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Potential for mesothermal gold and VMS deposits in the Lower Palaeozoic Welsh Basin

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Cover photograph
Early Silurian mudstones on the south-eastern limb of the Rhiwnant Anticline, Craig Llannerch-y-cawr, Claerwen valley, Powys, mid Wales.
BGS Photo MN32311.

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SUMMARY

The principal aim of the work described in this report was to determine areas within the Lower Palaeozoic Welsh Basin that are favourable for the occurrence of mesothermal turbidite-hosted gold and volcanogenic massive sulphide (VMS) deposits. These types were chosen because of the perceived potential for undiscovered deposits and the likelihood that they would form high-value deposits that could be worked economically with minimal environmental impact.

Favourable areas were determined by the application of computer-based prospectivity analysis using available regional digital datasets. The principal datasets used were (1) the 1:250 000 scale geological mapping, (2) chemical analyses of stream sediments collected across the whole area and panned stream sediments collected over part of the area at a similar density, (3) airborne magnetic survey results, (4) gravity measurements, (5) gold occurrences in alluvium and bedrock, (6) sites of metalliferous mineral workings and (7) structural features principally faults, major fold axes and linear features abstracted from processed geophysical data and satellite imagery. Datasets of specific environmental constraints (National Parks, Areas of Outstanding Natural Beauty, Sites of Special Scientific Interest, Nature Reserves) were also available and used to inform on the overall favourability of prospective areas defined by geological parameters.

Models and descriptions of mesothermal turbidite-hosted gold and VMS deposits were studied, and exploration criteria common to most deposits were abstracted. Particular account was taken of features found in known deposits in the Welsh Basin, principally at Ogofau and near Dolgellau (mesothermal gold) and at Parys Mountain and Cae Coch (VMS). Available datasets for the Welsh Basin were then analysed in relation to the key exploration parameters identified from the models. These were then combined, each with its own weight, style and zone of influence in relation to the occurrence pixel. A Boolean data model was used to integrate the quantified spatial relationships into a prospectivity map showing the distribution of relative favourability for the occurrence of the specified type of mineral deposit. This method, using soundly-based predictive deposit models combined with computer-based data-integration techniques, allows a fresh approach to estimating mineral potential and ranking prospective areas that maximises the use of the many relevant datasets now available.

The favourable areas identified for mesothermal turbidite-hosted gold include several areas where previous exploration or mining has shown the presence of gold. Besides the area of the Ogofau gold mine and the Dolgellau Gold Belt, these include the northern side of the Harlech Dome, the north-western side of the Berwyn Dome, the Rhiwnant Dome and central Pembrokeshire. Northern Anglesey is also known to contain gold mineralisation but did not show as prospective in this analysis. This is largely because key exploration features (mudstones and structures) recorded in detailed maps and reports were not present in the regional-scale datasets used. Areas identified in this report as prospective for this type of mineralisation but where there is no substantial record of gold mineralisation included north-east Snowdonia (Dolgarrog), parts of mid-Wales (Tal-y-Bont–Llandiloes, Tywyn–Dinas Mawddwy) and the Builth Wells area.

There appear to be good prospects for finding further mesothermal gold mineralisation in parts of the Welsh Basin which have not been previously worked for the metal. The most prospective ground appears to be around northern margin of the Harlech Dome, the north-western part of the Berwyn Dome, the Dolgarrog area, the Rhiwnant Dome and parts of south-west Wales. In all of these areas knowledge of the bedrock mineralisation is limited and further work is recommended to determine the likelihood of an

economically viable source being present, concentrating on those areas with the fewest environmental constraints.

Prospective areas for VMS mineralisation in the Welsh Basin contain submarine volcano-sedimentary successions at three stratigraphic levels: Llanvirn, Caradoc and Llandovery. The potential for VMS deposits in the basin has, however, been reduced by the recent finding that the volcanic rocks associated with the only significant known VMS deposit, at Parys Mountain, are of Llandovery rather than Caradoc age. This is because the only other substantial volcanic centre of Llandovery age and its products, the Skomer Volcanic Group, does not have many of the key features associated with this type of mineralisation. However, potential does exist in the Llanvirn volcanic rocks around the Harlech Dome and, to lesser extent, in south-west Wales. Caradocian volcanic rocks in Snowdonia and the Shelve area also have potential. Except for the Shelve area and the area around the Parys Mountain deposit, all the areas with VMS potential lie within or close to significant environmental constraints. This means that a clear national need would have to be demonstrated before permission to mine was granted and restrictions on any development would probably be harsh.

The potential for SEDEX-type mineralisation should also be examined, as data collected for the VMS mineralisation analysis suggests that areas of potential for SEDEX deposits may occur at similar stratigraphical levels in areas where environmental constraints are less stringent.

The degree of confidence that can be placed in the prospectivity maps depends on the accuracy of the model, in terms of its applicability to the Welsh Basin and the availability of necessary data of sufficient quality. More detailed prospectivity mapping is warranted, as additional detailed datasets become available, in areas where potential has been identified by this regional study. These data include 1:50000 to 1:10000 scale geological mapping, geochemical data from grid and traverse-based soil sampling and ground survey geophysical data. Some of the data highlighted in this regional study were also collected at sufficient density to be useable at larger scales, for example stream sediment analyses and thematic mapper interpretations and digital airborne data.

INTRODUCTION

The objective of the work reported here was to provide regional-scale maps that identified areas favourable for the occurrence of selected types of mineral deposit in the Lower Palaeozoic rocks of the Welsh Basin. This would be achieved by using knowledge-based prospectivity analysis software. The work involved identifying key exploration criteria for the chosen deposit mineral types, assembling digital datasets that would provide information on these criteria and integrating them using Boolean or Fuzzy logic data models to produce mineral potential (prospectivity) maps.

This method is particularly useful when, as in the Welsh Basin, a large number of datasets are available for integration and analysis. In this situation traditional exploration methods of visual inspection and transparent overlays are impractical, particularly if an unbiased result is required. The knowledge-based analysis system used allows the exploration geologist to determine the relative significance of the exploration data and then search for patterns which reflect the total effect of such significance. In practice this means selecting which data layers to use in the analysis and deciding the relative weight and pattern of influence that is assigned to each data layer.

The principal styles of mineralisation chosen for evaluation were mesothermal turbidite-hosted gold and volcanogenic massive sulphide deposits. These were chosen on the basis of the perceived potential for undiscovered deposits of this type in Wales, and their potential to form high-value deposits that could be worked economically while minimising the short and long-term environmental impact.

The rocks of the of the Welsh Basin occupy the greater part of Wales, overlying younger rocks being confined to parts of the north, east and south (Figures 1 and 2). Because of the convenience of retrieving information from databases using rectangles defined by British National Grid coordinates, information was collected and integrated from an area bounded by National Grid coordinates ^{1}70000 and ^{4}00000 east and ^{1}60000 and ^{4}20000 north. Although this area includes most of Wales and the Welsh borderlands (Figure 1) the current study did not extend to evaluating the prospectivity of ground lying outside the outcrop of the Lower Palaeozoic rocks deposited in the basin. This would have involved consideration and application of a much larger number of metallogenic models including, for example MVT (Mississippi Valley Type) and SCDs (Sediment-hosted Copper Deposits). Some late Precambrian rocks were included in this appraisal because of apparent similarity or continuity with overlying Lower Palaeozoic basinal successions, and/or their postulated Precambrian age is in doubt. The Lower Palaeozoic rocks of Anglesey are also included, although at the time of deposition their geographic position with respect to the principal area was almost certainly different to that of today, due to transverse movement along major north-east trending fractures.

Mining and exploration history

Metalliferous minerals have been extracted intermittently from the rocks of the Welsh Basin since pre-Roman times. The principal worked deposits (Figure 3) include stratabound iron and manganese, volcanogenic massive sulphide (VMS), mesothermal gold and base metal vein-style mineralisation (Colman et al., 1996). They include the Parys Mountain VMS deposit on Anglesey, which has produced over 130 000 tonnes of copper metal since its discovery in 1768, and the gold-bearing polymetallic veins of the Dolgellau Gold Belt. These have yielded 90% of Britain’s recorded gold production (c. 4 tonnes), mainly from the Clogau St Davids and Gwynfynydd mines. The other principal gold producer, the Ogofau mine, near Pumsaint in mid-Wales, was reputedly worked by the Romans and is a typical turbidite-hosted slate-belt deposit of Caledonian age. There has been notable production of lead and zinc from mines exploiting vein-style mineralisation in the basinal succession, notably in the Llanrwst area, which ended with the closure of the Parc mine in 1962, and the Central Wales mining district. These metals and baryte were also produced from veins in Precambrian to Ordovician rocks at the basin margin in the Shelve area of Shropshire. A number of small copper mines worked veins associated with the Ordovician caldera, on whose northern rim Snowdon stands, and on the Lleyn Peninsula where lead, zinc, copper and baryte were produced from veins. Stratabound manganese was worked from the Cambrian succession of the Harlech Dome and Ordovician rocks on the Lleyn Peninsula. Iron ore was extracted on a small scale from the Ordovician succession at several localities in North Wales.

Apart from Parys Mountain, which flourished from 1768 to about 1820, the main period of metalliferous mining activity in the area was the mid nineteenth century. Exhaustion of the mines, low metal prices and competition from imports led to the collapse of the lead mining industry at the end of the century with only a few zinc mines maintaining production. The small massive pyrite deposit at Cae Coch, near Llanrwst, was re-exploited as a domestic source of sulphur during the First World War.

There was a resurgence of exploration interest in North Wales during the late 1960s and early 1970s following the discovery by RTZ of the Coed-y-Brenin porphyry copper deposit north of Dolgellau in 1966. The deposit proved too small and low grade (300 million tons at 0.3% Cu (Pattrick and Polya, 1993)) to work in such an environmentally sensitive area. However, a number of companies, including Phelps Dodge, Noranda, Amax and Cominco, took up areas and carried out reconnaissance exploration for base metals. Much of this exploration was carried out with financial assistance under the Mineral Exploration and Investment Grants Act 1972 (MEIGA) and the information generated is held on open file at the British Geological Survey (Table 1, Figure 4). The Mineral Reconnaissance Programme (MRP), sponsored by the DTI, carried out by the British Geological Survey, completed more than 20 projects in Wales between the mid-1970s and 1997 (Figure 4). These included an airborne magnetic, EM and radiometric survey of northern Anglesey with a complementary drainage survey of the whole island, geochemical surveys of the Harlech Dome, Berwyn Dome, mid-Wales, and the Preseli Hills, and airborne geophysical surveys of part of the Harlech Dome and northern Pembrokeshire. Several smaller areas were also investigated for base metals, manganese and gold by various methods to the scout drilling stage (Table 2).

At Parys Mountain a number of companies sought workable ore reserves. Drilling by Cominco identified additional zones of mineralisation at the western end of the deposit and after their withdrawal in 1983 the lease was taken up by Anglesey Mining, a subsidiary of Imperial Metals of Canada. They carried out a further programme of diamond drilling before sinking an exploratory shaft, the Morris shaft, to 300 m in 1989. Over 1000 m of driving, raising and winzing, coupled with an extensive programme of underground diamond drilling, was used to delineate a total of 4.8 million tons of indicated reserves at 1.49 % Cu, 3.03 % Pb and 6.04 % Zn with 68 g/t Ag and 0.4 g/t Au plus larger resources of lower-grade copper mineralisation (Swallow, 1990). Full-scale exploitation of the deposit was planned, using decline access and shaft haulage, but low metal prices and consequent lack of financial investment prevented implementation. Further reserves are currently being sought to strengthen the economic viability of mining and a new metallogenic model has been developed with the aid of a number of scientific studies, including lithogeochemistry (Tennant and Steed, 1997; Barrett and MacLean, 1999).

Table 1 MEIGA-supported mineral exploration in the Welsh basin

Area	Target	Company	Activity	MEIGA Reference
Mynydd-y-Garreg, South Wales	Stratabound Cu, Pb, Zn	Aquitaine Oil UK	Ground surveys and drilling	142
Pumsaint, C Wales	Mesothermal Au	Anglo Canadian Exploration Ltd	Ground surveys and drilling	137
North Snailbeach, Welsh Borders	Vein Pb, Zn	British Gypsum Ltd	Ground surveys and drilling	157
Parys Mountain, Anglesey	Volcanogenic Cu, Pb, Zn	Cominco UK Ltd	Ground surveys and drilling	132
Dulyn, N Wales	Vein Pb, Zn	Noranda Kerr Ltd	Ground surveys	92
Rhiw, N Wales	Magmatic Cu, Ni	Noranda Kerr Ltd	Ground surveys	81
Clogau St Davids, N Wales	Vein Au	Caernarvon Mining Co Ltd	Trial mining	244
Coed-y-Brenin, N Wales	Porphyry Cu, Mo	Riofinex	Ground surveys and drilling	5
Prysor Gamallt, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	77
Arenig, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	78
Ffestiniog, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	75
Nantmor, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	87
Nantlle, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	88
Drws-y-coed, N Wales	Stratabound Cu, Pb, Zn	Kappa explorations	Ground surveys and drilling	93
Pennant west, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	80
Pennant east, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	79
Nantmor, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys	87
Hafod-y-llan, N Wales	Volcanogenic Cu, Pb, Zn	Noranda Kerr Ltd	Ground surveys and drilling	76

All data on open file except for Pumsaint and Parys Mountain.

Reference number refers to BGS records.

Table 2 MRP exploration in the Welsh Basin

Area	Target	Activity	Reference
Anglesey	Various	Geochemical drainage survey	Cooper et al., 1982
Anglesey	Various	Airborne geophysical survey	Smith and Cooper 1979
Carmel Head, Anglesey	Volcanogenic base-metal deposits	Ground surveys and drilling	Cooper et al., 1989
Anglesey	Various	Airborne geophysics and drainage survey follow-up	Cooper et al., 1990
South-east Anglesey	Magmatic segregation Cu, Ni	Geochemical and geophysical surveys	Colman and Peart, 1993
Lleyn Peninsula	Various	Geochemical drainage survey	Leake and Marshall, 1994
Rhiw, Lleyn Peninsula	Manganese	Ground surveys and drilling	Brown and Evans, 1989
Harlech Dome	Various	Airborne geophysical survey and ground follow-up	Allen, Cooper and Smith, 1979
Llanrwst, North Wales	Volcanogenic base metals	Geochemical drainage survey	Cooper and Rollin, 1978
Harlech Dome	Various	Geochemical drainage survey	Cooper et al., 1985
Benglog	Volcanogenic base metals	Geochemical and geophysical surveys	Cooper et al., 1983
Berwyn Dome	Various	Geochemical drainage survey	Cooper et al., 1984
Berwyn Hills	Gold	Geochemical survey	Smith, 1993
Preseli Hills	Various	Geochemical drainage survey	Cameron et al., 1984
Central Wales	Various	Geochemical drainage survey	Ball and Nutt, 1975
Central Wales	Monazite	Geochemical survey	Smith et al., 1994
Central Wales	Slate-belt-hosted mesothermal gold	Geochemical drainage survey	Brown, 1993
Llandeloy	Copper porphyry	Ground surveys and drilling	Allen et al., 1985
Treffgarne, South-west Wales	VMS	Ground surveys and drilling	Brown et al., 1987; Colman et al., 1995
Pembrokeshire	Various	Airborne geophysical survey	Cornwell and Cave, 1986
Builth Wells	Volcanogenic base metals	Ground surveys and drilling	Marshall et al., 1987
S W Wales	Mesothermal gold	Geochemical surveys	In preparation
Rhiwnant Dome	Mesothermal gold	Ground surveys	In preparation

Previous work

The current work builds upon geological, geophysical, mineralogical and geochemical data collected over many years. Summaries of geology and mineralisation, together with sources of more detailed information covering previous work in these fields, are provided below. Data from the principal regional-scale geochemical and geophysical surveys carried out in Wales were used in this study and are described in the datasets section. More detailed surveys in small areas have been carried out by the BGS, private-sector companies during mineral exploration work, and University-based researchers. Those carried out under the MEIGA scheme and the MRP are briefly mentioned and listed above (Tables 1 and 2). University-based geochemical surveys for mineral exploration purposes have often focussed on technique development. Several such studies have taken place around the Coed-y-Brenin deposit and involved vegetation sampling (Smith and Ball, 1983), lithogeochemistry (Allen et al., 1976) and geophysics. Similar studies have used the Ogofau gold mine as a test case (Al-Atia and Barnes, 1974; Steed et al., 1976). Several environmentally-oriented studies have examined the effects of mine drainage on water-courses, particularly in the Central Wales mining field (e.g. Davies and Lewin, 1974; Wolfenden and Lewin 1978; Mathews and Davies, 1988; Fuge et al., 1991).

Environmental constraints

The principal constraints on mineral development in Wales are the same as in most other areas of Britain and comprise areas already dedicated to human activities, either current or past (historical/archaeological), and areas of natural beauty or wildlife habitats. In terms of area, the principal constraint is provided by National Parks of which there are three in Wales: Snowdonia, Brecon Beacons and Pembrokeshire Coast. These occupy c. 4000 km^2 or about 20% of the land area (Figure 5). Mineral development is not banned in these or other environmentally sensitive areas and mining locally takes place within them, but there is a presumption against it and any application for mine development will be subject to the most rigorous examination and probably involve a public enquiry.

Areas of outstanding natural beauty (AONBs) also occupy appreciable areas, but most of the larger designations are marginal to the basin (e.g. Gower Peninsula, Shropshire Hills, Wye Valley and Malvern Hills). Areas of Special Scientific Interest (SSSIs) and National Nature Reserves are large in number but most only occupy small areas. There are exceptions, with some SSSIs in central and north Wales occupying several thousand acres (Figure 5).

GEOLOGY

The geology of the area covered by this report includes strata ranging from Precambrian to end Silurian in age, along with extensive deposits of glacial, and post-glacial sediments.

Regional tectonic setting

From the late Precambrian Wales lay on the north-western edge of the European continent (Armorica-Gondwana) and formed part of the Eastern Avalonia microcontinent where it abutted the Iapetus Ocean (Soper and Hutton, 1984). Here the oceanic plate was being consumed along a south-easterly dipping subduction zone and the intra-cratonic Welsh basin comprised a steep sided trough floored by Precambrian continental crust, its active, faulted margins usually defined by the Menai Strait and Welsh Borderland Fault systems (Figure 6). The Precambrian sedimentary volcanic, metamorphic and granitic rocks formed by the accretion of volcanic arcs during the late Precambrian and are exposed around the basin's margins in Anglesey, the Lleyn Peninsula, Pembrokeshire and the Welsh borderlands. Due to strike slip faulting during continental collision they may be displaced considerable distances from their original position with respect to each other and the basinal successions. The basin was the site of enhanced subsidence from Cambrian to late Silurian times and was bordered to the east by the Midland Platform and to the north west by a putative Irish Sea landmass (Irish Sea Horst) or submarine rise. The basin developed in a back-arc setting with the development of extensive volcanism and the potential for mineralisation commonly associated with this setting. Transgressive, regressive, volcanic and tectonic events continually affected the extent and configuration of the basin and sedimentation within it. Significant regional unconformities in the volcano-sedimentary successions reflecting tectonic and volcanic activity occur, notably at the end of the Tremadoc and Ashgill as well as in the late Precambrian and in the Devonian (Woodcock, 1990a). Basement faults and fractures strongly influenced sedimentary deposition and the location of volcanic centres (e.g. Kokelaar, 1988) throughout the life of the basin. Tectonic lineaments identified across the basin are an expression of the movement of these basement faults and their propagation into the cover sequences (e.g. Woodcock, 1990b; Smith, 1987). A shallow shelf sea of varying width lay to the south and east of the basin throughout the Lower Palaeozoic with the shelf/basin margin controlled by the line of the Towy anticline and the shelf edge related to the line of the Pontesford lineament and its extensions.

A marked unconformity at the base of the Cambrian is followed by a succession indicating shoreline through to deep water facies, ranging from basal conglomerates and sandstones to black shales. Only minor volcanism occurred but tectonic activity is reflected by unconformities in the rocks deposited in both north and south Wales. The Ordovician sequence is dominated by deepwater mudstones and siltstones with basal Arenig shallow water deposits and shelf facies at the basin margin. In contrast to the Cambrian, locally extensive and voluminous volcanic deposits characterise the successions from Tremadoc to Caradoc age. Andesitic volcanism characterises the early centres (Rhobell Fawr, Treffgarne) while the later events (Llanvirn and Caradoc) are characterised by bimodal tholeiitic basalt-rhyolite eruptions (Fishguard, Harlech Dome, Snowdonia). The composition of these rocks suggests an evolving island arc (Tremadoc) to extensional marginal basin (Caradoc) setting. Models suggest that initial rifting and subsidence of the Ordovician basin may have been related to the separation of Eastern Avalonia from Gondwana and its drift towards Laurentia in the mid-Ordovician.

The Silurian is characterised by the incursion of coarse turbidites with volcanism restricted to localised sub-alkaline to alkaline activity of Llandovery age in south Wales and the sources of more widespread tuffaceous horizons found in younger rocks. The thick clastic successions were deposited in a series of sub-basins, in a tectonic setting that is not fully clarified: fore-arc, passive margin, intra-continental rift and strike slip models have all been postulated. Closure of Iapetus, convergence of eastern Avalonia/Armorica and Laurentia and 'docking' of the continental plates occurred between late Ordovician and late-Silurian times, depending on which of the postulated models is favoured (e.g. Soper and Woodcock, 1990). It was marked by basin inversion and crustal shortening across the basin during the climax of the end-Caledonian (Acadian) orogeny. This event was accompanied by pervasive deformation, cleavage development and low grade (maximum biotite grade) metamorphism, but unaffected by batholithic plutonism. Sinistral strike slip fault movements, produced by the oblique collision, took place along terrane boundaries and other north-east trending major fractures during and after these events.

Basement (Precambrian) rocks

Precambrian rocks outcrop in North Wales, the Welsh Borderland and in south-west Wales (Shackleton 1975, Pharaoh and Gibbons 1994) at the margins of the Lower Palaeozoic rocks of the Welsh Basin

(Figure 2). They are included in this study as (1) some may be of Lower Palaeozoic age and (2) some pass up into the Lower Palaeozoic rocks of the Basin with little evidence of a significant break.

North-west Wales

In North Wales the Precambrian principally comprises a varied suite of tectonised igneous, metamorphic and sedimentary rocks outcropping on Anglesey and the Lleyn Peninsula (Mona Complex), and a succession of late Precambrian to early Cambrian volcanic rocks and associated sediments in northern Snowdonia (Arfon Group).

Mona Complex. Current models view this complex as a tectonic collage of once widely separated lithological elements brought together within a belt of transcurrent faulting (Gibbons, 1983, 1987) during late Precambrian to early Cambrian oblique plate convergence at the Avalonian margin. The complex broadly comprises three lithological assemblages: (1) granites and gneisses; (2) fine-grained (Penmynydd) schists and; (3) deformed metasedimentary rocks (the Monian Supergroup).

The gneisses and plutonic igneous rocks of the Lleyn Peninsula are mostly granitic to dioritic in composition with subordinate mafic lithologies, and include the Sarn Granite, a large, homogeneous calc-alkaline intrusion. The complex was metamorphosed and the granite intruded around 615 Ma within a subduction-related arc environment (Beckinsale et al., 1984; Gibbons and McCarroll, 1993; Horák et al., 1996). The main outcrop of granites and gneisses in central Anglesey includes the Coedana Granite, for which U-Pb isotopic dating suggests a similar age (Tucker and Pharaoh, 1991). The associated gneisses include basic amphibolites, granitic migmatites, sillimanitic pelites and calc-silicates.

Belts of fine-grained, intensely foliated schists and mylonites in central and south-east Anglesey and on the Lleyn Peninsula form the 'Penmynydd Zone' (Greenly, 1919). They include upper greenschist facies mica schists, amphibole schists, quartz and graphitic schists, recrystallised limestones, and blue amphibole- and lawsonite-bearing basic schists (blueschists). The zone is interpreted as a sliver of Avalonian accretionary prism spliced into the arc complex along deep-rooted, intracratonic shear zones (Horák et al., 1996).

The Monian Supergroup comprises three major lithostratigraphical divisions: the South Stack and New Harbour groups, which are confined to northern Anglesey and Holy Island, and the Gwna Melange, which also outcrops extensively in central and eastern Anglesey and on Lleyn. The South Stack Group is a thick sequence of deformed metasedimentary rocks, composed of interbedded greywacke sandstones, siltstones and pelites succeeded by massive, thick-bedded orthoquartzite, in turn overlain by interbedded sandstones and pelites with subordinate quartzites. The facies are consistent with deposition from turbidity currents in a prograding deep-sea turbidite fan complex, probably along a continental margin (Shackleton, 1969, 1975; Phillips, 1991).

In northern Anglesey, the New Harbour Group comprises quartz-veined chlorite-mica schists, which grade upwards into metamorphosed massive, volcaniclastic sandstones and schistose pelites (Khonstamm, 1980; Phillips, 1991), consistent with the progradation of turbiditic fan facies derived from a continental island arc (Phillips, 1991). The group is overlain in this area by tuffaceous pelites (Church Bay Tuffs) which pass upwards into volcaniclastic metasandstones, pelites and conglomerates (Skerries Grits), but their relationships are not clear (Gibbons and Ball, 1991). The western outcrops of the New Harbour Group comprise a succession of highly deformed chlorite-mica schists, which include small isolated masses of gabbro and sepentinite, deformed metabasic lavas and jaspery cherts. These were considered by Thorpe (1979) to represent remnants of a disrupted ophiolite complex, but Maltman (1977) favoured an intrusive origin.

The Gwna Melange is an olistostrome, in which a diverse assemblage of clasts, some over a kilometre in size, are dispersed within a matrix of grey-green slaty mudstone and siltstone. The clasts include stromatolitic limestones, quartzites, cherts, jasper, red mudstones, feldspathic and tuffaceous sandstones, pillowed basalts and granites and may reflect several phases of generation. The assemblage, comprising material derived from a continental margin and from the reworking of contemporary deeper water facies, suggests that it was the product of a continental or arc-continent collision (Gibbons, 1993).

Arfon Group. This comprises a succession of late Precambrian to early Cambrian volcanic rocks and associated sediments (Howells et al., 1985). Within the group the Padarn Tuff has been isotopically dated as 614 $\pm$ 2 Ma (Tucker and Pharaoh, 1991) suggesting that it was probably erupted during the same arc-related magmatic event as the Coedana Granite and Sarn Complex (Horák et al., 1996). It typically comprises strongly welded, acidic ash-flow tuffs (ignimbrites), subordinate air-fall tuffs and, locally, rhyolite lavas. The Bwlch Gwyn Tuff of Anglesey is considered to be the attenuated northern correlative of the Padarn Tuff.

In the Bangor area, the Padarn Tuff is succeeded disconformably by a 1.5-km sequence of laminated siltstones and acidic tuffs with subordinate lithic and feldspathic greywackes and conglomerates (Minffordd Formation). Comparable, and probably coeval, facies on Anglesey are represented by the Barron Hill Beds and the sponge-spicule bearing Careg Onen Beds, and arguably by a conglomerate outlier at Trefdraeth (Greenly, 1919). On Bangor Mountain the Mynffordd Formation is unconformably overlain by basal lithic sandstones and conglomerates followed by laminated and locally slumped siltstones with tuffs, tuffites and turbidite sandstones (Bangor Formation). South of Caernarfon, the Padarn Tuff is disconformably overlain by a westward thickening succession of basal conglomerates, composed mainly of clasts largely sourced from the Padarn Tuff, interbedded ash-flow and air-fall tuffs, and marine siltstones and mudstones (Fachwen Formation).

South-west Wales

The Precambrian succession of north and central Pembrokeshire, comprises a succession of acid to intermediate tuffs, lavas and tuffaceous sediments (Pebidian complex) cut by acid and intermediate intrusions, including the St David’s Granite radiometrically dated as 650–570 Ma (Patchett and Jocelyn, 1979), and dolerite dykes. The intermediate intrusions host copper porphyry-type mineralisation at Llandeloy (Allen et al., 1985). Several lithological assemblages or ‘groups’ are present in the volcanosedimentary succession although, due to faulting, the relationships between them are not always clear. The oldest rocks, exposed around St David’s are more basic in the upper parts and include predominantly red and green, coarse-grained tuffs with fragments of vesicular andesite and trachyte, interbedded rhyolitic rocks (‘halleflintas’) and coarse arkosic sandstones (Penrhiw and Treginnis groups). The overlying rocks comprise pale blue, green or purple feldspathic and porcellanitic tuffs with a quartz-chlorite matrix, and subordinate rhyolitic rocks (Caerbwdy Group). This succession is coarse-grained in the lower part and near the base there is a volcanogenic conglomerate (Clegyr Conglomerate) containing pebbles of quartz porphyry and rhyolite (Green, 1908). The Ramsey Sound Group comprises variegated, fine-grained, soft sericite-chlorite tuffs and porcellanitic rocks. It is succeeded in the St David’s area by a succession of andesitic and trachytic tuffs and lavas (Rhosson Group). The youngest rocks, which outcrop only at Whitesands Bay, are acid tuffs and dark green chloritic slates (Ogofgolchfa Group).

In south Pembrokeshire, the Precambrian comprises two groups of igneous rocks, which are locally strongly deformed within a thrust belt close to the Variscan orogenic front. The Johnston Series of intrusions consists of calc-alkaline diorites with lesser granodiorites, granites and pegmatites which have been dated as 643 $\pm$ 5 Ma (Patchett and Jocelyn, 1979). The Dutch Gin Schists of the coastal sections are considered to be the sheared equivalents of these rocks (Baker et al., 1968). The poorly exposed Benton

Volcanic Group contains spherulitic and autobrecciated lavas of sodic rhyolite and trachyte, with subordinate red and green tuffs resembling those to the north.

The Llangynog inlier south-west of Carmarthen exposes a succession of late Precambrian flow-banded and brecciated rhyolitic lavas, interbedded tuffs and volcaniclastic sediments, with a few doleritic and dacitic intrusions (Coomb Volcanic Formation). The rocks have been tentatively correlated with the Precambrian volcanic rocks of north Pembrokeshire (Cope and Bevins, 1993).

Welsh borderland

Inliers of Precambrian sedimentary, volcanic and intrusive igneous rocks outcrop at intervals along the Welsh Borderland Fault System (Woodcock and Gibbons, 1988) and form the part of the Malvern Hills. The relationships between these isolated outcrops are not clearly understood, but they can be broadly subdivided into suites of earlier, intrusive igneous rocks, and later, lithologically and geochemically distinct volcanic and sedimentary sequences (e.g. Thorpe, 1982).

Stanner Hanter and Malverns Complexes. These are the oldest rocks of this region, having been emplaced around 700–650 Ma, probably as parts of a volcanic arc within the Avalonian accretionary terrane (Patchett, et al., 1980; Thorpe et al., 1984; Tucker and Pharaoh, 1991). They comprise associations of basic and acid plutonic rocks which reveal several episodes of intrusion and alteration. Many of the primary lithologies are sheared, mylonitised and hydrothermally metamorphosed, and are commonly represented by quartz-mica schists, hornblendic gneiss, metasomatic granite and pseudotachilite. Lithologically, the calc-alkaline Malverns Complex is directly comparable to the Johnston Series of Pembrokeshire (Thorpe et al., 1984).

Rushton Schists. These rocks are predominantly metasedimentary quartz-chlorite schists, and striped semipelitic schists, locally garnetiferous and epidote-rich, with interbedded quartzites, quartzitic schists, and subordinate basic igneous rocks outcropping between splays of the Church Stretton Fault Zone west of the Wrekin. An Rb-Sr whole-rock isochron age of 667 $\pm$ 20 Ma has been interpreted as a metamorphic age (Thorpe et al., 1984). At the southern end of the Wrekin the schists and gneisses of Primrose Hill, have been considered as correlatives of the Rushton Schists (Baker, 1971), although lithologically they have more affinity with the sheared igneous rocks of the Malverns Complex (Hamblin and Coppack, 1995). They comprise banded hornblende schists and biotite gneisses, veined by granitic material and apparently overlain by acid feldspathic gneiss and granophyre.

Uriconian Volcanic Group. This suite of calc-alkaline volcanic rocks including, flow-banded and autobrecciated rhyolites, dacites, andesites and basalts, interbedded with coarse acid and basic ash-flow tuffs and subordinate sandstones and conglomerates outcrops along the Church Stretton and Pontesford–Linley fault zones. The tuffs and conglomerates locally contain clasts similar to the Rushton Schists and Primrose Hill gneisses (Greig et al., 1968; Earp and Hains, 1971; Hamblin and Coppack, 1995) and are considered to be younger. Minor intrusions of dolerite, rhyolite and granophyre occur in places. One, the Ercall Granophyre at the northern end of the Wrekin, provided an U-Pb isotopic age of 560 $\pm$ 1 Ma, only slightly younger than that of the Uriconian lavas at 566 $\pm$ 2 Ma (Tucker and Pharaoh, 1991).

Warren House Formation. These rocks, which lie in tectonic contact with the Malverns Complex and are generally less deformed yielded a U-Pb isotopic age of 566 $\pm$ 2 Ma (Tucker and Pharaoh, 1991), indistinguishable from the Uriconian Volcanic Group. They are chemically distinct, comprising a suite of sodic lavas, including spilitic basalts, locally with pillow structures, rhyolites, subordinate keratophyres and crystal-vitric tuffs. The compositional differences are considered to reflect differing tectonic environments: eruption of the Warren House lavas probably taking place in an oceanic marginal basin setting prior to preservation as a tectonic sliver along the Proterozoic Malvern Line (Thorpe et al., 1984; Pharaoh et al., 1987).

Longmyndian Supergroup. This is a thick (7 km) sequence of late Precambrian sedimentary rocks, disposed in a major overturned, eastward-facing, isoclinal syncline between the Pontesford–Linley and Church Stretton faults, with further outcrops along the Church Stretton Fault. The rocks are generally purple and greenish grey mudstones, sandstones, conglomerates and some tuffs, deposited in a shallow marine to fluviatile setting (Greig et al., 1968). They are generally regarded as younger than the Uriconian Volcanic Group and have whole-rock Rb-Sr ages of about 530 Ma (Bath 1974).

Cambrian basin and shelf deposits

The thickest and most complete succession of Cambrian rocks in Britain is preserved in the Harlech Dome. Other outcrops occur in northern Snowdonia, the Lleyn Peninsula, Anglesey, south-west Wales and the Welsh borderlands. The pronounced thickness and facies changes that occur between these areas record deposition in a series of fault-controlled extensional basins which coalesced through time to allow deep-water sedimentation to extend throughout the region, prior to inversion in late Cambrian to Tremadoc times.

Harlech Dome and St Tudwal's Peninsula

The succession comprises up to 4.5 km of clastic sediments with no major depositional breaks, resting unconformably on a sequence of andesite and dacite lavas, tuffs and epiclastic deposits of unknown, but possibly early Cambrian age, proved in a borehole (Bryn Teg Volcanic Formation, Allen and Jackson, 1985).The clastic succession has been subdivided into the Harlech Grits Group, dominantly of coarse deltaic and turbiditic sandstones with manganese-rich beds, and the overlying Mawddach Group, composed of fine-grained sandstones, siltstones and black mudstones. On St Tudwal's Peninsula, only the uppermost 630 m of the Harlech Grits Group and the lowest formations of the Mawddach Group are exposed.

Harlech Grits Group. The lowest rocks exposed comprise a 575-m-thick deltaic sequence of cross-bedded sandstones and siltstones, including a basal facies of coarse conglomerates and pebbly sandstones with abundant volcanic clasts (Dolwen Formation, Allen and Jackson, 1985). The top of the formation is locally tuffaceous and transitional into a prodeltaic facies consisting of well-cleaved mudstones, worked locally for slate, with subordinate beds of siltstone and rare sandstone. The overlying thick sequence (up to 780 m) of medium- to coarse-grained sandstones and quartz-pebble conglomerates with minor thin intercalations of siltstone and mudstone (Rhinog Formation), is interpreted as a sequence of proximal turbidites, sourced from the north (Crimes, 1970; Allen and Jackson, 1985). It correlates lithologically with the lowest division exposed on southern Lleyn and is followed by up to 300 m of thinly interbedded mudstones, siltstones and fine-grained, cross-bedded sandstones (Haffoty Formation). The Manganese Grit, which outcrops in the lower part of the formation around the southern part of the Harlech Dome, is a rare, persistent, coarse-grained sandstone unit containing a manganese-rich horizon which has been mined for metal. The ore bed is mainly composed of manganese carbonates and spessartine garnet, with small amounts of hematite and pyrite. Geochemical studies suggest that it is a chemical precipitate, possibly of volcanic (exhalative) origin, formed in a reducing environment during diagenesis (Mohr, 1964; Glasby, 1974; Bennett, 1987). The formation correlates, at least in part, with manganiferous rocks on St Tudwal's Peninsula (Trwyn-y-fulfran Formation).

Further proximal turbidites, similar in facies to the Rhinog Formation but with characterised by coarser, pebbly sandstones and less mudstone follow (Barmouth Formation, Allen and Jackson, 1985). At the top of the group purplish and greenish grey bioturbated mudstones, locally pyritic and hematitic, with subordinate planar and cross-laminated siltstones (Gamlan Formation). Horizons of coarse turbiditic sandstone include the Cefn Coch Grit. The upper part of the formation is manganiferous, the manganese occurring as spessartine with quartz and chlorite in concretions and disseminated throughout some of the siltstones (coticule rocks). Beds of tuffaceous mudstone appear near the top of the sequence. Comparable lithologies are recorded on St Tudwal's Peninsula (Pratt et al., 1995).

<u>Mawddach Group</u>. The base is marked by the incoming of black, pyritic, laminated pelagic mudstones of Middle Cambrian age (Clogau Formation). These rocks are the principal host of the gold-bearing quartz veins worked on the south and east sides of the Harlech Dome (see mineralisation section). The mudstones are thinly interbedded with silty mudstones, representing distal turbidite flows and in the lower part there are thin beds of fine-grained quartzose sandstone. The overlying rocks comprise up to 1200 m of fine-grained, planar and cross-laminated quartzose sandstones, siltstones and pale grey mudstones, interbedded with black, laminated mudstones (Maentwrog Formation). They mark an abrupt resumption of turbiditic sedimentation and represent a facies widely developed in the Welsh Basin at this time. A thick (450−1000 m) sequence of poorly bedded, bioturbated silty mudstones alternating with thinly bedded quartzose siltstone and fine-grained sandstone packets follow (Ffestiniog Flags Formation). Abundant sedimentary structures indicate derivation from the north and deposition in a shallow marine environment (Pratt et al., 1995). An abrupt change to about 100 m of pyritous and carbonaceous, laminated, black mudstones with a few thin siltstones, local cone-in-cone concretions and phosphatic nodules occurs (Dolgellau Formation) towards the top of the group These rocks represent a condensed pelagic sequence and are the youngest Cambrian strata in the area. A higher Tremadocian division of the Mawddach Group is described below.

Northern Snowdonia

In this area, towards the margin of the Cambrian basin, the succession is incomplete and contains unconformities as well as important facies changes. Along the Bangor and Padarn ridges transitional facies of the mostly late Precambrian Arfon Group are succeeded by purple, green and blue-grey, intensely cleaved silty mudstones (Llanberis Slates Formation), the principal source of slate in North Wales. Thick packets of coarse, graded, turbidite sandstones, occur at intervals and sedimentary structures suggest that the source area lay to the north-west. Channelised conglomeratic sandstones at the base of the succeeding division (Bronllwyd Grit Formation) are overlain by a sequence dominated by graded, coarse-grained and cross-bedded sandstones with partings of manganiferous mudstone. These pass transitionally into dark grey mudstones with thin sandstone laminae and impersistent beds of coarse sandstone and ironstone (Marchlyn Formation). A major unconformity marks the boundary between the Cambrian and Lower Ordovician (Arenig) in this area.

South-west Wales

The Cambrian of Pembrokeshire comprises a largely faulted succession of predominantly shallow-water sediments deposited unconformably on the eroded Precambrian. It records a transgression, with progressive deepening of the depositional environment from intertidal, through shallow marine, to below wave base. The succession around St David's has been subdivided into the Caerfai Group, correlating with the Welsh Hook Beds of Treffgarne, the overlying Solva and Menevian groups and the 'Lingula Flags'.

<u>Caerfai Group</u>. The Basal Conglomerate contains pebbles and boulders of vein quartz, schistose quartzite, jasper and acid igneous rocks from the underlying Precambrian, set in an arenaceous to argillaceous matrix. It is succeeded by up to 140 m of dark green, locally pebbly, feldspathic and micaceous sandstones with subordinate siltstones (St Non's Sandstone) and 15 m of purplish red, bioturbated

mudstones with thin tuffaceous beds (Caerfai Bay Shales). They are succeeded by up to 150 m of fine-grained, massive, micaceous and feldspathic purple sandstones with subsidiary mudstones (Caerbwdy Sandstone). Locally, near the top of the group greenish-grey beds with granules and pebbles of quartz and acid igneous rock appear in the sequence.

Solva Group. Conformably overlying the Caerfai Group, the lowest 50 m of the Solva Group (Lower Solva Beds), and the equivalent rocks in the Treffgarne area (Musland Grit), consist of greenish grey, pebbly, feldspathic sandstones and conglomerates, interbedded with subordinate fine-grained sandstones and dark siltstones. They are overlain by 75 m of purple and greenish grey sandstones, bioturbated siltstones and silty mudstones, with beds of conglomerate (Middle Solva Beds) and these in turn by 50 m of flaggy, bioturbated sandstones and mudstones with rusty-weathering concretions (Upper Solva Beds).

Menevian Group. The Lower Menevian Beds (Stead and Williams, 1971), transitional with the underlying Solva Group and correlating with the Ford Beds of Treffgarne, comprise about 100 m of black, pyritous, hemipelagic mudstones, thinly interbedded with paler silty mudstones. The rocks can be equated with the Middle Cambrian Clogau Formation of the Harlech Dome. The appearance of about 100 m of thin, often lenticular, sandstones and siltstones within the mudstone sequence, together with thin tuffaceous bands and sporadic small phosphatic nodule horizons, characterise the Middle Menevian Beds (Rushton, 1974). The latter are abruptly overlain by up to 30 m of coarse-grained, massive, dark grey sandstones with interbedded mudstones (Upper Menevian Beds), which mark the onset of turbiditic sedimentation in this area.

Lingula Flags. The informally named ‘Lingula Flags’ and the equivalent Treffgarne Bridge Beds conformably overlie the Menevian succession. They consist of up to 600 m of siliceous and feldspathic siltstone beds, thinly interbedded with greenish grey micaceous shaly mudstones, and local beds of coarse and conglomeratic sandstone. Sedimentary structures suggest that the sequence was derived from the south (Crimes, 1970).

The Cambrian succession south-west of Carmarthen (Cope and Rushton, 1992) unconformably overlies Precambrian volcanic rocks, and is much faulted. The lowest formation, the Allt y Shed Sandstones, possibly of Lower Cambrian age, comprises up to 100 m of olive-green quartzose siltstones and sandstones, with a basal conglomerate similar to that of the St David’s area. The sandstones are succeeded by sandstones, siltstones and mudstones of Upper Cambrian age, the contact being either unconformable or faulted.

Welsh borderland

The Cambrian rocks in this area are mainly known from the small outcrops that occur along the Church Stretton Fault Zone and the Malvern Line. In contrast to the Cambrian of the Welsh Basin, these well-sorted, shallow-marine shelf sequences are interrupted by a number of unconformities, some of which may relate to local movements along major fault zones (Rushton, 1974).

The Lower Cambrian Wrekin Quartzite, resting unconformably on the Uriconian Volcanic Group, is a white orthoquartzite with subordinate feldspar and glauconite grains. Pebbly beds near the base include fragments of the underlying Uriconian and Rushton Schists; at the top there are irregular conglomeratic beds with shaly partings. The Malverns Quartzite, possibly a partly coeval facies, consists of quartz-cemented sandstones and conglomerates containing pebbles of the underlying Malverns Complex. The Wrekin Quartzite is overlain conformably by up to 150 m of fine- to medium-grained glauconitic sandstones, often flaggy and micaceous, with subordinate shales and some calcareous units (Lower Comley Sandstone). The lowest beds are locally conglomeratic and contain decalcified ‘rottenstones’.

The lithologically similar Hollybush Sandstone of the Malvern Hills is probably a correlative. The Lower Comley Sandstone is overlain by a 2 m-thick unit of highly fossiliferous, brown, grey, pink and purplish red, glauconitic, phosphatic, sandy limestone and calcareous sandstone (Lower Comley Limestones). The recognition of five lithologically and faunally distinct units within this division suggests that it represents a condensed and winnowed shallow marine sequence. It is unconformably overlain by up to 200 m of brown and grey, quartzose, glauconitic, fossiliferous sandstones, subordinate micaceous shales and dark limestones of Middle Cambrian age (Upper Comley Sandstone). They in turn are disconformably overlain near Church Stretton by 150 m of grey silty mudstones, locally micaceous, with thin beds of calcareous sandstone (Orusia Shales) and a thin sequence of black mudstones with mildly radioactive bituminous limestone concretions and phosphatic nodules (Bentleyford Shales). In the Malvern Hills, strata of equivalent age are represented by a succession of black, pyritic, shales with thin bands of coarse, quartzitic sandstones, recording deposition in a poorly oxygenated environment (White-Leaved Oak Shales). The Orusia, Bentleyford and White-Leaved Oak shales are lithologically comparable, and equivalent in age, to the Mawddach Group and Menevian formations in north and south-west Wales.

Ordovician basin and shelf deposits

Ordovician rocks, formed within a subsiding intracratonic basin, between a Precambrian Irish Sea horst to the north-west, and the stable Midland Platform to the south-east, outcrop extensively. Coincident volcanism with an island-arc signature during the Tremadoc and other evidence indicates an active subduction zone to the north, at the margin of Avalonia with the Iapetus ocean. It was this volcano-tectonic episode, with concomitant folding, uplift and erosion, that terminated Cambrian basinal sedimentation; only around the margin of the Harlech Dome was sedimentation continuous from the Cambrian through the Tremadoc. Elsewhere, the onset of Ordovician deposition awaited the widespread Arenig marine transgression. During the subsequent Llanvirn and Caradoc, sedimentation dominated by black silty mudstones was interrupted by extensive volcanism from centres in North and south-west Wales. This bimodal (basaltic and rhyolitic) volcanism took place within an extensional back-arc basin setting and sinistral strike-slip movements on basement fractures may also have been important indetermining the routes for magma intrusion and eruption (Kokelaar et al., 1984; Kokelaar, 1988; Howells et al., 1991). Ridge-trench collision at the northern margin of Avalonia during the late Caradoc ended southerly subduction and, with it, Ordovician volcanism in the basin. Subsequent late Ordovician sedimentation, in common with coeval sequences throughout the world, was influenced by sea-level changes related to glaciation in Gondwana.

