volcanic Formation also crop out. These rocks are very variably magnetic and contain veins and lenses of carbonate as well as disseminated sulphide.

In these sections alteration and the distribution of sulphides (pyrite) appears to be related to (i) stratigraphic unit, (ii) faulting and, possibly, (iii) intrusions. On a larger scale it also appeared that distance from the volcanic centre and position in the volcanic pile may also be important. The distribution of pyrite suggests at least two generations: primary/syngenetic and epigenetic (shear/fault related).

Except in the Castle Point–Abergwaun section, the intermediate and basic intrusions provided little evidence of associated mineralisation. Some contain minor amounts of disseminated pyrite and some of the basic intrusions are magnetic (up to 43.0).

Llanrian Volcanic Formation

These volcanic rocks of Llanvirn age are well exposed in classic geological sections around Abereiddi Bay [SM 796 313] (Hughes et al., 1982). The lower part of the formation, the Lower Rhyolitic Tuff Member (Jenkins, 1979) comprises mainly rhyolitic tuffs and tuffaceous volcaniclastics, deposited from sediment gravity flows (Bassett et al., 1986). Dark graptolitic shales, the Cyffredin Shale Member (Jenkins, 1979), separates these rocks from the overlying Abereiddi Tuff Member (Jenkins, op. cit.), which is equated with the *D. murchisoni* ash. These tuffs are basaltic in composition and represent debris flow deposits. They are succeeded by tuffaceous turbidite deposits and pelagic muds which have slumped to form tephra/mud deposits. The Abereiddi Tuff Member is succeeded by the Caerhys Shale Formation, which contains dark tuffaceous mudstones and siltstones with at least one distinctive (air-fall) tuff horizon in the lower part. This bimodal volcanism may be partially contemporaneous with the activity responsible for the Fishguard Volcanic Group, though erupted from a separate centre (Thorpe et al., 1991). The youngest tuffaceous deposits represent the final Ordovician volcanic activity preserved in this part of Wales, in contrast to north Wales where the products of Caradocian volcanism are widespread.

The coastal section around Abereiddi Bay were the only outcrops of these rocks examined. The succession is repeated on the north and south sides of the bay due to an east-south-east trending synclinal structure, the Llanrian syncline, whose axial trace passes through the bay. Soft mudstones of Llandeilo–Caradoc age in its core are responsible for the bay, the volcanic rocks forming headlands on either side. The volcanic succession is much thicker on the north side of the bay (c. 220 m) than the south (Hughes et al., 1982). The section was examined from Traeth Llyfn [SM 801 318] in the north, where crystal and vitric tuffs at the base of the formation overlie the Abermawr Shale Formation, to Pwll Caerhys [SM 793 308] on the south side of Abereiddi Bay, where the base of the Abereiddi Tuff Member, the Caerhys Shale Formation and underlying crystal tuffs (Lower Rhyolitic Tuff Member) are all exposed in generally inaccessible cliffs. The rocks all dip steeply. They are overturned on the north side of the syncline and cut by many faults.

The Lower Rhyolitic Tuff Member on the north side of the bay contains locally silicified rhyolitic tuffs and breccias which are cut by numerous barren veins of white quartz on Trwyncastell [SM 793 315]. Pyritic mudstones occur close to the base in Traeth Llyfn. On the south side of the bay a pyritic zone (lensoid) can be seen in the inaccessible cliffs. The Cyffredin Shale Member contains disseminated pyrite locally, particularly in exposures on the north side of the bay. The Abereiddi Tuff Member is also locally pyritic, particularly near the top, where it passes into the Caerhys Shale Formation. Two samples of flinty (siliceous) rhyolitic tuffs (RPR 385, 386), a pyritic mudstone from close to the base of the Lower Rhyolitic Tuff Member in Traeth Llyfn (RPR 384) and three samples of pyritic lapilli tuff from the Abereiddi Tuff Member on the south side of Abereiddi Bay were analysed (RPR 349, 350, 383). One of these (RPR 349; Table 1) was extremely rich in pyrite and this is reflected in its composition (26% Fe). This rock contained minor enrichments in Pb (82 ppm) and As (82 ppm) compared with less pyritic rocks. None of the other samples contained atypical levels of the elements determined.

All the volcanic rocks yielded low magnetic susceptibility (0.08–0.49) and radiometric readings (5–15 μR/hr) with the higher radioactivity and lower magnetic susceptibility readings coming from the acid (rhyolitic) rocks. Intruded gabbros also gave low values (0.27–0.35 and 3–5 μR/hr).

Other volcanic rocks of Ordovician age

Brunel Beds

Traynor (1988) suggests that these acid lavas, tuffs and epiclastic rocks with intercalated dark fossiliferous mudstones of Lower Arenig age (Thomas and Cox, 1924) form part of the Spittal Member of the Treffgarne Volcanic Formation, while others have placed them within the overlying Ogof Hen Formation (British Geological Survey, 1992). Besides the type section in Brunel's railway cutting in Treffgarne Gorge, the rocks are also recorded in the Llandeloy area from where Williams (1933) described them as fossiliferous dark slates and mudstones with interbedded ashy and pebbly sandstone units.

The rocks were examined in the type section in the old railway cutting, where exposures are now badly overgrown, and in Spittal Brook. No evidence of hydrothermal activity or mineralisation was seen at outcrop, but chemical analyses indicate localised weak metal enrichments; a sample (RPR 293) of well cleaved ashy mudstone from Spittal Brook [SM 971 239] contained 60 ppb Au (Table 1) and a brecciated dacitic lava (RPR 292) from the cutting [SM 961 246] contained 0.15% Ba. Magnetic susceptibility (0.03–0.51) and total gamma radioactivity (8–10 μR/hr) values were low.

Llandeloy ashes

These rocks were described by Williams (1933) as two ashy bands within the Brunel Beds of the Llandeloy area. They comprise lithic and crystal tuffs of intermediate composition within a sequence of tuffite, sandstones and mudstones of Arenig age, but MRP boreholes at Llandeloy may have intersected these rocks. Recent work reported that there are now no good exposures of these rocks (Allen et al., 1985) and so the area was not visited during this survey.

Foel Tyrch Beds

These rocks, described by Evans (1945), are poorly exposed on Crugiau Dwy [SN 171 312] close to a dolerite intrusion. Evans (op. cit.) believed them to be of Arenig age and thought that they might form a precursor or initial part of the Sealyham volcanic event, to which he ascribed an Arenig to Llanvirn age.

Siliceous, flinty fine-grained rhyolitic ('chinastone') and grey-green bedded tuffs are poorly exposed in an old quarry on the north side of the hill [SN 171 313]. The rocks may have suffered contact metamorphism from one or more nearby dolerite intrusions. Pyrite forms patches and aggregates in the siliceous tuff and is disseminated throughout this and some other beds. The succession is cut by a low-angle fault containing quartz, pyrite and traces of galena. Two analyses of rocks from the bedded succession (RPR 347, 348) revealed no metal enrichments, but a pyritic sample from the fault zone, containing 17.8% Fe (RPR 346), confirmed the presence of weak base-metal mineralisation (426 ppm Zn, 1165 ppm Pb) in the fracture. This mineralisation is most probably either associated with the nearby intrusions or a weak expression of the end Caledonian fracture-controlled mineralisation worked to the east. Radiometric (7–15 μR/hr) and magnetic susceptibility (0.06–0.43) measurements showed no features of interest.

Ynys Castell ashes

Cox (1915) divides these rocks into a basal grit, which overlies the Tetragraptus shales (Penmaen Dewi Shale Formation), and overlying silicic ashes, well exposed on Ynys Castell at the entrance to Abercastle Harbour [SM 851 339]. They are overlain by Bifidus shales (Cox, op. cit.) and therefore probably equate with a horizon low in the Aber Mawr Shale Formation and are stratigraphically below the Llanrian Volcanic Formation. They may be partially contemporaneous with the Sealyham Volcanic Group (Thorpe et al., 1991).

The rocks were examined briefly at the type locality on Ynys Castell [SM 850 338] and on the western side of the harbour. A coarse basal conglomerate, probably containing fine-grained volcaniclastics, passes up into a succession of dominantly well-bedded acid tuffs with tuffaceous sandstones. Towards the top, mudstone and tuffite units appear but, in the north of the island and to the west of the harbour, the succession is cut out by a basic intrusion. No sulphides were seen except for pyrite in the overlying mudstone. Barren quartz veins cut the succession in places and some of the units are highly siliceous, perhaps as a result of silicification as reported by Cox (1915). An analysed sample from one of these units (RPR 387) contains a slight enrichment of gold (17 ppb). No other metals analysed were present in high concentrations, indeed many are very low (Table 1). Radiometric (10–15 μR/hr) and magnetic susceptibility values (0.11–0.28) were unremarkable.

Bifidus ashes

One or more tuffaceous horizons, including a feldspar crystal tuff unit, occur in the Llanvirn shales and mudstones exposed in the Carmarthen area (Evans, 1906; Strahan et al., 1907). These probably represent distal expressions of volcanism recorded elsewhere and were not examined during this study.

Conclusions and recommendations arising from the field reconnaissance

1. Pyritisation, quartz veining, silicification and argillic alteration, frequently not noted in the published literature, have been recorded in several sections examined in south-west Wales, most notably in the Abergwaun–Castle Point section of the Fishguard Volcanic Group. However, overall, few exposures revealed sufficient indications of hydrothermal alteration and/or mineralisation to merit further work. The rocks showing the strongest indications of alterations are the Roch Rhyolite Group, the principal subject of this report. Weaker indications are shown by some outcrops of the Sealyham and Fishguard volcanic groups.

2. Rock samples collected from pyritic and altered rocks showed few enrichments in metals besides Fe. The exceptions include (i) a slight enrichment in Au in a siliceous sample from the Ynys Castell ashes, (ii) weak metal enrichments in lavas of the Sealyham Volcanic Group from Goetty Mountain, Garn Turne Rocks and Carn Bwdcyn; (iii) localised weak enrichment of Au and Ba in the Spittal Member of the Treffgarne Volcanic Formation; and (iv) Ba enrichment in the Abergwaun section of the Fishguard Volcanic Group.

3. Sections that merit further attention include the Fishguard Volcanic Group at Abergwaun and at the eastern end of the Preseli Hills; the Spittal Member; and the Sealyham Volcanic Group, particularly around Brynhyfryd.

PETROGENESIS AND MINERAL POTENTIAL

The results from major and trace element analysis of volcanic rocks during the reconnaissance survey and work in the Treffgarne area were examined with the objective of determining their petrogenetic affiliations, the effects of alteration on their chemical compositions and subsequently their mineral potential. To aid in this work, 21 rock samples were analysed for rare-earth elements (REE) and Y by inductively coupled plasma spectrometry (ICPS) at Royal Holloway and Bedford New College (Table 2).

Benton Volcanic Group

These rocks are subalkaline andesites and rhyolites (Figure 2a) and are distinctly bimodal. They show mild LREE enrichment (La_n/Yb_n=3.87 to 4.47), and the two rhyolites (RPR 302 [SM 9705 0818]; RPR 313 [SM 8704 1094]) analysed for REE show a marked negative Eu anomaly (Table 2) in comparison to the andesite (RPR 315 [SM 8704 1094]), consistent with feldspar fractionation. The relative levels of mafic elements in the andesites and rhyolites, e.g. mean values 92 ppm Cr, 30 ppm Ni and 8876 ppm Ti in the andesites and 26 ppm Cr, <1 ppm Ni and 1494 ppm Ti in the rhyolites confirm the field identification and provide no evidence for substantial alteration.

Table 2 REE analyses of selected volcanic rocks. Values in ppm.

Sample	*Lithostratigraphic Unit*	*Rock Type*	*La*	*Ce*	*Pr*	*Nd*	*Sm*	*Eu*	*Gd*	*Dy*	*Ho*	*Er*	*Yb*	*Lu*	*Y*	*La_n/Yb_n*	*Eu/Eu**
RPR 188	Ramsey Sound Group	Dacitic tuff	20.57	44.92	5.66	22.20	5.46	1.37	5.52	6.22	1.21	3.69	3.82	0.58	32.70	3.59	0.76
RPR 353	Ramsey Sound Group	Andesite	17.51	36.28	4.30	16.33	3.45	0.89	3.21	3.43	0.67	2.02	1.88	0.28	17.20	6.21	0.81
RPR 372	Ramsey Sound Group	Rhyodacite	40.69	85.41	9.98	37.45	8.51	1.08	8.30	9.39	1.80	5.37	5.28	0.76	50.80	5.14	0.39
RPR 103	Ramsey Sound Group	Dacitic tuff	37.91	75.26	9.47	34.75	7.06	1.26	6.14	6.11	1.09	2.98	2.84	0.41	27.30	8.90	0.57
RPR 302	Benton Volcanic Group	Rhyolite	41.97	92.63	10.87	41.88	9.80	1.74	9.83	12.03	2.18	6.45	6.34	0.91	59.80	4.41	0.54
RPR 313	Benton Volcanic Group	Rhyolite	29.91	63.09	7.48	29.13	7.11	1.47	7.54	8.52	1.59	4.90	5.15	0.79	43.80	3.87	0.61
RPR 315	Benton Volcanic Group	Andesite	18.97	38.27	5.12	21.06	5.08	1.42	5.41	5.92	1.07	3.12	2.83	0.41	27.50	4.47	0.83
RPR 74	Roch Rhyolite Formation	Siliceous dacite	5.49	9.41	0.95	2.06	0.32	0.10	0.14	0.14	0.06	0.19	0.13	0.03	0.70	28.15	1.25
RPD 502	Roch Rhyolite Formation	Weathered dacite	22.40	45.30	5.14	20.18	3.70	0.88	2.91	2.10	0.43	1.30	1.46	0.23	9.90	10.23	0.79
RPD 507	Nant-y-Coy Formation	Dacitic tuff	25.20	48.82	5.50	18.49	2.15	0.47	1.59	0.98	0.26	0.80	1.04	0.19	4.60	16.15	0.75
RPD 554	Roch Rhyolite Formation	Siliceous dacite	11.97	18.79	2.51	9.39	1.14	0.23	0.94	0.89	0.25	0.74	0.81	0.16	4.50	9.85	0.66
RPR 295	Nant-y-Coy Formation	Andesitic tuff	40.68	82.23	9.47	35.12	6.71	1.41	5.65	5.90	1.11	2.98	2.96	0.43	27.9	9.16	0.68
RPR 282	Treffgarne Volcanic Formation	Andesite	16.88	35.48	4.19	15.93	3.49	0.97	3.30	3.47	0.67	1.96	1.86	0.28	17.40	6.05	0.86
RPR 291	Treffgarne Volcanic Formation	Dacitic tuff	18.85	42.89	5.65	22.79	5.25	1.39	4.99	4.91	0.91	2.64	2.41	0.35	25.20	5.21	0.82
RPR 320	Sealyham Volcanic Group	Rhyolite	19.87	37.83	4.35	16.58	3.18	0.86	2.86	2.87	0.56	1.64	1.60	0.25	14.40	8.28	0.86
RPR 325	Sealyham Volcanic Group	Dacitic tuff	22.46	48.69	5.58	21.06	4.18	1.20	3.73	3.60	0.66	1.93	1.80	0.26	16.90	8.32	0.91
RPR 343	Sealyham Volcanic Group	Rhyolite	36.04	85.31	10.88	46.35	11.22	2.76	11.74	13.09	2.44	7.23	7.00	1.02	63.10	3.43	0.73
RPR 383	Llanrian Volcanic Group	Lapilli tuff	14.95	38.33	5.42	25.00	6.35	1.89	6.80	7.61	1.42	4.14	3.68	0.53	38.20	2.71	0.88
RPR 390	Penmaen Dewi Shale Formation	Rhyolitic tuff	36.91	85.26	10.30	41.14	9.68	1.55	9.55	12.17	2.47	7.62	8.09	1.19	64.10	3.04	0.49
RPR 1009	Coomb Volcanic Formation	Rhyolite	39.08	85.63	10.67	40.83	9.28	1.18	9.06	10.20	2.00	6.14	6.43	0.95	52.60	4.05	0.39
RPR 1012	Coomb Volcanic Formation	Rhyolite	50.49	111.54	14.04	56.47	13.32	2.52	14.46	17.08	3.33	9.95	9.59	1.39	92.70	3.51	0.55

Eu/Eu* is calculated by interpolating between the chondrite-normalised values of Sm and Gd to give Eu*.

La_n/Yb_n is the ratio between chondrite-normalised values (Nakamura, 1974).

Ramsey Sound Group (Gignog and Rhyndaston Group)

Twenty-four rocks from the Pebidian Ramsey Sound Group (Pharaoh and Gibbons, 1994) were analysed for up to 21 trace elements. The samples include two andesites, three acid lavas and tuffs, seventeen intermediate lavas and tuffs, and two basic tuffs. On the Zr/TiO_2 vs. Nb/Y plot of Winchester and Floyd (1977), these rocks plot as predominantly subalkaline dacites to rhyolites, although there are two distinct groupings (Figure 2a). Firstly, samples from Gignog [SM 881 247], Cwm-bach [SM 841 230] and Rhyndaston [SM 893 237] have Nb/Y ratios of between 0.4 and 0.6. The second group has Nb/Y ratios between 0.15 and 0.25, and includes samples from the coastal sections at Porthmynawyd, near Newgale, [SM 829 229] and on the mainland at Ramsey Sound [SM 724 246]. Two samples from the Treglemais (Pebidian) and Treffynon (?Pebidian) volcanic groups also plot in this latter field. The geographical proximity of outcrops at Cwm-bach and Porthmynawyd belies their geochemical and geological (Thomas and Jones, 1912, p. 280) dissimilarity. The distinction between these two groups may indicate a difference in the petrogenesis of these lithologies, since the variation is explained predominantly by a two-fold difference in Nb (mean value of Nb in the first group is 19 ppm in comparison to 7 ppm for the second group).

A dacitic tuff (RPR 103) from Gignog, a rhyodacite (RPR 372) from Rhyndaston, an andesite (RPR 353) from Newgale Farm and a dacitic tuff (RPR 188) from Porthmynawyd were analysed for REE (Table 2). The Gignog and Rhyndaston samples have similar LREE concentrations, but RPR 103 [SM 8822 2472] is more depleted in HREE than RPR 372 [SM 8924 2363], probably as a result of fractionation from a similar source but at a deeper crustal level. Both of these samples have marked Eu anomalies. In contrast, RPR 353 [SM 8473 2271] and RPR 188 [SM 8285 2285] are relatively depleted in LREE, and do not have significant Eu anomalies. RPR 353 also has low HREE concentrations, suggesting fractionation of phases such as garnet and pyroxene (Henderson, 1984). RPR 188 has a lower La_n/Yb_n ratio than RPR 353, but higher absolute values of all the REE, indicating a shallower level of fractionation. Thus the andesite (RPR 353) is distinguished from other Ramsey Sound Group samples in displaying more mafic geochemistry.

In summary, this group of volcanic rocks can be further subdivided into two geochemically and, possibly geologically, distinct assemblages, those of the Gignog, Rhyndaston and Cwm-bach samples and the Ramsey Sound and Porthmynawyd samples.

Coomb Volcanic Formation

Twelve rhyolitic to andesitic lavas and tuffs and an intrusive feldspar porphyry were analysed for a variety of trace and major elements; two rhyolites were also analysed for REE (Table 2). All the extrusive rocks are subalkaline and there is an apparent bimodal sample distribution of andesites and rhyolites (Figure 2a). The andesites fall within the calc-alkaline basalt field of Pearce and Cann (1973) on a triangular plot of Ti, Zr and Y, and the rhyolites show evidence of fractionation of P_2O_5 and TiO_2 relative to the andesites. The intrusive porphyry (Strahan et al., 1909) is geochemically distinct from the other volcanic rocks in this district, falling within the trachyandesite field of Winchester and Floyd (1977).

The REE patterns for the two rhyolites are parallel with similar, low La_n/Yb_n ratios (3.51 and 4.05; Figure 2b). They both exhibit pronounced negative Eu anomalies ($Eu/Eu^* = 0.39$ and 0.55). These patterns are consistent with those of an evolved rock suite.

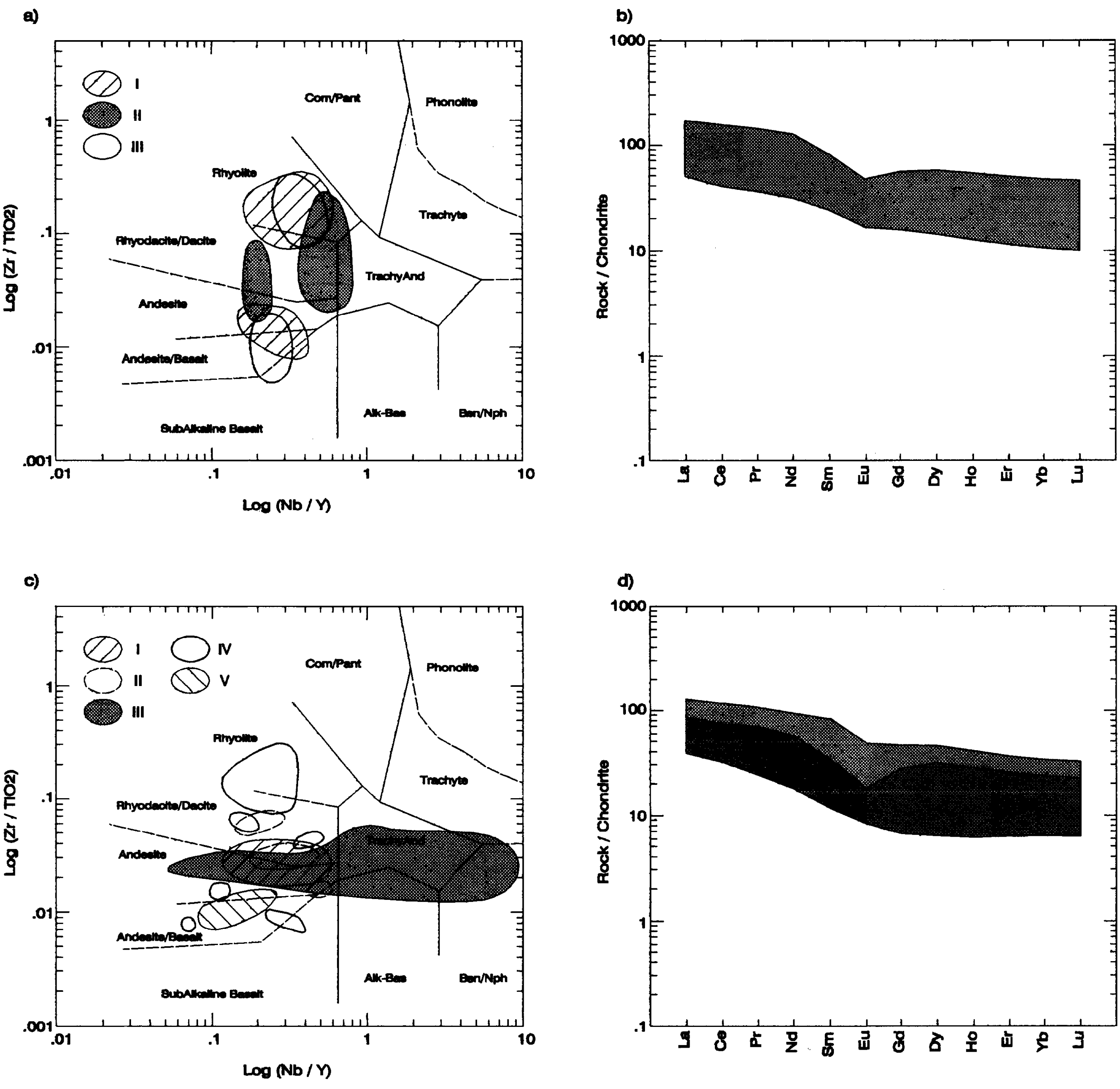


Figure 2: Geochemical discrimination diagrams for Precambrian and Ordovician volcanic rocks.

a. Trace element plot (after Winchester and Floyd, 1977) for Precambrian volcanic suites. I: Benton; II: Ramsey Sound; III: Coomb. b: Field of chondrite-normalised REE plots for Precambrian volcanic suites, south-west Wales. c: Trace element plot of Winchester and Floyd (1977) for Ordovician volcanic suites, south-west Wales: I: Treffgarne; II: Sealyham; III: Roch; IV: Fishguard, V: Llanrian d: Fields of chondrite-normalised REE plots for Ordovician volcanic suites (except the Roch Ryolite Group), south-west Wales. Dark stipple= basic; light stipple= acid.

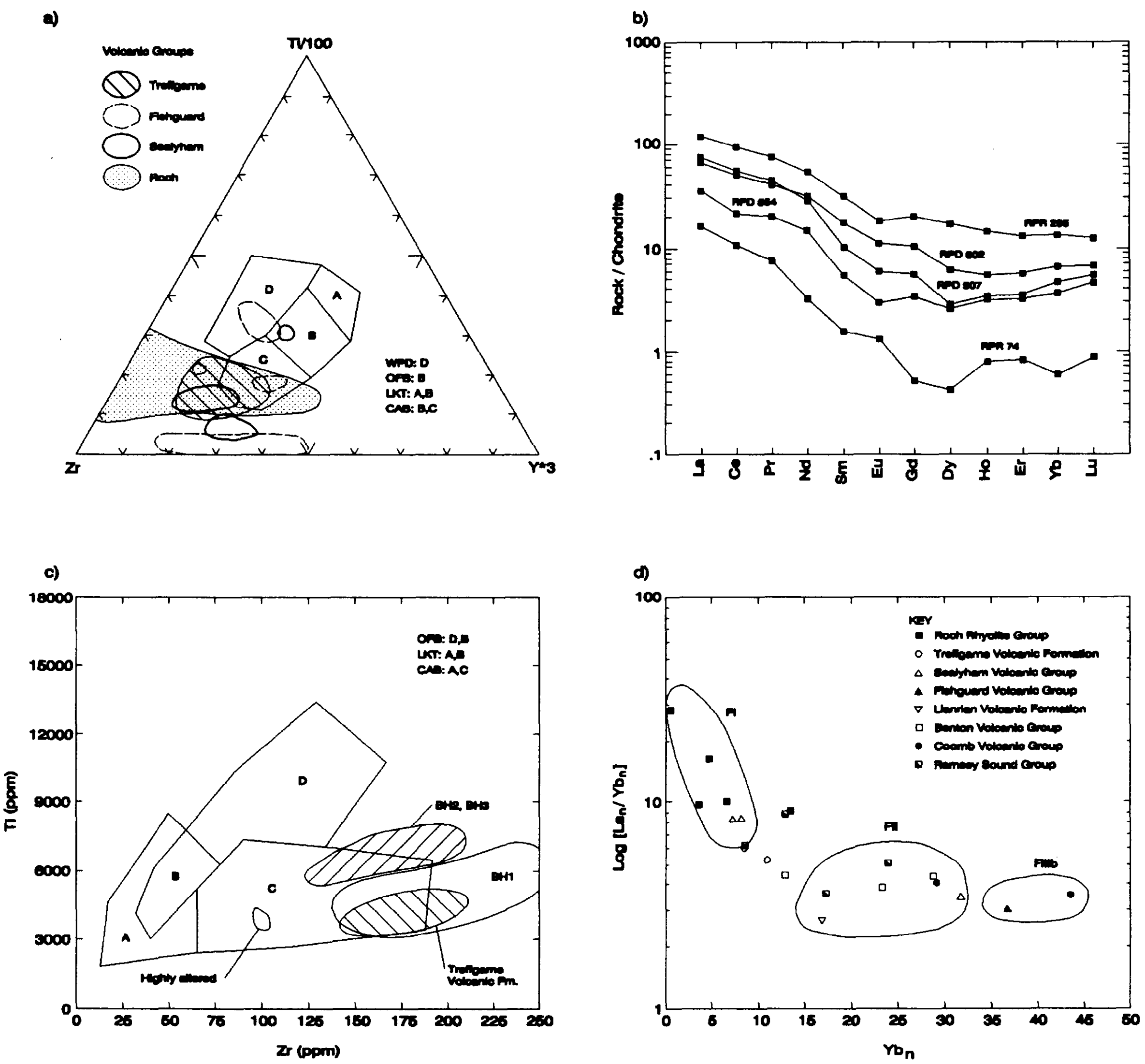


Figure 3 Geochemical discrimination diagrams and mineral potential plots for Ordovician volcanic rocks.

3a: Triangular plot of Pearce and Cann (1973) for Ordovician volcanic suites, south-west Wales. b: Chondrite-normalised REE plots for Roch Rhyolite Group, south-west Wales. c: Ti vs. Zr plot of Pearce and Cann (1973) for Treffgarne borehole samples (BH1–3) and Treffgarne Volcanic Group samples. d: Mineral potential plot of Lesher et al. (1986) applied to volcanic suites from south-west Wales

Treffgarne Volcanic Formation

The Treffgarne Volcanic Formation (Traynor, 1988) is one of the few volcanic formations in south-west Wales that has previously been studied geochemically. Bevins et al. (1992) published trace and REE data showing that the rocks of the volcanic member are largely basaltic andesites to andesites displaying calc-alkaline characteristics.

Following Traynor (1988), 10 analysed rocks from the Brunel Beds have been included in this formation (Spittal Member). Nine samples from the Treffgarne Volcanic Member were also analysed for trace elements. Two of these samples were analysed for REE (Table 2).

The trace element geochemistry of rocks from both the Treffgarne Volcanic and Spittal members is uniform, plotting within the andesite to dacite field of Winchester and Floyd (1977; Figure 2c). This is largely consistent with field identification, except that the rhyolitic tuffs appear to be more mafic than expected. The uniformity of the compositions suggests the lack of any significant alteration. On the Zr/Ti/Y plot of Pearce and Cann (1973; Figure 3a) the samples plot in or close to the calc-alkaline basalt field, confirming the conclusions of Bevins et al. (1992).

The REE patterns (Figure 2d) support this view, with moderate LREE enrichment in both the samples analysed (La_n/Yb_n: RPR 282 = 6.05, RPR 291 = 5.21) and a slight negative Eu anomaly (Eu/Eu*: RPR 282 = 0.86, RPR 291 = 0.82). These patterns are also similar to those of Bevins et al. (1991) (La_n/Yb_n = 4.97 and 4.00), although one of their samples has a more pronounced negative Eu anomaly (Eu/Eu* = 0.68).

Sealyham Volcanic Group

Fourteen samples were collected from the western outcrops of the Sealyham Volcanic Group, i.e. outcrops between Wolf's Castle and Sealyham Bridge, including the Garn Turne and Rinaston areas. Nine of them were identified in the field as rhyolitic in composition, and five as andesites. However, on the trace-element diagram of Winchester and Floyd (1977) all the samples plot in a closely defined group at Zr/TiO_2 between 0.02 and 0.04 (i.e. andesites to dacites). These values are similar to those of the Treffgarne Volcanic Formation and Roch Rhyolite Group, although the range of Nb/Y is not as great as in the latter (Table 3). In common with the Treffgarne Volcanic Formation, trace-element plots suggest that these rocks are calc-alkaline and were erupted in a volcanic arc environment (Figure 2c). Field and palaeontological evidence indicates that the Sealyham Volcanic Group is of Upper Arenig or Lower Llanvirn age, whereas the Treffgarne Volcanic Formation is close to the base of the Arenig. Thus there may have been calc-alkaline volcanic activity in this area throughout the Arenig and Llanvirn.

