Natural Environment Research Council

BRITISH GEOLOGICAL SURVEY

Mineral Reconnaissance Programme Report

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No. 84

An airborne geophysical survey of part of west Dyfed, South Wales, and some related ground surveys

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An airborne geophysical survey of part of west Dyfed, South Wales, and some related ground surveys

Geophysics
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A report prepared for the Department of Trade and Industry

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84 An airborne geophysical survey of part of west Dyfed, South Wales, and some related ground surveys

On 1 January 1984 the Institute of Geological Sciences was renamed the British Geological Survey. It continues to carry out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects; it also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

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DATA PACKAGE

This report contains a summary of the Mineral Reconnaissance programme project in west Dyfed, Wales. Two more detailed comprehensive packages are available:

Package A (£1000 sterling)
Contour maps of the airborne magnetic and VLF-electromagnetic data.
(i) Three sets of 1:10 000 scale maps, totalling 105 maps, showing total magnetic field contours, normalised intensity of the horizontal components of the VLF field and stacked profiles of the normalised in-phase and out-of-phase values of the vertical component of the VLF field. The maps cover the area shown in Figure 1 and are superimposed on subdued topographic bases.
(ii) Three maps at 1:50 000 scale compiled from photographic reductions of the geophysical data from the 1:10 000 scale maps.

Package B (£5000 sterling)
Tapes containing digital aeromagnetic, VLF-EM and radiometric data recorded at 1 second intervals and location of flight lines.

Consultation with British Geological Survey staff involved with the project included in both packages.

Not included in the packages but available from the British Geological Survey, Keyworth, Nottingham NG12 5GG (Regional Geophysics Research Group) are both regional aeromagnetic and gravity data for west Dyfed.

Enquiries regarding the Data Packages should be made to Dr D. J. Fettes, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, or Mr J. H. Bateson, British Geological Survey, Keyworth, Nottingham NG12 5GG.

SUMMARY

A detailed airborne geophysical survey has been made of part of west Dyfed at a flying height of 75 m with magnetic, electromagnetic (VLF-EM) and radiometric equipment mounted in a helicopter. The area of 670 km^2 includes the Precambrian anticlines of St David's and Hayscastle, the Fishguard, Sealyham and Trefgarne volcanic groups, and the adjacent Lower Palaeozoic sediments with associated basic intrusions.

Ground geophysical surveys were carried out at 33 localities to confirm the nature and the sources of the airborne anomalies, and a geological examination was also made at selected localities. Rock samples were collected for petrographical examination and physical property determinations. A regional gravity survey was also carried out.

Some details of the geophysical methods and data presentation are included together with a map at a scale of 1:50 000 summarising the main results obtained from interpretations of the airborne geophysical surveys.

The aeromagnetic data clearly show the distribution of the Precambrian rocks, the numerous dolerite intrusions, and some of the pillow lavas associated with the Fishguard Volcanic Group. This distribution generally confirms the outcrop pattern based on geological mapping. The magnetic data are likely to be more reliable for mapping on a more detailed scale, due to the extensive drift cover which hinders geological mapping in many places, and they have also revealed some large scale structures, including a previously unrecorded dyke at least 40 km long.

The airborne VLF anomalies are most obvious at lithological boundaries with large resistivity contrasts such as the Precambrian/Lower Palaeozoic sediment and dolerite/sediment contacts. The radiometric data provide little obvious additional information.

Although the west Dyfed area has no significant mining history, some exploration activity has taken place there in recent years (Allen, Cooper and others 1985; Cameron and others, 1984; Brown and others, 1987). One of the main restrictions on exploration has been the lack of rock exposure in much of the inland area and the airborne geophysical survey was undertaken as partial compensation for this.

INTRODUCTION

Much of west Dyfed consists of a peneplain lying at about 100 m OD with a few hills, including the Preseli Hills, rising to 500 m OD. This topography, combined with an extensive cover of drift, has resulted in there being comparatively few rock exposures away from the excellent cliff sections which have formed the basis for much of the geological work in the area. The Precambrian and volcanic rocks and intrusions of acid to intermediate composition provide an environment which might be favourable for mineralisation. In recent years there has been an increased interest in the mineral potential, based partly on the geological similarities with the Harlech Dome (Allen and others, 1979). The insignificance of previous mining activity might be due partly to the lack of exposure.

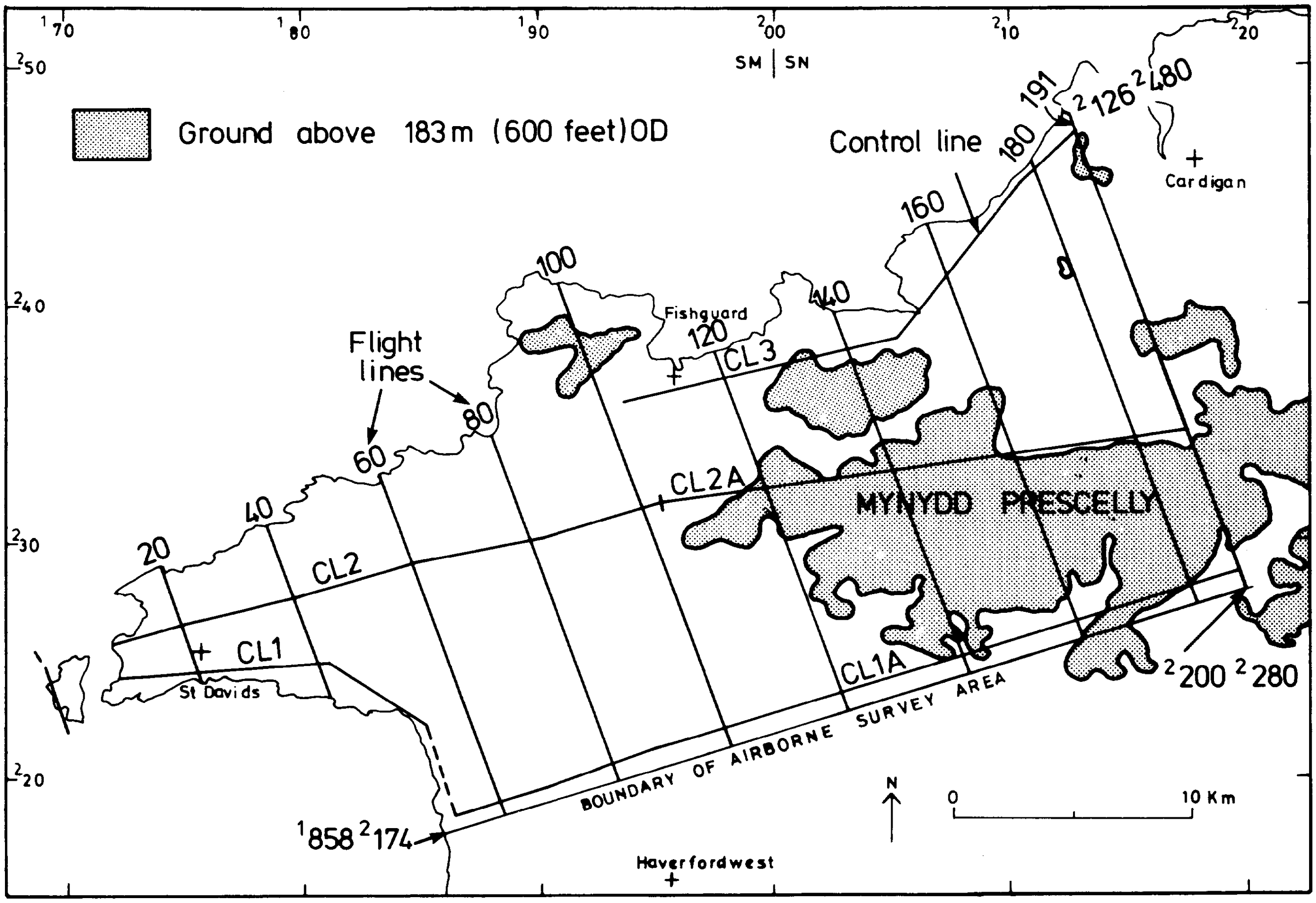

Figure 1 Location of airborne survey area with control lines and selection of flight lines

In an attempt to overcome the problem of poor exposure an airborne geophysical survey of part of Dyfed (Figure 1) was carried out in the autumn of 1978 using magnetic, very low frequency electromagnetic (VLF-EM) and radiometric methods. The survey was one of three carried out in 1978, the results for one area having been published previously (Evans and Cornwell, 1981).

The survey was carried out under contract to the Natural Environment Research Council by Sander Geophysics Limited, who were also responsible for the reduction of the survey data and for its presentation in map form at a scale of 1:10 000 (with the exception of the radiometric data which remain in the form of digital and analogue records of flight profiles).

This report contains a description of the airborne survey results and of those obtained from ground geophysical and geological surveys carried out to define more closely the sources of some of the main anomalies. The main emphasis is on providing general background information on the geology to aid any mapping or mineral exploration programmes. The magnetic method usually provides the basis for this type of work in areas where igneous or metamorphic rocks are known to exist. The VLF-EM method is also useful, for while it does respond to smaller, highly conductive bodies such as massive sulphide ores, it is generally more successful in locating larger bodies, such as conductive shale horizons and faults. The radiometric method can be used as a mapping tool in areas of thin overburden and is commonly included as a matter of course in surveys of this nature.

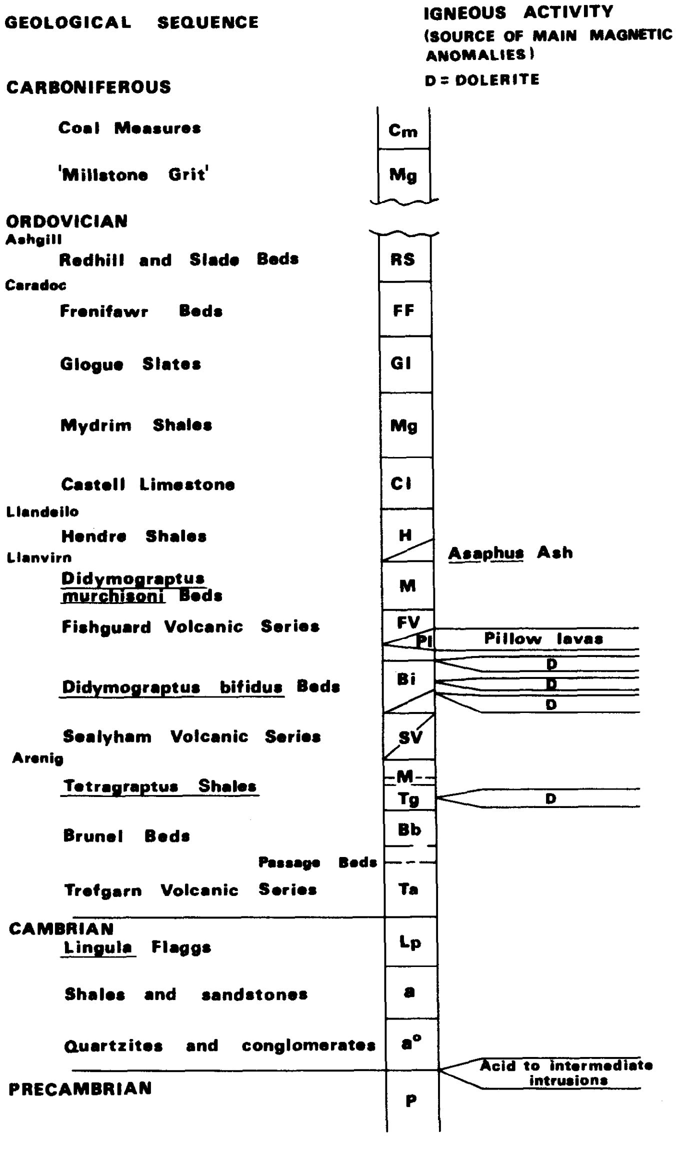

Figure 2 Geological succession in west Dyfed

The area covered by the survey extends across the margin of two Ordnance Survey 100 km × 100 km squares, SM and SN, between 170 km E and 220 km E.

GEOLOGY

The northern part of the old county of Pembroke was heavily glaciated during the Pleistocene period, and debris of sand, gravel and stony clay, which remained after the ice had melted, was spread liberally over the terrain. In geological history this glaciation was a very recent event, so that these glacial deposits are still fresh and in places thick. Inland they obscure large areas of the outcrop of older rocks and thus, in studies such as this one, in which the older 'solid' rocks are of great importance, these superficial Drift deposits are a hindrance. However, eminences in the glaciated terrain escaped much deposition and areas like the Preseli Hills, the hills between Trefgarne and Brawdy and the 'peaks' around St David's and Fishguard, together with coastal cliffs have thus provided the bulk of our data on the solid geology. In other areas data obtained visually are sparse, and the geophysical survey results are particularly valuable, although their interpretation still has to rely, to some extent, upon comparisons with less obscured areas.

The geological succession is summarised in Figure 2, and Figure 3 is a simplified geological map of the area.

Precambrian rocks

The oldest rocks in the area are of Precambrian age and crop out in the west of the area, around and to the north-east of St David's (Cox and others, 1930) and around Hayscastle. Away from the coast, their outcrop is not extensive. They have been divided into two groups:

1 Pebidian, consisting of volcanic rocks
2 Dimetian, consisting of igneous rock intrusive into the Pebidian

Pebidian

In the neighbourhood of St David's, the Pebidian tuffs occupy a broad anticlinal inlier extending east-north-east for several miles inland. They are well displayed in the cliffs south and west of the city, where the following divisions (in descending order) have been established:

	Thickness m
4 Ramsey Sound Series: fine-grained sericitic tuffs	212
3 Caerbwdy Series: greenish acid rocks with a quartz-chlorite matrix and with bands of halleflinta and conglomerate (Clegyr Conglomerate)	730
2 Treginnis Series: hard gritty rocks with abundant trachytic pumice and boulders of red keratophyre	180
1 Penrhiw Series: gritty red and green tuffs passing down into red and green halleflinta, base not seen	300 +

Thirteen kilometres east of St David's, from Dinas Fach [826 226] on the coast to the Western Cleddau near Wolf's Castle [957 267], the Hayscastle Anticline lies *en échelon* with the St David's inlier, from which it is separated by the complementary Solva Syncline [800 244] of Cambrian rocks. At Hayscastle the Precambrian

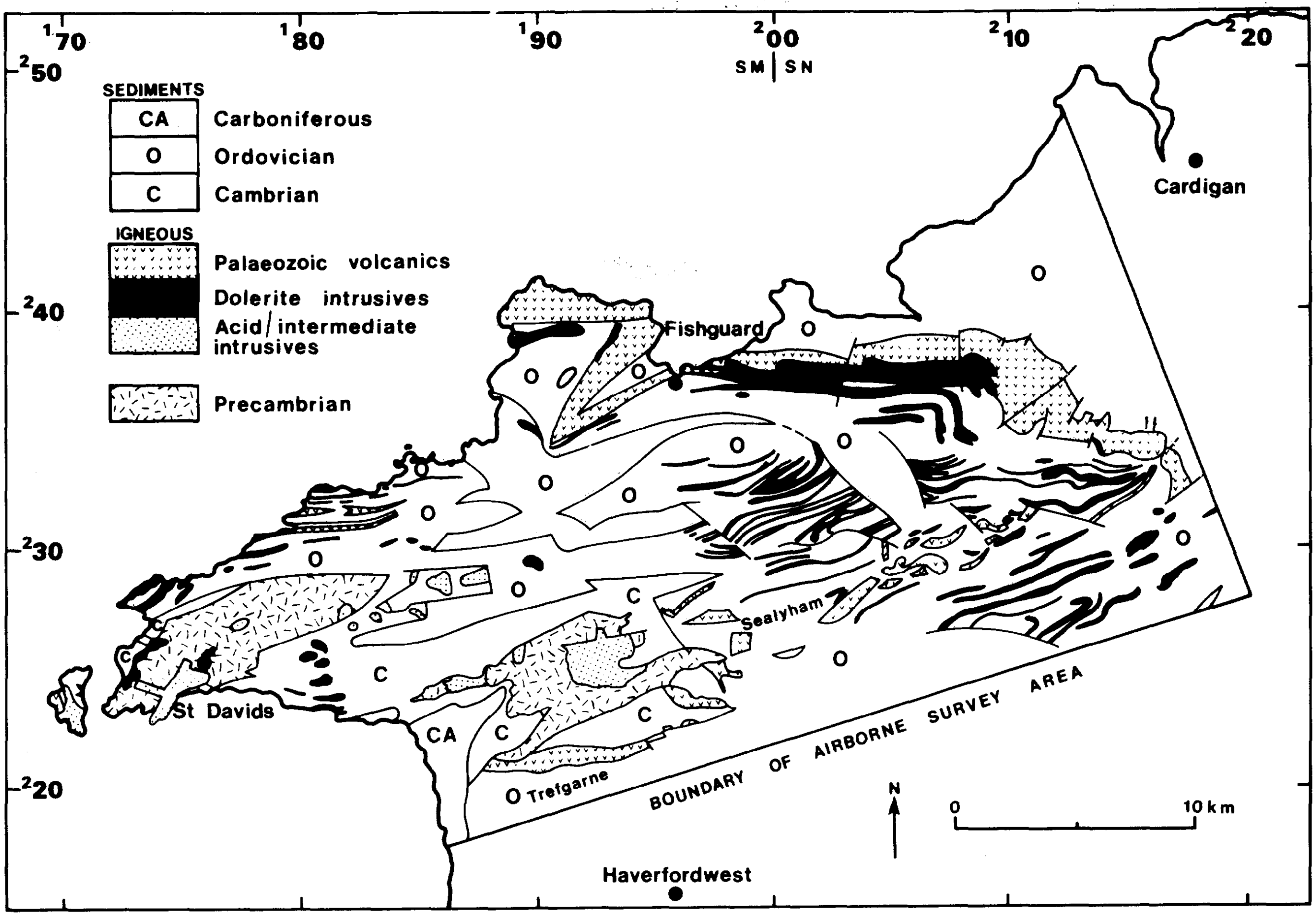

Figure 3 Geological map of the survey area based on various published and unpublished sources

volcanic suite comprises two main types of pyroclastic rocks: the lower (the Pont-yr-hafod) group of tuffs are andesitic; the upper (the Rhindaston and Gignog) groups are rhyolitic and keratophyric and are associated with rhyolite and quartz-keratophyre lavas, some of which show marked fluxion structure.

Although direct proof of age is lacking it is now generally accepted that the Roch rhyolites and the associated Nant-y-Coy Beds in the anticline between Roch [880 211] and Trefgarne [958 234] are also of Precambrian age (Thomas and Cox, 1924). The rhyolitic lavas and tuffs form an almost continuous ridge from Roch Castle [001 258] to the Cleddau Valley and beyond to Ambleston (Figure 3). They are best exposed in the gorge at Trefgarne. The rhyolites are greenish blue, white-weathering, fine-grained silicified rocks, and are associated with bluish green and pale mauve flinty tuffs. They are conformably overlain by the Nant-y-Coy Beds, flaggy tuffs probably about 100 m thick, and considered to be the equivalents of the Ramsey Sound Series.

Dimetian

The Pebidian tuffs were invaded by acidic rocks including granite, quartz porphyry, and quartz-dolerites, the best known being the granite or alaskite-granophyre at St David's. It is a highly siliceous coarse-grained rock traversed by crush bands; the principal constituents are quartz, orthoclase, oligoclase, and chlorite. The associated quartz-porphyry is related petrographically to the granite and was probably a differentiation product of the same magma. It also is a rock of coarse grain, consisting of large phenocrysts of quartz, alkali feldspar and a little biotite. Similar rocks are found farther east in the Llanhowel [818 275] and Hayscastle outcrops (Thomas and Jones, 1912).

Other igneous masses are relatively isolated, and not all of them fall into a consanguineous Dimetian suite. A small intrusion of diorite at Hollybush [861 291] is a medium-to coarse-grained greenish rock, composed of quartz and biotite with large hornblende crystals. In places quartz is present locally in sufficient abundance to make the rock a quartz-diorite, a rock showing a petrographic relationship with the quartz-diorites of the Johnston outcrop. The diorite near Knaveston, however, has no parallel; it consists of hornblende, albite-oligoclase feldspar, a little augite, and much sphene, with ilmenite and apatite as accessory minerals.

Palaeozoic rocks

Cambrian system

The Cambrian rocks rest with sharp disconformity upon the Precambrian, indicating clearly that a long interval separated their geneses, during which earth movements disturbed the disposition of the Precambrian rocks (Cox and others, 1930).

The earliest Cambrian rocks are pebbly and arenaceous shallow-water sediments were the products of marine transgression. Late Cambrian sediments are more argillaceous, probably reflecting a deeper water environment. The sequence is as follows:-

	Thickness m
4 *Lingula* Flags: thin siliceous sandstones and grey shales	600
3 Menevian Series:	
(c) coarse grits and shales	30
(b) dark flaggy mudstones	106
(a) grey flags	91

2 Solva Series:	
(c) grey flags	45
(b) green and purple mudstones and sandstones	76
(a) green pebbly sandstones	45
1 Caerfai Series:	
(d) purple feldspathic sandstone (Caerbwdy Sandstone)	75–150
(c) red shales with ostracods	12
(b) green fine-grained feldspathic sandstones, unfossiliferous	75–120
(a) red conglomerate	18

Ordovician system

The Ordovician rocks have three main components:

1. Shales and slates of relatively deep water origins
2. Volcanic lavas and tuffs interbedded with the shales and slates
3. Igneous rocks intrusive into the shales and slates and volcanic rocks

Coarse arenaceous rocks do occur, but mainly at the base of the system in the Arenig Series. In all, these rocks form a pile some 1000 m to 1500 m thick and represent an almost unbroken sequence through the Arenig, the Llanvirn, the Llandeilo and much of the Caradoc Series. Only the Ashgill Series, at the top, is not represented in the area.