Anglesey

Fossiliferous Arenig conglomerates and grits at the base of the succession provide evidence for a rapid, widepread marine transgression. In western Anglesey they are overlain by a sequence of distinctive green conglomerates, more than 900 m thick, of Arenig to Llanvirn age, containing clasts derived from the Precambrian. In the north-east of the island, coeval rocks contain matrix-supported conglomerates with the same clast assemblage, emplaced within a mudstone sequence by debris flows. These successione reflect proximity to the active northern boundary of the basin. In east and south-east Anglesey the corresponding mudstone succession is free of conglomeratic horizons and compares with that of Snowdonia. Strata of Llandeilian age are absent throughout the island but Caradoc graptolitic shales with oolitic ironstones succeed this hiatus in southern and central Anglesey. On the northern coast at Carmel Head basal Caradoc breccias overstep earlier Ordovician strata to rest on the Mona Complex, and are succeeded by a graptolitic mudstone sequence. At Parys Mountain a thick sequence of highly altered coarse, fiammé-rich, acid ash-flow tuffs, amygdaloidal basalts and intercalated tuffaceous sediments associated with VMS mineralisation overlies the local Ordovician (Arenig-Llanvirn) succession. The age of the volcanism previously assumed to be Caradocian, has been proven by recent dating to be Llandovery (R. Parrish *in* Barrett and MacLean, 1999).

Northern and central Snowdonia

The basal Arenig fan delta and shoreface sandstones of northern (Graianog Sandstone) and southern Snowdonia (Garth Grit) provide evidence for a rapid, widepread marine transgression that marked the start of sedimentation and assocaited volcanism that persisted into the Silurian. Bioturbated facies with local developments of pisolitic ironstone towards the top of the Graianog Sandstone underlie a gradation into a sequence of dark silty mudstones up to 1.5 km thick (Nant Ffrancon Formation). Additional beds of pisolitic ironstone containing trilobites and brachiopods indicate brief periods of shoaling and benthic colonisation during the Llanvirn and early Caradoc. Close to the top, slumped horizons with intraformational debrite provide the first evidence for seismic activity, prior to the first of two major episodes of Caradoc (Soudleyan-Woolstonian) volcanism to affect northern Snowdonia. The products of this volcanism are represented by the Llewelyn and Snowdon volcanic groups, which are separated by a sedimentary sequence, the Cwm Eigiau Formation.

In the Llewelyn Volcanic Group, several adjacent, and in part laterally equivalent, volcanic formations, representing the products of several contemporaneous volcanic centres, are separated by a thin sedimentary sequence from the overlying, widely developed Capel Curig Volcanic Formation. A centre located close to Conwy produced flow-banded and locally brecciated rhyolites intercalated with sediments which were erupted subaqueously (Conwy Rhyolite Formation). This division terminates against, and locally interfingers with, trachyandesitic tuffs and intrusive porphyritic trachyandesites largely restricted to an elliptical outcrop up to 4 km across interpreted as the fill of a small caldera (Foel Fras Complex). On Carnedd Llewellyn to the south-west, a 180 m thick dome-like accumulation of basic lavas and breccias are considered to be the proximal extrusions of a short-lived vent (Foel Grach Basalt Formation). Basalt lava flows and interbedded marine siltstones north of the Nant Ffrancon Pass are interpreted as its more distal derivatives. The heterolithic Braich tu du Volcanic Formation underlies the distal flows of the Foel Grach Basalt Formation, to form the westernmost component of the group. Here, flow-banded and nodular rhyolite lavas and welded ash-flow tuffs give way southwards to a sequence of acid and basic tuffs and tuffites interbedded with marine siltstones. The sediments in the middle of the group are dominated in the north by 50 m of conglomeratic alluvial fan and braidplain facies, sourced from the north, while to the south, the sequence is largely composed of coarsening-upwards siltstone to sandstone sequences locally rich in magnetite and includes the Gwern Gof Tuff which is over 500 m thick. The succeeding Capel Curig Volcanic Formation includes the products of at least four major ignimbritic eruptions from three separate volcanic centres and include both subaerial and submarine deposits.

A major break in volcanic activity in northern Snowdonia followed, during which sedimentary rocks of late Soudleyan to early Longvillian age were deposited (Cwm Eigiau Formation). The rocks, recording a marine transgression, comprise a northern sequence of fluvio-deltaic sandstones and conglomerates with fossiliferous, nearshore marine sandstones and siltstones. The formation thickens southward, to almost 1 km near Capel Curig, accompanied by a lateral passage into off-shore mudstone facies.

By the mid-Caradoc, new volcanic centres were established in central and north-eastern Snowdonia, and the eruptive products from these constitute the Snowdon Volcanic Group. Uplift and erosion preceded eruption from a caldera centred on Llwyd Mawr (Pitts Head Tuff Formation). At its source, the tuff was erupted subaerially, but to the north of Snowdon the ash-flow continued for 10 km beneath the sea. The remaining tuff formations of the Snowdon Volcanic Group record the growth, collapse and reworking of a major caldera centred near Snowdon. Pre-existing fault lines controlled the shape of the caldera and the location and pattern of eruptions. Early acidic volcanism, associated with initial up-doming and fracturing, is marked by the localised eruption of 180 m of acidic welded ash-flow tuffs, pyroclastic breccias and rhyolite domes (Yr Arddu Tuffs). Elsewhere submarine sequences of pillowed basalts, basic tuffs and hyloclastites were extruded. The main phase of explosive, acidic volcanism associated with the collapse of the Snowdon Caldera comprises up to 600 m of sedimentary and pyroclastic breccias, acidic ash-flow tuffs, including welded and non-welded varieties, acid tuffites, rhyolites and locally fossiliferous tuffaceous sandstones and siltstones (Lower Rhyolitic Tuff Formation). To the north, turbiditic facies were discharged into the marine environment from the degrading caldera margin. The succeeding rocks records an episode of dominantly basaltic volcanism, sourced from separate centres within the Snowdon Caldera and comprise up to 450 m of basalts, basaltic breccias, hyloclastites and reworked basic tuffs and tuffites (Bedded Pyroclastic Formation). Peralkaline ash-flow tuffs and rhyolites forming sequences up to 100 m thick (Upper Rhyolitic Tuff) mark a resurgence of acid volcanism from the caldera.

In north-eastern Snowdonia, a 600 m sequence of acid ash-flow tuffs and tuffites, interbedded with off-shore graptolitic siltstones and mudstones, were the product of deep submarine, acidic eruptions from the Crafnant volcanic centre. This sequence overlies the distal outflow tuff of the Snowdon Caldera, and thus postdated eruption of the Lower Rhyolitic Tuff from that centre. North of the Crafnant area, the 500 m thick products of a separate centre are preserved (Tal y Fan Volcanic Formation). Pillowed and brecciated basalts, hyloclastites, and basaltic tuffs, interbedded with black mudstones, were extruded at the same time as the earliest acidic eruptions from the Crafnant centre. A closely comparable 400 m thick sequence of basaltic rocks and mudstones (Dolgarrog Volcanic Formation) records a subsequent and final resurgence of the Crafnant centre and represents the final eruptive event in the area. They are associated with the Cae Coch massive pyrite deposit (see below).

The succeeding late Caradoc sequence of black, pyritic, graptolitic mudstones up to 400 m thick (Cadnant Shales) compare with coeval facies throughout the Welsh Basin (e.g. the Nod Glas Formation). They are thought to record deposition at the acme of a mid- to late-Caradocian marine transgression, when anoxic bottom conditions were widespread and terrigenoclastic sediment input low. In contrast, the succeeding bioturbated and locally calcareous succession (Conwy Mudstone Formation) of Ashgill age was deposited in oxygenated bottom waters. Its introduction may mark the onset of the widely recognised Ashgill glacioeustatic marine regression.

Harlech and Berwyn Domes

The oldest strata are grey mudstones and siltstones locally up to 480 m thick of Tremadocian age (Dol-cyn-afon Formation). They conformably overlie the Cambrian Dolgellau Formation and are the highest division of the Mawddach Group. Locally, towards the top of the formation, shallow marine quartzose sandstones and beds of strongly bioturbated mudstone provide evidence of shoaling prior to the emergence and erosion which affected the whole of North Wales.

The Rhobell Volcanic Group, which unconformably overlies Tremadoc and Cambrian strata, is a succession of up to 1000 m of basic lavas, autoclastic breccias and shallow subvolcanic intrusives of tholeiitic to calc-alkaline affinity with subordinate sediments, including talus breccias, coarse-grained mass flow units and alluvial deposits; lahars occur locally at the base. The volcano was centred over the Rhobell Fracture, an important structural feature on the eastern side of the Harlech Dome, which was tectonically active throughout the Tremadoc and responsible for contemporaneous uplift and erosion of the volcanic complex prior to deposition in the Arenig.

Around much of the Harlech Dome, the subaerial erosion at the end of the Tremadoc was followed by deposition of a shallow marine Arenig sequence comprising bioturbated quartzose sandstones and conglomerates, flaggy siltstones and silty mudstones (Allt Llwyd Formation). In the south of the Harlech Dome, the rocks are transitional and conformable with the underlying Dol-cyn-afon Formation suggesting continued deposition in local basins. Towards the top of the formation the sandstones become volcaniclastic with interbedded tuffs, signalling the eruption of the Aran Volcanic Group. The Aran Boulder Bed, at the top of the formation, is a clast-supported conglomerate composed mostly of andesitic lava interpreted as a sequence of alluvial-fan gravels and subaqueous to subaerial sediment gravity flows, derived from a nearby contemporaneous shallow intrusion or extrusive dome (Allen and Jackson, 1985).

A marked difference in depositional environment between the north and south of the Harlech Dome then developed. Increased subsidence in the south, controlled by north-east-trending faults, subparallel to the Bala Lineament, allowed the accumulation of the Aran Volcanic Group, a thick succession of acid and basic tuffs, lavas, and intercalated sediments of early Llanvirn to Caradoc age which thins northwards. In the north, up to 700 m of silty mudstones with intercalations of ash-flow tuff, rhyolite and dacite, the sole representatives of the Aran Volcanic Group in this area, were deposited.

In the south, the lowest volcanic division of the Aran Volcanic Group is a succession of up to 290 m of massive to thinly bedded acid tuffs and tuffites, deposited both subaerially and subaqueously, interbedded with dark grey mudstones of Lower Llanvirn age (Offrwm Volcanic Formation). It is succeeded by 350 m of dark grey mudstones with impersistent basic tuffs and tuffites, acid tuffs and rare pillowed basaltic extrusions (Cregennen Formation) and, locally by basic tuffs, tuffite and thin pillowed, hyaloclastic flows, with basaltic breccias and gravity-flow breccias, interbedded with siltstones (Melau Formation). There is also a local development of up to 230 m of welded acidic ash-flow tuff and subordinate conglomerates (Brithion Formation) resting disconformably on Tremadoc-Arenig rocks adjacent to the Bala Fault. These rocks were derived from an adjacent rhyolite dome and locally appear to underlie a sequence of submarine, locally pillowed basalt lavas and basic tuffs with a few acid tuffs and mudstones (Llyn y Gafr Volcanic Formation), which reaches a maximum thickness of 360 m on the Cadair Idris range and represents the first major effusive volcanic episode in that area.

The Llyn y Gafr and Brithion formations are both disconformably overlain by a Caradocian sedimentary sequence (Ty’r Gawen Mudstone Formation) in which the lowermost beds comprise black, pyritic mudstones with numerous phosphate nodules and impersistent bands of oolitic and pisolitic ironstone, mainly of chamosite or limonite. South of the Llanegryn Fault, these beds are markedly unconformable on older strata. In the north the non-sequence is associated, in places, with an olistostrome (Rhyd Melange) which contains rafts of older Cambrian and Ordovician rocks some hundreds of metres across.

Caradoc volcanism began earlier around the Harlech Dome than in Snowdonia, with the second period of activity in the Aran Volcanic Group. Here 250 m of subaqueous crystal tuffs interbedded with tuffaceous siltstones, pillow lavas and hyaloclastites of Costonian age (Benglog Formation) rest unconformably on the earlier volcanic rocks. To the south-west, intercalated hyaloclastites, basalt lavas and gravity-flow breccias become more common as these rocks pass into the Pen y gadair Volcanic Formation. The following deposition of dark grey mudstones, and subordinate tuffaceous siltstones (Ty’r Gawen Mudstone Formation) was interrupted by the eruption of up to 210 m of acid ash-flow tuffs (Craig y Ffynnon Formation) and up to 300 m of basaltic and andesitic lavas, crystal tuffs and laharic (mudflow) breccias with intercalated mudstones (Pistyllion Formation). However, the climax of volcanism in the Arans came towards the end of the Costonian stage, with the widespread eruption of an extensive, 400-m-thick acidic ash-flow tuff (Aran Fawddwy Formation). This is the highest volcanic unit of the Aran Volcanic Group and its correlatives, the Craig Cau and Llyn Conwy formations, can be traced around much of the Harlech Dome. Acid eruptions, with debris flows, tuffs and tuffites from local centres, continued in the northern part of the area during the Costonian and Harnagian stages (Lower and Upper

Moelwyn Volcanic formations) and material erupted during the subsequent activity from centres to the north is preserved as the local representatives of the Llewelyn Volcanic Group and Snowdon Volcanic Group (see above).

With the close of volcanic activity, there ensued a period of uninterrupted marine basinal sedimentation, represented by black, laminated hemipelagic mudstones and thinly bedded, turbiditic, silty mudstones with thin, laminated siltstones, and slumped beds in the lower part of the succession (Ceiswyn Formation). Intercalated tuffs allow subdivision of the succession and equivalent deposits in the Berwyn Dome are represented by the Llangynog and Allt-tair-ffynnon formations. Over most of Berwyn, however, relatively low-energy, shallow marine conditions prevailed throughout the Soudleyan and Longvillian (Brenchley and Pickerill, 1980), with deposition of laminated and bioturbated mudstones and siltstones, together with cross-laminated, storm-generated sheet sands, massive, channelised sandstones and intraformational mudstone conglomerates separated by tuff horizons. The succeeding Nod Glas Formation, correlative of the Cadnant Shales of northern Snowdonia, is a widely developed division of up to 10 m of fissile, pyritic, black mudstones with phosphatic-nodule horizons in places and, locally a phosphatic limestone at the base. These rocks have been worked locally in the Berwyn Hills for phosphate.

The top of the Nod Glas is marked by a non-depositional break or erosional unconformity, above which the lowermost Ashgill is missing. The lowest Ashgill strata of the Derwen Anticline comprises up to 1600 m of calcareous, grey, burrow-mottled, silty mudstones, siltstones and subordinate shelly sandstones (Maerdy Mudstone Formation and its equivalents, the Moelfryn and Broad Vein formations) with local development of fossiliferous limestone at the base (Rhiwlas Limestone). Black, pyritous, laminated hemipelagic mudstones are present in the upper part of the succession (‘Red Vein’ of Pugh, 1929), and can be traced across large areas of the basin. North-eastwards, into Berwyn, the succession becomes generally coarser, with an increasing number of thin shelly sandstones (Dolhir Formation). The closing stages of the late Ashgill glacioeustatic regression are marked by deposition of massive, coarsely silty and sandy mudstones with beds of sandstone and conglomerate (Garnedd Wen Formation and Foel y Ddinas Mudstones). The acme of the regression is recorded by the transition into coarse shoreface sandstones and local bioclastic limestones (Glyn Formation; Brenchley and Cullen, 1984).

Lleyn

Basal arenaceous rocks (Parwyd Grit) and an Arenig to lower Llanvirn silty mudtone to sandstone sequence containing pisolitic ironstone and manganiferous horizons (Aberdaron Bay Group, Nant Francon Group) is followed by a substantial depositional hiatus prior to deposition of further sandstones and siltstones (Cwm Eigiau Formation). Extensively mined black massive pisolitic manganese ore occurs with manganiferous and pyritic mudstones of this age in tectonically disrupted faulted slices at Benallt near the western end of the Peninsula (Brown and Evans, 1989; Gibbons and McCarroll, 1993). The products of two mid-Caradocian volcanic centres, Llwyd Mawr and Llanbedrog, that form an integral part of the Snowdonia volcanism replace and follow the Cwm Eigiau Formation (Gibbons and Young, 1999). The volcanic rocks largely comprise intermediate to acid tuffs and lavas with intercalated marine siltstones (Dwyfach Formation) and volcaniclastic sediments (Yoke House Formation). Intermediate to acid high-level intrusions, including microgranites, microdiorites and dacites, are associated with the Llanbedrog volcanic event. These are overlain by graptolitic mudstones (Nod Glas Formation), up to 100 m of late Caradoc tholeiitic basalts and tuffs, and mudstones and siltstones of Ashgill age (Crugan Mudstone Formation).

South-west Wales

A broad belt of Ordovician volcanic and sedimentary rocks rocks crops out and runs northeastwards into the central Wales successions. The oldest strata exposed in the area south of Carmarthen are Tremadocian blue-grey and olive-green micaceous silty shales and subordinate sandstones (Cope et al., 1978; Owens et al., 1982). A series of andesitic lavas, tuffs and intercalated volcaniclastic sediments, with distinctive volcanogenic conglomerates in the upper part (Treffgarne Volcanic Group) may also be of Tremadoc age. They appear to lie unconformably beneath strata dated as early Arenig and is compositionally similar to the Rhobell Volcanic Group (Bevins et al., 1984).

The early Arenig records rapid transgressive deepening above the sub-Arenig unconformity. Locally preserved basal conglomerates grade upward through 150–350 m of hummocky cross-laminated sandstones, into laminated sandstones, siltstones and bioturbated mudstones (Ogof Hen Formation). In the Treffgarne area the Arenig succession includes a basal sequence of dark grey tuffaceous sandstones and mudstones with some tuffs (Brunel Beds). Thick tuffs of intermediate composition (Llandeloy Ashes) also occur locally and near the top there are mass-flow deposits of volcaniclastic sandstone (Traynor, 1988). Contemporary volcanicity is recorded by a faulted succession of silicified rhyolitic lavas and tuffs, volcanic and laharic breccias, tuffaceous mudstones, laminated siliceous siltstones and thin sandstones (Roch Rhyolitic Group). Evidence of volcanogenic massive sulphide mineralisation has been found associated with this event (Colman et al., 1995).

In the area around Carmarthen, the Ogof Hen Formation grades upwards into a sequence of micaceous mudstones and siltstones (Carmarthen Formation). Pebbly, quartzo-feldspathic turbidite deposits in the upper part of the succession indicate derivation from a Precambrian source to the south. In areas to the south and south-west, shallow-water facies of early mid-Arenig age (Blaencediw Formation) include sandstones containing clasts of Precambrian and Treffgarne volcanic rocks (Fortey and Owens, 1987). North-eastwards these rocks pass laterally into a basinal succession of acidic volcaniclastic turbidites and interbedded mudstones (Afon Ffinnant Formation).

Continuing subsidence during the mid-Arenig introduced a thick (300 m) succession of rusty-weathering, dark mudstones and siltstones (Penmaen Dewi Shale Formation, formerly the Tetragraptus Shales) in Pembrokeshire. Intermittent volcanic activity is recorded by thin beds of rhyolitic tuff within the sequence. In Carmarthenshire, comparable facies (Colomendy Formation and Pontyfenni Formation), are separarated by a turbiditic sequence of coarse, well-graded acid volcaniclastic sandstones with interbedded black shales (Cwmfelin Boeth Formation, Fortey and Owens, 1987). The uppermost Arenig strata in this area are pale grey mudstones which range into the Llanvirn (Llanfallteg Formation).

The main episode of volcanism in south-west Wales occurred during the Lower Llanvirn, with eruptive centres developed on Ramsey Island (Kokelaar et al., 1984, 1985), around Fishguard (Thomas and Thomas, 1956), and near Abereiddy (Cox, 1915). At the same time transgressive deepening introduced offshore environments in which black mudstones were deposited (Aber Mawr Shale Formation, formerly the D. bifidus Beds, and Caerhys Shale Formation, formerly the D. murchisoni Shales) and these are intercalated with the volcanic sequences. From the volcanic centre on Ramsey Island, rhyolitic and subordinate dioritic magmas were erupted. The emergence of a volcanic island and development of littoral conditions to the west of the Ramsey Fault introduced conglomerates, which rest unconformably on Cambrian rocks. The conglomerates are the basal member of a succession of up to 600 m of mostly subaqueous rhyolitic tuffs, commonly turbiditic and deposited close to their source (Carn Llundain Formation).

The Fishguard Volcanic Group comprises 1800 m of subaqueously emplaced acid to basic lavas and volcaniclastic deposits (Thomas and Thomas, 1956; Bevins, 1982; Bevins et al., 1984, 1992). The oldest unit consists of rhyolitic lavas, autobreccias, debrite breccias and tuffs, with a lesser amount of rhyodacitic lavas (Porth Maen Melyn Formation). It is overlain by over 1000 m of mostly basaltic pillow lavas, with subordinate thin basaltic hyaloclastites, tuffs and intercalated turbiditic sediments (Strumble Head Volcanic Formation) largely confined by a subsiding graben (Kokelaar et al., 1984). The overlying and youngest unit (Goodwick Volcanic Formation) is composed of rhyolitic lavas and autobreccias, with acid and basic tuffs. A series of hypabyssal doleritic and gabbroic rocks, with subordinate diorites, microgranites and microtonalites, intruded the volcanic pile and underlying strata, and deformed the wet sediments into which they were emplaced (Bevins et al., 1989). They extend beyond the outcrop of the Fishguard Volcanic Group, and are especially prominent to the east on Mynydd Preseli. To the south-west of Fishguard, they are represented by the gabbroic intrusions of Carn Llidi and St David's Head (Bevins and Roach, 1982), and by the Bishops and Clerks Islands (Bates et al., 1969). The volcanic pile thins rapidly away from its source centre. To the east the complex is dominated by thick rhyolitic lavas, subaqueous ash-flow tuffs and distal volcaniclastic turbidites (Lowman and Bloxham, 1981); the latter may be traceable as far east as Narberth (Kokelaar et al., 1984).

In west Pembrokeshire, near Abereiddi Bay, a 300 m development of rhyolitic tuffs, volcaniclastic sandstones and siltstones (Llanrian Volcanic Formation) may correlate with parts of the Fishguard Volcanic Group or be the products of a separate volcanic centre. These volcanic rocks are overlain by dark grey, locally tuffaceous mudstones (Caerhys Shale Formation) which in turn pass up into the Castell Limestone, a 15 m sequence of fossiliferous, blueish grey argillaceous limestones and shales. The succeeding dark silty mudstones and pyritous shales probably extend well up into the Caradoc. In the east of the region, where deep-water mud deposition continued unabated throughout the Llanvirn, evidence of volcanic activity is provided by a sequence of silicified tuffs with interbedded fossiliferous shales and siltstones of late Llanvirn age (Asaphus Ash). The overlying strata comprise argillaceous, flaggy limestones and thicker blue-grey calcarenites, with some thin tuffs at the base (Llandeilo Flags, Williams et al. 1972). This carbonate facies, which records the re-establishment of shallower platform environments towards the margins of the basin, is well developed in the Haverfordwest and Narberth areas, where it appears to overlie a non-sequence or unconformity (Williams et al., 1972). To the north, black calcareous mudstones (Hendre Shales) represent coeval off-shore facies.

Conformable deposition of black, pyritous, graptolitic mudstone facies, continued throughout the Caradoc in south-west Wales (Mydrim Shales, formerly the Dicranograptus Shales) but in Carmarthenshire lower Caradoc strata include the Mydrim Limestone, a 45 m sequence of impure calcareous mudstones and argillaceous limestones which formed due to a reduced supply of terrigenous mud. In north Pembrokeshire, the upper Caradoc succession is punctuated by thick sequences of south-westerly-derived turbiditic and mass-flow deposits, comprising sandstones and mudstones with subordinate siltstones and pyritous black mudstones (Newport and Poppit formations). The Nod Glas anoxic mudstone facies is mostly unrepresented in this part of the basin, possibly due to faulting or dilution of the anoxic component with turbiditic mudstone.

As in north Wales, a disconformity is locally associated with the Caradoc-Ashgill boundary in south-west Wales. Subsequently during the lower Ashgill shallow platform conditions promoted carbonate mud and sand deposition in Carmarthenshire (Robeston Wathen Limestone and Shoalshook Limestone Formation). These units are overlain by bioturbated mudstones, with micaceous and highly calcareous, fossiliferous sandstones (Slade and Redhill Formation). The succeeding rocks, consisting of 65 m of dark grey shales and a distinctive fine-grained buff sandstone (Portfield Formation) are overlain by highly fossiliferous mudstones of the late Ordovician to early Silurian (Haverford Mudstone Formation).

Central Wales and the Welsh borderland

Tremadocian rocks are preserved in a series of fault-bounded inliers within the Welsh Borderland Fault System and the Malvern Hills. In the Shelve Inlier they are unconformably overlain by a succession of up to 4500 m of Arenig to early Caradoc sediments with volcanic deposits at a number of levels. Similar successions are found elsewhere along the Welsh Borderland Fault System and the core of the Tywi Anticline is composed of rocks of Ashgill age. Ashgill strata also occur around Welshpool and in a series of major anticlinal fold cores within the basinal succession of mid-Wales, providing an important correlative link with North Wales sequences.

Tremadoc rocks. The Tremadoc succession of the Welsh borderlands is most complete in the Wrekin district, where it is represented by 1000 m of mottled bluish green and reddish mudstones passing upwards into bioturbated, micaceous sandstones and shales (Shineton Shales Group). Comparable strata are found in faulted contact with Precambrian rocks in the Shelve area (Habberley Shales Formation), and a sequence of olive-green and grey shales at Pedwardine to the south-west has also been referred to the Tremadoc (Stubblefield and Bulman, 1927). On the south-western flank of the Malvern Hills 300 m of greyish green and blue, silty, micaceous mudstone (Bronsil Shales) similar to the Shineton Shales are found (Bulman and Rushton, 1973).

Arenig and Llanvirn: Shelve Inlier. Here over 1000 m of sandstones, siltstones and shales (Shelve Group) unconformably overlies the Tremadoc rocks (Habberley shales). At the base is a 120 m thick transgressive shallow marine facies, comparable with other early Arenig sequences in Wales and composed of thick-bedded pale-grey quartzose sandstones with subordinate shales and, commonly, a basal polymict conglomerate (Stiperstones Quartzite Formation, Whittard, 1979). These rocks pass upwards into a thick sequence of flaggy, micaceous siltstones and shales containing abundant graptolites and inarticulate brachiopods (Mytton Flags Formation). A disconformity possibly separates these rocks from the overlying Llanvirnian (Hope Group, formerly D. bifidus Beds) which mostly comprises up to 1200 m of widely deposited dark-grey and black, pyritous, graptolitic mudstones and siltstones.

Eruptions from two local volcanic island centres interrupted marine sedimentation. The older, deposits consist of acid vitroclastic tuffs and volcaniclastic sandstones interbedded with black shaly mudstones (Hyssington Volcanic Formation), while the younger comprises up to 1000 m of volcaniclastic beds of basic to intermediate composition interbedded with mudstones (Stapeley Volcanic Formation). The rocks include crystal and scoriaceous tuffs and agglomerates, together with debrites and beach deposits formed around emergent volcanic islands. The overlying rocks records a phase of renewed transgressive deepening that drowned the islands. Thick bedded to flaggy, rippled and cross laminated shelly sandstones and siltstones, indicative of inner shelf sediments, are followed by dark grey, micaceous siltstone and mudstone with thin tuffs. These in turn are succeeded by 300 m of late Llanvirn black graptolitic shales and some limestones.

Llanvirn: Builth Inlier. Comparable Llanvirn strata are preserved in the Builth Inlier which lies along the Pontesford Lineament. In common with other areas, black graptolitic mudstones form the dominant background sediment to thick intercalated sequences of subaerial and shallow-water calc-alkaline volcanic and pyroclastic rocks (Bevins et al., 1984). Over 600 m of mudstones with locally interbedded tuffs (Camnant Mudstones, formerly D. bifidus Beds) are succeeded by up to 700 m of lavas, ashes and agglomerates ranging from spilitic to keratophyric in composition (Builth Volcanic Formation) with interbedded mudstone representatives of the former D. Murchisoni Shales. Fossil sea stacks and cliff lines associated with shoreline deposits comprising boulder beds and coarse feldspathic sandstone provide evidence of an emergent volcanic island, similar to that of the Shelve area. At the top of the volcanic sequence is a widespread white, porcellaneous tuff (Cwm-amliw Tuff), which is succeeded by 600 m of grey shaly late Llanvirn to Caradoc mudstones with scattered tuffaceous bands and thin argillaceous limestones (Llanfawr Mudstones).

The rocks of Llanvirn age which outcrop around Llandeilo, south-west of Builth, provide a link with sequences in south-west Wales and includes the type development of the former Llandeilo Series. Graptolitic mudstones and tuffaceous shales (D. bifidus Beds) grade upwards into a diverse 90 m thick sequence of sandstones, conglomerates and rhyolitic tuffs with subordinate siltstones, mudstones, argillaceous limestones, agglomerates and tuffites (Fairfach Group). The volcaniclastic material indicates reworking of various lavas and pyroclastic deposits derived from the Builth centre in a range of sublittoral to intertidal settings. The fining-upward transition at the top of the group (Llandeilo Flags) into the black graptolitic mudstones of the Caradoc records the major transgression that followed the cessation of Llanvirn volcanism.

Caradoc. Shallow-water Caradoc shelf sequences of Shropshire record a rapid, but pulsed marine encroachment from the west in south Shropshire. These facies include quartz conglomerates, feldspathic grits and sandstones, calcareous sandstones and shelly limestones (Coston Formation and Hoar Edge Grits). Comparable sequences of conglomerate and sandstone are seen in faulted inliers at Pontesford and in the Pedwardine area.. The offshore equivalents in the Shelve area comprise a 90 m sequence of sublittoral calcareous sandstones in the Shelve area (Spy Wood Sandstone Formation). Upward and lateral transition of these lithologies into shales was the result of transgressive deepening and in offshore areas mud deposition was sustained throughout the remaining Caradoc. In the Shelve area these rocks form the bulk of the Chirbury Group, but which also includes two thick volcaniclastic sequences (Hagley and Whittery volcanic formations). Laterally equivalent Caradoc mud facies are found in the Pontesford Fault Zone (Pontesford Shales), around Welshpool (Trelydan Shale and Middle House Mudstone formations), and in the the Breidden Hills (Stone House and Hill Farm shale formations).

The south-eastward shift of facies belts as a result of transgressive deepening introduced offshore micaceous siltstones and laminated mudstone deposition to the former nearshore areas of south Shropshire (Harnage Shale and Smeathen Wood formations). Deposition of this facies continued in places throughout Soudleyan times (Glenburrel Formation) but it passes laterally (inshore) and upwards into sandstone dominated successions (Chatwall Flags, Chatwall Sandstone, Horderley Sandstone Formation). Sandstone facies also occur in the Welshpool area (Pwll-y-glo and Gaerfawr formations). In South Shropshire the sandstones are followed by a coquinoid limestone which also includes shell-rich beds of sandstone and siltstone (Alternata Limestone Formation). It marks a renewed transgressive pulse which reworked the surface of the underlying sandstones and the presence of phosphate nodules locally suggests that, in places, it also transgressed a non-depositional surface. A comparable non-sequence separates the Gaerfawr Formation from the Nod Glas in the Welshpool area. In Shropshire the Alternata Limestone is succeeded by 180 m of laminated sandstone and siltstone, representing a further storm-generated offshore facies (Cheney Longville Formation), 60–70 m of mudstones and siltstones (Acton Scott Formation), and 50–60 m of bioturbated and laminated mudstones (Onny Shale Formation), marking the transition to low-energy offshore deposition.

Basinal Caradoc facies comprising black graptolitic mudstones occurs to the west of the Welsh Borderland Fault System, in faulted inliers along the Tywi Anticline. They are recorded near Rhayader (St Cynllo’s Church Formation), south of Welshpool (Forden Mudstones Formation) and around Llanwrtyd Wells (Sugarloaf Formation). White bentonites occur scattered throughout these successions and in places thick sequences of turbiditic sandstone are developed. Black shales, equivalent to the Nod Glas, occur at the top.

Caradoc volcanicity in the Welsh borderlands was subordinate to that in North Wales, but the products of both subaqueous and subaerial eruptions from local centres are preserved. In the northern part of the Builth Inlier, coarse basaltic breccias (Trelowgoed Volcanic Formation) overlie the late Llanvirn to early Caradoc mudstones. To the south-west in the Llanwrtyd area agglomeratic tuffs, rhyolitic breccias and spilitic rocks with well developed pillow structures, occur interbedded with tuffaceous mudstones and black shales equivalent to part of the Mydrim shales. In the Shelve area andesitic and rhyolitic tuffs, agglomerates and interbedded shales (Hagley and Whittery volcanic formations) were deposited and in the Breidden Hills, rhyolitic tuffs and andesitic conglomerates interbedded with sandstones, thin limestones and micaceous shales (Breidden Volcanic Group, Dixon, 1990) are preserved. In both the Shelve and Builth inliers, and locally along the Tywi Anticline, the Caradoc and older rocks are intruded by sheets and lenses of dolerite whose their high-level emplacement is indicated locally by contemporary wet-sediment deformation of the surrounding mudstones.

Ashgill. Shelf facies of this age are generally not preserved to the east of the Welsh Borderland Fault System, though there is evidence that the Ashgill shoreline lay some distance to the east of the Tywi Anticline. The Ashgill rocks of the Tywi Anticline and the mid-Wales Ordovician inliers are predominantly of basinal character, consisting of at least 2000 m of mudstones and subordinate sandstones with thick slumped sequences. The lowermost Ashgill strata generally comprises over 1000 m of bioturbated grey silty mudstones with thin sandstones and siltstones and scattered thin phosphate-nodule horizons (Nantmel Formation, Trawscoed Mudstone Formation, Nant-y-moch Formation, Tresaith Formation). Horizons of laminated hemipelagic mudstone within the upper part of the succession represent anoxic levels, correlating with the Red Vein of North Wales. Some lenticular bodies of massive quartzose sandstone and conglomerate probably accumulated along narrow fault-defined submarine troughs.

In the Tywi Anticline the overlying rocks, of late Ashgill age, consist of up to 700 m of massive and laminated, micaceous silty mudstones with subordinate fine-grained sandstones (Yr Allt Formation). Thick units of slumped and destratified mudstone ('disturbed beds'), and horizons of coarse quartzose sandstone, polymict conglomerate and pebbly mudstone are present in the upper part of the formation. Correlatives within the central part of the Welsh Basin are successions of dark grey, massive mudstones, sandstones and slumped beds (Drosgol Formation, Bryn-glas Formation and Llangranog Formation) that may also equate with parts of the Slade and Redhill Beds of south-west Wales. In places along the faulted eastern margin of the Tywi Anticline a Rawtheyan medial to distal shelf facies of dark, micaceous, bioturbated, sandy mudstones and thin sandstones with brachiopod and trilobite detritus is found (Pentre and Wenallt formations). Westward migration of facies belts in response to the late Ashgill glacio-eustatic regression progressively introduced inshore environments along the Tywi Anticline which, by this time, broadly delimited the basin margin. Littoral and sublittoral, fine to coarse sandstones and interbedded mudstones containing a Hirnantian fauna characterise these strata (e.g. Cwmcringlyn and Scrach formations). A subsequent transgressive sequence (e.g. upper part of the Cwm Clyd Sandstone of the Garth area, Williams and Wright, 1981) formed as a result of postglacial sea-level rise during the latest Ordovician. The effects of this transgressive deepening were to create anoxic conditions within the basin that persisted into the early Silurian.

Silurian basin and shelf deposits

Large areas of mid- and North Wales are underlain by Silurian basinal facies dominated by turbiditic mudstone and sandstone. Shelf facies of Llandovery to Ludlow age were deposited to the east of the Tywi Anticline and Welsh Borderland Fault System, although intra-Llandovery uplift and erosion removed much of the earlier parts of the succession. The highest Silurian comprises Pridoli (Downtonian) continental strata in the Welsh borderland and South Wales.

North Wales

A full Llandovery sequence is present only in the Vale of Conwy, although comparable incomplete sequences are preserved on Parys Mountain (Anglesey) and at Llanystumdwy. In the Vale of Conwy a mixed sequence up to 400 m thick of dark grey turbiditic and hemipelagic graptolitic mudstones and pale, burrow-mottled mudstones is recorded (Bryn Dowsi Mudstone Formation). The alternation of the two facies is a common feature of contemporary basinal facies throughout Wales (Davies et al., 1997). The succeeding Pale Slates, up to 118 m thick, comprise basal passage beds, overlain by locally burrow-mottled, pale grey-green mudstones of turbiditic and hemipelagic origin; typical of coeval strata throughout the Welsh Basin. In the Derwen Anticline, an unconformable sequence of middle Llandovery sandstones and siltstones (Bron y graig Formation) is overstepped by the local representative of the Pale Slates, the Bettws Mudstones (British Geological Survey, 1993).

At Parys Mountain, Anglesey, graptolite-bearing blue-grey to black thinly laminated shales of Llandovery age are preserved in a folded and faulted inlier. They are important in constraining the age of underlying volcanic rocks that are associated with substantial base-metal sulphide mineralisation of volcanogenic affinity. Until recently these volcanic rocks were assumed to be Caradocian but recent isotopic dating (using zircons) indicates that they are of Lower Silurian age (Parrish *in* Barrett and MacLean, 1999). This indicates that Parys Mountain was the site of submarine eruption of a series of rhyolites and subordinate basalts in the Llandovery. The chemical signatures of the bimodal volcanism indicates that it was originally sub-alkaline in character and formed in an inter-plate setting where submarine continental crust was being rifted (Barrett and Maclean, 1999).

Wenlock strata outcrop principally to the west and south of the Denbigh Moors with smaller outcrops in the Clwydian Range. South of the Bala Lineament, they underlie Llantysilio Mountain and Maesyrychen Mountain. Contiguous Ludlow facies occur in all these areas. So called 'ribbon-banded' mudstones, in which structureless turbidite mudstones alternate with laminated hemipelagite mudstones on a 1–2 cm scale, enter in the upper part of the Pale Slates and, on Maesyrychen Mountain, make-up the entire 600 m Wenlock sequence. To the west, the appearance of the westward- and northward-thickening Denbigh Grit Group divides this ribbon-banded sequence and separates the basal Nant-ysgollon Shales from the younger Nantglyn Flags. In the Denbigh Grits, packets of thick- to thin-bedded, commonly coarse-grained, turbidite sandstones and 'disturbed beds' (slumps and debrites) are subordinate to silt-laminated turbidite mudstones in a sequence up to 1.1 km thick. Clasts and heavy-mineral assemblages suggest that sand and pebble-grade detritus was supplied from emergent local tracts of Precambrian and Ordovician rocks (Warren et al., 1984).

Ludlow Series rocks underlie much of the Denbigh Moors and the Clwydian Range and occupy the core of the Llangollen Syncline. Throughout these areas the base of the series lies within the upper part of the Nantglyn Flags. The base of the succeeding Elwy Group marked a major resurgence in the supply of westerly derived silt-laminated turbidite mudstones and disturbed beds to the basin. A sequence in excess of 1.75 km in thickness accumulated in the west, but a little over 600 m is present in the Llangollen Syncline and just 450 m in the Clwydian Range. Packets of turbidite sandstones are less common, and the individual turbidites are generally fine grained and of more distal aspect than in the otherwise comparable Denbigh Grits (Warren et al., 1984).

Mid-Wales

The Silurian of mid-Wales, linked with the North Wales succession by strata in the core of the Llandderfel Syncline, comprises a comparable succession of alternating dark grey, graptolitic mudstones and paler bioturbated mudstones. Thick sequences of turbiditic sandstone facies occur in the upper Llandovery and Wenlock. The late Ashgill to early Llandovery postglacial sea-level rise introduced anoxic bottom conditions to the basin resulting in the deposition of up to 500 m of thinly interbedded turbidite mudstones and thinly laminated, graptolitic, hemipelagic mudstones (Cwm yr Aethnen Mudstones and Cwmere Formation). Equivalent strata are found in west Wales (Gaerglwyd Formation, Anketell, 1987). Along the western margin of the Tywi Anticline south of Rhayader, and around the adjacent Rhiwnant Anticline, the mudstones pass locally into a 700 m thick lenticular body of turbidite conglomerates, sandstones and subordinate mudstones (Caban Conglomerate Formation). The conglomerates include extrabasinal clasts of rhyolite, granite, granophyre and diorite, as well as shelly debris derived from the south-east. It mostly represents a braided channel system which sourced a westerly sequence of turbidite sandstones, mudstones and hemipelagites, locally with shelly turbidite sandstone and phosphatic conglomerate (Ystrad Meurig Grits Formation) exposed in the Ysbyty Ysteryth Inler. In places along the eastern side of the Tywi Anticline, a 750 m mudstone sequence, the correlative of the Cwmere Formation further west, includes intervals of burrowed oxic mudstone (up to 50%) and slumped strata (Tycwtta Mudstones). It also includes the Allt-y-clych Conglomerate, a distinctive 20 m thick unit of massive debrites, turbiditic pebble-cobble conglomerates and sandstones. These rocks are everywhere conformably overlain by a 650 m succession mainly composed of thinly interbedded greenish-grey turbidite mudstones and burrowed hemipelagites, but with a few thin horizons of anoxic mudstone. The M. Sedgwickii Shales, a thin horizon of black, laminated hemipelagic mudstones that is found throughout mid-Wales divides the group. A silt- and sand-rich facies in the upper part of the group is associated with the expansion of south-east-derived turbidite fan systems which introduced extensive sequences of thinly interbedded, mainly oxic turbidite sandstones and mudstones. (Hafdre Formation and Devil's Bridge Formation). These strata, 400–500 m thick, occupy large areas of the Llanilar and Aberystwyth districts and extend northwards into the Corris area.

Major tectonic reconfiguration of the basin during the mid- to upper Telychian saw the introduction of southerly sourced sandstone-turbidite lobe systems which progressively replaced the earlier mud-dominated facies eastwards. Large-scale faults were important in controlling the disposition of these individual systems, which are now represented by the Aberystwyth Grits Group and Cwmystwyth Grits Group; a third turbidite lobe system was introduced in the Wenlock into eastern parts of the basin (see below). They mainly consist of medium- to thin-bedded sandstone-mudstone turbidite deposits with laminated and burrowed hemipelagites. Over wide areas, they are intercalated with packets of thick-bedded turbidite sandstone and subordinate pebbly mudstone. The Aberystwyth Grits Group is the most westerly system, occupying the coastal tract between New Quay and Clarach while the younger Cwmystwyth Grits Group to the east occupies the core of the Central Wales Syncline. Sequences of grey turbiditic mudstone with both burrowed and laminated hemipelagite interdigitate with, and grade into, the turbidite sandstone facies (Borth Mudstones, Blaen Myherin Mudstones, Adail Mudstones and Caerau Mudstones). In the youngest (Wenlock) and most easterly sandstone-lobe facies (Penstrowed Grits Formation) Bouma-type turbidites interdigitate with high-matrix sandstones. The presence of abundant bioclastic material in the latter reflects the proximity of this system to the eastern shelf area. In turbiditic mudstone facies flanking this Wenlock sandstone system, the intercalated hemipelagic deposits are principally of the laminated type (Nant Ysgollon Mudstones and Nant Glyn Mudstones). In the Montgomery area, Ludlow turbidite facies comprising interbedded shelly sandstones and mudstones (Barley Hill Formation) are confined by the Church Stretton Fault.

South Wales and the Welsh borderland

A shelly, shallow shelf succession was deposited in muddy, marine environments to the east and south of the Welsh Basin where global sea-level rise caused by late Ordovician deglaciation resulted in eastward and southward extension of the depositional area. Re-newed volcanism occurred locally.

At the type locality, the Llandovery succession comprises 1200 m of silty mudstones and fine-grained sandstones. Comparable Llandovery facies also occur further north in the Garth and Builth areas. Rifting on the margins of the Midlands Platform in Lower and Middle Llandovery times resulted in thick, localised accumulations of sandstones and siltstones in the Usk and Woolhope basins, while in the Malvern Hills a basal red-bed sandstone and conglomerate with overlying marine mudstone, siltstone and sandstone facies was deposited (May Hill Sandstone Group).

In western Pembrokeshire the Llandovery is represented by a c. 760 m thick succession of lavas and pyroclastic deposits with minor sedimentary rocks (Skomer Volcanic Group) which thin rapidly eastward so that around Havefordwest 800 m of shelly mudstones and siltstones rest conformably on uppermost Ordovician strata., The volcanic rocks comprise alkaline and subalkaline basalts, rhyolites and tuffs whose chemistry suggests eruption in a within-plate setting (Thorpe et al., 1989). They have always been considered to be the youngest substantial volcanic event associated with the Caledonian known in Wales, but recent work (Barrett and Maclean, 1999) indicates that a similar suite was erupted at Parys Mountain, where it hosts substanial massive sulphide deposits.

The oldest rocks of the Wenlock Series in the Welsh borderland are shelly siltstones and mudstones with nodular, shallow-water impure carbonate beds (Buildwas Formation and Woolhope Limestone Formation). The overlying pale-green mudstones and siltstones with thin, nodular limestones and bentonites (Coalbrookdale Formation) are succeeded by bioclastic limestones with sporadic small patch reefs (Much Wenlock Limestone Formation). Shelly calcareous mudstones and impure limestones of shelf facies are present at Llandeilo. A thick succession of laminated calcareous mudstones of distal shelf aspect, but with local slumped horizons (Builth Mudstones and Striped Flags) makes up much of the Wenlock and early Ludlow succession in the Builth area. The Pen-y-lan Mudstone of the Rhymney Inlier, Cardiff (equivalent to the Coalbrookdale Formation) comprises grey-green mudstones with thin sheet sandstones and some impure limestones. The overlying succession (Cae Castell Formation) is predominantly arenaceous with the Rhymney Grit, a cross-stratified, pebbly sandstone at its base. In south Pembrokeshire a succession of richly fossiliferous cleaved silstones and thin limestones and thin bentonites (Coralliferous Group) passes up into grey and green sandstones containing marine fossils in the lower part but becoming upwardly deltaic (Gray Sandstone Group), indicative of regression and onset of Old Red Sandstone environments.