The eastern outcrop of the Sealyham Volcanic Group consists of an apparently discontinuous set of outcrops between Ambleston and the south-eastern side of the Preseli Hills. Eleven samples were analysed for trace elements from this area but, unlike the western group, they do not lie in a single distinct cluster on the plot of Winchester and Floyd (1977). Sample RPR 1014 from near Eithbed [SN 0836 2913] shows trace-element values characteristic of a basaltic andesite, and is geochemically very similar to the most mafic andesites of the Treffgarne Volcanic Formation, but differs from the main dolerite intrusions of the Preseli Hills. A group of samples from Ambleston [SN 005 257], Carn Afr [SN 0928 3020] and Waun Clyn Coch [SN 1058 3112] lie within the field of the western Sealyham Volcanic Group; a further group of more evolved samples from Rosebush Reservoir and Goetty Mountain [SN 061 291], Carn Bwdcyn [SN 155 326] and Carn Ty-cwta [SN 145 315] plot towards lower Nb/Y and higher Zr/TiO_2. This variability in the trace-element composition and juxtaposition of magma types in a small area suggests that the volcanic suite in the eastern part of the Sealyham Group represents either an evolving suite of calc-alkaline andesitic to rhyodacitic rocks or diachronous volcanics brought into coincidence by faulting. The former conclusion is favoured, since the age of these volcanics is reasonably well constrained in the Upper Arenig or Lower Llanvirn.

Three samples from the Sealyham Volcanic Group were analysed for REE (Figure 2d and Table 2). Two samples (RPR 320 and RPR 325) are from the western outcrop (Wolf's Castle – Sealyham Bridge); the third sample is a silicified rhyodacite from one of the easternmost outcrops, Carn Bwdcyn (RPR 343). The first two samples have slight LREE enrichment (La_n/Yb_n = 8.28, 8.32) and only a very small negative Eu anomaly (Eu/Eu* = 0.86, 0.91). This is consistent with the trace-element geochemistry and indicates an intermediate composition for these rocks. RPR 343 is more enriched in all REE, with a flatter normalised pattern (La_n/Yb_n = 3.43); there is a more significant Eu anomaly (Eu/Eu* = 0.73). This confirms that this lithology is more evolved than those from the western Sealyham Volcanic Group. Thus the Sealyham Volcanic Group can be divided into two spatially and geochemically distinct groups: a western group that is geochemically similar to the Treffgarne Volcanic Formation, and an eastern group that includes both basic and more evolved rhyodacitic compositions.

Roch Rhyolite Group

The Roch Rhyolite Group is of probable Arenig age, and consists of a succession of tuffs and siltstones (Nant-y-Coy Formation), together with lavas and associated laharic breccias and ash (Roch Rhyolite Formation). This group was the focus of detailed exploration in the early 1980s (Brown et al., 1987) when 3 boreholes were drilled to investigate IP anomalies coincident with the group. The lithological and geochemical logs of the boreholes are shown in Appendix 3 and their location is shown on Figure 9. A summary of the results of these holes, together with additional data from more recent investigations, are presented in the section 'Follow-up surveys in the Treffgarne area'. As a result of this work, 202 drill core and 62 surface rock samples have been analysed for a variety of trace and major elements. Five samples were analysed for REE (Table 3).

The rocks from the Roch Rhyolite Group are variably, and commonly extremely, altered. Extreme alteration is characterised by very low Na, K, Ca and Rb, and SiO_2 contents up to 96.9% (RPR 174 [SM 9580 2520]). Brown et al. (1987) also suggested that Nb might be depleted, but the levels in the Roch Rhyolite Group are comparable with those in the little altered Treffgarne Volcanic Formation (Table 3). Ti correlates well with Zr for the Roch Rhyolite Group. On the discrimination plot of Winchester and Floyd (1977), the surface rocks from the Roch Rhyolite Group plot in a broad group with constant Zr/TiO_2, between 0.015 and 0.030, but with highly variable Nb/Y (Figure 2c). Hence it is proposed here that the so-called 'rhyolites' were actually predominantly andesitic in composition, and that the extreme silicification has also resulted in loss of Y.

A comparison of the average trace element composition of the Roch Rhyolite Formation with that of the Treffgarne Volcanic Formation and Sealyham Volcanic Group (Table 3) shows that the Zr/TiO_2 ratios of each of these groups are comparable, and are typical of calc-alkaline andesitic to dacitic rocks erupted in a volcanic arc setting. Additionally, the Nb/Y ratios of these groups are remarkably similar excepting the lower Y levels in the Roch Rhyolite Formation. Hence it is likely that all of these volcanic groups are genetically related and were erupted in this tectonic setting.

Y values of the Roch Rhyolite Formation are up to an order of magnitude lower than the average values for the other volcanic groups. These findings are consistent with the work of Finlow-Bates and Stumpfl (1981) who concluded that although Ti and Zr are relatively immobile during large-scale, massive sulphide-forming, hydrothermal circulation, concentrations of Nb and, particularly, Y are likely to change. However, it is noteworthy that the absolute average values of Ti and Zr are higher than would be expected for andesites and dacites. Hence the importance of using trace-element ratios from highly altered rocks is stressed.

Table 3 A comparison between immobile trace-element concentrations and ratios for the Roch, Sealyham, Treffgarne and main Precambrian volcanic groups

Stratigraphic Unit	*Rock type*	*No. of samples*	*Mean Nb ppm*	*Mean Y ppm*	*Mean Nb/Y*	*Mean Zr ppm*	*Mean TiO_2 %*	*Mean Zr/TiO_2*
Roch Rhyolite Formation	Rhyolite	21	7	6	1.17	241	0.96	0.025
Nant-y-Coy Formation	Tuff	6	8	18	0.44	167	0.74	0.023
Sealyham Volcanic Group	Andesite	1	16	34	0.47	156	1.00	0.016
Sealyham Volcanic Group	Dacite	17	6	19	0.29	168	0.57	0.030
Sealyham Volcanic Group (east)	Rhyodacite	6	11	50	0.21	303	0.46	0.065
Fishguard Volcanic Group	Rhyodacite	3	22	50	0.44	307	1.14	0.027
Treffgarne Volcanic Member	Andesite	9	6	18	0.33	146	0.62	0.024
Spittal Member (Brunel Beds)	Andesite	7	6	20	0.30	159	0.67	0.024
Coomb Volcanic Formation	Rhyolite	6	25	76	0.34	395	0.21	0.215
Coomb Volcanic Formation	Andesite	6	6	26	0.23	126	1.15	0.012
Benton Volcanic Group	Rhyolite	8	22	62	0.37	374	0.25	0.170
Benton Volcanic Group	Andesite	5	14	45	0.31	262	1.48	0.019
Middlemost (1985)	Orogenic dacite	124	21	28	0.75	170	0.63	0.027
Middlemost (1985)	Island arc dacite	24	2.4	26	0.09	53	0.60	0.009
Taylor (1968)	Andesite	18	4	21	0.19	110	0.70	0.016

Grouped by area, there is a variation in composition across the outcrop of the Roch Rhyolite Formation. This variation reflects the degree of hydrothermal alteration, which varies along strike, together with pre-existing differences in the lithologies. The altered rocks plot as alkaline basalts on Figure 2c, but this is primarily a result of loss of Y from the samples. The most altered rocks are seen in Treffgarne Gorge [SM 9580 2520] and on Plumstone Mountain [SM 9165 2340], with rocks from Forest Quarry [SM 9075 2245], Dudwell Mountain [SM 9050 2280], and Rock Farm [SM 8990 2225] being altered to a lesser degree, except for minor vein-style baryte and pyrite mineralisation. Samples from Poll Carn [SM 9520 2450] and Maiden Castle [SM 9540 2490] show a trend towards higher Zr (up to 414 ppm) which is associated with increased Fe, Ca, V, Mn, Ni and Co. This association is also seen in one sample from Rock Farm which has accompanying high Ba (RPR 84: 10300 ppm Ba); it is thought that this is due to small-scale hydrothermal circulation and subsequent deposition of ore minerals such as baryte and pyrite.

Each of the boreholes has distinct lithologies, alteration patterns and chemistry. Borehole 1 [SM 9052 2298] intersected a series of rhyolites, tuffs and breccias up to 130 m depth (see Appendix 3). These rocks are all highly altered, with loss of alkalis together with high alumina and silica in some samples. Average Zr/TiO_2 ratios are very similar to the surface rocks, although the tuffs have slightly lower ratio'd values. Borehole 2 [SM 9312 2380] and Borehole 3 [SM 9432 2461] are relatively monotonous with intersections of predominantly sedimentary rocks attributed to the Nant-y-Coy Formation. Alteration is less apparent in the latter two holes, although there are several brecciation zones, felsic intrusives and quartz veins. Additionally, one sample from Borehole 2 (RPD 594) yielded a gold value of over 2.5 ppm in siltstones with quartz veins.

Samples from Borehole 2 and Borehole 3 differ in trace-element geochemistry from the surface lithologies and the samples from Borehole 1. At surface, the tuffs and siltstones of the Nant-y-Coy Formation have Zr/TiO_2 ratios similar to those of the lavas of the Roch Rhyolite Formation, but lower Nb/Y ratios (Table 4). It is proposed that this is evidence that the Nant-y-Coy Formation represents volcaniclastic sediments deposited at the same time as the lavas, but having suffered less alteration or silicification. The intimate association of the tuffs and siltstones of the Nant-y-Coy Formation with the Roch Rhyolite Formation suggests that the lavas were extruded subaqueously. On the plot of Pearce and Cann (1973) of Zr vs. Ti (Figure 3c), samples from Borehole 2 and Borehole 3 lie in a closely defined area. Borehole 1 samples plot in a much more widely dispersed group, overlapping the field of Borehole 2 and Borehole 3 but with a generally more evolved signature. The more widely variable nature of both the lithology and alteration styles of the samples from Borehole 1 explains the more dispersed nature of their geochemistry.

Table 4 Average Zr/TiO_2 ratios: a comparison between surface rocks and drill-core samples

Drill core lithology	*Number of samples*	*Average Zr/TiO_2*	*Surface lithology*	*Number of samples*	*Average Zr/TiO_2*
BH1 Rhyolites	10	0.024	**Rhyolites**	22	0.023
BH1 Tuffs	45	0.020	**Tuffs**	6	0.022
BH2 Siltstones	67	0.014	**Siltstones**	23	0.021
BH2 Tuffs	1	0.014			
BH3 Siltstones	56	0.015			
BH3 Tuffs	15	0.015			

The degree of silicification in Borehole 1 may be estimated by assuming that the composition of these rocks are comparable to those at surface. Thus their original composition must have been andesitic to dacitic (Figure 2c), and SiO_2 in excess of the expected normal content of 65% for dacites must have been added by hydrothermal activity. All ten rhyolites analysed for silica content, and 36 of the 61 tuffs analysed, show levels greater than 65%. It is interesting to note that samples relatively *depleted* in SiO_2 from the Que River massive sulphide deposit in Tasmania are those in which sulphide is most abundant (Finlow-Bates and Stumpfl, 1981).

A plot of the REE concentrations (Figure 3b) shows that there is a large differential between the Roch Rhyolite Group sample that is most depleted in REE (RPR 74: a rhyolite from Plumstone Mountain [SM 9165 2336]) and the most enriched sample (RPR 295: a tuff from the Nant-y-Coy stream section [SM 9541 2533]), and indicates the relative loss of REE from the highly silicified lithologies. All three borehole samples (RPD 502, 507 and 554) are altered to some degree, although clearly the silicification is most intense in the latter sample. This is confirmed by the REE patterns. These observations are consistent with the pattern from the trace-element concentrations of the Roch Rhyolite Group and demonstrate that, under conditions of extreme alteration, even the REE are mobile and can no longer be used as a guide to the petrogenesis of these rocks. Alteration has mobilised the middle REE and HREE to a greater extent than the LREE, with La_n/Yb_n increasing to

28.15 for RPR 74. However, the general pattern from the least altered samples is a slight LREE enrichment (La_n/Yb_n = 9.16 for RPR 295) and a slight negative Eu anomaly (Eu/Eu* = 0.68).

Fishguard Volcanic Group

31 rocks were collected, 20 of which have an acidic composition. The trace-element geochemistry of the rhyolitic ashes from the Fishguard Volcanic Group (Figures 2c and 3a) is closely constrained and compares well with the felsic intrusive suite of Bevins et al. (1989). This suggests an association between these intrusive and the extrusive products. These authors showed that there is a clear distinction between the suites of intrusions to the east and west of Fishguard (Figure 4 of Bevins et al., op. cit.). However, this dichotomy is not apparent between the geographically separate groups of acid extrusive rocks sampled in the current work.

The basic rocks collected from outcrop of the Fishguard Volcanic Group vary widely in composition: five sample plots in the dacitic field of Winchester and Floyd (1977), five plots in the andesite–basalt field, and one sample plot in the alkali–basalt field (Figure 2c). In addition, there is no consistent grouping of the samples. This variability can be explained in part by sediment contamination of the tuffs, and in part by alteration of the samples. As a result, it is difficult to draw definite conclusions about their petrogenetic and tectonic affinities. However, the continuous succession of ashes with both acid to basic compositions in the coastal exposure at Castle Point, Fishguard (Lowman and Bloxam, 1981) shows that these magmas were coeval. Indeed a wide range of compositions are represented; this implies that, as would be expected, explosive volcanism distributed the volcaniclastic products over a large distance, and eruptive centres with different compositions were active synchronously across Pembrokeshire.

Llanrian Volcanic Formation

Four samples of andesitic tuffs from the coastal exposures of this formation were analysed. One sample was analysed for REE. The geochemical signature indicates volcanic-arc affinities (Figure 3a), and the resulting REE pattern (Figure 2d) is slightly LREE enriched with La_n/Yb_n = 2.71 with a negligible Eu anomaly (Eu/Eu* = 0.88). The REE pattern closely mirrors that of the intrusive dolerites of the Fishguard Volcanic Group analysed by Bevins et al. (1989), and thus may be an extrusive equivalent of these sills.

Penmaen Dewi Shale Formation

REE were analysed for one sample from this formation: RPR 390, a rhyolitic tuff from Pwll Deri [SM 892 384]. This sample has trace-element characteristics similar to those of the eastern tonalite suite of the Fishguard Volcanic Group, despite lying stratigraphically below this group. The REE pattern can be compared favourably with those of the tonalite intrusions from eastern Pembrokeshire (cf. Figure 2d and Figure 3 of Bevins et al., 1989). The sample is slightly enriched in LREE (La_n/Yb_n = 3.04) and shows a distinct negative Eu anomaly (Eu/Eu* = 0.49). This is consistent with an intermediate composition with fractionation of plagioclase.

Mineral potential

Wide variations in major and trace element geochemistry, excepting the most immobile trace elements (Ti, Zr, Nb ± Y), indicate that significant fluid movement has occurred through many of the volcanic lithologies from south-west Wales, most notably the Roch Rhyolite Group and the Sealyham Volcanic

Group. In the Roch Rhyolite Group, extreme silicification has taken place (up to 97% SiO_2), resulting in the loss of mobile elements and the relative retention of Al thus producing corundum-normative compositions, together with sericitic, illitic and kaolinitic alteration (Brown et al., 1987). Although the Sealyham Volcanic Group is less well studied, a similar style of silicification is seen in places, for example, at Garn Turne.

A method of quantifying the mineral potential of volcanic rocks has been put forward by Lesher et al. (1986), who divided the Archaean felsic metavolcanic rocks of the Superior Province, Canada into three major groups on the basis of their trace-element geochemistry. F1: dacites and rhyodacites with steep REE patterns, weakly negative to moderately positive Eu anomalies, high Zr/Y ratios, low abundances of HREE, Y, Zr and Hf (High Field Strength elements: HFS), and high Sr; F1 are barren with respect to base-metal sulphide deposits. F2: rhyodacites and rhyolites with gently sloping REE patterns, variable Eu anomalies, moderate Zr/Y, and intermediate abundances of HFS elements and Sr; F2 host base-metal deposits only when they have a pronounced negative Eu anomaly. F3: rhyolites and high-silica rhyolites with flat REE patterns; F3a have variable Eu anomalies, low Zr/Y and intermediate HFS elements and Sr; F3b have pronounced negative Eu anomalies (giving the so-called 'gull's wing' pattern), low Zr/Y, high HFS elements and low Sr; both groups of F3 metavolcanics host important base-metal deposits in Canada.

The mineral potential of a volcanic sequence is attributed by Lesher et al. (op. cit.) to the residence time and depth in the crust of the magma chamber, two factors that control the degree of fractionation and the nature of the crystallising phases. For example, a high-level, long-lived magma chamber is considered to supply the heat energy required for the formation of hydrothermal cells, and thus increase the likelihood of volcanogenic mineralisation. However, Lesher et al. (op. cit.) have not taken into account the effects of extreme hydrothermal alteration of the volcanic pile, and the proven mobility of Y, Nb and REE under certain conditions will render many of the predictive diagrams useless. As an illustration of this effect, samples from south-west Wales have been plotted on a diagram equivalent to Figure 3 of Lesher et al. (1986) (Figure 3d). For the samples illustrated, the degree of alteration is undoubtedly a factor in both the absolute and normalised concentrations of the REE, and enhances the apparent LREE enrichment (or rather the HREE depletion, together with Y). This effect moves samples both left and up on the figure of Lesher et al. (1986) and thus, paradoxically, renders the most altered rocks (Roch Rhyolite Group and Sealyham Volcanic Group) least prospective.

Comparative data for REE patterns in hydrothermally altered rocks are provided by Hopf (1993) who analysed altered and unaltered rhyolites from the Taupo Volcanic Zone in New Zealand. By comparing REE patterns in rocks from hydrothermal systems containing either acid or alkaline fluids, this author identified four main types of alteration. These groups vary petrographically and geochemically, and give an indication of the degree of alteration and fluid/rock ratios involved in the alteration. It is also suggested that the style of alteration may be controlled by the original mineralogy of the volcanic rock, and that the chemistry of the hydrothermal fluid exerts only a limited control on the resulting rock chemistry.

A comparison of the REE patterns illustrated by Hopf (op. cit.) with the REE patterns from Roch Rhyolite Group rocks indicates similarities between the highly silicified alteration styles in both studies, strongly supporting the view that the Roch Rhyolite Group has locally suffered extreme hydrothermal alteration. The REE pattern of the most silicified Roch sample (RPR 74) is depleted in all the REE, but particularly the middle HREE, giving a 'bowed' trend (cf. Figure 6a in Hopf, op. cit., and Figure 3b, this work). Hopf (op. cit.) suggests that these patterns are a result of high fluid/rock ratios, and are not controlled primarily by the chemistry of either the hydrothermal fluid or the host rock. The three REE patterns from Borehole 1 samples are less depleted in the REE, and are not as distinctly bowed as RPR 74. These patterns are probably a result of lower fluid/rock ratios, and thus may be more remote from the centre of hydrothermal circulation. Hence the importance of Plumstone Mountain is emphasised in relation to the degree of alteration and possible proximity of economic mineralisation.

Conclusions on petrogenesis and mineral potential of south-west Wales volcanic groups

1. The geochemistry of Precambrian and Ordovician volcanic groups in south-west Wales has been briefly described above. For the Precambrian volcanic groups, the ratios of the immobile trace elements show that the Benton and Coomb volcanic groups are very similar, displaying subalkaline compositions and marked bimodality. The mafic compositions plot within the calc-alkaline basalt field of Pearce and Cann (1973), and within the volcanic-arc basalt field of Meschede (1986). However, rocks of the Ramsey Sound Group show a distinct subdivision on the plot of Winchester and Floyd (1977). The less alkaline group includes samples from Porthmynawyd, Ramsey Sound, and the Treglemais group, and geochemically resembles the Benton and Coomb volcanic groups. Conversely, samples from Gignog, Rhyndaston and Cwm-bach lie around the alkaline/sub-alkaline divide at intermediate dacitic–rhyodacitic compositions. The higher Nb in these samples also suggests a within-plate tectonic setting (Meschede, 1986). These latter samples are thus quite different from both the other Precambrian and the Ordovician volcanic groups, and may represent a geologically distinct phase of volcanism.

2. In the Ordovician volcanic succession, the Roch Rhyolite Group, Treffgarne Volcanic Formation and part of the Sealyham Volcanic Group have similar pre-alteration geochemical signatures, and may also be temporally or tectonically equivalent. The Treffgarne Volcanic Member, and by implication Roch Rhyolite Group and Sealyham Volcanic Group, consist of a series of calc-alkaline andesitic to dacitic lavas and breccias, erupted in a subaqueous volcanic-arc setting in Early Arenig to Llanvirn times.

3. The geochemistry of the Sealyham Volcanic Group varies across its outcrop, and may be representative of a transition between the calc-alkaline intermediate magmatism in the Arenig and the bimodal, tholeiitic magmatism that is characteristic of the Llanvirn Fishguard Volcanic Group. Conversely, four samples from the Llanrian Volcanic Formation, thought to be temporally related to the Fishguard Volcanic Group, have an andesitic composition and show calc-alkaline affinities from within a volcanic-arc setting.

4. There is no direct evidence of a plutonic source for any of the above mentioned volcanic suites. The geochemistry of the Preseli Hills intrusions within the Fishguard Volcanic Group shows that these magmas are tholeiitic, and probably occurred in a marginal basin setting (Bevins et al., 1989); therefore these rocks cannot be related directly to the Sealyham, Treffgarne, and Roch volcanic groups.

5. The main body of the Roch Rhyolite Group has locally suffered extreme silicification resulting in SiO_2 values to over 96%, depletion in many other elements and relative enrichment in Al. The trace-element characteristics of the Roch Rhyolite Group show that although Ti and Zr are largely immobile under the alteration that has affected these rocks, other elements that are normally considered to be immobile, have been variably depleted. These latter elements include Y and the REE. A geochemical interpretation of the Roch Rhyolite Group indicates a spatial variation in the degree of alteration

across the area, which could indicate the proximity of significant mineralisation. The extreme alteration and silicification of the Roch Rhyolite Group is indicative of a high fluid/rock ratio, particularly in the area around Plumstone Mountain. This is considered to be the most prospective area.

6. Considering the degree of silicification of the Roch Rhyolite Group, this group is thought to have high mineralisation potential. Nevertheless, these rocks are not highly fractionated, and were probably derived from deep or intermediate level magma chambers. This scenario is unlikely to produce a significant volcanogenic massive sulphide (VMS) deposit, but may result in epithermal mineralisation. The analytical values for Au in the boreholes are particularly encouraging for epithermal-type mineralisation, and confirm that the Roch Rhyolite Group is prospective for gold.

7. As the intensity of alteration of some parts of the Sealyham Volcanic Group is comparable to that of the Roch Rhyolite Group, further work is recommended over outcrop of the former to test whether the silicification has any associated base or precious-metal enrichment.

REGIONAL GEOPHYSICAL SURVEY DATA

Sources of geophysical data

Aeromagnetic and Bouguer gravity data for south-west Wales exist in digital form as part of the national coverage in BGS databanks. The aeromagnetic data were acquired in 1960 at a mean terrain clearance of 305 m along north–south flight lines 2 km apart. Part of the area was covered in 1978 by a low-level helicopter survey (the south-west Dyfed survey) as part of the MRP programme, and high-resolution digital data were recorded using magnetic, Very Low Frequency electromagnetic (VLF-EM), and radiometric instrumentation (Cornwell and Cave, 1986). The survey was flown with a mean terrain clearance of 60 m with a flight line separation of 250 m. Digital datasets of the total magnetic field and VLF horizontal field component are available, together with four channels of radiometric data (total count, U, Th and K). The regional gravity data coverage for the area was supplemented by additional in-fill and detailed traverses, mainly as part of the MRP programme. The regional gravity and aeromagnetic data are presented as contour plots in Figures 3 and 4. Physical property data were acquired as contributions to the present and previous MRP studies in south-west Wales.

Large-scale seismic refraction studies carried out in south Wales (Brooks et al., 1983) included a north–south line extending across the Precambrian outcrops of Hayscastle and the Johnston Complex.

Physical properties of rocks in south-west Wales

Some physical property measurements (magnetic susceptibility and density) were made during the course of the investigation, primarily on material examined in the regional assessment of volcanic rocks in south-west Wales. The results are summarised below and complement those reported by Cornwell and Cave (1986).

Magnetic susceptibility data were collected, along with measurements of radioactivity levels during the course of visits to west Dyfed. All the susceptibility measurements were made on outcrops using a 'Kappameter' (*Geofysika Brno*). All values in this report are given in dimensionless units of 10^{-3}. Most of the volcanic units were included, together with a few of the adjoining intrusions and sedimentary rocks. The results for rocks from individual sites have been averaged and combined to produce the means listed in Appendix 1.

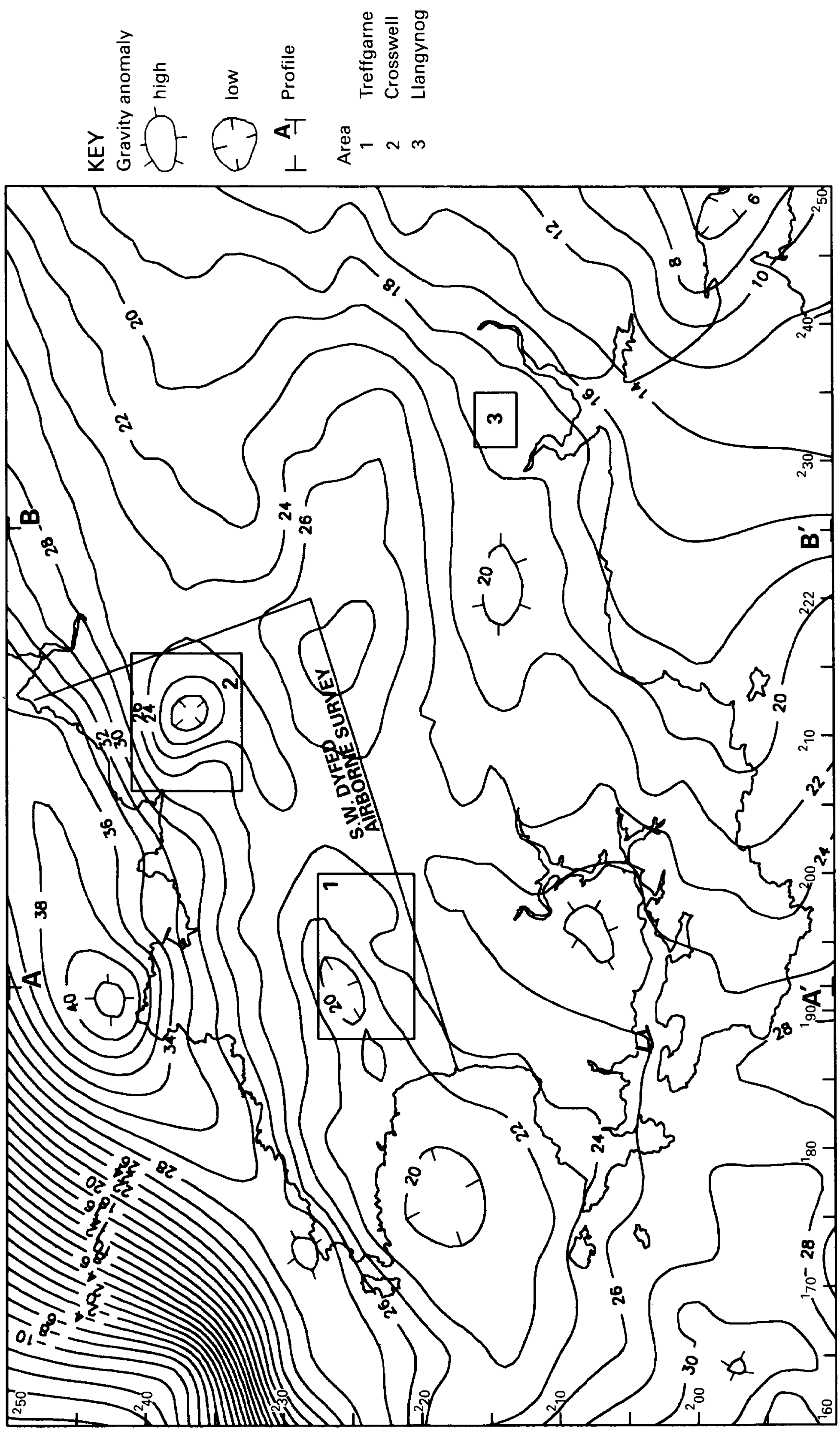


Figure 4 Bouguer gravity anomaly map of south-west Wales. Variable Bouguer reduction density. Boxes 1–3 show locations of detailed survey areas. AA' and BB' are the sections shown in Figure 6.

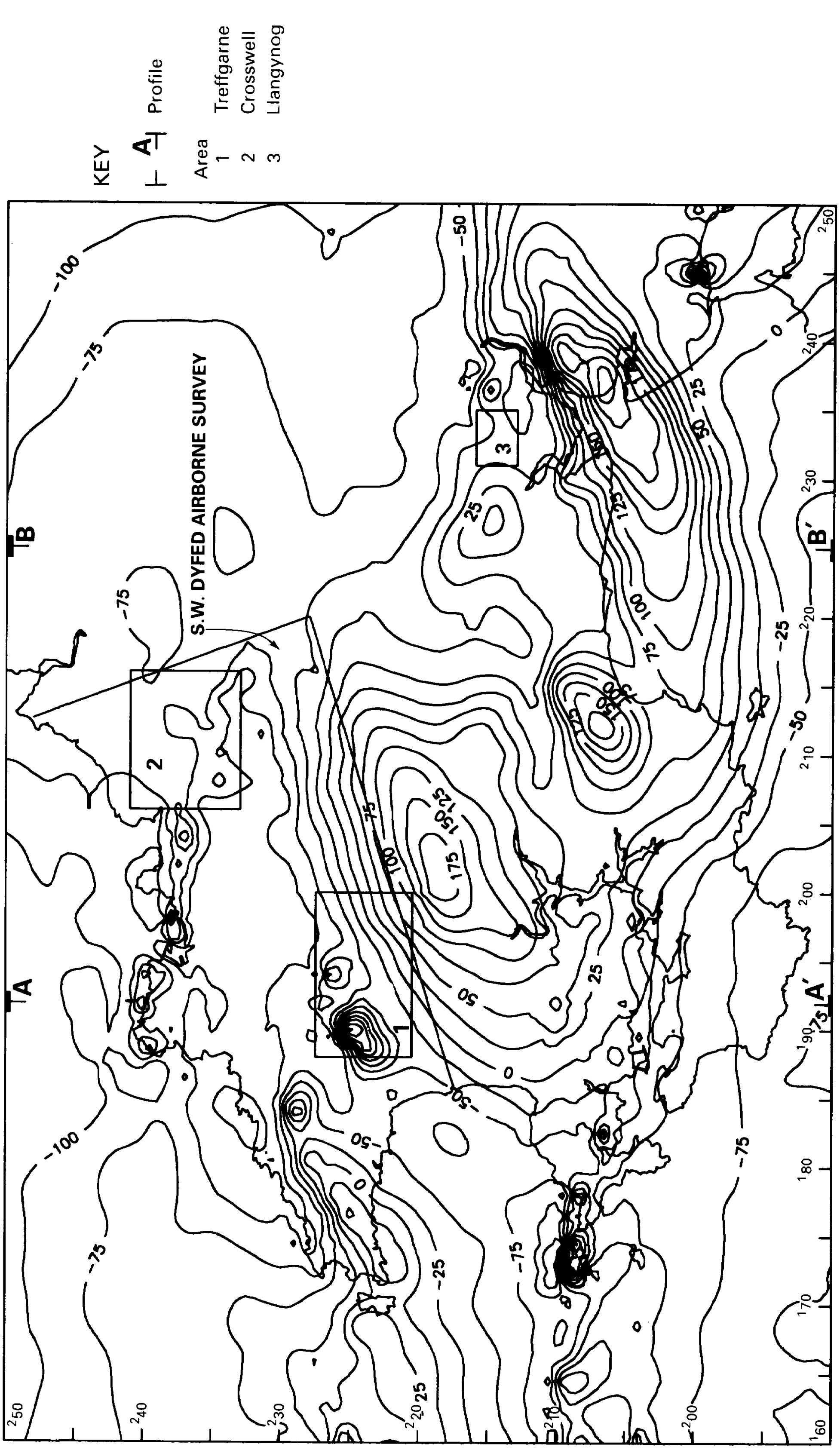


Figure 5 Aeromagnetic anomaly map of south-west Wales. Boxes 1–3 show locations of detailed survey areas. AA' and BB' are the sections shown in Figure 6.