Shales and slates The main marine sedimentary component of the rocks is a monotonous, dark grey to black argillite. Where it has undergone vertical compaction, by loading, it cleaves along the bedding as a shale; where it has been compacted by lateral pressures it cleaves discordantly as a slate.

These rocks are fine grained and pyritous, representing mainly pelagic deposits formed under anoxic conditions. Coarse clastic sediment is subordinate and where present was introduced probably by low density turbidity currents.

The depth of their marine depositional environment may not have been very great, for, as well as graptolites, the remains of trinucleid trilobites, inhabitants of fairly shallow seas, are preserved in places.

Volcanic rocks Volcanic rocks are present in the basal Arenig Series and also in the succeeding Llanvirn Series. They represent a number of major and minor volcanic episodes, occurring for the most part as quite effusives in a submarine environment. There were occasional explosive episodes as witnessed in some sediment gravity flows with high proportions of pyroclastic debris. Subaerial or shallow water conditions are not common and may in fact be restricted to the oldest volcanic episode on Ramsay Island (Bevins and Roach, 1979a).

In the Arenig the highly localised Trefgarne Volcanic Group reaches a thickness of some 150 m. It consists of basic to intermediate lavas and tuffs. Above these, near the base of the Llanvirn Series, equally localised volcanic rocks occur at Sealyham [965 280]. Volcanic rocks at this level in north Pembrokeshire are up to 60 m thick and consist mainly of vesicular soda-rhyolites.

In the Llanvirn Series rhyolitic welded pyroclastic flow deposits, lavas and ashes are thick. In the west, the Llanrian volcanic rocks thicken westward from 150 m around Llanrian [820 315] (Cox, 1915), to 425 m on Ramsay Island (Pringle, 1930). They are of the same age as, and indeed may have merged with, the even greater pile of volcanic rocks around Fishguard. These are the Fishguard Volcanic Group and they crop out from Strumble Head, where they are over 1800 m thick, to Goodwick (Thomas and Thomas 1956) and thence through Fishguard eastward to the Preseli Hills. These rocks have been subdivided (Bevins and Roach, 1979b, p.604; Bevins, 1982) with the lowermost subdivision consisting largely of rhyolitic and dacitic lavas and welded pyroclastic flow deposits. The middle subdivision consists of basic pillow lavas, up to 1500 m thick at Strumble Head, but thinning rapidly eastward to be absent in the Preseli Hills. The uppermost subdivision is largely of acidic welded pyroclastic flow deposits, lava flows and domes, with attendant mass-flow deposits and volcanoclastic breccias.

Where the Fishguard Volcanic Group is present in the sequence the intensely black shales of the *D. murchisoni* Zone are absent or thin. The absence of the *D. murchisoni* Shale has been viewed as a non-sequence, but it may merely indicate that the shales and the volcanics are in general two mutually exclusive facies. Where both formations do occur together, the *D. murchisoni* Shale overlies the Fishguard Volcanic Group.

Intrusive igneous rocks Numerous sill-like doleritic intrusions are emplaced in the Arenig and Llanvirn sediments of Pembrokeshire. They range in texture from fine-grained to coarsely crystalline and show wide variation in silica content, but are nevertheless intimately related and appear to have been derived from a common magma. The type near St David's is a quartz-enstatite dolerite, but the closely allied rocks of Strumble Head are quartz-free. The thick sills forming Carn Llidi and St David's Head, described by Roach (1969), are coarsely crystalline quartz-enstatite gabbros, products of multiple injection and differentiation: they often show ophitic structure, but where quartz is a relatively abundant constitutent granophyric intergrowths occur. The doleritic masses of Carn Ysgubor, Pen Beri, and Porth Gain are medium- to fine-grained, and are more acid than the typical dolerites of the district. In the Preseli Hills the dolerites are characterised by the presence of pink and white spots, and form a striking rock type. The Llanvirn intrusions are mainly acid rocks like the contemporary lavas. Sills of quartz-albite porphyry on Ramsey Island (Pringle, 1930; Bevins and Roach, 1979b, p.606), occurring at a constant horizon in the '*bifidus* Shales', appear to have no counterpart on the mainland: they are fine grained, with phenocrysts of quartz and albite set in a felsitic groundmass.

The intrusive activity seems to be related temporally to the volcanic activity, for the basic injection sheets are absent from rocks above the Fishguard Volcanic Group. Some of the magma/sediment interfaces reveal loading structure and flame-structures, indicating that the sediment was wet and unlithified when the magma was emplaced.

Geochemical evidence (Bevins, 1982; Bevins and Roach, 1979b) further supports close connection between volcanic and intrusive rocks. Both are tholeiitic and show strong iron-enrichment trends.

Carboniferous System

A small outcrop of Carboniferous rocks occurs in the extreme south of the area, at the north end of St Bride's Bay (Jenkins, 1962). These rocks belong to the Millstone Grit and Coal Measures of Namurian and Westphalian age. They rest unconformably upon Lower Palaeozoic rocks with a very sharp overstepping relationship. Furthermore, the Coal Measures overlap the Millstone Grit, beneath which there is no Carboniferous Limestone. The thickness of these rocks within the area is not known, but they are interbedded sandstones and shales of a brackish, shallow water, paralic type. Some coal seams are present in the sequence.

Structure

North Dyfed is situated on continental crust just north of an interface between two major structural styles. In south Dyfed the fold trend is WNW-ESE and of Hercynian age while in north Dyfed it is ENE-WSW, a product of the earlier Caledonian orogenesis. The interface has been viewed, traditionally, as the Hercynian Front though at best it is a broad tract and not a sharp line, trending parallel with the Hercynian folds. With one exception all the structure of the area under review is considered to belong to the Caledonian.

Folds

Most strata in north Pembrokeshire exhibit steep dips such as are evident around Whitesand Bay, Abereiddy Bay and inland in cuttings south of Fishguard and quarries at Bellstone. Since entire folds are not commonly seen in exposures, it is inferred that the scale of the folds is large, for example the syncline of Abereiddy Bay and the anticline of Pwll Dawnau-Pont Iago further north. The pattern of outcrops in this area indicates that the latter anticline forms most of the Strumble Head-Pen Caer peninsula, while a complementary syncline lies to the south with its axis through Goodwick. Strike faults in the limbs of these folds complicate the pattern.

Cleavage

The argillaceous sedimentary rocks are usually cleaved. The strike of this cleavage is generally parallel with the fold axes and dips to the NNW at angles between 40° and 80°.

Faults

Most geological maps of the northern part of the area (e.g. Cox, 1915; Evans, 1945) depict an anastamosing plexus of major faults. Many of these appear to have been conceived in order to separate conveniently tracts of outcrops which are juxtaposed incongruously, and such a pattern may not be worthy of detailed analysis.

In general the south-west area is dominated by two horsts of Precambrian rocks, one trending WSW-ENE from St David's the other trending more to the north-east— 'the Hayscastle Anticline'.

Most of the rest of the faults mapped have the same WSW-ENE trend and are thus near-strike faults. However, it may be significant that few such faults disrupt the outcrop of the Fishguard Volcanic Group in the north. It would seem that these volcanics act as a stratigraphical cap. Indeed from the outcrop of the volcanics northward the structure appears to remain less complex while the rocks become progressively younger under the influence of northward dips.

Cox (1915) described faults on the coast between Abereiddy and Abercastle, which are considered to be representative of the fault pattern in much of the poorly exposed hinterland. He recognised two main sets:

1. Strike Faults (WSW-ENE). These are by far the commonest. They bifurcate, swing in direction slightly and anastamose. They usually hade to the north at angles of up to 60°. They are sharp fractures making little impact on the topography inland, even when of large throw.
2. Transverse Faults (NE-SW or NNE-SSW). These are less common and are invariably of small throw. They have significant effect on the course of outcrops only cumulatively.

The most effective fault of this part of the coast is the Pwll Strodyr Fault. It is of unusual trend (NW-SE), of large throw down to the south-west and is marked by considerable cataclasis on the country rock.

Metamorphism

Bevins and Rowbottom (1983) reported that the Ordovician rocks of North Pembrokeshire have suffered only low-grade metamorphic effects largely of the prehnite-pumpellyite facies.

Mathry Dyke

One exception to the above structural style is the fracture followed by the Mathry Dyke, an intrusion recognised for the first time from the results of the detailed airborne geophysical survey (Cave and others, 1987, in preparation). This dyke has a singular trend just north of east, parallel with the 'Hercynian Front', and it is reasonable to associate this structure with the Hercynian movements, rather than the Caledonian. Since the dyke presumably records a tensional stage of those movements it is also reasonable to associate it with some extensional phase of the upper Palaeozoic basin which existed over and to the south of Pembrokeshire. Radiometric dates show the age to be Carboniferous (Bradley and Snelling, 1985).

Mining history

There are very few records of mining activity in west Dyfed and, within the area of the airborne survey, only a few mines and trials are known (Hall, 1971). These are:

Ramsay Head [715 235]
Mine working a north to south copper-bearing lode.
St Elvis [813 231]
Workings for lead and copper on an east to west lode.
Maen Jaspis [939 404] and Fron-las [166 339]
Trial workings for ?gold.
Fron-lwyd [178 339]
Trial workings for lead and copper in two east to west lodes.
Pant-y-Gafel [192 300]
Small level

The more important lead and zinc mines at Llanfyrnach lie just outside the survey area at [225 316].

PREVIOUS GEOPHYSICAL INVESTIGATIONS

The Dyfed survey area was included in the regional aeromagnetic coverage of Great Britain (Geological Survey of Great Britain, 1965) and the relevant part of this map is shown in Figure 4. It was clear from this that there were anomalies in the area which could be related to surface geological features and that a detailed, lower level survey would probably provide far more useful information. The Dyfed area was included in a regional gravity survey of Wales (Griffiths and Gibb, 1965) and this also revealed anomalies which appeared to require a more detailed regional gravity survey for accurate interpretation.

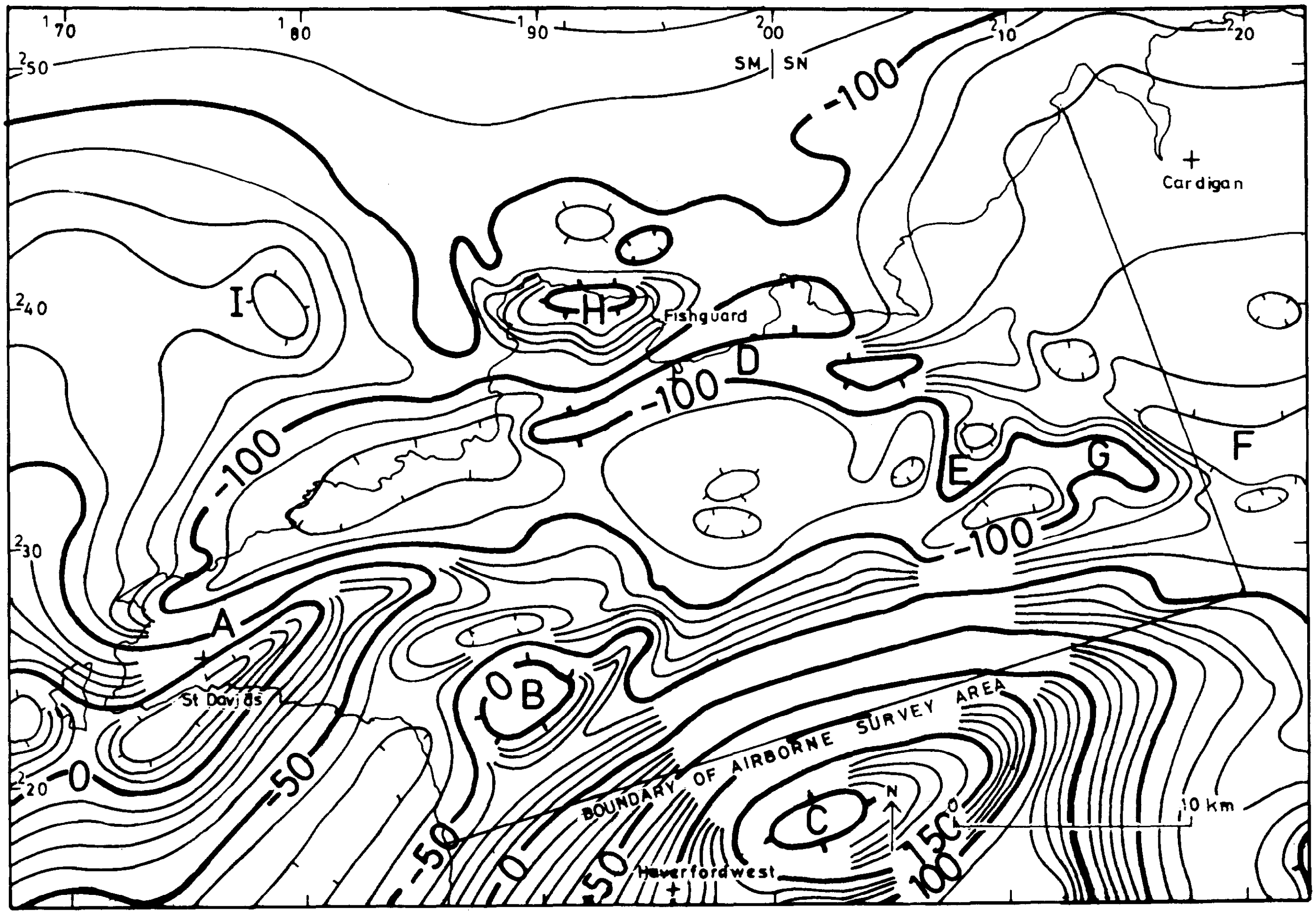

Figure 4 Aeromagnetic map for part of Dyfed and adjacent offshore areas with contours at 10 nT intervals based on data recorded at 305 m (1000 ft) mean terrain clearance (Geological Survey of Great Britain 1965). Lettered anomalies A to I referred to in text

The aeromagnetic map shown in Figure 4 is based on data recorded in 1960 at a height of 1000 ft (305 m) along N–S flight lines, 2 km apart, and E–W tie lines, 10 km apart. The main anomalies in the area, labelled A to I in Figure 4, are considered to have the following causes:

A This is clearly related to the Precambrian inlier in the core of the St David's Anticline. It can be followed off the coast for a short distance before being apparently offset by a fault to continue westwards for a further 10 km.

B Another anomaly clearly related to Precambrian rocks, this time in the Hayscastle Anticline.

C Anomaly C has a deeper unknown origin and is one of a series of major anomalies, each with a similar ENE elongation, extending eastwards for about 70 km across South Wales.

D An elongated anomaly associated with dolerite intrusions adjacent to the Fishguard Volcanic Group.

E A small isolated anomaly over a group of dolerite intrusions.

F The positive anomaly F appears to be a continuation of anomaly D but is probably a flanking anomaly to G.

G This magnetic low appears from the results of the detailed aeromagnetic survey to arise from reversely magnetised bodies, rather than simply being a flanking anomaly to a normally magnetised body.

H This well defined anomaly again coincides with outcropping volcanic rocks and dolerites.

I Anomaly I could be an extension of H and can be followed westwards for at least a further 30 km with progressively deeper source rocks. The anomalies H and I are separated by the southern boundary fault of the offshore Mesozoic basin (Dobson and others, 1973).

The E–W trend of the anomalies H and I is repeated by that of the magnetic anomalies due to the Skomer Volcanic Series, 6 km south of the area shown in Figure 4, and is discordant to the general ENE trend within the area.

Bouguer gravity anomaly data for the area were first reported by Griffiths and Gibb (1965). Figure 5 is based mainly on more recent surveys by BGS, including one specifically designed to cover the area of the airborne survey. The map is dominated by the regional increase of values towards the northern coast and, just offshore, the anomaly reaches a maximum before decreasing over the thick Mesozoic and Tertiary sediments in the St George's Channel Basin (Blundell and others, 1971; Dobson and others, 1973). This gradient has an origin deep within the crust but superimposed on it are local Bouguer anomalies of near-surface origin. Several of these were obvious on the original survey by Griffiths and Gibb (1965), who ascribed anomaly A (Figure 5) to low density Precambrian acid intrusives and volcanic rocks in the Hayscastle Anticline, anomaly B to acid intrusives in a concealed extension of the Hayscastle Anticline and anomaly C to high density Precambrian rocks in the core of the Towy Anticline.

The more detailed BGS data (Figure 5) have confirmed the existence of the above anomalies and provide additional information on these and other less well defined anomalies. The Hayscastle low (A Figure 5) is discussed later in this report and marine gravity data (Blundell and others 1971) suggest that it could extend offshore to near Skomer [72 09]. The St David's Anticline also gives rise

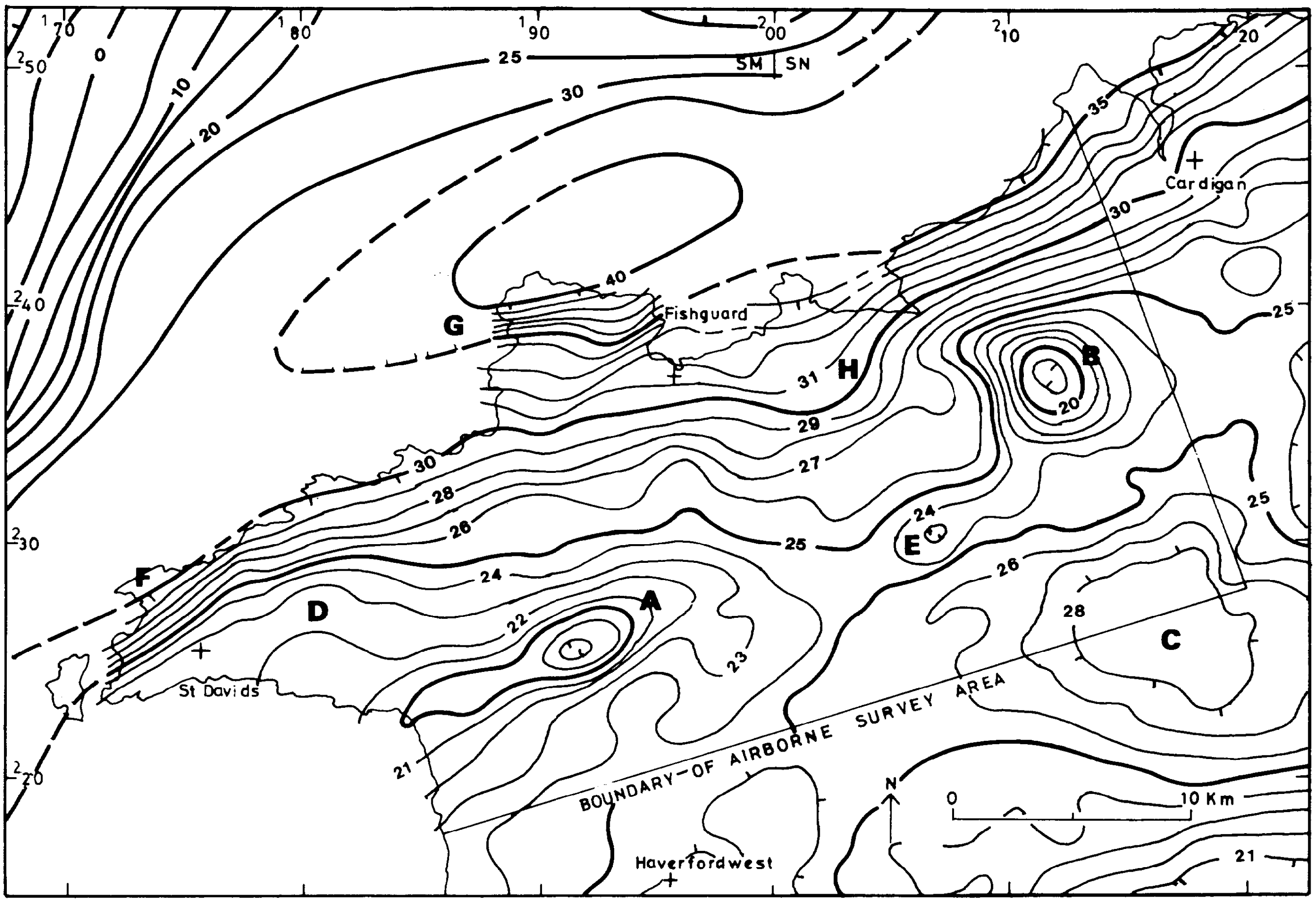

Figure 5 Bouguer gravity anomaly map for part of Dyfed and adjacent offshore areas with contours at 1 mGal (10 gravity units) intervals, based on BGS land survey data and published 1:250 000 scale maps. Lettered anomalies A to H referred to in text

to a Bouguer anomaly low (D Figure 5), although it is less pronounced than the Hayscastle feature, and acid intrusions are thought to be largely responsible in both cases. The source of the pronounced circular low B appears to be related to the Fishguard Volcanic Group. Anomaly E is a weak low elongated to the south-west; its origin is unknown but could be the various volcanic rocks in the area. Basic igneous rocks are probably responsible for poorly defined local gravity highs suggested by the steepening of the gradients at St David's Head (F Figure 5) and Strumble Head (G) and the bend in the contours indicated as H in Figure 5. The Bouguer anomaly C remains a well defined feature and, if it does represent the high density Precambrian rocks postulated by Griffiths and Gibb (1965), indicates a basement quite different to the essentially acidic type of St David's and Hayscastle.