Ludlow sedimentation represents a shallowing, regressive sequence while evidence of continuing minor volcanism is provided by several thin bentonite horizons. In the Welsh borders, the type area comprises comprises olive green, shelly mudstones and siltstones at the base (Elton and Lower Bringewood formations) followed by limestones and calcareous siltstones with hardgrounds and limestone conglomerates (Upper Bringewood Formation). Green-grey mudstones and siltstones with a restricted brachiopod fauna follow (Leintwardine and Whitcliffe formations of the Ludlow area). To the west of Ludlow, west-directed slumping and sliding resulted in the local removal of older strata and deposition of a boulder bed and a thick succession of sandy siltstones with slump beds. The Ludlow rocks in south-east Wales consist of mudstones, thin siltstones and subordinate thin sandstones and bioclastic limestones (Cardiff Group) while is Pembrokeshire there are redbeds (Milford Haven Group) formed in mudflat to alluvial environments and a possible conformable transition into the Lower Devonian.

In the Welsh borders the base of the Pridoli Series is marked by a phosphatic fossiliferous lag deposit, the Ludlow Bone Bed, at the base of the shallow marine Downton Castle Sandstone Formation (or Tilestones Formation of Powys). This is overlain in mid-Wales and the west Midlands by grey to olive-green siltstones (Temeside Shales) of possible estuarine mudflat origin (Allen, 1974). The red mudstone- and siltstone-dominated successions above span the Silurian–Devonian boundary (Sandy Haven and Moors Cliff formations in Pembrokeshire, Raglan Mudstone or Ledbury Formation in SE Wales and Gwynfa Formation in Powys). The strata consist of red mudstones and siltstones with sporadic fluvial sandstones and abundant calcretes with air-fall tuffs near the top of the succession providing evidence of continuing volcanic activity.

Post-Caledonian cover

Devonian

The Devonian (Old Red Sandstone) rocks are the molasse deposits of the Caledonian Orogeny and were deposited following inversion of the Welsh Basin, thereby falling outside the remit of this study. The rising Caledonian mountain front to the north shed alluvial detritus southwards towards a shoreline that remained mostly south of the Bristol Channel. The main outcrop is in south and mid-Wales and the Welsh borderland, with smaller outcrops in Anglesey. Shallow marine and coastal plain environments in the late Silurian were succeeded by increasingly proximal terrestrial alluvial facies.

Carboniferous

Lower Carboniferous (Dinantian) rocks (the Carboniferous Limestone) were deposited as warm-water carbonates in shelf to ramp and carbonate platform settings on the northern (North Wales) and southern (South Wales and Forest of Dean) flanks of the Wales–Brabant Massif. In North Wales they are exposed on Anglesey and along the Menai Strait, on the west side of the Vale of Clwyd and adjacent coastal tract and along the eastern flank of the Clwydian Range. In the south, they form narrow outcrops peripheral to the South Wales, Pembrokeshire and Forest of Dean coalfields. There are also small outliers at Titterstone Clee in Shropshire and Pen Cerrig-calch in the Black Mountains.

Namurian strata (‘Millstone Grit’) outcrop around and underlie the South Wales Coalfield. In North Wales, they are present at outcrop only in a narrow belt from Prestatyn in the north to Ruabon and Oswestry in the south. In South Wales, basin development commenced in the south-west with pulsed, eustatic sea-level rises causing the depositional area to expand, reaching the present north-east and east crops of the coalfield. Consequently, there are 550 m of strata in the Gower area of south-west Wales and less than 20 m in the east. The rocks in North Wales represent a thin, basin-margin succession in which the complete age range is represented.

Westphalian strata (Coal Measures) outcrop most extensively in South Wales and Pembrokeshire, in the Flintshire and Denbighshire coalfields of North Wales and in the Forest of Dean with a smaller outliers preserved in Anglesey. The succession mostly comprises cycles of fluvio-deltaic parasequences deposited in lower-delta-plain, fresh-water lacustrine environments. These consist of coarsening-upwards lacustrine mudstones, siltstones and fine-grained sandstones which then fine upwards into siltstones and claystone palaeosols overlain by coals, most of which formed as basin-wide peat mires. Glacio-eustatic marine incursions introduced saline to brackish water and deposited marker marine mudstones. Thick sandstones throughout the succession are the infill of incised valleys and distributary channels while thinner sandstones were deposited as levées, crevasse splays, lake-mouth bars and deltas. Red beds succeed the productive, grey, coal-bearing Coal Measures, representing oxidising alluvial environments and more arid climatic conditions. Bedded and nodular sideritic ironstones within the argillaceous strata were formerly of major economic importance. Thin volcaniclastic layers (tonsteins) occur sporadically.

Permian, Triassic and Jurassic

Inversion and erosion of the Carboniferous basins during the Variscan orogeny was followed by east–west extension and rifting in the Triassic. Rocks of possible Permian age in the Welsh borderland include some coarse, alluvial-fan and scree deposits on the flanks of the Worcester and Staffordshire basins (the Clent Formation and Haffield Breccia) and the aeolian Bridgnorth Sandstone Formation. Much of Wales remained as a positive area, with rifting on its margins. Triassic rocks occur in the Vale of Clwyd in the north and along the south coast eastwards from Porthcawl. Most of the succession comprises red beds, deposited in a hot, tropical climate.

Jurassic seas may have covered most of Wales but rocks at surface are now restricted to the Cardiff-Porthcawl area of South Wales where a typical Liassic succession of impure limestones and shales is found. Thick successions are recorded offshore and in the Mochras borehole, on the coast south of Harlech. No Cretaceous rocks are preserved in the area of the study.

Tertiary

In North Wales, Palaeogene deposits occur as pockets and cavities in the outcrop of the Carboniferous Limestone and a small fault-bounded basin along the coast between Porthmadog and Barmouth. The former consist of variously coloured sands, silts, clays and breccias, thought to represent remnants of a formerly continuous sheet of fluvio-lacustrine sediments let down and preserved in the solution pipes. In Pembrokeshire similar deposits (Flimstone clays) occur either as cavity fills in, or down-faulted against, the Carboniferous Limestone.

Dolerite dykes of this age are widespread in North Wales, particularly on the Lleyn and Anglesey, where magnetic surveys have indicated that they are more common and persistent than mapped (Smith and Cooper, 1979). They have a north-westerly trend and are part of a more extensive Irish Sea dyke swarm, probably associated with igneous centres in Northern Ireland (Bevins et al., 1996).

Quaternary

The widespread Quaternary deposits are largely the products of the latest (Devensian) glaciation. They blanket much of the low-lying areas and the deposits of localised ice-caps and valley glaciers are preserved in many parts of Wales. Flandrian sediments are mainly associated with present-day river systems, and are commonly developed within the coastal tracts.

The high ground of Wales generated ice caps, from which glaciers flowed radially. Irish Sea ice flowing south-eastwards was divided by the Welsh massif, one branch flowing into the Vale of Clwyd and the lowlands to the east, the other flowing southwards across Anglesey and the Lleyn into Cardigan Bay and on to Pembrokeshire and the Gower. Complex sequences were deposited where the Welsh and Irish Sea ice sheets met. Lodgement till was deposited under the advancing glaciers and on their retreat a range of melt-out and flow tills, morainic deposits and outwash sands and gravels were deposited. Glaciolacustrine deposits laid down in ice-ponded lakes formed both on advance and retreat of the glaciers. The latest glacigenic deposits were formed by cwm glaciers in Snowdonia during the Loch Lomond Stadial. All the glacial erosional and constructional landforms, including cms, drumlins, eskers, kame terraces and kettle holes, are the products of the last main glaciation, except for the protalus ramparts and small moraines of the Loch Lomond Stadial.

There is widespread tripartite succession in North Wales, comprising basal till, middle glaciofluvial sand and upper till, interpreted as the product of the advance and retreat of a single ice sheet (e.g. Bowen, 1974). Drift thicknesses range up to 100 m, but generally are up to 20–30 m. There are two basal till types, reflecting their provenance: (1) a stiff, overconsolidated, purple-grey clay lodgement till containing erratics of Cumbrian and Scottish provenance and abundant comminuted shell debris, and (2) a red-brown till rich in Triassic erratics deposited by ice streams that crossed the Triassic of the Lancashire coast and the margin of the Irish Sea. In areas with thin drift cover, this basal lodgement till is the only deposit; in areas of thicker drift the till is the basal unit of a multi-layered complex. In the lowland areas, the till forms a variety of landforms, including drumlins, ridges and hummocky terrain. The upper till is sandier and less compact than the lower one, brown to blue-grey in colour, with a similar erratic suite. It forms the surface layer over wide areas, draping the underlying glaciofluvial sands conformably. It is interpreted as a flow till.

In Anglesey, the lower till is blue and compacted, the upper one is red and unconsolidated. The coalfield valleys are lined with till from glaciers fed from ice accumulating on the Brecon Beacons in the Late Devensian. Morainic deposits of these and other valley glaciers are found in the main river valleys in south-east Wales and the Welsh borderland. Beyond the Devensian ice limit in South Wales till, solifluction and fluvial deposits related to an earlier glaciation are preserved locally.

Glaciofluvial sands and gravels occur as constructional landforms such as kames and kame terraces, as sheet deposits of proglacial outwash fans, and as locally stratified deposits underlying or interbedded with till. Glaciolacustrine deposits formed in temporary ice-dammed lakes and are almost entirely of Late Devensian age exceprt for some older deposits outside the Devensian ice limits in the Welsh borderland. River terrace deposits occur throughout the area and consist of sands and gravels deposited during cold and temperate stages of the Pleistocene.

Head is ubiquitous throughout the area, most of it originating by a combination of gelifluction, solifluction and colluvial processes during deglaciation at the end of the Devensian, although these processes continue today, particularly in the mountainous area. Landslip deposits are common on the flanks of the steeply incised valleys of the South Wales Coalfield; most were inititiated when the Late Devensian valley glaciers melted, but movements continue today.

There are widespread areas of recent alluvium, particularly in the estuaries and valleys of major rivers. The deposits comprise fresh-water, estuarine and marine alluvial silts, clays and sands. Aeolian deposits also occur locally as dune sands, mostly in coastal areas. All these recent deposits may locally contain concentrations of heavy minerals, dictated by source and, in some cases, human activity. For example, gold is present in the estuarine sediments of the Afon Mawddach and nodular monazite widespread in alluvial deposits (e.g. Smith et al., 1994).

Peat deposits, which occur in some low-lying areas and widely as upland blanket bogs, can can form an appreciable obstacle to mineral exploration.

Structure

Two events, the Caledonian and Variscan orogenies, have profoundly affected the rocks and control their current form and distribution. For most of its history the bathymetric axis of the Welsh Basin, which is a product of Caledonian events, ran through central Wales in a present-day south-west–north-east direction and the major Caledonian structures are roughly parallel with this alignment. In the south the Variscan orogenic front impinges upon the southern side of the basin (Figure 6). The structures seen in the rocks of the basin are the product of two main processes, regional tectonic forces, modified and influenced by basement structures, and gravitational (soft sediment) deformation. Within the basin the separate effects of the two processes are not always easy to determine.

Caledonian

Caledonian events affecting the Welsh Basin centre on the closure of the Iapetus Ocean and the resulting collision of Laurentia, Avalonia and associated microcontinents. It is believed that the development and form of the Welsh Basin in the late Precambrian onwards was influenced by pre-existing basement fractures: the south-east margin being controlled by the Welsh Borderland fault system and the north-west side by the Menai Straits fault system (Woodcock, 1984a, Gibbons, 1987). Other major lineaments (e.g Bala, Trawsfynydd, Beddgelert, Llangranog, Central Wales and Tywi) exerted control within the basin itself on both sedimentation and volcanism (e.g. Fitches and Campbell, 1987, Woodcock, 1984b, 1990b; Craig, 1987; Smith, 1987; Gibbons, 1987; Woodcock and Gibbons, 1988; Davies et al., 1997).

From its inception a series of tectonic events affected the basin, producing regional or local unconformities, non-sequences and changes of depositional environment, but by far the most significant event recorded is the climax of the orogeny at the end of the Silurian (Acadian event). This produced several major north-east trending structures widely recognised in the basinal rocks and on its margin. Strike slip movement along major faults reflected the oblique nature of collision and closure. Several authors have described the polyphase nature of the end-Caledonian events but in many cases these may be local phenomena related to fault and block movement rather than regional correlatable events.

In south-west Wales, the northern Pembrokeshire area is dominated by two anticlinal axes: the east–west trending Velindre anticline with Fishguard Volcanic Group rocks along its northern limb, and the east–north-east trending Fishguard anticline. Tight, upright to gently-verging folds were created with associated axial planar cleavage. To the south, blocks of Precambrian basement and the Variscan front influence the structure of the Lower Palaeozoic rocks. The major, east-west trending, periclinal, asymmetric anticlines and synclines have steep, northerly dipping axial planes and coaxial mesoscale folds, with amplitudes of between 0.5 and 1 km, affect the limbs of the major structures. Still-smaller-scale folding is widely observed. The anastomosing pattern of faults which affect the Lower Palaeozoic succession appears complex but regionally the faults can be viewed as elements of an east-west striking belt of dislocation broadly co-linear with the folds.

In Central Wales the outcrop pattern is dominated by three major north-easterly-trending complex open fold structures with axial planes between 10 and 15 km apart: the Teifi Anticline, Central Wales Syncline and Tywi Anticline (Figure 6). The Teifi Anticline is an upright to steeply inclined periclinal structure whose axial trace is less well defined north of the Ystwyth Fault. The complementary Central Wales Syncline has a similar open structure and preserves a thick sequence of late Llandovery turbidite sandstones in its core. The Tywi Anticline is a tight inclined structure with a vertical to overturned south-eastern limb disrupted by a network of anastamosing strike faults and cored by Ordovician rocks. To the east pervasive Caledonian deformation ceases in the shelf facies rocks of the basin margin. In the north-east the Berwyn Dome is a broadly east-west oriented periclinal structure which, together with some other domes, may represent a horst-like structure supported by low density acid intrusives. Also evident at the regional scale in Central Wales are prominent periclinal second order folds with axial plane separations of 1 to 5 km (e.g. Rhiwnant Anticline on the north-western flank of the Tywi Anticline). Several lower order folds with varying orientation, form and facing directions are also present. Strike faults in Central Wales, some traceable for 15 km sub parallel to the regional fold trend, have large pre-Acadian displacements but little evidence for substantial movement during the Acadian (end-Silurian) event. Sets of transverse faults cross-cut the folds and cleavage. The most prominent of these is the east-north-east-trending Ystwyth Fault, which is associated with vein mineralisation structures and at one point has a sinistral displacement of 1.3 km and vertical downthrow of 300 m to the north (Davies et al., 1997).

The major folds of Central Wales do not persist north of the Bala Fault and in North Wales the regional fold pattern is less regular with orientations controlled by pre-existing structures and the competency of the rocks. Consequently narrow zones of intense heterogeneous deformation are interspersed with areas of less intense but consistent deformation (Howells and Smith, 1997). The major structures, such as the north–south Harlech Dome and north-east–south-west Snowdonia synclinorium, are tens of kilometres in extent with other major periclinal folds (e.g. Snowdon Syncline, Dolwyddelan Syncline) developed on the largest structures and smaller structures with wavelengths of up to a kilometre also occurring. The Snowdon district is dominated by large upright to steeply inclined south-east verging folds whose strike varies across the area and is influenced in the north by the Menai Straits Fault and competent Precambrian rocks.

Anglesey is separated from the remainder of Wales by the Menai Fault System and here the Lower Palaeozoic rocks, influenced by the basin margin and surrounding competent rocks, are strongly folded and locally overthrust with slaty cleavage and axes parallel to Precambrian trends (Bates, 1974). As on the mainland, zones of intense deformation are interspersed with almost undeformed rocks. Major and minor south-east verging asymmetrical folds are accompanied by reverse faults and post-dated by dyke intrusion and low angle thrusting inclined to the north (e.g. Carmel Head Thrust).

Deformation in the basin was not all due to the end-Caledonian event. On the eastern flank of the Harlech Dome there is evidence of early Tremadoc folding (Allen and Jackson, 1985) and elsewhere in North Wales the Arenig rests uncoformably on older rocks, but it is not clear whether this was a regional deformation event or restricted to movement along fault zones involving block uplift. There is also evidence for strike-slip faulting in the Ashgill (Woodcock, 1984b), and local movements related to volcanism and other events.

Cleavage. With the exception of some competent volcanic rocks, most of the Lower Palaeozoic succession in the basin carries one or more cleavages. A single penetrative cleavage of variable orientation occurs very widely. Its intensity depends largely on the degree of metamorphism, location with respect to structures and intrusions, and competency of the rocks. It is most strongly and perfectly developed where bedding parallel in mudstones, and in these locations it gave rise to the Welsh slate industry. Locally more than one cleavage is present and, along with other considerations, has given rise to much debate on the age of cleavage formation. It now seems probable that development of the principal cleavage was progressive, with isotopic data (see below) suggesting culmination in the the late Silurian. Strain studies indicate that deformation in the basin involved overall substantial horizontal shortening and vertical extension, but by very variable amounts locally with the highest strain found in rocks above basement fractures (Wilkinson and Smith, 1988).

The rocks of the basin suffered low-grade metamorphism during the Caledonian, culminating in the end Silurian/Lower Devonian (Acadian event). Regional studies of argillaceous rocks based on mica crystallinity established the overall pattern of metamorphism across the basin (Merriman and Frey, 1999). The degree of metamorphism which ranges from late diagenetic to epizonal (low greenschist) is related to depth of burial and strain, with grade generally increasing toward the centre of the basin and into older rocks, but modified locally with higher grades occurring in high strain (strongly cleaved) zones. Earlier studies recognised a range of zeolite, prehnite-pumpellyite and greenschist facies in metabasic rocks that can be correlated with the mica-crystallinity results. A maximum of biotite grade in the greenschist facies is recorded with temperatures in excess of 300^{o}C and pressures in excess of 2.5 Kbars. Isotopic dating (argon-argon) of the slaty cleavage suggest a metamorphic event at 414–421 Ma (Dong et al., 1997), i.e. late Silurian.

Variscan

The postulated northern boundary of major Variscan disturbance impinges on the southern margin of the Welsh basin (Hancock et al., 1981; Duff and Smith, 1992). The boundary runs in an easterly direction along the Johnston–Benton thrust zone in south-west Pembrokeshire, across the Gower and through south Glamorgan. Its exact nature and precise position have been disputed but it can be regarded as a zone where relatively simple deformation (folding and faulting) to the north is replaced to the south by high strain overfolding and thrusting related to the southern edge of the pre-Variscan basement. Consequently in the southernmost parts of Wales east-west trending Variscan fold and fault structures can be distinguished in the Devonian and Carboniferous rocks, and in Pembrokeshire northward-directed thrusting juxtaposes rocks of greatly contrasting ages, e.g. Devonian sandstones against Precambrian volcanics.

To the north of the Variscan front (i.e. virtually all of the Lower Palaeozoic basin deposits), the principal effect of these earth movements was to reactivate pre-existing fractures, with the nature and amount of dip- or strike-slip displacement varying according to the orientation of the structure. In Lower Palaeozoic rocks the extent of Variscan movements cannot be easily distinguished unless there are adjoining Upper Palaeozoic strata. In south-west Wales Variscan activity is manifest as narrow fold and fracture belts such as the Red Roses Disturbance, the Eastern Cleddau Disturbance and the Haverfordwest Disturbance. In Central Wales, ENE-trending faults which displace Caledonian folds and thrusts and are mineralised in places are common and may be manifestations of early Variscan rather than end-Caledonian movement (Fitches, 1987). Movement on major linears such as the Bala fault, Vale of Clwyd faults and the Menai Straits fault system can also be related to Variscan events. It is likely that many Caledonian features such as the Harlech Dome were accentuated by these movements.

MINERALISATION

The principal metalliferous mineral deposits are listed in Table 3 with key reference sources. Their locations are shown on Figure 3 together with the generalised locations of the principal mining fields. Details and locations for all the known mineral species in Wales are given in Bevins (1994), who also provides a brief overview of the principal occurrences.

Despite a large number of papers on the structure and tectonic evolution of the Welsh Basin, surprisingly little has been written on metallogenesis, nearly all publications restricting themselves to individual deposits or groups of deposits. The few exceptions include discussion of the constraints on the metallogenic evolution placed by the results of lead isotope studies (Fletcher et al., 1993), the significance of K/Ar ages for clay minerals associated with Welsh mineral deposits (Ineson and Mitchell, 1975), an analysis of veins with respect to regional deformation (Fitches, 1987), and the tectonic setting of the Welsh ore deposits in relation to those of the Lake District and Ireland (Wheatley, 1971).

Table 3 Principal metalliferous mines in the Welsh Basin (from Colman et al., 1996)

Name	Easting	Northing	Style	Metals	Host rock	Reference
Beaufort Consols	263300	187200	Vein	Pb	Mdst	Foster-Smith, 1981
Belgrave	320050	358900	Vein	Pb	Lst	Dewey and Smith, 1922
Benallt	222200	328150	Stratabound	Mn	Mdst/Dol	Brown and Evans, 1989
Bettws Garmon	254100	357500	Stratabound	Fe	Mdst	Trythall, 1989
Britannia	261500	354700	Vein	Cu, Pb, Zn	Volc	Colman & Laffoley, 1986
Bryntail	292100	287100	Vein	Pb, Ba, Zn	Mdst	Jones, 1922
Cae Coch	277700	365200	VMS	Fe	Mdst	Ball & Bland 1985
Camdwrmawr	275200	287700	Vein	Pb, Zn	Mdst	Jones, 1922
Cathole	320500	362700	Vein	Pb	Lst	Dewey and Smith, 1922
Clogau St Davids	267200	320100	Vein	Au	Shale/Dol	Shepherd & Bottrell, 1993
Coed-y-Brenin	274700	325500	Porphyry	Cu, Au	Microdte	Rice & Sharp, 1976
Cothercott	340700	300200	Vein	Ba	Sst	Dines, 1958
Cwmystwyth	280500	274700	Vein	Pb, Zn	Mdst	Jones, 1922
Daren	267900	282900	Vein	Pb, Zn	Mdst	Jones, 1922
Drws-y-Coed	254500	353600	Vein	Cu, Pb, Zn	Qtzite	Colman 1990
Dylife	285400	293900	Vein	Pb, Zn	Mdst	Jones, 1922
Frongoch	272100	274400	Vein	Pb, Zn	Mdst	Jones, 1922
Glasdir	274200	322300	Breccia Pipe	Cu, Au	Mdst/Slst	Allen & Easterbrook, 1978
Glogfawr	274700	270600	Vein	Pb, Zn	Mdst	Jones, 1922
Goginan	269000	281800	Vein	Pb, Zn	Mdst	Jones, 1922
Gwynfynydd	273800	328200	Vein	Au	Mdst	Shepherd. & Bottrell, 1993
Hafotty	261800	319000	Stratabound	Mn	Mdst	Down, 1980
Halkyn	320300	370700	Vein	Pb, Zn	Lst	Smith, 1921
Huglith	340500	301500	Vein	Ba	Sst	Dines, 1958
Jamaica	321500	360800	Vein	Pb, Zn	Lst	Smith, 1921
Llandegai	259840	370040	Stratabound	Fe	Mdst	Trythall, 1989
Llandeloy	185460	228500	Porphyry	Cu	Diorite	Allen, P M, et al., 1985
Llandudno	277000	383100	Vein	Cu	Lst	Williams, 1985
Llanengan	229000	327500	Vein	Pb, Zn, Ba	Sst	Foster-Smith, 1977a
Llanfair, Abergele	293600	370300	Vein	Pb, Zn, Cu	Mdst	Dewey & Smith, 1922
Llanfyrnach	222500	231600	Vein	Pb	Mdst	Hall, 1971
Llangynog	305400	325600	Vein	Pb, Ba, Zn	Mdst/Volcs	Foster-Smith, 1978
Llanharry	301800	180980	Replacement	Fe	Lst	Gayer and Criddle, 1970
Llanwrst	293500	370500	Vein	Pb, Zn	Mdsts	Haggerty & Bottrell, 1997
Lliwedd	263400	353100	Vein	Cu, Pb, Zn	Volcs	Foster-Smith, 1977a
Logaulas	274300	271800	Vein	Pb, Zn	Mdst	Jones, 1922
Maeshafn	320300	360950	Vein	Pb, Zn	Lst	Earp, 1958
Moelwyn	267600	343700	Vein	Pb, Zn	Mdst/Volcs	Dewey & Smith, 1922
Mynydd y Garreg	243300	208900	Vein	Cu	Lst	Anon, 1977
Nantymwyn	278700	244500	Vein	Pb	Mdst/Sst	Hall, 1971
Ogofau	266300	240300	Vein	Au	Mdst/Slst	Annels & Roberts, 1989
Parc	278700	360400	Vein	Pb, Zn	Slst	Haggerty & Bottrell, 1997
Parys Mountain	243900	390500	VMS	Cu, Pb, Zn	Rhy/shale	Pointon and Ixer, 1980
Pennant	308500	375500	Vein	Ba, Pb, Zn	Mdst/Sst	Warren et al., 1984
Pennerley	334500	297700	Vein	Pb, Zn	Mdst	Dines, 1958
Pompren	216700	326400	Vein	Ba	Mdst	Carruthers et al., 1915
Prince Edward	274300	338500	Vein	Au	Shale	Allen and others, 1979
Rhiw	222200	328100	Stratabound	Mn	Mdst/Bslt	Brown & Evans, 1989
Rhinog	265400	326700	Stratabound	Mn	Mdst	Down, 1980.
Rhiwnant	289800	261700	Vein	Cu, Au	Mdst	Ball and Nutt, 1975
Snailbeach	337500	302200	Vein	Pb, Zn, Ba	Sst	Dines, 1958
Taffs Well	312500	183750	Replacement	Fe	Lst	Gayer and Criddle, 1970
Tankerville	335500	299500	Vein	Pb, Ba	Mdst	Holding, S R. 1992
Towy	243600	219900	Vein	Pb, Ba	Sst	Foster-Smith, 1981

Table 3 Principal metalliferous mines in the Welsh Basin continued

Name	Easting	Northing	Style	Metals	Host rock	Reference
Trecastell	276000	374500	Vein	Pb, Zn	Sst	Carruthers et al., 1915
Trecastell	288000	229000	Vein	Pb, Zn	Sst	Carruthers et al., 1915
Turf	274400	325500	Surficial	Cu	Peat	Dewey and Eastwood, 1925
Van(Fan)	294200	287900	Vein	Pb, Zn	Mdst/Sst	Foster-Smith, 1978
Votty(Fotty)	267600	321300	Stratabound	Mn	Mdst	Down, 1980.
White Grit	331900	297900	Vein	Pb, Zn	Sst	Holding, 1992
Wotherton	327700	303000	Vein	Ba	Volcs	Holding, 1992
Wrentnall	341500	303200	Vein	Ba	Gwke	Dines, 1958

Abbreviations: Mdst, mudstone; Sst, sandstone; Lst, limestone; Volcs, volcanic rocks; Slst, siltstone; Dol, dolerite; Microdte, microdiorite; Qtzite, quartzite; Gwke, greywacke.

The mineral deposits within the rocks of the basin are divided here into eleven types on the basis of their style and metallogenetic affinity:

1. Mesothermal (turbidite-hosted) gold mineralisation, e.g. Dolgellau Gold Belt and Ogofau.
2. Volcanogenic massive sulphide mineralisation in Ordovician volcanic and sedimentary rocks, e.g. Parys Mountain, Cae Coch.
3. Porphyry copper deposit in Cambrian-Ordovician intrusive and sedimentary rocks, e.g. Coed-y-Brenin.
4. Breccia pipe deposits, e.g. Glasdir.
5. Volcanogenic base-metal vein mineralisation in Ordovician volcanic and sedimentary rocks, e.g. Snowdon caldera, Llanwrst and Ffestiniog.
6. Base-metal and baryte veins in Lower Palaeozoic sedimentary rocks, e.g. mid-Wales, Shropshire and Pennant.
7. Disseminated and vein copper-lead-zinc mineralisation in Cambrian sandstones, e.g. Drws-y-Coed.
8. Molybdenum mineralisation in acid intrusives, e.g. Tan y Grisiau.
9. Stratiform manganese deposits, e.g. Rhiw (Lleyn), Harlech.
10. Stratabound replacement iron deposits, e.g, Cadair Idris.
11. Other stratabound mineralisation.
12. Recent (placer) deposits

Other types, such as vein and replacement deposits in limestones, occur in younger rocks excluded from this study. Overviews of mineral occurrences and deposits throughout Wales are provided by a number of authors including Thomas (1961), Dunham et al., (1979) and Bevins (1994).

Mesothermal (turbidite-hosted) gold mineralisation

Harlech Dome

More than 70 small mines have worked vein-style deposits for gold lead, silver and copper in a narrow belt round the south and south-east of the Harlech Dome. Some started as base-metal producers but most developed as gold mines after the discovery of gold in the area in 1844. The most productive period was 1888-1916 when the Clogau St Davids and Gwynfynydd mines, by far the largest and longest-lived producers, were most active. Total recorded production is over 130000 oz (Hall, 1988) though a considerable additional amount may not have been recorded. The mineralisation is now regarded as being of black-shale-hosted auriferous quartz vein-type (Shepherd and Bottrell, 1993). The veins occur in Cambrian clastic sediments overlain by Ordovician (Tremadocian) volcanic and intrusive rocks of the Rhobell and Aran Volcanic Groups. The Cambrian sediments consist of numerous arenaceous rocks of the Harlech Grits and Mawddach groups with occasional mudstones which host most of the gold and manganese mineralisation.

The gold-bearing veins mainly occur within black, laminated pelagic silty mudstones of the Middle Cambrian Clogau Formation with some hosted in overlying turbiditic mudstones, siltstones and sandstones of the Maentwrog Formation. A few worked occurrences occur in other rocks, most notably the Carn Dochran mine on the eastern margin of the dome where the exploited lode is hosted by mudstones of Ordovician age (Hughes, 1994). The lodes occur typically as complex polyphase braided structures within faults which trend from 030 to 060^{o}. A characteristic of the lodes is the variability of gold values with rich pockets and almost barren zones, leading to a history of boom and bust in individual mines. The veins contain base-metal sulphides, most commonly chalcopyrite, galena and sphalerite in a quartz matrix. Pyrite and pyrrhotite are common, while a large number of other minerals, besides gold, are also recorded occasionally. These include arsenopyrite, marcasite, electrum, cobaltite, bismuth minerals, tellurides and platinum-group minerals (PGMs). At Clogau St Davids the main vein is up to 3 m wide and over 2 km long with sharply defined contacts. Large masses of later, barren milky-white quartz commonly crosscut the earlier, bluish-grey lode quartz together with horizontal quartz veins indicating later brittle fracture of the initial mineralised quartz lode. The main sites for gold enhancement are at the intersections of side lodes, where diorite intrusions and shale form the wall rocks and in braided structure with enclosed lenses of black shale. The gold can also occur in small, lensoid, steeply plunging rich shoots containing over 70 g/t Au. The Gwynfynydd mine occurs on the eastern side of the Harlech Dome and has worked up to five east-north-east-trending quartz veins (Shepherd and Bottrell, 1993). Like those at Clogau St Davids, the veins have had a complex history of repeated dilation, fluid flow and mineralisation. Shepherd and Bottrell (1993) consider the mineralisation formed as a result of the interaction of auriferous fluids with black shales. The fluids were derived from the dewatering of the underlying Cambrian sediments and Precambrian volcanoclastics at the close of the Caledonian orogeny.

Ogofau (Dolaucothi)

The Dolaucothi gold mine is approximately 80 km south of the Dolgellau area and lies at the southern margin of the mid Wales Pb-Zn field near Llandovery. It is hosted by siltstones and black silty mudstones associated with the conformable Ordovician/Silurian boundary. Mineralisation is centred around the Ogofau open pit, which worked a north-east striking lode structure over 1 km long on the north-west margin of the Tywi Anticline (Annels and Roberts, 1989). The gold-bearing mineralisation is developed where black carbonaceous pyritic shales occur within the zone of folding and thrusting which is up to 100 m wide. The shales are enriched in As and Au in the cores of isoclinal folds. There are also networks of quartz-carbonate veinlets and conformable quartz saddle-reefs, both of which contain gold. Other metalliferous minerals present include arsenopyrite, galena chalcopyrite, and sphalerite. Mineralisation was polyphase with the a late base-metal sulphide phase possibly related to the vein mineralisation in Central Wales (Annels and Roberts, 1989). The main, gold-bearing mineralisation involved deposition from metalliferous hydrothermal fluids at temperatures between 345 and 450^{o}C during the main (Acadian) deformation (Pryor, 1988). The metals are believed to be derived from the underlying sedimentary and volcanic rocks in the basin and its basement (Annels and Roberts, 1989). The deposit is thought to have been worked by the Romans due to the presence of extensive leats and traces of hushing, reflecting then current Roman technology (Annels and Burnham, 1986). Estimates of Roman production range up to 830 kg of gold. More recent working in the nineteenth and twentieth centuries, ending in 1940, produced only about 50 kg of gold from the saddle-reef and pyritic shales. Much of the gold was locked in sulphides and lost to the tailings. The property has been the subject of renewed exploration at intervals since the 1970s (e.g. Steed et al., 1976; Anglesey Mining, 1999) but has not yet come back into production.

Other occurrences

Smaller occurrences of vein-style gold mineralisation probably of this type are recorded from several other parts of the basin and its margins. Cooper et al. (1989) report the presence of gold associated with weak base-metal sulphide mineralisation in large quartz-vein structures and altered basic rocks along faulted and thrust boundaries, commonly between Mona Complex and Ordovician mudstones rocks, in north-west Anglesey. Gold reported in drainage from the Rhiwnant Dome area of Central Wales (Brown, 1993) and the Berwyn Hills (Smith, 1993) is likely to be derived from mineralisation of this type. Mesothermal gold mineralisation may also be present in south-west Wales (Norton et al., 2000), but gold reported from the Treffgarne area (Brown et al., 1987; Colman et al., 1995) may be of epithermal type.

Volcanogenic massive sulphide mineralisation in Ordovician and Silurian volcanic and sedimentary rocks

The best-known example of this type of mineralisation is the Parys Mountain deposit. It is the only VMS deposit in Britain from which large quantities of base metals have been extracted. Other lesser known examples of VMS mineralisation occur in Wales at Cae Coch and, possibly, Treffgarne.

Parys Mountain

This deposit was worked intensively from its discovery in 1768 by underground workings on a series of steeply dipping copper-bearing 'lodes' and in two open pits which exploited more extensive disseminated sulphide mineralisation. Bodies of 'bluestone', a local term believed to refer to massive lead-zinc with subordinate copper sulphide mineralisation, were also extracted. All mining had ceased by 1920, although small amounts of copper were produced by precipitation from acid mine-water drainage until the 1950s. The old mine workings extend to a maximum depth of 320 m in a mineralised zone 2 km long and up to 500 m wide. Cumulative historic production probably exceeds 130000 tonnes of copper metal from around 3 million tonnes of ore.

Since 1955, ten companies have investigated various aspects of the mineralisation and over 47 km of drilling has been completed in 145 surface holes, some of which have reached depths in excess of 600 m. A large number of underground holes were also drilled by Anglesey Mining during their underground exploration from the Morris shaft during 1988–1990. This work identified a resource containing 6.5 million tonnes with a combined base-metal grade (zinc, copper and lead) of 10.3% but additional reserves are required to justify re-opening the mine under current economic conditions (Anglesey Mining, 1999).

Previously considered to be an epigenetic deposit associated with a 'felsite' intrusion of probable Caledonian age (Greenly, 1919), the deposit is now considered to be volcanogenic (Pointon and Ixer, 1980) with the ‘felsite’ interpreted as a thin (<200m thick) package of strongly silicified extrusive volcanic rocks lying between Ordovician (Llanvirn) and Silurian (Llandovery) black mudstone sequences. Two zones of silica sinter of possible exhalative origin have been recognised; the White Rock zone at the western end (Morpha Ddu) and the Carreg y Doll ‘lode’ along the northern side of the deposit. The White Rock zone consists of a series of stacked silica lenses hosting steeply dipping lead-zinc mineralisation above the flatter-lying massive sulphide lenses of the Engine Zones, which host most of the copper mineralisation defined by the more recent drilling and underground investigations. These massive sulphides may equate with 'bluestone' and principally comprise a fine-grained intergrowth of chalcopyrite, galena and sphalerite. The Carreg y Doll 'lode', which is about 1000 m long and up to 30 m thick, contains sporadic small lenses of massive pyrite with chalcopyrite up to 7 m thick. It is underlain by a stockwork zone (?feeder zone) in the Parys Shales, up to 50 m thick, which has been estimated to contain around 30 million tons of 0.76 % copper (Dunham et al., 1979).

Besides pyrite, quartz and the principal sulphide ore minerals, the ore contains gold and a number of other metallic minerals including bismuthinite, pyrrhotite, tetrahedrite, and tennantite. A range of secondary minerals have also been recorded and originally a thick gossan rich in lead sulphate (anglesite) covered the deposit (Bevins, 1994). Alteration of the host rocks is locally intense, obscuring the original lithology, with silicification and chloritisation most common.

The volcano-sedimentary succession hosting the mineralisation has for many years been considered to be folded into an overturned, northward-dipping tight synclinal structure in which the Silurian shales are preserved in the core (Manning, 1959). The structure is cut by faults at near right angles to the axis and some workers have considered the synclinal structure also to be modified by northward dipping thrusts parallel to the axial plane. Westhead (1993) interpreted the structure as a series of low angle north-ward dipping thrust slices, parallel to the Mona and Rwnc thrusts. A new model has now been developed in which the observed lithological dispositions are interpreted as at least in part the product of massive sulphide mineralisation adjacent to two north-east trending chains of rhyolite domes (Anglesey Mining, 1997). Most recently, isotopic dating of the volcanic suite using zircons indicates that the volcanism is of Llandovery age, not Caradocian as previously thought. It is postulated that at this time a series of rhyolites were erupted accompanied by hydrothermal and mineralising activity which persisted after the cessation of volcanism (Barrett and Maclean 1999). It is also possible that later remobilisation and deposition has affected the deposit (Nutt et al., 1979).

Cae Coch

The Cae Coch deposit, occurs at the contact of basaltic hyaloclastites (Dolgarrog Volcanic Formation) and overlying pyritic silty mudstones of Ordovician age, close to a major intrusive rhyolite about 4 km north-west of Llanwrst (Ball and Bland, 1985). The area was known to the Romans who used the sulphur springs which emerge at Trefriw below the deposit. The mine worked a two-metre-thick bed of massive pyrite for a total production of around 110 000 tonnes. Ball and Bland (1985) considered it to be a Kuroko-type ore-body, formed by the exhalation of metal-rich fluids onto the sea floor, because of its stratabound nature and geological setting. They also point out that the laminated pyrite quartz mineralisation, which forms the bulk of the deposit, suggests that it formed in a sea-floor brine pool. However, Bottrell and Morton (1992) contend that sulphur isotopes show a dominantly bacterial source for the sulphur, with little or no contribution of magmatic seawater sulphur, and hence support a syn-diagenetic inhalative and replacive origin for the deposit.

Treffgarne

Exploration for VMS deposits in south-west Wales discovered pyritic mudstones and bartye mineralisation associated with highly altered (silicified) volcanic rocks of the Roche Rhyolite Group near Treffgarne. The rocks, formerly thought to be Precambrian are most likely to be of Lower Ordovician age (Brown et al., 1987; Colman et al., 1995). Exploration has so far failed to locate any significant base-metal concentration but the geological environment appears favourable. Traces of gold were reported from some samples and the published reports suggest that there is some potential for epithermal gold mineralisation.

Porphyry copper deposits in Cambrian-Ordovician intrusive and sedimentary rocks

Two well-documented examples of this type of mineralisation are known in Wales, at Coed-y-Brenin and Llandeloy. An overview of this style of mineralisation in all the Caledonian rocks of Britain, including the Welsh Basin, is provided by Rice (1993).

Coed-y-Brenin.

The Coed-y-Brenin copper deposit was discovered by RTZ in the mid 1960s during an investigation of the old Turf Copper mine which had recovered copper from a peat bog in the Coed-y-Brenin forest, north of Dolgellau (see below). Drainage and soil sampling revealed Cu-Mo anomalies around the Turf mine. Detailed exploration, including drilling over 14 000 m in 110 cored holes delineated a deposit within a porphyritic microtonalite complex containing up to 200 Mt at 0.3% copper with minor molybdenum and gold (Rice and Sharp, 1976; Rice 1993). The mineralisation consists of chalcopyrite and minor molybdenite in thin veins and disseminations and occurs within a phyllitic alteration zone as a copper-rich core, surrounded by pyrite and an outer zone of weak Pb-Zn values. It is considered to have formed during the emplacement of the Tremadocian Rhobell Fawr volcanic complex exposed to the north-east. The mineralising fluids were moderately saline (mean 8 weight % NaCl equivalent) and at a temperature of between 160 and 280^{o}C (Shepherd and Allen, 1985). Veins carrying gold silver and antimony are probably related to a later epithermal system (Bevins, 1994).

Llandeloy

In the Llandeloy area, 12 km south-west of Fishguard, rock and soil geochemistry together with IP, VLF-EM and magnetic surveys, identified anomalous zones associated with poorly exposed intermediate (tonalitic and dioritic) intrusions that drilling showed were related to buried porphyry-style copper mineralisation. Locally thick unconsolidated lacustrine deposits of Tertiary or Quaternary age and enriched in copper hampered surface exploration. Drilling revealed pervasive hydrothermal alteration of the intrusives over an area of at least 1 km^2 with low-grade copper mineralisation reaching a maximum of 0.1% Cu over 3.4 m. The style of alteration (polyphase propylitic and local potassic) and mineralisation is consistent with the deeper levels of a porphyry copper system that may have been largely eroded away. There is only very weak and erratic enrichment in Mo, As, Pb and Zn (Allen et al., 1985).

Gold was not determined at the time of the original investigation but subsequently analysis of 15 samples taken from six boreholes revealed a significant enrichment in gold (range 5–139 ppb) with one sample containing 649 ppb Au. The samples all came from the more highly altered and mineralised core sections containing 47–3515 ppm Cu. Silver concentrations are low (0.6–1.7 ppm). These results and other similarities with the Coed-y-Brenin mineralisation led Allen et al. (1985) to speculate that they are of similar age.

Breccia pipe deposits

A mineralised breccia pipe occurs at Glasdir, 2 km south of Coed-y-Brenin, in Cambrian sedimentary rocks intruded by Tremadocian sills and thin dykes of microdiorite and feldspar porphyry. The hydrothermal breccia consists of angular fragments of wallrocks, veined and cemented by chalcopyrite, pyrite and quartz. The worked orebody was on the south-eastern side of the breccia which at outcrop occupies an oval area that measures 100 m by 200 m. The mineralisation was worked to a depth of 210 m and produced around 75 000 tons of ore at 1.5% Cu with minor Au and Ag. It is considered to be coeval with Coed-y-Brenin (i.e. pre-Acadian) and was probably part of the same hydrothermal system (Allen and Easterbrook, 1978). Several other oval or irregular breccia pipes have been mapped in the area but these appear to be unmineralised at surface except for the presence of pyrite (Allen et al., 1979).

Volcanogenic base-metal vein mineralisation in Ordovician volcanic and sedimentary rocks

Snowdon

There are numerous small mines beneath and to the south of Snowdon which have worked thin veins in the Snowdon Volcanic Group rocks associated with the development of a major Ordovician (Caradoc) caldera structure (Howells et al., 1991). The mineralisation occurs mainly at, or just above, the contact of a thick acid tuff unit (Lower Rhyolitic Tuff Formation) with the overlying basaltic rocks of the Bedded Pyroclastic Formation. It is concentrated at the northern and southern margins of the caldera and also within a north-east trending apical graben structure and predates the regional metamorphism and cleavage. Five ore-bearing assemblages have been reported that variably comprise chalcopyrite, sphalerite, galena, pyrite, pyrrhotite, marcasite, hematite, magnetite, quartz and calcite. Alteration has produced a wide range of secondary minerals including the unusual copper chloride, connellite, and rare-earth minerals such as lanthanite (Pollard et al., 1989; Bevins et al., 1985; Bevins, 1994). The primary mineralising event is thought to have occurred during the final, fumerolic stages of the volcanic episode and to have involved convection of fluids that leached metals from the underlying volcanic pile (Reedman et al., 1985; Ball and Colman, 1998). Small quartz-magnetite-hematite breccia veins that occur in Cwm Tregalan, south of Snowdon and contain up to 1000 ppm Sn and W are thought to be of magmatic origin (Colman and Appleby, 1991). Limited exploration, including shallow drilling, was carried out by Noranda-Kerr in the early 1970s. The results are available in a MEIGA open-file report (Anon, 1973).

The largest mine, the Britannia mine beneath Snowdon, has been worked on at least six levels over a vertical distance of about 100 m with adits extending up to 300 m into the hillside (Colman and Laffoley, 1986). Total production is estimated at 3160 tons of copper ore (Bick, 1985) which is in accordance with the observed remains of the mine works. Other mines included Sygun, Lliwedd and Hafod-y-llan. Outside of the apical graben area lead-zinc-copper mineralisation has been worked at a number of other locations and at Deganwy in northern Snowdonia antimony-bearing veins of probable volcanogenic origin occur in an Ordovician (Caradoc) silicic ignimbrite (Bevins et al., 1988; Bevins, 1994).

To the south of Snowdon, there are a number of veins in the Ordovician sediments and volcanics of the Ffestiniog area. The main mines were Moelwyn and Gamallt (Dewey and Smith, 1922). They run mainly east-west and contain pyrite, chalcopyrite, sphalerite and galena in a quartz gangue within strongly silicified wallrock. They have had only a small output of ore.