Results for the various groups are discussed in the section on lithogeochemistry. The susceptibilities measured show a wide range of values (10^{-5} to 10^{-1}) which are useful in the first instance in distinguishing magnetite-bearing rocks (susceptibilities > 10^{-3}) from samples with low contents of ferromagnesian minerals (susceptibilities <10^{-4}). The measured susceptibility values are in good agreement with magnetic signatures indicated by aeromagnetic data (see below). The susceptibilities of the acid lavas are generally less than 0.3 and are frequently similar to those of the sedimentary rocks. Values of less than 10^{-4} appear to be associated with silicification of the lavas and are typical for the Llanrian and Roch volcanic groups and for some of the acid lavas from the Sealyham, Fishguard and Benton volcanic events. For the groups which do have distinct aeromagnetic responses, such as the Fishguard and Skomer volcanic groups, it is possible to define more specifically the sources of the anomalies on the basis of the susceptibility data. Variations in the susceptibilities of tuffs would be expected to reflect the composition of the source material, but all the values observed were low. However, values of up to 100 were recorded for Precambrian tuffs from the Hayscastle Anticline (Cornwell and Cave, 1986). Previous experience has shown that dolerite intrusions are responsible for many aeromagnetic anomalies in south-west Wales but that there are 'magnetic' and 'non-magnetic' types of dolerite. This is also demonstrated by the results in Appendix 1.

Low susceptibility values were recorded for volcanic rocks which have no aeromagnetic responses. For the Sealyham and Roch volcanic groups this appears to be due to the preponderance of acid lavas and tuffs, coupled locally with intense silicification, but within the Treffgarne Volcanic Formation the andesitic lavas are typically only weakly magnetic. In the Fishguard Volcanic Group it is the basic lavas in the Strumble Head Volcanic Formation, together with the numerous dolerite intrusions, that give an aeromagnetic response.

Laboratory measurements were made of the densities of a selection of samples collected primarily for geochemical analysis (Appendix 2). These data are reasonably consistent with the geological classification of the material, although extreme values were recorded for the two Precambrian quartz porphyries. Porosities for these rocks would be expected to be about only 1–2% and the few higher values measured probably reflect the weathered nature of the samples.

Aeromagnetic surveys

The aeromagnetic map is dominated by two east-north-east trending anomalies (Figure 5) centred at [SN 201 219] and [SN 236 207] shown as the Deep Magnetic Basement (DMB) anomalies on the aeromagnetic profiles in Figure 6. These form part of a series of similar anomalies across south Wales which appear to be truncated to the south by the Variscan Front. Their source is unknown but their interpreted depths indicate that Precambrian rocks are responsible. This interpretation is supported by the existence of more local anomalies over the exposed Precambrian rocks of the St. David's and Hayscastle anticlines where the volcanic rocks provide the main magnetic sources. The east-north-east trend of these major anomalies represents a continuation of the Caledonian trend observed in central Wales, although the near-surface geological strike has a more east–west trend where it abuts the Variscan Front.

Post-Precambrian volcanic rocks associated with significant magnetic anomalies include the Skomer and Fishguard volcanic groups. The Skomer Volcanic Group (SVG) in particular gives rise to an elongated zone of high-amplitude anomalies extending for at least 40 km offshore (Figure 5). Interpretation of the anomaly form suggests that remanent magnetisation is probably an important factor. Onshore, the anomaly pattern is more disrupted and is also superimposed on the larger anomaly due to the deep-seated source (DMB on Figure 6). Susceptibility measurements (Appendix 1) indicate that aeromagnetic anomalies associated with the Skomer Volcanic Group are probably due to the basic lavas and mugearites and that the acid lavas and tuffs are weakly magnetic. Magnetic anomalies associated with the Fishguard Volcanic Group (FVG on

Figure 6) are less pronounced in Figure 5, but the low-level airborne survey provides a detailed map of their distribution. This map, and evidence from susceptibility measurements, indicate that anomalies are associated with the basic lavas in the sequence (Strumble Head Volcanic Formation) and with the numerous dolerite intrusions.

The absence of anomalies associated with volcanic rocks elsewhere in south-west Wales is consistent with the susceptibility measurements which indicate low values for those sampled from the Llanrian, Sealyham, Foel Tyrch, Treffgarne, Roch and Benton volcanic groups (Appendix 1). This is largely related to the preponderance of acid lavas and tuffs in the groups but, for the Treffgarne Volcanic Formation, the andesitic lavas are typically only weakly magnetic. There is a suggestion that andesites in the Benton Volcanic Group might contribute to the low-amplitude aeromagnetic anomalies (BF on Figure 6) but a more likely source lies in the adjacent diorite intrusions.

Gravity surveys

The Bouguer anomaly map of south-west Wales is dominated by the regional increase of values towards St. George's Channel, reflecting density changes at mid- to deep crustal levels.

In the south-west Dyfed area, several gravity lows are superimposed on the regional gradient. One pronounced feature occurs over the Hayscastle Anticline (H on Figure 6) where it is interpreted as being due to the low-density granitic intrusions at Brimaston. The Treffgarne survey area occurs on the flank of this anomaly, which affected the results of the detailed gravity surveys described later in this report. A second gravity low, which is obvious in Figure 4, occurs over the Fishguard Volcanic Group where it reaches maximum outcrop width near Crosswell (Location C on gravity profile BB'). This area was selected for some reconnaissance surveys described later in this report. Elsewhere the Fishguard Volcanic Group is not distinguishable on regional gravity evidence. The Roch Rhyolite Group in the Treffgarne area appears to give rise to local gravity highs because of the relatively high densities of both the rhyolites and sedimentary rocks.

A series of less well defined lows appears to be associated with outcrops of the Sealyham Volcanic Group, the most pronounced of which occurs at Rosebush [SN 207 230]. Geological evidence indicates a thickness of only about 30-80 m for these rocks (Evans, 1945), which is insufficient to give to a significant regional gravity anomaly. The geophysical evidence therefore indicates that this estimate, based on examination of the poor outcrops available, could be in error and that at least 500 m of acid lavas are needed to explain the observed anomalies, assuming a density contrast of about -0.1 Mg/m^3. The total thickness could be significantly greater if andesitic lavas are present, as these have densities (about 2.73 Mg/m^3) similar to those of the country rocks (Appendix 2).

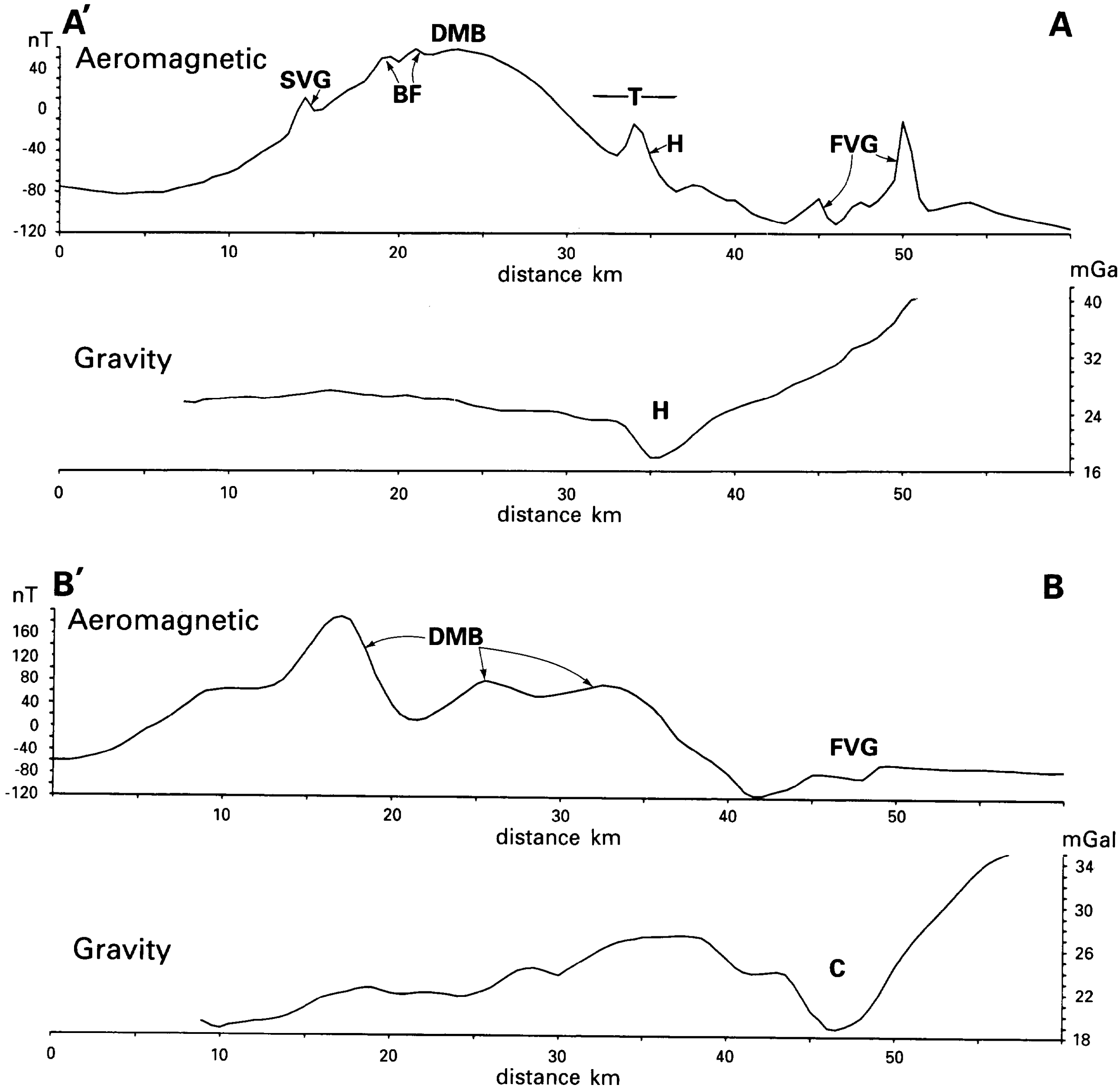


Figure 6 Regional gravity and aeromagnetic profiles. The locations of the profiles are shown on Figures 4 and 5

GEOPHYSICAL AND GEOCHEMICAL SURVEYS IN THE CROSSWELL AREA

A brief study was made near Crosswell in an area between two fold axes, the Brynberian syncline and the Velindre Anticline (Evans, 1945), where the outcrop width of the Fishguard Volcanic Group attains a maximum. The area is structurally complex and contrasts with adjacent areas of the Fishguard Volcanic Group where these rocks largely follow an undisturbed east–west trend. The area was selected on the basis of the following geophysical evidence from regional gravity and detailed airborne survey data. The presence of a pronounced gravity low centred over the Fishguard Volcanic Group (Figure 4 and area C on profile BB' (Figure 6) indicates that either (i) the low-density acid lavas must reach a maximum thickness here due to ponding of the lavas or the proximity of the volcanic vent or (ii) that a concealed acid intrusion with significant depth extent could exist (Cornwell and Cave, 1986). The asymmetry of the anomaly, with the steepest gradients on the western side, is consistent with the geological evidence for the easterly dip of the lavas. The area is exceptional from the aeromagnetic survey point of view in that anomalies occur just above the volcanic rocks; elsewhere significant magnetic features are stratigraphically restricted to the lower part of the Fishguard Volcanic Group, where they are associated with the dolerite sills. The anomalies are negative with respect to background values, suggesting the presence of a strong remanent magnetisation, and coincide approximately with Upper Ordovician sedimentary rocks overlying the lavas. The *D. murchisoni* Shales (black pyritic mudstones) occur immediately over the volcanic rocks, but their thickness decreases significantly across the Crosswell area (Figure 7a). The most pronounced magnetic anomaly occurs along the north-west margin of the Fishguard Volcanic Group but the similarity of its trend with the north-north-west flight-line direction of the airborne survey reduces definition of the feature. However, if the broadness of the feature (Figure 7) is real, the source rocks must lie at depth, perhaps more than 100 m below the surface. This relatively deep-seated origin appears to be a characteristic of many of the negative magnetic anomalies in the south-west Dyfed survey area (Cornwell and Cave, 1986). Discontinuous VLF-EM anomalies occur in the same area suggesting the presence of conductive mudstones. The geophysical evidence together points to the presence of pyrrhotite and possibly other sulphide minerals. The existence of either a thickened lava sequence or a vent also makes the area of interest, particularly as there is geological evidence that the sedimentary rocks overlying the Fishguard Volcanic Group were deposited immediately after the lavas were extruded.

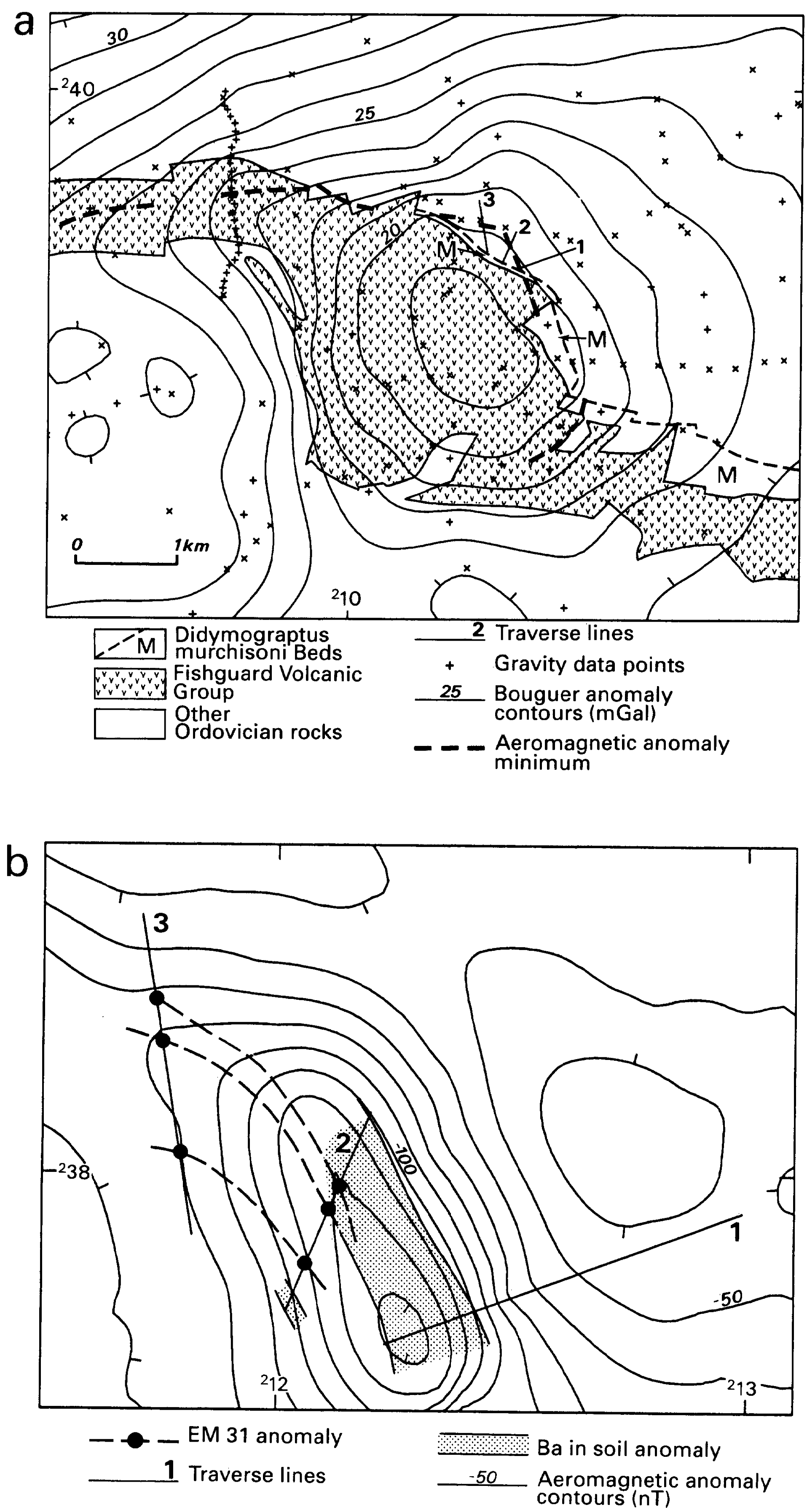


Figure 7 Geophysical and geochemical investigations in the Crosswell area

Detailed geophysical surveys

The initial assessment of the area consisted of geophysical and geochemical sampling along three profiles crossing the magnetic anomaly near Castell Mawr [SN 119 378]. Magnetic measurements were made to confirm the airborne anomaly and measurements using the Geonics EM31 were intended to check for the presence of near-surface (5–6 m) electrical conductivity variations. The results are shown in Figures 7 and 8 for lines 2 and 3 and part of 1, the western end of line 1 being inaccessible because of large wire fences. The magnetic data for line 2 clearly confirm the presence of a reversely magnetised body and the broad form of the anomaly is consistent with the results of the airborne survey in that the main source must be at depth. The magnetic anomaly on line 3 is poorly defined but is consistent with the airborne survey evidence for a weak anomaly here (Figure 8). The electrical conductivity variations on lines 2 and 3 are large and well defined and their presence shows that the sources must occur well within the depth of exploration of the EM31 (i.e. at the bedrock surface). Low values occurring at the southern ends of both lines are probably due to the acid lavas of the Fishguard Volcanic Group, but the boundary then differs from that mapped geologically. The similarity of the two EM31 profiles is consistent with the presence of several highly conductive sedimentary layers in the bedrock set in a broader moderately conductive zone. Geological evidence indicates that the *D. murchisoni* Shales, which are a potential source of EM anomalies, have insufficient thickness and that part of the overlying Upper Ordovician sequence must be involved. The part of line 1 shown in Figure 8 indicates a low-conductivity bedrock and the probable presence of a magnetic minimum to the west (c.f. Figure 7a). Magnetic susceptibility measurements were made in the Crosswell survey area on available material, mainly in the form of loose blocks or in stone walls. Occasional blocks of cleaved mudstone gave values of up to 1.5 , about five times the usual value for these rocks.

Geochemical surveys

Sixty-eight soil samples were taken at 40–120 cm depth at 25 m intervals from three lines, corresponding to the geophysical lines. The main geochemical features of interest were two zones of enhanced Ba. On line 1, Ba exceeds 3500 ppm for 200 m (maximum 4717 ppm Ba) before declining gradually to the east. Unfortunately no ground geophysical measurements were possible at the western end of the line but the zone coincides here with the aeromagnetic anomaly (Figure 7). On line 2 Ba exceeds 2000 ppm over 175 m and reaches 8510 ppm in a single-point anomaly at the southern end of the line. Some base-metal enrichments were noted, including single-point anomalies (defined as median + 2 standard deviation) with 153 ppm Zn on line 2 and 133 ppm Zn on line 1. Broader zones over 75 m of anomalous values with up to 138 ppm Pb on line 2 and over 200 m with up to 33 ppm Cu and a single point value of 75 ppm Pb on line 2 also occurred (Figure 8).

Summary

The Fishguard Volcanic Group at Crosswell is overlain by moderately conductive rocks with an outcrop width of at least 400 m, but containing several conductive beds and some moderate Ba soil anomalies. The source rocks are believed to be mudstones containing graphite and/or pyrite and comprise the *D. murchisoni* Shales and part of the overlying Upper Ordovician sequence. The presence of coincident magnetic anomalies is tentatively interpreted as being due to pyrrhotite which could have been formed by the thermal effects of the underlying lavas, which immediately preceded the deposition of the mudstones. The enhanced Ba values in soil, indicated by the earlier stream-sediment survey (Cameron et al., 1984), may be due to stratabound baryte. This is of some interest in the black-shale environment as it may be associated with some form of volcanogenic mineralisation and thus enhances the prospectivity of the area.

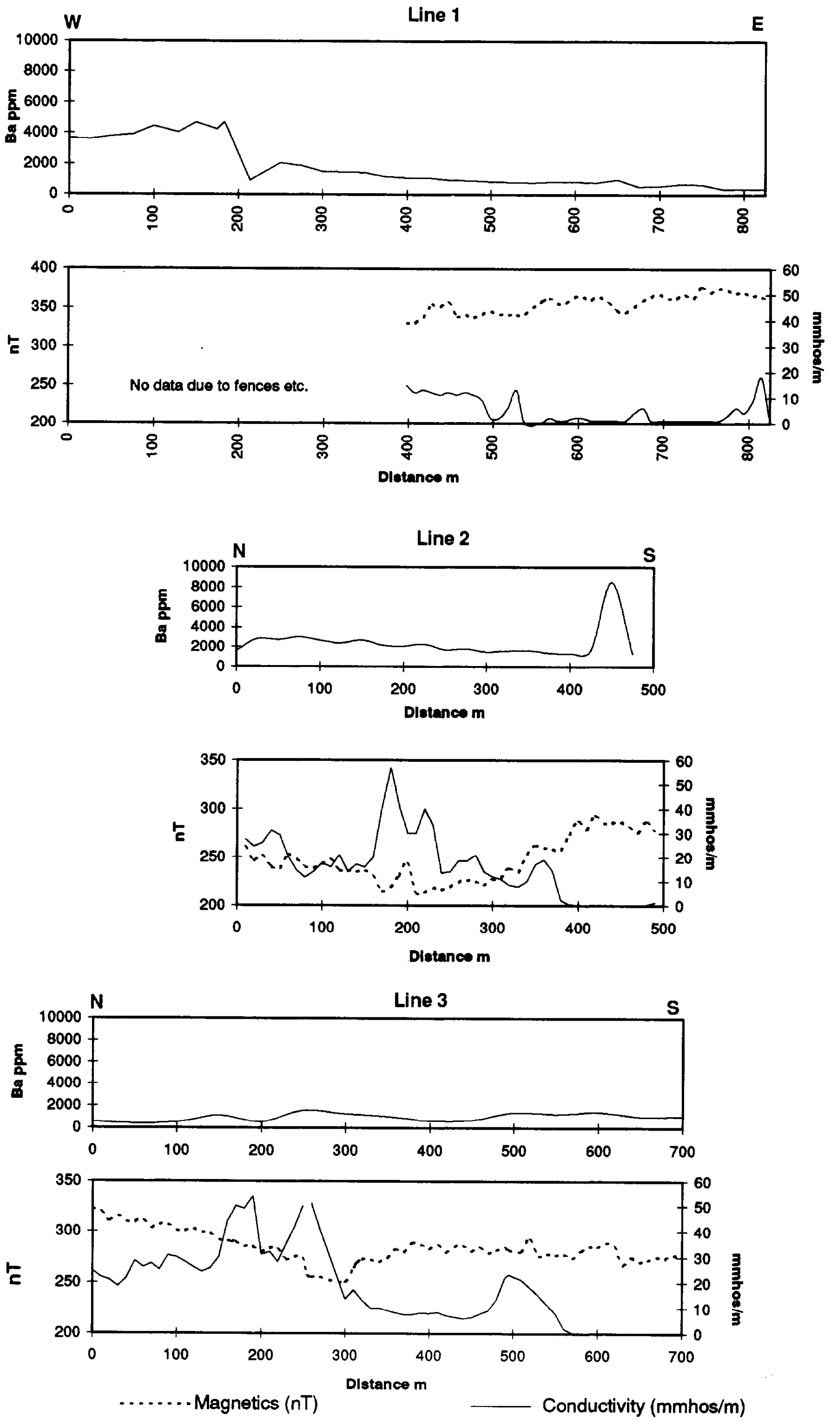


Figure 8 Geophysical and geochemical soil profiles in the Crosswell area. Locations of profiles are shown on Figure 7b

FOLLOW-UP SURVEYS IN THE TREFFGARNE AREA

Introduction

The Treffgarne area was considered prospective for volcanogenic sulphide mineralisation, due to the presence of extremely silicified volcanic rocks of possible Ordovician age and abundant pyrite in the adjacent volcaniclastic rocks. The area was first investigated from 1979 to 1982, culminating in the drilling of three boreholes into IP targets, which revealed extensive zones of pyrite-bearing rocks, but little base-metal mineralisation (Brown et al., 1987). Re-evaluation of the results of this survey led to the conclusion that massive volcanogenic base-metal mineralisation (which had previously avoided detection) might be present, and a further programme of mineral exploration was carried out from 1991 to 1993, the results of which are reported here.

Location

The area lies 8 km north of Haverfordwest, partly within the BGS geological map sheet 209 (St. David's), and is dominated by a ridge about 8 km long, running east-north-east from Roch in the south-west to Little Treffgarne Mountain in the north-east. There are several tor-like outcrops of rhyolite along the ridge at Roch Castle, Plumstone Mountain, Maiden Castle and Great Treffgarne Rocks. The Western Cleddau river flows south through the deeply incised Treffgarne gorge; there are few other streams. The land is mainly given over to dairy farming and rough grazing, though other arable crops such as rape are increasingly grown.

Geology

The geology and mineralisation of the area are described by Brown et al. (1987) so only a summary is presented here. Table 5 lists the main lithological units present in the area with a brief description, and Figure 9 shows a geological map of the area based on the mapping of Brown et al. (1987), Thomas and Cox (1924) and Thomas and Jones (1912).

Table 5 Main lithological units in the Treffgarne area

Group/Formation			Main lithology	System
Sealyham Volcanic Group	Sealyham andesites		Andesitic lavas, breccias and tuffs	Ordovician
	Sealyham shales		Blue-black shales	
Penmaen Dewi Shale Formation (Tetragraptus Beds)			Graptolitic black shales	
Roch Rhyolite Group	Nant-y-Coy Formation		Siltstones and volcaniclastics	
	Roch Rhyolite Formation	Flinty rhyolite	Silicified rhyolite	
		Rhyolitic ash & breccia	Laharic breccias	
Treffgarne Volcanic Formation	Spittal Member		Shales and tuffs	
	Treffgarne Volcanic Member		Basaltic andesite and andesitic tuffs	
Treffgarne Bridge Beds (Lingula Flags)			Shales, mudstones and grits	Cambrian
Ford Beds			Pyritic shales and quartzite	
Welsh Hook Beds			Conglomerate, sandstones, shales	
Ramsey Sound Group (Rhyndaston and Gignog Group)			Tuffs	Precambrian
Granodiorite and other intrusions				

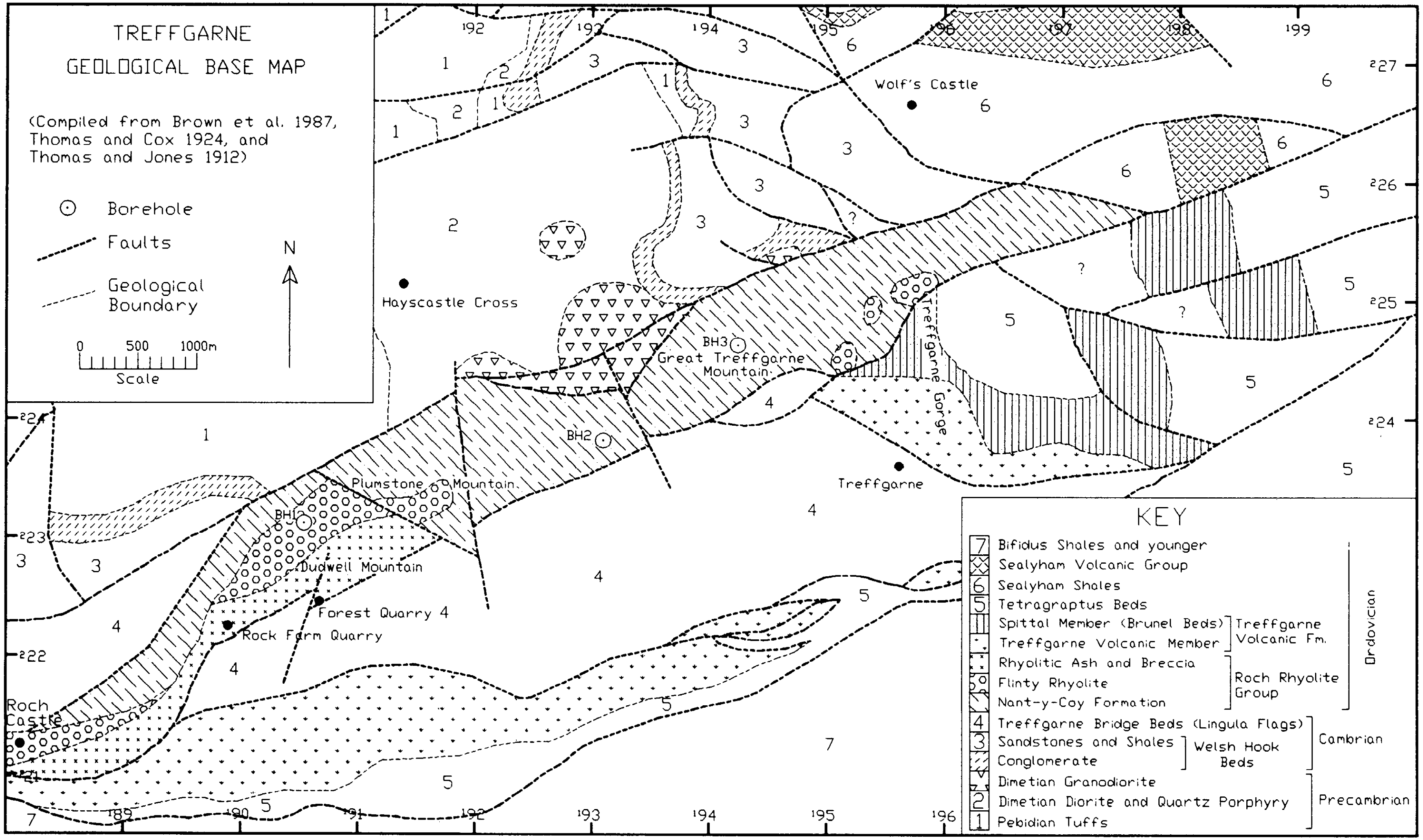


Figure 9 Geological map of the Treffgarne area showing borehole locations

The main rocks of interest are within the Roch Rhyolite Group, the age of which is still not certain. Thomas and Cox (1924) considered both an Arenig (Lower Ordovician) and a Precambrian age before deciding it was Precambrian. Brown et al. (1987) suggest that an Arenig age is the more likelyon evidence providd by the discovery of a trilobite fragment in MRP Borehole 2 in the Nant-y-Coy Formation and the absence of a major break from the Spittal Member into the overlying Roch Rhyolite Group in Treffgarne Gorge. The Nant-y-Coy Formation is considered to be a probable lateral equivalent of the Spittal Member of proven Arenig age which consists of dark grey shales, tuffs and ashes. The Roch Rhyolite Formation is poorly exposed as a series of tor-like outcrops which may be the eroded remnants of a more continuous body of lavas and volcaniclastic tuffs and breccias. Alternatively the tors could represent separate small plugs of lava surrounded by laharic breccias, ashes and sedimentary rocks.