As part of an investigation of the deep structure of South Wales, Brooks and others (1983) recorded a long N–S seismic refraction profile across western Dyfed. The results demonstrated that the Precambrian rocks of the Hayscastle Anticline could be traced at depth for a considerable distance, unlike the situation further south where rocks of a similar age in the Johnson-Benton fault block appear to form part of an isolated horst slice.

Detailed geophysical surveys have been carried out in the Llandeloy and Trefgarne areas (Figure 8) as parts of the Mineral Reconnaissance Programme. Reports on these (Allen, Cooper and others, 1985 and Brown and others, 1987) include the results of induced polarisation (IP), magnetic and VLF surveys as well as of geological and drilling investigations.

PHYSICAL PROPERTIES OF ROCKS

The physical properties relevant to the interpretation of the geophysical data discussed in this report comprise magnetisation, density and electrical resistivity, but only the first two were examined as part of the present survey.

The magnetic susceptibilities of the main rock type were measured on rock outcrops using a portable susceptibility meter or on cores taken from hand samples. The susceptibility values obtained have been summarised, according to rock type, in Figure 6. In addition, a suite of orientated rock samples was collected and the magnetic properties were measured in the University of Liverpool (Appendix 2).

The most highly magnetic rocks include the dolerites, diorites and spilitic lavas, although all of these types also have low magnetisation variants. Tuffs are normally weakly magnetised although one site (6 Appendix 2) produced magnetite-bearing samples. Gabbro samples (mainly from the St David's Head intrusions) are only weakly magnetic. The sediments are typically very weakly magnetic, but locally they can have significant susceptibilities (c.f. Allen, Cooper and others, 1985).

The intensities of the natural remanent magnetisations (NRM) are generally low (Appendix 2) and the 'Q' values (the ratio of the remanent to the induced magnetisation) are correspondingly small. There is, therefore, no evidence from the samples collected that the NRM contributes significantly to the formation of magnetic anomalies, although it will be shown later that this is not true generally for the area.

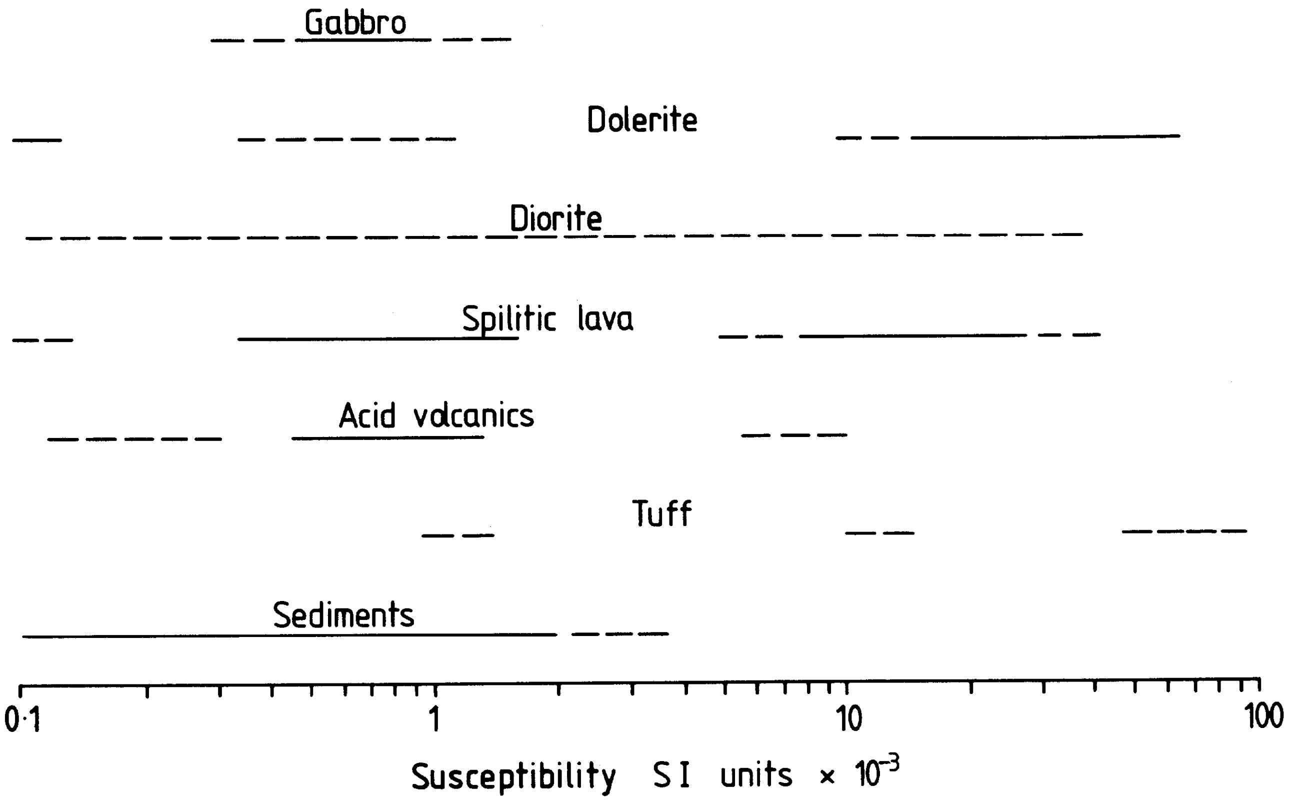

Figure 6 Magnetic susceptibility ranges for some of the main rock types

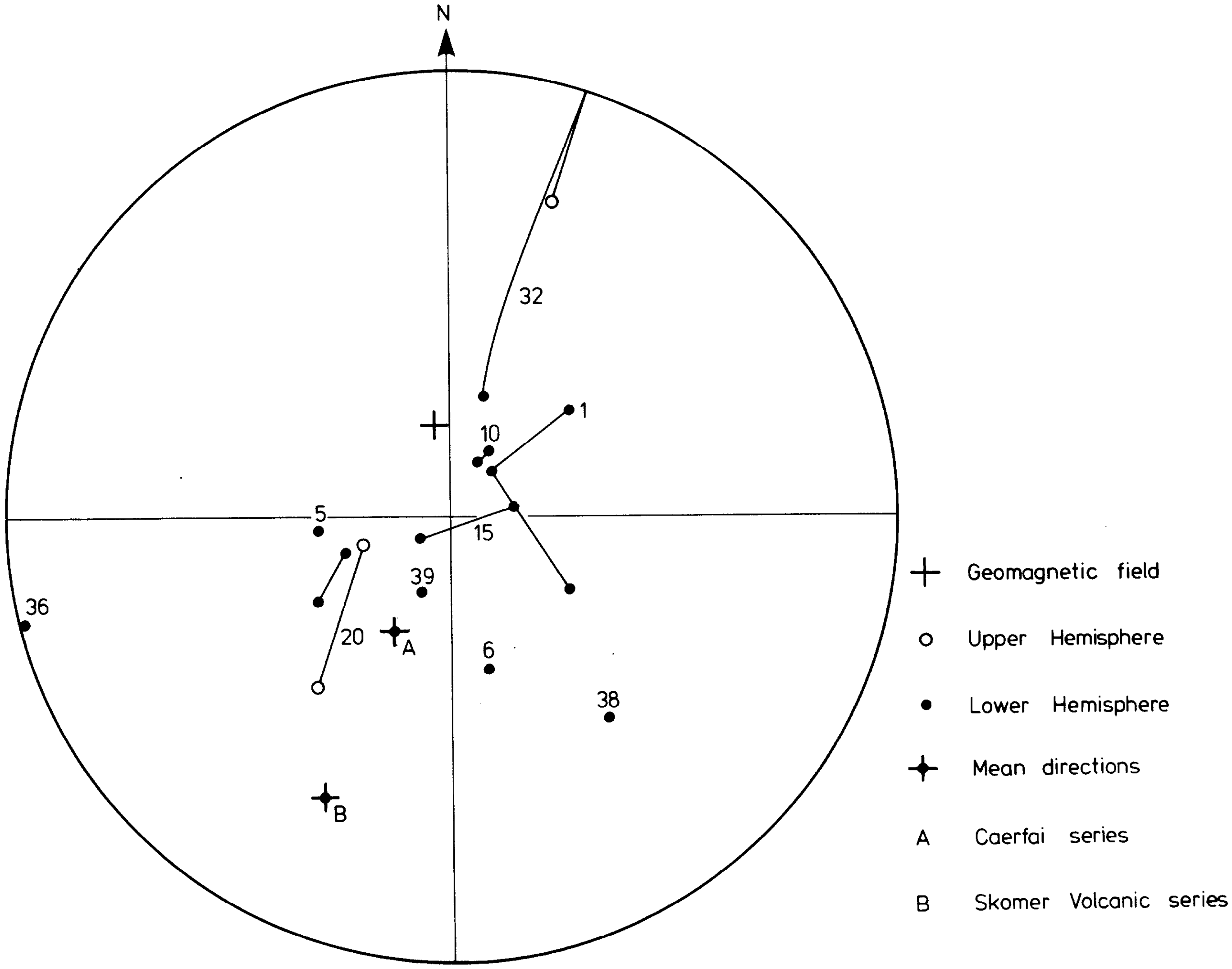

Figure 7 Directions of magnetisation for samples from west Dyfed

The directions of the NRM of all the specimens are plotted in Figure 7 together with mean directions obtained from other studies (see below). Nearly all of the directions are downwards, that is in the same sense as the present geomagnetic field, although the declinations vary considerably.

The Curie temperatures were determined from thermomagnetic balance measurements and give some indication of the nature of the magnetic components. Temperatures in the range 500°C – 590°C, indicative of magnetite, are the most common, especially in the higher susceptibility samples. Haematite, with Curie temperatures greater than 600°C, occurs in four samples while pyrrhotite (site number 40) and disseminated hematite (site number 21) are responsible for the low Curie temperatures (J. Piper, personal communication).

Some of the rocks within the survey area have also been examined in palaeomagnetic investigations by Briden and others (1970) and Morris and others (1973). The NRM of the sandstones and shales of the Lower Cambrian Caerfai Series from the St David's area is low (0.5 to 9.5×10^{-3} A/m) and is due to detrital hematite (Briden and others, 1970). Morris and others (1973) examined samples from a total of 51 sites in the Trefgarne Volcanic Series, the Fishguard Volcanic Group and basic intrusive rocks. For the andesites of Trefgarne, the NRM intensities range between 0.8 and 200×10^{-3} A/m and it is noted that samples containing pyrite and titano-magnetite as the principal opaque minerals are less magnetically stable. The NRM of the Fishguard Volcanic Series is secondary in origin and is due to iron oxides formed as by-products of the albitisation of the volcanic rocks and also, partially, of the alteration due to the intrusion of the sills (Morris and others, 1973). The NRM directions for the basic intrusions are not consistent and even the mean directions after magnetic cleaning appear to be randomly scattered. No mean directions are given for these rocks or the Fishguard Volcanic Group but the means for the Caerfai Series and the Skomer Volcanics Group (Briden and others, 1970) are shown in Figure 7.

The densities of the main rock types in Wales have been summarised by Griffiths and Gibb (1965):

Silurian — (north-central Wales)	2.73 ± 0.10 Mg/m^3
Ordovician — (South Wales)	2.74 ± 0.20 Mg/m^3
Cambrian — (Pembrokeshire)	2.72 ± 0.10 Mg/m^3
Precambrian — (Pembrokeshire)	2.65 ± 0.10 Mg/m^3

Although there seems to be little difference between the Lower Palaeozoic formations, the Precambrian rocks have a significantly lower density, probably due to the high proportion of acid igneous rocks present. Some additional values are listed in Appendix 2.

AIRBORNE AND GROUND SURVEY EQUIPMENT AND PRESENTATION OF DATA

The airborne geophysical survey was carried out using equipment, mostly developed by Sander Geophysics Limited, installed in an Alouette II helicopter.

The survey area comprises 670 km^2 and is shown in Figure 1 together with the position of the tie lines and a selection of flight lines. The NNW flight line direction is perpendicular to the dominant structural trend of the area (Figure 3). The ground clearance of the helicopter carrying the VLF receivers was 75 m, with the magnetometer sensor flown in a separate towed bird with a ground clearance of about 55 m. The flight lines were spaced 250 m apart.

Airborne survey equipment

The survey equipment, described in greater detail elsewhere (Broome, 1979; Evans and Cornwell, 1981), included the following:

Magnetometer A Sander NPM-5 proton precession magnetometer recording the total magnetic field at 1s intervals was installed in the helicopter and a second NPM-5 magnetometer was used as a ground base station.

VLF equipment The Sander VLF-EM II equipment used three orthogonal coils to measure the ellipsoid of polarisation of the EM field. The attitude of the helicopter in the air was recorded by a vertical gyro. The VLF transmitter at Rugby (GBR 16.0 kHz) was used throughout the survey.

Gamma-ray spectrometer The Sander SPM-12 spectrometer coupled to two 9 inch by 4 inch cylindrical NaI(Tl) crystals produced multi-channel data which were divided into windows for K, U and Th as well as total count.

Additional equipment. This consisted of radar altimeters, tracking camera, a data acquisition system and a chart recorder for in-flight checks.

Data processing

Data from the magnetometer, the VLF equipment and the spectrometer were recorded at 1s intervals and transferred from the field tapes onto standard nine-track tapes, together with digitised information on the flight paths. The magnetic data were corrected for diurnal variation and a normal geomagnetic field removed.

The VLF data were corrected for the attitude of the helicopter in the air and the normal field strength (indicated as 100% on the horizonal intensity map) estimated by averaging values along the flight line.

The radiometric data were not processed.

Data presentation

The geophysical data for the Dyfed area were presented by the contractor as three sets of maps at a scale of 1:10 000 showing (a) total field magnetic anomaly contours, (b) contours of the normalised intensity of the horizontal components of the VLF field and (c) stacked profiles of the normalised in-phase and out-of-phase values of the vertical component of the VLF field. The two modes of presentation of the related VLF data were chosen to provide maps giving both a good regional impression of the conductor distribution (b above) and the more detailed information available in stacked profile form (c). All these maps are available in a separate data package.

General comments on interpretation of airborne survey maps

Magnetic interpretation The magnetic map generally shows a series of well defined, elongated anomalies, separated by larger areas of low magnetic gradient. The anomaly amplitudes are frequently several hundred nT, but weaker anomalies of a few tens of nT are often persistent and have been used in the interpretation. Many of the anomalies are consistent with a direction of magnetisation coincident with the geomagnetic field, that is with dominant positive anomalies and minor negative anomalies to the north. There is a group of anomalies whose dominant negatives (e.g. in SN 03 SE) suggest that any interpretation requires a strong remanent magnetisation approximately anti-parallel with the geomagnetic field. The rock types responsible were unfortunately not found amongst those sampled (Appendix 2) but the significance of negative anomalies is discussed more fully later in the report.

Most of the observed magnetic profiles can be reproduced by the theoretical curves for two-dimensional sheet-like magnetic bodies and this model has usually been used in interpretations.

VLF interpretation The VLF-EM method responds mainly to current flow induced in conductive material in the ground by the EM field produced by VLF transmitters. The method is particularly responsive to large conductive structures, such as faults, but will produce anomalies over smaller, highly conductive objects including those of man-made origin, such as power lines.

The VLF data presented by Sander Geophysics Limited comprise the intensity of the horizontal component of the VLF field, measured as a percentage of the normal field (100%), and the in-phase and out-of-phase components of the vertical component, again measured as percentages. The relationship between these components is such that the presence of a conductor in the ground is revealed by a maximum reading of the horizontal intensity and a 'cross-over' in the vertical component. Various interpretational methods have been developed to derive estimates of the depth and dip of the conductors from VLF data (e.g. Baker and Myers, 1980).

The amplitudes of VLF-EM anomalies decrease less rapidly with height than those due to a moving transmitter configuration with a dipole source (e.g. Slingram). In parts of the survey area, however, anomalies on adjacent flight lines differ in such a way as to suggest systematic differences in recording altitude. This might occur, for example, when strong winds along the flight line direction required a larger height safety margin for down-wind flights.

VLF anomalies of non-geological origin arise from topographic effects and from man-made conductors such as power lines and buried pipes. Anomalies due to topographic effects can usually be recognised because they tend to have a long wavelength and coincide with hill tops and valleys. The Dyfed survey area is comparatively flat and VLF-anomalies probably due to topographic effects are generally recognisable.

Power lines can produce distinctive large amplitude anomalies, particularly when they are aligned in the direction of maximum coupling with the VLF-EM field. Such anomalies in the Dyfed area were determined by comparing the geophysical map with one showing the distribution of power lines.

Many groups of VLF anomalies in the Dyfed area were sufficiently distinctive to facilitate the recognition, with some confidence, of the presence of continuous conductors of geological origin (Plate 1). These are almost certainly mainly conductive shale horizons. There are apparently few indications of fault lines but these will be less likely to occur as the strike directions need not coincide with the direction of maximum coupling with the VLF transmitter.

It is likely that most of the less extensive VLF anomalies have geological significance but this cannot generally be fully assessed because of the lack of detailed geological information. In an area where detailed resistivity measurements can be compared with an airborne VLF map (Figure 12) the correlation is good although the geological control is not sufficiently detailed to assess the significance of all the results.

VLF field anomalies reflect mainly variations in the bedrock resistivities, and patches of thick, conductive overburden. High resistivity values would be expected over Precambrian rocks and the various igneous extrusions and intrusions. High values of several thousand ohm metre are reported, for example over the diorite intrusions of the Llandeloy area (Allen, Cooper and others, 1985) and the Roch Volcanic Series (Brown and others, 1987). Values of several hundred ohm metre are likely to be typical of the normal Lower Palaeozoic sediments but black, pyritous and/or graphite-bearing shales, such as the *D. murchisoni* horizon, can be very good electrical conductors.

Radiometric survey results Four channels of radiometric data were measured (total count, U, Th and K) and the results are available as analogue flight profile records as well as in digital form. The analogue records for the entire area were examined by Mrs S. Kimbell, whose observations are summarised below.

The general background level for the total count is 300 to 400 cps, the variation being mainly dependent upon flying height and thickness of overburden. About 50% of the flight line records show no significant anomalies and for the remainder most of the anomalies were 150 to 300 cps above background. These anomalies were generally less than 0.5 km long and only rarely extend laterally for more than one flight line. They tend to be scattered widely throughout the area, with two more pronounced concentrations at Rhyndaston Mountain [890 240] and near Treleidir [770 295]. Most of the anomalies can be correlated with topographic features, probably associated with areas of thin or no overburden, and buildings. It is difficult to draw any conclusions of geological significance from the radiometric data.

Ground surveys

Ground geophysical surveys were carried out within the airborne survey area with the intention of more accurately defining the location and form of the geophysical anomalies (e.g. Figures 17 and 18), in particular the magnetic anomalies. By combining these surveys with a geological examination of the ground and petrological and susceptibility examinations of rock samples it was hoped that the sources of the anomalies could be determined, thus facilitating the use of the geophysical maps as an accurate guide to improve the geological mapping, especially of drift-covered areas.

Equipment used for the ground geophysical surveys consisted of proton magnetometers (Geometrics Limited), VLF receivers (EM 16, Geonics Limited) and a resistivity meter (Terrameter, ABEM). A portable susceptibility meter (Kappameter, Geofysika Brno) was used for examination of outcrops.

The basis for selecting an area for examination using ground methods was that it included one, or more, of the following:

(a) Major anomalies, particularly if they are extensive
(b) Anomalies apparently associated with a well defined structure
(c) Anomalies not well defined by the airborne survey — for example those striking parallel with the flight line direction
(d) Anomalies possibly due to non-geological causes — for example VLF anomalies due to power lines.