Llanrwst

The vein-style base-metal mineralisation worked in this area is considered to be derived from metals leached from the underlying Ordovician volcanics and volcaniclastic sediments and emplaced along faults during extensional events from the late Devonian to Lower Carboniferous (Haggerty and Bottrell, 1997). The veins trend either north-south or east-west. The former can be up to 25 m wide with poorly defined margins while the latter are narrower, but have sharper margins and are generally more productive (Dunham et al., 1979). The dominant minerals are sphalerite, galena and pyrite with minor chalcopyrite in a quartz gangue; brecciation is common.

There were over twenty mines over an area of 20 km^2, the two largest being Trecastell and Parc. Trecastell's production is estimated at 6552 tonnes of lead ore and 12716 tonnes of zinc ore between 1892 and 1913 (Archer, 1959). Parc was reopened in 1953 by Johannesburg Consolidated Investments and worked until 1958. It finally closed in 1962 after a brief period supplying ore for a processing project (Williams, 1980).

Berwyn Dome

Vein-style mineralisation exploited from about a dozen small mines occurs around the village of Llangynog in the Berwyn Hills. The Ordovician host rocks comprise mudstones, siltstones, sandstones and limestone with thin volcanic units including rhyolites and tuffs. Intrusions include a quartz feldspar porphyry and dolerite sills and dykes. The principal ore mineral was galena, with sphalerite, witherite, baryte, cerussite, pyrite quartz and calcite also commonly present in the veins. Chalcopyrite occurs locally, but rarely formed the principal metallic mineral. Lodes are fault-controlled, with mineralisation commonly found along the junctions of sedimentary and igneous rocks.

The most productive mine was Llangynog, from which an estimated 70000 tonnes of lead ore was extracted (Bick, 1978). Other workings included Nant-y-blaidd, Craig Rhiwarth, Cwm Orag and Craig-y-mwyn (Cooper, et al., 1984). The age of the mineralisation and its relationship to the igneous rocks is unclear but Williams (1985) suggests that it may be similar to that proposed for Snowdon, with a hydrothermal system driven by the igneous intrusions leaching metal from the volcano-sedimentary pile prior to their deposition in fractures.

Base-metal and baryte veins in Lower Palaeozoic sedimentary rocks

North Wales

A number of mines were worked for lead-zinc and sometimes also copper in the Llanfair Talhaiarn mining district (Warren et al., 1984). The main mines were the Llanfair mine (Dewey and Smith, 1922) which was mainly worked for copper ore and Nant y Plum lead mine. The Pennant mine, near St. Asaph, worked a vein up to 3 m wide for over 500 m in Silurian shales (Carruthers et al., 1915). Galena was the main mineral, though some baryte and witherite were also produced. Seven mines in the Llanengan area at the south end of the Lleyn Peninsula worked an east-south-east-striking copper-lead-zinc-baryte vein in Ordovician sedimentary rocks over a length of about 3 km. Production has been poorly recorded, but at least 13500 tons of lead, with up to 150 g/t silver, and 2500 tons of zinc ore were produced (Dewey and Smith, 1922). About 8000 tons of copper ore was also raised from the western end of the vein. Baryte occurs in some quantity but has never been worked (Foster-Smith, 1977a). The small Pompren mine, 500 m west of Aberdaron, worked a 3 m wide north-south vein of baryte with quartz.

Central Wales

Over 50 veins have been worked for lead, zinc and copper from over 130 mines in the area between Aberystwyth and Llanidloes in mid Wales (Jones, 1922). The veins occur in the Ordovician and Silurian succession dominated by turbiditic mudstones. They are sub-vertical, fault-controlled veins mainly striking west-south-west with a length of several kilometres, though normally only a small proportion of this length contains substantial amounts of metallic minerals. The dominant mineralogy is relatively simple with galena, sphalerite and usually lesser chalcopyrite, associated with pyrite and more locally marcasite in a gangue of quartz and ankerite. In detail the veins are frequently complex and/or brecciated with successive phases of mineralisation being superimposed. Mason (1997) distinguishes two main generations of mineralisation: an early, complex, fine-grained stage containing minor amounts of cobalt-nickel arsenides and a later simple phase comprising mainly coarse-grained galena. The later phase follows the same fracture systems as the earlier and commonly forms breccia zones up to 15 m wide with angular to rounded clasts of wallrock and earlier sulphides in a matrix of sulphides and quartz.

The largest mines were Cwmystwyth, Daren, Dylife, Frongoch, Glogfawr, Goginan, Logaulas and Van, each with recorded outputs exceeding 10000 tonnes of ore (Jones, 1922). The silver content of galena is variable but is generally around 200-250 g/t. Although the main metal worked was lead, zinc became more important towards the end of the active life of the district with Cwmystwyth, Frongoch and Van being the main producers. The Pb:Zn production ratio can be misleading as zinc was only worked on a large scale towards the end of the district's history. It had been largely ignored or discarded until the later part of the nineteenth century.

At the highly productive Van mine, near Llanidloes at the eastern limit of the district, stratabound mineralisation occurs. Here a series of en-echelon ore bodies known as the Van flats occurred within shallow dipping massive sandstone units. The mineralisation comprised vertical veins up to 6 m high and the orebodies extended over widths of up to 100 m and for some distance downdip. Zonation was evident with the mineralisation became sphalerite-dominant in depth. Similar features were noted at the Llanerchyraur mine in the north of the orefield.

Also at the eastern end of the orefield, north-west of Llanidloes, the mineral veins are characterised by the presence of baryte, witherite and harmotome. Baryte is notably absent from most of the mid-Wales orefield and only occurs in any quantity in this area, for example in the Bryntail and Pen-y-clun mines. Several small calcite veins in the Rhiwnant valley south-west of Llanidloes strike almost north-south and contain chalcopyrite as the dominant sulphide mineral with only minor galena and sphalerite.

To the south and west of the orefield, mineralisation of presumed similar origin occurs more sparsely but has been extensively worked at some locations, notably around Rhandirmwyn, and to the south of Cardigan and east of Carmarthen (Hall, 1971). At Rhandirmwyn, about six miles north of Llandovery, the Nantymwyn mine and nearby working produced in excess of 80000 tonnes of lead ore from a series of veins cutting coarse, competent sandstone beds. Sphalerite was also present in abundance but was not extracted during much of the life of the mine. In some of the workings south and east of Cardigan the galena was particularly argentiferous and the small Llanfair Clydogau mine near Lampeter returned assays of over 80 oz silver per ton of ore (Hall, 1971). To the south-west, the Llanfyrnach mine produced more than 15000 tons of argentiferous lead concentrates and minor zinc from veins in Ordovician black shales, making it the second most productive in southern Wales after Nantymwyn. Some of the veins near Carmarthen are characterised by the presence of baryte, one of the few places in the Welsh Basin that this mineral occurs. The veins, which occur within the Ordovician shales and mudstones, were worked at a number of sites, notably Vale of Tywi and Cystanog. Other minerals include baryte, galena, pyromorphite, sphalerite, chalcopyrite, pyrite, calcite, quartz and chalybite with local variations related to host-rock lithology. Most of the workings were primarily for lead, though some also sold baryte and sphalerite (zinc) at various periods.

Attempts have been made to interpret the regional zonation of the mineralisation (e.g. Raybould, 1974), but these are hampered by the incomplete records and the lack of active production of sphalerite in mines worked before the late nineteenth century. Various metallogenic models have been proposed to account for the presence of the metalliferous veins. Early ideas favoured a magmatic hydrothermal source, but the lack of any association with igneous intrusions and the absence of geophysical evidence for any substantial buried intrusion has undermined these theories. Recent models, supported by stable isotope data and fluid inclusion studies, involve the leaching of metals from the basin during dewatering and low-grade metamorphism followed by circulation and deposition in fractures, at least some created by hydraulic fracturing during pressure release (Phillips, 1986). The regional distribution of mineralisation is still not clearly understood, but the spatial distribution suggests some control by the Glandyfi and Tywi lineaments (i.e. basement fractures). The early complex veins of Mason (1997) formed around 360 Ma and the later veins around 330 Ma (Fletcher et al., 1993).

Welsh Borderland

Several veins were worked for lead and zinc in the Shelve area of Shropshire. They mainly trend east-north-east and occur in the Ordovician Mytton Flags and Shales beneath a cap rock of overlying Hope Shales (Dines, 1958). The most important mines were the Snailbeach, Tankerville, Bog, Pennerley and Grit mines with a total production of around 180 000 tonnes of lead (Nexus, 1980). Baryte was produced from the Wotherton mine in the Mytton Flags and also from the Huglith, Cothercott and Wrentnall mines which cut Precambrian Longmyndian snadstones. The area was a major producer of baryte with a total output of over 500 000 tonnes (Dines, 1958). The baryte was associated with bitumen and minor secondary copper. Pattrick and Bowell (1991) show that the mineralising fluids were of high salinity and moderate temperature and suggest that they were similar to basinal brines of the Mississippi Valley type. They also suggest that the mineralisation formed during Lower Carboniferous times.

Disseminated and vein copper-lead-zinc mineralisation in Cambrian sandstones

The Drws-y-Coed mine in the Nantlle valley has a very long history with a reputed visit by King Edward 1 in 1284 (Bick, 1985). The mineralisation occurs as a series of east-west north-dipping veins up to 4 m wide within Upper Cambrian Ffestiniog Flags (Dewey and Eastwood, 1925). The main mineral was chalcopyrite in a quartz gangue. The same lodes were worked from the nearby Tal-y-sarn mine where the ore at depth contained galena and sphalerite as well as chalcopyrite. Sphalerite and galena also occur in the Benallt mine to the west of Drws-y-Coed and in the Cwm y Ffynnon and Cwm Dwyfor mines at the north end of Cwm Pennant (Colman, 1990). In Nant Ffrancon, the Ceunant copper mine and Gwaith mine (Dewey and Eastwood, 1925) are in similar host-rock lithologies. Total production from the Drws-y-Coed area is estimated at about 15 000 tonnes of copper ore from 1804 (Bick, 1985). Kappa Explorations carried out exploration in the area in 1972-3 and drilled a number of cored holes without success (Anon, 1975).

Molybdenum mineralisation in acid intrusive rocks

Veins in the Tan-y-Griseau Granite near Blaneau Ffestiniog contain pyrophyllite, allanite and rarely molybdenite (Bromley, 1965). The veins are ascribed to late-stage hydrothermal activity associated with the emplacement of the granite, which is a steep-sided sub-vertical body consisting of a homogeneous fine-grained mosaic of quartz, plagioclase, potash feldspar and perthite with interstitial biotite and chlorite. Sericitic alteration is locally intense. A marginal pegmatitic facies and thin granophyric sills with brecciated and tourmalinised outer zones are also recorded. Drainage geochemical data (Cooper et al., 1985) suggests that molybdenum may be more common than recorded previously and suggests that it is also associated with the Cregennen microgranite on Cadair Idris.

Stratabound manganese deposits

Rhiw

The Benallt and Rhiw mines on the Lleyn Peninsula worked a series of lenticular manganese deposits in a structurally complex setting within Lower Ordovician mudstones associated with high-level basic intrusions (Gibbons and McCarroll, 1993). The mineralisation is thought to have been of volcanogenic exhalative origin (Brown and Evans, 1989). The mines were active between 1894 and 1928 with a total production of 134 770 tons (Woodland, 1956). The mineralogy of the deposits is complex due to later dislocation and alteration. The main manganese minerals are rhodocroisite, pennantite and, unusually, the magnetic mineral jacobsite which is a member of the Fe_3O_4 - Mn_3O_4 system. The Mineral Reconnaissance Programme carried out exploration for buried unworked deposits in the area using ground magnetics and geochemistry. Boreholes were drilled to test magnetic anomalies thought to be caused by jacobsite but no additional significant manganese mineralisation was found and some of the anomalies were attributed to stratabound ironstones (Brown and Evans, 1989).

Harlech Dome

An extensive but thin and steeply dipping, bed of syngenetic manganese mineralisation occurs in the Cambrian Hafotty Formation over an area of 190 km^2 in the Harlech Dome. The bed, containing principally rhodochrosite, spessartine and rare rhodonite, is usually only 30–45 cm thick and contains c. 38 % MnO. Other minerals present include quartz, garnet, kutnohorite, chlorite, magnetite, hematite, albite, apatite, baryte and todorokite. Ore was extracted, mostly from open working, at numerous points along the length of the outcrop in the nineteenth and early twentieth centuries. Above the main horizon thin beds, lenses and nodules of spessartine-quartz rock occur in the younger Gamlan Formation and some of these have also been worked (Down, 1980; Allen and Jackson, 1985; Bennett, 1987). Total production is estimated to have been 44 000 tonnes of manganese ore (Woodland, 1956) but considerable amounts of manganese-rich rocks remain. In the 1950s a mining company took out several leases in the area north of Barmouth but no development took place. The ore is considered to be of syndiagenetic origin and to have formed from submarine exhalative hydrothermal solutions with later remobilisation (Mohr, 1964; Glasby, 1974; Bennett, 1987).

Stratabound iron deposits

Ordovician (Arenig to Caradoc) low grade oolitic ironstones have been worked in several parts of north-west Wales. The ironstones are frequently highly deformed by folding and faulting and near Tremadoc occur as large rafts in a melange (Howells and Smith, 1997). Individually they are of limited extent and grade laterally into ferruginous grits and black shales. The ironstones, up to 7.5 m thick, contain ooliths up to 2 mm in diameter and pisoliths from 2–6 mm. Unaltered ooliths are composed of chamosite or thuringite, replaced locally by siderite, magnetite, pyrite and secondary chlorite. Thin pyrite veins and the growth of chlorite, particularly stilpnomelane, at the expense of iron oxide is attributed to diagenesis, metasomatism or metamorphism. Composition is highly variable with an average of c. 35% Fe. Silica ranges from 13.7–41.8% and phosphorus from 0.35 to 4.9% (Slater and Highley, 1977). Most were worked at a shallow level, where weathering had reduced the phosphorus and sulphur contents. The principal workings were around Llandegai near Bangor, at Bettws Garmon west of Snowdon, in northern Anglesey, near Tremadoc, and at sites on the southern side of the Harlech Dome (Pulfrey, 1933; Trythall, 1989). Mining occurred through most of the nineteenth century and continued at some locations until about 1918. Production records are incomplete but about 300 000 tonnes of ore was extracted between 1855–60 and 1900–15. The ironstones are likely to have been formed on short-lived submarine rises produced by syn-sedimentary faulting in the basin. The occurrence of most is related to a eustatic regression and subsequent transgression, and the to emergence of the Irish Sea landmass to the north-west, the probable source of iron (Trythall et al. 1987).

Other stratabound deposits

At Pen-Rhiw Frank, near Builth Wells, stratiform lead mineralisation occurs at the interface of a basaltic lava and reworked tuffs in the Builth Volcanic Formation (Marshall et al. 1987). The gently dipping mineralised zone was located by drilling and comprises secondary lead minerals in a clay matrix. The mineralisation is weak (average grade 0.58% Pb) and metallogenic affinity uncertain, but the possibility that more significant base-metal concentrations are associated with the volcanism cannot be ruled out.

It has been suggested that mudstones of the Welsh Basin could host stratiform base-metal mineralisation (Badham, 1981) but little evidence for any substantial deposit has been found. Weak uraniferous concentrations (c. 50 ppm) are associated with some mudstones, notably the Upper Cambrian Dolgellau Member of the Cwmhesgen Formation in the Harlech Dome (Ponsford, 1955). Besides uranium, these pyritiferous and carbonaceous rocks are also enriched in many other elements commonly concentrated in black mudstones. A phosphatic black mudstone unit of uppermost Caradocian age, the ‘Nod Glas’ has been mined at several sites in the Berwyn Hills. The worked phosphatic horizon is between 15 and 50 cm thick and is underlain by a thin phosphatic limestone. The mudstone also contains pyrite and is locally cut by ramifying veins up to 0.3 m wide containing baryte with minor galena, sphalerite and chalcopyrite (Cooper et al., 1984). The phosphatic rocks are thought to have been formed by slow sedimentation on uplifted blocks within the basin (Cave, 1965).

Recent (placer) deposits

These are currently of little economic significance but tend to impact strongly on geochemical drainage survey data. Small alluvial concentrations of grey authigenic monazite nodules are reported from many streams draining the Lower Palaeozoic rocks of the Welsh Basin (Cooper et al., 1983; Read et al., 1987). The nodules are characterised by a higher europium and lower thorium content than many other monazites. The highest concentrations in streams are associated with Upper Ordovician and Lower Silurian mudstones and siltstones, but the abundance of nodules and levels of rare-earth-element enrichment in these source rocks is low and of no economic interest (Milodowski and Zalasiewicz, 1991; Smith et al., 1994). Levels of monazite exceeding minimum grades exploited in placer deposits have, however, been recorded in stream sediments from south central Wales and larger resources may exist in some of the larger river estuaries, where they may be associated with other minerals of economic interest (Smith et al. 1994).

Gold occurs in many streams, particularly those draining the Dolgellau Gold Belt as a result of natural processes and the erosion of mine dumps. Most of these steams flow into the Mawddach estuary and unsuccessful attempts were made in the last century to extract gold commercially from the extensive estuarine sands close to Penmaenpool (Hall, 1988). A more recent proposal to dredge the estuary for gold met very strong opposition on environmental grounds.

A unique nineteenth century mine extracted copper from a peat bog covering about 70 acres in Coed-y-Brenin forest. The half metre thick layer of peat impregnated with copper was pared off the surface and burned in kilns, prior to removing copper from the ashes. Only material that yielded more than 2.5% Cu in the ashes was considered worthy of extraction. The copper rich bog is said to have contained native copper as well as, presumably, a range of other secondary minerals (Dewey and Eastwood, 1925). None of the peat remains but precipitation of copper minerals continues in the boulder clay which is now at surface and previously underlay the peat (Allen and Jackson, 1985). The source of copper, not known at the time, is the Coed-y-Brenin porphyry copper deposit found in the late 1960s a few hundred metres to the east.

PROSPECTIVITY ANALYSIS

Generic or empirical mineral deposit models can be used to identify the exploration criteria for a particular type of mineralisation. These criteria form the basis of any analysis of a region for exploration potential. The simplest form of prospectivity analysis would involve appraisal of the region for the presence or absence of the identified criteria. Often this analysis would be subjective, depending on the preferences given to particular criteria and on the availability of data to assess the criteria. In some cases crucial geological or geochemical data might be absent or incomplete. In other areas there may be several phases of data collection, possibly collected for other deposit types, and the exploration geologist has to decide which of the data are suitable for inclusion in the prospectivity appraisal. In some cases, such as Wales, where a large number of datasets are available, the traditional methods of visual inspection aided by transparent overlays are impractical.

Prospectivity appraisal is now generally carried out using digital data and GIS-based computer software, designed for a data-driven analysis of the data relationships or a knowledge-based analysis using exploration expertise. Data-driven analysis aims to relate all specified data to known occurrences of the particular deposit type within the region and, by association, highlight those data relationships which closely mimic the patterns at the known occurrences. A knowledge-based system, which can be applied to regions with few or no recorded mineral occurrences, uses the expertise of the exploration geologist to determine the relative significance of the exploration data and then search for patterns which reflect the total effect of such significance. In practice, this involves selecting which of the available data layers to use in the analysis and the relative weight and pattern of influence to assign to each of them.

BGS has developed a knowledge-based prospectivity system that uses Boolean Binary Weights of Evidence (BWE) or Fuzzy Logic models to integrate multivariate data for applications in mineral exploration. The system used to assess prospectivity in this work uses BWE. The parameters for the relative weight of influence, zone of influence and style of influence for a particular input data layer were entered by the authors (on the basis of their knowledge) and the system calculated and plotted a pixel-based prospectivity grid from the information provided. The usefulness of the product relies heavily on the data available for input, the weights assigned to them, and the assessment of the importance of the data to the signature of the mineral deposit model.

Various classes of multivariate geoscience data are frequently available in digital form for inclusion in the prospectivity analysis. For example, geological maps, remotely sensed information (air- and space-borne), geochemical analyses and geophysical data were all available for Wales. These include several types of data, such as points, grids, vectors, polygons or sets. In addition, relationships between datasets can give rise to new features called event occurrences which may be of significance and can include in a prospectivity model as separate data layers. Common examples of event occurrences are intersections, for example the intersection of two faults or a fault with a particular geological horizon.

The BGS system allows numerous data plotting options (including annotation and insets) with repeated procedures (multiple data layers) for many of the plot options. The plot options represent combinations of the data classes and types typically available to the explorationist. Most analyses will use only a few data layers. Each data layer consists essentially of data attributes related by a series of [x,y] values. For point and vector data the [x,y] pairs define the occurrence pixels for those data. For polygon data the [x,y] pairs define an area within which are a set of occurrence pixels and a vector which defines the margin of this set. Event data provide [x,y] occurrences which define the intersection of two data layers. All occurrence pixels can be used to contribute to the prospectivity appraisal according to the significance defined in a table of index parameters for each data layer.

Exploration criteria (logic model, data parameters) are defined on the basis of generic and empirical mineral deposit models built from a knowledge of many deposits world-wide, modified by specific features of any known local mineralisation in the area being assessed. Multivariate data are analysed using these criteria to define the relative weight for occurrence events of any particular data layer. Combination of the data layer weight arrays provides a prospectivity map to assist decision-making in mineral exploration. The degree of confidence and value that can be attached to the prospectivity maps depends on the availability, quality and relevance of the data, together with the reliability of the exploration model. The methodology used in this study is summarised in Table 4.

Table 4 Summary of the main stages in knowledge-based prospectivity analysis

1	Selection of mineral deposit model and area for prospectivity analysis
2	Review of published information on the selected deposit model to determine key indicators (e.g. presence of submarine volcanism, high values of base metals in stream sediment)
3	Acquisition of digital datasets necessary to provide the key indicators and integration (in GIS)
4	Data processing to extract key indicators (e.g. geophysical lineaments, geochemical anomalies)
5	Assignment of weightings, zones and styles of influence to key indicators; selection of prospectivity resolution
6	Combination of weighted criteria using Boolean, Binary Weights of Evidence or Fuzzy logic model; calculation of prospectivity and plotting of prospectivity maps

Boolean logic (BL) model

In the simplest form this displays a set of information which has a binary code representing present (1) or absent (0). More commonly, the model is used to produce binary weights of evidence (BWE) maps to incorporate the effects of numerous populations. For example if 5 populations were plotted together, each with a weight of 1.0 then the maximum prospectivity score would be 5 and the minimum 0. By normalising the score to the sum of the weights a binary weights of evidence map in the range 0.0−1.0 can be generated.

Pixel size

The resolution of the prospectivity model is determined by the pixel size for analysis and is independent of the plot area or any of the plot option parameters. However if the analysis includes gridded data effects of the pixel size in relation to the grid mesh size need to be considered.

Similarly the contribution of any vector to prospectivity is based on the [x,y] pairs for the line so that 'simple' vectors defined by a few widely space points might not give the expected contribution to the prospectivity map.

Prospectivity parameters

For each active data layer in a model, prospectivity is analysed by use of a table of index parameters which define the zone of influence, the style of influence (exponent and peak distance) and the weight of influence for any data layer. By default the table of index parameters is set to a negative weight. Since zones with zero or negative weights are not cumulative in either of the logic models this would generate a prospectivity grid of zero. Definition of the zones and weights for analysis is based on generic and empirical models of the target mineralisation and the specific knowledge of the region.

Most of the plot options with multiple data layers allow individual definition of the index parameters during program execution using the 'weight n' string where n is an index number in the range 01−100. This allows previously defined index parameters to be used in the prospectivity analysis. This is useful, for example when plotting a series of lineament vectors with different perceived prospectivity potential.

For fuzzy algebraic logic, the defined weights for data layers are always less than 1.00, whereas for Boolean models individual data layer weights can be greater than unity.

The sum of weights, essential for normalisation of the prospectivity map, is defined by the sum of weights for each plotted data layer. Each data layer is treated therefore as a level of evidence. Consequently, if data layers contain non-unique data, i.e. duplicate data points, or overlapping polygons then these will be scored twice in the prospectivity analysis, although the sum of weights will not reflect this. This can mean that some BWE models will have final prospectivity scores at or above 1.00. To compensate for this, if the non-normalised prospectivity grid contains elements greater than the sum of weights, then the maximum prospectivity score is used to normalise the BWE map before plotting.

Zone of influence (buffer zone)
The zone of influence (buffer zone) allows the user to specify the zone of prospectivity contribution for an individual data layer or for several options. For example the user may wish to emphasise the significance of the intersection of two vectors, say faults and lineaments or the significance of say gold occurrences in bedrock. For a zone value of zero, only the pixel (target pixel) which contains the data element (vector intersection/data point) would contribute to the prospectivity model; for a zone value of 1 the adjacent 8 pixels are also included in the proximity window and scored into the prospectivity model. A zone of influence value of 3 will mean that each data element affects a window of 7x7 pixels centred on the target pixel into the analysis. All the defined zone of influence will not necessarily contribute to the prospectivity depending on how the style of influence (distance exponent, peak distance) is defined.

Style of influence (distance exponent - peak distance)
Linked to the concept of a zone of influence or buffer zone is the distance effect within the zone. Significance of any target data element is assumed to be constant or decrease (increase) away from the occurrence pixel according to a simple cosine distance law. The user can define the nature of this distance relationship during definition of the table of index parameters. The style of influence assumes the value **f** in the relationship:

$$\mathbf{f} = \cos [|(\mathbf{n}-\mathbf{x})|^{\mathbf{a}}]$$

where **n** is the distance from the target pixel in pixel widths **x** is the peak distance (see below) **a** is the distance exponent and **f** is always greater or equal to 0.

Suitable values of the distance exponent are in the range between 0.0 and 3.0. For example, for a zone of influence of 10 pixels and a distance exponent of 2.5 the relative weight at a pixel distance of 5 would be 0.56 of the maximum weight; at a distance of 6 pixels would be 0.03 and beyond this would be zero. Similarly, a zone of influence of 10 and a distance exponent of 2.2 would mean that the actual zone of influence (**f** > 0.) would only extend to 7 pixels away from the target pixel.

Peak distance
The influence of the data layer might not be a maximum at the occurrence point. For example 'halo' effects might be important at specified distances from data occurrences. A simple shifting of the zone of maximum weight away from the target pixel can be achieved by use of the peak distance (x) parameter. A peak distance of 0 (pixels) will mean maximum relative weights occur at the target pixel. A peak distance of 5 will mean maximum weights occur at a radius of 5 pixels from the data events and decrease at greater and lesser distances. For the present study 'halo' effects were not considered appropriate and all peak distance parameters were zero.

Weight of influence

The weight of influence (w) is defined in the table of index parameters by any real value. It is the maximum value of the function describing the effect within the zone of influence. Negative weights will not be scored into the prospectivity grid. For Boolean and Binary weights of evidence prospectivity maps any positive values can be used. For fuzzy logic maps then all weights should be less than or equal to 1.00. For a peak distance of zero, the maximum weight for any data layer will only be scored in the target pixel. The apparent weight, within the zone of influence is given by product of the weight and distance function **f** described above.

Prospectivity map and grid

The prospectivity maps are generated by combination of the contributions from the selected data layers using a Boolean or fuzzy logic model. Prospectivity maps based on the fuzzy logic algebraic sum will always be in the range 0.0 - 1.0. Binary weights of evidence (BWE) maps will also have values less than unity, but for the simple Boolean model prospectivity values above 1.0 occur and the contour interval and range should be chosen to accommodate this range.

DATASETS

Numerous data layers were available to the prospectivity study. Table 5 shows the main types of data layers considered with an indication of the utilisation of the data in relation to VMS and mesothermal gold exploration.

Geology

The BGS 1:250 000 geological map of Wales (British Geological Survey, 1994) was used to provide the basic geological information in this study (Figure 2). It is part of the UK map at this scale and is available in provisional digital form as polygon vectors of faults, chronostratigraphy and lithology. Alphameric codes have been assigned to the chronological codes so that a range of chronostratigraphy or a series of specified units can be selected and plotted. Lithological codes are associated with some of the shape polygons and were also used in prospectivity analysis. The shape polygon vectors have been used throughout so that true topological selections are not available for prospectivity assessment. These constraints have placed some limitations and approximations on the abstraction of some key indicators for the prospectivity analysis, such as dark mudstone/black shale units and acid volcanic rocks. These selections are affected by the quality of data behind the 1:250 000 map. Large areas of North Wales, for example, have been re-mapped recently to a very high standard at 1:10 000 scale, while for some areas of central and south-west Wales there is no up-to-date mapping and existing maps are at smaller scale. This has little effect at the regional scale of assessment but becomes progressively more important if sub-areas are examined at larger scales.

Table 5 Data layers available for prospectivity analysis

Data type	Used	Data Layer
v	y	1:250K Geological Map chronostratigraphy
v		1:250K Geological Map lithology
v	y	1:250K Geological map faults
v	y	Major basement fractures and shear zones
v	y	Inferred minor fold axes in mudstone units
p	y	Metalliferous mineral occurrences
p	y	Gold occurrences in rocks, alluvium and panned concentrate
g		Aeromagnetic anomaly map of the UK and surrounding area
g		Gravity anomaly map of the UK and surrounding area
g	y	Residual magnetic anomaly
g	y	Residual gravity anomaly
p		Depth solutions from gravity data
p		Depth solutions from magnetic data
v	y	Lineaments taken from images of gravity data
v	y	Lineaments taken from images of aeromagnetic data
g		Detailed airborne magnetic data
g		Detailed airborne EM data
p	y	G-BASE regional stream sediment geochemical data 15404 sites
p	y	Detailed MRP stream sediment and panned concentrate data 4680 sites
v		Lineaments taken from Landsat Band 5 Thematic Mapper images
v		Folds and structures on the Tectonic Map
p	y	Intersections of lineaments, faults, geological horizons
p	y	Inferred and published locations of volcanic centres

Data types: v vectors, p points, g grids

Some other geological indicators used in the prospectivity analysis, for example the location of volcanic centres and breccia pipes, have been obtained by abstracting and interpreting information from published and unpublished geological maps, reports and scientific papers supplemented by personal observations (Figure 7).

Structure

Information on the location of faults at a regional scale was taken from the digital 1:250 000 geological map of Wales. The fault data is held in a simple vector file with no attributes regarding throw or amplitude (Figure 8).

Separate data was required to provide information on more fundamental (deep-seated) fractures that might exert control on the distribution of mineralisation (Figure 9). This was obtained from a number of sources. The major zones of basement fracture and shear from the map produced by McDonald et al.

(1992) were taken and used in conjunction with the major gravity lineaments from the 1:1.5M gravity anomaly map of Britain (British Geological Survey, 1997). Major magnetic lineaments abstracted from the magnetic map of Great Britain (British Geological Survey, 1998).

Currently the only readily available regional-scale digital fold-axis data is that published on the 1:1.5M Tectonic Map of Britain, Ireland and adjacent areas (British Geological Survey, 1996). Fold axes are important features for focussing stress and fluid concentration and play an important role in one of deposit models considered by this study. The fold structures portrayed on the Tectonic Map are generally the largest-scale features, and were supplemented by mesoscopic fold features evident on the geological map. These were captured digitally by applying a moving-window curvature routine to vector elements of the geological map related to the main outcrop pattern of mudstone-dominant units. Zones of strong curvature (typically above 1.2 radians) were identified easily in this way but the procedure did construct the axial traces.

Metamorphism

Regional studies of metamorphic grade based on illite crystallinity of metapelitic rocks (e.g. Merriman and Roberts, 1985; Roberts et al., 1996) have established the overall pattern in the Welsh Basin. Together with other studies, these have allowed a regional-scale contoured map of metamorphic grade for the Lower Palaeozoic rocks to be produced (Bevins and Robinson 1988; Merriman and Frey 1999). This classifies the rocks as ranging in grade from late diagenetic along the eastern margins to epizone in the centre, with grade broadly increasing with age of strata from mid-Silurian in the east to Cambrian in the north-west. However, when looked at in more detail, there is evidence that grade is also related to tectonism, with the highest grades occurring is areas where penetrative slaty cleavage is well developed. Grade can therefore be correlated with depth of burial and high strain zones, though in detail several studies have indicated the possibility of a more complex pattern in which metamorphism is related to different events in the basin's history (Roberts et al., 1991; Merriman and Frey, 1999).

Metamorphic grade has been cited by some authors as a control on the location of slate-belt-hosted gold deposits. In Wales, most bedrock gold occurrences occur in epizone rocks relatively close to basement (e.g. Dolgellau Gold Belt), or are associated with high strain zones in regions of lower grade metamorphism (e.g. Ogofau). However, the information on metamorphic grade summarised in Merriman and Frey (1999) is not currently available in digital form. Since proximity to basement and presence of high strain zones are controls reflected in other datasets (e.g. major structures, magnetic residuals) no attempt was made to construct a digital data layer of metamorphic grade for this study.

Metalliferous mineral workings

Data for metalliferous mineral workings in Wales (Figure 10) were taken from the BGS mineral occurrence database containing information on the name, location (grid reference, nearest village or town and county), activity (open or closed), commodities worked, minerals present and information source. The database was increased substantially for this project and contains information abstracted principally from Ball and Nutt (1975), Bick (1974, 1983, 1985, 1988, 1990), Burt et al. (1987, 1990, 1992), Colman (1990), Cooper et al. (1982), Dewey and Smith (1922), Dewey and Eastwood (1925), Down (1980), Foster-Smith (1977a; 1977b; 1978; 1979; 1981), Greenly (1919), Hall (1971, 1988), Holding (1992), Hughes (1988), Lewis (1967), Morrison (1975), Smith (1921) and Warren et al. (1984). Date on baryte were also included because of its association with metalliferous minerals, but other industrial and constructional minerals were excluded.

Gold occurrences

Data on gold occurrences were also abstracted from the BGS minerals occurrence database containing information on all recorded gold occurrences in Britain (Figure 11). Information is held on the occurrence location (name and grid reference), type of occurrence (in rock, river alluvium etc), activity (worked or unworked) and information sources. Several information sources were used to construct this dataset including gold observations in panned concentrates collected for the BGS G-BASE (Geochemical Baseline Survey of the Environment) programme.

Characteristics of alluvial gold

The composition, inclusions, zoning and other characteristics of alluvial gold grains can provide useful information on the type of source. Some information on the characteristics of alluvial gold grains is available from Wales (e.g. Leake et al., 1993), but the data are restricted to a few localities and is insufficient to form a regional dataset which could be included in this study. However, the data are useful at the stage of interpreting and comparing prospective areas for which results are available.

Geophysics

Regional gravity and magnetic data are complete across Wales. The magnetic data (British Geological Survey, 1998) were collected by airborne survey at a mean terrain clearance of 305m along flight lines spaced 2 km apart. The original analogue data were digitised in the 1980s and are suitable for regional assessment of the type undertaken by this study. More detailed airborne magnetic data were collected for parts of Wales by the MRP (Harlech Dome, Anglesey, NW Pembrokeshire) using a helicopter platform in the 1970s (Cornwell et al., 1995). These were not used in this study but could be used in any more detailed, larger-scale, assessment of these areas.

Gravity data come from a variety of sources collected between 1950 and 1992. They include onshore point measurements taken specifically for the national survey supplemented by marine data, collected on traverses, from a number of sources (British Geological Survey, 1997).

These data provide maps of total magnetic field (Figure 12) and Bouguer gravity anomaly (Figure 13), based on grids of mesh size 0.5km. These data highlight the integrated effects of density and magnetisation variation across the region.

The main features of the aeromagnetic anomaly map are the strong positive anomaly over the Cambrian and Precambrian rocks of North Wales and the significant anomaly in South Wales extending from Haverfordwest to Swansea. Magnetic sources have been identified in Precambrian and Cambrian rocks in north Wales and in the Bryn Teg borehole. The anomaly in south Wales may be due to Precambrian basement or to Lower Palaeozoic volcanic centres. The Welsh Basin has no significant calc-alkaline intrusions but the annular magnetic anomalies near Weobly in the Welsh Border are very indicative of an acid-intermediate intrusion, buried beneath Devonian cover rocks.

The main features of the Bouguer gravity anomaly map are the strong positive ridge extending along the coast from Fishguard to Barmouth and the positive feature running through west Lleyn and Snowdonia.

The gravity and magnetic datasets contain gradient and amplitude information which can be analysed to provide additional parameters for use in prospectivity modelling. Consequently, geophysical lineaments have been picked from colour and greyscale images of the Bouguer gravity anomaly and the total field anomaly and derivatives of these data. These lineaments are considered to reflect the distribution of density and magnetisation across geological structures at various depths in the upper crust and their location reflects the position of geological boundaries or fractures that may or may not have a surface expression.

Residual geophysical anomalies may also reflect important geological features which may not be obvious at surface but nevertheless exert a control on mineralisation. For example, both positive and negative residual gravity anomalies can be significant in reflecting the presence of basic and acid igneous intrusion or, in some cases, volcanic centres (Figure 14). Annular magnetic anomalies might indicate the location of intrusions, while strong gradients in the regional magnetic anomaly might locate the faulted margins of basement blocks with significant magnetisation.

In the Welsh Basin, depth to basement is not simple to define by geophysical methods, partly because the contrast in density between the variable late Precambrian volcanosedimentary succession and equally variable Lower Palaeozoic rocks is small. However, the Precambrian appears to be more magnetic and this is particularly clear in south-west Wales (Cornwell and Cave, 1986; Colman et al., 1995) where there is a widespread unconformity at the base of the Cambrian. For this study, depth to source estimates for gravity and magnetic anomalies were made using deconvolution and analytic signal techniques operating on the gridded data. Focused 3D Euler deconvolution, pseudo-3D Werner deconvolution, slope analysis and 3D analytic signal techniques were all used. However, a simple residual magnetic anomaly map provided the most useful guide to the presence of relatively shallow Precambrian basement (Figure 15).

There is no uniform regional-scale electromagnetic coverage available, but airborne electromagnetic data are available those parts of the basin flown by the MRP. As these data are useful in exploration for the mineralisation types studied (see below) they could be incorporated in larger-scale more detailed studies of those areas for which data are available (e.g. Harlech Dome. north-west Pembrokeshire).

Geochemistry

BGS Geochemical Baseline of the Environment (G-BASE) dataset

This dataset comprises chemical analyses of active stream sediment samples collected at a density of approximately 1 sample per 1.5 km^2 across the whole of Wales as part of the BGS G-BASE (Geochemical Baseline Survey of the Environment). The methods used for sample collection and preparation for chemical analysis are those recommended as international standards for geochemical mapping (Darnley et al., 1995) and conform to the standards set by the International Geological Correlation Programme 360. Details are given in Plant and Moore (1979). Samples of the < 150 µm fraction of the sediment were analysed for over 30 elements by G-BASE. For this study only site location information and associated analytical data for the elements As, Ba, Bi, Cu, Ni, Pb, Rb, Sb, Sn and Zn were abstracted for integration with other information. The eastern boundary was arbitrarily set at the $^{3}50000$ grid line, resulting in the capturing of data for 15404 sites (Figure 16).

Mineral Reconnaissance Programme (MRP) panned stream sediment datasets

Panned stream-sediment heavy-mineral concentrates were collected across large areas of Wales during the earlier phases of the Mineral Reconnaissance Programme, mostly between 1972 and 1980. The principal areas covered (Figures 4 and 17) were Anglesey (Cooper et al., 1982), Snowdonia, Lleyn Peninsula (Leake and Marshall, 1994), Harlech Dome (Cooper et al., 1985), Berwyn Dome (Cooper et al., 1984), Central Wales (Ball and Nutt, 1975) and the Preseli Hills (Cameron et al., 1984). All of these surveys were aimed primarily at the detection of base-metal mineralisation, and elements relevant to the detection of gold deposits, such as As, were often not determined. A later survey (Brown, 1993) collected data specifically aimed at detecting gold mineralisation from part of Central Wales. The samples from all the surveys were collected at a similar density of about 1 sample per 1.5 km^2 using the same methodology

(Leake and Aucott, 1973). Briefly, a heavy-mineral concentrate was obtained at each site by wet screening active stream sediment though a 2 mm sieve to obtain about 4 kg of < 2 mm sediment which was then panned at site to produce a about 100 g concentrate. Sample were all analysed by x-ray fluorescence for metals pertinent to mineral exploration and many anomalous samples were examined mineralogically to determine the mineral phases responsible for high metal values. The resulting data are particularly useful when compared with stream-sediment results from the same site as they provides strong evidence for the probable source of many anomalies.

Analytical data for As, Ba, Bi, Cu, Fe, Mn, Pb, Sb, Sn and Zn in panned concentrates from 4680 sites held in the BGS geochemical database for the survey area were abstracted (Figure 17). Because of the differing objectives of the individual surveys, different groups of elements were analysed in samples from different areas, giving rise to a variable number of sites where data is available for each element. The elements for which relatively little data are available are, unfortunately, the gold pathfinders Bi, Sb and As (Table 6).

Table 6 Numbers of panned concentrate analyses

Element	As	Ba	Bi	Cu	Fe	Mn	Pb	Sb	Sn	Zn
No. of sites	1489	4288	268	4517	4378	4378	4644	2595	4551	4516

Data processing

The MRP and G-BASE geochemical drainage data were subject to elementary statistical screening to achieve clarity of presentation. Cumulative frequency plots were constructed for each element and analysed following the methods described by Parslow (1974) and Sinclair (1976) to provide information on the number and distribution of populations present.

For all elements except Rb in stream-sediment the analysis suggested the presence of multiple overlapping normal and lognormally distributed populations, including at least one lognormally distributed group of high values which could be related to enrichment above levels normally encountered in unmineralised rocks. The distribution of Rb in stream-sediment has an approximately normal form with a slight deficiency of very high values. For three elements (Bi, Sb and Sn) in both datasets the distributions were obscured by heavy truncation at the lower end, caused by a high proportion of samples containing concentrations of these elements below the detection limit of the analytical method employed. The truncation is worst for Bi in panned concentrate, where only two values greater than 4 ppm are recorded, making the data of little use. Tin in stream sediment is least affected, but in all cases values close to the theoretical detection limit tend towards a normal distribution which may be a product of analytical scatter.

Threshold levels were set to isolate samples derived from sources containing metalliferous enrichments. Because background and anomalous sample populations overlap to varying degrees for most elements, some enriched samples will fall into the background groupings and vice versa. However, thresholds were set at such a level as to eliminate nearly all samples from the background populations. For most elements in stream sediment, the 97.5 percentile of the total population was chosen, which equates to >99% for the background populations. The 97.5 percentile was used for Rb although no separate population of enriched values is evident while for Bi all values above the practical detection limit of 3 ppm (99.8 percentile) were plotted. For panned concentrate the distributions are more variable and complex and thresholds were set to exclude 97.5–99% of the background populations. Consequently nearly all plotted values will be related to some form of metal enrichment. Above the threshold the enriched samples were arbitrarily split into clusters on a percentile basis to allow distinction between near threshold and very high values.

Experience from individual mineral exploration surveys in Wales (e.g. Cooper, Nutt and Morgan, 1982; Cooper et al., 1985; Cooper, Rollin and Cornwell, 1984) indicates that strong metal enrichments in stream sediments and panned concentrates are most likely to be due to the presence of mineralisation and associated alteration, or contamination, or a combination of both. A few clusters could also be due to natural enrichments of no economic significance in a particular rock type, although the intentional setting of thresholds at relatively high levels will have eliminated many of these. Variations in background levels related to individual lithologies is described in detail in the geochemical atlas of Wales (British Geological Survey, 2000). In stream sediments high values could also be generated by hydrous oxide precipitates in streams flowing from uplands containing acidic soils and peat. Due to the lack of significant Sn mineralisation in Wales the presence of high Sn and, to a lesser extent Sb, in a sample could be used as an imperfect qualitative guide to samples likely to contain enhanced metal levels due to contamination. Experience from previous surveys showed that untapped mineralisation may only generate weak anomalies. Consequently, threshold levels should, where practical, be related to backgrounds generated by individual lithologies, allowing them to be set lower and enabling the identification of more subtle features related to individual mineral deposits and associated alteration rather than prospective areas. In these circumstances areas of very low metal levels that may be related to alteration can also be distinguished.

Soils

Information on soils in Wales is provided by the Soil Survey of England and Wales at both regional (Rudeforth et al., 1984) and local scales (maps and memoirs). Data on soil type was considered to be of limited use for this study at the regional scale and so this information has not been included. Data on the concentration of base metals in soils has been published both by the Soil Survey and by the Mineral Reconnaissance Programme, but coverage is limited and the information has not been included in this regional-scale exercise. If more detailed prospectivity analysis of a selected part of the basin is undertaken, based on a scale of c. 1:50 000 or larger, then these data would merit inclusion if available for the area selected.

Satellite imagery

Landsat Thematic Mapper (TM) imagery has been interpreted to produce a lineament map for Wales, with the aim of mapping any surface expressions of geological structure. The raw data were subject to geometric correction to the British National Grid (BNG), edge-enhancement and contrast-stretching, prior to the writing of colour and black-and-white negatives. The TM band 5 (1.55–1.65 µm) from the short-wave infrared wavelength region was used to produce 1:250 000 scale photographic prints for the lineament interpretation. There are a great number of picked TM lineaments in the resulting dataset, mostly of relatively short length (Figure 21). These are of limited use at small (1:1m) scales but would be useful when used in the detailed analysis of sub-areas at larger scales.

Environmental constraints

Information on regional-scale protected areas was included in the final assessment and ranking of prospective areas but not in the calculation of prospectivity, which was based solely on geological criteria. Four types of planning constraints were considered: National Parks, Areas of Outstanding Natural Beauty (AONBs), Sites of Special Scientific Interest (SSSIs) and National Nature Reserves (Figure 5).

The latter mostly occupy only small areas, as do many of the SSSIs, but a few much larger designations in this category are present in Wales. Information on some other constraints which mostly occupy small areas have not been included, notably ancient monuments and coastal/marine sites.

The listing and weighting of key parameters to determine prospective areas was achieved by the analysis of mineralisation models built up from world-wide sources, modified to take account of the local geological setting and specific environments encountered in the Welsh Basin. Prospectivity for two types of mineralisation was determined: mesothermal slate-belt hosted gold and volcanogenic massive sulphide deposits (see above).