Previous exploration

The first programme of MRP soil sampling in 1978–79 collected 1360 samples at 25 m intervals along 11 lines at 600 m spacings from Cuffern to Treffgarne Gorge (Figure 5 in Brown et al. 1987). Sampling, preparation and analytical details are described in the report. Statistical analysis of the results using cumulative frequency plots indicated threshold values for Cu, Pb and Zn of 51, 51 and 81 ppm respectively. The soil sampling located two substantial, low-order anomalies at Mountain Water over the Nant-y-Coy Formation [SM 921 241], and at Prescelly View over the Treffgarne Bridge Beds [SM 924 227]. Values ranged up to 110 ppm Cu, 170 ppm Pb and 480 ppm Zn. These anomalies were tested by a programme of deep overburden sampling using a Minuteman power auger and a Cobra lightweight drill. Both anomalies were considered to be due to secondary enrichment processes as there was a strong correlation between Cu, Fe and Mn.

Following the airborne geophysical survey of part of Dyfed (Cornwell and Cave, 1986), four phases of IP/resistivity and supplementary ground magnetic and VLF surveys were carried out in the Treffgarne area in 1980–82. The results of the airborne and ground surveys were summarised in Brown et al., 1987. The geophysical surveys were made along the same traverse lines as the geochemical surveys. The IP survey comprised a reconnaissance survey using the dipole–dipole configuration with a dipole length of 50 m and a separation of 100 m (n = 2). More detailed surveys were carried out locally using dipole–dipole and gradient arrays. Ground magnetic and VLF measurements were made at 10 m intervals. The IP data have since been digitised (Evans and Armistead, 1992) to provide datasets of apparent resistivity and chargeability.

In addition to the local surveys, infill gravity surveys were undertaken to increase the regional data coverage from c. 1 station per km^2 to 2 or 3 stations per km^2.

The IP survey revealed a belt of high chargeability and resistivity coincident with acid volcanic and associated sedimentary rocks of the Roch Rhyolite Group. Three boreholes were drilled to investigate the chargeability anomalies and down-hole geophysical logs were run. Graphical lithological and geochemical logs of the boreholes are given in Appendix 3 and their locations are shown on Figure 9. The first hole (Borehole 1), was drilled into flinty rhyolite of the Roch Rhyolite Formation on Dudwell Mountain [SM 9052 2298]. Several sections of the core, up to 15 m long, contained considerable amounts of pyrite in veins and fine-grained disseminations, with up to 11.3% S at about 100 m depth. There are two zones which contain visible fine-grained baryte. One zone contains 2.01% Ba over 10 m from 26.8 m. The other contains 3.9% Ba over 4.5 m including 2 m at 8.6% Ba within a siliceous tuff unit from 85.9 m. Base-metal values are only slightly elevated; Cu reaches a maximum of 513 ppm over 0.85 m from 41.15 m. Pb and Zn are very low at <100 ppm. Sodium and potassium are highly depleted in several sections of the hole where pyrite levels are also low. The second and third holes (Borehole 2 and Borehole 3), drilled into mudstones and siltstones of the Nant-y-Coy Formation contained low to moderate (1–5%) levels of pyrite throughout, though without significant base metals. They are notable for the relative uniformity of the chemistry of the borehole samples, compared to Borehole 1. Borehole 3 [SM 9432 2461] contained a few metres of pyrite veining at 90 m with slightly elevated As, Cu, Pb and Zn (maximum 275 ppm Pb). 40 rock and drill-core samples were analysed for Au. All contained less than 80 ppb Au except for two samples of pyritic mudstone in Borehole 2 which contained 2.5 ppm Au from 106–109.1 m and 1.4 ppm Au from 148.7–151.8 m depth.

Follow-up surveys (1992–93)

Further geochemical and geophysical investigations were carried out during 1992 and 1993. The geochemical surveys consisted of soil sampling to infill the widely spaced (600 m line spacing) sampling used in the previous investigations, as well as pitting and additional rock sampling. It was successful in locating a zone of elevated lead in soil (up to 6 times background) in the vicinity of Plumstone Mountain. A zone of hydrothermal alteration with baryte and pyrite mineralisation was located in Rock Farm Quarry, but without significant base- or precious-metal enrichment. The geophysical investigations included gravity traverses and the use of TEM equipment in an attempt to locate massive sulphides at depths of up to 100 m.

Geochemical surveys (1992–93)

Rock geochemistry

The Roch Rhyolite Group was recognised during the initial exploration as being strongly altered with surface rock samples containing exceptionally low total alkalis ($Na_2O + K_2O \leq 0.5\%$ in most samples) and high Al_2O_3, Fe, S and locally Sr. Additional rocks were collected and analysed. These revealed samples with 1% and 0.9% Ba in the area of Rock Farm Quarry and 224 ppm Pb in rhyolite on Plumstone Mountain (Figure 9). Sampling during the current phase located a 1 m wide vertical zone of strong hydrothermal alteration with pyrite and baryte mineralisation (up to 30% Ba) within rhyolitic breccias in Rock Farm Quarry [SM 8990 2226], though without significant base-metal values.

Soil geochemistry

The follow-up sampling programme was designed to infill between the relatively widely spaced original soil lines, given the short strike length (1–400 m) of many volcanogenic massive sulphide deposits. It was initially focused on the western end of the area because baryte mineralisation had been located in Rock Farm Quarry, the encouraging intersections of pyrite and baryte in Borehole 1 and elevated base-metal rock-sample results over the Roch Rhyolite Group to the west of Plumstone Mountain. A total of 435 soil samples were collected at 25 m intervals on six lines at 300 m spacings, between the original soil lines, with one line beyond the original survey area from Ferny Glen to Cuffern (Figure 10). 202 similar samples were collected along four lines on the east side of Treffgarne Gorge (EAST 1–4) to check for any metal anomalies associated with the strong IP response in that area (Figure 10). Following these results, 323 samples on eight further lines were collected over and east of Plumstone Mountain and west of Rock Farm Quarry to check that subtle metal anomalies had not been missed by the earlier, less precise AAS methods and also to provide more information, including pitting, on the Pb anomaly at Plumstone Mountain. The soils were collected from as deep as possible, using a 1.2 m hand auger, and prepared in a similar manner to the earlier samples, with the addition of elvacite binder to the sieved (-180 μm) and milled fraction for the production of a pressed powder pellet. All samples were analysed by XRF for Cu, Pb, Zn, Ba and Rb with a much greater precision than by the earlier AAS method.

Results. Statistical analysis of all the current soil sampling shows that the Cu, Pb and Zn data (960 samples) give very similar results to the previous sampling (1366 samples), as shown in Table 6. However, analysis of the initial sampling showed that the XRF results provide much more information than the earlier samples analysed by AAS, as shown by the plot of line 1200E for both methods (Figure 11). The AAS analyses show little variation related to bedrock lithologies, except for a slight decrease in Zn over the flinty rhyolite, although the XRF results show Pb variations up to 2.5 times background with a distinct decrease in values from the Treffgarne Bridge Beds over the flinty rhyolite onto the Nant-y-Coy Formation. Rb values, not analysed by AAS, show an abrupt break between soils over the flinty rhyolite and the Nant-y-Coy Formation, and between the Nant-y-Coy Formation and the Precambrian. This implies that there has been little smearing of the overburden across formation boundaries and that the soil values reflect metal concentrations in the underlying rocks. The flinty rhyolite has a particularly low Rb content, reflecting the loss of alkalis during the breakdown of feldspars. The contact between the Nant-y-Coy Formation and the Precambrian is nearly coincident with a sharp Zn peak and a drop in Rb values on lines 1500E and 1200E.

Table 6 Summary statistics of soil data, Treffgarne area

Element ppm	*As new*	*Ba new*	*Cu new*	*Cu old*	*Pb new*	*Pb old*	*Rb new*	*Zn new*	*Zn old*
Minimum	2	5	1	<3	7	<5	2	3	<5
Maximum	61	1007	264[1]	110	177	170	169	154	480[2]
Median	15	402	20	20	21	30	76	33	40
Standard Deviation (SD)	7	164	13	11	21	10	35	20	28
Median + 2 SD	30	729	45	42	63	51	146	74	97

[1] Single value > 102 ppm

[2] Five values > 154 ppm

A significant Pb anomaly occurs over 200 m on line 1500E on Plumstone Mountain over the flinty rhyolite, with Pb up to 164 ppm or around six times background (Figure 12). Zn, Cu, Rb and Ba levels are very low due to the intensely altered nature of the rhyolite. A similar, though less intense, Pb anomaly occurs on line 1200E at the faulted contact of the flinty rhyolite and the Treffgarne Bridge Beds. Here the soil is quite thin (<1 m) and peaty, so the anomalous Pb may be due to Pb-rich rock fragments or secondary concentrations of Pb in peat. Additional sampling was therefore undertaken over the rhyolite along lines 100 m on either side of 1500E. The anomaly was confirmed, but without any increase in values. Eleven pit samples over this area showed no increase with depth, though they did confirm the anomalous panned soil results with values ranging up to 310 ppm Pb and 1381 ppm Ba. Cu and Zn values were low. Values for As vary considerably over Plumstone Mountain: over the flinty rhyolite the soils are uniformly low in As, but to the north of this outcrop, over the Nant-y-Coy Formation, this element is considerably higher (to 45 ppm). This may reflect the presence of pyritic bedrock or be an indicator of mineralisation.

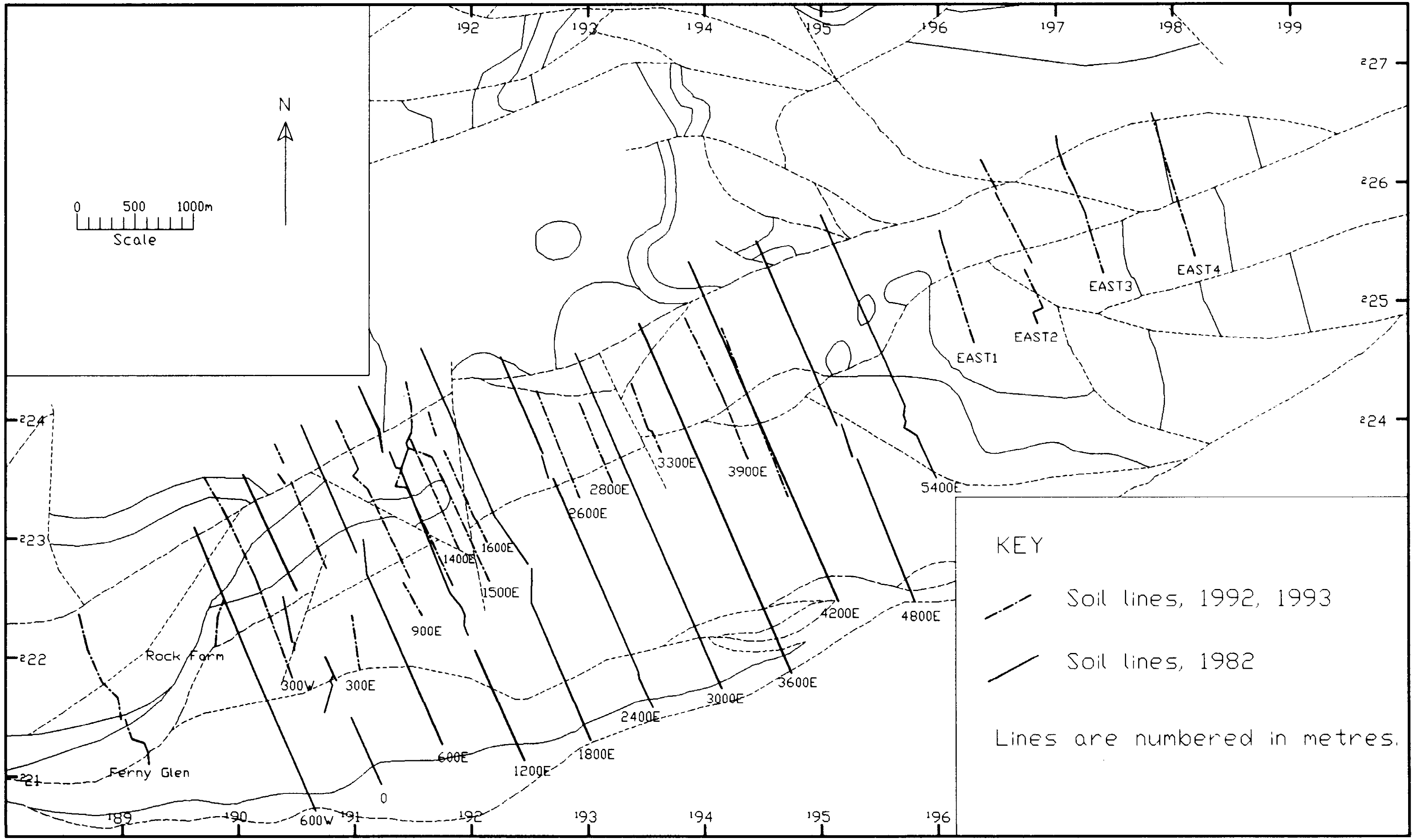
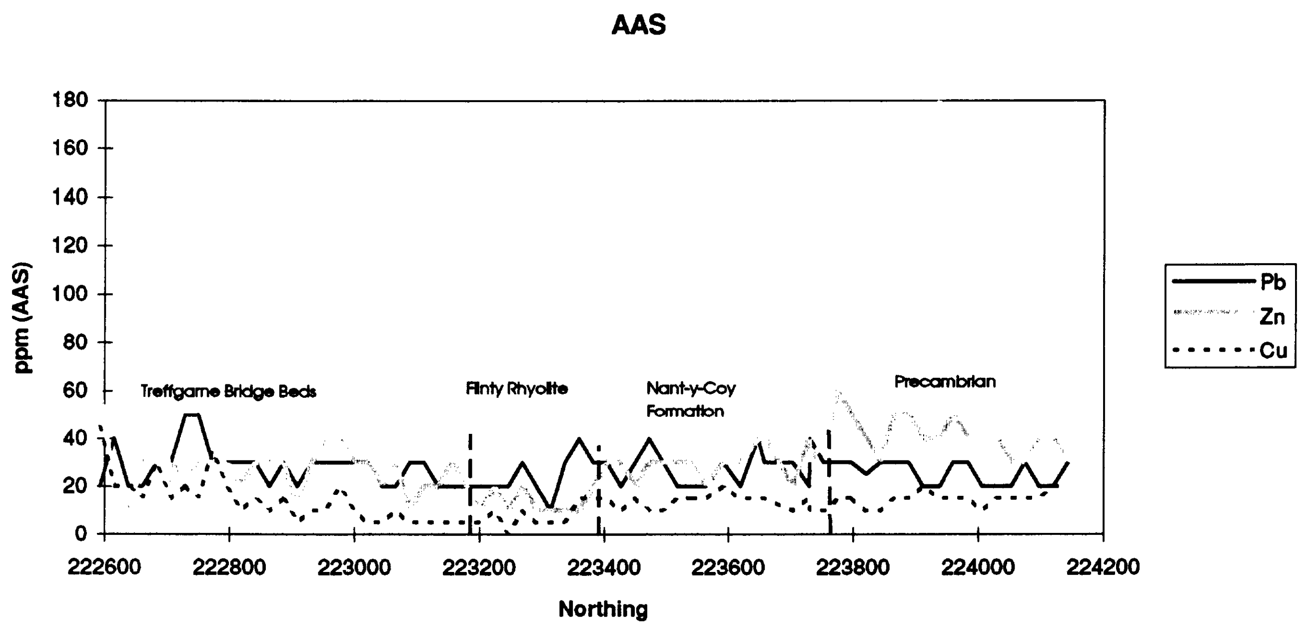


Figure 10 Location of Treffgarne soil-sample lines, 1982, 1992 and 1993. Geological lines as in Figure 9.



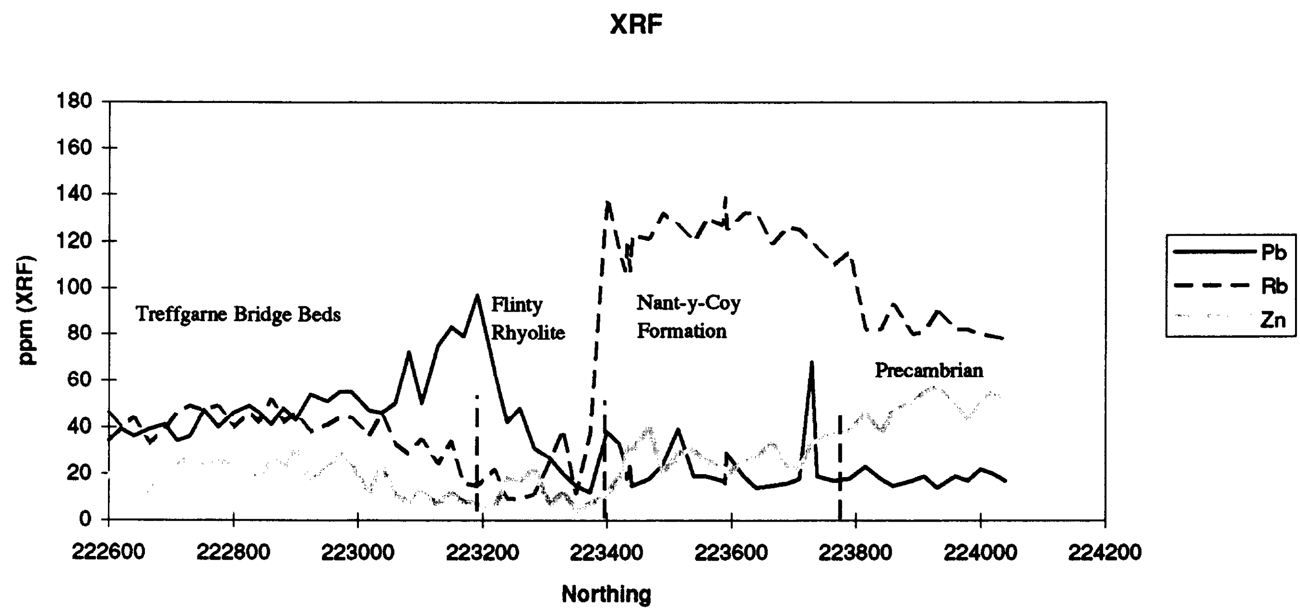
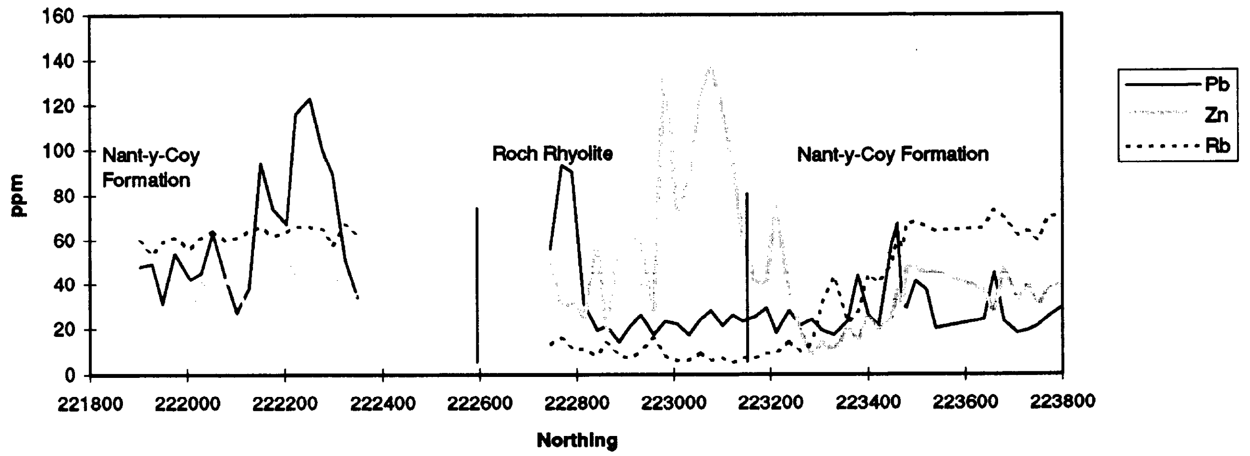


Figure 11 Comparison of AAS and XRF analysis of soil samples at Treffgarne on line 1200E

300E



1500 E

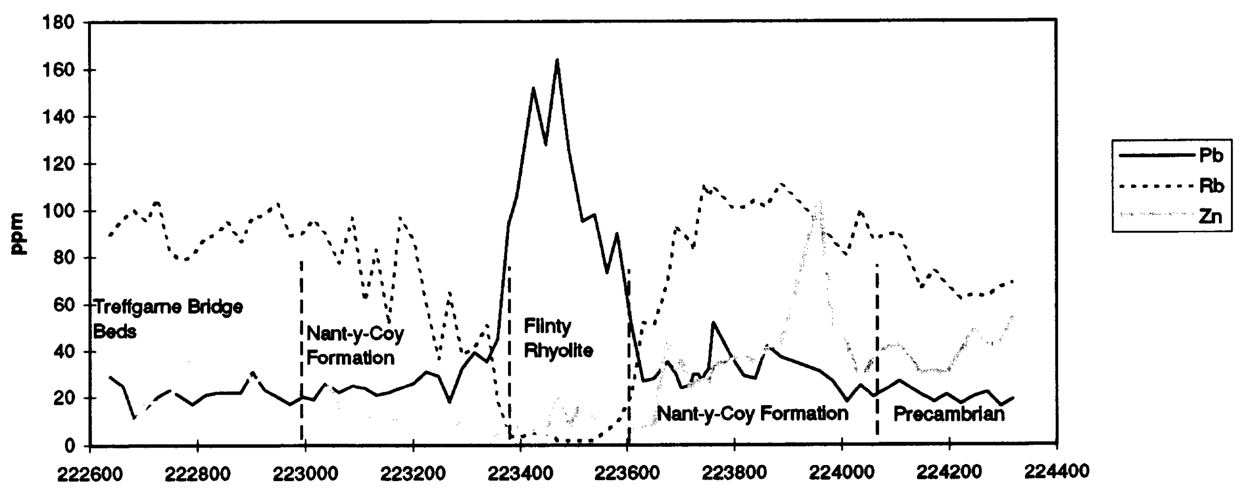


Figure 12 Lead and zinc anomalies at Treffgarne on lines 300E and 1500E

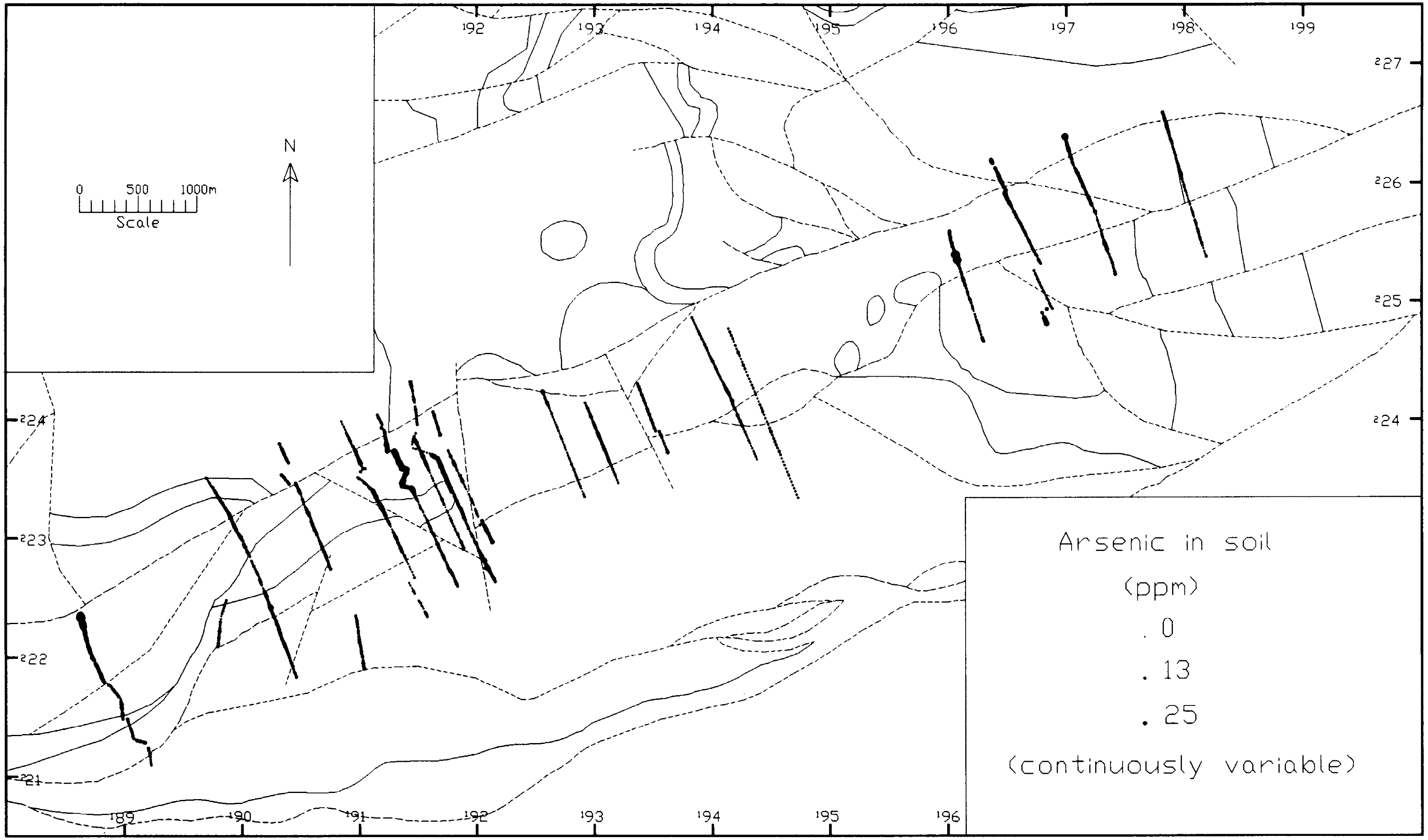


Figure 13 Plot of arsenic in soils at Treffgarne 1992 and 1993. Geological lines as on Figure 9.

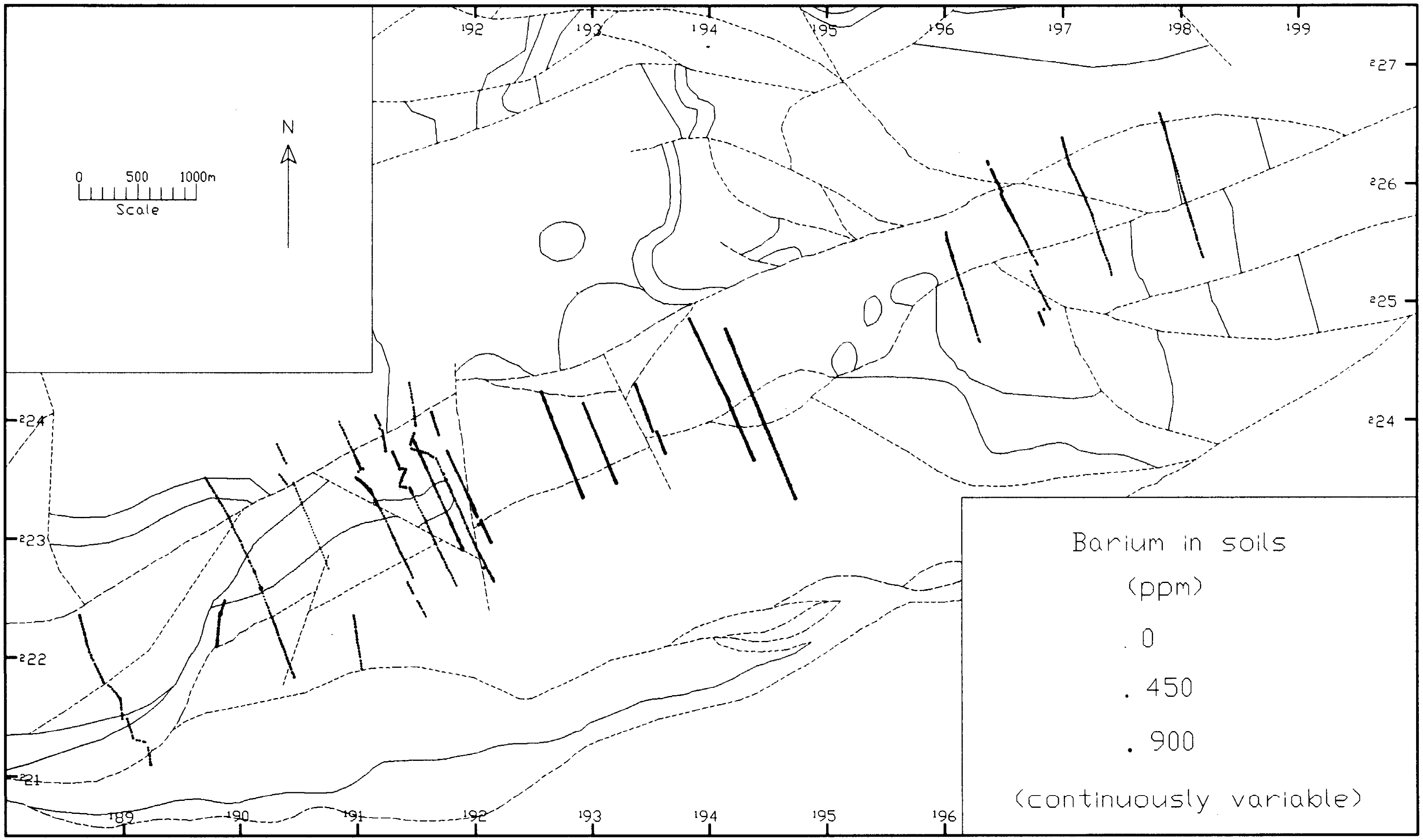


Figure 14 Plot of barium in soils at Treffgarne 1992 and 1993. Geological lines as on Figure 9.