These ground geophysical surveys usually consisted of a few traverses across the site of the airborne anomaly using a magnetometer and/or VLF equipment and any outcrops in the area were examined with the susceptibility meter. Appendix 3 lists all the areas visited and the methods used and Figure 8 shows the locations. The results of the ground surveys have been incorporated

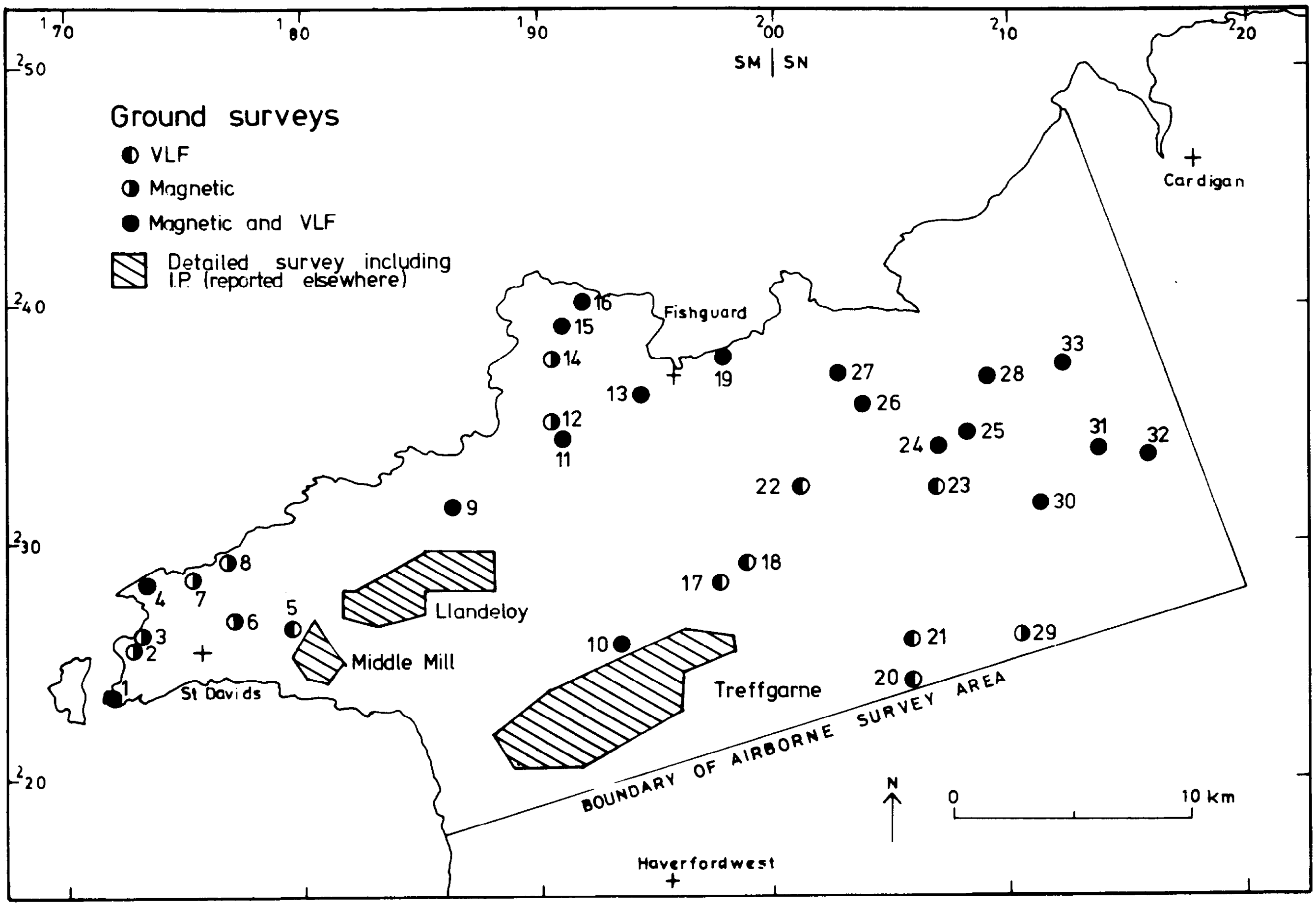

Figure 8 Locations of ground survey areas in west Dyfed 21

where relevant into the general interpretation of the geophysical survey. Resistivity soundings were made at nine sites (Appendix 4).

SYSTEMATIC INTERPRETATION OF GEOPHYSICAL RESULTS

Introduction

A general evaluation of the airborne geophysical data was made for the survey area from an examination of the 1:10 000- and 1:50 000-scale maps and the analogue flight records. A summary of the main results is presented in Plate 1 by showing trends of the main magnetic and electrically conductive horizons, together with the interpreted locations of the main linear geophysical features. These linear features are probably due to fault lines which either displace horizons or controlled the location of later igneous activity. The widths of the various horizons shown in Plate 1 are not accurately represented.

The stratigraphic positions of the main magnetic horizons are shown in Figure 2; a similar exercise for the conductive horizons is not so helpful as the main VLF anomalies (Plate 1) occur mainly at boundaries of marked resistivity contrasts, such as sediment/dolerite contacts.

The aeromagnetic, VLF and Bouguer anomaly maps show many anomalies varying in both intensity and form. These anomalies can be arranged for descriptive purposes into zones, showing approximately similar characteristics, and these are indicated in Plate 1. The magnetic data have proved the most useful for the recognition of the zones, but the electromagnetic and the gravity responses, where relevant, are also listed in Table 1. Even though most of the zones in the survey area are fairly obvious from the aeromagnetic data there are still uncertainties in the locations of many boundaries.

Zones 1a – 1c

The western part of the survey area is characterised by two well defined zones of magnetic rocks which are clearly related to the Precambrian rocks in the St David's and Hayscastle anticlines (cf. A and B in Figure 4). Zone 1 comprises the more elongated St David's structure and can be divided into the larger area of lower amplitude anomalies (Zone 1a) and the isolated area of larger anomalies in the extreme eastern part of the anticline (Zone 1b).

Zone 1a

The lower amplitude and irregular nature of the magnetic anomalies in this zone makes the definition of the boundaries uncertain but the overall correlation with the mapped outcrop of the Precambrian is clear. The magnetic anomalies are associated with most of the Precambrian groups, notably the Rhossan and Ramsey Sound groups and, apparently in places, the Dimetian granophyre. Rocks of the Caerbwdy Group (tuffs and conglomerates) (Figure 9) tend to be weakly magnetic. The mapped boundaries of the Precambrian groups (Geological Survey, 1973) correspond well with boundaries of magnetic areas near St David's, but the linear nature of the latter suggest that faults control these and the margin of more deep-seated magnetic material (Figure 10b). East of St David's (Figure 10) a pronounced ENE-trending linear magnetic feature passing through [750 253] coincides, at this point, with a boundary between Lower Pebidian rocks and those of the Caerbwdy Group, but is apparently a major structure which can even be traced

Table 1 List of zones recognised on the basis of geophysical characteristics

General characteristics and interpretation	Zone	Magnetics	EM	Gravity	Comments
Zones 1a–1c Moderately magnetised Precambrian rocks of the St David's Anticline	1a	Moderate isolated anomalies	Some anomalies along faults	Low	
	1b	Higher anomalies than 1a	?Along faults		
	1c	Weak	Low		?Concealed extension of zones 1a and 1b
Zones 2a–2c—Moderately magnetised Precambrian rocks of the Hayscastle Anticline	2a	Strong	Moderate along faults		Mainly Pebidian rocks
	2b	Weak			
	2c	Weak	Low	Low	Quartz-diorite intrusion
	2d				Concealed extension of zone 2a
Zones 3a–3c—Extensive zone of essentially non-magnetic Lower Palaeozoic sediments	3a	All weak	Weak and extensive anomalies		
	3b		Moderate		
	3c		Weak to moderate		
	3d		Weak		
	3e		Weak to moderate		Extensive area of sediments only
Zone 4—Isolated group of magnetic anomalies associated with the St David's Head intrusions		Weak to moderate (Reversed magnetisation)	Strong at margins in intrusion	?High	Negative magnetic anomalies dominate
Zones 5a–5c—Extensive elongated area of high linear magnetic anomalies due mainly to dolerites associated with the Fishguard Volcanic Group	5a	Strong	Moderate to strong		Complex fold structure Pillow lavas also magnetic
	5b		Strong		Linear pattern
	5c	Weak	Strong		Isolated area of ?dolerite anomalies
Zone 6—Strong negative anomalies in area of numerous dolerite intrusions		Moderate to strong	Strong at margins of intrusions		Reversely magnetised rocks (probably dolerites)
Zones 7a–7c—Generally low magnetic values with numerous isolated negative anomalies	7a	All weak	Moderate	Pronounced circular low	cf. zone 6
	7b				
	7c		Moderate		Anomalies more elongate
Zone 8—Long linear magnetic anomaly oblique to general strike of rocks		Weak to moderate	Some associated anomalies in places		Subsequently proved to be due to a dyke

through the centre of the Dimetian granophyre at [743 246]. The sources of the magnetic anomalies have not been clearly established at outcrop. Detailed ground measurements (sites 2, 3 and 6, Appendix 3 and Figure 8) show the anomalies to be irregular and small in area, suggesting that minor intrusions or small fault blocks might be responsible.

The magnetic character of zone 1a does not change eastwards from near St David's, except for a gradual narrowing, until the magnetic rocks disappear at the surface around [827 289] (Figure 11). To the west, however, there is a marked contrast with the essentially non-magnetic rocks of Ramsey Island, but still further to the west, magnetic anomalies apparently related to those over the St David's Anticline reappear on the regional aeromagnetic map (Figure 4). There is, therefore, some suggestion of a major fault zone on one side, or both sides, of Ramsey Island.

Zone 1b

This oval-shaped area of high magnetic anomaly values is distinct from the main part of the St David's Anticline, although its northern margin appears to be formed by a (?) fault common to both zones 1a and 1b. This area is characterised geologically by the presence of diorite intrusions, some of which have been examined by detailed ground surveys in the Llandeloy area (Allen, Cooper and others, 1985). Detailed susceptibility measurements on drill core samples indicated several possible sources for the magnetic anomalies, including acid to intermediate intrusions, especially if hydrothermally altered, sediments, and even lacustrine deposits of Tertiary age. There is no clear evidence from geological mapping of a correlation between the diorite and the magnetic anomalies, although the latter might indicate a large intrusion at depth. Interpretation of a profile (AA' Figure 11) through the main anomaly forming zone 1b suggests a

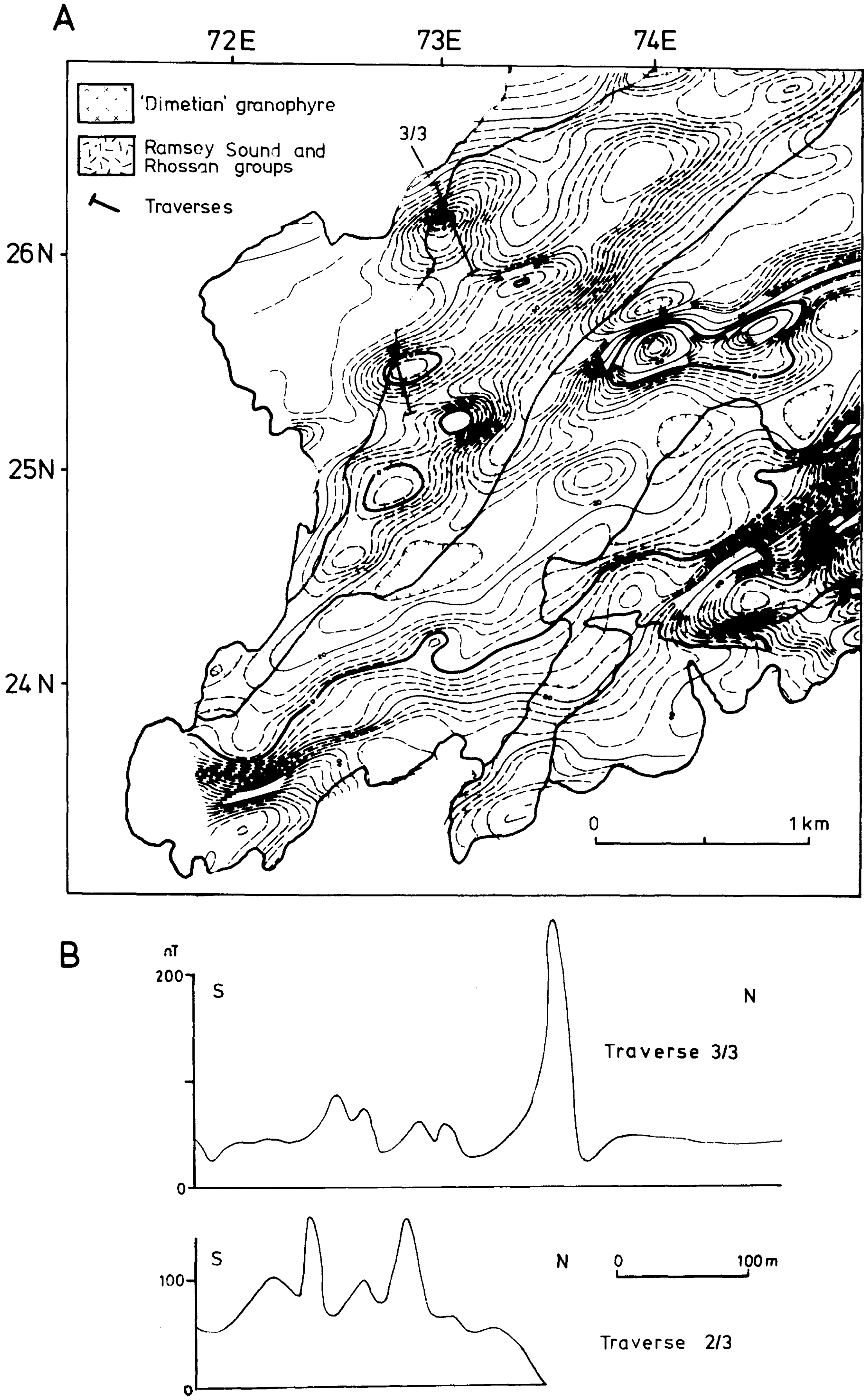

Figure 9 (A) Aeromagnetic map of area west of St David's with simplified geology, (from Geological Survey of Great Britain 1973), and (B) ground magnetic profiles for traverses 3/3 and 2/3

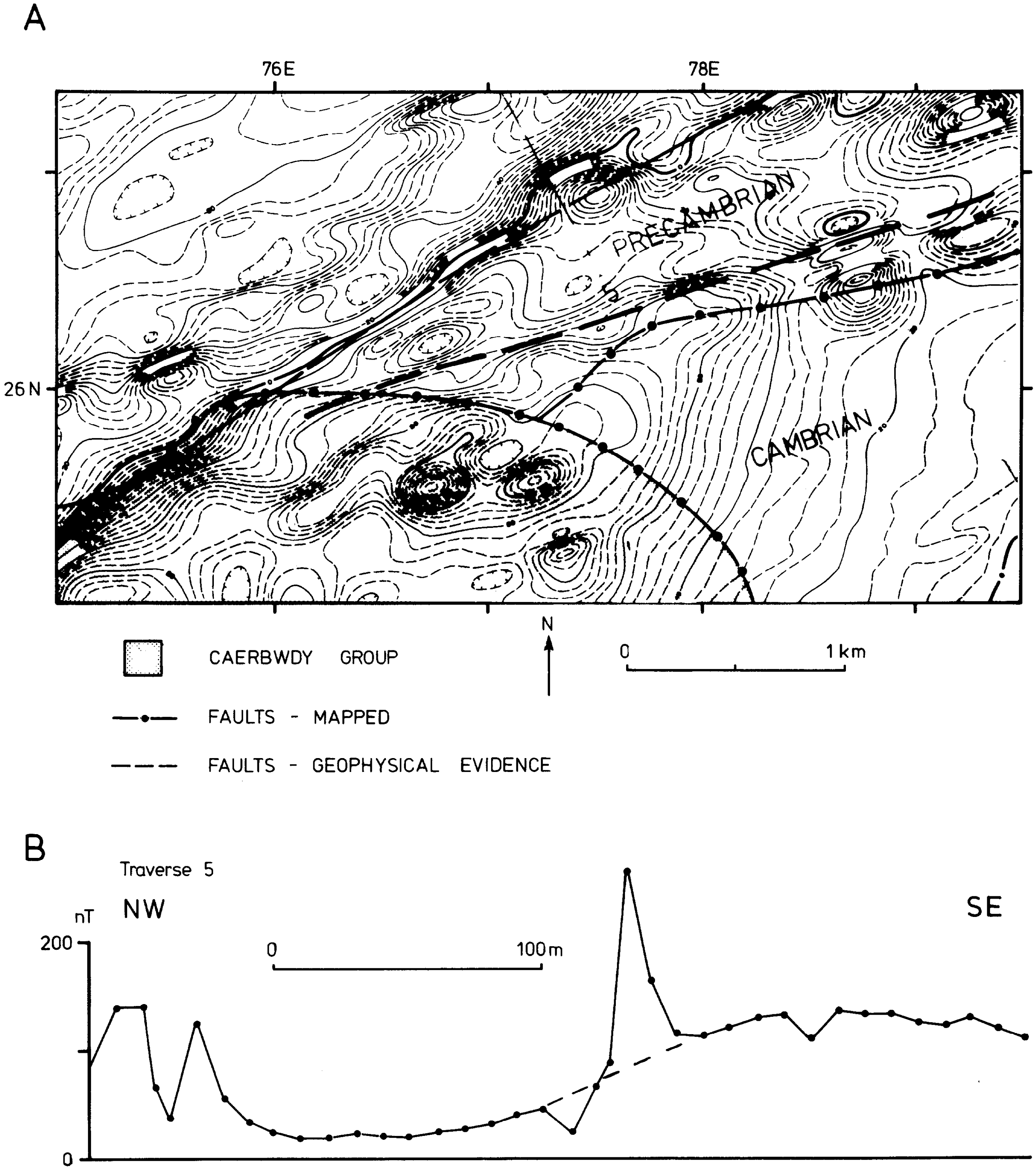

Figure 10 (A) Aeromagnetic map of area east of St David's, mapped extent of the Caerbwdy Group and faults based on geological and geophysical evidence. (B) Ground magnetic profile for traverse 5

large asymmetrical body with a less steep northern margin and a depth extent of several kilometres.

The detailed geophysical surveys carried out for mineral exploration in the Llandeloy area (Allen, Cooper and others, 1985) also included ground resistivity results which provide an interesting comparison with the airborne VLF results (Figure 12). There is a general inverse correlation, as would be expected, between the resistivity highs and the VLF horizontal intensity lows. One of the more pronounced features of the VLF map is the series of highs along the northern margin of the area giving way southwards to a series of lows (A and B in Figure 12). This double feature is believed to be due to the contrast along an E–W fault between *Tetragraptus* Shales to the north (200 to 300 ohm-metres) and the igneous rocks to the south (more than 2000 ohm-metres). Some of the NE-trending anomalies are probably due to the effect of faulting, including the VLF anomaly C (Figure 12) (Allen, Cooper and others, 1985). An unusually thick sequence of lacustrine ?Tertiary sand and clay deposits is probably responsible for the VLF anomaly D.