MINERALISATION MODELS

Turbidite-hosted or slate-belt gold deposits

The mineralisation at Ogofau and in the Dolgellau Gold Belt has many features in common with well-documented examples of this type of gold deposit from a few countries. Typical examples include those at Ballarat and Bendigo in Victoria, Australia (Sandiford and Keays, 1985; Sharpe and MacGeehan, 1990), at Banjas in the Valongo-Gondomar belt in northern Portugal (Gunn et al., 1995) and, most closely relevant to the Welsh Basin, the Meguma slate terrane in Nova Scotia (Graves and Zentilli, 1982; Haynes, 1986; Kontak et al., 1990). Many descriptions of this type of deposit are included in Keppie et al. (1986) and Nesbitt (1991), while a succinct summary of the principal characteristics of the type is provided by McMillan (1996).

The mineralisation typically consists of quartz-gold veins, segregations and/or sheeted zones hosted by fractures, faults and dilation zones in fold structures and along bedding planes in clastic sedimentary successions of dominantly turbiditic origin. Typical host-rock lithologies include greywackes, siliceous wackes and turbiditic and hemipelagic mudstones or shales. Other rock types present may include bedded cherts, ironstones, fine-grained impure carbonates, polymict conglomerates and volcanic rocks. These host rocks were typically deposited in submarine troughs, periarc, foreland or remnant ocean basins from continental margins or back arc basins. The sedimentary successions, with or without interbedded volcanic sequences, have suffered one or more deformational events and, typically, low-grade metamorphism. Younger granitoid intrusions may be present but, like the presence of volcanics, are not considered to play a vital role in the metallogenesis. Some of the best known deposits are associated with rocks of Lower Palaeozoic age, but deposits in rocks from the Archaean to Tertiary have been described.

Ore deposits typically comprise multiple quartz veins up to a few metres in width which are strata controlled and may be discordant, bedding-parallel or axial-plane-parallel. Veins are variably deformed and may occur in en-echelon sigmoidal groups, ladder veins, stockworks, sheeted arrays and saddle reefs or troughs (bedding-parallel veins in the axes of anticlines and synclines) related to the local structure. Discordant veins are generally massive and all veins are well defined with sharp contacts. Although normally not prominent, sericite, silica and/or carbonate alteration and disseminated arsenopyrite, pyrite and tourmaline may be developed in the wallrocks. Arenaceous wallrocks are usually least altered, while in pelitic and particularly mafic igneous rocks alteration may be pervasive and intense. Native gold typically occurs in polymetallic quartz-dominated veins with pyrite, arsenopyrite and a variable range of other sulphides and sulphosalts, generally in small amounts. Carbonates (calcite, dolomite, ankerite or mixed), and in some cases subordinate feldspar and/or chlorite may also be present. Ore sulphide minerals most commonly found in the gold-bearing veins include chalcopyrite, galena, sphalerite and stibnite.

Pyrrhotite may occur, which can have important implications for exploration because of its magnetic nature. Late, post-deformational, veining is common but the veins are not auriferous.

As is apparent from the above descriptions that local ore controls are dominated by dilational structures and favourable (chemical or physical) host-rock lithologies. In some districts the mineralisation appears to be confined to a specific stratigraphic interval, often coinciding with a lithological change, or even a specific unit. The overall structural level of the sequence is also often seen as an important control, with higher levels (lower-grade metamorphism) being most prospective for disseminated mineralisation and deeper structural levels favouring massive vein deposits.

All deposits show individual variations, with all those in Wales having a relatively large amount of associated sulphide minerals. The lithological control is well demonstrated in nearly all the Welsh occurrences while the structural controls at Ogofau are a classic of the type. Perhaps less typically, at Ogofau the gold occurs disseminated in the host pyritic mudstones and sulphides. Recent work on the characterisation of gold from different sources indicates that in Britain gold from this type of deposit is characterised by the presence of inclusions of sulphide minerals, such as galena, sphalerite and chalcopyrite commonly found associated with gold at the macro scale. Gersddorffite, tetrahedrite, hessite and Bi tellurides are also present. Other characteristic features of the gold are the common presence of Hg, a relatively high Cu content and a wide ranging but appreciable Ag content (Leake et al., 1993). Pyrrhotite occurs in the gold-bearing veins of the Dolgellau Gold Belt but its use for exploration is limited by its relatively widespread occurrence elsewhere not associated with gold (Bevins, 1994).

Genetic models dominantly favour the deposition of gold from metamorphogenic fluids, the gold having been leached from sedimentary/volcanic piles in or under the basin (Figure 25). In this model high geothermal gradients, with or without plutonic heat, cause regional metamorphism and devolatilisation. The fluid acquires CO_2, Si, S and Au by water-rock interaction as it migrates through the metamorphosed volcano-sedimentary pile towards major structures, often strike-slip faults. Convection currents may be set up. As the fluids rise they cool, release CO_2, and lose S to the gas phase or in sulphidisation of the host rocks, causing precipitation in veins and wallrock alteration. Deposition is typically penecontemporaneous with the main deformational/metamorphic events and controlled locally by wallrock reaction and structural location with episodic reopening common. A variation on this model involves the deep convection of meteoric water, rather that dewatering by metamorphism. Other proposed models range from magmatic hydrothermal to syngenetic origins, but these have received no support in any of the recent papers arising from recent research into Welsh deposits.

Deposits are variable in size, occur in groups within a terrane and may be individually small but rich. For example, production of over 35 tonnes from the Meguma belt in Canada has come from some 60 individual deposits ranging in grade from 8 to 50 g/t. The Bendigo field in Australia can be considered world class, having produced more than 373 tonnes (12 M oz) from non-alluvial sources since 1851. The high-grade nature of many occurrences make them attractive targets in countries such as Britain because they lend themselves to underground working with limited surface environment impact.

Erosion and weathering of these deposits frequently produce alluvial gold, so gold panning is a useful exploration method for this type of mineralisation. The geochemical signature is likely to include, besides enrichment in Au, anomalies in Ag, As, S, Fe, B, As, and often Bi, Cu, Cd, Mg, Mn, Pb, Sb, and Zn. Elements such Ca, Co, F, Hg, In, Li, Mo, Ni, Se and Te may also show some enrichment. The deposits tend not to produce characteristic direct geophysical signatures unless the sulphide content is relatively high, but regional gravity and magnetic data can be useful in locating controlling structures and locally electromagnetic or induced polarisation methods may be useful in detecting associated sulphides and carbonaceous mudstone units. Good lithological and structural information is crucial.

Key exploration parameters

Taking into consideration the overall properties of the type and the particular features of the known deposits in the Welsh Basin, the following key parameters were considered in determining prospectivity for this type of mineralisation in the Welsh Basin:

- Presence of dark (carbonaceous and/or pyritic and/or pelagic/hemipelagic) mudstone units within the basinal clastic succession.
- Presence of tightly folded strata and/or shear zones (reflecting underlying anisotropy).
- Record of gold in bedrock and/or stream sediment (with mesothermal signature).
- Record of polymetallic sulphide mineralisation.
- Presence of anomalous levels of elements listed in the previous section in stream sediment and/or panned concentrates.
- Presence in the vicinity of major (deep seated) fractures as indicated by high strain zones, major mapped faults, major fold axes, major satellite lineaments and/or geophysical lineaments.
- Depth of burial or proximity to basement.
- Presence of electromagnetic and/or induced polarisation anomalies (related to mudstone units at the appropriate stratigraphic level).
- Presence of carbonate, sericite or silica alteration in wallrocks adjacent to vein-style mineralisation.

Volcanogenic massive sulphide (VMS) deposits

These are synvolcanic accumulations of sulphide minerals that form part of a larger grouping of concordant hydrothermal submarine ore deposits formed by the discharge of hydrothermal solutions into the sea floor. The other major grouping is normally termed sedimentary-exhalative (SEDEX), sediment hosted or shale hosted massive sulphides and include world-class deposits such as Sullivan, Mt Isa, Rammelsberg and, in Britain the Foss-Duntanlich baryte deposits. VMS deposits occur in rocks of all ages and processes similar to those which led to their formation can be observed on the sea floor today. Well-known deposits or groups of deposits include those in the Iberian pyrite belt at Neves Corvo in Portugal, Bathurst and Windy Craggy in British Columbia, the classic Hokuroko district of Japan and the Tasman geosyncline in Australia. In Caledonian Lower Palaeozoic rocks, well-described deposits are known from Buchans in Newfoundland, Avoca in Ireland and Parys Mountain in North Wales. Many extensive reviews are available, including Klau and Large (1980), Franklin (1993), Lydon (1984, 1988) and Swinden et al., (1988).

The term volcanic-hosted deposit is preferred by some geologists as it does not imply that the deposits themselves are an integral part of the volcanic process, which may not be the case. Rather, they are the product of a particular type of hydrothermal system developed in submarine volcanic environments. Because of the large number and range of deposits, several classification systems defining sub-groups have been proposed based on tectonic setting, host rock or ore composition.

In this study attention was focussed on deposits occurring in Phanerozoic terranes with volcano-sedimentary successions associated with subduction zones at plate margins, particularly those formed in island arcs or continental margins (e.g. the classic Kuroko type). Many deposits were formed during periods of extension following island-arc construction and may be related to caldera resurgence.

Mineralisation occurs typically in a volcano-sedimentary succession which includes bimodal piles of rhyolite-basalt lavas, tuffs and breccias with varying quantities of interbedded clastic sediments, typically fine-grained (mudstones) ocean-floor deposits. Footwall sequences typically comprise calc-alkalic felsic porphyritic ash flow tuff, rhyolite domes and flows and felsic epiclastic rocks, sometimes with basalts near the base. The stratigraphy may be dominated by volcanic rocks (e.g. in the Hokuroku district of Japan) and complicated by deposition in submarine calderas and syntectonic faulting, producing units of very variable extent and thickness. Strong alteration often accompanies these deposits and may locally severely modify the host-rock lithologies to the extent that their original composition and textures are almost totally obscured (e.g. at Parys Mountain).

Mineralisation tends to occur at a single stratigraphic interval, within which several individual deposits may be developed. For example, Sangster (1980) analysed eight VMS districts of Precambrian to Miocene age and found that each has between 4 and 20 deposits. The location of these is dictated by topographic features on the ocean floor at the time of formation and substrate structures such as syn-volcanic faults and regional-scale fractures. Frequently deposits are spatially associated with felsic volcanic rocks, particularly rhyolite domes or fragmental deposits (breccia units), even in successions dominated by mafic volcanics.

Ore bodies are typically well-zoned, massive and bulbous in form and are underlain stratigraphically by stringer ore. The detailed classic Kuroko sequence from the stratigraphic bottom up is (i) discordant siliceous pyrite, chalcopyrite and quartz stockwork (ii) stratabound gypsum, anhydrite, pyrite, chalcopyrite, sphalerite, galena, quartz and clay, (iii) stratiform pyrite, chalcopyrite and quartz, (iv) stratiform pyrite, chalcopyrite, sphalerite, baryte and quartz, (v) stratiform sphalerite, galena, chalcopyrite, pyrite, and baryte (vi) bedded baryte, locally with calcite dolomite and siderite, and (vii) ferruginous chert.

A more generalised and widely applicable zonation is (i) discordant stockwork or veins of pyrite, chalcopyrite and quartz; (ii) chalcopyrite-pyrite zone; (iii) pyrite-sphalerite-galena; (iv) sphalerite-galena-pyrite baryte. The ore zones form a characteristic mushroom shaped architecture (Figure 26) in which the Cu/Zn ratio decreases upwards and outwards. Massive, rubbly and brecciated textures predominate towards the centre of the deposit and clastic sulphide rocks, often containing spectacular sedimentary structures arising from slumping, are common at the periphery. Mechanically transported breccia ore is also characteristic of some deposits (e.g. Buchans, Newfoundland). The upper contact of the orebodies is usually sharp but the lower is usually gradational into the stringer zone. In sediment-dominated successions orebodies tend to be more tabular and laterally extensive with less-prominent zoning. The ore is typically a fine-grained and intergrown mixture of the principal sulphides (pyrite, sphalerite, galena and chalcopyrite), making it difficult to process. Baryte is common and a range of other minerals such as arsenopyrite, pyrrhotite, sulphosalts, cassiterite, stannite, hematite and magnetite may be present in individual deposits. Gangue minerals are quartz, carbonates, gypsum and chlorite. Parys Mountain is atypical in its lack of baryte, although this may be due to post-mineralisation events.

Hydrothermal alteration of the host rocks is often intense and also well zoned with a sericitic halo to a chloritic core. The chloritic zone is typically enriched in Fe and Mg and depleted in Si, Na, K and Ca, reflecting the destruction of feldspar, while the sericitic zone is enriched in K. Strong silicification is common around the upper part of the stringer zone in the core of several deposits. Local variations are common within this generalised framework and four zones have been defined around the classic Kuroko deposits: (i) outer montmorillonite, zeolite and cristobalite, (ii) sericite, mixed sericite-montmorillonite, Fe-Mg chlorite and minor feldspar, (iii) sericite clays, and (iv) quartz and sericite in the core. In some deposits chemical signatures (e.g. Nadepletion) related to alteration may be detected more than a kilometre from the deposit, including stratigraphically below the mineralised horizon. However, some deposits do not have well-developed alteration, while other strong hydrothermal alteration zones in volcano-sedimentary successions contain little or no ore.

The typical economic deposit contains 1 to 10 Mt of ore with an average grade of 2–10% combined Cu, Pb and Zn. The largest deposits contain in excess of 100 Mt of ore. Individual ore deposits cluster at a single stratigraphic interval to form mineralised districts, on average c. 30 km in diameter and containing 4 to 20 individual deposits (Sangster, 1980). This suggests strongly that, unless they have been removed by geological processes, further deposits are likely to be present in the Welsh Basin.

Although the basic model for VMS mineralisation was established more than 30 years ago, the understanding of how these deposits form has been greatly aided by the discovery and study of sea-floor hydrothermal vent systems from which massive sulphide deposits are currently forming. Some outstanding problems remain, for example with respect to the size and nature of the geochemical haloes, and precisely which hydrothermal systems form the large ore deposits, but many of the principles are now well established.

Fluids in the venting hydrothermal system come from cold, heavy, descending sea water that reacts with the heated crust as it passes through it, losing Mg, Sr and Ca, and leaching metals from it as higher temperatures (c. 350^{O}C) are reached. Some contribution from magmatic waters may be involved in at least some systems, and it is possible that modified sea water may enter high level magma chambers. The buoyant, heated metal- and silica-rich fluids then rise to the surface through fracture zones produced by tectonic activity to complete the convection cycle (Figure 26). As the fluid rises it cools and reacts with the wall rocks causing silicification. Copper is preferentially (with respect to Pb and Zn) precipitated prior to venting, forming the stringer zones. On sea-floor venting, the fluids cool rapidly. Anhydrite, derived entirely from ambient sea water is the first mineral to precipitate and forms structures which are infilled and replaced by precipitating metal sulphides. Individual vents and chimneys have short lives and the sulphide-rich mound builds as they collapse and/or are overgrown. Zonation develops continually by overgrowth and replacement at the surface and within the mound, while tectonic activity will trigger slump deposits. Baryte forms regardless of source rock, but its presence appears to be dependent on the discharge temperature, with low temperature discharges being rich in baryte and low in metals. Therefore systems that were abruptly terminated while venting high-temperature fluids would not have formed significant baryte accumulations. At relatively shallow sea water depths boiling may occur which is likely to enhance precipitation at or near the surface in the vent zone. There is some evidence to suggest that Au-rich deposits form in such conditions (water depth <1900 m) (Kappel and Franklin, 1989).

The uppermost strata of a deposit appear to have diverse origins but they probably fulfill an important role in sealing the deposit, as in modern oceans particulate sulphides from vents are commonly rapidly dispersed and oxidised unless protected by sedimentation or volcanic strata. Some ferruginous caps are probably the result of syn-depositional oxidation, while a ferruginous-siliceous zone may arise from low-temperature discharges. Baryte and Mn-oxide layers could only form if the bottom waters were oxidising, while if the bottom water is reducing then sulphide fallout could form distal concentrations of significance for exploration. Ancient deposits suggest that preservation is enhanced by sheltering in sea-floor depressions or by the flanks of rhyolitic domes.

Geochemical exploration signatures related directly to the mineralisation and accompanying alteration are common where the mineralised system reaches the surface. In these cases combined anomalies for Ba, Cu, Pb and Zn in stream sediment and heavy-mineral concentrates are commonly recorded, though the relatively fine-grained nature of the mineralisation and its presence in resistant siliceous rocks may compromise the signature. In areas with acid groundwater the presence of abundant Fe from the breakdown of pyrite and other sulphides may generate large stream-sediment anomalies when secondary hydrous oxides precipitate. High levels of K and depletions of Ca and Na related to alteration may also be detectable. Zonation in these and other elements (Si, Mn, Mg) is frequently well developed close to and within a deposit and may provide useful exploration guides. Likewise, mineralogical variations such as those produced by chlorite and sericite alteration zones, can indicate position in the overall deposit architecture.

This type of deposit frequently yields geophysical exploration signatures and several methods have played an important role in the discovery of individual deposits. Many deposits produce ground and airborne electromagnetic anomalies although there are resistive deposits, usually Fe-poor and Zn-rich or highly silicified, which may be missed by these methods (Bishop and Lewis, 1992). IP and resistivity can also provide effective data while, particularly in deposits containing pyrrhotite, magnetic surveys can usefully complement other methods. Drill-hole electromagnetic methods and detailed gravity surveys can be effective within prospects. Potassic alteration zones may generate radiometric anomalies, while silicified zones may result in complementary lows. At the regional scale, methods generating features related to fractures, volcanic centres or specific lithologies defining the mineralised stratigraphic interval, for example pyritic horizons or carbonaceous mudstones, can be very effective.

The strike length of individual VMS deposits in a mining field can be small and thus close-spaced drilling is needed to delineate them. Many areas have been explored repeatedly over several decades before significant discoveries were made, sometimes after considerable work had failed to find the major deposit. For example at Mount Chalmers in Queensland (Large and Both, 1980) a volcanogenic massive sulphide deposit (Main Lode) was discovered in 1898 and worked at intervals until 1943. Exploration from 1963 continued to prove sub-economic extensions to the Main Lode before the discovery of the economic concealed West Lode, 150 m from the Main Lode outcrop, in 1977.

Key exploration parameters

By applying the general model to the Welsh Basin, these are determined to be:

- Proximity to submarine volcanic centre.
- Tholeiitic or calc-alkaline bi-modal volcanism.
- Presence of rhyolite domes, felsic fragmentals, flanking mudstone and slump breccia deposits.
- Evidence of hydrothermal alteration of the volcano-sedimentary succession (silicification, quartz veining, chloritisation, sericitisation).
- Presence of stratabound base-metal or pyrite mineralisation or other metalliferous enrichments.
- Identification of favourable stratigraphic interval.
- Presence of major faults and/or lineaments (geophysical or satellite).
- Panned concentrate or stream sediment anomalies for Cu, Pb, As, Fe and or Zn, without Sn or Sb which are normally related to contamination sources. Stream sediment anomalies for K and/or Rb and panned concentrate anomalies for Ba.

- Magnetic anomalies and/or ground SP anomalies and/or (T)EM anomalies and/or radiometric (K) anomalies.
- Prospect-scale gravity anomalies within the favourable stratigraphic interval.

INTERPRETATION

For both mesothermal gold and VMS models, binary weights of evidence (BWE) prospectivity was calculated on a pixel size of 0.5 km using geological, geochemical and geophysical data layers selected to directly or indirectly quantify the key parameters applicable to the Welsh Basin at a regional scale.

Mesothermal gold mineralisation

Datasets

The presence of carbonaceous mudstone is an important local control on mesothermal gold mineralisation in Wales but not all carbonaceous (black) mudstones could be identified from the digital geological data available. Mapped stratigraphical sub-divisions could, however, be selected with ease and so stratigraphic sub-divisions dominated by mudstones were selected for inclusion.

Proximity to major fractures or shear zones is also a common feature of mesothermal gold deposits, so major faults, gravity and magnetic lineaments, faults and fold axes have been included, together with their intersections with the mudstone-rich units.

All known alluvial gold occurrences, most from MRP and G-BASE surveys, have been included as they indicate a source of gold in the catchment (unless the gold is derived from external areas and has been redeposited). Mines and trials containing copper mineralisation were selected from the list of known mineral workings, as available information suggests that in general these come from types of mineralisation generally indicative of higher temperatures (i.e. mesothermal) than deposits dominated by Pb-Zn.

G-BASE regional geochemical stream-sediment values and MRP panned-concentrate analyses were used to identify catchments containing high levels of metals commonly associated with mesothermal gold mineralisation. High levels of the individual metals might have come from other sources (e.g. contamination, vein-style mineralisation) and are therefore lowly weighted, but in conjunction and in spatial coincidence with other parameters they become of increased significance. Because a geochemical anomaly normally reflects a source at an unknown distance from the sample site a zone of influence has been incorporated. Some G-BASE stream sediment samples (e.g. As) have been assumed to have a greater zone of influence than many MRP panned concentrates. The samples in both datasets were mostly collected at a density of about 1 sample per 1.6 km^2 from small first-and-second order streams, so the zone of influence for individual samples is set at a relatively short distance (1–4 km).

G-BASE stream-sediment geochemistry for As, Sb, Bi has been used with values above the 97.5 percentile level for As (>150 ppm) and Sb (>7 ppm) abstracted from the dataset for inclusion in the analysis. All Bi values above the practical limit of detection, 3 ppm in stream sediment, were included. Arsenic levels >39 ppm in MRP panned concentrates (96 percentile) were also incorporated. Sample population distribution analysis indicated that in all cases the samples plotted were largely derived from an enriched source (less than 2 in 100 from background populations). Although these elements are commonly used as pathfinders for gold, Sb in particular has a number of other sources in Wales, with many high values either associated with lead mining (Central Wales Mining Field, Halkyn) or industrial activity (Liverpool, South Wales Coalfield).

In north and south-west Wales there is an apparent association between gold occurrences and proximity to the margins of relatively shallow Precambrian basement, but no such coincidence is apparent at Ogofau in mid-Wales. Nevertheless proximity to magnetic basement margins has been incorporated by choosing a wide zone around high magnetic gradients (> 30 nT/km) in the regional magnetic anomaly at 1 km above observation level.

The selected data layers and the weightings used in the prospectivity analysis are shown in Table 7 and plotted in Figure 27. Details of the data for the Harlech Dome, central Wales and west Wales are shown in Figures 27A, 27B, 27C and the derived prospectivity maps in Figures 28, 28A, 28B, 28C.

Table 7 Data parameters for mesothermal gold prospectivity model

Data Index	Zone *	Distance exponent	Weight	Description
1	0	2.0	0.1	250K geology vectors
2	1	2.0	0.5	250K geology Llanvirn, Caradoc polygons
31	0	2.0	0.5	Magnetic residual anomaly > 25 nT
80	4	2.0	0.4	G-BASE Bi in stream sediment > 3 ppm
4	8	2.0	0.5	G-BASE As in stream sediment > 100 ppm
81	4	2.0	0.4	G-BASE Sb in stream sediment > 7 ppm
82	4	2.0	0.4	MRP As in panned concentrate > 39 ppm
83	2	2.0	0.3	Mineral working for copper
84	8	2.0	0.6	Gold in panned stream sediment (alluvium)
91	4	2.0	0.2	Intersections of NE gravity and magnetic lineaments with black shales
92	4	2.0	0.2	Intersections of fold axes with black shales
94	2	2.0	0.5	Mudstones and black shales
95	4	2.0	0.4	Fold axes in mudstone and black-shales
96	2	2.0	0.6	Major structures

* Zone radius in number of pixels. Peak distance was zero for all data layers.

The combination of key features provides several areas of potential interest. The principal features of the prospectivity map are fairly robust in that modest changes to the data weightings and modification of some derived data layers (e.g. raising or lowering geochemical thresholds) results in minimal changes in the map. This gives some degree of confidence to the result. Several of the prospective areas identified have already been investigated in varying degrees of detail and with mixed success. These will be discussed first, together with a few areas which have been the subject of exploration but do not show as having potential on the prospectivity map and followed by comments on areas shown here as favourable but in which no exploration is believed to have taken place.

Prospective areas with gold exploration

<u>Northern Anglesey.</u> Despite the presence of gold this area does not show as prospective. The reasons for this are instructive in highlighting the limitations of the methodology. Because of the scale of the source

datasets, mudstones and faults recorded on the ground were not registered. In addition no alluvial gold has been recorded from this area (although there are bedrock occurrences). This is almost certainly due to the poorly developed surface drainage over the prospective area (Cooper et al., 1982; 1989; 1990).

Harlech Dome. The Dolgellau Gold Belt shows as prospective (Figure 27A, 28A) and it is highly probable that unworked veins containing gold remain to be found in this area. Recent mining activities at Gwynfynydd and Clogau St Davids also show that worked vein structures and their probable extensions still have some potential. Perhaps of more interest is the prospective area outlined along the north side of the Harlech Dome, where there is little recorded mining for gold. Attention was drawn to this area by the MRP (Cooper et al., 1985) which found gold in panned concentrates taken from streams in the Talsarnau–Maentwrog area. Gold-bearing sites appeared to show some correlation with intersecting fractures controlling drainage directions. Old workings into polymetallic quartz-carbonate veins about which little is known are present close to some of the gold-bearing sites in this area and it is highly probable that mesothermal gold mineralisation is present, particularly where fractures intersect mudstones of the Clogau Formation. Further work is merited to allow a judgement to be made on the extent and magnitude of any mineralisation and whether permission could be obtained to extract it in this part of the Snowdonia National Park.

The prospective area extends eastward to include the ground east of Trawsfynydd and south of Blaenau Ffestiniog. The small but productive Prince Edward mine, the northernmost mine commonly included in the Dolgellau Gold Belt as well as some other small trials along Cwm Prysor occurs within this area. This analysis suggests that there is potential for gold mineralisation to the north of Prince Edward, although the absence of the Clogau Formation in the north of the prospective area reduces favourability. Previous exploration work by the MRP (Allen et al., 1979) focussed on the explanation of magnetic and electro-magnetic anomalies recorded by a detailed airborne survey, looking to find VMS or SEDEX mineralisation. Mesothermal gold mineralisation was not sought and the geochemical samples collected were not analysed for Au.

A combination of geochemical anomalies, a gold occurrence in alluvium and worked vein-style copper mineralisation, workings is largely responsible for a weak prospective area between Blaenau Festiniog and Beddgelert (Figure 28). The rocks comprise a volcano-sedimentary succession of Llanvirn and Caradoc age (Nant Ffrancon and Snowdon Volcanic groups). Part of the area was investigated by a company in the early 1970s for volcanogenic base-metal mineralisation using stream sediment and soil geochemistry and geophysical (IP) methods, but no exploration for gold is thought to have been carried out. Apart from ground around Ffestiniog, the area lies within the Snowdonia National Park and problems in obtaining planning permission to work any discovery could be anticipated.

Berwyn Hills. Alluvial gold was found in a catchment south of Corwen by the MRP, in part coincident with the area identified as prospective by this study (Cooper et al., 1984). The area contains Upper Ordovician clastic sediments dominated by mudstones and siltstones with intercalated pyroclastic units of Caradocian age. Although no documentation could be found, ground features suggested that some ancient excavation or working for minerals may have taken place at a few localities. Follow-up sampling failed to find in situ gold mineralisation but suggested that a source of gold probably existed under the extensive drift deposits (Smith, 1993).

Central Wales: Rhayader–Pumsaint (Rhiwnant Dome). The area to the south-west of Rhayader, which includes the prominent Rhiwnant Dome structure forms an elongate prospective area. The zone, largely dictated by the outcrop of Upper Ordovician and Lower Silurian rocks (Mackay and Smallwood 1987), extends as far as the old gold mine at Pumsaint (Figures 27B, 28B). This region and the Llanidloes area (see below) were identified as prospective by the MRP following an analysis of the controls on mineralisation at Ogofau and reconnaissance panned-concentrate sampling carried out to look for evidence of gold mineralisation. This survey identified a small but coherent group of analytical Au anomalies, accompanied by observations of fine-grained gold, in the upper reaches of the Afon Irfon on the western side of the Rhiwnant Dome (Brown, 1993). Follow-up work was recommended and the MRP subsequently carried out further drainage sampling accompanied by traverse-based soil sampling and geophysical surveys across much of the structure. No in situ gold mineralisation was found, but substantial geophysical and geochemical anomalies were found associated in part with uppermost Ordovician rocks in the anticlinal closure. Gold was not measured in the soil samples, but arsenic anomalies were generally low and scattered with lead forming the principal geochemical anomaly (Cooper et al., in prep.). Except for massive sandstone and grit outcrops, exposure is poor and the source of gold and the other anomalies detected remains unexplained. Two sources for the gold seem most probable: (1) `Ogofau-type' mesothermal mineralisation associated with mudstones in the anticlinal structure or (2) palaeoplacers in the thick mudstone and grit units. The absence of any close association of gold with metals concentrated in sulphides (Cu, As, Pb, Zn) tends to favour the latter.

The same survey found alluvial gold to the east of Ogofau, in the catchment running north-east from Caeo. It is not clear whether the alluvial gold is derived from extensions of the mineralisation worked at Ogofau, or another source, or even contamination from Ogofau.

South-west Wales. The presence of favourable host-rocks and geological structures followed by the discovery of gold grains in stream sediments by the G-BASE Programme led the MRP to carry out reconnaissance surveys in this area which would appear to be prospective (Figures 27C, 28C). However, the MRP work carried out enabled some important conclusions to be reached (Norton et. al., 2000). These were that (1) much of the alluvial gold was likely to be derived from palaeoplacers in sandstone/grit units within the Ordovician and Silurian succession and (2) some of the gold, particularly in the north of the area may be derived from mesothermal vein-style mineralisation. Quartz veining in sheared and fractured pyritic host-rocks was discovered in one anomalous catchment but no gold enrichment was found in hand specimens. No further follow-up work was carried out and the mineral potential of the area remains in doubt.

Other prospective areas

Dolgarrog. This area (Figures 27A, 28A) is shown as prospective largely on the basis of coincident mudstones, geochemical anomalies, intersecting structures and residual magnetic anomalies. The shape of the prospective area is largely dictated by the major fracture trending north-north-west, the Conwy Valley Fault, and mudstone outcrop. In this area the rocks, which comprise an Ordovician volcano-sedimentary succession and associated intrusions related to several volcanic centres, have suffered relatively high-grade metamorphism (Upper Anchizone). The youngest of the volcanic centres in the area, Dolgarrog, is associated with the Cae Coch massive pyrite deposit described above. Black mudstones of Upper Ordovician age, up to 450 m thick, interbedded with and overlying the volcanic succession, provide a suitable host rock for any mesothermal gold mineralisation. In view of the apparent suitability of the geological environment, the absence of alluvial gold observations is surprising and the most significant factor against any appreciable gold mineralisation being present in this area.

Tywyn–Dinas Mawddwy. Weakly prospective areas forming a near linear zone between these two villages are generated by the presence of dark mudstone host rocks, geochemical anomalies and proximity to major structures.

Central Wales: Llanidloes. This area was identified as prospective for gold mineralisation by the MRP on the basis of a comparison with the setting of the mineralisation at Ogofau. Consequently a reconnaissance-scale panned concentrate survey was carried out to look for evidence (Brown, 1993). The BGS G-BASE sampling programme, which collected observational data on gold in panned stream sediment included in this analysis, also crossed the area. Neither survey found good evidence for significant gold mineralisation: only a few isolated observations of gold grains in the pan were recorded and analytical gold concentrations were mostly below the 10 ppb detection limit. Some modest enrichments (10–70 ppb) were recorded in a few samples, mostly those containing waste material from the old base-metal mines, confirming the presence of traces of Au in this mineralisation (Mason, 1997). Tip samples collected during the MRP work contained up to 500 ppb gold. Given the well developed drainage pattern and relatively high density of these surveys, it is unlikely that any significant gold mineralisation with a surface expression will have escaped detection by this work unless buried under superficial deposits in interfluvial areas.

Central Wales: Ffostrasol. This area, north of Newcastle Emlyn and east of Cardigan (Figures 27C, 28C) is defined because of the presence of mudstones, fold structures on the flanks of the Llangranog Lineament and alluvial gold, providing similarities with the Rhiwnant Dome and Ogofau mine. However, in contrast to the other two areas, there is no record of gold exploration in this area.

Central Wales: Llandeilo. This area (Figures 27C, 28C) shows as prospective largely because of a coincidence of Llanvirn mudstones, major lineaments and geochemical anomalies. The mudstones contain rhyolitic tuffs and are overlain by limestones, sandstones and shales containing a shelly fauna (Llandeilo Series) and grey to black calcareous and graptolitic shales (Caradoc). The area lies on the south-east flank of the Tywi anticline close to the southern margin of the basin, and pulsatory movements along the anticline produced marked facies changes in the succession (Bassett, 1982). No mineralisation has been recorded in the area, although it has been covered by regional geochemical surveys.

Central Wales: Builth Wells. A similar combination of features (geochemical anomalies, structure and mudstones) generates a prospective area centred on the Builth–Llandrindod inlier (Figures 27B, 28B). This area contains mainly Llanvirn to Caradoc mudstones with intercalated volcanic rocks and intrusions. Course clastic sediments associated with volcanics have been interpreted as representing a shoreline setting for the volcanism (Jones and Pugh, 1949), but a more recent interpretation suggests a submarine canyon setting (Furnes, 1978). Exploration for volcanogenic base-metal mineralisation involving geochemical sampling (stream sediments, panned concentrates and soils), geophysical measurements (IP, VLF, SP and magnetics) was carried out in the area by the MRP (Marshall et al., 1987). Short drill holes were sited on geophysical anomalies and weak lead mineralisation of uncertain affinity was intersected. Gold mineralisation was not sought and there has been no published search for the metal in the area.

Volcanogenic massive sulphide mineralisation

Datasets

The location of volcanic centres and rocks was a fundamental part of the prospectivity analysis for VMS deposits. These rocks are grouped on the geological map as basic, intermediate and acid lavas or tuffs, and as the majority of VMS deposits occur in acid lavas and tuffs these lithologies were identified and weighted separately in the prospectivity analysis. Submarine lavas and volcanic centres are not specifically identified in the digital geological datasets available so an additional dataset of volcanic centres was constructed from available information and used in the analysis. Because, by definition, the presence of volcanic rocks and centres is essential to the model these items were weighted heavily in the model with a zone of influence set arbitrarily at 5 km. Attempts were made to overcome the lack of information on submarine eruption by the inclusion of data on mudstones, making the assumption that where mudstones and volcanic rocks were adjacent submarine eruption was probable. However, the classification of the geological data and its combination with other parameters resulted in distortions which led to the abandonment of this route.

A key feature of VMS deposits is their association with a particular stratigraphic level, and an approach considered here was to select and weight stratigraphic intervals known to contain VMS style mineralisation, namely the Llandovery (Parys Mountain) and Caradoc (Cae Coch). It was decided not to adopt this approach as it effectively pre-judged the results of the study and could easily result in the elimination of another prospective unit.

G-BASE regional geochemical stream-sediment values and MRP panned-concentrate analyses were used to identify catchments containing high levels of metals found in VMS deposits. High levels of the individual metals might have a number of sources (e.g. contamination, vein-style mineralisation) and are therefore lowly weighted, but in conjunction and in spatial coincidence with other parameters become of increased significance. Because a geochemical anomaly normally reflects a source at an unknown distance from the sample site, a zone of influence has been incorporated. The samples in both datasets were mostly collected at a density of about 1 sample per 1.6 km^2 from small first and second order streams, so the zone of influence for individual samples is set at a relatively short distance (1–4 km).

The geochemical datasets selected were Cu and Zn in stream sediment and panned concentrate and Fe in panned concentrate. Values of Cu above 71 ppm and Zn greater than 690 ppm in stream sediment (97.5 percentile) were abstracted and plotted. Threshold levels for panned concentrate were set at As 38.5 ppm (96%), Cu 100 ppm (97.5%), Fe 11% (97%) and Zn 300 ppm (95%). Sample population distribution analysis indicated that in all cases the samples plotted were largely derived from an enriched source (less than 2 in 100 from background populations). Previous surveys indicate that the enriched source is most likely to be mineralisation, with contamination and natural but economically insignificant concentrations in some unaltered rocks such as black mudstones and basic rocks being other likely contributors to the anomalies.

Many other metals are concentrated in VMS deposits and commonly generate associated geochemical anomalies. In Wales other strong sources of variation are known to affect the distribution at high levels of these elements, obscuring high values related to mineralisation. Even at a low weighting these anomalous values generate false prospective areas often in conjunction with other variables. Lead, for example has many anomalies related to vein-style mineralisation, particularly in mid-Wales, and is a common contaminant in all lowland areas. False prospective areas can be generated by high geochemical values when these occur at fault/linear intersections (e.g. in South Wales).

Baryte is commonly present in VMS deposits but Ba was not included because of a large number of high values, particularly in stream sediment, are not caused by the presence of baryte. They are related to the presence of barium-rich black mudstones of Upper Cambrian (Cwmhesgen Formation) and Ordovician (e.g. Nod Glas) age in North Wales and similar lithologies of Caradoc-Ashgill age in South and Central Wales (British Geological Survey, 2000). The source of Ba is unknown but it must be largely held in a light mineral phase, perhaps feldspar or mica, as panned concentrates taken from the anomalous sites show little or no upgrading of Ba except in the few cases where discrete baryte mineralisation is present within the mudstones. The possibility exists that some of these high levels of Ba and associated metal enrichments in mudstones might be of exhalative origin and should therefore be included into any prospectivity mapping of this type of mineralisation.

The absence of MRP panned-concentrate data from parts of the area must be taken into account, but the effect of incomplete coverage is small in this model, as information is available for the principal areas containing volcanic rocks. The Shelve area and western Pembrokeshire are the principal exceptions, and coverage of Snowdonia is at a lower density than elsewhere.

All sites containing worked base-metal (Cu-Pb-Zn) mineralisation were included in the analysis. Although most of these are clearly related to vein-style mineralisation, the style of mineralisation has in the past been misinterpreted (the Parys Mountain mineralisation was originally described as a lode) and veins may be formed by a VMS system. Consequently the presence of base-metal mineralisation of whatever description in or adjacent to volcanic rocks was considered to merit incorporation but at a low level of weighting.

Major structures and their intersections play a role in the location of volcanic centres and associated hydrothermal systems, so the intersections of linear features (gravity and magnetic lineaments, major faults) were included. Similarly, large residual magnetic (>80 nT) and gravity anomalies, which show a broad correlation to the location of magmatic centres have been included.

The data and weightings used in the VMS analysis are shown in Table 8.

Prospective areas

The data layers (Figure 29) and the resulting prospectivity map (Figure 30) yielded prospective areas which indicated that potential for VMS mineralisation exists associated with volcanism at three broad stratigraphic levels: the Llanvirn, Caradoc and Llandovery. Most of the potential is in the North Wales region (Figures 29A, 30A).

Llanvirn. In terms of known potential these rocks are the least promising as no VMS mineralisation has been found at this level. However, rocks of this age stretching around the eastern perimeter of the Harlech Dome show as prospective (Figures 29A, 30A) and exploration work in the Harlech Dome by the MRP indicates considerable potential for VMS deposits. Geological, geochemical and geophysical surveys found indications of metalliferous enrichments and hydrothermal activity associated with submarine volcanism accompanied by the formation of rhyolite domes within the Aran Volcanic Group (Cooper et al., 1983; Cooper et al., 1985). Interbedded mudstones indicate that the critical level in this area coincides with the *D. bifidus* or possibly *D. murchisoni* zone (Allen and Jackson, 1985). In the Cross Foxes area one of these pyritic mudstones locally contains an oolitic and pisolitic ironstone unit (Pratt et al., 1995). The northern flanks of the Harlech Dome, to the south and east of Blaenau Ffestiniog are also prospective. Recorded indications of potential include mentions of silicified rhyolites, quartz rock and pyritic mudstones in the Rhiw Bach Volcanic Formation (Lynas, 1973; Howells and Smith, 1997).

Table 8 Data parameters for VMS mineralisation prospectivity model

Data Index	Zone *	Distance exponent	Weight	Description
2	0	2.0	0.5	Lower Palaeozoic volcanic rocks
8	0	2.0	0.5	Total magnetic field residual anomaly > 80 nT
31	0	2.0	0.8	Contacts of acid lavas and tuffs
33	0	3.0	0.5	Small (<1km^2) residual gravity anomalies
84	8	2.0	0.2	Volcanic sites/centres (subaerial)
81	10	2.0	0.8	Volcanic sites/centres (submarine)
82	4	2.0	0.4	Site of worked Cu-Pb-Zn mineralisation
83	4	2.0	0.2	MRP Cu in panned concentrate > 100 ppm #
85	4	2.0	0.2	MRP Zn in panned concentrate > 300 ppm #
9	4	2.0	0.2	MRP Fe in panned concentrates > 11% #
91	4	2.0	0.4	Intersections basement structures-acid lavas
91	4	2.0	0.4	Intersections NE gravity lineaments-main faults
4	4	2.0	0.3	G-BASE Cu in stream sediment > 71 ppm #
92	4	2.0	0.2	G-BASE Zn in stream sediment > 690 ppm #

All within 5 km of acid volcanic rocks. * Zone of influence radius in pixels. Peak distance was zero for all data layers.

Weaker prospective areas in rocks of this age are found in south-west Wales. The mineral potential of these was reviewed under the Mineral Reconnaissance Programme (Colman et al., 1995). Reconnaissance fieldwork found evidence of hydrothermal activity (silicification, brecciation and quartz veining) in the poorly known Sealyham Volcanic Group, and some rocks of the Fishguard Volcanic Group (including the possibly contemporaneous Llanrian Volcanic Formation) were found to be pyritic. Rock sampling at these localities provided few indications of metalliferous enrichment but it was considered that both groups merited further limited investigation. The volcanic rocks of Ramsey Island, which record two volcanic events of which the latter involved submarine rhyolitic volcanism of early Llanvirn age were not investigated. Published accounts do not indicate the presence of intense hydrothermal activity or mineralisation but the geological setting, including the presence of near to source bimodal submarine extrusives and cosanguineous high-level intrusions (Kokelaar et al., 1985) suggests some potential.

Work by the MRP found some evidence that that VMS mineralisation might be associated with the Roche Rhyolite Group in south-west Wales. The volcanism is of uncertain age: originally thought to be late Precambrian, more recent works indicates that it is more likely to be Ordovician, but Arenig rather than Llanvirn. The area, close to Treffgarne, fails to register on the prospectivity map (Figure 30), probably because of an absence of geochemical anomalies for base metals. This may be a correct decision as exploration failed to detect any base-metal mineralisation in the highly altered volcanic rocks and associated pyritic tuffaceous mudstones, and detailed lithogeochemical studies suggested that the magmatism was more likely to be associated with epithermal than VMS-type mineralisation (Colman et al., 1995).

Other volcanic centres of Llanvirn age are preserved close to the eastern margin of the basin at Shelve and in the Builth Inlier. The Builth rocks appear to have only limited prospectivity on the basis of the model used (Figure 30) and geological evidence of a shoreline eruptive environment with mixed subaerial and submarine deposits of dominantly intermediate to basic composition accounts in part for this rating. However, investigation of the Builth volcanic rocks by the MRP revealed weak gently dipping stratiform lead mineralisation at the interface of a basaltic lava and reworked tuffs in the Builth Volcanic Formation (Marshall et al., 1987). The mineralisation comprises secondary Pb minerals in a clay matrix. Its origin remains uncertain, but the possibility that more significant base-metal concentrations are associated with the volcanism cannot be ruled out. In the Shelve Ordovician inlier a prospective signature is generated by volcanic rocks of Llanvirn and Caradoc age (see below). The Llanvirn succession comprises andesitic tuffs and lavas erupted from two centres, termed the Stapely Volcanic Formation (Lynas, 1973). Reconnaissance soil sampling across the outcrop of these rocks by the MRP revealed local Pb, and to a lesser extent Zn, enrichments but these were not judged to merit further investigation at the time. The dominance of intermediate to basic volcanism and basin margin environment appears to limit their potential but, interestingly, both these areas show some potential for the occurrence of gold mineralisation (see above).

Caradoc. Areas identified as prospective in Snowdonia are associated with volcanism of this age and include the ground west of Dolgarrog (Figures 29A, 30A) that contains the known volcanogenic mineralisation at Cae Coch, identified as VMS by Ball and Bland (1985). The mineralisation is associated with the last stages of eruption from the Crafnant Volcanic Centre in north-east Snowdonia which post-dates most of the Caradocian volcanism in North Wales (Howells et al., 1991). This severely limits the opportunity of finding exact stratigraphic equivalents and there is even some doubt, from sulphur isotope studies, that the mineralisation is of exhalative origin (Bottrell and Morton, (1992). Similar but slightly older volcanic centres occur in a belt across Snowdonia and the Lleyn Peninsula (Howells et al., 1991; Gibbons and Young, 1999) and the prospectivity analysis identifies areas occupied with the products from some of these as prospective, notably the rhyolitic Crafnant, Snowdon and Llanbedrog (Lleyn) events. Most of the rocks associated with these centres have been the subject of detailed mapping in recent years (Howells et al., 1991; Gibbons and McCarroll, 1993; Howells and Smith, 1997). The caldera-related vein-style mineralisation around the Snowdon centre has been well documented (Reedman et al., 1985, Howells et al., 1991) but no evidence of further VMS mineralisation has been identified. However, reconnaissance drainage and soil surveys for mineral exploration purposes by the MRP and companies working under the MEIGA scheme indicated the presence of base-metal anomalies possibly caused by stratiform metalliferous enrichments in Snowdonia and the Lleyn Peninsula (e.g. Leake and Marshall, 1994). These indications have never been thoroughly investigated, in part because some are in environmentally very sensitive areas (Figure 5).

The products of volcanism of similar age to some of the earlier episodes recorded in North Wales (Soudleyan) are found in the Berwyn Hills, Briedden Hills and the Shelve area, where there are two thick volcaniclastic sequences (Hagley and Whittery volcanic formations). The prospectivity analysis generates a weakly positive signature in the Berwyn Hills and a somewhat stronger signal in the Shelve area (Figure 30). The igneous rocks in these areas comprise intermediate to acid volcaniclastic deposits with some lavas and high level intrusions. No evidence of stratiform mineralisation has been reported though, vein mineralisation associated with the igneous rocks has been worked in the Berwyn Hills around Llangynog and silicification linked to hydrothermal activity and a high level andesitic intrusion is reported from the Breidden Hills (Dixon, 1990).