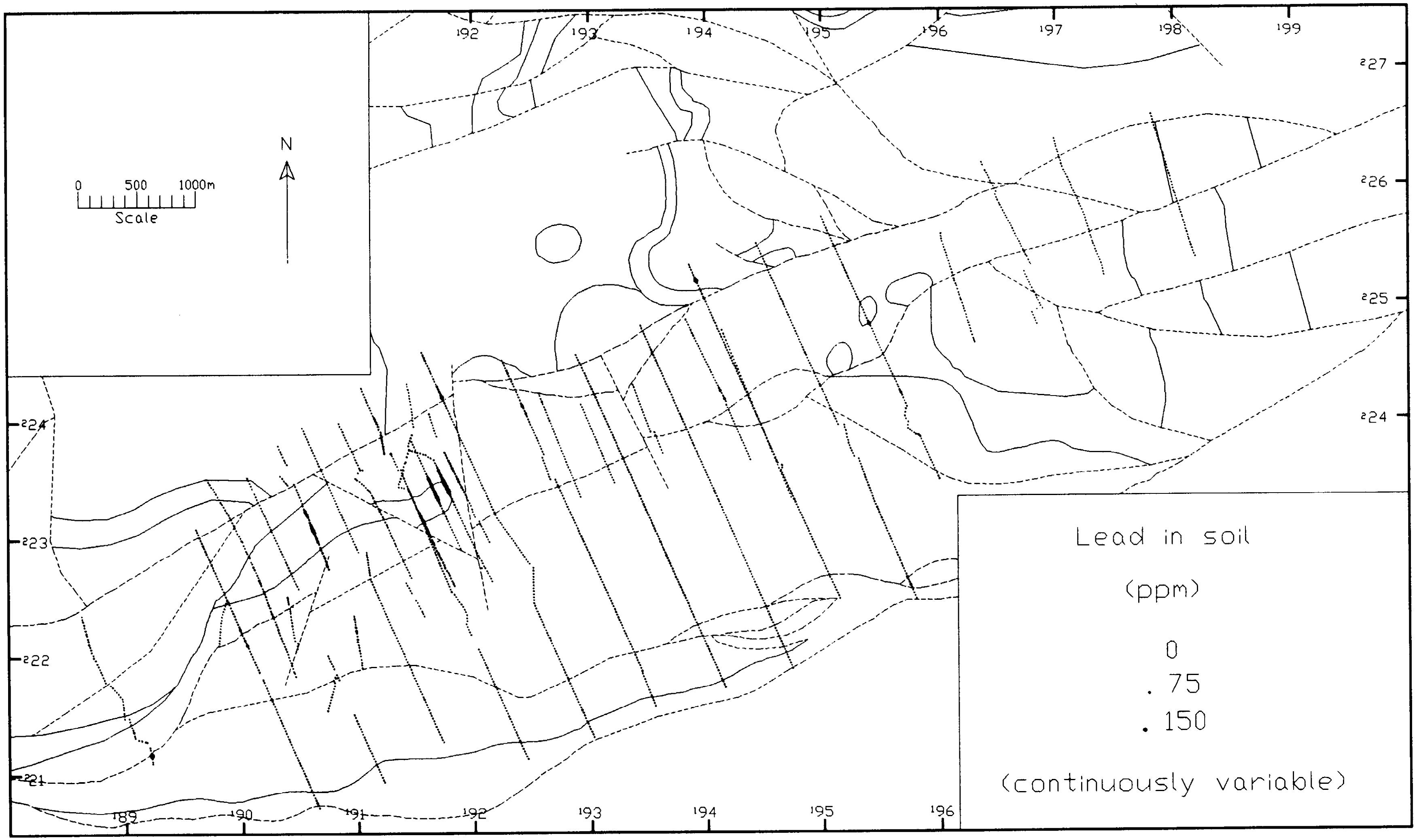


Figure 15 Plot of lead in soils at Treffgarne 1982, 1992 and 1993. Geological lines as on Figure 9.

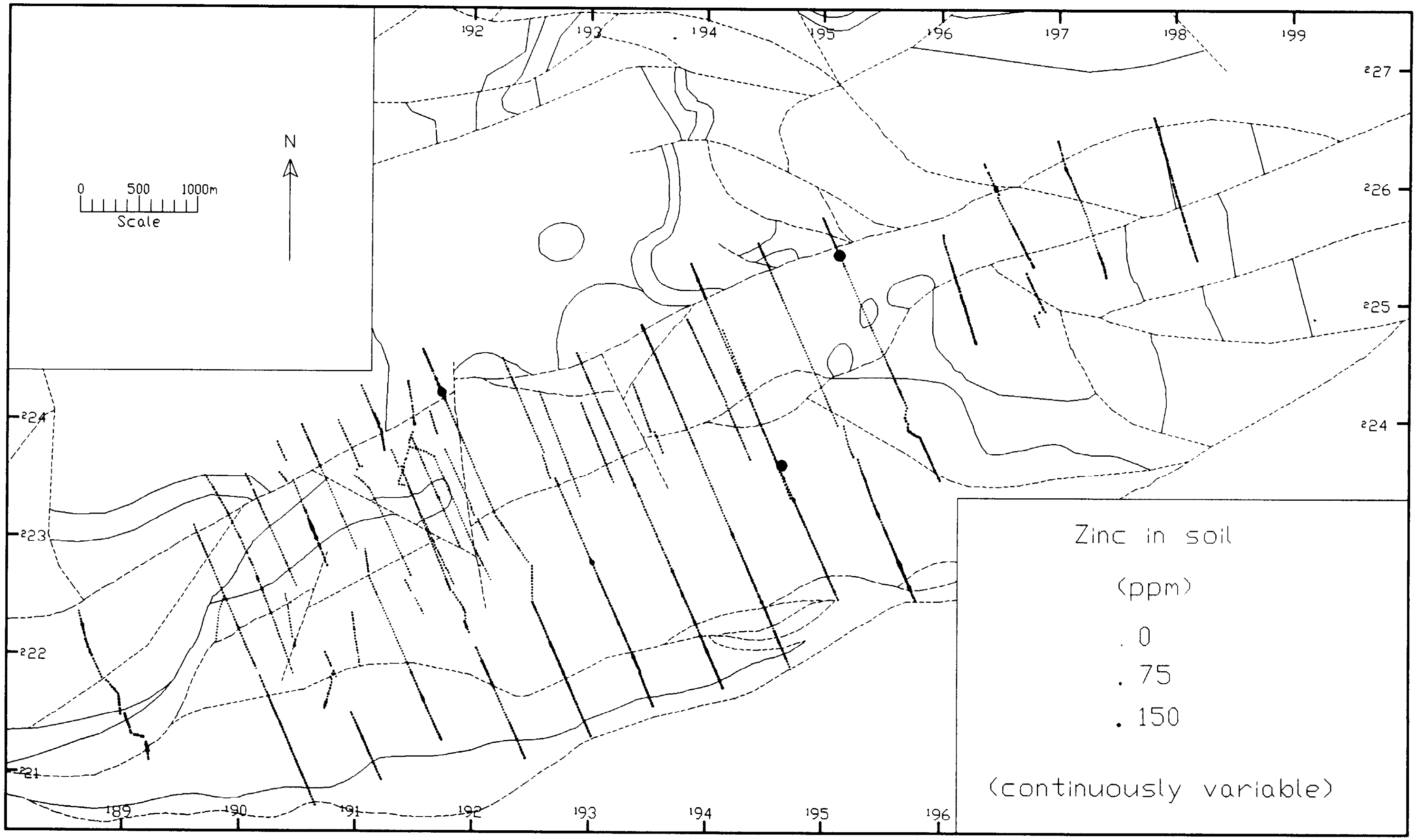


Figure 16 Plot of zinc in soils at Treffgarne 1982, 1992 and 1993. Geological lines as on Figure 9.

An anomalous zone of Ba enrichment over 400 m wide occurs on line 900E with a peak value of 954 ppm Ba from a background of around 400 ppm. The anomaly is over the contact between the flinty rhyolite and the Nant-y-Coy Formation, and there are no significant base-metal values. It may be the surface expression of the Ba mineralisation seen in Borehole 1 at 85–90 m depth. To the south-south-east on line 900E, a single-point Cu value of 102 ppm occurs over the rhyolitic ash and breccias. Separate Zn and Pb anomalies, exceeding 100 ppm, occur over the Roch Rhyolite Formation on line 300E (Figure 12). Ba and Rb values are very low, again reflecting the intensely altered nature of the rhyolites. The additional lines to the east of Plumstone mountain reveal additional anomalies, although they did show the sensitivity of soil geochemistry to different bedrock lithologies.

The line running from Ferny Glen to Cuffern shows little variation of any interest except for enrichment in As at the northernmost end of the line. This is probably due to outcropping of black shales from within the Treffgarne Bridge Beds.

The area to the east of Treffgarne Gorge is poorly known geologically; the only mapping is that of Thomas and Cox (1924). Rock clasts in fields suggest that there may be substantial outcrops of volcanic rocks of either the Treffgarne Volcanic Formation, the Sealyham Volcanic Group or the Roch Rhyolite Group. The soil sampling shows little variation in Rb and Ba except for slight decreases on the southern ends of all four lines. This may reflect the influence of underlying volcanic horizons. Cu and Pb show no enrichment in the soils in these areas, but noticeable variations in Zn do occur, again probably related to underlying bedrock lithology. An As peak of 57 ppm to the north-east of Little Treffgarne Rocks over the Nant-y-Coy Formation may be related to quartz veins exposed in Treffgarne Gorge. This is particularly interesting, since anomalous gold values (up to 597 ppb) have been recorded from these veins, and the soil anomaly may indicate a lateral extension of this style of mineralisation. Arsenic is also enriched over the northern parts of these lines, probably reflecting relative enrichment in the underlying Sealyham Shales.

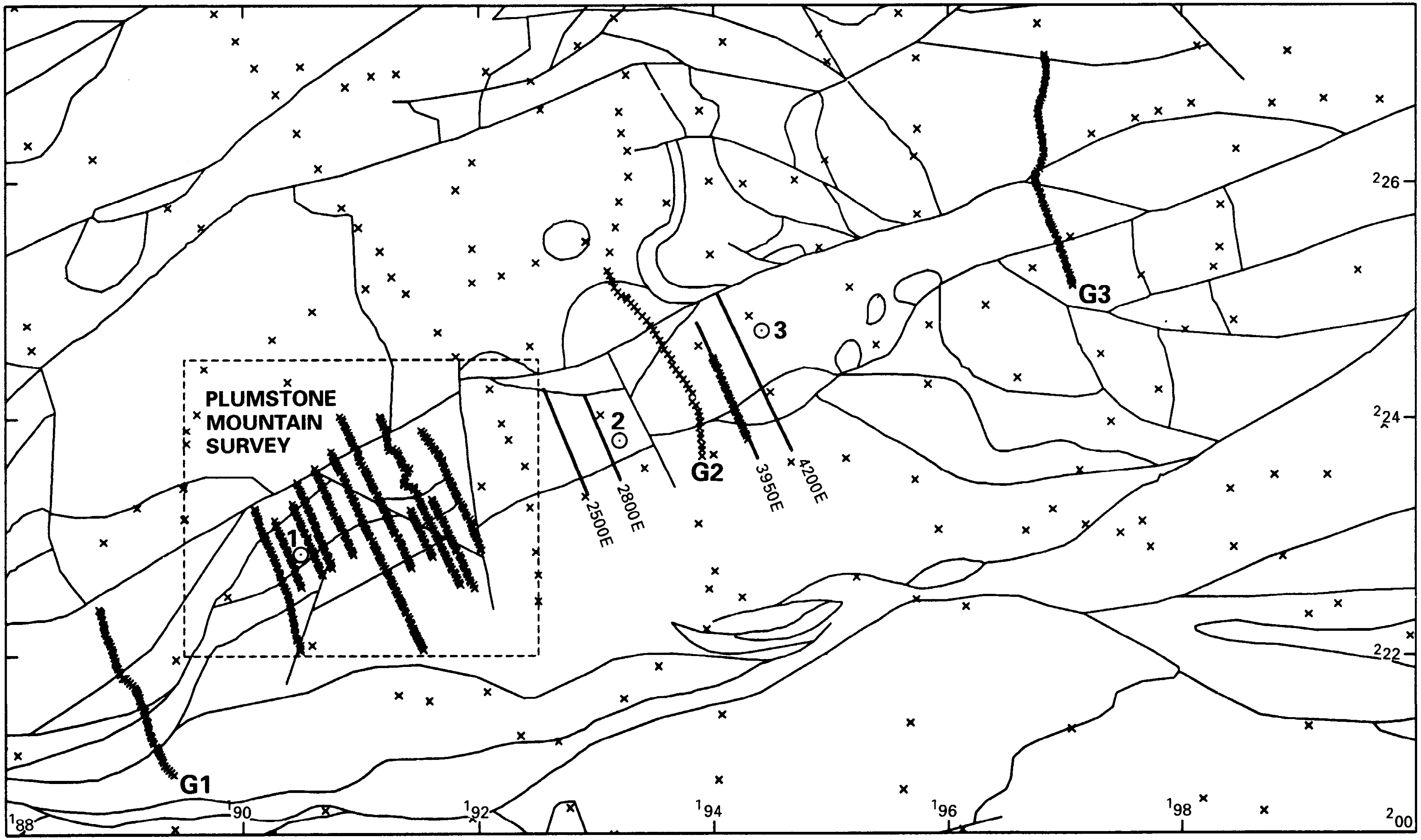
Plots of the soil data are shown in Figure 13 (arsenic), Figure 14 (barium), Figure 15 (lead) and Figure 16 (zinc).

Geophysical surveys

The location of follow-up geophysical surveys undertaken in 1992 and 1993 are shown in Figure 17. In 1992 detailed gravity traverses were carried out at Plumstone Mountain over the IP chargeability zone in conjunction with infill soil geochemical sampling on the previous survey grid. A trial transient electromagnetic (TEM) survey was also carried out. In 1993 further detailed gravity traverses were surveyed across other IP anomalies at Ferny Glen, Great Treffgarne Mountain, and east of Treffgarne Gorge. These were accompanied by electromagnetic and SP surveys.

Review of previous data on the Treffgarne area

For this report the digital IP and airborne survey data arising from previous work (Evans and Armistead, 1992; Cornwell and Cave, 1986) have been re-evaluated, using new digital processing techniques, and integrated with the geophysical and geochemical survey data acquired in 1992–93. Images were generated using the BGS COLMAP mapping package.



KEY
× gravity station
HLEM/SP traverse
⊙ borehole

Figure 17 Location of Treffgarne geophysical surveys (1992–1993). Geological lines as on Figure 9.

Magnetic data. The detailed airborne magnetic survey data (Plate 1) show a series of short-wavelength magnetic highs (shown as high relief) associated with Precambrian biotite granodiorites, granophyres and tuffs in the Hayscastle Anticline. Magnetic susceptibility values for tuffs in the Hayscastle area show values up to 100 (Cornwell and Cave, 1986). The belt of magnetic rocks appears to continue beneath the Nant-y-Coy Formation in the western part of the district and probably extends at shallow depth beneath the Welsh Hook Beds to the south-west of Wolfs Castle. There is a notable absence of short-wavelength anomalies over a large part of the Precambrian east of Hayscastle, where a lower-density granitic intrusion is inferred (see section on gravity).

Magnetic anomalies are absent over all the exposed Palaeozoic volcanic rocks in the area. Magnetic susceptibility values for the rhyolites (0.24–0.34) are low and reflect a general absence of magnetite in these rocks. The only short-wavelength magnetic high outside the Precambrian outcrop not associated with visible cultural noise is an isolated 140 nT high on the south side of Plumstone Mountain (anomaly a, Plate 2), coincident with a ground VLF anomaly.

In the south-east part of the area, magnetic contours trend roughly east-north-east and depict a broad regional increase in the magnetic field towards the south-east, associated with a regional magnetic high of unknown origin.

VLF-EM data. The VLF-EM data are shown in Plate 2 as a map of the intensity of the horizontal field component of the VLF field (VLF-IH) measured as a percentage of the normal field. Low VLF-IH values indicate electrically resistive rocks whilst high values indicate conductive rocks, faults or thick overburden. The data are affected by topography and to a lesser extent by roads, buildings and power lines, and it is difficult to correlate individual anomalies precisely with the surface geology. Generally the Treffgarne area shows no particularly strong VLF-IH anomalies. The Nant-y-Coy Formation exhibits low VLF-IH values (high resistivity) over Great Treffgarne Mountain, and the flinty rhyolite outcrop on Plumstone Mountain is clearly defined as a belt of resistive rocks. However a local high (anomaly A, Plate 2) occurs within the Nant-y-Coy Formation on Plumstone Mountain and is nearly coincident with radiometric and chargeability highs (anomaly A, Plates 3 and 5). Abundant pyrite in float on Line 900E at 250N suggests that a small pyrite body at shallow depth may be the cause of this anomaly.

Radiometric data. There is generally poor correlation between total-count radiometric values and the surface geology. Much of the observed variation is due to changes in flying height and thickness of the overburden. The background level is difficult to determine but the overall data range lies between 400 and 600 counts per second (cps). Anomalies above 650 cps occur in several places but rarely extend for more than one flight line.

There are no prominent anomalies but there is a distinct cluster of high values above 600 cps in the central part of the area over the Nant-y-Coy Formation and Treffgarne Bridge Beds (Plate 3). This radiometric high region correlates broadly with a regional gravity high (Plate 6) and may be related to a displaced crustal block (see gravity), It is abruptly terminated in the west along a line coincident with a north-north-west trending fault (F1). This fault may therefore represent a deep crustal fracture (see gravity below). To the south and east, the high terminates at the contact with the Treffgarne Volcanic Formation and within the Treffgarne Bridge Beds east of Treffgarne Gorge. A local radiometric high (anomaly A) occurs over the Nant-y-Coy Formation within a faulted block at Plumstone Mountain coincident with a chargeability high (Plate 3). This and other radiometric highs coincide with high Rb values in soils and probably relate to relatively high values of K, and possibly U in the Nant-y-Coy Formation. Low radiometric values, indicating an absence of R in the exposed silicified volcanics, occur over the flinty rhyolites at Plumstone Mountain where these rocks are most altered and silicified.

Induced Polarisation data. The reconnaissance IP survey data were acquired along traverse lines generally 600 m apart, with infill over anomalous areas at 100 or 200 m intervals. The data were digitised and processed to provide a rectangular grid at 25 m intervals along the direction of the traverse lines, and 100 m along strike between traverse lines. The gridded data were used to produce the images of apparent resistivity and chargeability (Plates 4 and 5). Apparent resistivity values are expressed on a $\log_{10}$ scale where values between 1.5 and 3 approximately represent the 1000 to 10000 ohm.metre data range.

The Roch Rhyolite Group is characterised by high resistivity values throughout the Treffgarne area. At Plumstone Mountain the highest values occur over the flinty rhyolite outcrop where they commonly exceed 4000 ohm.metre and are accompanied by high chargeability values locally greater than 40 ms. Borehole 1 showed that the high chargeability at this location was due to disseminated pyrite. Anomaly A (Plate 5) however was not drilled. Other high resistivity/chargeability anomalies of comparable magnitude occur at Leweston Mountain and Great Treffgarne Mountain and are related to pyrite-rich volcanic and sedimentary rocks within the Nant-y-Coy Formation found in Boreholes 2 and 3. The broader chargeability anomalies in the far east and west of the area are accompanied by lower resistivity and are thought to be caused by pyritic mudstones. The remainder of the Treffgarne area is characterised by low chargeability.

Gravity data. The observed and residual anomaly maps (Plates 6 and 7) include regional gravity data and detailed gravity survey data described below. The residual map was generated by subtracting a 10th order polynomial surface from the observed field to remove the broader-wavelength regional anomalies.

The observed regional map (Figure 4) shows a pronounced gravity low associated with Precambrian acid tuffs within the Hayscastle Anticline. This feature forms part of a more extensive east–west gravity low across south-west Wales which extends offshore as far as Skomer Island (Figure 4). Within this, a circular gravity low occurs east of Hayscastle. Its circular nature and the absence of short-wavelength magnetic anomalies here suggests a concealed lower-density granitic intrusion (Cornwell and Cave, 1986).

The residual map shows a north-east trending gravity high over the outcrop of the Nant-y-Coy Formation as far east as Treffgarne Gorge, with a pronounced gradient centred along the contact with the Precambrian rocks within the Hayscastle Anticline. The gravity high is probably caused by higher-density rhyolites and sedimentary rocks of the Roch Rhyolite Group. The observed Bouguer gravity anomaly map, however, shows that in the central part of the region a broader-wavelength gravity high continues over and beyond the Treffgarne Bridge Beds, and extends from roughly east of Plumstone Mountain to Treffgarne Gorge. This feature appears to be a northward continuation of a regional gravity high over southern Pembrokeshire seen on the gravity data (Figure 4), the source of which is unknown. The gravity high is broadly coincident with the radiometric high and the gravity contours run parallel to the north–south fault (F1) which may represent a deeper crustal fracture. The residual map shows a clear displacement along fault F2. The source of the circular gravity low over Lower Palaeozoic rocks east of Treffgarne Gorge is unknown.

Ground surveys (1992–1993)

Gravity surveys. In July 1992, a detailed traverse-based gravity survey was carried out between Plumstone Mountain and Dudwell Mountain in an attempt to detect any massive sulphide deposits which did not respond to the previous IP survey. A massive sulphide body would have an estimated density contrast of up to + 1.3 Mg/m^3 with the surrounding rocks and hence should produce a detectable local gravity high. The calculated gravity response for models representing VMS deposits at various depths is shown in Figures 18a (modelled on the major Hellyer deposit in Tasmania) and 18b (modelled on the small Balcooma prospect in Queensland (Bishop and Lewis, 1992). Anomalies greater than 0.1 mGal over a horizontal distance of 100 m or less were considered detectable using this method. Thus in certain circumstances a massive sulphide body may be detectable at a depth beyond 100 m.

487 gravity stations were surveyed along 11 survey lines 100 m or 200 m apart. Measurements were made at 25 m intervals using a LaCoste and Romberg gravity meter. Station positions were determined using a measuring tape along a fixed compass bearing. All stations were related to a baseline pegged at 100 m intervals with the same grid origin and line orientation as the previous survey grid. Topographic elevations were surveyed with a WILD autoset level and tied to a triangulation point on Dudwell Mountain [SM 9070 2314] and to a spot height at Plumstone Rock [SM 9169 2338], in order to determine the height above mean sea level of each gravity station.

In September 1993 three longer gravity traverses were surveyed (G1, G2, G3; Figure 19) across the regional structure to measure the gravity response of the main rock types and to investigate further prospective ground. The traverses at the extreme ends of the survey area (G1 and G3), in particular, were intended to examine areas of high chargeability located by the earlier IP survey. A shorter gravity traverse was also surveyed over an isolated IP anomaly on line 3950E at Great Treffgarne Mountain. Gravity measurements were made using the same gravity meter, station interval, and gravity base as that adopted for the Plumstone Mountain survey. All observed gravity values were calculated relative to a local gravity base located at the entrance to Plumstone Reservoir [SM 9187 23400] where a value of 981228.75 mGal was obtained via a previous base link to the primary base station at Haverfordwest on the National Gravity Reference Network (NGRN 73). Bouguer gravity anomalies were derived using the Gravity Reference Spheroid 1980 and a reduction density of 2.74 Mg/m^3. The gravity effect due to the local terrain was applied to Hammer Zone G using a digital terrain model derived from Ordnance Survey elevation data.

The detailed gravity results for Plumstone Mountain are presented as stacked profiles in Figure 20. A pronounced decrease in gravity in the northern part of the area is attributed to Precambrian acidic rocks within the Hayscastle Anticline. Gravity values increase to about 23 or 24 mGal over the outcrop of the denser Roch Rhyolite Group, consistent with the regional pattern. Gravity values remain high with little variation over the rhyolitic breccias, flinty rhyolites and the Nant-y-Coy Formation implying there is no significant density contrast between these rock types. The densities of the rhyolite tuffs (2.82 Mg/m^3) measured from Borehole 1 are comparable to basic igneous rocks and are far higher than rhyolites obtained from elsewhere (Appendix 2). Their abnormally high density probably relates either to their high pyrite and/or Ba content or to their original mafic composition.

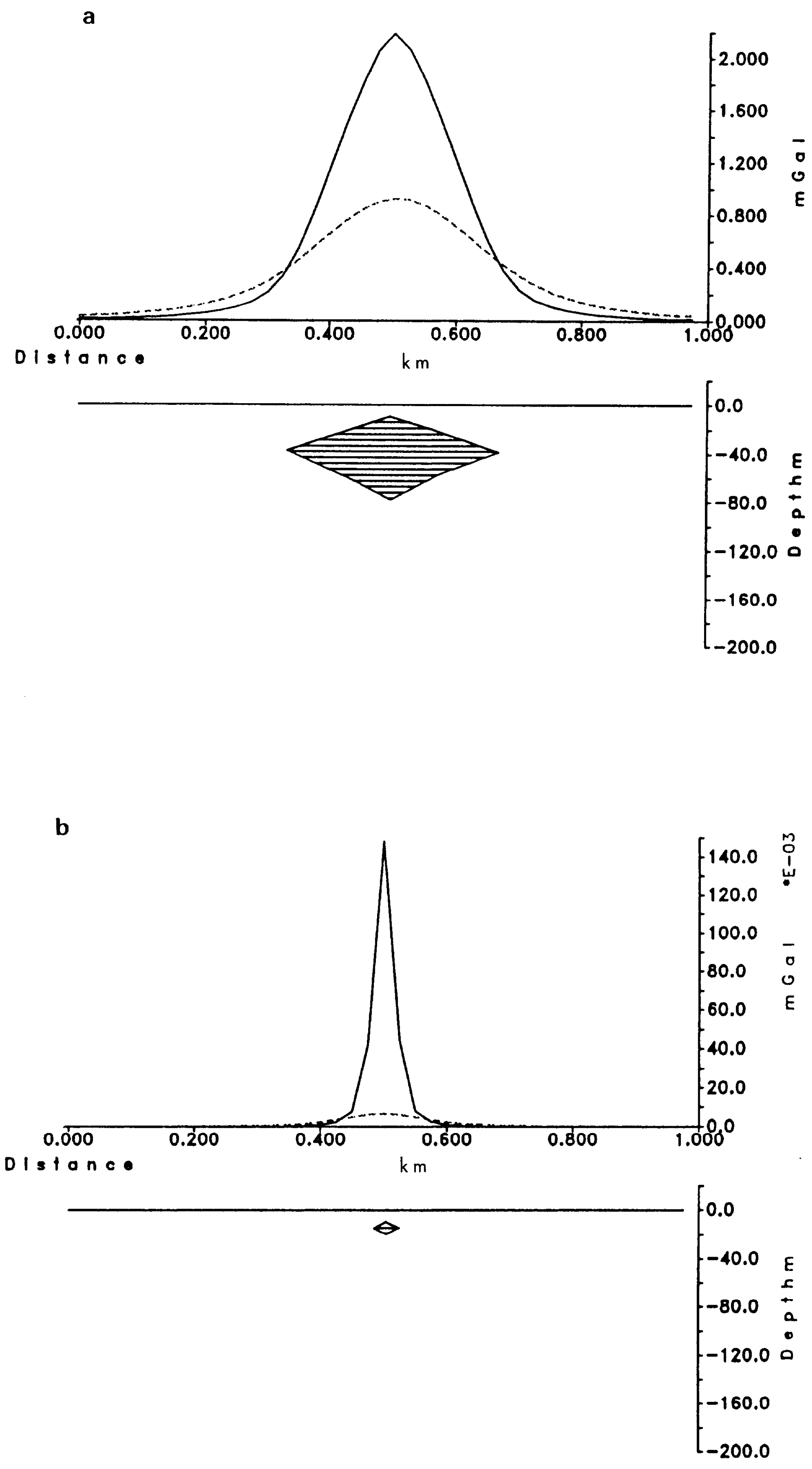


Figure 18 Calculated Bouguer anomaly profiles for models representing VMS deposits at depths of 10 m (solid line) and 100 m (dotted line) a) Hellyer b) Balcooma

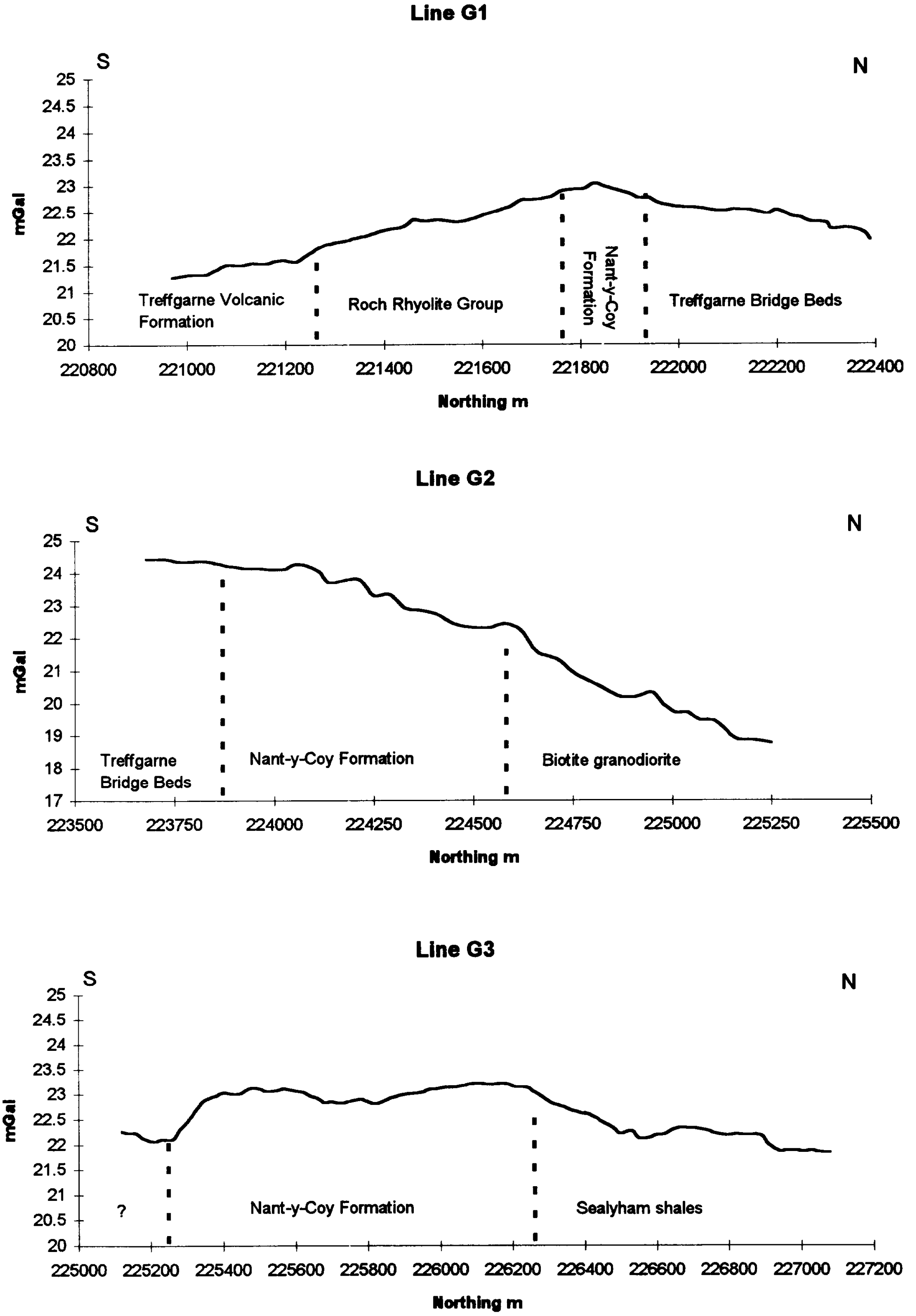


Figure 19 Detailed gravity profiles across the Treffgarne area. Locations of traverse are shown on Figure 17

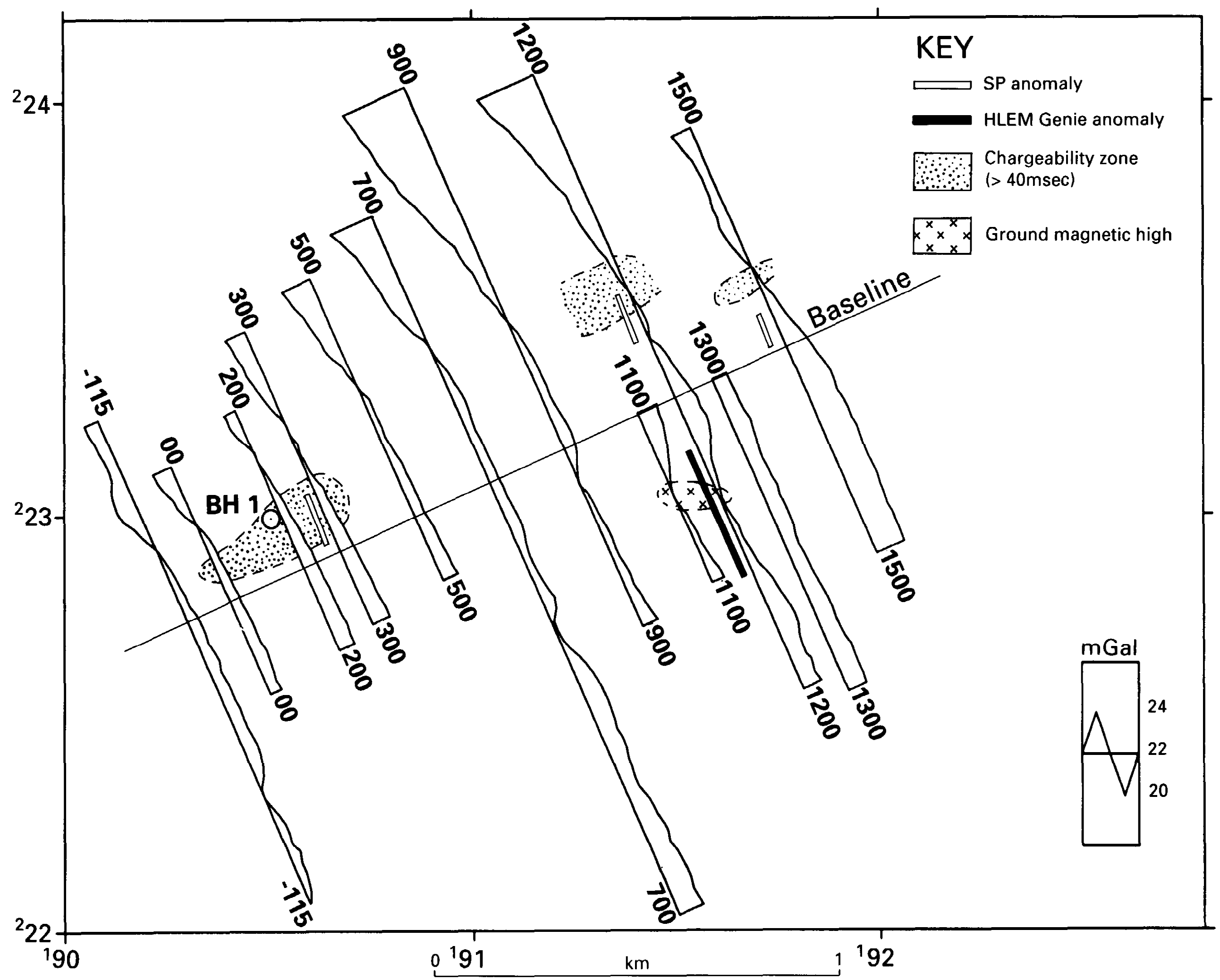


Figure 20 Stacked profiles of detailed gravity data and locations of geophysical anomalies over Plumstone Mountain

The only notable gravity variation along the profiles is a small east–west gravity trough south of the baseline between lines 900E and 1200E which signifies lower density material. The lowest gravity values correlate with a 150 nT magnetic anomaly identified from airborne and ground magnetic surveys. On line 1200E this feature correlates with the mapped outcrop of the Treffgarne Bridge Beds and occupies a zone of higher conductivity. The increase in conductivity may be caused by a local increase in the thickness of the overburden, but the source of the magnetic anomaly is not known.