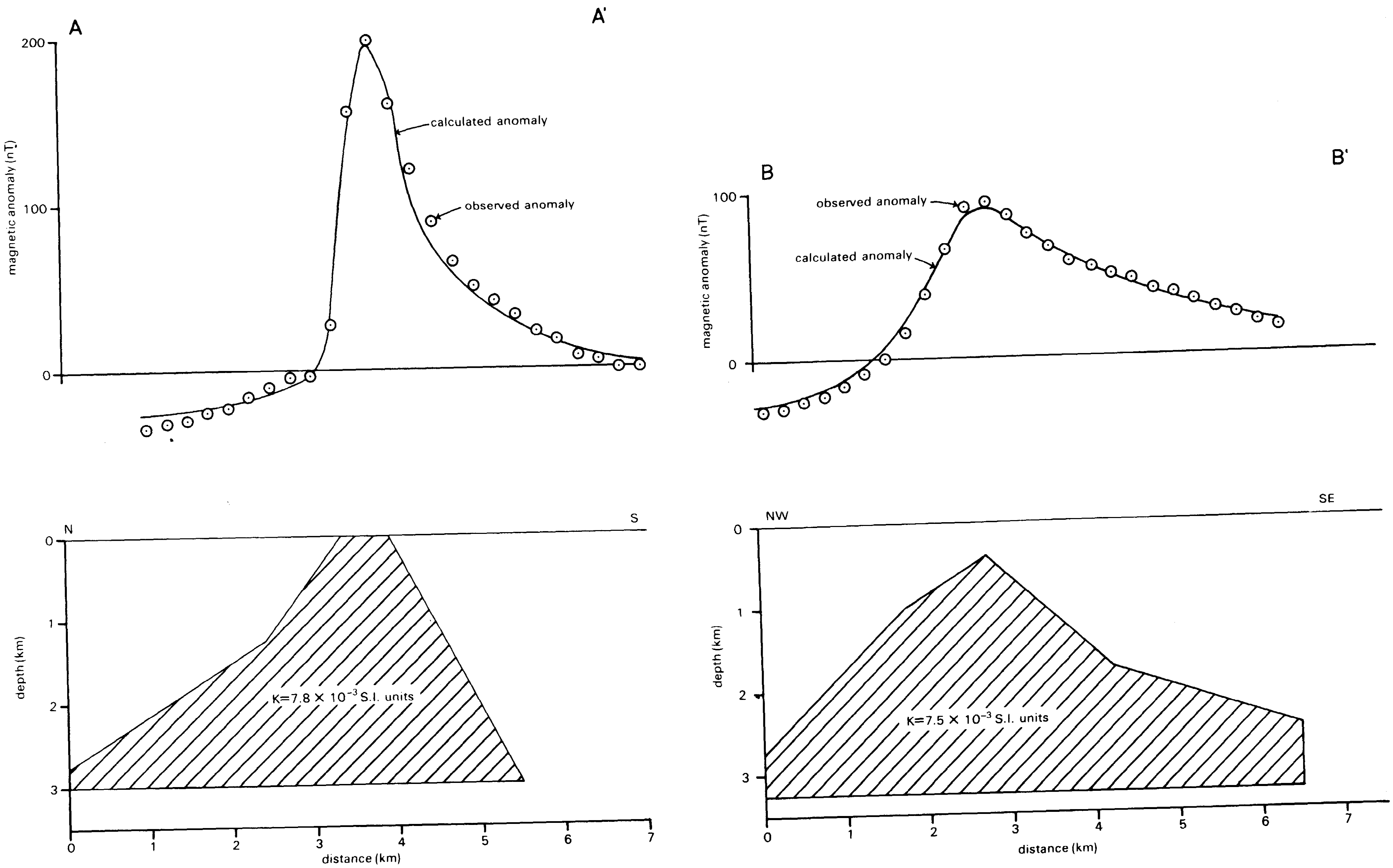

Figure 11 Aeromagnetic profiles AA' and BB' (see Plate 1 for locations) and models producing the theoretical profiles shown

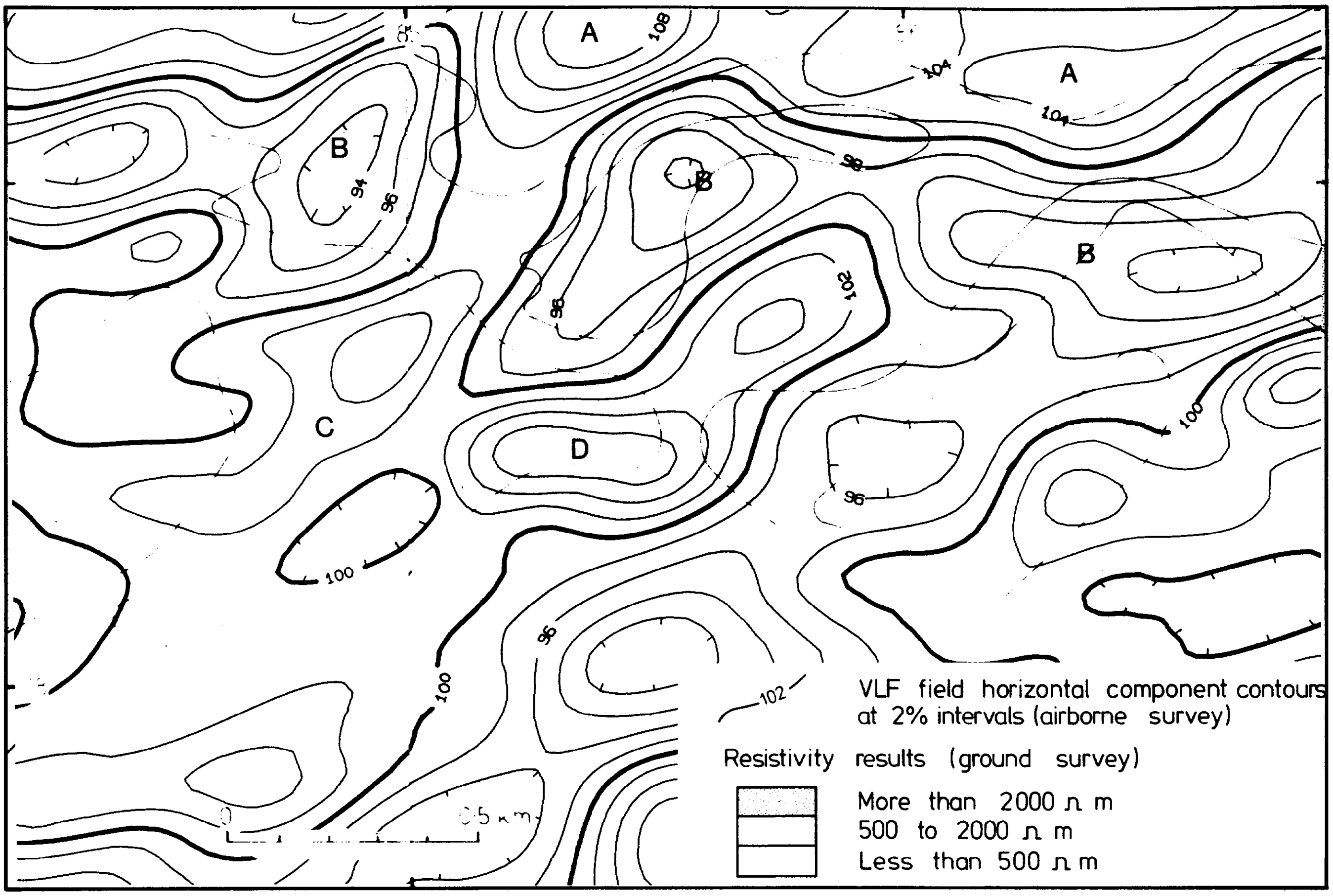

Figure 12 Ground resistivity results (from Allen, Cooper and others 1985) and airborne VLF map for the Llandeloy area

Three exposures in the Treffynon area [850 285] were examined in the present study (localities 3, 4 and 5, Appendix 1). Two consisted of hornblende diorite and hornblende andesite and were found to have moderate susceptibilities but the third, a brecciated soda rhyolite with pyrite disseminated in veinlets, was weakly magnetised.

Zone 1c

The low amplitude, broad anomaly forming zone 1c suggests the existence of magnetic material at depths of several hundred metres beneath a cover of Ordovician and Cambrian sediments. Its location adjacent to the magnetic Precambrian rocks of zones 1a and 2 suggests a similar origin, and therefore, the presence of a concealed link between the Hayscastle and St David's anticlines. If this interpretation is correct the overall structure for the Precambrian in the area would appear to be a complex double horst.

Zones 2a – 2d

The second of the two Precambrian areas, the Hayscastle Anticline, is distinguished by the presence of a volcanic suite, mainly acid volcanics and tuffs (the Pebidian Group). The zones 2a and 2b form a well defined triangular shaped area coinciding with the mapped outcrop of these rocks; zone 2d has a different character and lies over an area of Precambrian and Cambrian rocks with some dolerite intrusions. The continuity of the northern margin of zones 2a and 2d and the form of the contours suggests that zone 2d could be a largely concealed extension of Precambrian rocks.

In common with zone 1 the gradual decrease of magnetic anomaly values suggests that the Precambrian rocks slope south-westwards at depth. The northern margin of the zone is marked by sharp gradients and pronounced flanking negative anomalies, suggesting a steep contact, probably a fault plane.

Zone 2a

This area of high magnetic values and gradients coincides approximately with the mapped extent of Pebidian quartz-keratophyres and tuffs (Thomas and Jones, 1912) but rock exposure is generally poor. In the quarries near Rhyndeston, however, very magnetic tuffs were discovered (Plate 1 and localities 7, 8, 10 and 11, Appendix 1). The northern margin of this zone coincides with a mapped fault, but to the north and east an extensive area, mapped as the same rock types as zone 2a, does not appear to contain magnetic material (Figure 13).

Zone 2b

This appears magnetically to be very similar in character to zone 2a but the only available geological evidence for the existence of the Pebidian quartz-kerotophyres and tuffs is an isolated area at [942 266]. Ground surveys at Carmina (site 10, Appendix 3) revealed magnetic anomalies of up to 800 nT amplitude, with forms suggesting that the bulk of the magnetic material lay at depth, and strong VLF anomalies. It is suggested that zone 2b represents an extension of Pebidian rocks into an area previously mapped largely as quartz-porphyry (Figure 13).

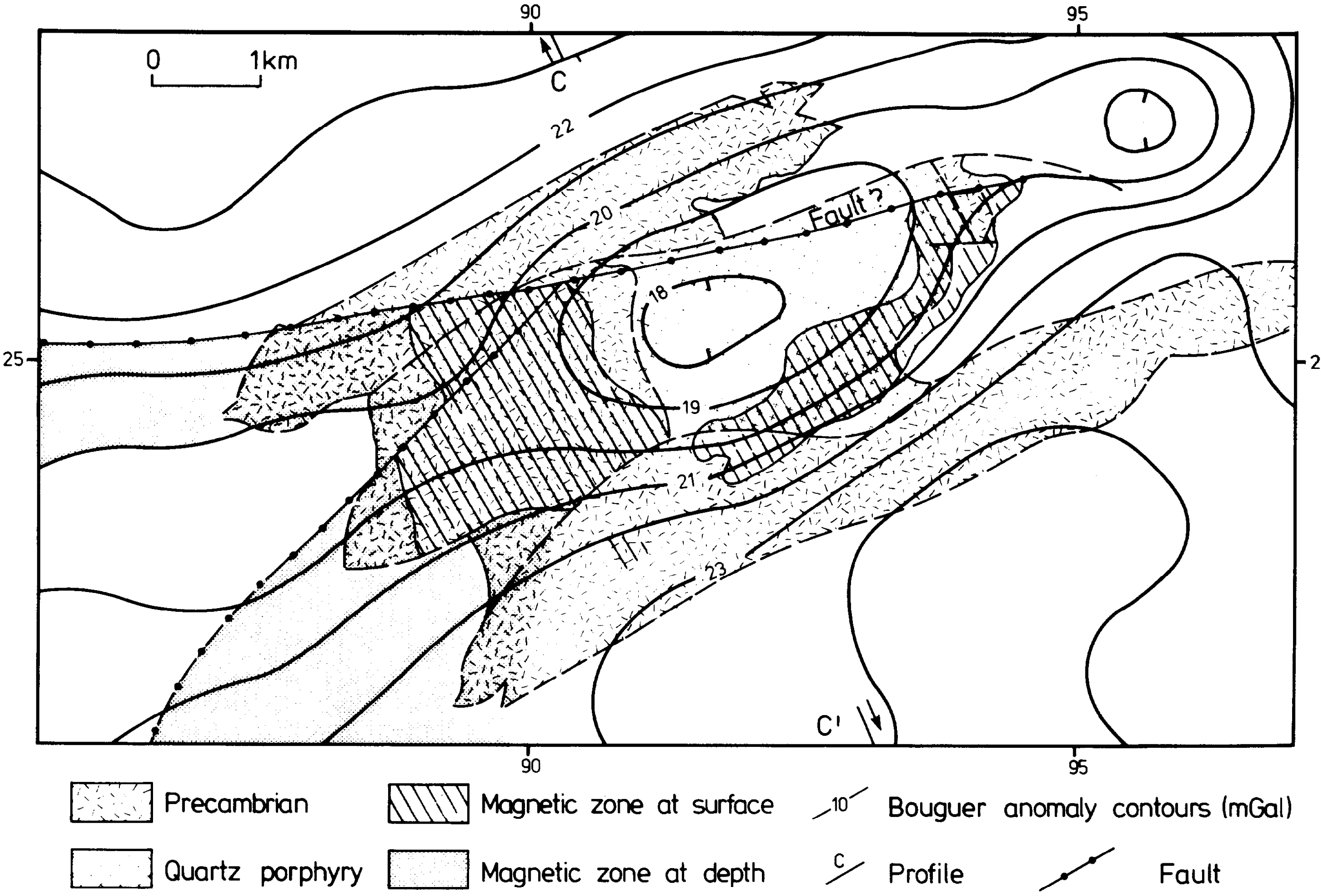

Figure 13 Bouguer gravity anomaly contours and selected geological and magnetic features for the Hayscastle Anticline

The forms of the magnetic anomalies in zones 2a and 2b suggest small surface bodies expanding considerably in size at depth, that is with forms more consistent with intrusive plugs rather than with the sheet-like bodies tuffs would be expected to form. The highly magnetic zones 2a and 2b are also characterised by moderate sized VLF anomalies of unknown origin. Intrusive rocks and tuffs would not normally be expected to cause such anomalies and the main quartz-porphyry (zone 2c) has a low VLF response.

Zone 2c

A quartz-porphyry intrusion forms an irregularly shaped area of lower amplitude magnetic anomalies, abutted on three sides by the large anomalies of zones 2a and 2b. The fourth, northern side is formed by an ENE-trending fault.

The presence of an elongated Bouguer anomaly low over the Hayscastle Anticline is known from the earlier gravity survey (Griffiths and Gibb, 1965) but more recent data indicate that the low is centred on the outcrop of the quartz-porphyry (Figure 13). It is probable that extensions at depth of this comparatively low density intrusion are largely responsible for the Bouguer anomaly feature and in Figure 14 a model based on the two-dimensional interpretation of profile CC' (Figure 13) is shown. The intrusion appears to have a depth extent of about 2–3 km and steeper slopes on the south-east side. The magnetic anomalies are associated with the margins of the highest part of the low density body. Ridge-like extensions of the gravity anomaly to the ENE and WSW have no magnetic response, indicating that the quartz-porphyry is not invariably intruded into magnetic Pebidian rocks.

Zone 2d

The eastern end of this elongated zone appears to include an extension at depth of the magnetic tuffs of zone 2a beneath non-magnetic rocks of the same Precambrian type (Figure 13). The form of the magnetic anomaly in the central part of the zone [860 245] suggests the extension is here largely concealed by Cambrian sediments.

Anomalies near the western end of this zone around [845 245] appear to form a continuation with the same structural trend but have a near surface origin (although some are due to farm buildings). The area has been mapped as *Lingula* Flags but the anomalies could be due to minor intrusions, some of which have been located nearby.

Zones 3a–3e

A large part of the survey area is occupied by essentially non-magnetic Lower Palaeozoic sediments ranging in age from Cambrian to Upper Ordovician. On the aeromagnetic map these rocks are characterised by low magnetic gradients or very gradual changes in anomaly values due to adjacent or underlying magnetic bodies. Non-magnetic sediments occur within other zones of predominantly magnetic igneous rocks, such as in zone 5b, and conversely zone 3 includes some igneous rocks.

Black shales containing pyrite and/or graphite commonly occur within Lower Palaeozoic sequences and are known in the Dyfed area, for example those belonging to the *D. murchisoni* zone. These shales frequently have very low electrical resistivities and are probably responsible for many of the VLF anomalies (cf. Allen and others, 1979 for comparable examples in the Harlech Dome).

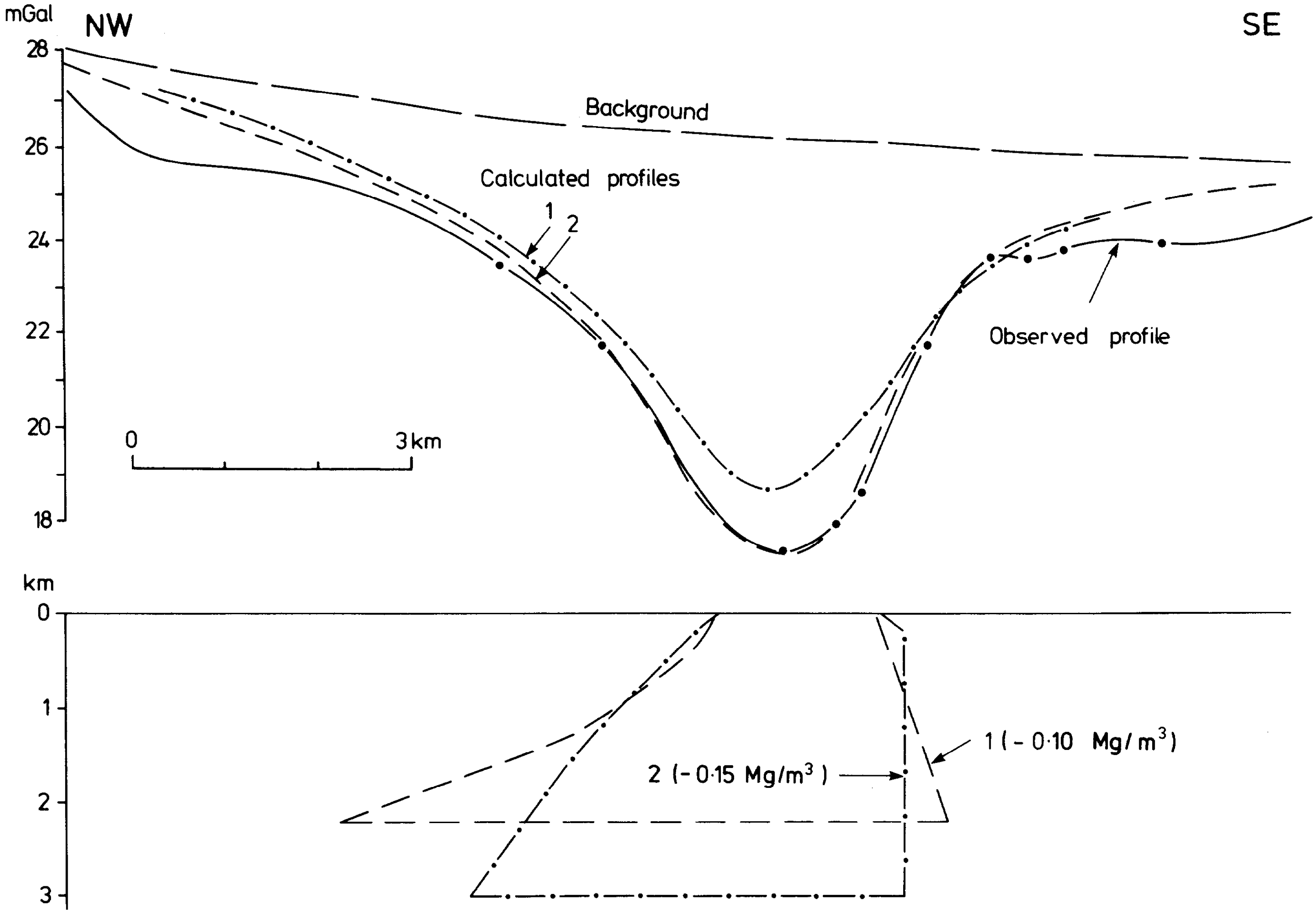

Figure 14 Observed Bouguer anomaly profile CC' (see Figure 13 for location) and models for quartz-porphyry intrusion

The division of the area into zones 3a, 3b etc, is largely geographical with no definite boundaries between them.

Zone 3a
This zone, north of the St David's Anticline, includes the *Tetragraptus* Shales, the *D. murchisoni* Beds, the Fishguard Volcanic Group and some dolerite intrusions. The igneous rocks produce very little magnetic response apart from minor anomalies due to a) the probable eastward extension of a quartz dolerite dyke at [761 280], b) an isolated anomaly over a dolerite intrusion on the coast at [806 325] and c) a weak ENE-trending negative anomaly at [777 300]. This last anomaly coincides with an extension of the quartz-gabbro intrusions responsible for the larger anomalies of zone 4.

The VLF anomalies are generally weak in this area, although the mapped fault at [804 315] seems to be associated with a pronounced feature.

Zone 3b
This area between zones 5a, 5b, 7b and 8 includes sediments belonging to the *Lingula* Flags, the Brunel Beds, the *Tetragraptus* Shales and the *D. bifidus* Beds. Dolerite intrusions are not common and there is little magnetic response, a group of anomalies around [9732] probably being due to buildings.

The largest VLF anomalies in zone 3b are due to either power lines or topographic features (particularly the deeply incised valley of Cwm Gwaun [e.g. 970 369 to 030 340] but the other indications are of stratigraphic conductors.

Zone 3c
This extensive zone in the southern part of the survey area has practically no anomalies due to near surface magnetic bodies, despite the occurrence of volcanic rocks of the Roch, Sealyham and Trefgarne Series. The magnetic pattern is dominated by the gradual increase of values towards the SSE, part of the large deep-seated magnetic anomaly culminating just outside the survey area (C in Figure 4). Sediments in zone 3c include the *Lingula* Flags, the *Tetragraptus* Shales, the *D. murchisoni* Beds, and near the coast of St Brides Bay, Upper Carboniferous strata.

At three sites (17, 18 and 20, Appendix 3) significant airborne VLF anomalies were proved to be due to power lines. At site 21, near site 20, a long wavelength VLF anomaly was recorded on the ground.

Zone 3d
This zone, between the St David's and Hayscastle anticlines, has magnetic gradients due to deep-seated parts of these structures, including the completely concealed extension 1c (Plate 1). The surface sediments are largely Cambrian in age but a group of dolerite intrusions are responsible for a small area of weak irregular anomalies. VLF anomalies are generally weak in this zone but in the area around Middle Mill, where detailed geophysical surveys have been carried out (Allen, Cooper and others, 1985), they show a good correlation with ground resistivity results.

Zone 3e
This is a zone of particularly low magnetic gradient over the Hendre Shales and younger sediments in the north-eastern corner of the survey area. The VLF anomalies are weak except for those due to topographic effects near the coast.

Zone 4

This zone includes a distinctive group of gabbroic intrusions and is characterised geophysically by a series of magnetic anomalies, the more important of which are negative, and significant VLF anomalies. The two composite, layered and parallel igneous intrusions of St David's Head and Carn Llidi have been described by Roach (1969). They are roughly concordant (sill-like) and composed essentially of quartz-gabbros. Roach (1969) holds the view that the two parallel intrusions may in fact be outcrops of a single intrusion folded into a syncline.

Although certain horizons in the intrusion have been described as being magnetite-bearing (Roach, 1969 and locality 1, Appendix 1), two traverses using the susceptibility meter revealed only weak responses (cf. sample 1, Appendix 2). An examination of the relevant samples, including the interpretation of a XRD film by R. C. Merriman, indicates that the opaque minerals are in fact ilmenite.