Llandovery. In terms of known mineralisation rocks of this age would appear to have most potential as the volcanics associated with the highly productive Parys Mountain deposit have now been shown to be of this age. Because previous workers had assumed the volcanism at Parys Mountain to be most probably of Caradoc age, little attention has been paid to the mineral potential of the Llandovery volcanic rocks. The prospectivity analysis, however, suggests that the only locality with rocks of this age with potential is Parys Mountain. Although probably a valid conclusion the analysis is influenced by the relative lack of volcanic rocks of this age in the exposed parts of the Welsh Basin and the absence of MRP panned concentrate data over the outcrop in south-west Wales.

A further complication is provided by uncertainty with respect to the relative position in the Silurian of Anglesey and the rocks of the Welsh mainland due to large-scale sinistral fault movements during and after the Caledonian orogeny. Within Anglesey the opportunities of finding stratigraphic equivalents of the Parys Mountain mineralisation are greatly restricted by the preservation of the volcanic rocks within an overturned synclinal and/or thrust-bound structure.

The Skomer Volcanic Group (Zeigler et al., 1969; Thorpe et al., 1989), between the Smalls and Grassholm Island in the west and St Ishmaels in the east, were also originally thought to be of Ordovician age. The group, know known to be of Llandovery age, comprises over 700 m of hawaiite/mugearite and rhyolitic lavas and pyroclastic rocks with interbedded sediments and crops out over 43 km. A submarine ridge and reefs extends the group offshore. The more basic flows cover a wide area but rhyolites formed domes of considerable relief and provided material for the associated sediments. The rock chemistry (alkaline/subalkaline affinity with high concentrations of Ti, Nb, Ta, Hf and Zr) is taken to indicate a within plate (ocean-island basalt) source modified by the effects of subduction (Thorpe et al., 1989). Detailed studies of the rocks indicate eruption under sub-aerial to shallow submarine conditions: some basic lavas include pillows, indicating subaqueous conditions; some have weathered tops. Associated sediments, some fossiliferous, comprise mainly conglomerates, sandstones and siltstones. They indicate terrestrial to paralic (lagoonal) environments. Except for the presence of rhyolite domes, most of the features listed provide little encouragement for the formation of VMS deposits similar to Parys Mountain. The geological setting, depositional environment and absence of evidence of hydrothermal activity are taken as crucial.

The source of the regional magnetic anomaly in South Wales with local maxima near Haverfordwest, Saundersfoot, Kidwelly and Swansea is unknown. Part of the source might be Precambrian basement or Lower Palaeozoic volcanic rocks including prospective Llandovery units. There may therefore be potential for VMS deposits at the faulted southern margin of the Welsh Basin buried beneath Carboniferous and Devonian strata. Depth solutions for many of these magnetic anomalies suggest source depths at less than 1 km below sea level.

CONCLUSIONS AND RECOMMENDATIONS

1. The degree of confidence that can be placed in the prospectivity maps depends on the accuracy of the model, in terms of its applicability to the Welsh Basin and the availability of necessary data of sufficient quality. For example, lack of panned concentrate analyses in some areas and of recent high-quality mapping in others constrains the results.

2. There appear to be good prospects for finding further mesothermal gold mineralisation in the rocks of the Welsh Basin. Prospective areas include several where exploration work has found evidence of gold, such as the northern side of the Harlech Dome, the north-western part of the Berwyn Dome, the Rhiwnant Dome in Central Wales and south-west Wales. In all of these areas knowledge of the bedrock mineralisation is very limited, and further work is recommended to determine the likelihood

of an economically viable source being present, concentrating initially on those areas with least environmental constraints.

3. The potential for VMS deposits in Wales appears to be largely restricted to rocks associated with volcanic centres of Llanvirn, Caradoc and Llandovery age. The potential has undoubtedly been reduced by the recent finding that the volcanic rocks associated with the only significant known deposit of this type at Parys Mountain are of Llandovery rather than Caradoc age. The only other significant exposed volcanic centre of Llandovery age, the Skomer Volcanic Group, lacks many of the key features associated with this type of mineralisation. However, potential does exist in the Llanvirn volcanic rocks around the Harlech Dome and to lesser extent, in south West Wales, possibly beneath cover sequences. Caradocian volcanic rocks in Snowdonia and the Shelve area also show some potential. Except for the Shelve area and the area around the known deposit at Parys Mountain, all the areas with VMS potential lie within or close to significant environmental constraints. This means that a clear national need would have to be demonstrated before permission to mine was granted, and restrictions on any development would probably be harsh.

4. In view of the above, the potential for SEDEX-type mineralisation should be examined: data collected for this study suggest that more areas of potential for this type of mineralisation may occur outside the areas subject to the most stringent environmental constraints. The Welsh Basin is comparable in size with others hosting significant SEDEX deposits. It has significant Pb-Zn vein mineralisation, and SEDEX deposits could occur at suitable sites within the basin and at the faulted margins.

5. More detailed prospectivity mapping is warranted in some of the zones with identified mineral potential as additional detailed datasets become available, for example 1: 50,000 to 1:10,000 scale geological mapping, geochemical data from grid and traverse based soil sampling, ground survey geophysical data. Some of the data complied for this study was also collected at a resolution useable at larger scales, for example stream sediment data, Landsat thematic mapper interpretations and detailed airborne geophysical data.

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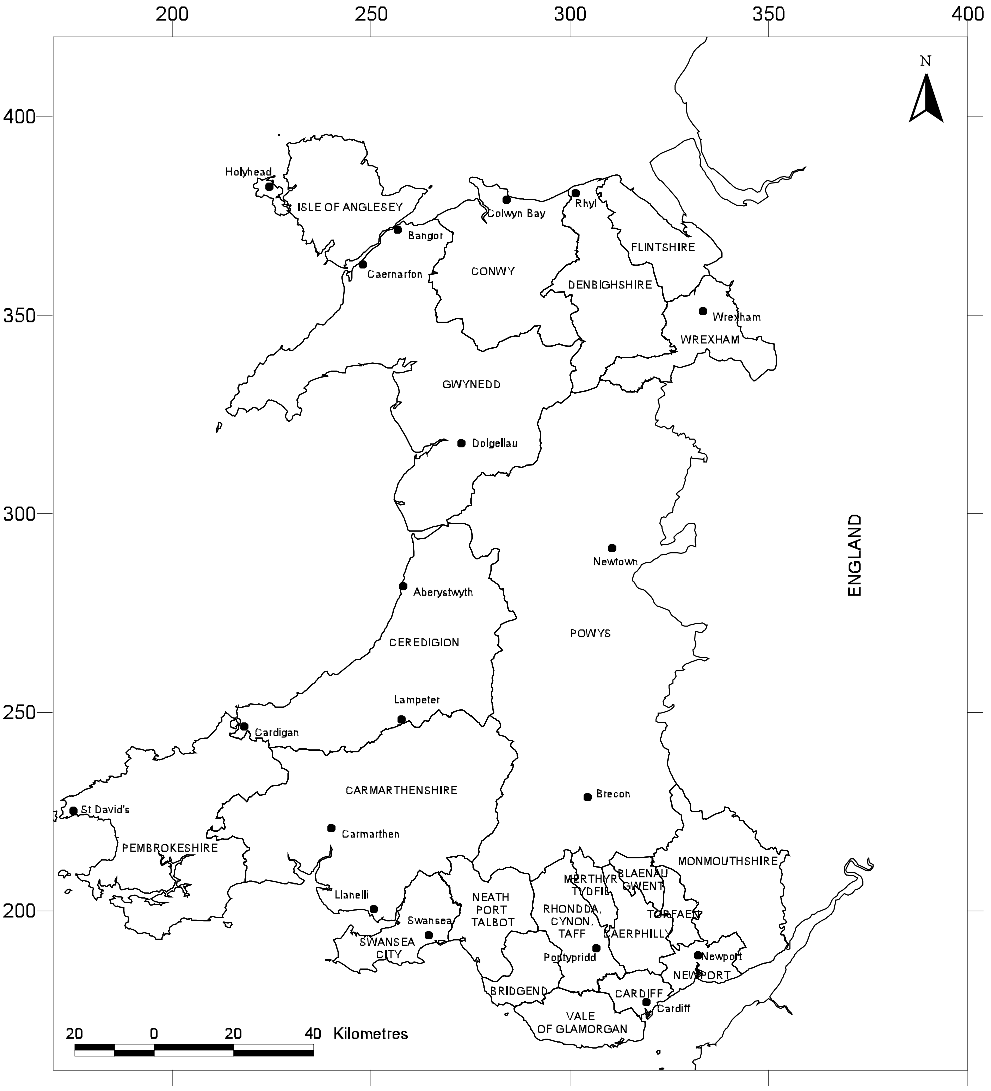

Figure 1 Outline map of Wales, showing principal towns and administrative areas

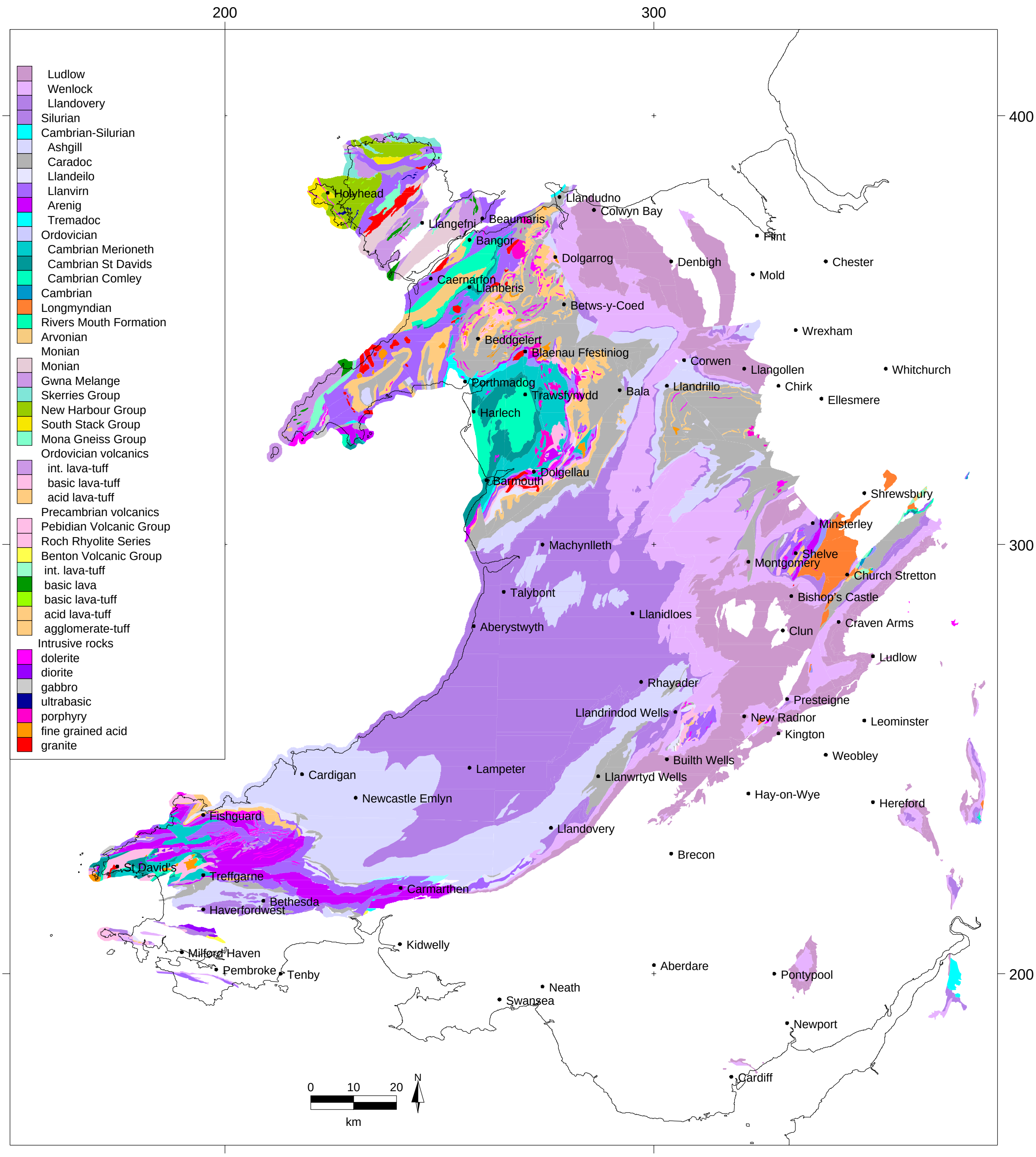

Figure 2 Outline geological map of Wales showing Precambrian and Lower Palaeozoic rocks from 1:250000 Series maps

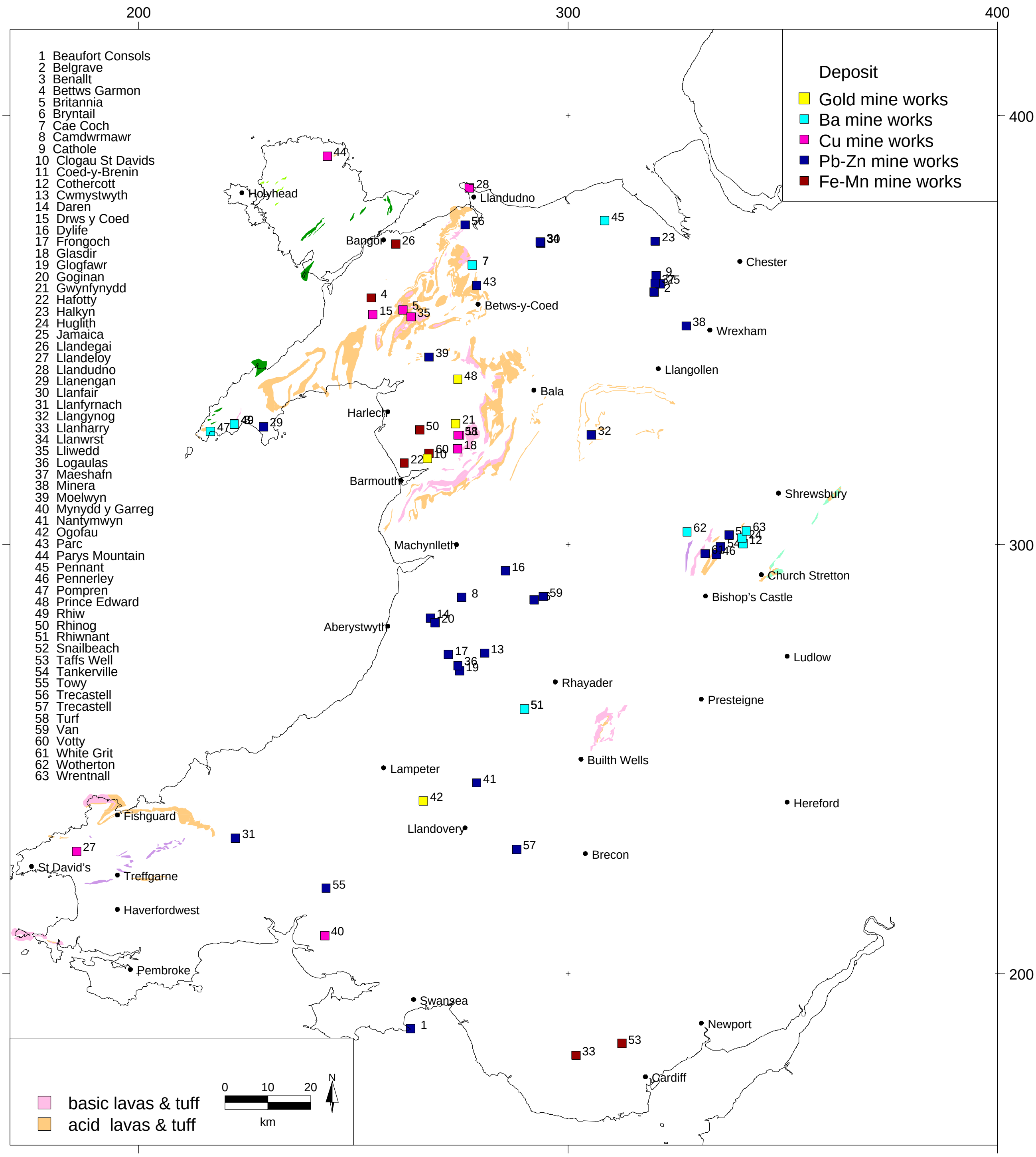

Figure 3 Principal metal mines in Wales

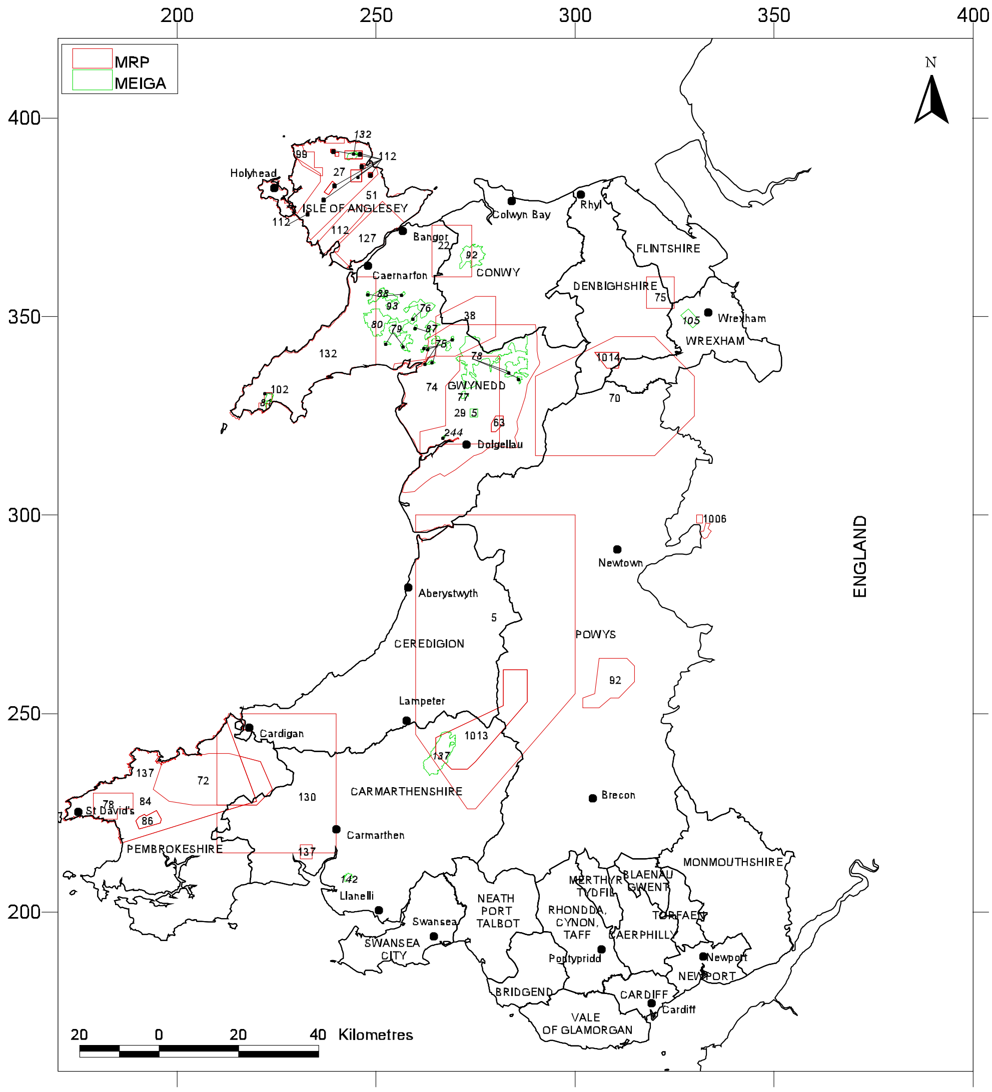

Figure 4 Outline map of Wales, showing the location of MRP and MEIGA project areas

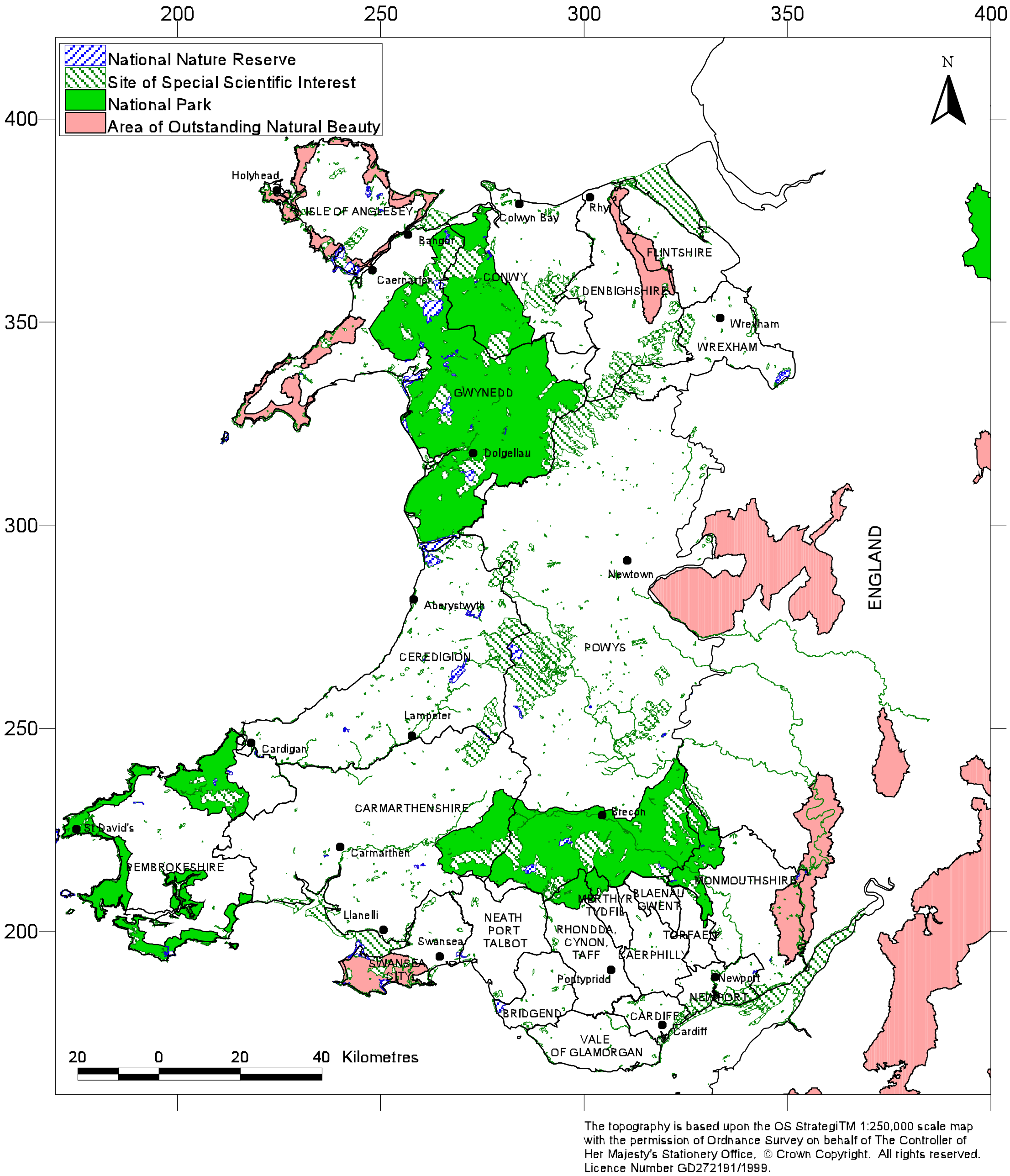

Figure 5 Principal environmental constraints

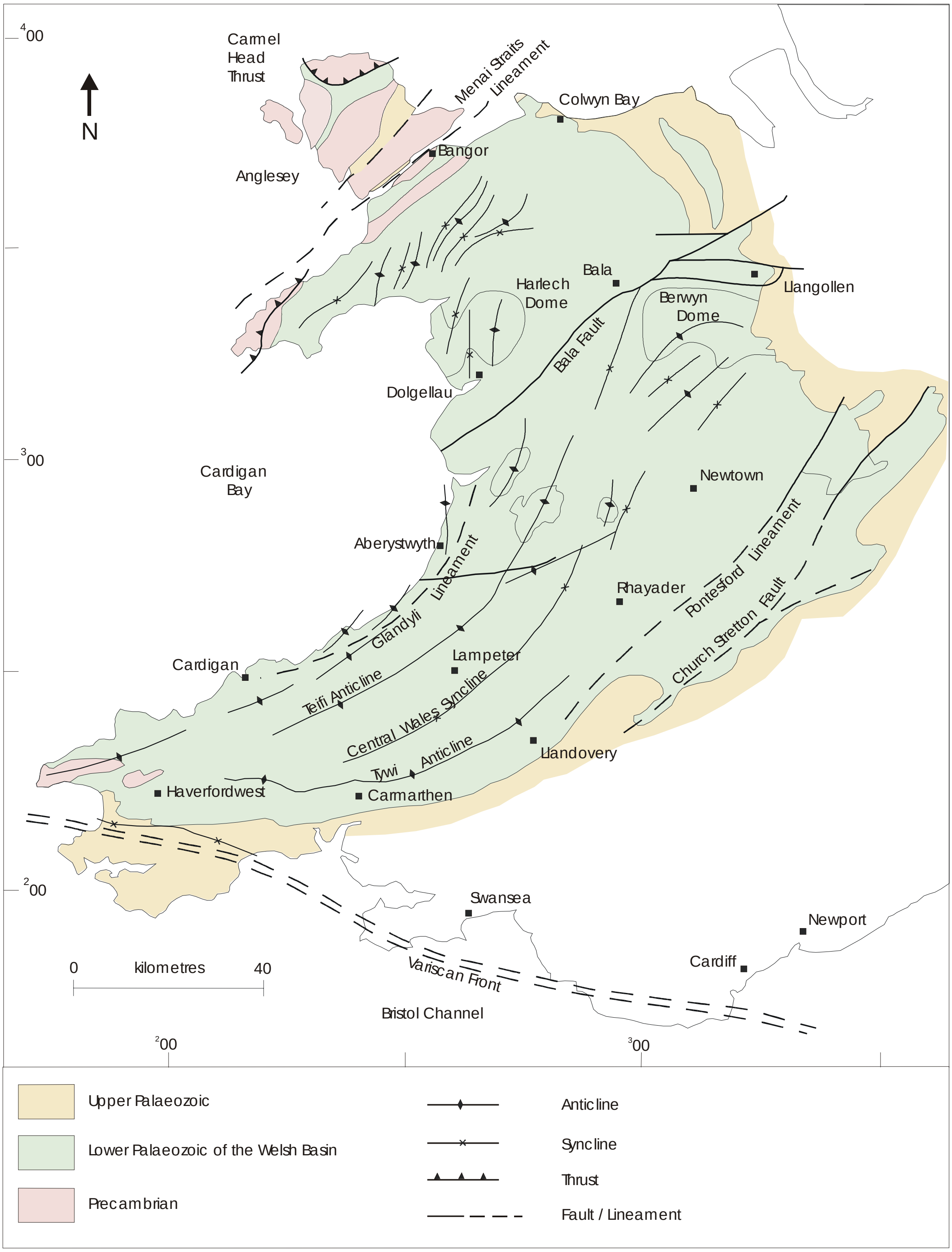

Figure 6 Selected major structures

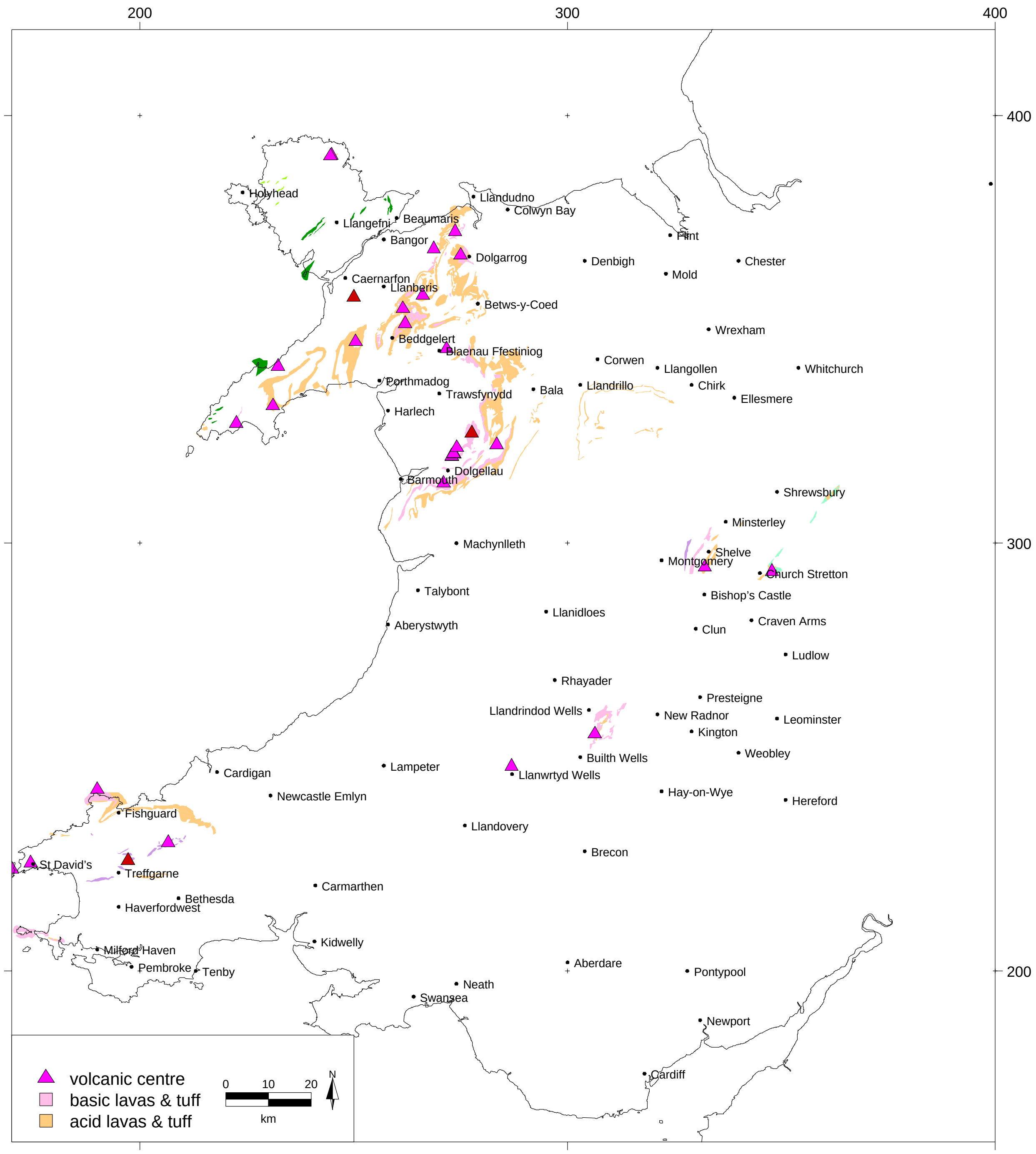

Figure 7 Outcrops of pre-Devonian volcanic rocks and probable location of Lower Palaeozoic volcanic centres

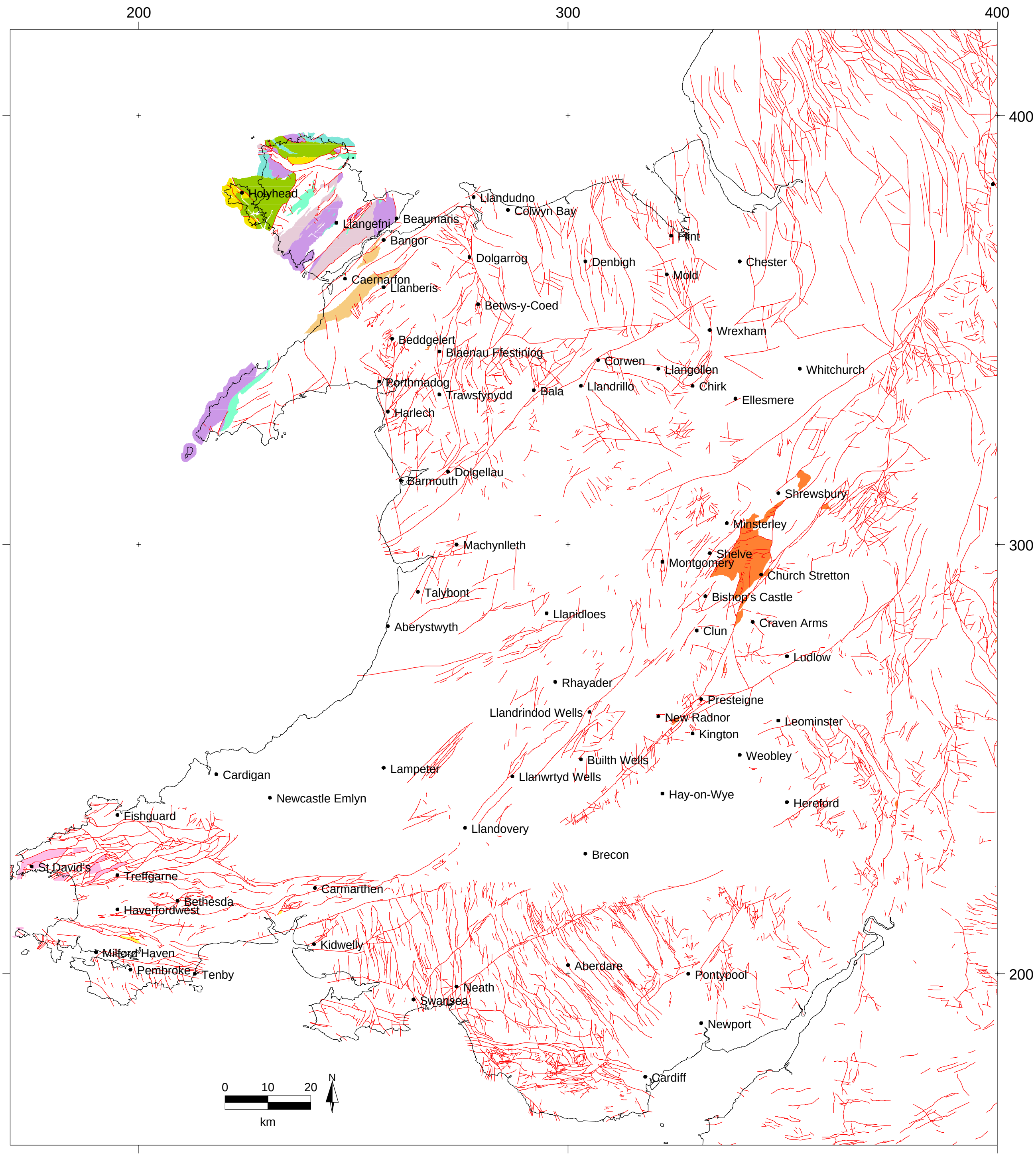

Figure 8 Fault pattern from 1:250,000 Series Maps with outcrops of Precambrian and Longmyndian rocks (key in Fig 2)