The detailed gravity data were gridded at 25 m intervals and a fifth-order polynomial surface was removed to separate the broader wavelength features due to general lithological variations from any shorter wavelength gravity highs which may indicate local massive sulphide mineralisation.

The residual map (Plate 8) shows a very small positive anomaly of c. 0.2 mGal amplitude broadly coincident with the zone of high chargeability on line 300E adjacent to Borehole 1 (Figure 20) where there is a small coincident Pb–Zn anomaly. This is consistent with the presence of higher-density baryte- and pyrite-rich tuffs in the borehole. A second isolated gravity high on line 1500E south of the baseline correlates with a smaller chargeability anomaly and has a Pb anomaly located on its northern margin. Other highs outside the survey grid may be artefacts of the gridding process where the data distribution is thinner or data are absent.

On profile G1 (Figure 19) the maximum gravity values occur over the Nant-y-Coy Formation with a gradual, near symmetrical decrease in gravity either side of this formation. The lowest gravity values occur over the Treffgarne Volcanic Formation in the southern part of the profile with a pronounced change in gradient at the contact with the Roch Rhyolite Formation. The gravity anomaly over the Treffgarne Bridge Beds in the northern part of the profile is about 0.5 mGal higher than in the southern part.

In contrast, profile G2 shows the highest gravity values over the Treffgarne Bridge Beds and a gradual decrease in gravity to the north over the Nant-y-Coy Formation and biotite granodiorite. There is no notable decrease in gravity over the granodiorite which suggests that either this intrusion is very thin or it is not related to the main gravity low at Brimaston.

Profile G3 is similar to profile G1 with a pronounced gravity high over the Nant-y-Coy Formation. At the southern end of the profile a sharp decrease in gravity occurs at the contact with an unknown rock unit composed of presumably much lower density material. The gravity decrease in the northern part over the Sealyham shales suggests these are of a comparable density to the rocks at the southern end of the profile.

Background values for profile G2 are about 2 mGal higher than those of profiles G1 and G3. This increase is reflected in the regional pattern where profile G2 is located on a broader-wavelength gravity high (Figure 19) suggests a distinct local crustal block of higher-density rocks. The short gravity traverse on line 3950E is very similar to profile G2 and shows no local positive anomaly over the chargeability anomaly.

Electromagnetic (EM) surveys. Electromagnetic surveys were carried out over survey lines 300E, 1200E and 1500E at Plumstone Mountain (Figures 21 and 22), where gravity data had also been obtained. Further trial lines were surveyed over lines 2500E and 2800E (close to Borehole 2) at Leweston Mountain, lines 3950E and 4200E (near Borehole 3) at Great Treffgarne Mountain, and over a short line along the central part of gravity traverse G3 east of Treffgarne Gorge.

The EM Genie method was chosen as it is specifically designed to detect massive sulphide bodies. It is particularly suitable for rapid surveying in moderate to rough terrain since it is relatively insensitive to errors in coil separation and orientation. It also provides a better spatial resolution for a given depth than the IP method and thus is better at identifying and resolving thin sheet-like conductors at depth.

Measurements were made at 25 m interval using a Scintrex IGS-2/EM4 Genie/Horizontal Loop Electromagnetic (HLEM) receiver and a 'portable' TM-2 transmitter. The equipment was operated in the 'Genie' mode as opposed to the more conventional time-consuming HLEM 'Slingram' mode which requires an interconnecting cable.

In the Genie mode of operation the sensor measures the vertical magnetic field amplitudes at two well-separated frequencies, the higher frequency being the signal frequency and the lower one the reference frequency. The ratio between the two is expressed as a percentage or the 'Genie' ratio. In an area with no conductors or conductive overburden the reading is 100% regardless of coil separation. When a conductor is present a negative anomaly is commonly recorded with a minimum centred over the conductor. The amplitude of the anomaly is governed by the chosen frequency pair so that as the signal and reference frequencies converge the amplitude of the anomaly decreases. Similarly, increased separation of the receiver and transmitter coils increases the sensitivity of the instrument, increases the anomaly ratio and gives deeper penetration.

A receiver–transmitter separation of either 50 m or 100 m was used, giving a maximum theoretical effective depth of exploration of between 75 and 150 m. The choice of separation was determined by the amount of noise present due to the local ground and atmospheric conditions. Where time permitted both separation distances were used.

The results of the EM surveys for Plumstone Mountain are shown in Figures 21 and 22. Lines 300E and 1200E were surveyed with a 100 m receiver–transmitter coil separation while a 50 m separation was used for line 1500E because of local atmospheric noise. The profiles show a generally noisy background with no major EM anomalies which would indicate massive sulphide mineralisation. The very small isolated negative anomaly on the wider frequency pair at –50 m over rhyolitic ash and breccia on line 300E is not regarded as being sufficiently large to suggest a significant conductor. There is no appreciable change in conductivity over the chargeability zone on this line.

Similarly, on line 1200E there is no obvious EM anomaly over the chargeability anomaly, although there is a general increase in the background noise level. Higher values over the Treffgarne Bridge Beds suggest that these rocks are more conductive. They correlate with the gravity low and with the intermediate conductivity layer R2 on the TEM profile. Line 1500E is generally featureless with no response over the anomalous lead zone. The isolated anomaly at 125S is attributed to a buried pipe.

The EM traverses on lines 2500E and 2800E at Leweston Mountain and lines 3950E and 4200E at Great Treffgarne Mountain were badly effected by wire fences, power lines, buried pipes and scrap metal. Thus severe cultural noise masked any mineral conductors which may have been present.

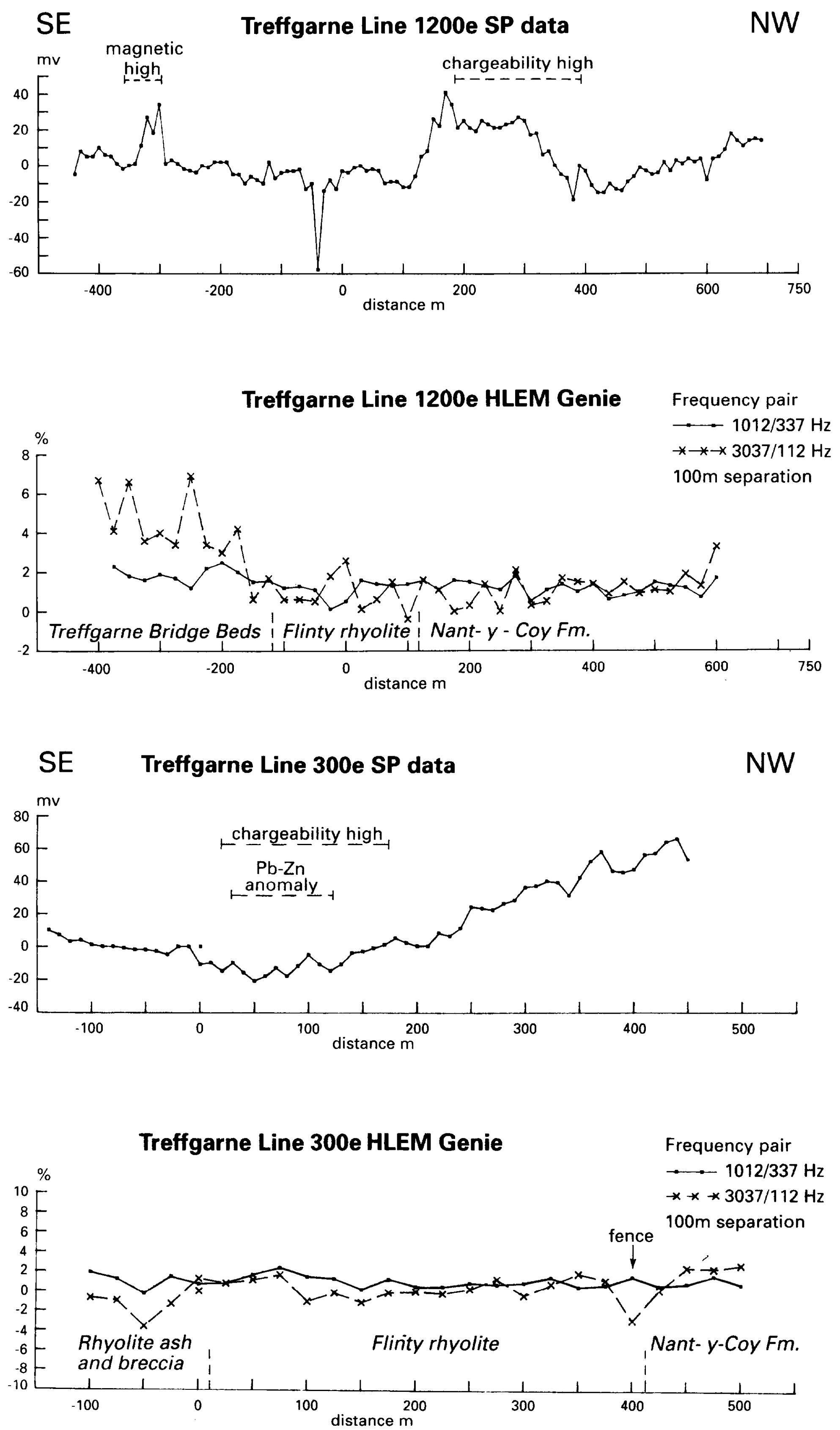


Figure 21 Profiles of SP and HLEM Genie data on lines 300E and 1200E over Plumstone Mountain

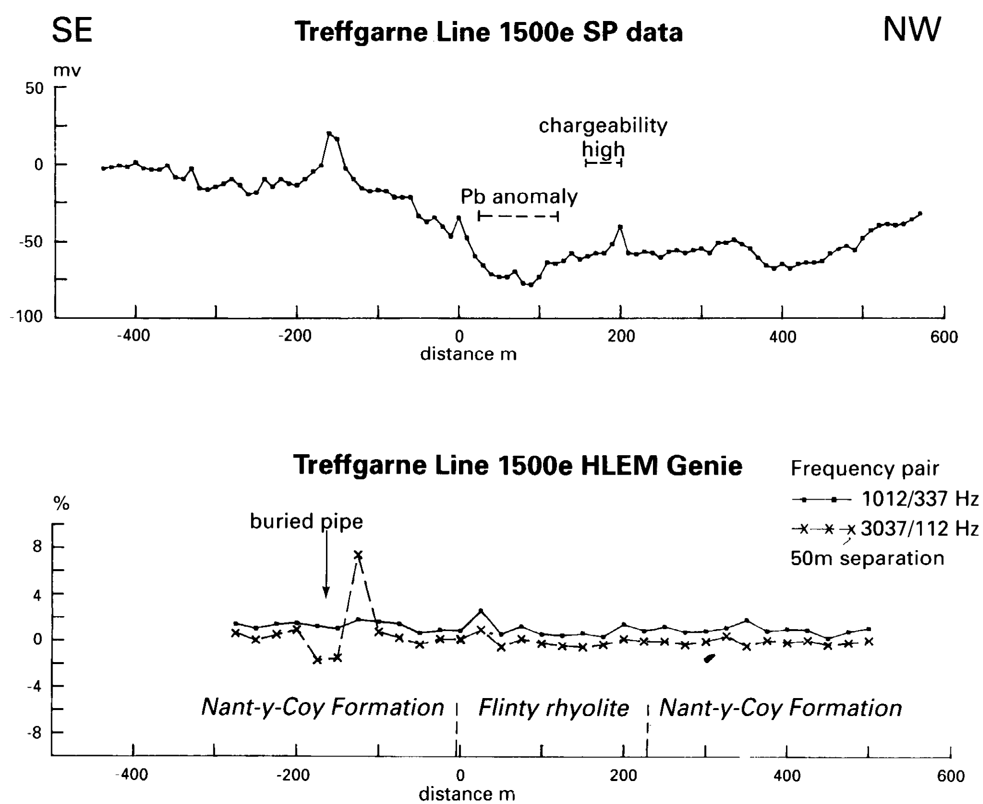


Figure 22 Profiles of SP and HLEM Genie data on line 1500E over Plumstone Mountain

Self Potential surveys. The Self Potential (SP) method was used to identify any natural current flow in the ground related to zones of chemical weathering associated with a concealed massive sulphide deposit. This method is relatively rapid and can provide valuable additional information, especially when combined with the gravity method. SP was used over all the EM survey lines.

The results of the SP survey at Plumstone Mountain are shown in Figures 21 and 22. There is very little similarity between the SP profiles, rendering correlation difficult. However a small, broad SP low between 00 and 100N on line 300E occurs over the Pb–Zn anomaly, and broadly lies within the chargeability zone near Borehole 1. Similarly there is a small SP anomaly on line 1500E where the lowest values occur within a local low immediately north of the baseline within the anomalous Pb zone. Line 1200E is relatively flat by comparison but there is a notable positive anomaly between 175N and 350N, roughly coincident with the chargeability high. There is no obvious explanation for this feature. The SP response over the other survey lines was flat except for a narrow negative anomaly on line 2800E indicative of a narrow conductor such as a buried pipe.

Transient electromagnetic (TEM) surveys. A trial survey using transient electromagnetic (TEM) equipment was carried out using Geonics EM47 equipment. This method was used in an attempt to determine if good electrical conductors, representing possible massive sulphide deposits, existed but escaped detection during the earlier reconnaissance IP surveys. The TEM method has good spatial resolution and has been shown to be sensitive to the presence of conductors at considerable depths, particularly in the resistive type of terrain known to exist at Treffgarne. The present investigation made use of the results from the previous surveys at Treffgarne as reported briefly by Brown et al. (1987).

The TEM method involves the use of transient current pulses of approximately square wave form to induce currents in the ground. The decay of these induced currents, which is measured during the time between the primary current pulses, varies with time, dependent upon the resistivity, with more rapid decay occurring in highly resistive ground. The locus of the maximum induced current vortices diffuses downwards and outwards with time and it is possible to model the observed decay in terms of the variation of resistivity with depth (using the late-time asymptotic formula). Over a uniform half-space the apparent resistivity calculated approximates to ground resistivity at later times, but diverges (towards higher apparent resistivities) at earlier times. The TEM sounding data are displayed as logarithmic plots of late-time apparent resistivity vs. time (Figure 23). The results are therefore analogous to those from resistivity soundings. The primary current is fed to a transmitter coil and the smaller receiver coil can be placed outside with various offsets or at the centres of large transmitter coils.

The ground penetration of the various TEM systems varies; the Geonics EM47, with a small battery transmitter, has the shallowest penetration, with depths reported as being up to 100 m.

The Treffgarne survey was carried out using a 20 m x 20 m square transmitter coil with the receiver coil offset by 20 m from the centre. Using a primary current of 2.5 A, twenty channels of data were recorded over the time range 6 μs to 80 ms. Test measurements indicated that the low signal strengths required high instrumental gains but these were inevitably limited by the ambient noise levels. The operating repetition frequency was also set on the basis of the tests (at 315 Hz). At least three sets of data were acquired at each station.

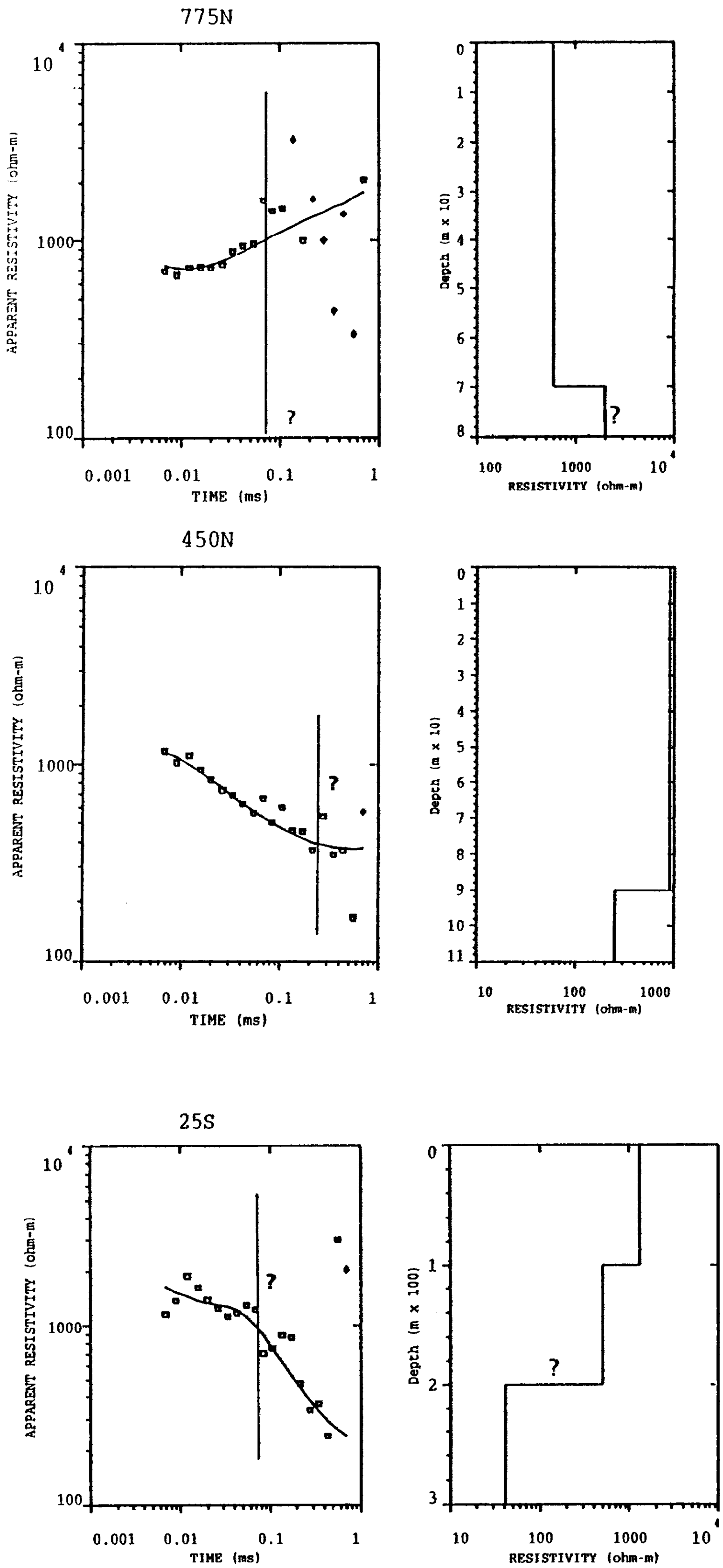


Figure 23.1 Examples of TEM sounding curves on line 1200E for a selection of stations from 775N to 25S. Apparent resistivity versus delay time observed data (squares) and interpreted models. Areas indicated by question marks indicate unreliable data points or parts of interpreted model. The resistivity and thickness of the layers are shown for horizontally stratified earth models and the curve is the calculated response for the model

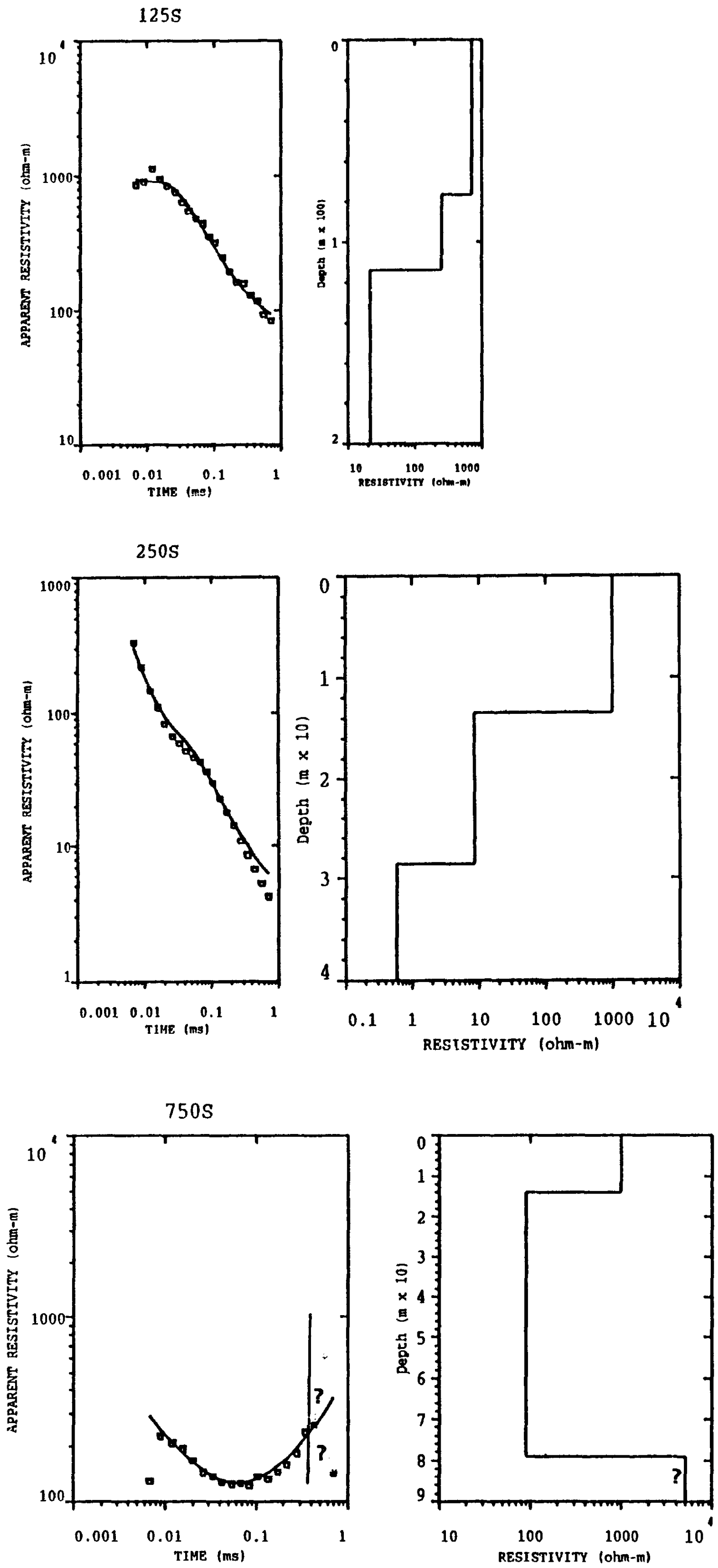


Figure 23.2 As Figure 23.1 but with a selection of stations from 125S to 750S

Profile 1200E (Figure 23) was selected for the trial survey because of the existence of other data sets, which showed pronounced chargeability anomalies and, near 300S, magnetic and VLF anomalies. Measurements were made with the centres of the transmitter loop at the 25 m spaced stations used for the other surveys. Some stations were omitted because of crops (650N to 700N) and farm machinery (500S).

The data were recorded in digital form and subsequently transferred to a floppy disc using a PC. The digital data sets were reduced in the office and plotted using proprietary computer software (*GSPx7, Geonics Limited*). The observed data sets were examined to remove obvious spurious data points but in many cases the noise level was high and therefore the entire data set was retained. The data sets were averaged to provide a single curve for interpretation. Additional interpretations of individual TEM soundings were made using *Temix (Interpex Limited)* to provide resistivity layer models for selected parts of the profile.

Preliminary reduction of data in the field indicated that many data sets suffered from low signal levels and subsequent processing confirmed this, revealing erratic, sometimes negative signals which can only be interpreted in very general terms.

The resistivity values observed during the survey were often high and similar to those recorded during the earlier IP survey, with values of hundreds or thousands of ohm.metre. This highly resistive ground means that the induced currents are small and the signal to noise ratio low; in several cases usable data were recorded only by the first few channels. Consequently the data for many stations exhibit a large scatter in values (Figure 23) and are not suitable for accurate interpretation. However the overall consistency found in the data enables the recognition of broad patterns. The variations along the line broadly reflect those seen on the earlier IP/resistivity survey and there is reasonable correspondence with the mapped geology.

A comparison can also be made with the results of a resistivity sounding using a Schlumberger array carried out near 0N on line 1200E in the earlier survey. Initial interpretation of the sounding indicated a thin (2 m) surface layer (resistivity = 610 ohm.metre) overlying a highly resistive layer (6200 ohm.metre) extending to a depth of 53 m. Below this the resistivity decreases to 1600 ohm.metre. This resistivity distribution is similar to that observed with the TEM sounding but the TEM values are lower (maximum about 2000 ohm.metre).

The highest values occur in the central part of the line between about 300N and 200S, i.e., coincident with the resistivity highs from the IP survey. The more pronounced decrease in resistivity values occurs to the south; the decrease to the north is less marked and continues beyond the end of the measured profile at 825N.

More detailed interpretation of the individual curves using *Temix* software provided a series of interpretations based on horizontally layered-earth models. Examples of apparent resistivity/delay time plots are shown in Figure 23.

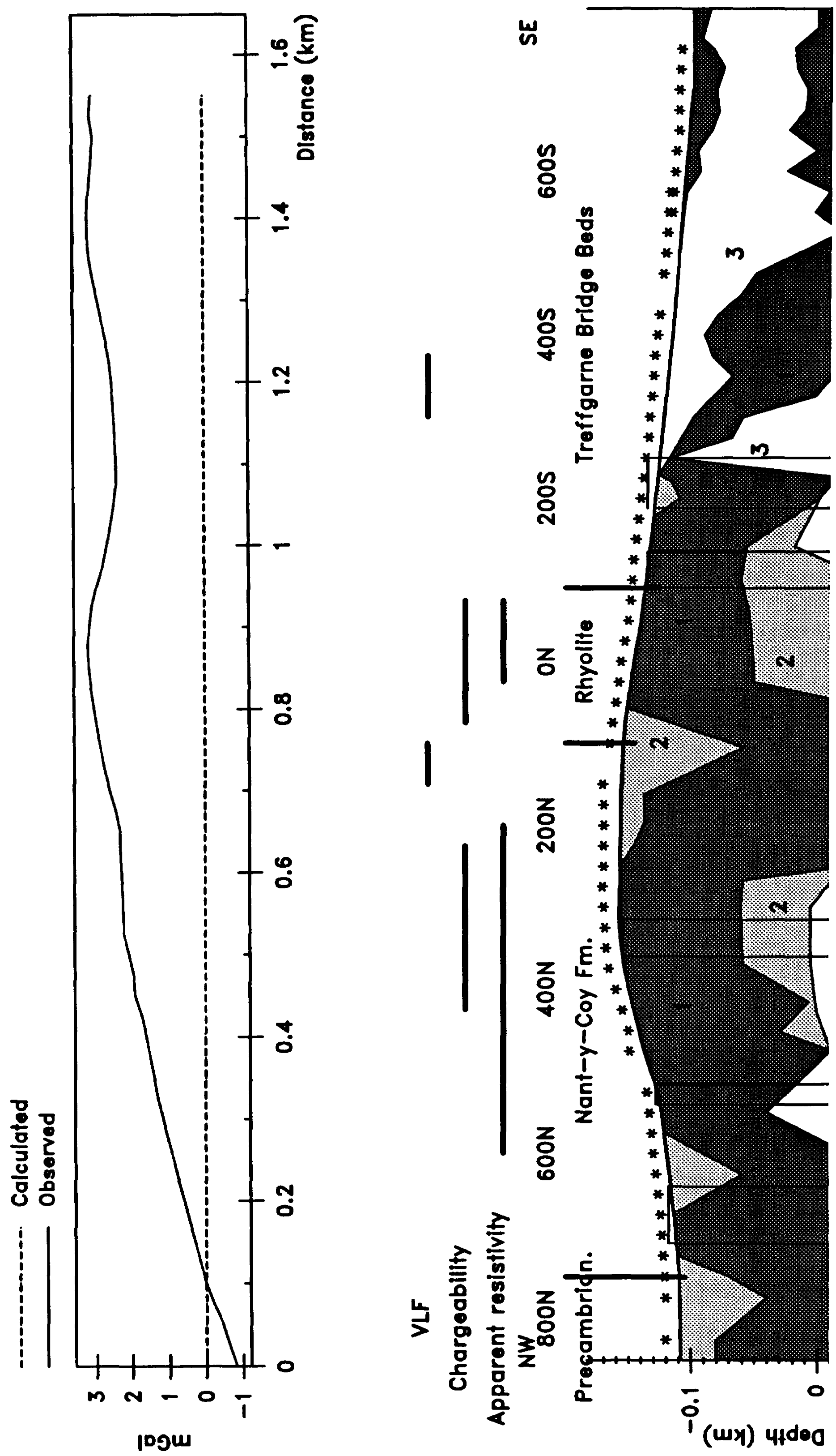


Figure 24 Geophysical data for line 1200E. a: Bouguer gravity anomaly profile. b: locations of anomalies from surveys indicated. c: compilation of resistivity interpretations based on TEM data. Resistivity units recognised (see text): R1: more than 1000 ohm metre; R2: 100 to 1000 ohm metre; R3: less than 100 ohm metre. Asterisks at surface indicate locations of TEM soundings and rectangles indicate particularly noisy data sets

For the purpose of description, the interpreted resistivities have been divided into three broad groups:

R1: High values of more than 1000 ohm.metre. These are likely to be associated with crystalline rocks, such as the rhyolites, with negligible amounts of contained pore fluid. The TEM method is not sensitive to changes in values at this end of the resistivity range because of low signal strengths.