The magnetic anomalies are obviously spatially related to the gabbro intrusions (Figure 15) with weak highs to the north over the outcrops and more strongly developed magnetic lows close to the southern margins of the intrusions. This relationship is the reverse of that expected over a body magnetised in the present geomagnetic field direction and a strong remanent magnetisation is therefore suspected. Although such a remanence is likely to rest in concealed portions of the gabbros, it is not impossible that the negative anomalies could be due to a reversely magnetised horizon in the Ordovician sediments which strike parallel with the intrusions. This second alternative is advanced in respect of the well defined nature of the negative anomaly, its confinement to only one margin of the several intrusions and its coincidence with sulphide-rich shales, which could be pyrrhotitic in places. The shales were examined at Porth Lleuog in Craig y Creigwyr [7309 2758] (samples RC 1427 and 1428), some 100 m below the gabbro, where one thin bed gave moderate (c.1.5 × 10^{-3} SI units) susceptibility values. It is considered however that the gabbro intrusion is more likely to be responsible and that the magnetic horizons occur at depth. The latter conclusion was confirmed by ground magnetic traverses.

The geophysical evidence suggests that some modifications to the geological model for the gabbro intrusions is required. The VLF data confirm the outcrop pattern in the west of the area (Figure 15) and can perhaps be used to produce a better map of the less well exposed eastern part of the area. The magnetic results indicated that Carnedd-lleithr is part of the same intrusion. The proposed subsurface extent of the main magnetic intrusion is shown in Figure 15 together with faults which are suggested on the basis of interruptions of geophysical anomalies. The buried intrusion appears to terminate east of Carnedd-lleithr but reappears beneath the outcrops of Penberry.

The St David's Head intrusion can be traced offshore for a further 11 km to the WSW (Dobson and others, 1973, figure 8).

Zones 5a – 5c

A group of strong magnetic anomalies along the northern coast in the survey area, obvious even on the original aeromagnetic survey (D, Figure 4) is associated with dolerite intrusions adjacent to the Fishguard Volcanic Group and to some of the volcanic rocks.

Zone 5a

The magnetic anomaly pattern in this zone is complex but the main features, such as the fold in the south, and the east to west strike in the north, clearly reflect the mapped geological structure. The anomalies are elongated, with amplitudes of a few hundred nanotesla.

The very elongate belt of anomalies marking the southern end of zone 5a coincides, west of about Grid line 93E, with a diorite intrusion but the magnetic anomalies continue towards the ENE to join those due to dolerite mapped near Fishguard. Ground surveys at site 13 (Appendix 3) showed magnetic anomalies of up to 800 nT amplitude with pronounced negative components, suggesting a dip to the south-east. Ground magnetic anomalies at the western end of the same magnetic zone (11, Appendix 3) also have amplitudes up to 800 nT but the dip appears to be steep towards the NNW. Within this last ground survey area a magnetic horizon up to 800 m wide passes laterally into two separate horizons about 100 – 170 m apart.

The main magnetic horizon appears to change strike by about 180° at [905 350], in agreement with the geological mapping, but then disappears after continuing to the north-east for about 1 km. The relationship between this horizon and the anomalies further west around [885 355], and due probably to small diorite intrusions, is not clear. One interpretation of the anomaly pattern in this area is that it is partly determined by a fault trending to the ESE on the southern margin of the zone.

The magnetic anomaly pattern around [905 375] is confused, partly as a result of the coincidence of the flight line direction with the geological strike and also because of the great changes in the latter in the area. Diorite intrusions occur in the area of the anomalies at [910 320] and it is likely these continue into the area mentioned above, although there are no outcrops.

In the northern part of zone 5a the strong magnetic anomalies adopt the east – west direction characteristic of zone 5b. The area north of Grid line 395N has been mapped largely as pillow lavas belonging to the Fishguard Volcanic Group but there is also some evidence for the existence of magnetic dolerite intrusions.

Ground magnetic measurements (16 Appendix 3) on the large aeromagnetic anomaly at [917 400] revealed two types of anomalies; a group of narrow high amplitude anomalies indicating near-surface beds with a near vertical dip and a second anomaly, lying mainly to the north, indicating a more deep-seated magnetic body. This body seems to dip to the north, causing the gradient seen on the airborne results [915 405] and on the ground.

The area of this anomaly is badly exposed and the nearby cliffs at Aber Fynon [928 401] are inaccessible except by boat. At the west end of the anomaly high susceptibility metamorphosed dolerites were discovered in rock debris (locality 12 Appendix 1) and in one exposure (12a Appendix 1). A dolerite (13 Appendix 1) at the east end of the anomaly is similar in appearance but the iron oxides have been altered to sphene and the susceptibility is low (about 1 × 10^{-3} SI). Samples of spilitic pillow lavas at two nearby sites (14 and 15 Appendix 1) also produced contrasting susceptibility values (averaging 12 and 1 × 10^{-3} SI respectively). It is possible that the two rock types are responsible for the two anomaly types described above but it is also clear that in this area no one rock type can invariably be expected to produce anomalies.

Further to the east the anomaly at [9419 3898] appears to be due to a keratophyre with susceptibility values of

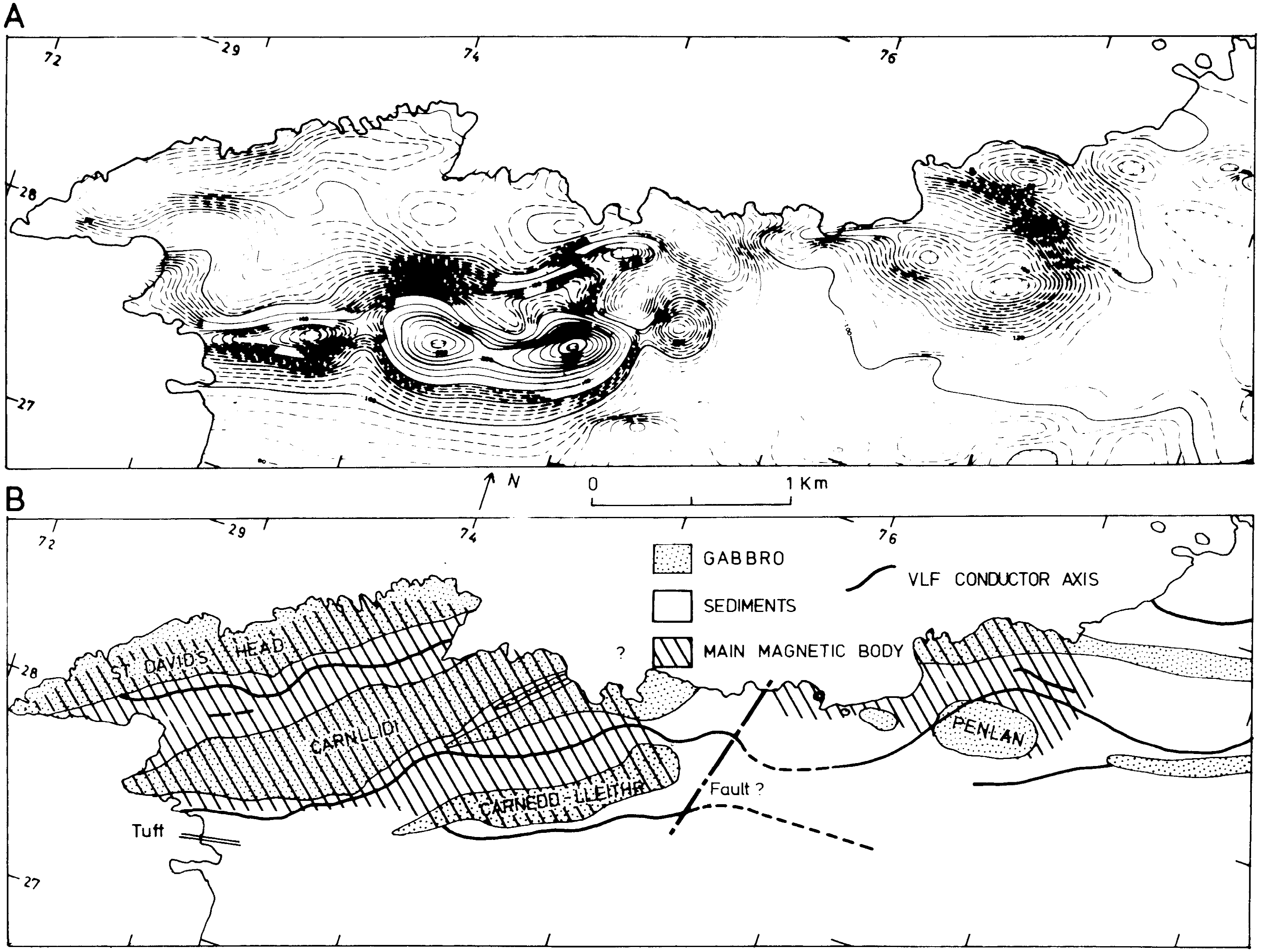

Figure 15 (A) Aeromagnetic map of the St David's Head area and (B) simplified geological map with some geophysical information

about 50 × 10^{-3} SI, (21 Appendix 1). In the same area spilitic lavas (18, 20, 22 to 24 Appendix 1) show both high and low susceptibility values and include the sample with the strongest remanent magnetisation measured (20 Appendix 2).

Zone 5b

This is a pronounced zone of large magnetic anomalies which is characterised by its clear correlation with the dolerite intrusions associated with the Fishguard Volcanic Group and by its unusually linear appearance. The latter feature is consistent with the fault-defined nature of the geological boundaries indicated by Lowman and Bloxham (1981) but at the eastern end the strike swings abruptly to a north to south trend (zone 5c). The maximum development of the anomalies appear on mapsheet SN 03 NW where the greatest thickness of dolerite has also been mapped (Lowman and Bloxham, 1981). There appear to be four magnetic dolerite horizons, the largest of which is the second from the north, (Figure 16). Magnetic measurements on the ground reveal more magnetic highs (Figure 17), but there does appear to be evidence for a long wavelength anomaly (Figure 17) representing the effect of a broad magnetic zone 700 m wide whose northward dip is consistent with the geological evidence. VLF anomalies in the area indicate conductive horizons striking parallel with the geological horizons and also to the ENE, the latter possibly representing a fault direction (Figure 16).

Ground magnetic measurements at a site at [980 377] (19 Appendix 3) revealed anomalies of up to 1800 nT amplitude and a sudden truncation of the main magnetic horizon.

Although the correlation of the magnetic anomalies with the mapped outcrop of the dolerite appears to be good, an inspection of part of the relevant outcrop area showed that basaltic pillow lavas were also present. These appear to be weakly magnetic (26 and 27 Appendix 1) although a nearby dolerite intrusion was strongly magnetic (28 Appendices 1 and 2). In the same general area, as elsewhere east of Fishguard, rocks belonging to the Fishguard Volcanic Group proved to be only weakly magnetic (25 and 29 Appendix 1).

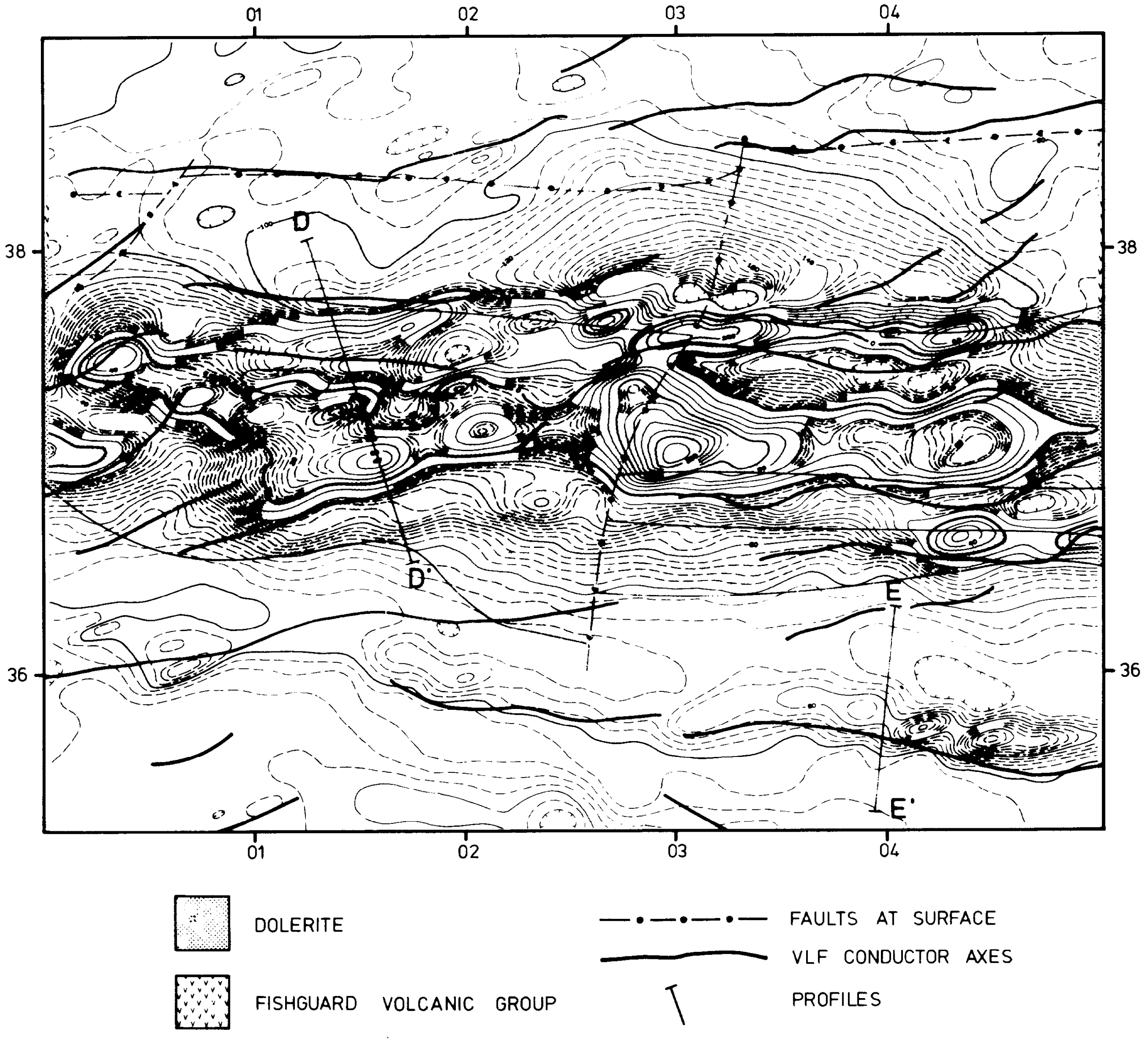

Figure 16 Aeromagnetic map of part of the Carningli Common area showing selected geological features and conductive horizons

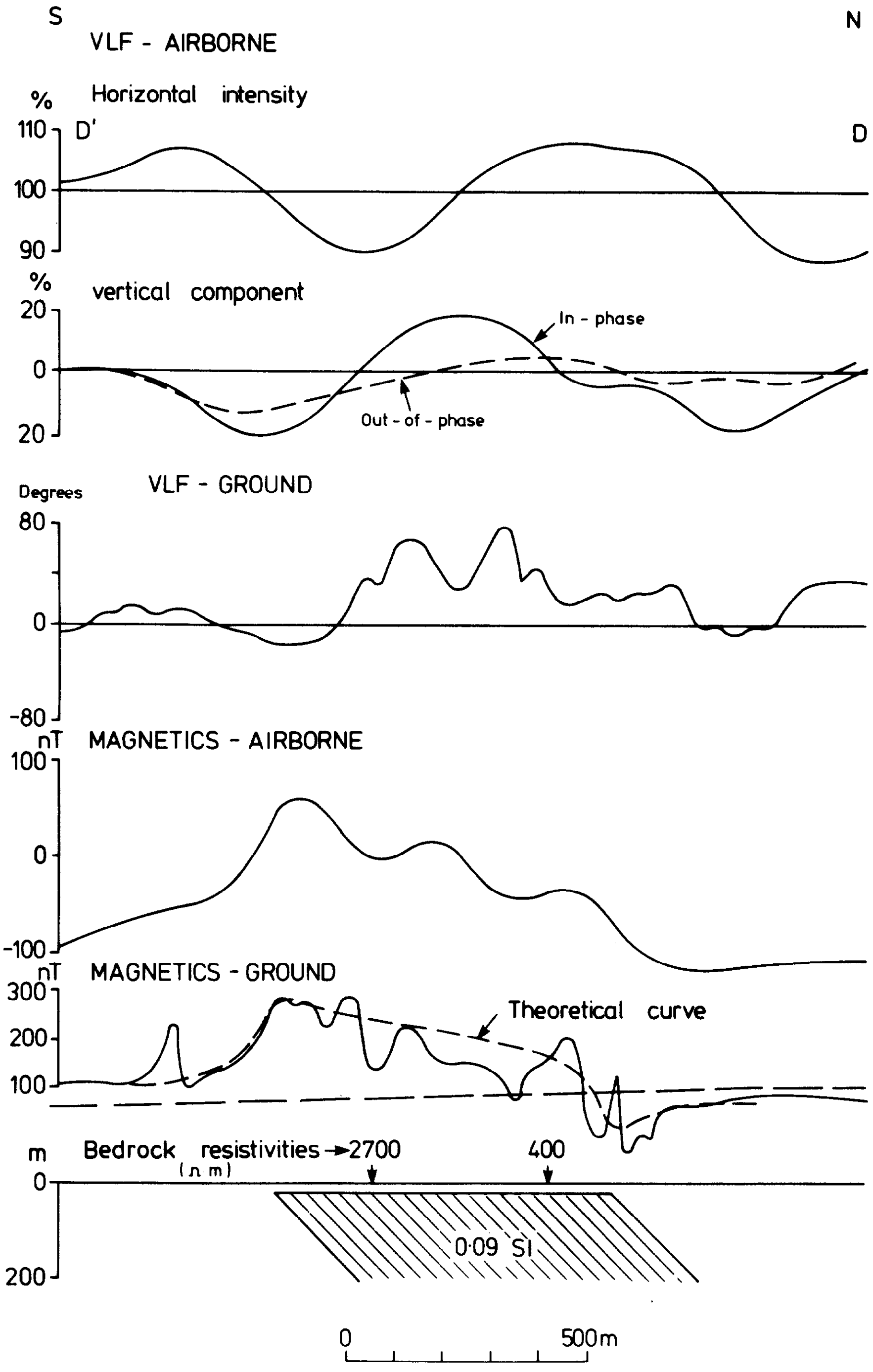

Figure 17 Airborne and ground geophysical profiles for traverse DD' (see Figure 16 for location) and resistivity results

The southern margin of zone 5b has been located along the comparatively weak but significant magnetic anomaly coinciding closely with the boundary between the *Tetragraptus* Shales and the *D. bifidus* Beds which is also marked in places by a dolerite intrusion. The anomaly is well developed at [045 356] (Figure 16) where it reaches an amplitude of 100 nT on the ground (Figure 18). Ground measurements at site 26 (Appendix 3) also confirmed the presence of associated EM anomalies recorded by the airborne survey (Figure 18) which are ascribed to the occurrence of conductive shale horizons. Dolerite has been mapped in this area but an examination was also made of the outcrops further to the west at Trenewydd [994 363] and locality 31 [021 360] (Appendix 1). At the former are tuffaceous brown mudstones while a fawn, banded turbiditic mudstone has been quarried at the latter. At locality 31 dips are 50° northwards and susceptibility values were about 0.4 × 10^{-3} SI. The mudstones are altered, probably by low temperature baking, and, noting that a doleritic sill was intruded at this horizon further to the east, it is suggested that the weak magnetic anomaly in this area is caused by this, or a similar doleritic intrusion, at a shallow depth below the present surface level.