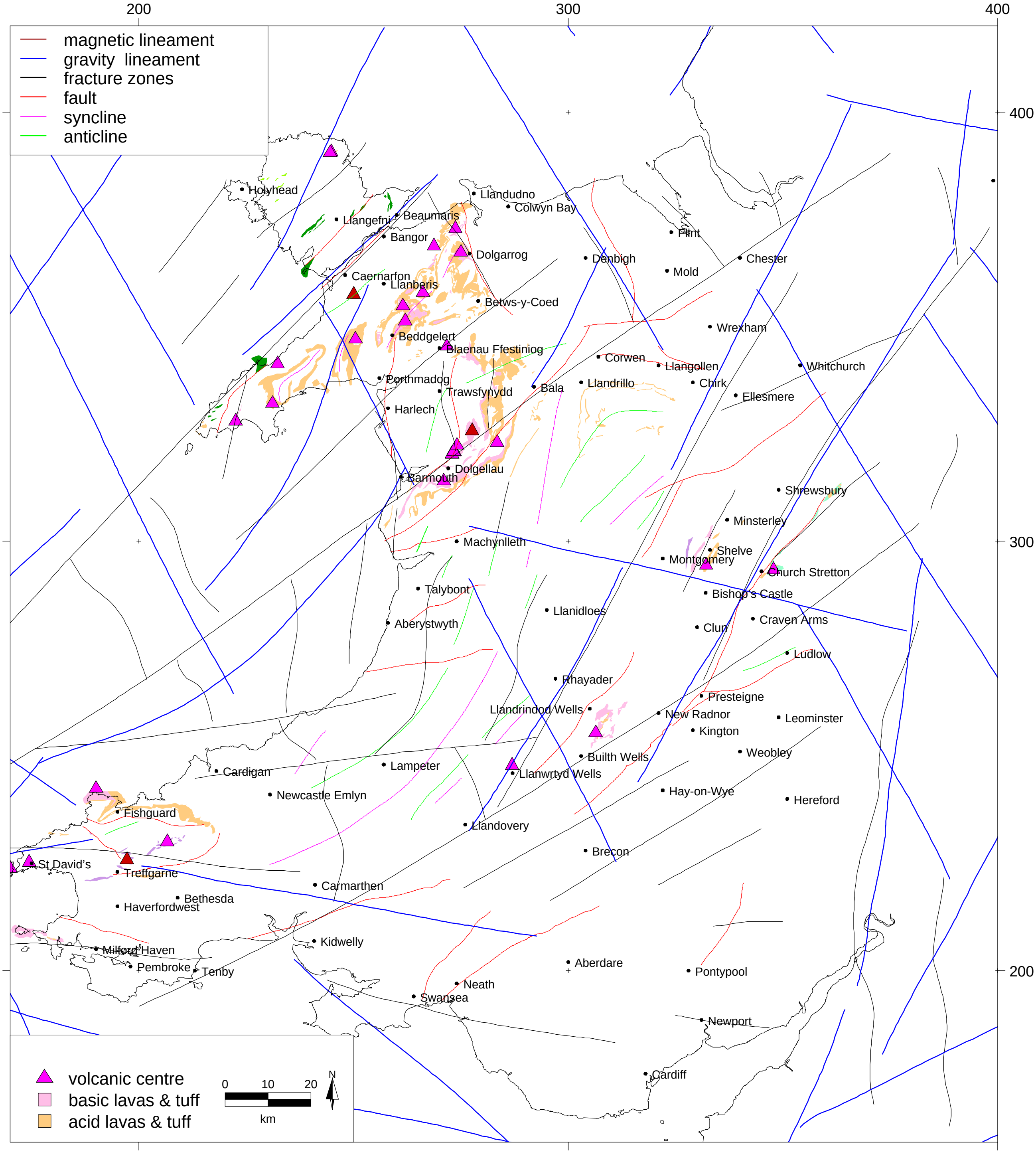

Figure 9 Major lineaments and fractures from geological and geophysical datasets

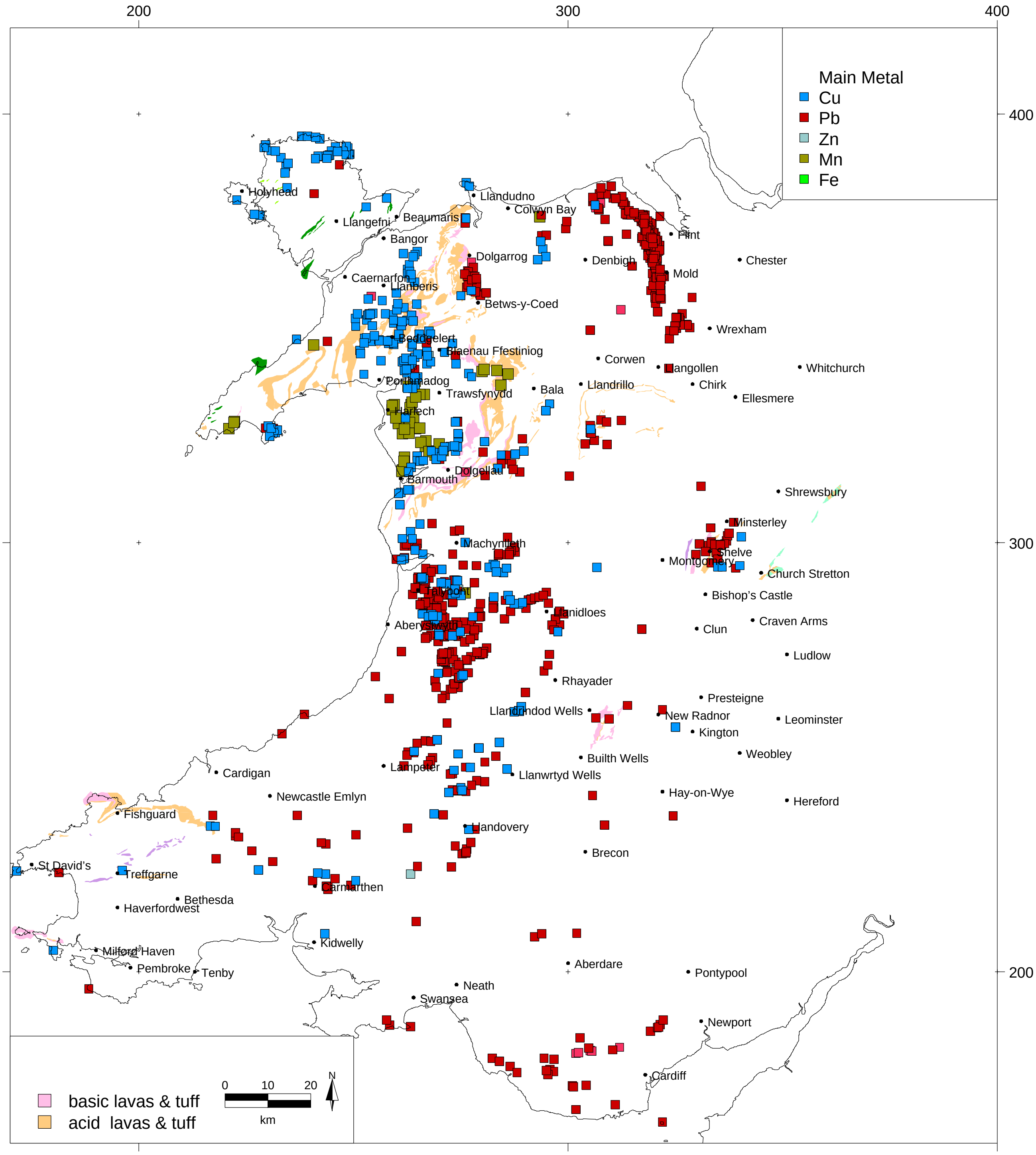

Figure 10 Metalliferous mineral workings

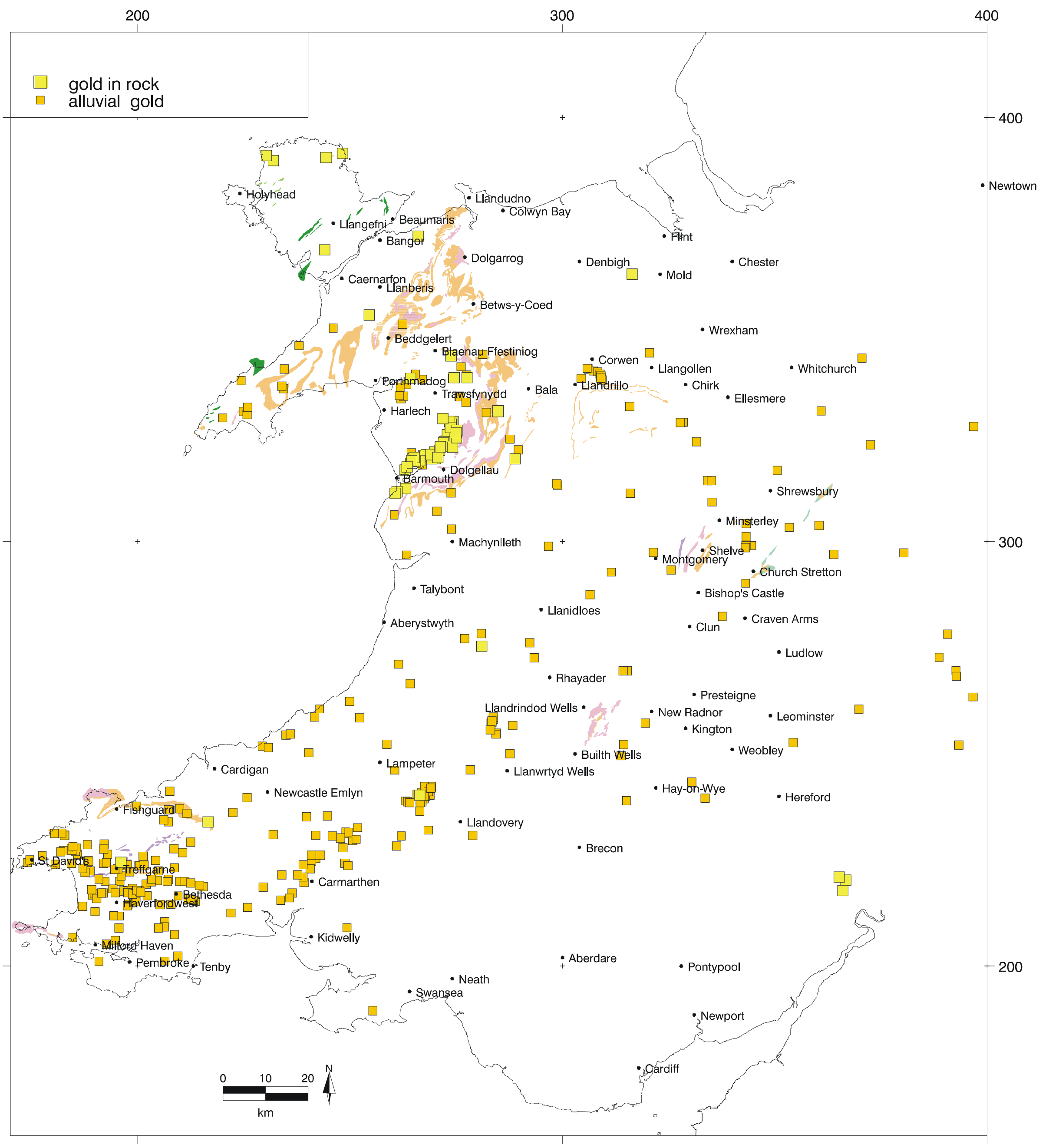

Figure 11 Gold occurrences

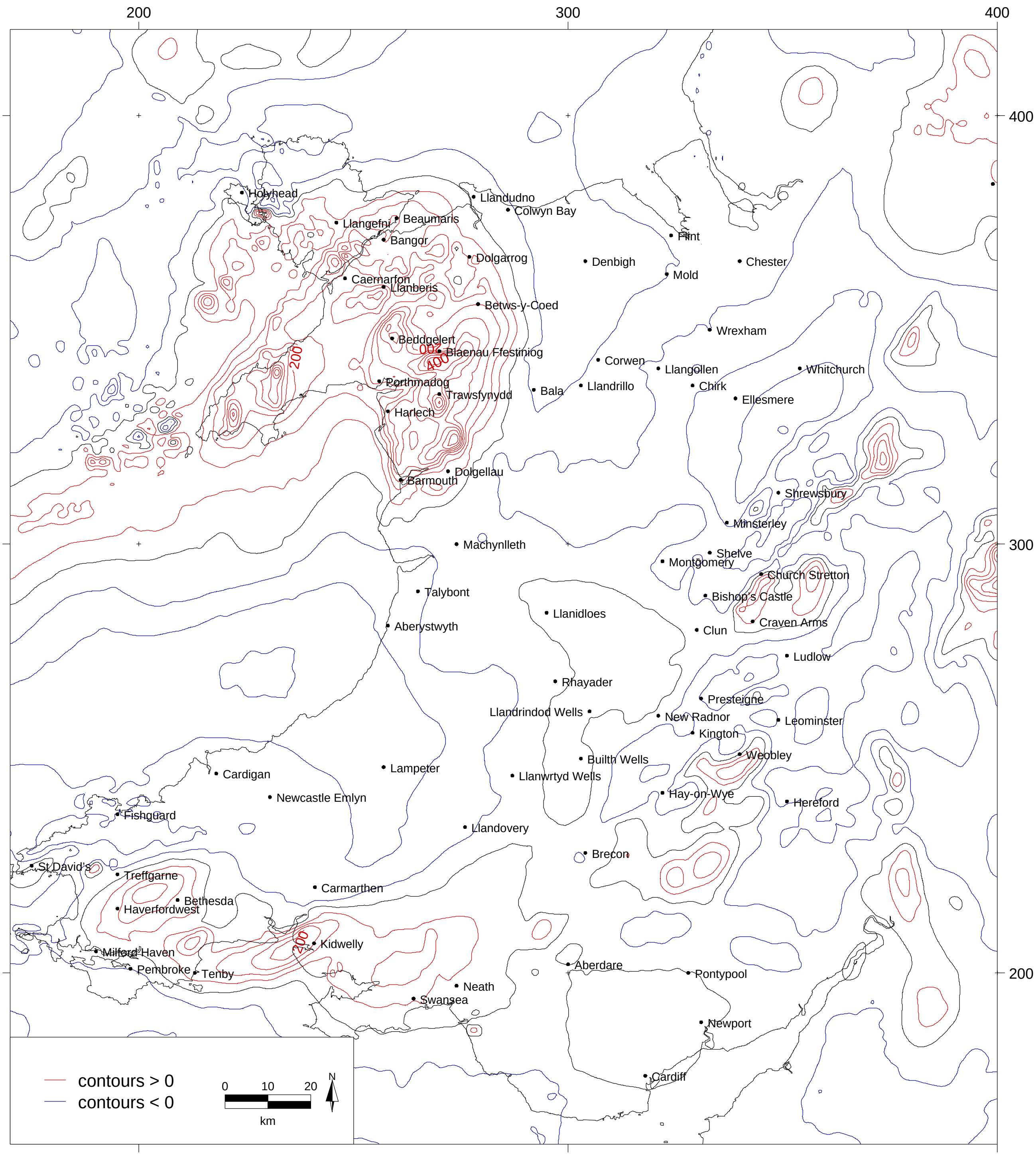

Figure 12 Geophysical data: total field magnetic data

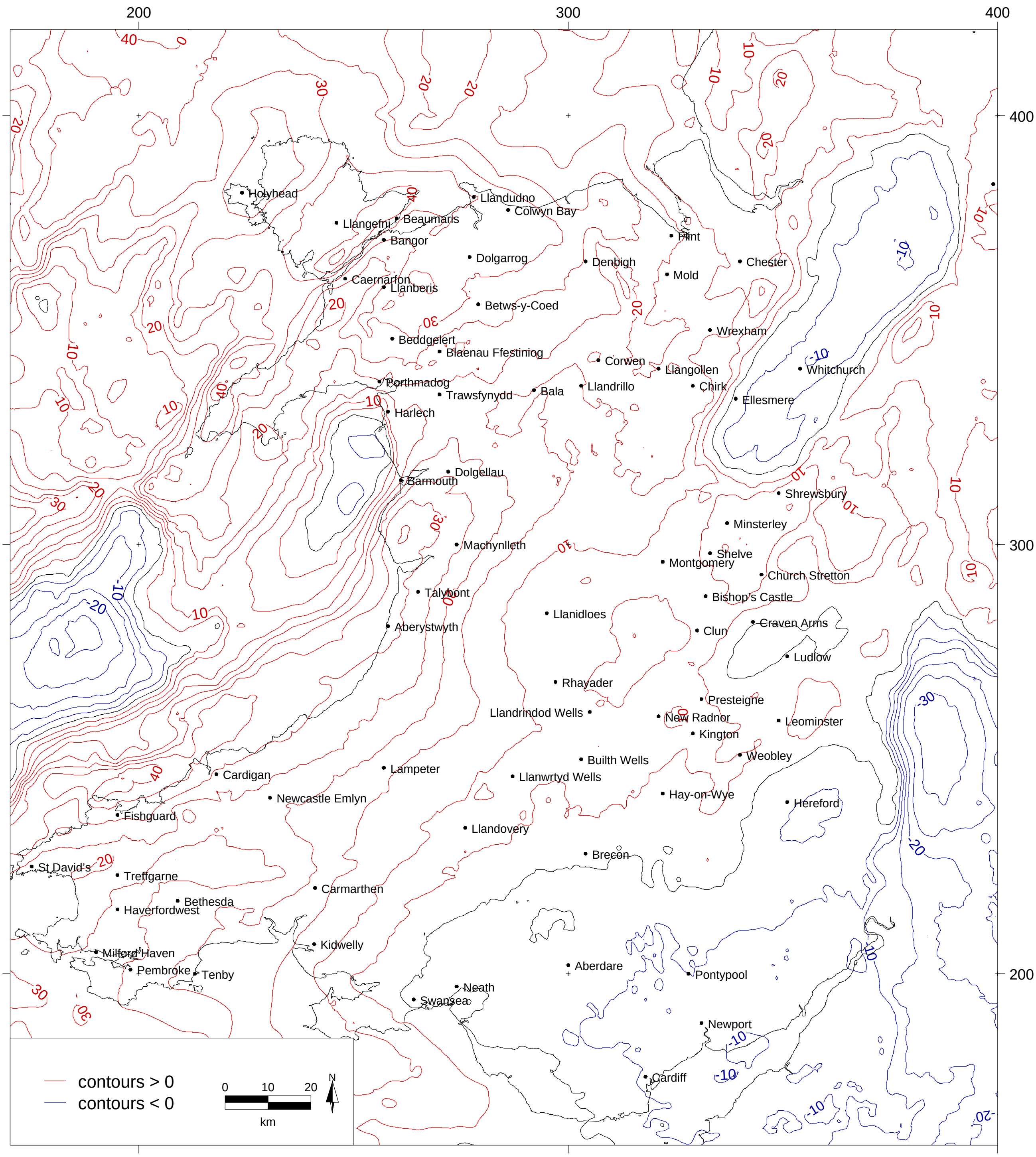

Figure 13 Geophysical data: Bouguer gravity anomalies

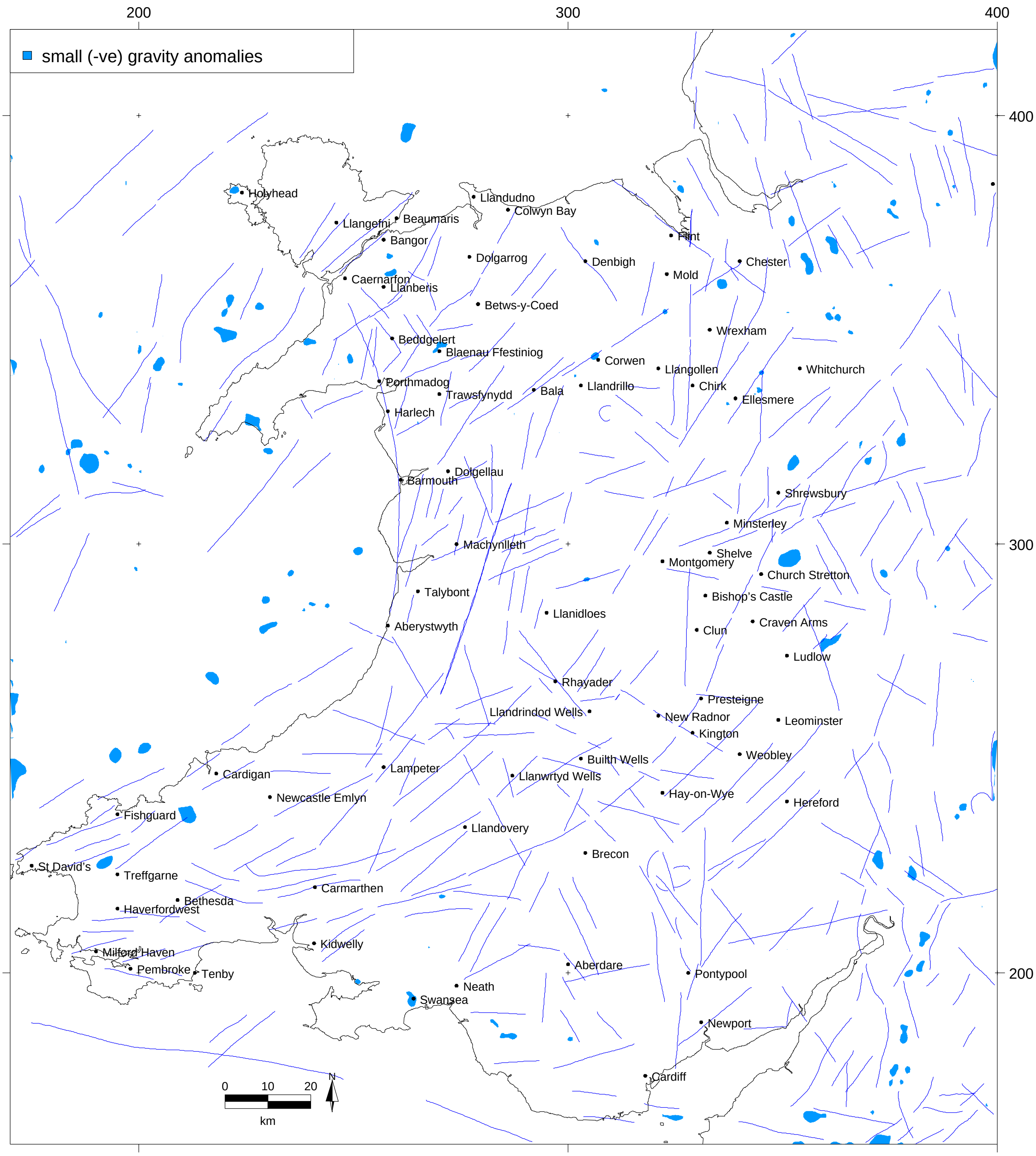

Figure 14 Geophysical data: gravity lineaments and residuals

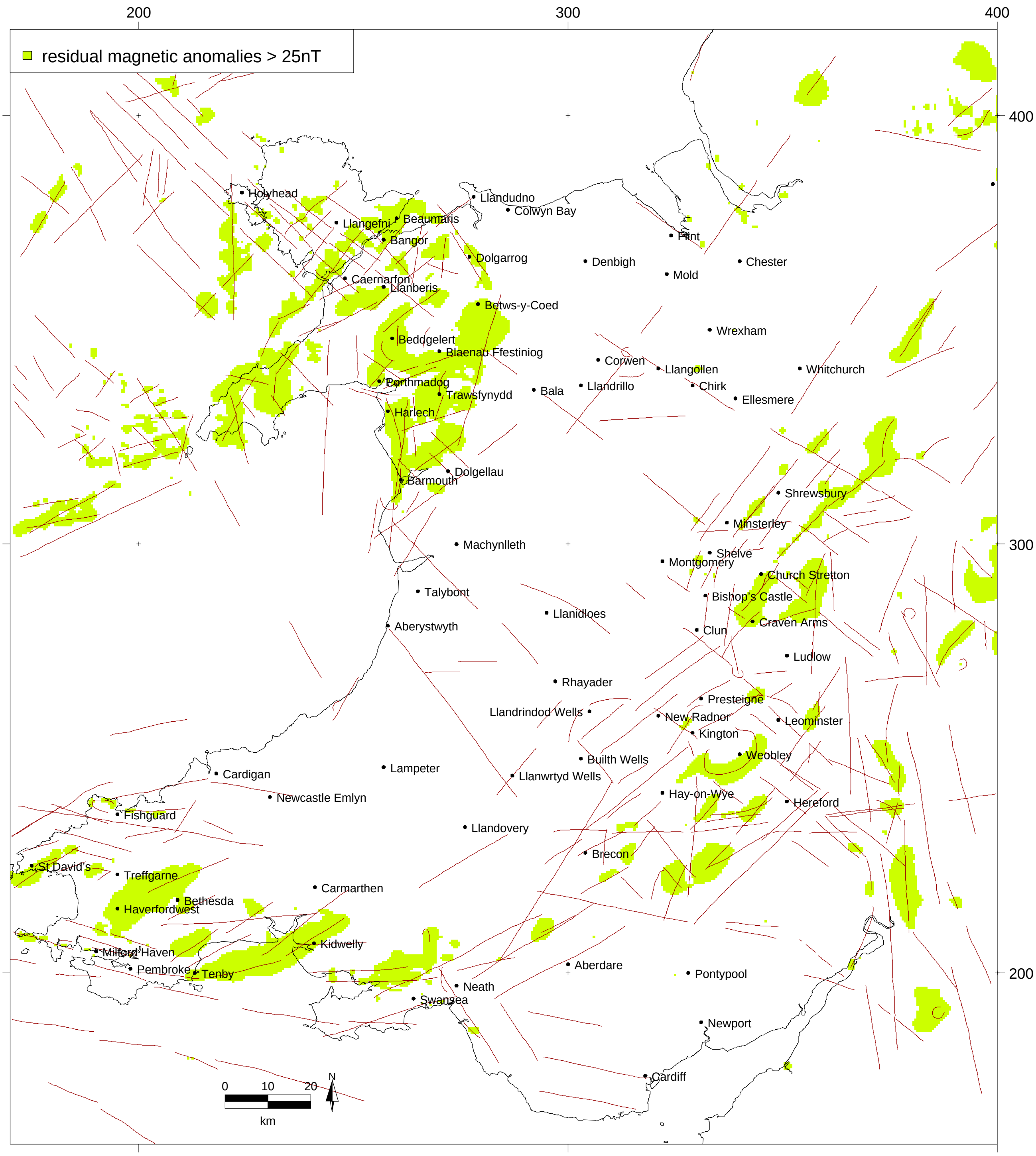

Figure 15 Geophysical data: magnetic lineaments and residual highs

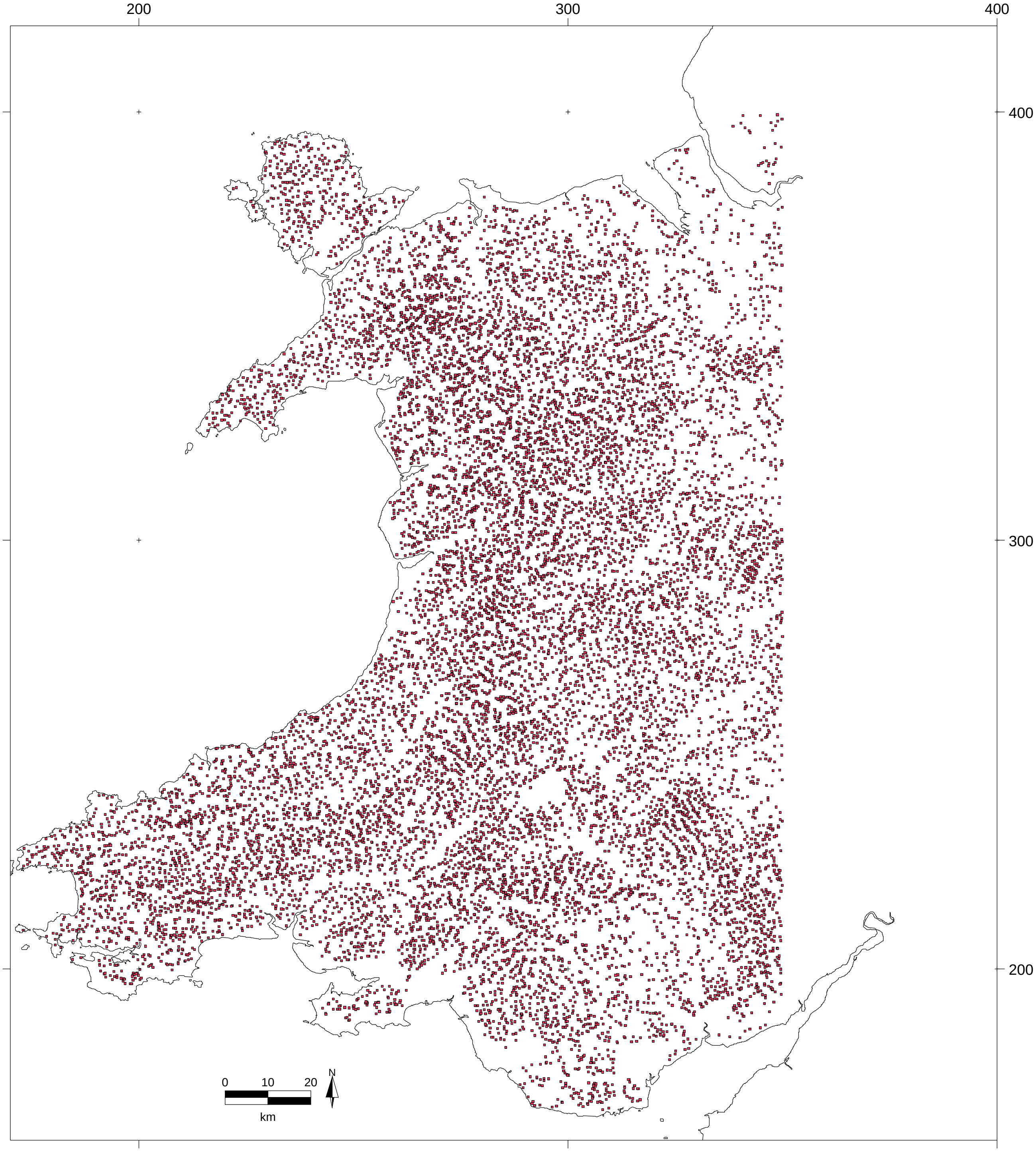

Figure 16 Geochemical data: G-Base stream-sediment sites

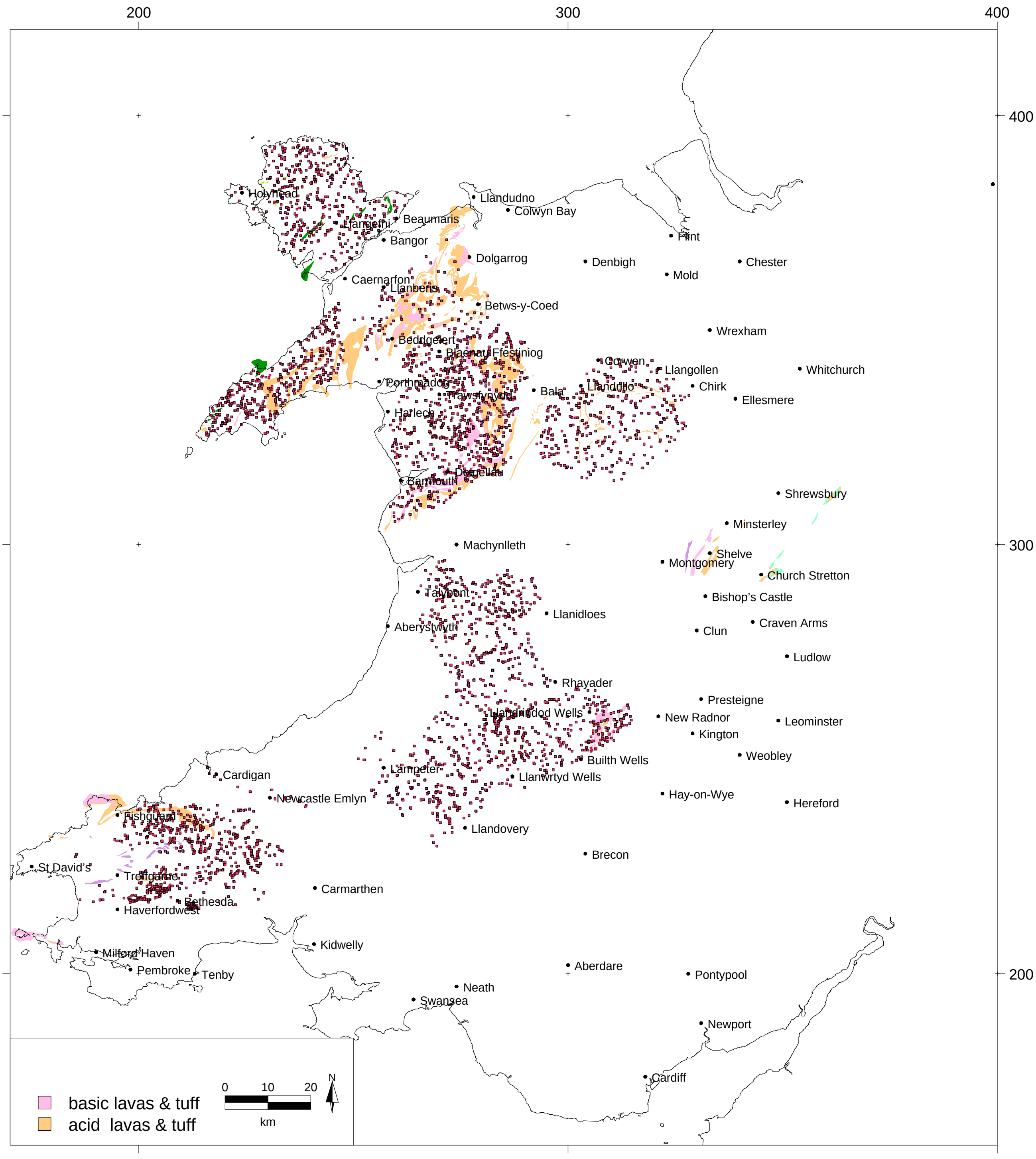

Figure 17 Geochemical data: MRP panned stream-sediment sites

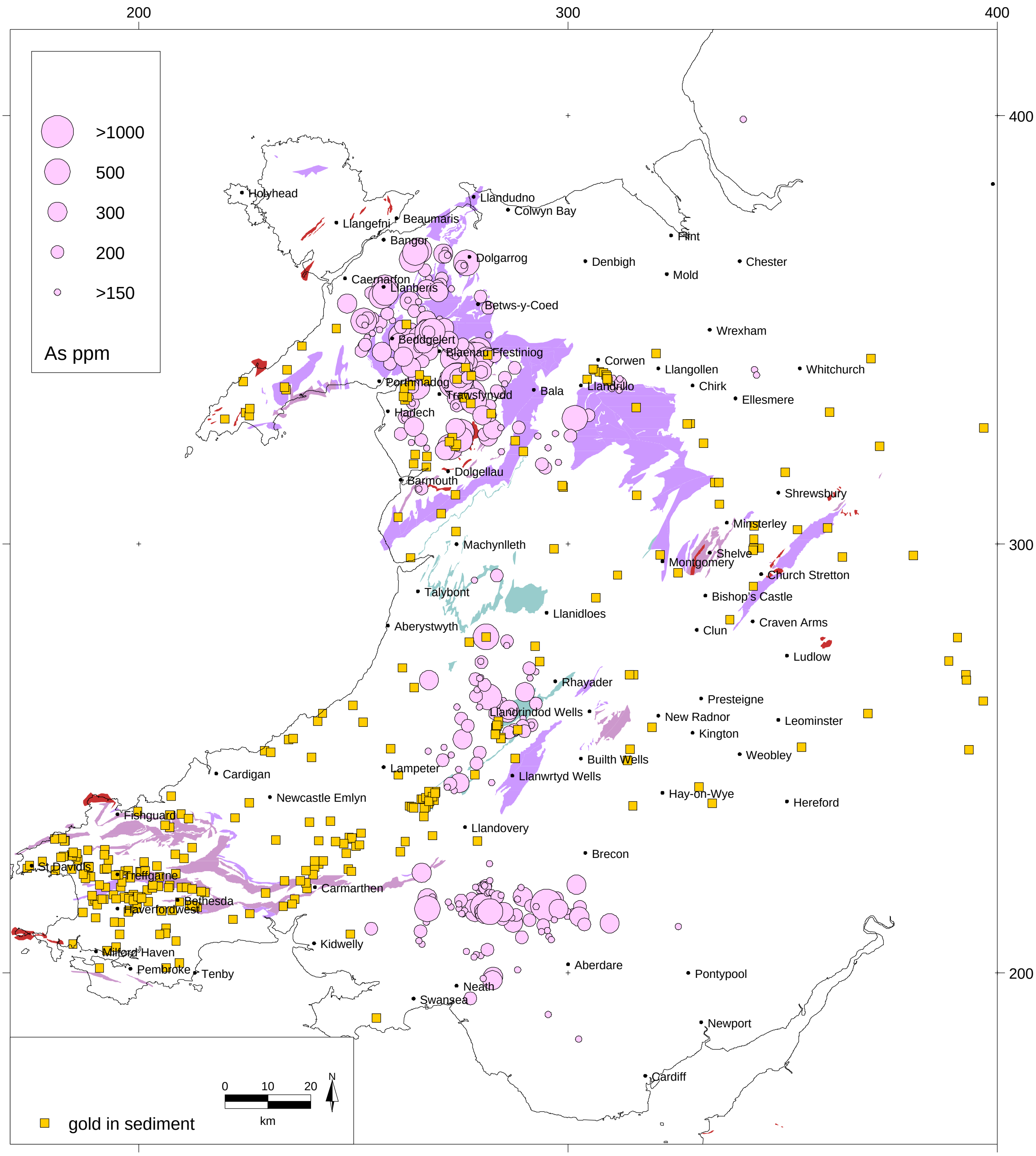

Figure 18 Geochemical data: G-BASE arsenic in stream sediment

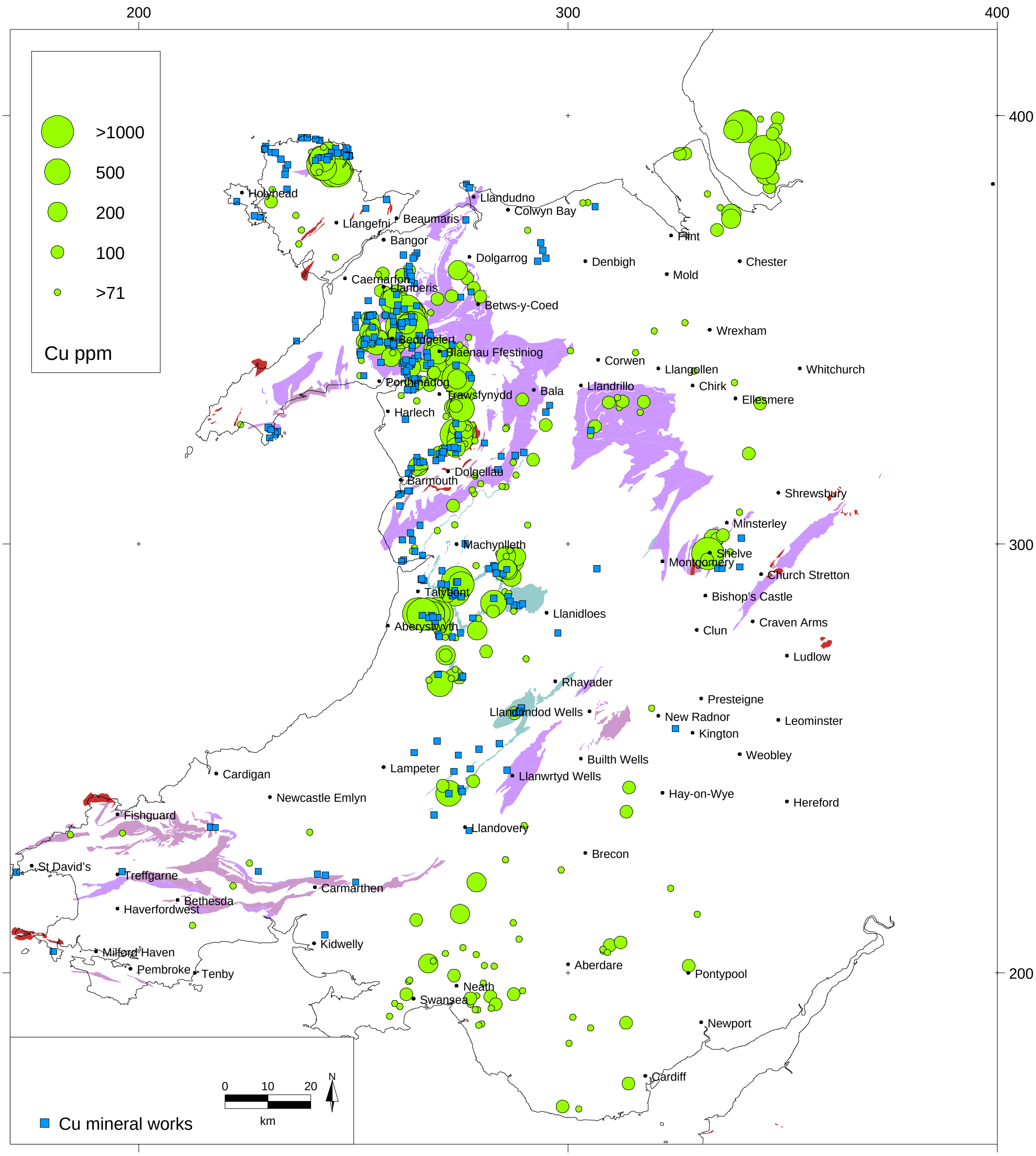

Figure 19 Geochemical data: G-BASE copper in stream sediment

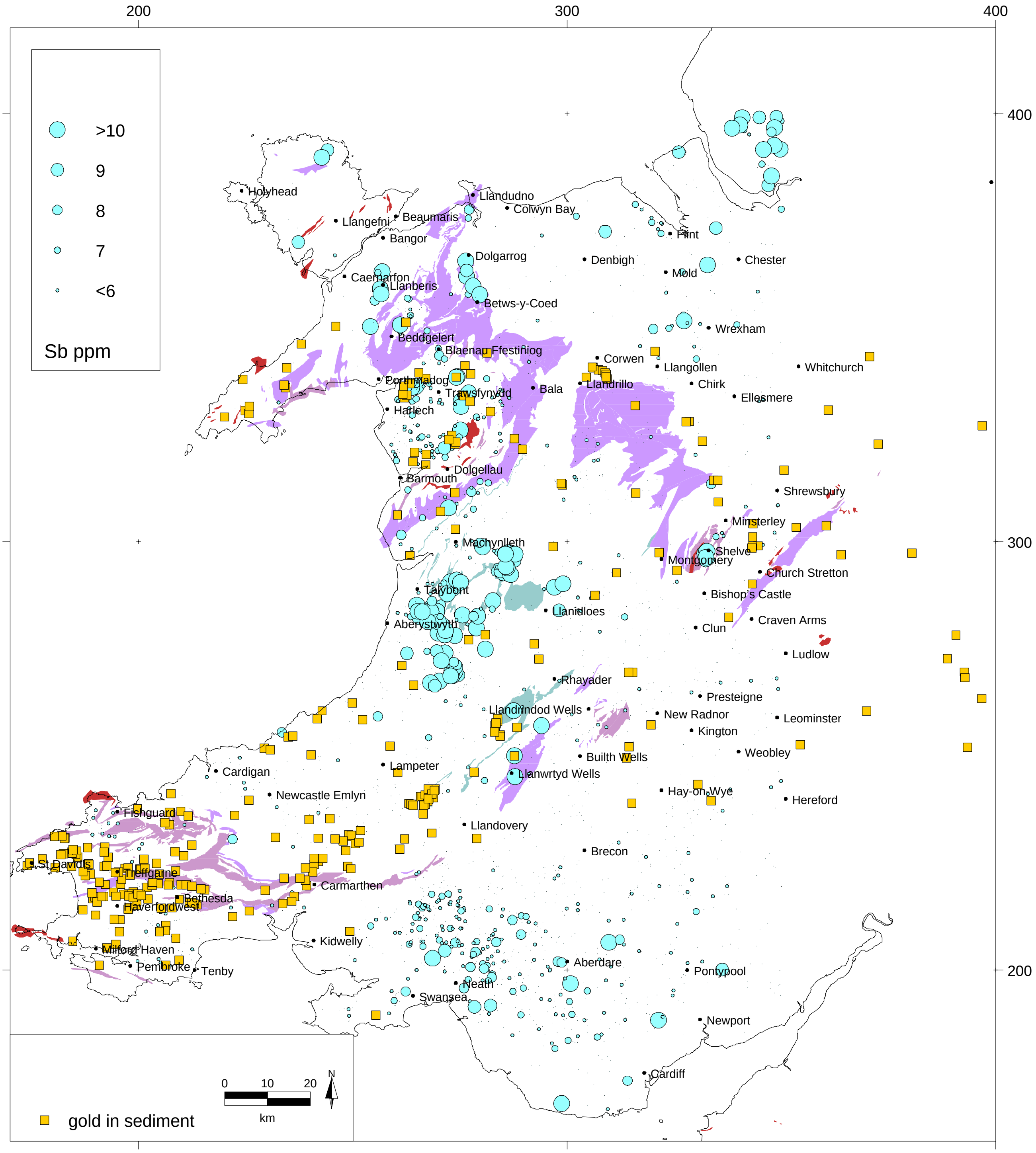

Figure 20 Geochemical data: G-BASE antimony in stream sediment

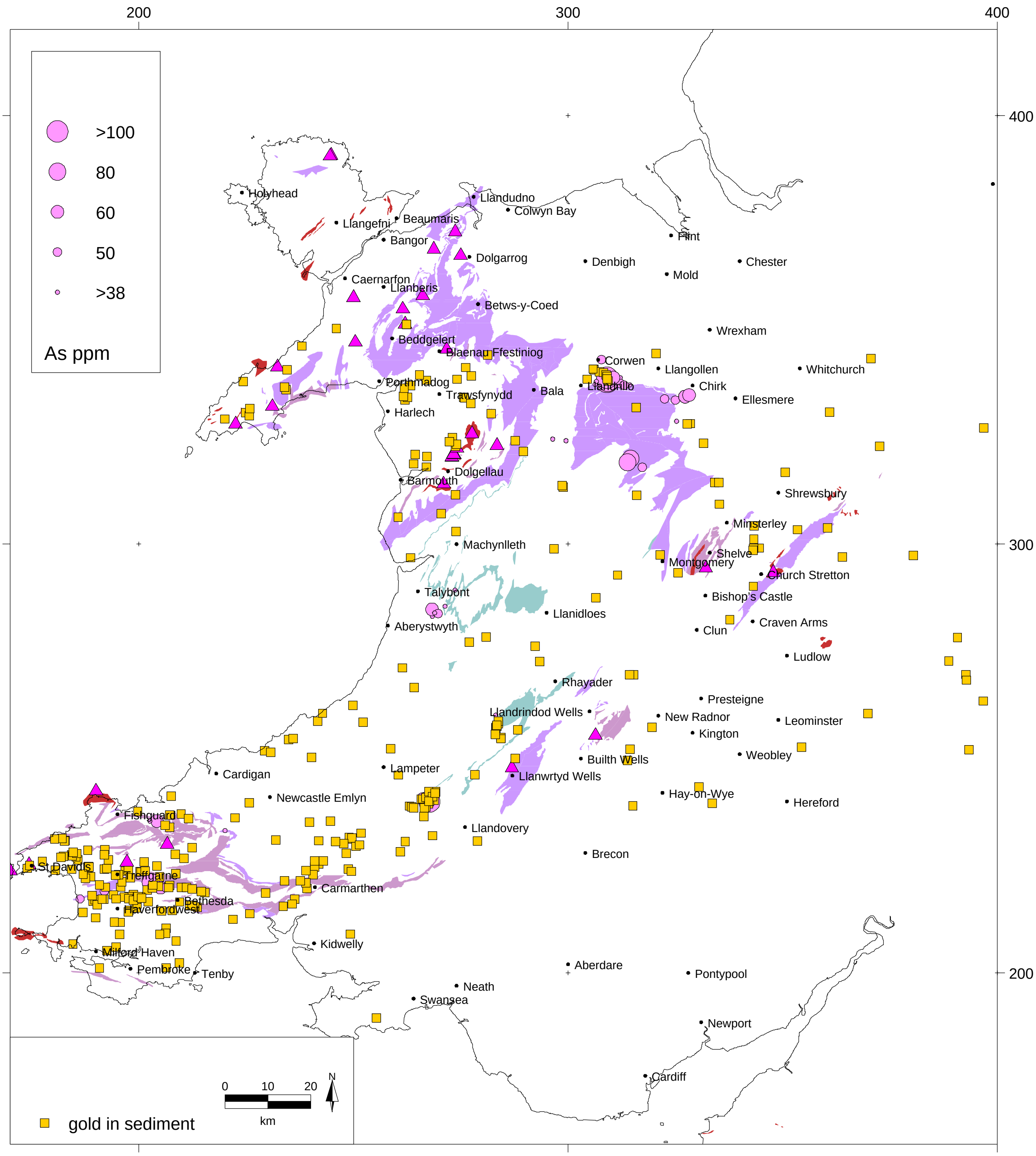

Figure 21 Geochemical data: MRP arsenic in panned stream sediment

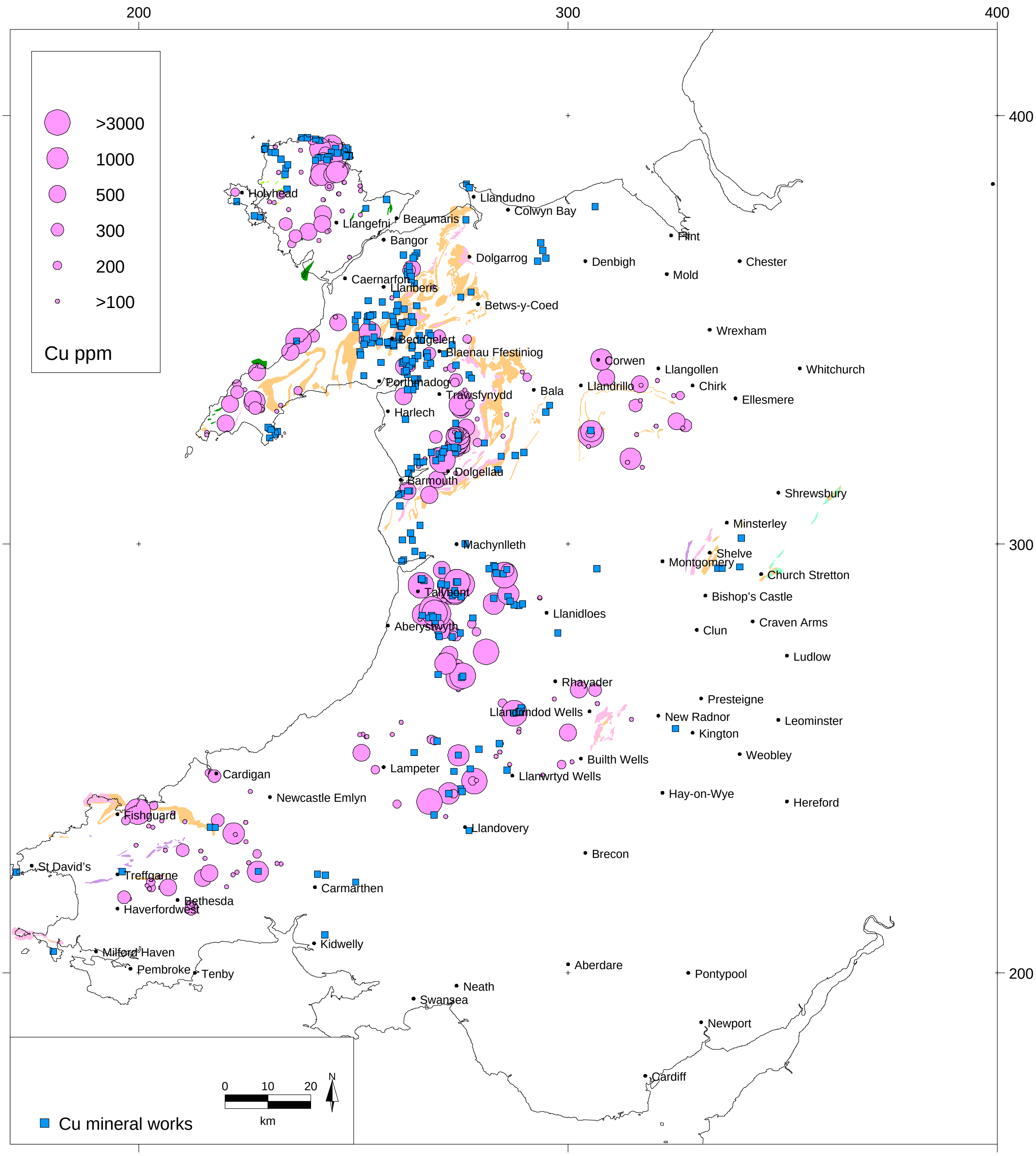

Figure 22 Geochemical data: MRP copper in panned stream sediment

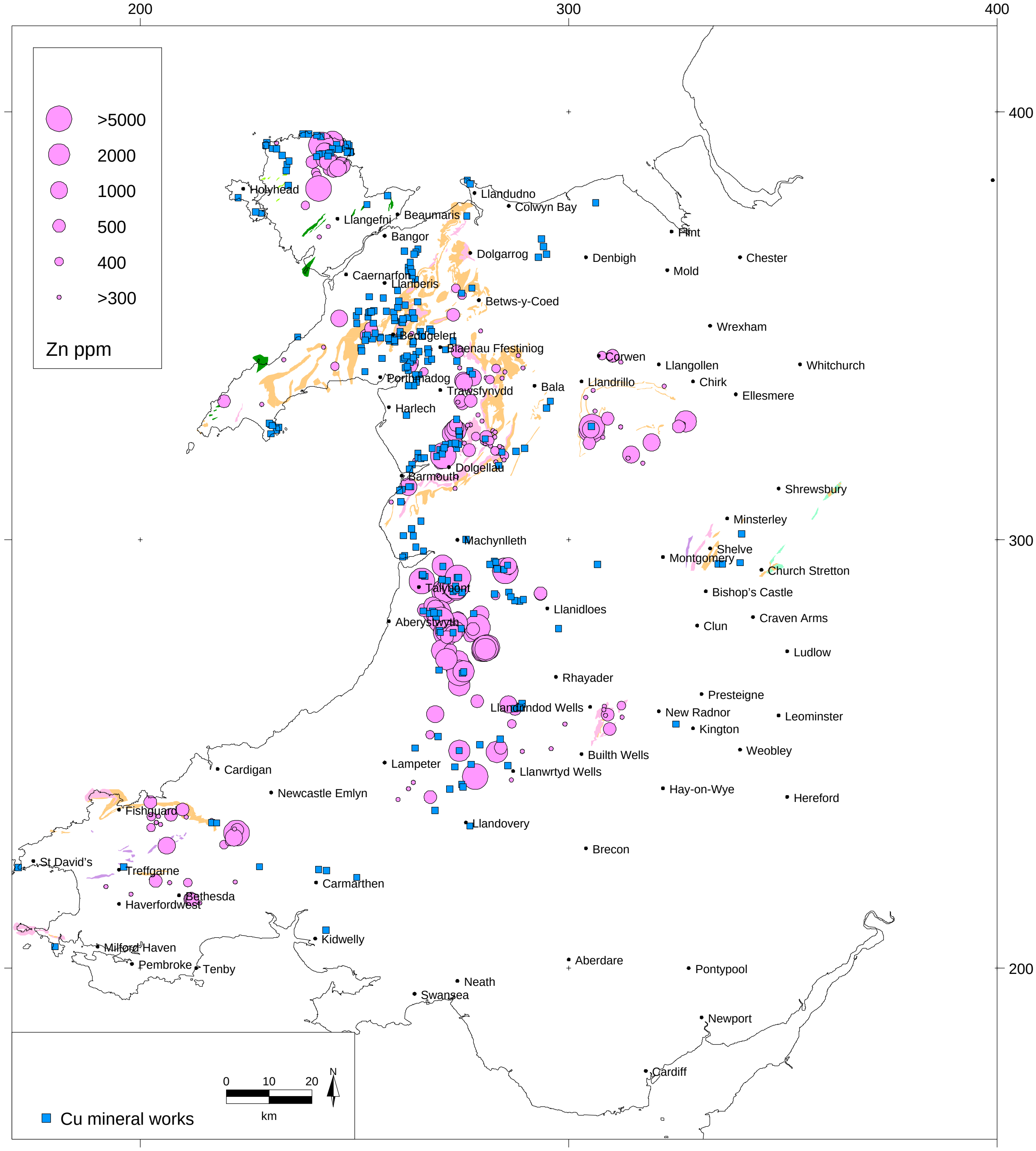

Figure 23 Geochemical data: MRP zinc in panned stream sediment

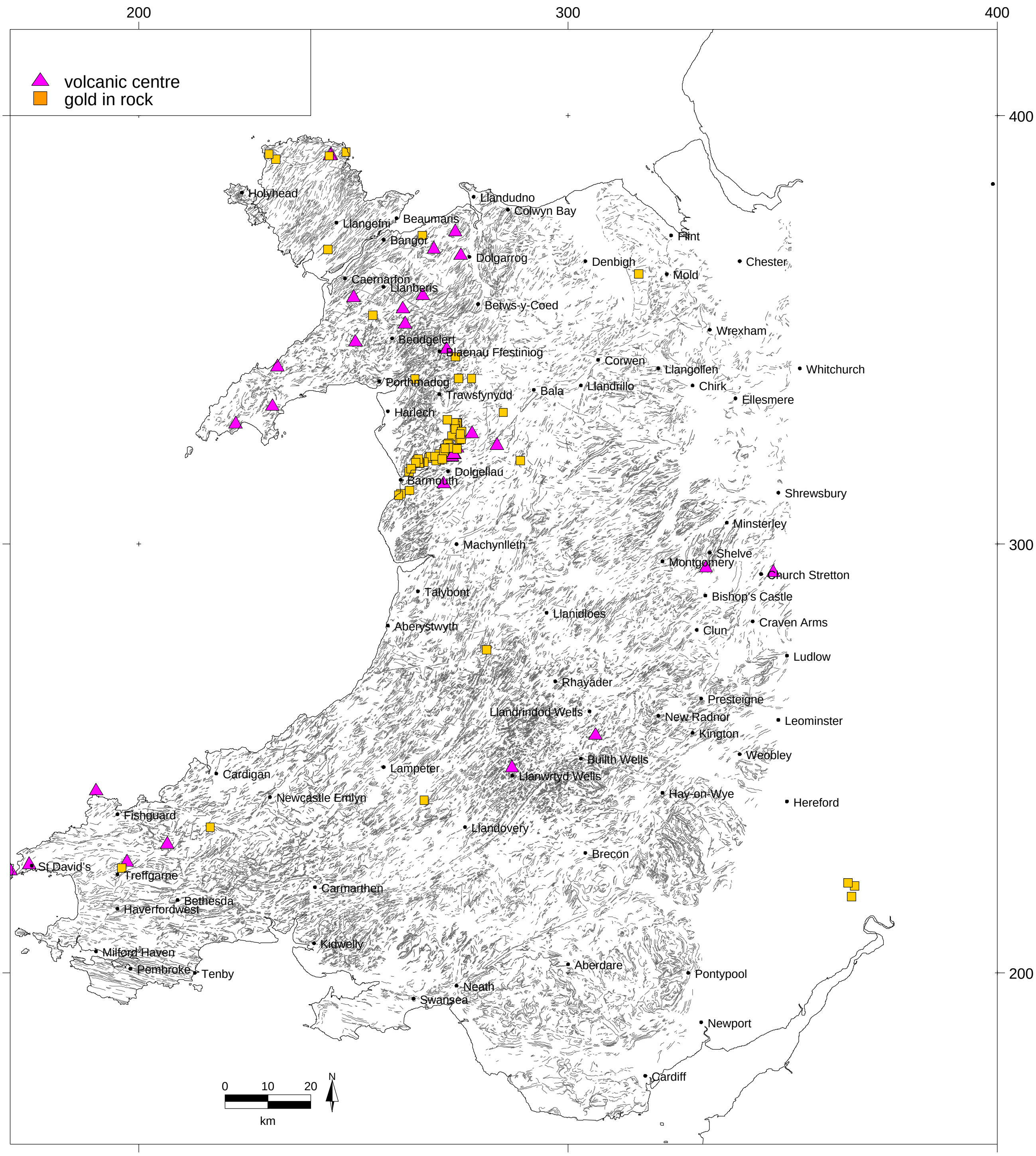