R2: Intermediate values of 100 to 1000 ohm.metre. This range would be expected to include fractured crystalline rocks and most of the sedimentary rocks.

R3: Low values of less than 100 ohm.metre. These values imply highly fractured or high-porosity rocks with a significant fluid content. Very low values of a few ohm.metre, determined at a few sites, are particularly significant as they could indicate highly conductive mineralised zones or conductive shale beds. However, they can also occur over man-made conductors, such as buried pipes. In the present study the evidence for these low-resistivity layers occurs at late delay times where signal strengths are often so low that interpretation is not justified. A few stations produced clear evidence for very low resistivity layers, including 250S (Figure 24) where a buried pipe is considered to be responsible.

Examples of the three groups can be seen in the following zones along the line. The character of the observed decay curves changes along the line and several distinct types can be recognised.

825N to 600N

The variable R2 surface layer, up to 30 m thick, overlies a R1 layer. This part of the profile corresponds approximately with Precambrian rocks of the Hayscastle Anticline (mainly quartz porphyry) and the variable top layer probably reflects weathered rock. The resistivity pattern extends about 100 m to the south of the mapped margin of the Precambrian into ground mapped as Nant-y-Coy Formation.

575N to 250N

This zone is characterised by high resisitivity values at the surface, which decrease with depth, possibly with a R3 layer in places. However the zone contains several particularly noisy stations with only a few reliable data channels. It corresponds broadly with the section of high resistivities (3000 ohm.metre or above) and a chargeability anomaly on the IP survey.

225N to 225S

Broadly similar to the previous zone, with resistivity values decreasing with depth, this part of the profile is distinguished mainly on the basis of the forms of the decay curves. The zone contains more complex variations, the section near 100N being particularly interesting. It is characterised by the presence of resistivity and chargeability minima on the IP survey, a VLF feature and, on the TEM section, by the presence of a near-surface R2 layer. These features are probably associated with a faulted boundary of the rhyolite. Between 50N and 75S the high chargeability and very high resistivity anomalies correspond with a near-surface R1 layer.

250S to 775S

The general character of the decay curves and the nature of the corresponding models in the southern part of the profile are distinguished by the presence of an upper R3 type layer as far south as 600S, where it is covered by a thin R1 layer. This zone corresponds to the outcrop of the Treffgarne Bridge Beds and the resistivity models are consistent with a southerly increase in the thickness of these beds. The R1 layer at depth is interpreted as the southward extension of the high-resistivity Roch Rhyolite and Nant-y-Coy Formations occurring at the surface betwen 200S and 600N. The TEM station at 250S produced exceptionally strong signals and the decay curve indicated very low resistivity values (Figure 23). The results here, and probably on adjacent soundings, are likely to be disturbed by two iron water mains leading from the reservoir at about 250S and 300S.

Discussion

Bishop and Lewis (1992) list the geophysical signatures of a number of Australian VMS deposits ranging from Archaean to Upper Palaeozoic in age. Some form of EM method generally produced a response, though sometimes over a limited area (as at Hellyer). IP was often unsuccessful, though some sulphide lenses, such as the PQ lens from the Que River deposit only responded to IP. Some deposits (e.g. Mons Cupri) appear as resistivity highs, compared with the host rock, and thus would not be expected to respond to EM methods. The high resistivity is ascribed either to silicification, with layers and veins of chert and chalcedony, or to tectonic disruption of sulphide bands coupled with the insulating effects of sphalerite. Gravity methods on known deposits have shown positive anomalies in the range of 0.26 mGal (modeled for Teutonic Bore), 0.3 mGal (Thalanga) and 1.7 mGal at Rosebery (Leaman, 1991), in spite of extensive mining of the last deposit. The high resistivity and chargeability over parts of the Treffgarne area have been ascribed to disseminated pyrite within the highly altered volcanic rocks of the Roch Rhyolite Group, though some contribution to the chargeability in the extreme north-east and north-west may come from pyritic black shales of the Treffgarne Bridge Beds or Sealyham shales. The silicification and quartz veining of the rhyolite, similar to that described from Mons Cupri, may mask the effect of the disseminated pyrite and cause the high resistivity. The massive sulphide deposits associated with acid volcanic rocks at Parys Mountain, Anglesey, generate strong IP, but only weak EM anomalies. VLF-EM indicated steeply dipping conductors and gravity surveys showed anomalies (lows) over acid volcanic rocks rather than any highs associated with massive sulphide (Cooper et al., 1990).

At Treffgarne, most of the prominent geophysical anomalies derived from airborne and ground reconnaissance surveys can be correlated with the mapped geology. Short-wavelength magnetic anomalies are almost all confined to the Precambrian rocks within the Hayscastle Anticline, with the exception a small anomaly south of Plumstone Mountain. The rhyolites are weakly magnetic, reflecting an absence of magnetite.

The belt of high resistivity and chargeability is caused by highly altered rocks of the Roch Rhyolite Group containing disseminated pyrite. These rocks have a higher density than the Precambrian rocks of the Hayscastle Anticline, and cause the residual gravity high. Ground profiles G1–G3 show local maxima occur over the Nant-y-Coy Formation.

A broader wavelength gravity high over the central part of the Treffgarne region correlates with a cluster of high total-count radiometric values which are abruptly terminated by a near north–south fault. The source of the gravity high is unknown.

At Plumstone Mountain detailed gravity traverses showed a gravity high over the Roch Rhyolite Group consistent with the regional gravity data. There is little variation in gravity over the Roch Rhyolite Formation, but small (0.2 mGal) residual positive anomalies occur coincident with the high chargeability zone, and probably relate to dense baryte and pyrite-rich Nant-y-Coy Formation encountered in Borehole 1.

The source of a small local east–west gravity low between 900E and 1200E is not known but it may be related to an increase in overburden thickness. However, no prominent gravity highs were found which would suggest a significant massive sulphide orebody.

Very low radiometric values to the west of the regional gravity high occur where the volcanic rocks are most highly altered and silicified. An isolated radiometric high occurs to the north of Plumstone Mountain on the northern end of line 1200E, over a chargeability anomaly.

The HLEM survey did not detect any notable conductive zones but the TEM survey confirmed a near-surface resistive layer coincident with the Nant-y-Coy Formation and the flinty rhyolite and an increase in conductivity with depth, consistent with results of previous surveys. This pattern characterises the high chargeability zone, compared with those over the Precambrian and Treffgarne Bridge Beds. The TEM method also responded to local variations, such as that associated with the chargeability low and VLF anomaly at the margin of the flinty rhyolite. The SP method identified a broad SP low on line 300E within the anomalous Pb–Zn zone, and on line 1500E over the high Pb zone.

The VLF-IH anomalies are generally noisy and show no particularly strong conductors, although there is a small high on line 900 E where abundant pyrite was visible in float. No electrical methods were tried over this feature.

Elsewhere in the Treffgarne area EM surveys were badly affected by noise from man-made sources which masked any mineralised conductors which may have been present. The SP method was less affected by cultural noise but showed no response over the IP anomalies.

Comparisons between Treffgarne and known volcanogenic massive sulphide (VMS) areas

Volcanogenic massive sulphide (VMS) style deposits commonly display strong hydrothermal alteration, coupled with base-metal sulphides, pyrite and baryte, especially in Palaeozoic and younger deposits (Table 7). Pointon and Ixer (1980) describe the extensive alteration, including pyritisation and silicification, at the Parys Mountain polymetallic deposit in Anglesey. The deposit is hosted by Ordovician acid volcanic rocks, siliceous sinters and volcaniclastic shales. Mineralisation occurs as stratiform lenses and remobilised fracture fillings and veins. The Avoca copper mine in south-east Ireland occurs in Ordovician (Llandeilo–Ashgill) acid volcanic and volcaniclastic rocks close to local volcanic centres (Williams et al., 1986). The mineralisation is similar to that at Parys Mountain. Swinden et al. (1988), in a study of the Lower Palaeozoic VMS deposits of Newfoundland, describe the relative fertility of ophiolite, island-arc and back-arc settings in the late Cambrian to mid Ordovician Dunnage Zone which hosts most of the mineralisation and is of similar age to the Roch Rhyolite Group. The Newfoundland mineralisation is concentrated in the late-Arenig island-arc sequence which hosts the polymetallic Buchans deposits in a mixed mafic and felsic sequence. Deposits in felsic-dominated sequences are rich in Pb and Zn and poor in Cu, reflecting the relative availability of metals into the hydrothermal cells during leaching. It is interesting to note that some of the Newfoundland deposits, thought to have formed in back-arc settings away from tectonic activity, are metal-poor overall and tend to have low Zn/Pb ratios. Swinden et al. (1988) speculate that the hydrothermal systems may have been cooler and less capable of transporting large amounts of dissolved metals than hotter, more active systems. No sulphide deposits have yet been found in the Treffgarne area. The prospectivity for VMS style deposits is based on the similarity of the geological setting, coupled with the abundant pyrite and extensive hydrothermal alteration which is also common to known VMS districts. Only three holes have been drilled in the Treffgarne area; VMS deposits, with their short strike length and frequent tectonic dislocation (e.g. Parys Mountain) often require extensive and prolonged drilling programmes to fully delineate the area's potential. Thus Treffgarne is at a very early stage of exploration. The surface exploration carried out to date does not indicate outcropping or very near surface mineralisation; any further work will involve additional drilling.

Table 7 Comparisons between Treffgarne and known VMS areas.

Established VMS areas (Lydon, 1984)	**Buchans (Swinden et al., 1988; Thurlow et al., 1975)**	**Avoca (Williams et al., 1986)**	**Parys Mountain (Pointon and Ixer, 1980; Swallow, 1990)**	**Treffgarne**
Geology				
Archaean to Tertiary	Ordovician (Arenig)	Ordovician (Caradoc)	Ordovician (Caradoc)	Ordovician (Arenig)
Island Arc / Greenstone	Island Arc / Rifted Arc	Continental Margin Arc	Ensialic Back Arc (Southwood,1984)	Island Arc
Bimodal basalt–rhyolite submarine volcanics	Mixed mafic–felsic submarine volcanic rocks	Felsic dominated submarine volcanic rocks	Felsic dominated submarine volcanic rocks	Dacite–andesite, submarine volcanic rocks
Pyritic black shales	Present	Present	Present	Present
Mineral potential of more than 100 Mt containing Cu, Pb, Zn + Au/Ag	16 Mt at 1.33% Cu, 7.56% Pb, 14.51% Zn	16 Mt at 0.6% Cu + 5 Mt poorly recorded massive sulphide previously mined	4.8 Mt at 1.5% Cu 3% Pb 6% Zn + 3Mt copper ore at ?10% Cu previously mined	No deposits yet known
Clusters of deposits at one or more horizons	Numerous deposits	Several deposits	Several deposits	No deposits yet known
Minerals				
Pyrite (common)	Common	Massive and disseminated	Massive and disseminated	Disseminated in volcanic and sedimentary rocks
Chalcopyrite (common)	Common	Common	Common	Minor
Galena (common in Phanerozoic deposits)	Common	Common	Common	Not seen
Sphalerite (common)	Common	Common	Common	Not seen
Baryte (common in Phanerozoic deposits)	Common	Little reported	Little reported	Sporadic
Hydrothermal alteration				
Strong - loss of alkalis	Strong - variable loss of alkalis	Strong - loss of alkalis	Strong - loss of alkalis	Strong - loss of alkalis
Chloritisation (common)	Chloritisation	Chloritisation	Chloritisation	Not seen
Silicification (common)	Silicification	Silicification	Silicification	Silicification

Discussion on exploration in the Treffgarne area

The soil and rock geochemistry has shown that there are some low-order Pb and stronger Ba anomalies in the area, which remain to be tested by drilling. They may be related to the same style of mineralisation and the Ba is probably associated with the baryte found in Borehole 1. They form part of a hydrothermal system which has not yet been fully delineated. The strong alkali depletion in Borehole 1 shows that a large-scale system was intersected. Geophysics has been unable to provide a convincing target apart from the extensive IP chargeability anomaly which has only been partly tested. Many volcanogenic base-metal sulphide areas consist of clusters of small to large deposits which have formed within a relatively short time interval. The strike length of individual deposits can be small and thus close-spaced drilling is needed to delineate them. Many areas have been explored repeatedly over several decades before significant discoveries were made, sometimes after considerable work has failed to find the major deposit; a case in point is the Mount Chalmers deposit in Queensland (Large and Both, 1980). Here, a volcanogenic massive sulphide deposit (Main Lode) was discovered in 1898 and worked at intervals until 1943. Exploration from 1963 continued to prove sub-economic extensions to the Main Lode before the discovery of the economic, and now mined out, concealed West Lode, 150 m from the Main Lode outcrop, in 1977. The Treffgarne area has only received detailed surface exploration; the subsurface remains largely unknown.

CONCLUSIONS AND RECOMMENDATIONS

Reconnaissance geochemical and geophysical investigations have been carried out over most of the volcanic formations of south-west Wales. In addition, more detailed exploration has been concentrated on the Treffgarne and Crosswell areas. The main conclusions from this work are as follows.

1. The regional lithogeochemistries have shown that alteration, quartz veining and pyrite are more common in south-west Wales than previously noted: for example the 4 m-wide pyritic tuff unit in the Goodwick Volcanic Formation of the Fishguard Volcanic Group at Abergwaun. However, there are few significant enrichments in base-metals or baryte except in the Crosswell area and in the Roch Rhyolite Group, both of which have been the subjects of additional investigations.

2. Petrogenetic investigations have shown that the Roch Rhyolite Group may not be as prospective for base-metal volcanogenic massive-sulphide deposits as previously thought, as the magma was probably derived from a deep-level, intermediate-composition chamber. This would not have the same effect of causing large-scale sea-water circulation through the upper crust as a long-lived high-level magma chamber of the type thought to be responsible for the VMS mineralisation observed at Avoca and Parys Mountain. However, the extreme alteration and silicification of the Roch Rhyolite Group has been caused by a high fluid/rock ratio, which could be favourable to epithermal gold mineralisation.

3. Further work is recommended on outcrop of the Roch Rhyolite Group, to the west of Plumstone Mountain and especially in the vicinity of Rock Farm Quarry, to elucidate the extent of the baryte and pyrite mineralisation. This may be the feather edge of mineralisation, as VMS deposits commonly have a distal baryte enrichment or, less commonly, a baryte cap followed by Pb/Zn and then Cu/Pb/Zn and finally Cu/Au at the centre of the hydrothermal activity, for example at Mount Chalmers in Queensland (Large and Both, 1980).

4. Additional drilling to the east and west of Borehole 1 on Dudwell Mountain at Treffgarne may help to provide a vector to more promising mineralisation. A hole inclined to the south and drilled from a position north of Borehole 1 would intersect the baryte and pyrite enriched zones of that borehole at

about 60 m (down hole) and possibly pass through the faulted contact of the Roch Rhyolite Group and Treffgarne Bridge Beds at about 150 m.

5. The Sealyham Volcanic Group exhibits similar intensity of alteration to the Roch Rhyolite Group in the area from Sealyham to Garn Turne Rocks, and additional work is recommended although no base-metal enrichments have yet been noted. The existence of Bouguer gravity anomaly lows over these rocks also points to their being considerably thicker than previously reported. The Sealyham Volcanic Group is poorly exposed and soil sampling, coupled with EM surveys, would be the most effective way of examining this ground.

6. Geophysical evidence indicates that the Fishguard Volcanic Group at Crosswell is overlain by moderately conductive rocks with an outcrop width of at least 400 m which are also associated with magnetic anomalies, due possibly to pyrrhotite. The source rocks are believed to be mudstones containing graphite and/or pyrite and comprise the *D. murchisoni* Shales and part of the overlying Upper Ordovician sequence. Further work should be carried out at Crosswell to close off the Ba-in-soil and EM anomalies, as base-metal mineralisation may exist along strike in the black pyritic mudstones of the *D. murchisoni* Shales.

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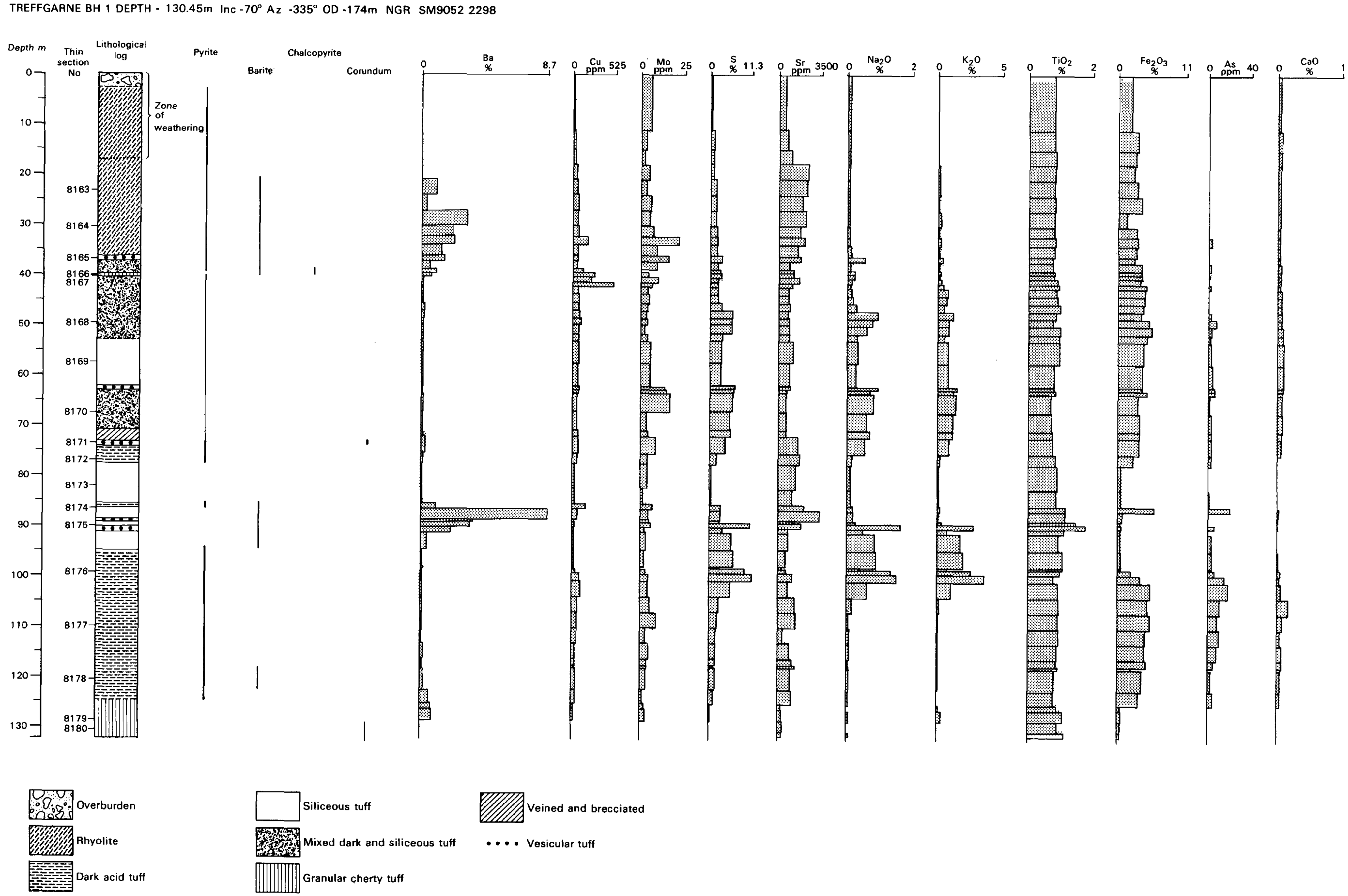
Appendix 1 Mean magnetic susceptibilities for main rock groups, measured at outcrop

Lithostratigraphic name	Rock type	Mean susceptibility x 10^{-3}	S.D.	Number of sites
Volcanic rocks	Rhyolite & tuff	0.33		2
Skomer Volcanic Group*	Mugearite	22.30	4.2	3
	Keratophyre	8.60	5.4	5
	Basic lavas	24.90	10.6	3
Murchisoni Ash		0.46		1
Llanrian Volcanic Formation	Tuffs & rhyolite	0.05		1
Fishguard Volcanic Group*	Acid lavas	0.12		2
	Basic lavas	40.4	31.5	3
Sealyham Volcanic Group	Acid lavas	0.18	0.03	9
	Intermediate lavas	0.62		2
Foel Tyrch Beds	Ash	0.10		1
	Tuffs	0.33		2
Treffgarne Volcanic Formation	Andesites	0.24	0.07	6
Roch Rhyolite Group	Rhyolites	0.02	0.01	3
Benton Volcanic Group*	Rhyolites	0.18	0.12	8
	Andesites	3.30		1
	Tuffs	0.40		1
Intrusions	Quartz porphyry (Precambrian)	0.17		1
	Feldspar porphyry	0.31		1
	Microtonalite	0.22		2
	Gabbro	0.41		2
	Dolerite* a	24.70		1
	Dolerite b	0.47		3
Sedimentary rocks	Brunel Beds	0.23	0.03	3
	Treffgarne Bridge Beds	0.25		1
	Sandstone (Skomer Volcanic Group)	0.05		2

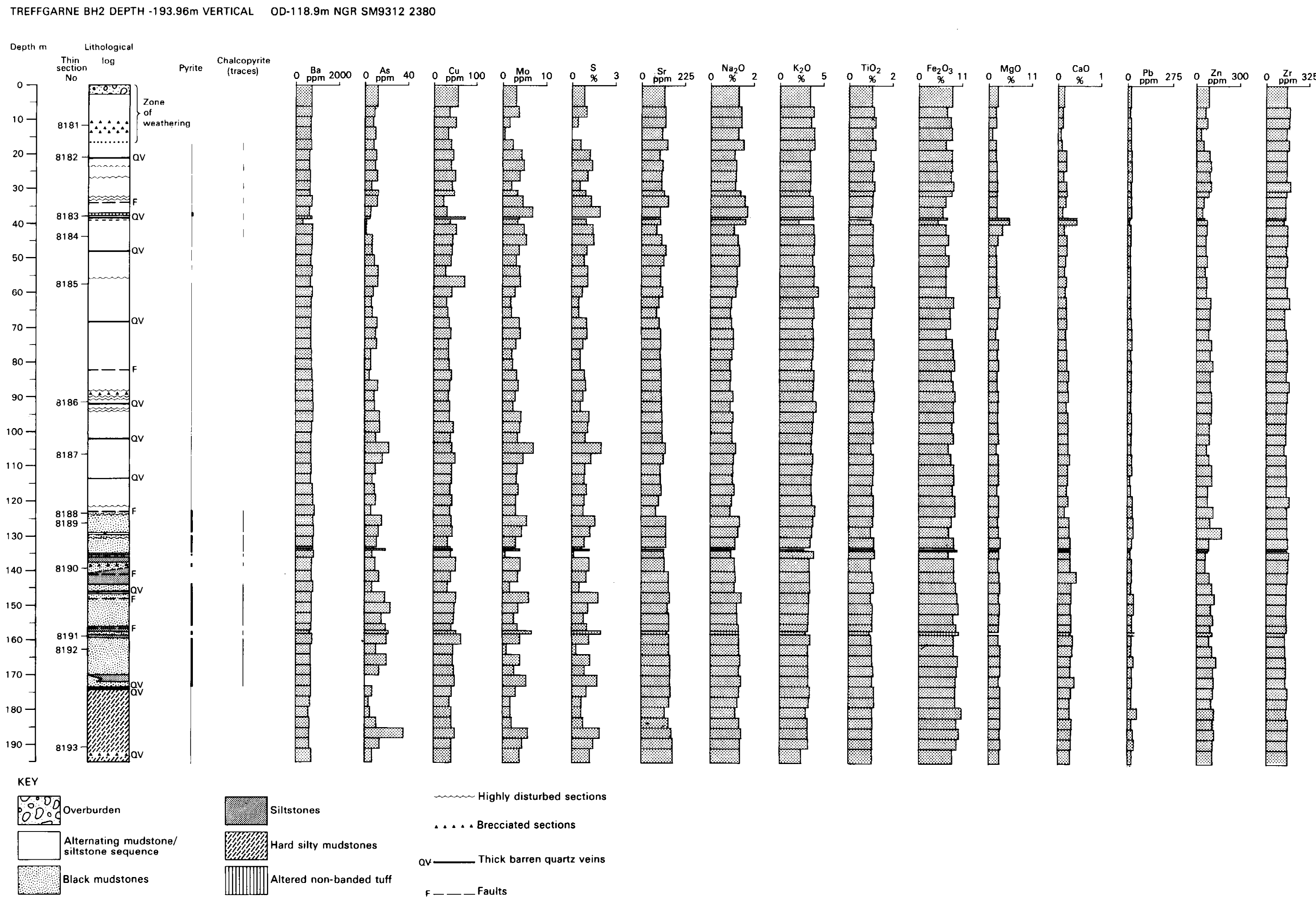
*: associated with aeromagnetic anomalies

Appendix 2 Site mean densities and susceptibilities based on sample measurements

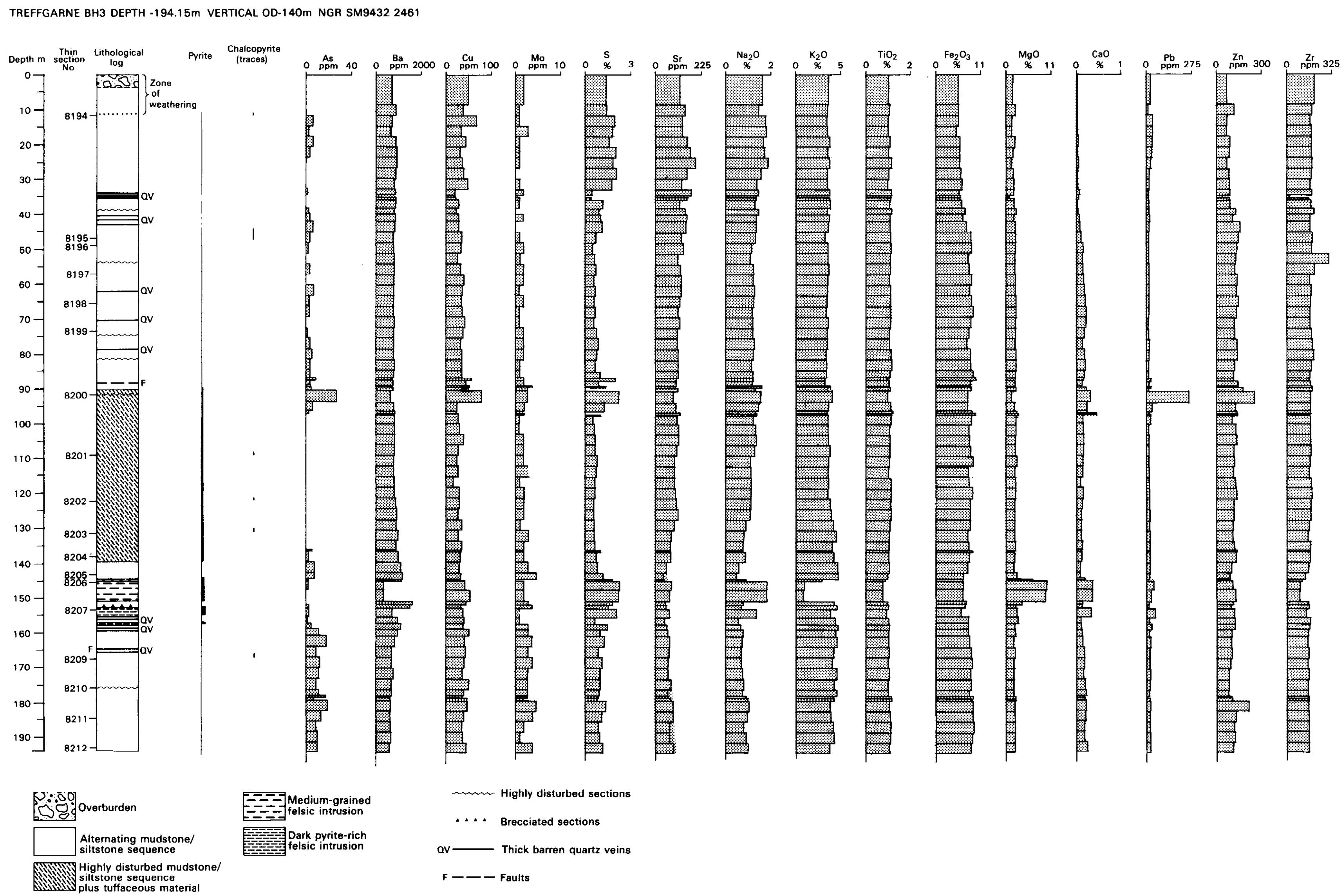
Stratigraphic name	Lithology	National grid reference	Number of samples per site	Density (Mg/m^3) Saturated	grain	Porosity (%)	Susceptibility ($x10^{-3}$)
Treffgarne	Andesite	SM 927 214	2	2.75	2.76	0.61	0.71
Volcanic	Andesite	SM 886 213	1	2.74	2.76	0.84	1.33
Formation	Andesite	SM 961 238	2	2.72	2.73	0.70	0.39
	Sediment	SM 923 233	1	2.48	2.76	13.00	0.80
Roch Rhyolite	Rhyolitic breccia	SM 899 223	3	2.73	2.77	0.98	0.34
Group	Rhyolite	SM 905 230	5	2.83	2.87	2.03	0.24
	Tuff	Borehole core	7	2.82	2.85	2.01	0.46
Spittal	Shale	SM 975 240	1	2.52	2.71	10.9	0.72
Member	Shale	SM 977 243	1	2.70	2.72	1.13	1.31
Sealyham	Andesite	SM 960 276	1	2.73	2.73	0.44	0.69
Volcanic	Slate	SM 960 276	1	2.79	2.81	1.17	0.10
Group	Andesite?	SN 009 258	1	2.74	2.75	0.60	
	Andesite?	SM 982 261	2	2.72	2.73	0.80	
Rosebush area	Keratophyre	SN 069 291	1	2.66	2.68	1.1	
	Keratophyre	SN 069 291	2	2.64	2.66	1.2	
Coomb	Felsite	SN 336 161	1	2.67	2.68	0.42	0.74
Volcanic	Rhyolite	SN 363 157	1	2.62	2.64	1.00	0.40
Formation	Rhyolite	SN 326 141	1	2.61	2.66	2.79	0.44
Intrusions	Feldspar porphyry	SM 880 246	1	2.65	2.73	5.08	1.13
	Quartz porphyry	SM 892 237	1	2.91	2.91	0.40	30.00
	Quartz porphyry	SM 892 237	1	2.73	2.74	0.27	0.59



Appendix 3.1. Graphical lithological and geochemical log for Treffgarne borehole 1 reproduced from the MRP Data package accompanying Brown et al (1987).