Zone 5c

East of Grid line 08E the strong dolerite anomalies of zone 5b disappear and are replaced by weaker, less continuous anomalies with a different strike. The less well defined

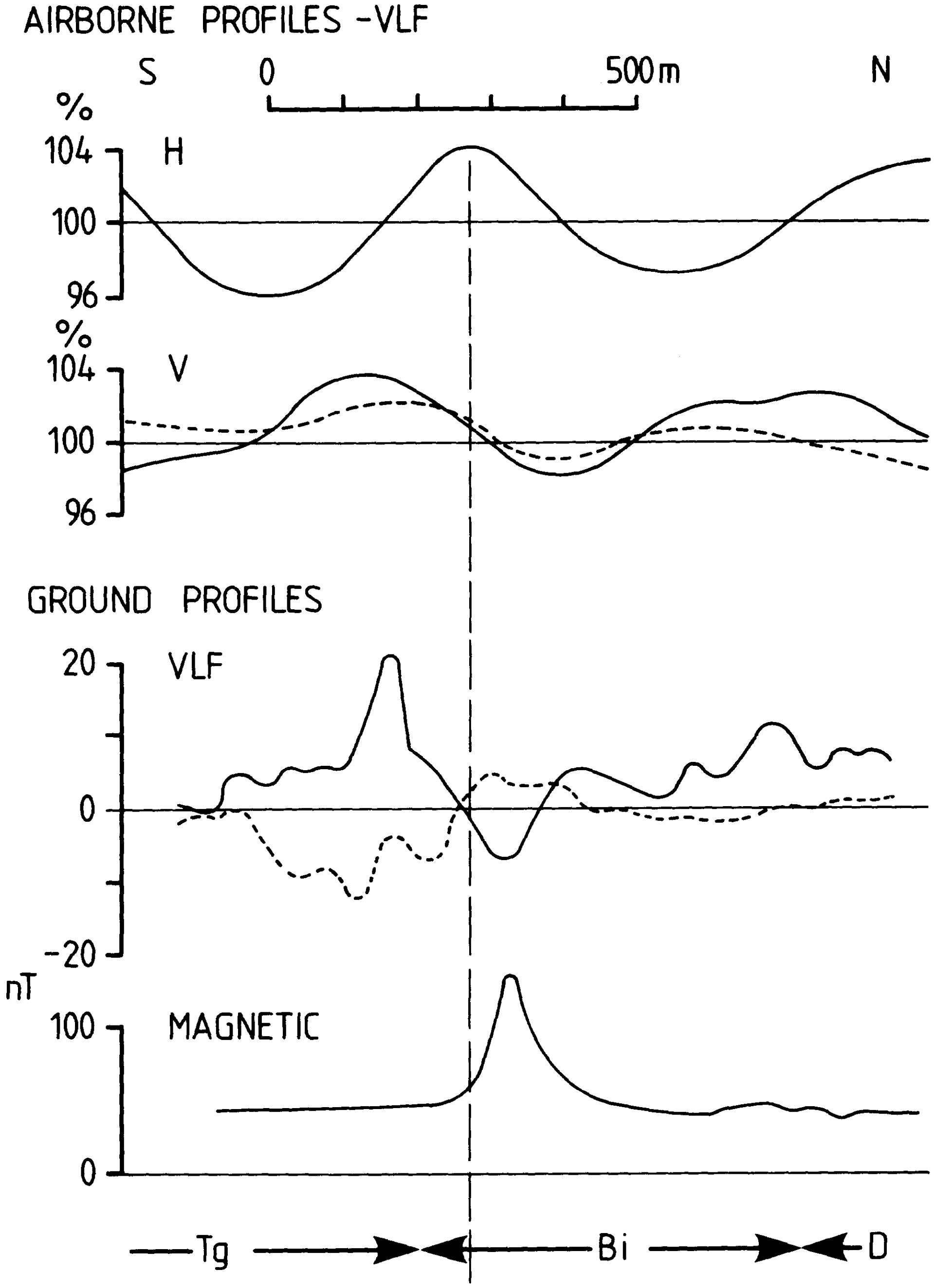

Figure 18 Airborne and ground geophysical profiles for traverse EE' (see Figure 16 for location and Figure 2 for geological symbols)

nature of the anomalies increases the difficulty in determining the boundaries of zone 5c and is due, in part at least, to the small angles between the flight lines and the anomaly strike. The abrupt change in the strike of the magnetic anomalies in this zone is a reflection of a similar change in the strike of the Fishguard Volcanic Group (cf. zone 7a and Figure 20).

A ground survey over the north-trending anomaly at [082 346] (25 Appendix 3) revealed a single magnetic horizon, at least 0.6 km long, with dips both to the east and west, causing a maximum anomaly of about 1000 nT.

The linearity of the magnetic anomaly passing through [07 34] suggested the presence of a fault but the ENE trend direction, commonly found to the south-west, has not previously been recorded in this area. A ground survey (24 Appendix 3) revealed a magnetic horizon, 60 m thick dipping at about 80° to the south-east and a coincident VLF anomaly at [077 344]. Further to the south-west the magnetic horizon appears to continue at depth.

Zone 6

The magnetic anomalies in this zone, as in zone 5, appear to be associated with dolerites intruded mainly into *D. bifidus* Beds and near the base of the Fishguard Volcanic Group, i.e. at comparable horizons to those responsible for the anomalies in zone 5. The anomalies are characterised however, by being negative, i.e. with values lower than the background field value, and therefore likely to be due to a strong remanent magnetisation. Reversely magnetised rocks are also characteristic of zone 7a and there appears, therefore, to be an approximately east to west boundary (Plate 1) between rocks characterised by normal and reverse magnetisations.

Three main explanations are possible for the geographical distribution of the two types of magnetisation: (1) the dolerites all carry a strong remanent magnetisation and the positive and negative anomalies are a result of two groups of geological dips, (2) the reversely magnetised dolerites have distinctive ferromagnetic minerals which have preserved a strong remanence or are capable of self-reversal, (3) one group of dolerites was re-magnetised at a later date.

There is no stratigraphic evidence for any distinction between the two groups and the few magnetic property data (e.g. 28 and 37 Appendix 2) do not indicate a strong remanent magnetisation for the rocks in the 'normal' group, thereby making the first possibility unlikely. The explanation might be associated with the distinctive petrological character of the Preseli Hills dolerites mentioned earlier. The boundary line between the two groups (Plate 1) coincides very approximately with the Brynberian Syncline but at the present time its true significance cannot be assessed.

Ground magnetic measurements were made at two sites to check the nature of these negative anomalies in areas where there was no interference from adjacent anomalies. At one site, Carnalw (31 Appendix 3), there are also strong anomalies on the airborne VLF maps but at the second site (30 Appendix 3) the VLF anomalies are weak. The presence of the negative anomalies and the difference in the VLF responses were confirmed at these sites and an example of a ground profile is shown in Figure 19. The negative anomaly on this profile at Carnalw is the largest for the area and coincides with a pronounced VLF 'cross-over' which can be traced over several traverses. There appears to be more than one conductor in this area, but the more localised feature at 250S (Figure 19) is probably associated with the magnetic material. The almost symmetrical negative magnetic anomaly indicates that the magnetisation vector must lie close to the plane of any sheet-like model but without any knowledge of the direction of magnetisation or the dip, an unambiguous interpretation is not possible. The dip

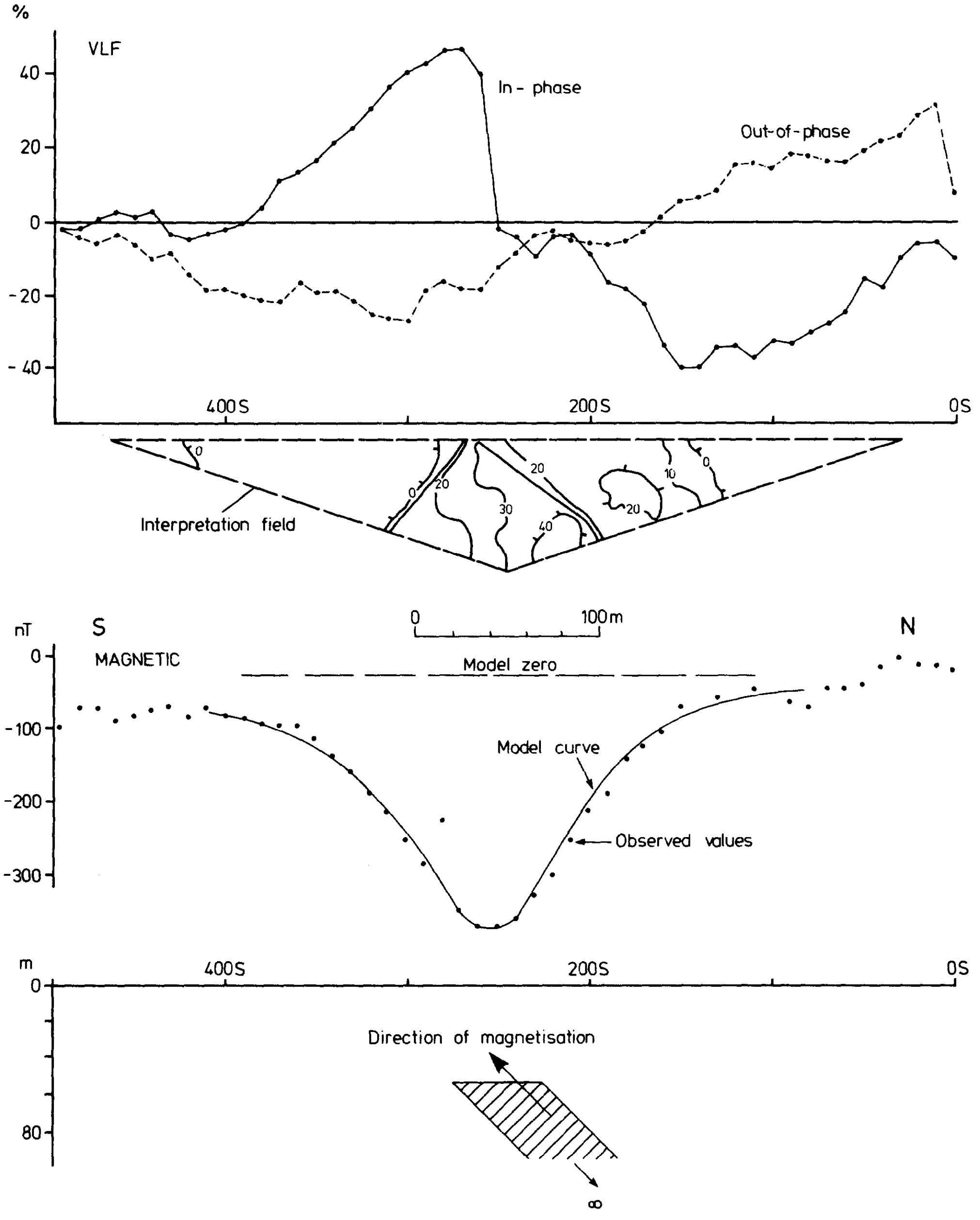

Figure 19 Ground VLF and magnetic profiles and interpretations for traverse 4, Carnalw (see text for explanation)

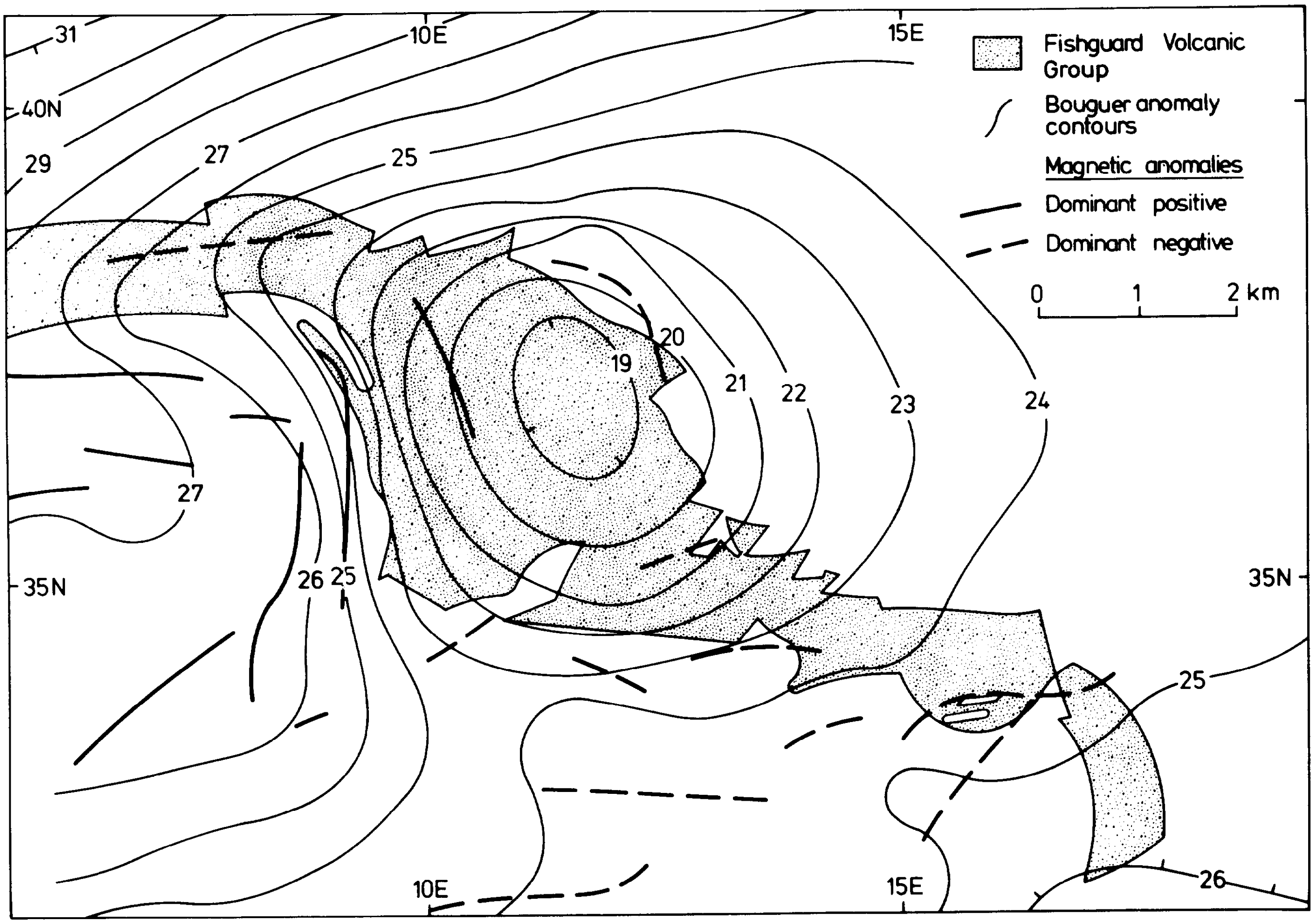

Figure 20 Bouguer anomaly map of the Crosswell area, outcrop of the Fishguard Volcanic Group and magnetic anomaly trends

shown for the magnetic model Figure 19 is based on that indicated by the interpretation of the VLF data (the 'interpretation fields' in Figures 19 and 21 show the current density derived according to the interpretation procedure of Karous and Hjelt (1983)). It seems likely that on this profile the magnetic body is itself conductive as well as some of the host rocks.

Figure 19 shows another characteristic of the negative anomalies in that they appear to be due to source rocks at depth, in this particular case at about 50 m below the ground surface. This is unlikely to be fortuitous in all cases and it is therefore suggested that the magnetic material has been destroyed by weathering down to this depth. The presence of pyrrhotite, rather than magnetite, is suggested both by its lower resistance to alteration and by the strong remanence indicated.

Magnetic anomalies at Cwm Garw (30 Appendix 3) occur just below the boundary between the *D. bifidus* Beds and the *Tetragraptus* Shales (c.f. locality 31 in zone 5b). No intrusive igneous rocks were observed in an examination of the ground, only grey ashy mudstone (locality 36 Appendix 3) in the mountain stream over the axis of the anomaly. A WNW-trending fault occurs just to the north and this has the effect of truncating the anomaly. Taking into account this fault and the change of strike of the strata across the fault, it is suggested that the anomaly is due to a basic concordant intrusion, perhaps concealed, following a horizon near the Sealyham Volcanic Group. This horizon must occur again at a very shallow depth on the north side of the fault just north of locality 36 and this could account for the east–west anomaly there.

A linear NE–SW magnetic anomaly through Carn Garn [1590 3275] and Carn Bwdcyn again approximates to the position of the boundary between the *D. bifidus* Beds and the *Tetragraptus* Shales. A doleritic intrusion occurs along the horizon at the north end of the anomaly, though on the ground this was not noticeably magnetic. South of this outcrop the Sealyham Volcanic Group is interposed between the *D. bifidus* Beds and the *Tetragraptus* Shales. It seems more likely that a concealed extension of the sill, rather than the thin Sealyham Volcanics, which appear generally to be very weakly magnetised, is the cause of the southwards continuation of the anomaly.

Samples of the east–west doleritic sill which crops out on the south flank of Foel Drygarn (locality 38 Appendix 1) also proved to be weakly magnetic.

Zones 7a–7c

Zones 7a to 7c are characterised by low amplitude, often broad negative anomalies dispersed between areas of low magnetic gradient. These zones are, therefore, intermediate in character between zone 3 (predominantly non-magnetic sediments) and zone 6, which also contains negative anomalies but of greater amplitude. The negative anomalies appear to be associated with both volcanic rocks and dolerite intrusions, or their adjacent host rocks, but the poor rock exposure in the area makes a more exact correlation difficult.

Zone 7a

This broad area of low magnetic gradient corresponds with the maximum development of the Fishguard

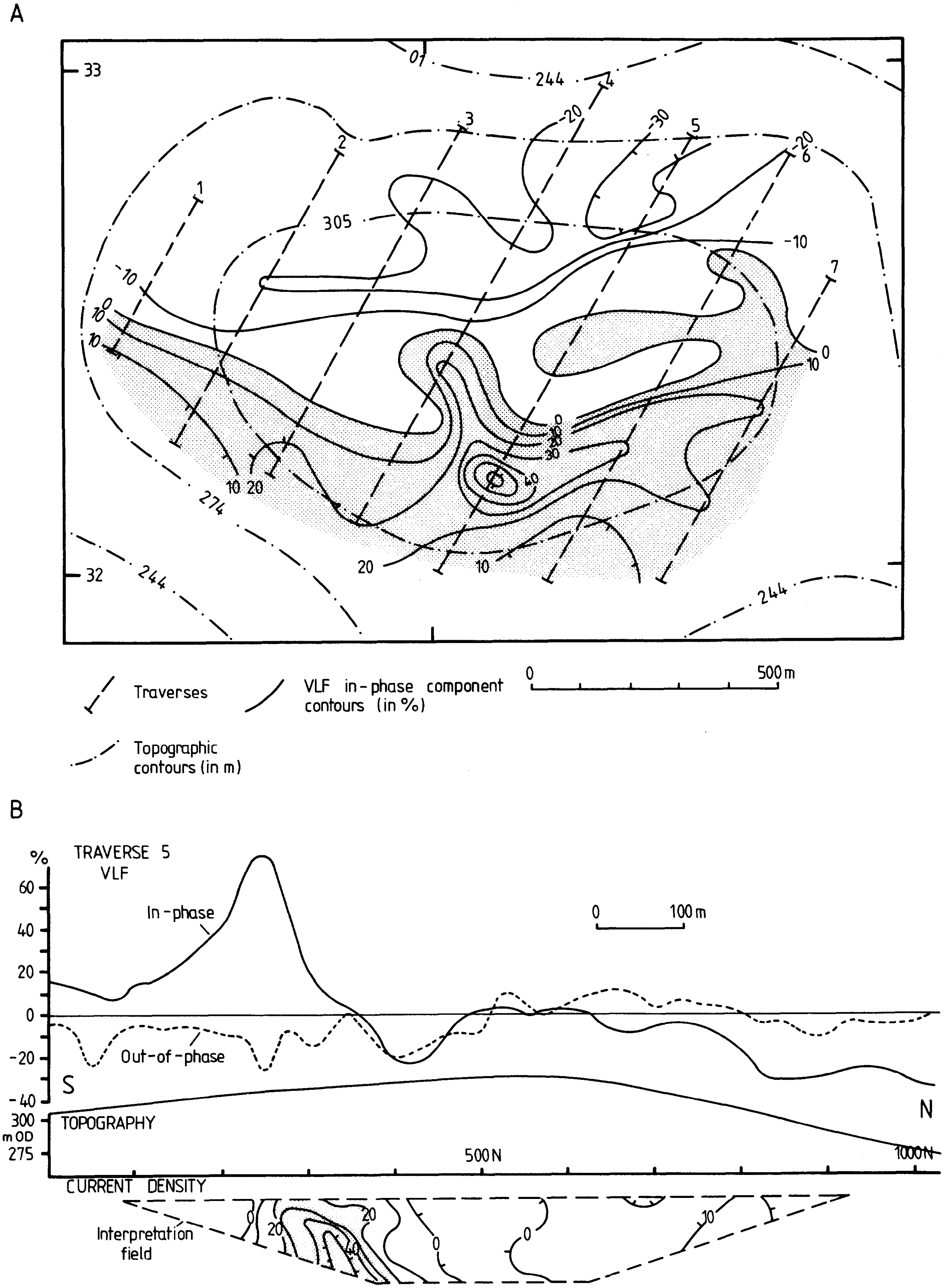

Figure 21 (A) Ground VLF-EM map (in-phase component) for the Mynydd Cilciffeth area and (B) profiles for traverse 5, with interpretation

Volcanic Group and is also marked by the presence of a pronounced circular Bouguer anomaly low (Figures 5 and 20). The northern and eastern margins of the volcanic rocks have been taken at a series of negative magnetic anomalies. These anomalies closely follow the strike of the rocks at the top of the Fishguard Volcanic Group but have no obvious cause; the volcanic rocks are non-magnetic except for some spilitic lavas (zone 5a), which were not extruded this far east, and there are no dolerite intrusions known at this horizon.

The Bouguer anomaly low centred at [12 37], ascribed by Griffiths and Gibb (1965) to a concealed granite, has been more accurately defined by recent BGS surveys and the contours are shown in Figure 20 superimposed on the outcrop of the Fishguard Volcanic Group. Several features of the Bouguer anomaly low are apparent from this map:

a) it is approximately circular but has steeper gradients to the north and west.
b) it is located over a particularly wide part of the outcrop of the volcanic rocks where they also attain maximum thickness.
c) it coincides with an area where the strike of the Fishguard Volcanic Group outcrop (and of the magnetic anomalies in Plate 1) changes direction.
d) it coincides with the line (Plate 4) which divides the magnetic anomalies with positive amplitudes from those with negative amplitudes.