Appendix 3.2. Graphical lithological and geochemical log for Treffgarne borehole 2 reproduced from the MRP Data package accompanying Brown et al (1987).



Appendix 3.3. Graphical lithological and geochemical log for Treffgarne borehole 3 reproduced from the MRP Data package accompanying Brown et al. (1987).

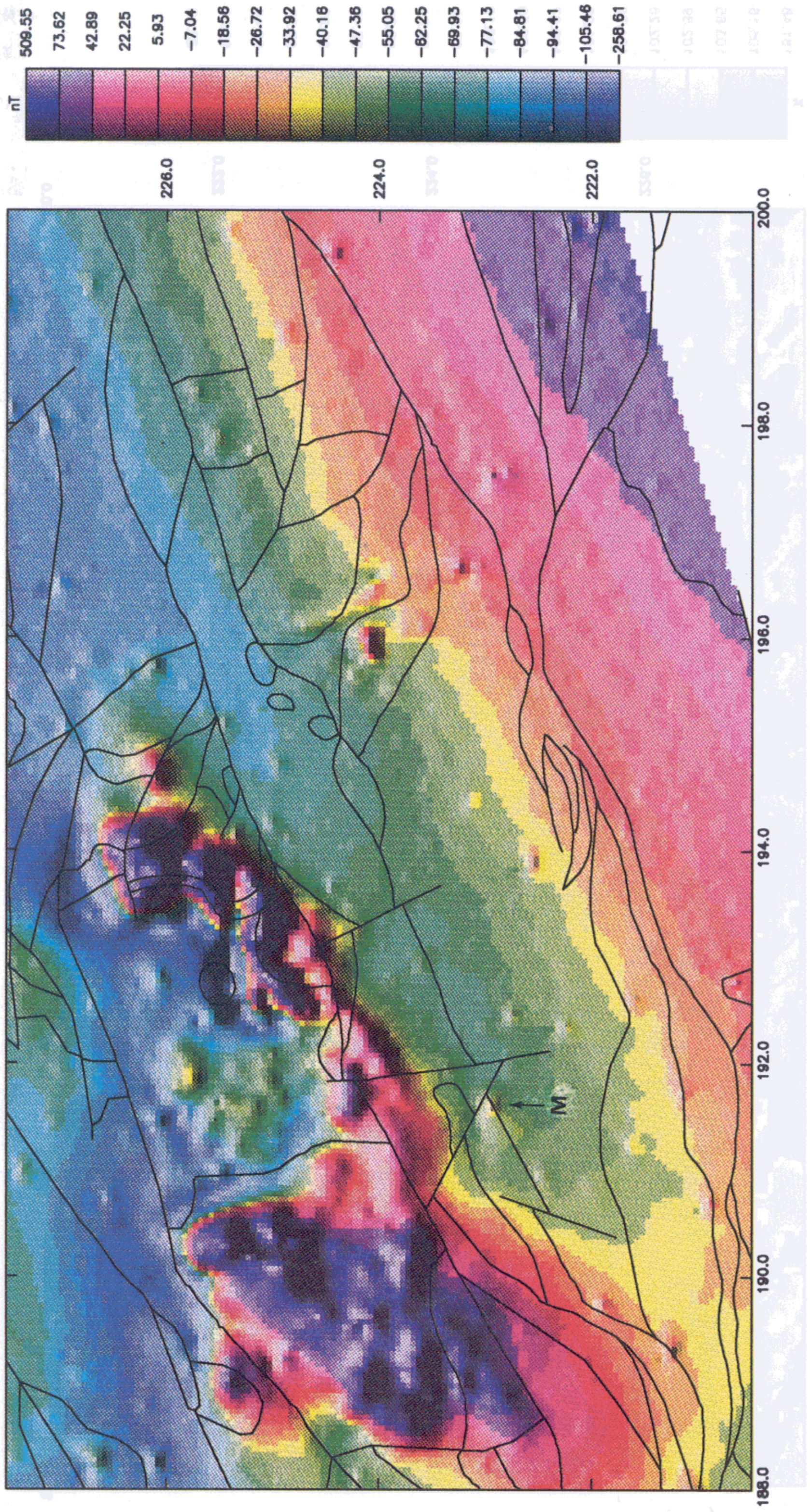


Plate 1 Equal-area colour-shaded relief aeromagnetic anomaly map of Treffgarne illuminated from the north

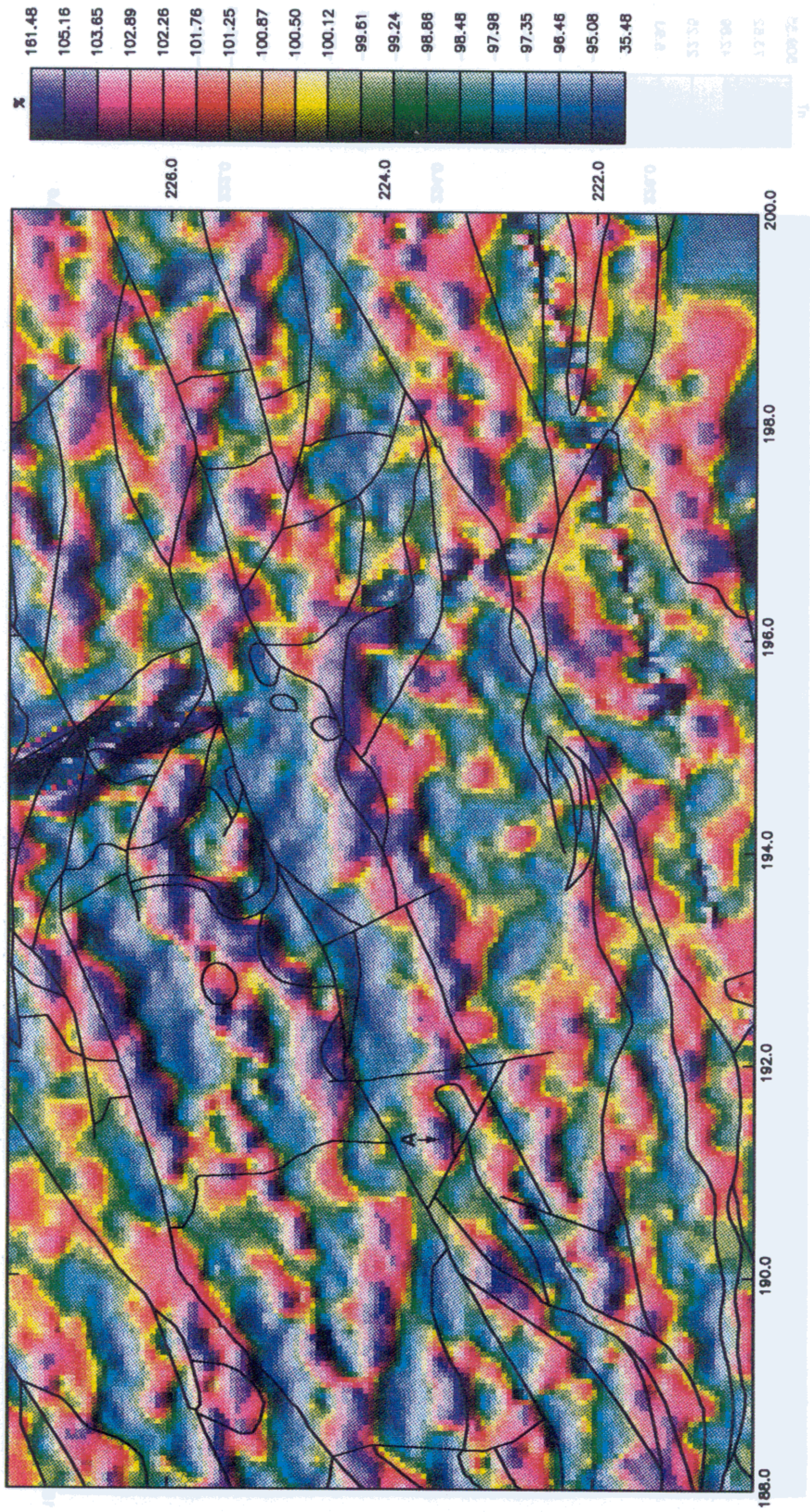


Plate 2 Equal-area colour-shaded relief VLF-EM (horizontal field) anomaly map of Treffgarne illuminated from the north

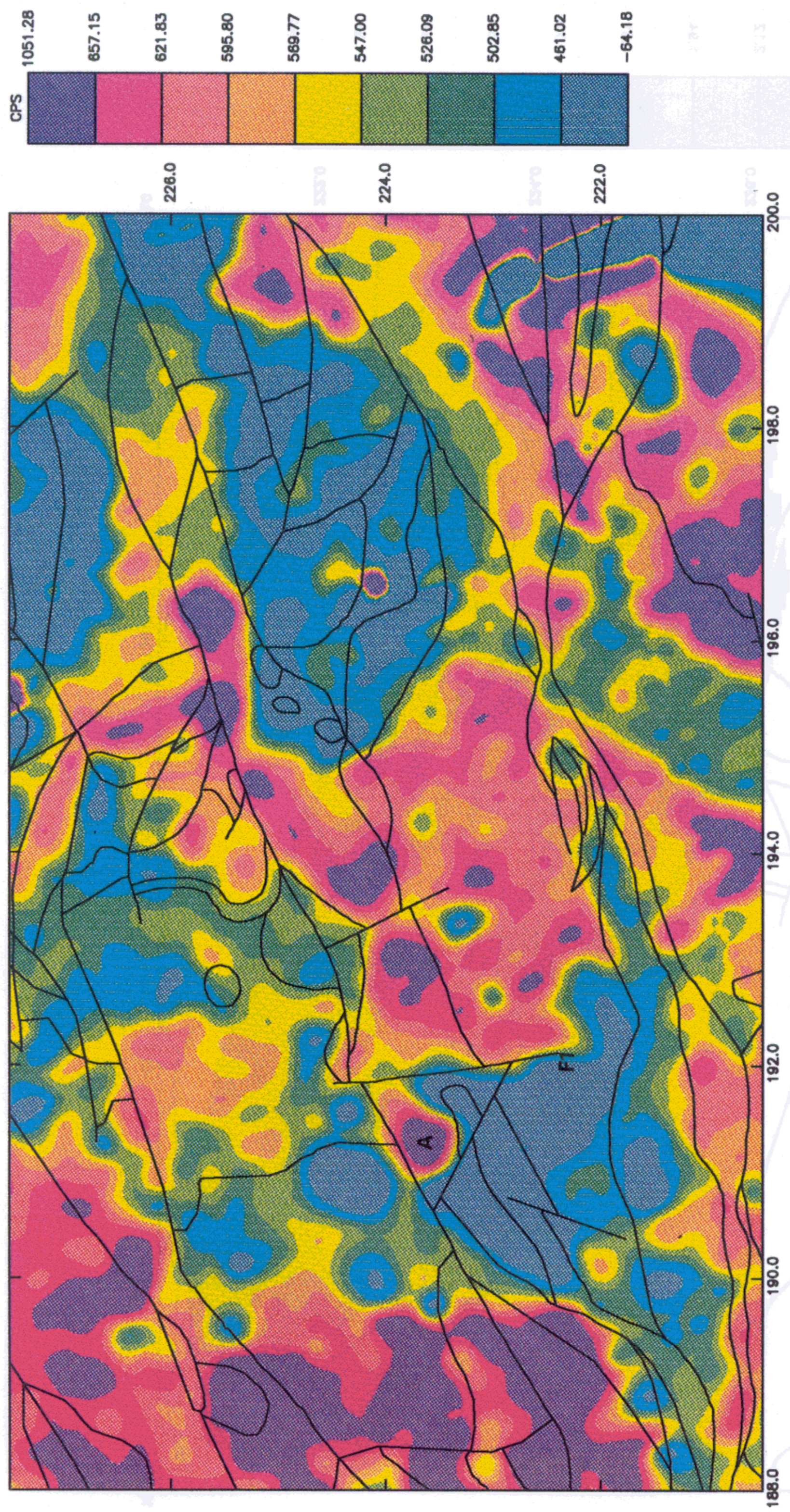


Plate 3 Equal-area total count radiometric map of Treffgarne

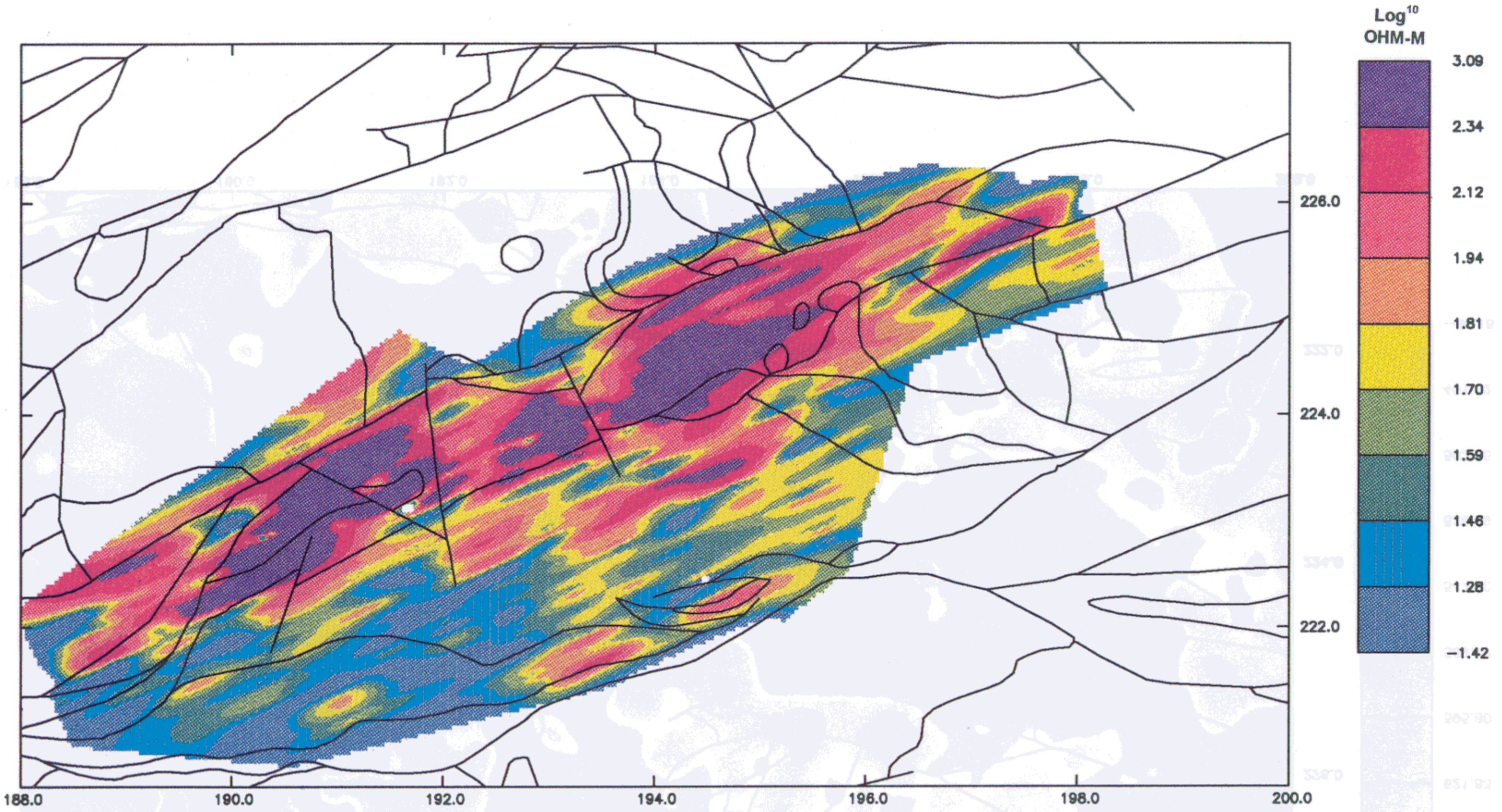


Plate 4 Equal-area apparent-resistivity map of Treffgarne area

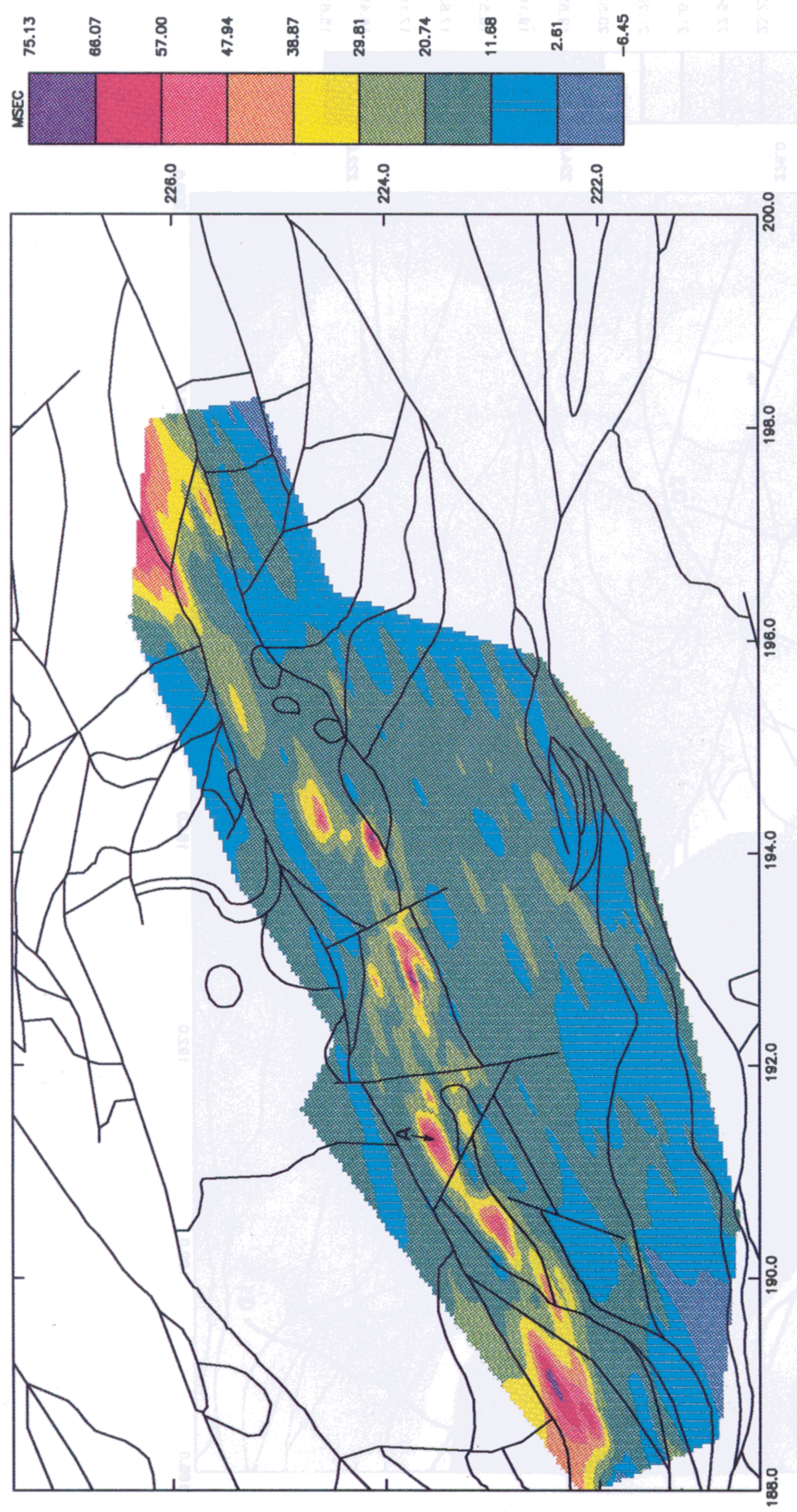


Plate 5 Equal-area chargeability map of Treffgarne area

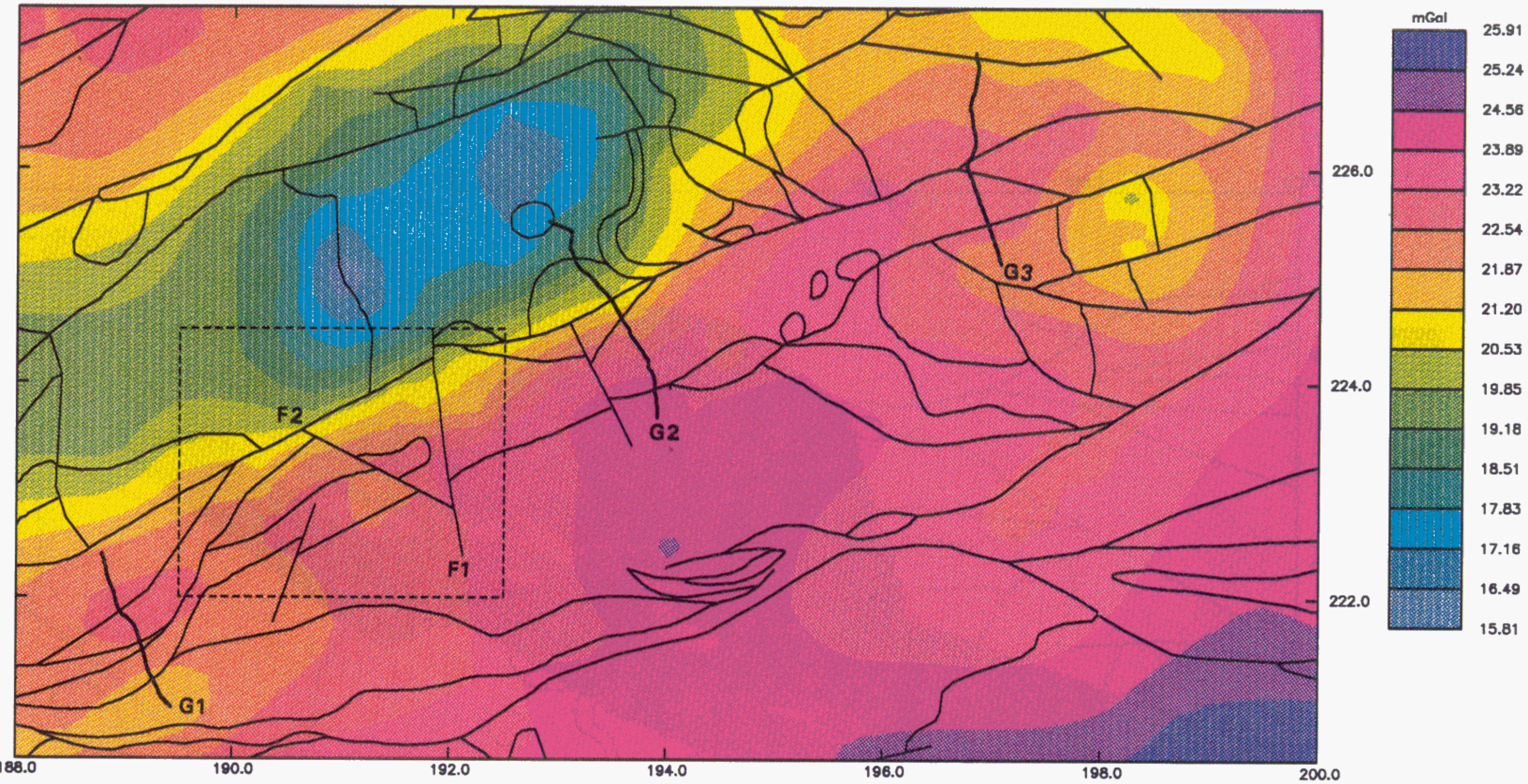


Plate 6 Bouguer gravity anomaly map of Treffgarne. Reduction density = 2.74 Mg/m^3

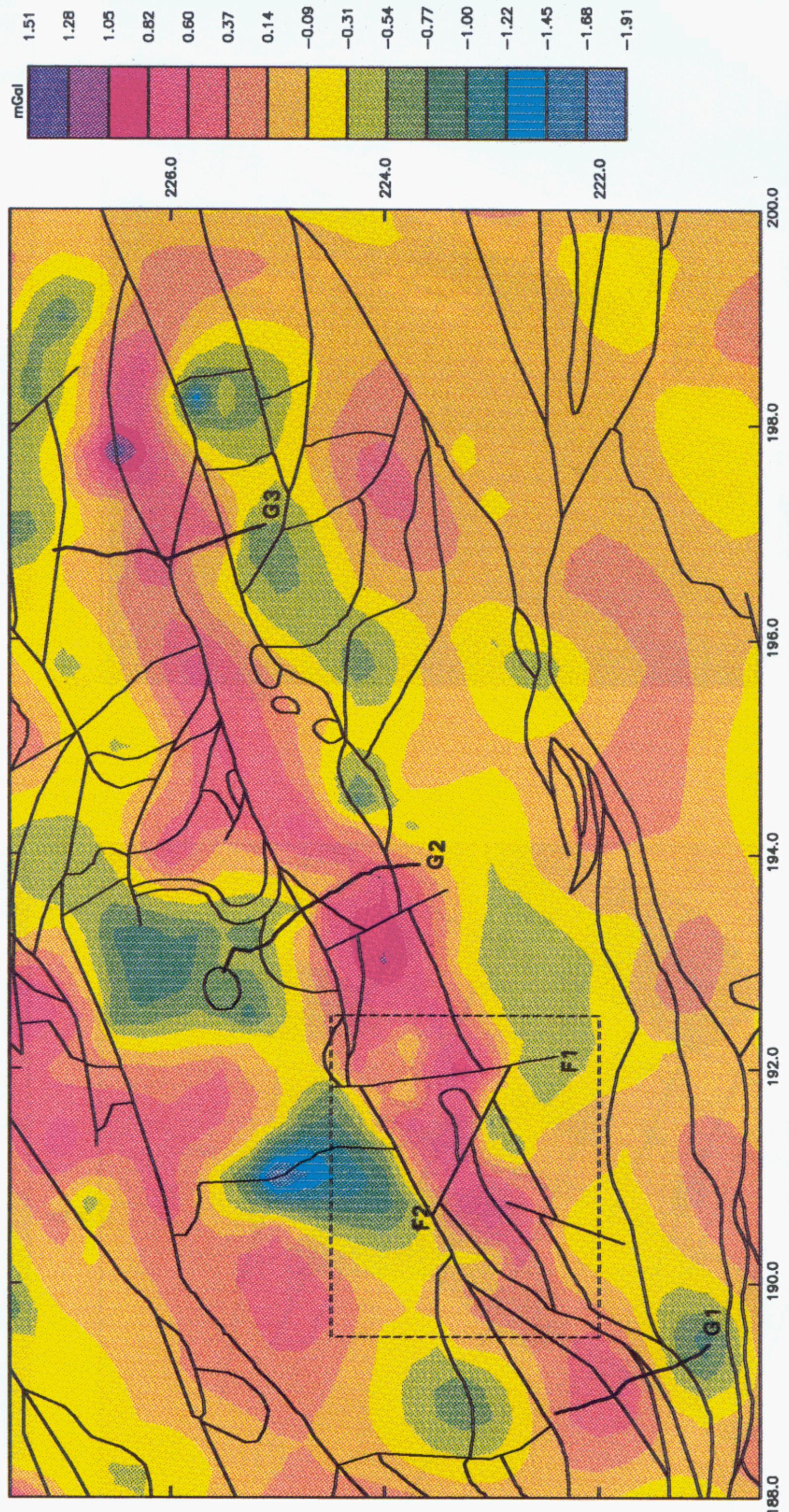


Plate 7 Residual Bouguer gravity map of Treffgarne. Reduction density = 2.74 Mg/m³

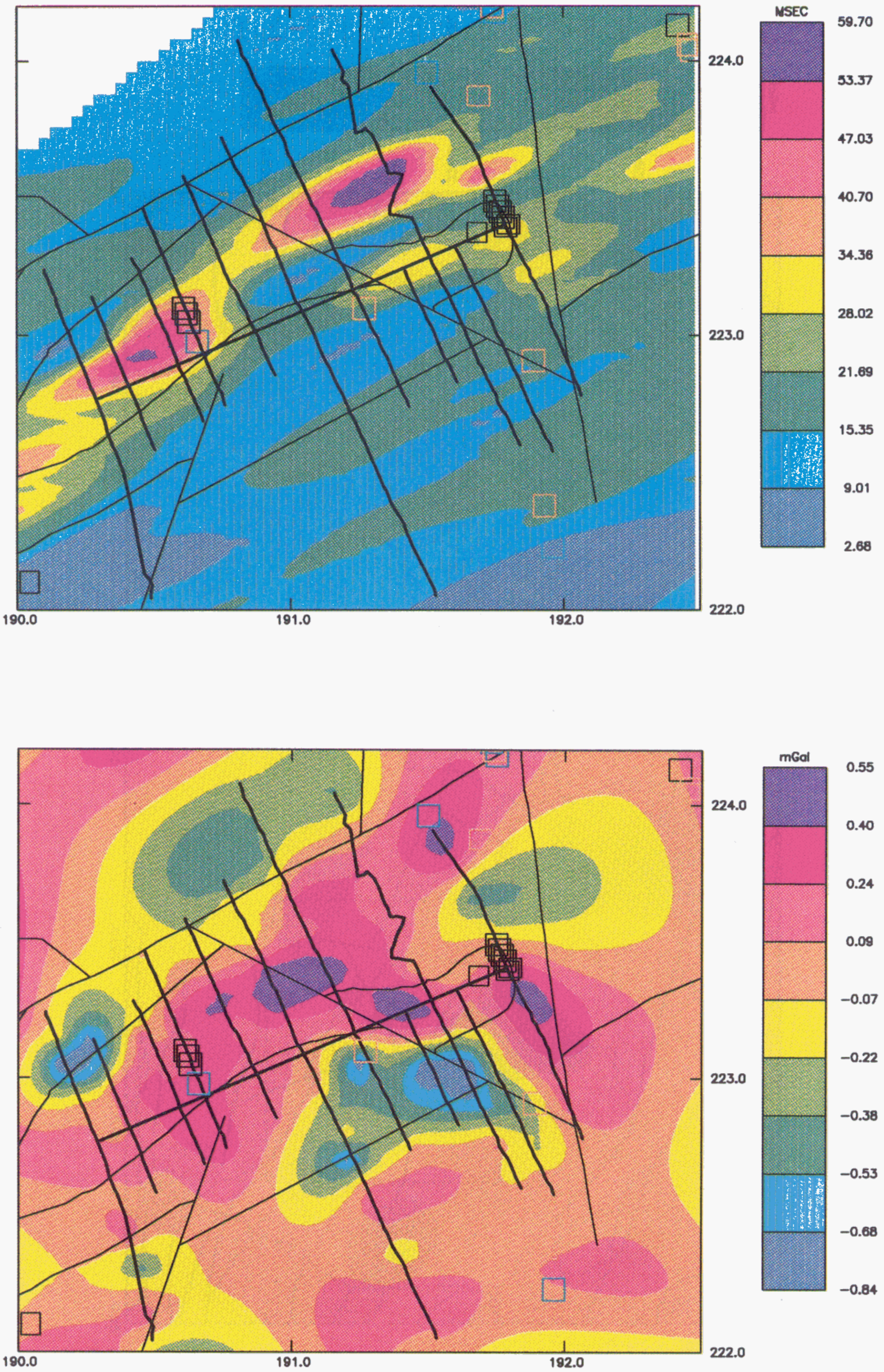


Plate 8 Integrated geophysical and geochemical data from Plumstone Mountain. a. IP chargeability contour map. b. Fifth-order residual Bouguer gravity anomaly map. Thick black lines, detailed gravity traverses. Thin black lines, outline geology. Open squares, geochemical data: Pb>100 ppm (black); Zn>100 ppm (blue); Cu>50 ppm (orange)