The Bouguer anomaly low must in some way be related to the Fishguard Volcanic Group rocks but the thickness of low density material needed to cause the 8 mGal anomaly is at least 1.9 km, assuming a density contrast of -0.10 Mg/m^3, far in excess of the maximum thickness in the area of 0.21 km estimated for the group (Evans 1945). Although measured densities of the Lower Palaeozoic sediments (2.70–2.75 Mg/m^3) and the acid intrusives or extrusives (2.65 Mg/m^3) indicate that this contrast is reasonable, the form of the Bouguer anomaly seems to require a larger contrast for the interpretation to be accurate.

Two geological interpretations are possible; one is that a synbasinal body of volcanic material underlies the Fishguard Volcanic Group at this point (as suggested by Harrison, in discussion to Evans, 1945) and the second is that the volcanic rocks overlie a granite boss. In either case the low density body must be assymetrical, with steeper margins to the west. Additional gravity data are required to enable a choice to be made between the two models (basically an upright or an inverted cone). Interest in determining the origin of the gravity feature has been increased by the discovery in a regional geochemical survey (Cameron and others, 1984) of high Ba, Cu, Pb and Zn values, perhaps associated with volcanogenic mineralisation.

Ground surveys were made in two areas within zone 7a to check the existence of negative magnetic anomalies at [123 377] (area 33 Appendix 3) and [091 373] (28 Appendix 3). Their existence was demonstrated in the former area but no VLF anomaly corresponding to a pronounced airborne VLF feature at [126 376] was located. The southern end of the magnetic anomaly overlies an outcrop of the black *D. murchisoni* Beds. These were examined near the bend in the Afon Nevern where the anomaly is strong. In a field on the left bank [1223 3735] and in the steep right bank [1227 3751], susceptibility values of 1 to 2 × 10^{-3} SI were obtained but in other exposures to the north-west the black shales gave much lower readings, as did rocks of the underlying Fishguard Volcanic Group to the west. An examination of the outcrops near geophysical area 28 revealed the presence of metamorphosed dolerite (locality 33 Appendix 1) and acid volcanic rocks, both of which proved to be weakly magnetic (?0.1 and 0.5 × 10^{-3} SI, respectively). The interstitial opaque oxides in the dolerite have been replaced by granular sphene. No definite explanation for the magnetic anomaly can therefore be offered other than that it has a strata-bound origin, and is possibly caused by selective metamorphism of pyritous mudstone (? due to the source of the Bouguer anomaly low in this area), or a basic intrusion.

Zone 7b

This broad area includes a series of negative anomalies which tend to decrease in amplitude westwards until they disappear altogether along the line of the linear anomaly forming zone 8. A negative magnetic anomaly around [022 295] occurs within the line of zone 8 but could represent a feature at the western end of zone 7b.

The negative anomalies coincide at various places with outcrops of the Sealyham Volcanic Series, as at [08 29], and with dolerite intrusions [08 31]. Many of the anomalies suggest that the rocks responsible lie at depth; a feature at [065 300], for example, indicates a depth of about 0.4 km below the ground surface.

Two parallel magnetic anomalies at [085 313] indicate a significant increase in depth eastwards for the causative bodies. The anomalies are concordant with the strike of the rocks in the area and fit closely with the outcrops of two sill-like dolerite intrusions, although visual evidence of these rocks is sparse.

In the Afon Sygwy [0817 3153] exposures of the northerly 'sill' coincide with the positions of the outcrop as indicated by the magnetic evidence and gave low susceptibility values of 0.5 and 0.6 × 10^{-3} SI. An apparently separate body of dolerite is visible lower in the stream [0808 3137] which, when originally mapped, was probably considered part of the northerly sill. Exposure of altered mudstone is much more common; spotted mudstone being visible by the ford [0806 3153] giving susceptibility values of 0.5, 0.8 and 0.5 × 10^{-3} SI. It seems possible that this northerly of the two sills is in fact a composite of several doleritic intrusions within a thickness of altered mudstone. The southern intrusion crosses the stream near [0810 3105] but only altered mudstone was seen, which gave susceptibility values of about 0.6 × 10^{-3} SI.

A ground VLF survey at Mynydd Cilciffeth (22, Appendix 3) in an area of moderately sized airborne VLF anomalies near the boundary with zone 3b revealed a regular anomaly pattern indicating a conductor following the crest of the gentle hill top and a larger amplitude, more localised conductor on traverse 5 (Figure 21). Topographic effects contribute to the longer wavelength anomaly but it is probable that the sharp anomaly shown in Figure 21B is due to the resistivity contrast between the *D. bifidus* Beds and dolerite intrusions.

Zone 7c

Separated from the other negative magnetic anomalies of zones 6 and 7 by non-magnetic sediments (zone 3c), the anomalies in zone 7c are distinguished by their pronounced elongation and the presence in several places of flanking positive anomalies on the northern sides. The WSW elongation of the anomalies runs parallel with the

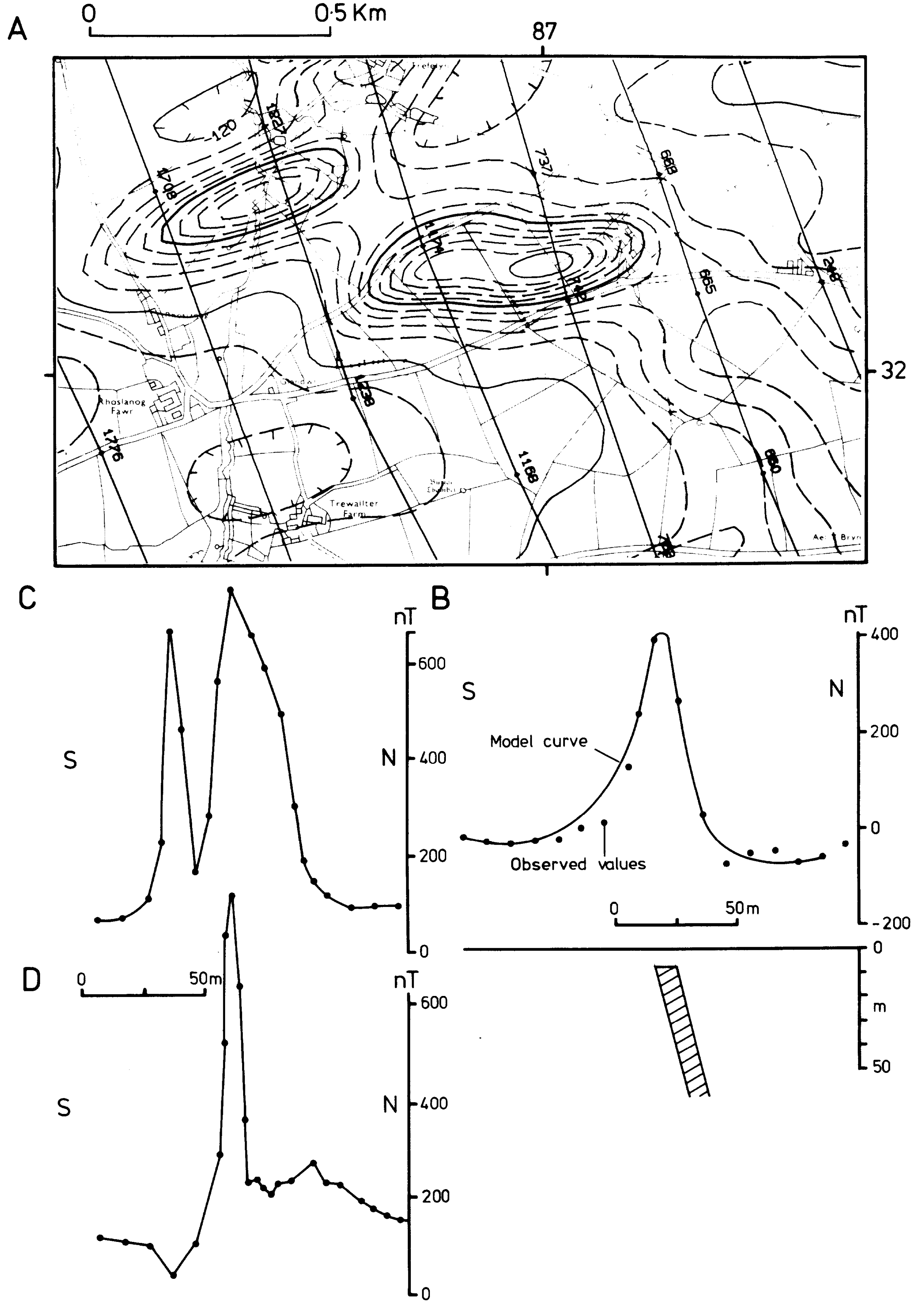

Figure 22 (A) Aeromagnetic map for the Mathry area and ground magnetic profiles from (B) Mathry (with model), and (C) (D) Tirbach (SN 104 260)

strike of the doleritic intrusions in the area (there are no volcanic rocks in zone 7c), but the combination of negative and positive anomalies implies an in-situ direction of magnetisation different from those in other related zones.

Zone 8

One of the most extensive magnetic anomalies in the airborne survey area is a narrow positive feature trending in a WNW direction from the boundary of the area at [117 257]. There are no recognised outcrops of a rock-type capable of producing this anomaly but its length, its narrowness and the fact that its trend is oblique to the general strike of the strata indicated the presence of a dyke. Recent drilling has confirmed this (Cave and others, 1987 in preparation), and further geophysical work has proved its continuation outside the airborne survey area, indicating a total strike length of at least 40 km.

Although the dyke is a relatively minor feaure it is of significance to the structural history of the area. Its presence has not hitherto been recorded and there are no features in this part of the Dyfed with a similar WNW trend. This trend, however, is dominant in the Hercynian structure, particularly along the southern margin of the South Wales Coalfield, and, although north of this, the dyke is considered to be associated with these Hercynian movements rather than the earlier Caledonian earth movements which have been affected most of Wales north of the South Wales Coalfield.

The general trend of the dyke is about 70° to 75° west of north but between [960 288] and [004 286] the dyke runs due west and there are several places where it is interrupted and apparently displaced laterally or vertically. Both types of displacement occur near Mathry (Figure 22A), where a ground magnetic survey accurately located the position of the dyke for a drilling site.

At the other extremity of the dyke anomaly, ground magnetic measurements at Tirbach Farm [105 261] (site 29 Appendix 3) revealed two separate anomalies on one profile (Figure 22C). The larger of the two anomalies had disappeared on the adjacent traverse 100 m away (Figure 22D) and the remaining anomaly, indicating a narrow but strongly magnetised dyke, continued through the survey area. A search for outcrops at this site revealed only loose blocks of metamorphosed dolerite and an epidote quartz rock (34 and 35 Appendix 1). A subsequent drillhole, however, proved a dolerite dyke some 15 m wide (if vertical) beneath 1.5 m of drift and within Ordovician shale.

General comments

The preceding descriptions of the geophysical survey results indicate that the sources of most of the main anomalies can be explained in geological terms, although in several areas more specific investigations are required to provide complete interpretations. The broad pattern of geophysical anomalies, summarised in Plate 1, agrees with the previously accepted concepts of the geology but the geophysical data indicate local deviations from the mapped geological boundaries, as might be expected in a largely drift-covered area. Further information of interest to local lithostratigraphical mapping could be extracted from a study of the 1:10 000-scale geophysical maps and in particular no attempt has been made at systematic interpretation of dips from the aeromagnetic results, although this would undoubtedly be of value. The present survey has demonstrated the considerable increase in the amount of information of use for geological mapping available from a low-level, close line-spaced survey compared with that available from the national aeromagnetic average flown at 305 m.

The instrumentation for the airborne survey was selected to provide a good general indication of the geological structure and there are no obvious anomalies which can be ascribed to mineralisation. Any mineralisation in the form of massive sulphides might produce VLF anomalies but most of the latter appear to be related to stratigraphic conductors, such as shale horizons, particularly at the contacts with dolerites, with a few anomalies ascribed to fault zones. Using both the VLF and the magnetic data numerous faults have been postulated (Plate 1) and these frequently show a northeast or NNE trend. The postulated dyke (zone 8) could also occupy a major fracture or boundary zone for it also forms the SSW margin of the area of dolerite intrusions. A distinction between areas of positively and negatively magnetised ?intrusions is clear, and, while a complete explanation is not available, it may mean that they indicate areas with different geological histories. It is suggested that pyrrhotite may be responsible for the reversely magnetised anomalies; and it is possible that this mineral might be associated with other sulphides of greater economic interest.

The gravity survey has confirmed the existence of three distinct gravity lows; the new data indicate that the low over the Hayscastle Anticline is due to a quartz-porphyry intrusion with the strong possibility that the St David's Anticline anomaly has a similar explanation. The low at [115 370] is of particular interest for it indicates either a concealed granite or a feeder plug for the Fishguard Volcanic Group.

CONCLUSIONS

The airborne geophysical survey of part of west Dyfed has been successful in achieving the main objective of providing information of value to the general understanding of the geology. This information is valuable to any future mineral exploration programme as the extensive drift cover of the area limits the amount of conventional geological mapping possible. Ground surveys have been used to establish the cause of the main geophysical anomalies.

The aeromagnetic data clearly outline areas of Precambrian rocks and give some indication of their extent at depth. Dolerites, largely intruded conformably with the sediments, can be traced across the entire area, although there is a distinct change in their magnetic character from north to south. Pillow lavas west of Fishguard are sometimes highly magnetic but volcanic rocks of the Fishguard, Sealyham and Trefgarne volcanic groups generally contain little or no magnetite.

The VLF data indicate the presence of many conductive horizons, most of which appear to be within the Lower Palaeozoic sediments. The margins of igneous rocks are frequently well defined by VLF anomalies because of the large resistivity contrast these rocks have with the sedimentary host rocks.

The airborne radiometric survey failed to indicate extensive anomalies of use for mapping purposes.

An attempt has been made to locate recognisable 'marker' horizons based on the geophysical data but a great deal more information could be extracted for detailed surveys of more restricted areas. Several major structural features can be recognised, including a previously unknown dyke at least 40 km long.

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Appendix 1 List of rock samples examined petrographically (by R. J. Merriman). Localities shown in Plate 1.

Locality	Grid refernce	Rock type	Age*	Susceptibility of hand sample ($\times 10^{-3}$ SI units)
1	SM 7320 2860	Quartz gabbro	O	1.0
2	SM 7966 3164	Metamorphosed dolerite	O	Low (i.e. <0.3)
3	SM 8343 2906	Soda-rhyolite	PC	0.8
4	SM 8478 2886	Hornblende-andesite	PC	7.0
5	SM 8601 2897	Hornblende-diorite	PC	35.0
6	SM 8902 2542	Tuff	PC	35.0
7	SM 8914 2367	Lapilli Tuff	PC	Up to 100
8	SM 8914 2367	Vitric Tuff	PC	
9	SM 8922 2367	Vitric Tuff	PC	1.2
10	SM 8924 2361	Crystal Tuff	PC	10
		Lapilli Tuff	PC	12
12	SM 9120 3988	Metamorphosed dolerite	O	
12a	SM 9137 3992	Metamorphosed dolerite		Up to 20
13	SM 9263 4008	Metamorphosed dolerite	O	
14	SM 9275 4006	Spilitic lava	O	
15	SM 9275 4003	Spilitic lava	O	17
16	SM 9377 4030	Metamorphosed diorite	O	0.4
17	SM 9389 4044	Metamorphosed diorite	O	1.0
17a	SM 9393 4040	Metamorphosed diorite	O	40
18	SM 9413 3898	Spilitic lava	O	
19	SM 9413 3898	Jasper	O	
20	SM 9413 3895	Spilitic lava	O	80
21	SM 9419 3898	Keratophyre	O	50
22	SM 9442 3974	Spilitic lava	O	1.2
23	SM 9442 3974	Spilitic lava	O	20
24	SM 9442 3974	Spilitic lava	O	20
25	SM 9790 3763	Soda-rhyolite	O	Low
26	SM 8915 3752	Oligoclase basalt	O	Low
27	SM 8915 3752	Vesicular glass	O	Low
28	SM 9841 3758	Metamorphosed dolerite	O	39
29	SM 9910 3766	Quartz-keratophyre	O	Low
30	SM 9817 3773	Metamorphosed dolerite	O	
31	SM 0211 3599	Semi-pelite	O	
32	SM 0501 3236	Tuff	O	0.8
33	SM 0934 3729	Metamorphosed dolerite	O	0.3
34	SM 1060 2598	Epidote-quartz rock	C	
35	SM 1060 2598	Metamorphosed dolerite	C	
36	SM 1115 3127	Cleaved mudstone	O	0.8
37	SM 1561 3352	Metamorphosed rhyodacite or dacite	O	0.7
38	SM 1562 3340	Metamorphosed dolerite	O	0.8
39	SM 0817 3153	Metamorphosed dolerite	O	

Age* PC Precambrian C Cambrian O Ordovician

Appendix 2 Physical properties of some samples from west Dyfed

Locality[1]	Zone[2]	Rock type	Density (Mg/m^3)		Porosity (%)	No. of Specimens	Magnetic properties			Curie temperatures (°C)
			Saturated	Grain			Susceptibility (SI × 10^{-3})	Remanance intensity A/m	Q-value[3]	
1	4	Quartz gabbro	2.84	2.86	0.9	3	1.42	0.02	0.29	550* 630-660
5	1b	Hornblende-diorite	2.83	2.84	0.7	1	38.15	0.17	0.11	560
6	2a	Crystal tuff				1	36.12	0.20	0.14	570
10	2a	Crystal tuff	2.70	2.71	0.5	2	14.89	0.36	0.62	565 590-620
15	5a	Spilitic lava	2.84	2.88	2.1	2	16.67	0.08	0.12	630*
20	5a	Spilitic lava	2.78	2.79	0.7	2	87.63	1.73	0.50	630* 590 ?670
21	5a	Keratophyre	2.80	2.82	0.6	2	12.52	0.13	0.26	150-200* 565
28	5b	Dolerite	2.91	2.92	0.7	2	55.28	0.46	0.21	580
32	7b	Cleaved tuff	2.64	2.78	7.8	2	0.75	0.0002	0.01	
36	6	Cleaved mudstone	2.56	2.78	2.1	1	0.80	0.0002	0.00	None
37	6	Dacite	2.77	2.77	0.0	2	0.67	0.002	0.08	?510*
38	6	Dolerite	2.94	2.94	0.2	1	0.78	0.001	0.03	None
39	3c	Mudstone	2.63	2.77	8.0	1	0.73	0.0003	0.01	
40		Graptolitic Shale				2	1.86	0.001	0.02	580

[1] c.f. Appendix 1 [2] c.f. Table 1 [3] Q = Remanent magnetisation/induced magnetisation

* Not repeated on cooling curve

Appendix 3 List of ground survey areas

Area number	Grid reference	Name	Number of traverses	Total line km	Method*
1	720 235	Treginnis-isaf	7	5.2	MV
2	728 254	Rhosson Ganol	5	1.5	M
3	731 262	Upper Treleddyn	5	1.8	M
4	735 281	St David's Head	5	4.0	MV
5	796 264	St David's Airfield	1	0.6	V
6	771 268	Dowrog Common	7	2.7	M
7	756 286	Llanferran	4	3.0	M
8	769 292	Penberry	3	2.0	M
9	866 313	Trefelyn	7	1.9	M
10	937 260	Carmina	10	5.2	MV
11	910 347	Moel Ddu	5	2.3	MV
12	908 353	Carn-llys	2	0.9	M
13	942 363	Tre-groes	2	1.0	MV
14	906 380	Llandruidion	3	1.0	M
15	910 392	Garn Folch	2	2.5	M
16	920 400	Tre-howel	5	3.3	MV
17	979 282	Whitehall	3	0.7	V
18	989 293	Martel	4	1.5	V
19	980 377	Carn Fran	4	2.2	MV
20	059 241	Forehill	5	2.5	V
21	059 260	New Moat	5	3.0	V
22	012 324	Mynydd Cilciffeth	7	5.6	V
23	070 322	Waun-maes	5	3.7	V
24	072 341	Gernos	7	2.5	MV
25	082 346	Waun-mawn	4	2.3	MV
26	039 358	Penlanisaf	2	2.2	MV
27	030 371	Parc Mawr	3	5.3	MVR
28	092 370	Ty-canol	5	2.6	M
29	105 261	Tirbach	6	1.2	M
30	114 317	Cwm-Garw	6	2.9	MV
31	138 341	Carnalw	6	3.2	MV
32	161 337	Foeldrygarn	7	4.9	MV
33	124 374	Babylon	7	3.2	MV

* Methods: M-magnetics, V-VLF, R-resistivity

Appendix 4 Results of resistivity depth soundings

No.	Site NGR	**Layer 1** Resistivity (Ωm)	Thickness (m)	**Layer 2** Resistivity (Ωm)	Thickness (m)
1	016 375	900	1.8	390	
2	017 372	5700	2.9	2440 (N-S array)	
3	017 372	6900	2.5	2950 (E-W array)	
4	040 370	4200	2.2	1300	
5	053 376	2000	1.8	200	9.2
			Layer 3 resistivity 670		
6	126 376	470	4.5	870	
7	123 369	1150	1.5	1400	
8	743 279	7600	1.1	2500	
9	743 284	7800	2.1	2600	3.2
			Layer 3 resistivity 7800		

PLATE 1

BRITISH GEOLOGICAL SURVEY

Regional Geophysics Research Group

AIRBORNE GEOPHYSICAL SURVEY
OF
PART OF WEST DYFED

GENERAL COMPILATION MAP