Figure 24 Plot of lineaments extracted from Thematic Mapper Band 5 imagery

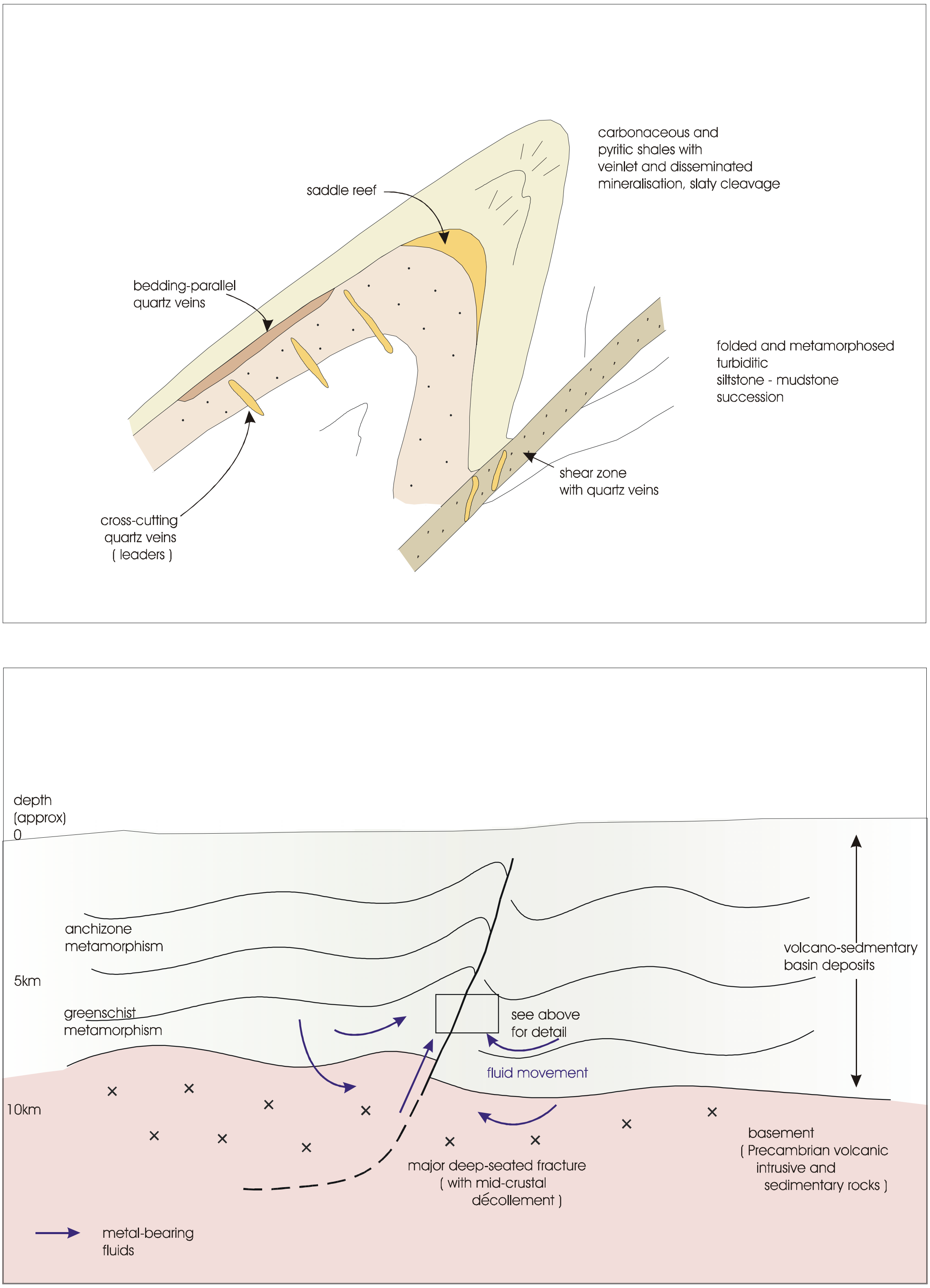

Figure 25 Simple generalised schematic model for turbidite-hosted mesothermal gold mineralisation (based on Annels and Burnham, 1986)

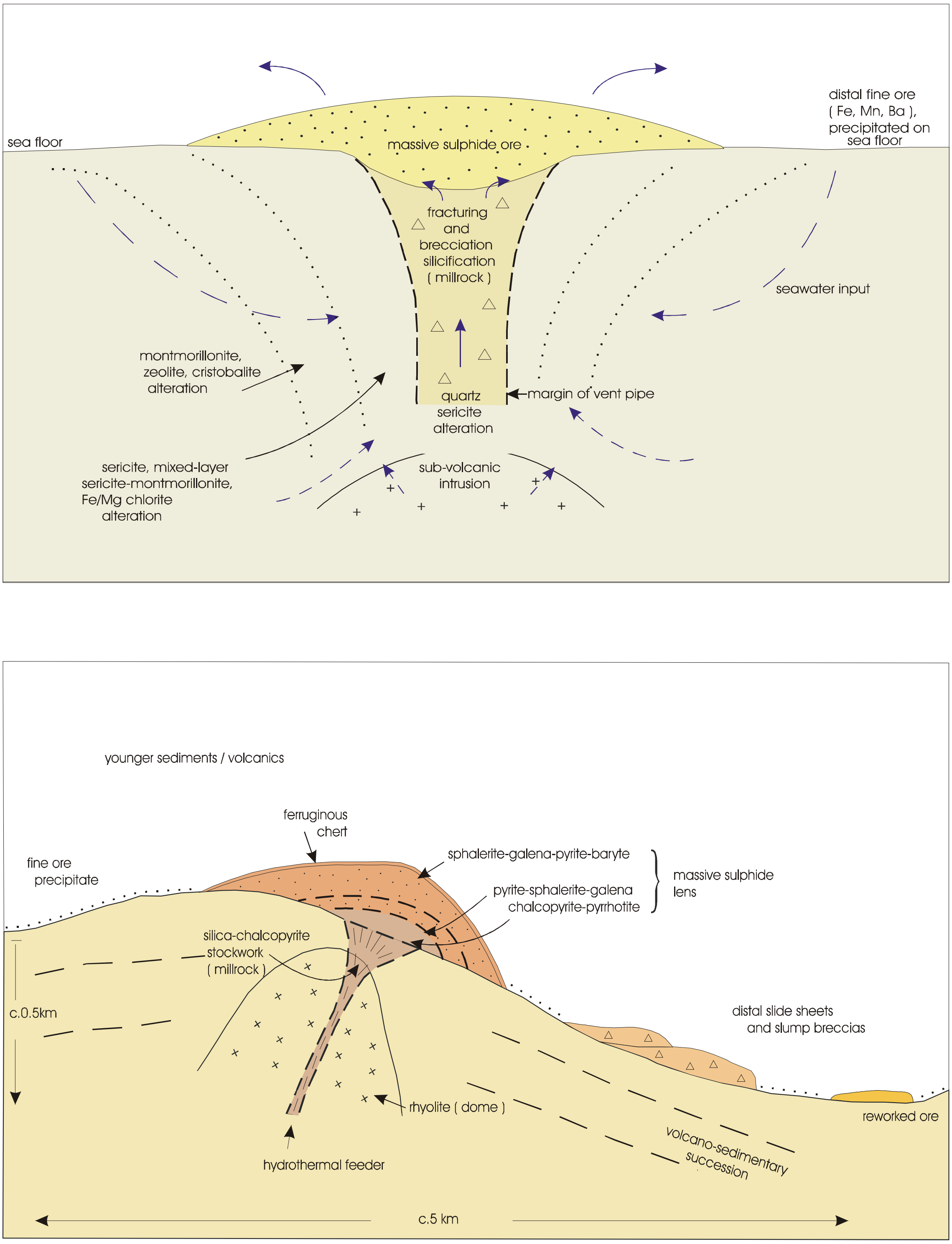

Figure 26 Simple generalised schematic model for volcanogenic massive sulphide deposits (based on Franklin, 1993 and Lydon, 1988)

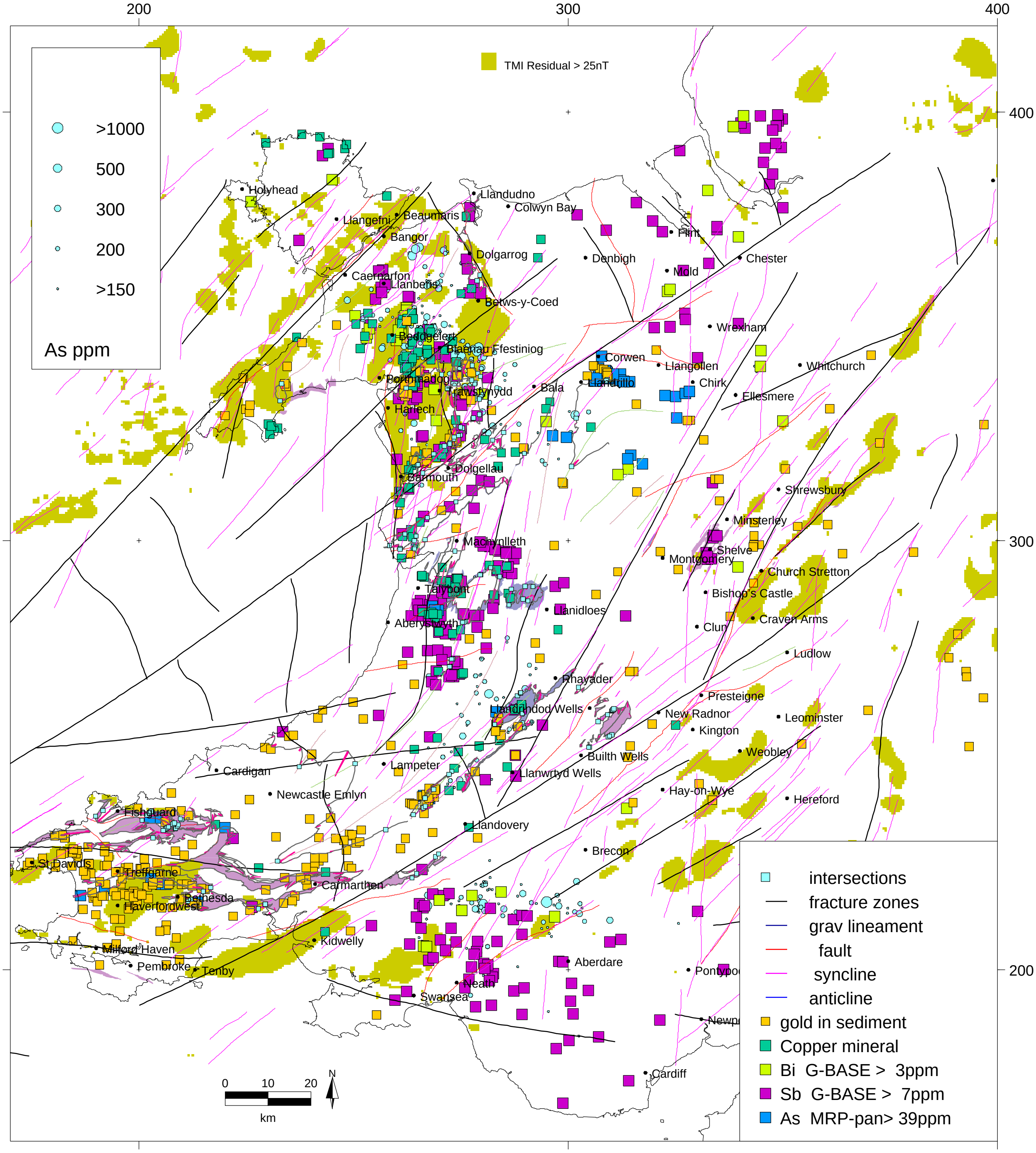

Figure 27 Selected data layers for mesothermal gold prospectivity analysis

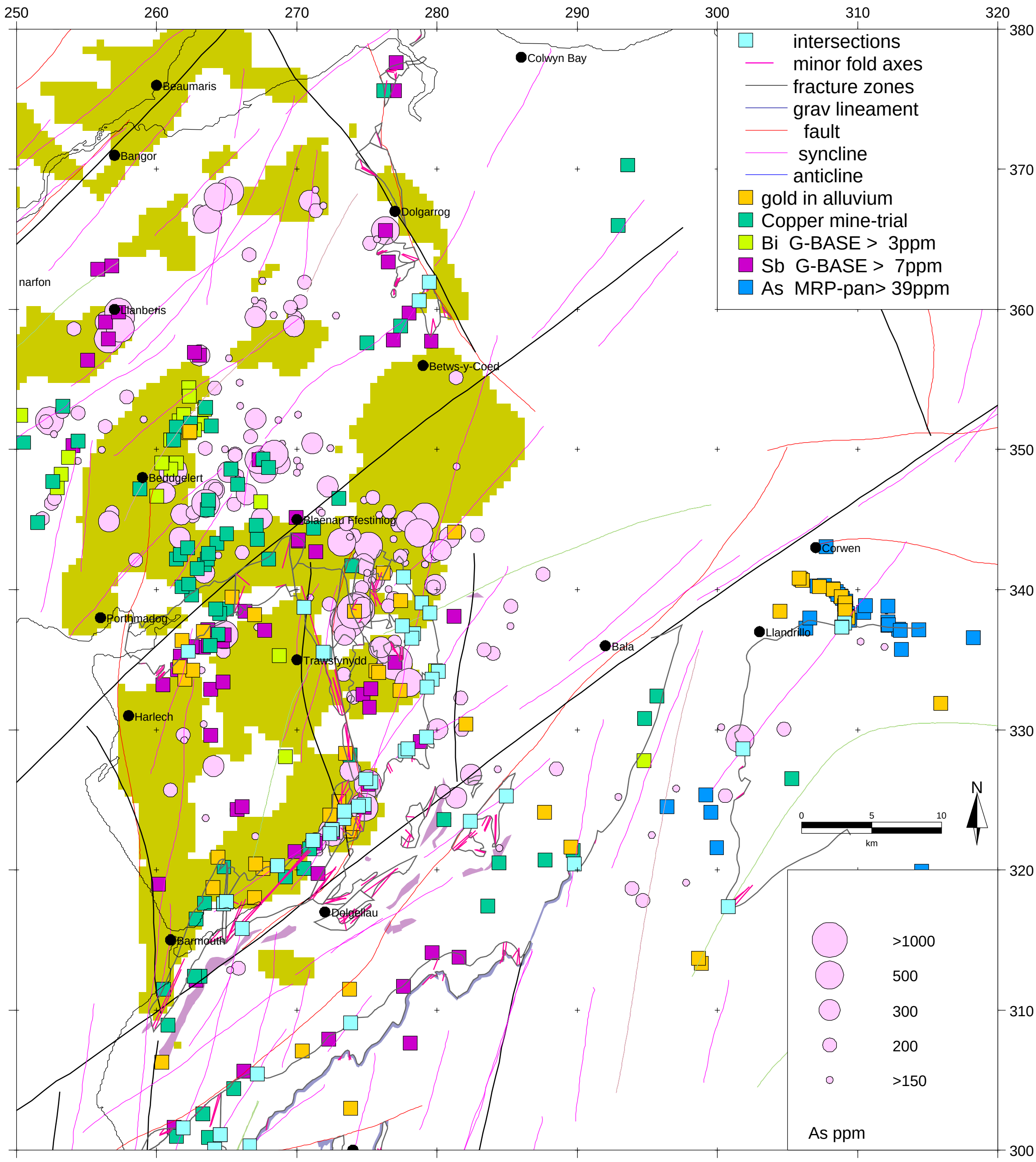

Figure 27A Detail of data layers for mesothermal gold prospectivity analysis around Harlech

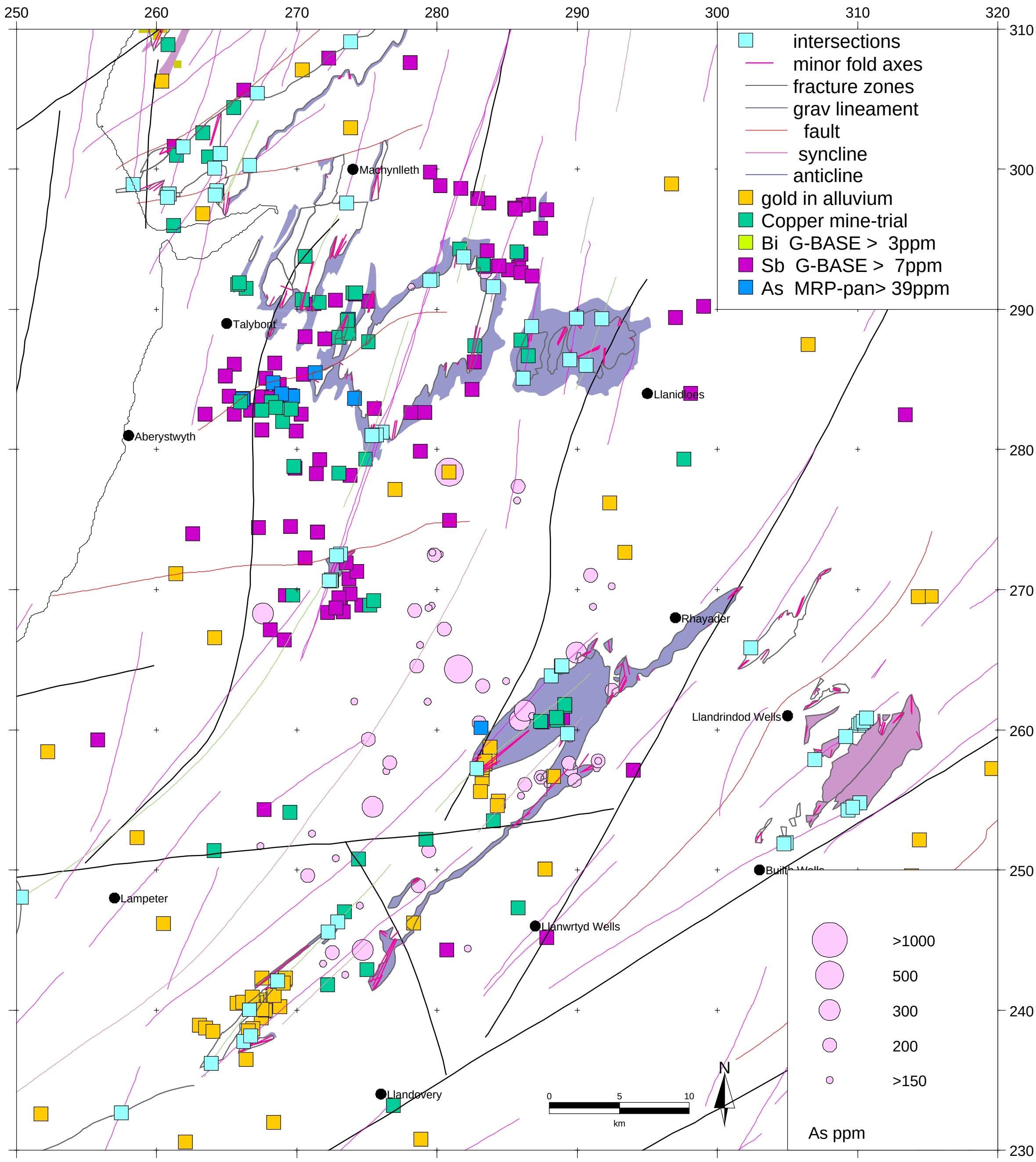

Figure 27B Detail of data layers for mesothermal gold prospectivity analysis in Central Wales

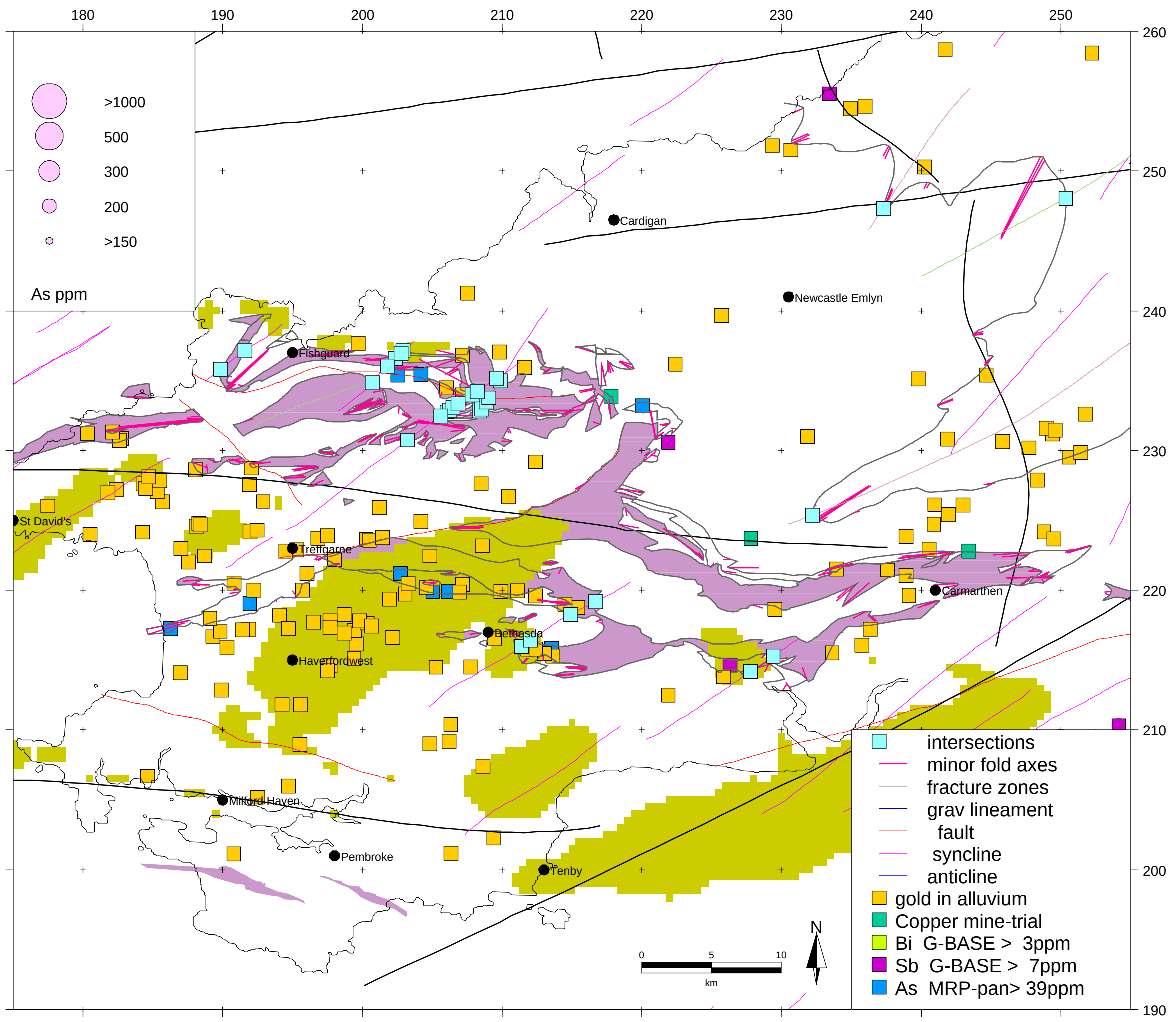

Figure 27C Detail of data layers for mesothermal gold prospectivity analysis in south-west Wales

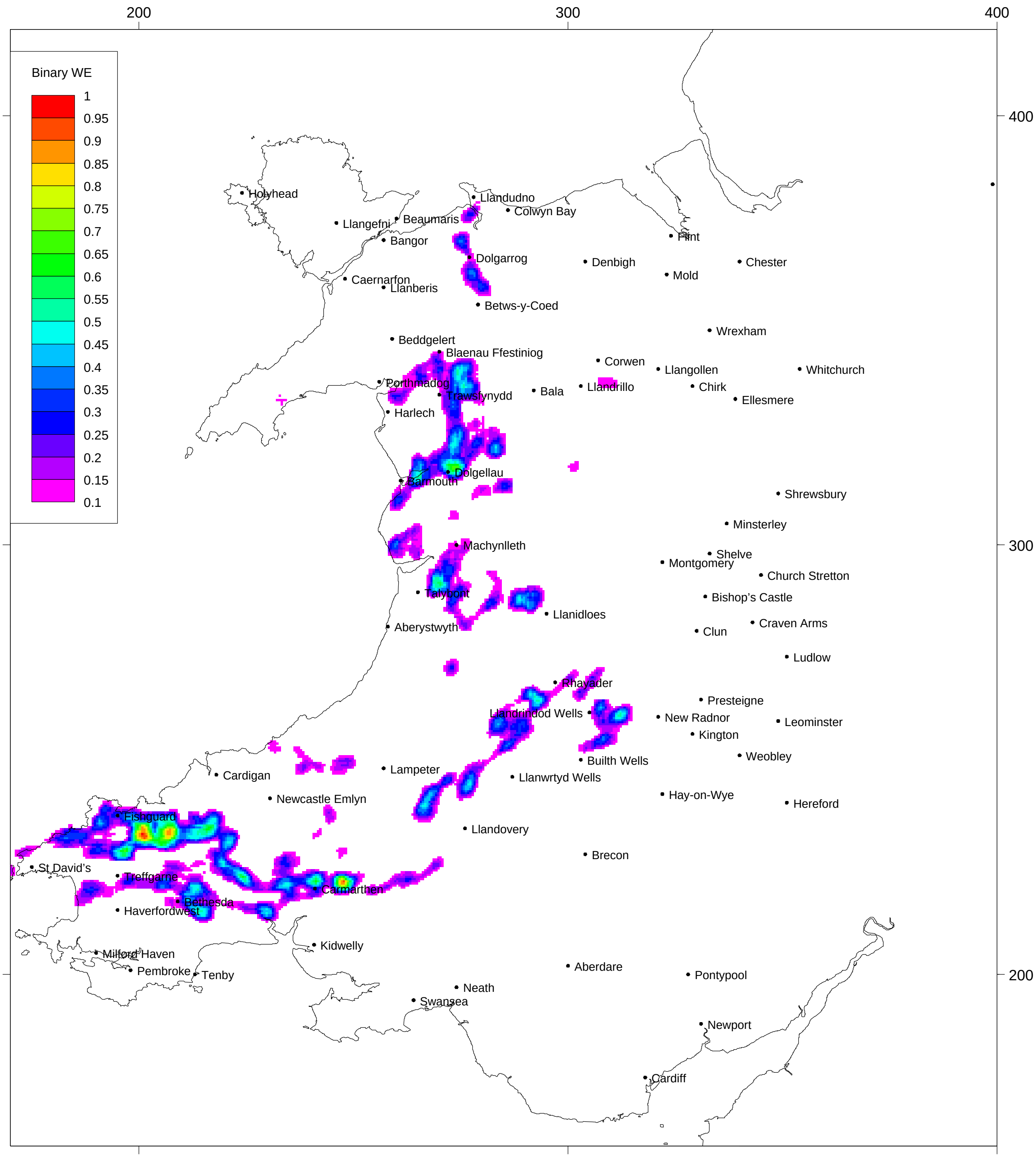

Figure 28 Binary weights of evidence mesothermal gold prospectivity map

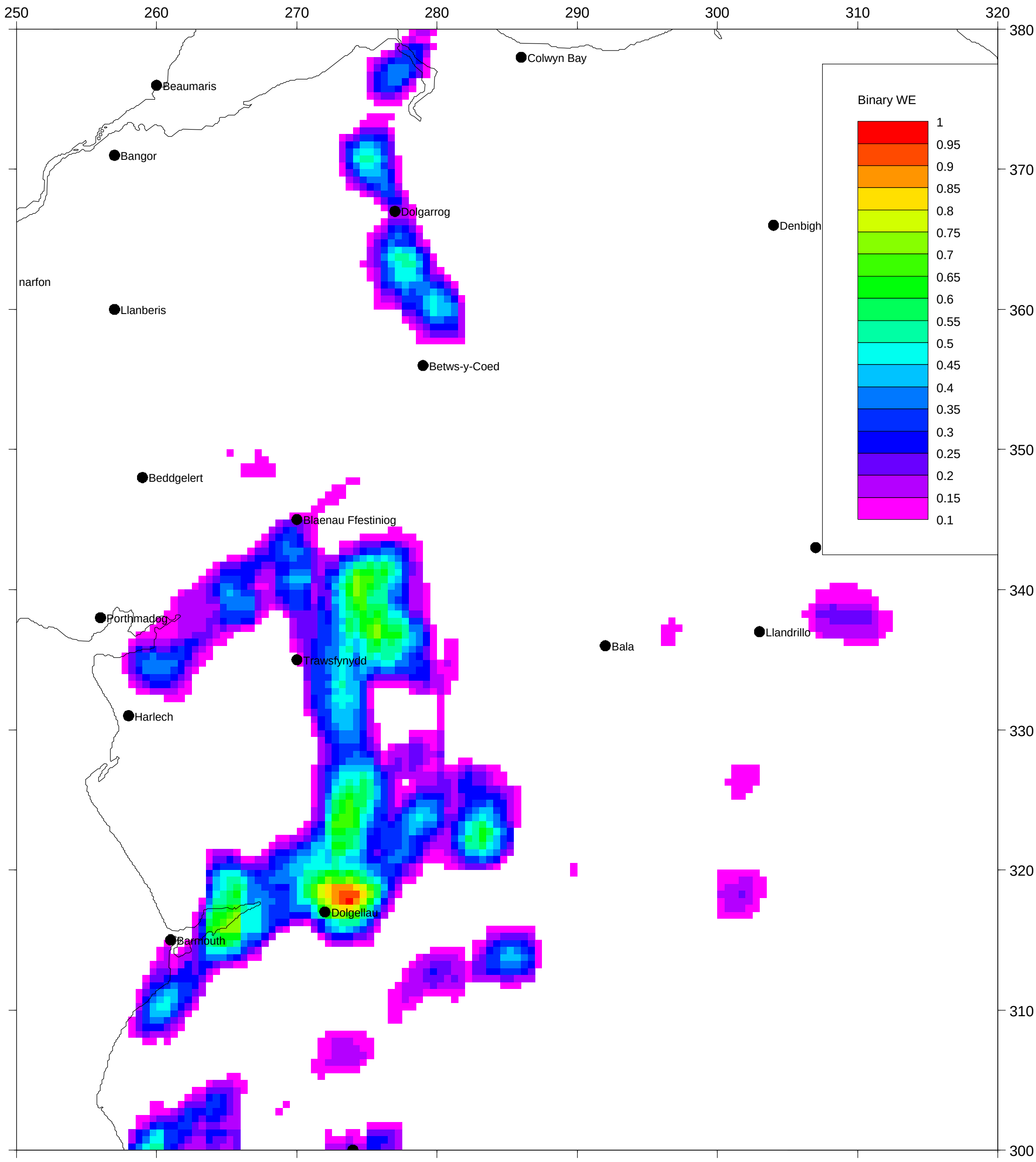

Figure 28A Detail of Binary weights of evidence mesothermal gold prospectivity map, Harlech area

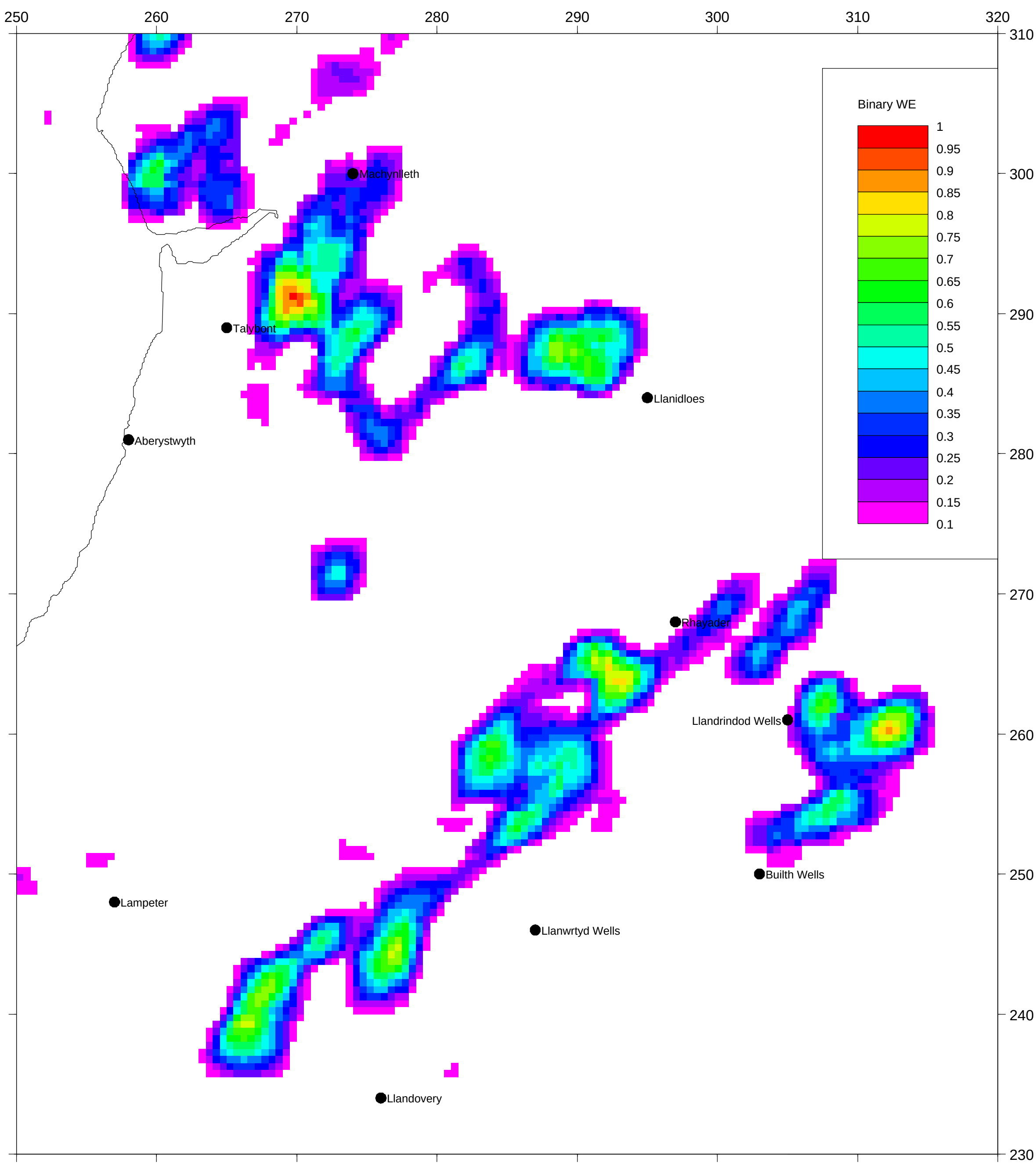

Figure 28B Detail of Binary weights of evidence mesothermal gold prospectivity map, Central Wales

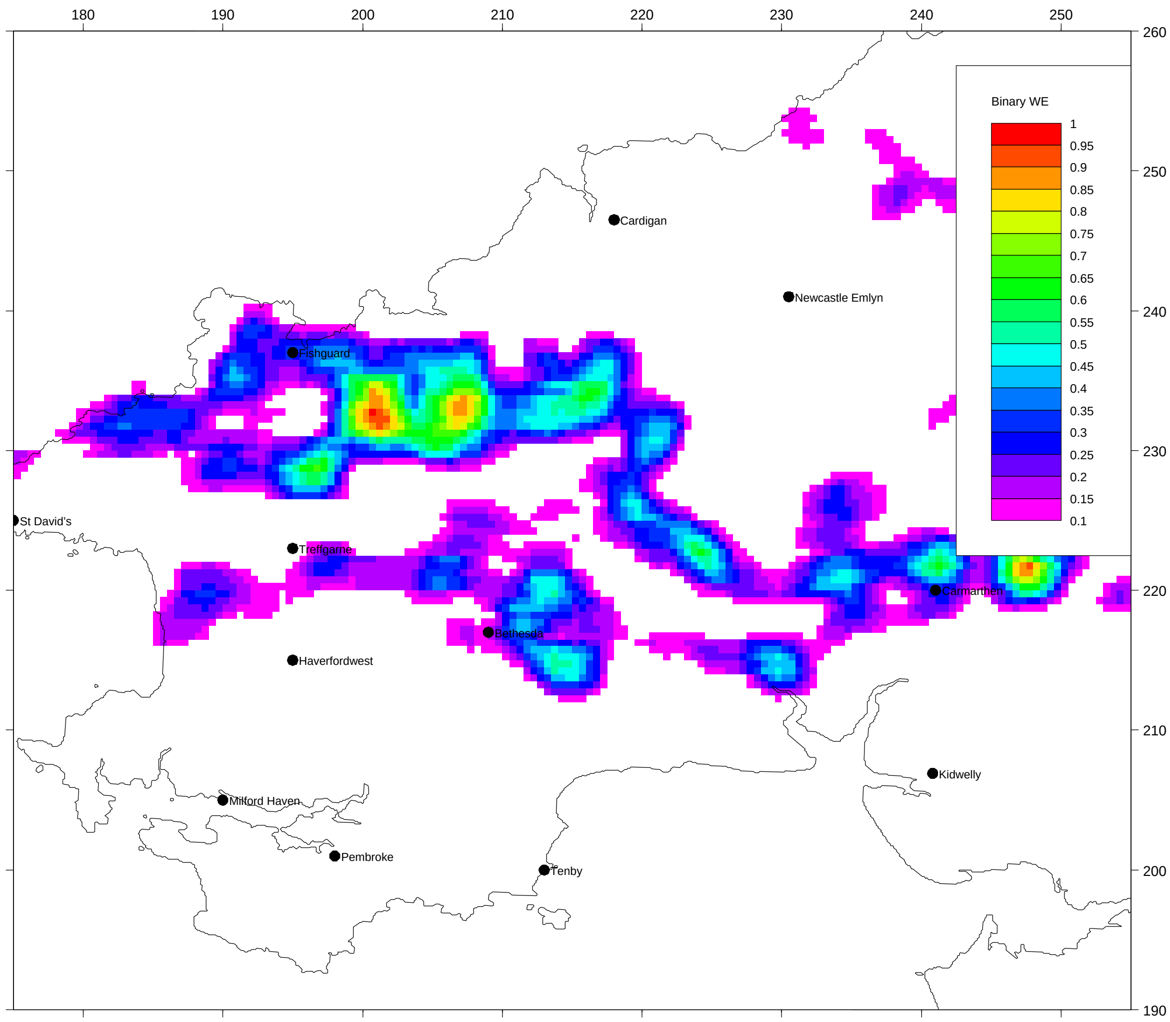

Figure 28C Detail of Binary weights of evidence mesothermal gold prospectivity map, south-west Wales

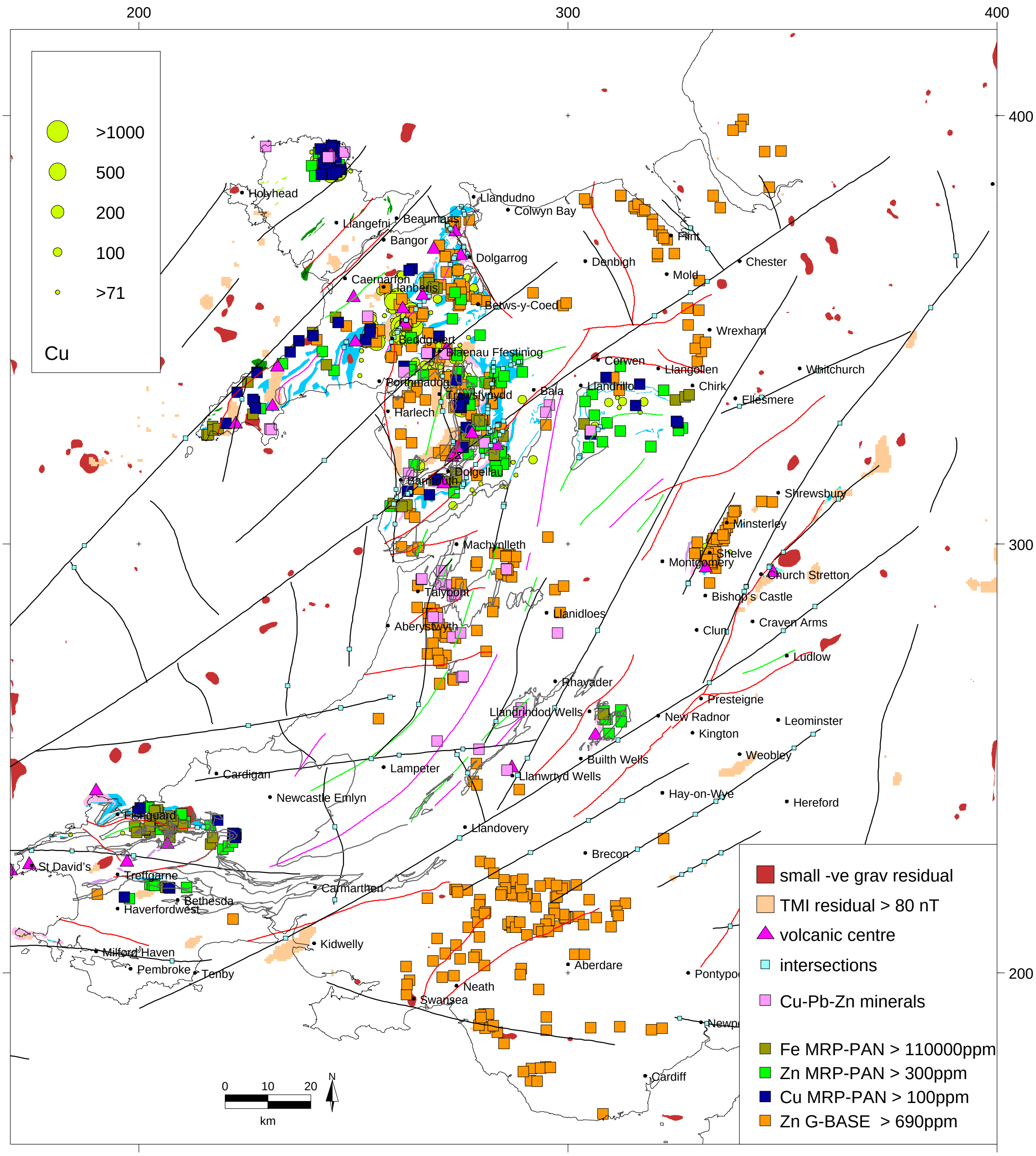

Figure 29 Selected data layers for VMS prospectivity analysis

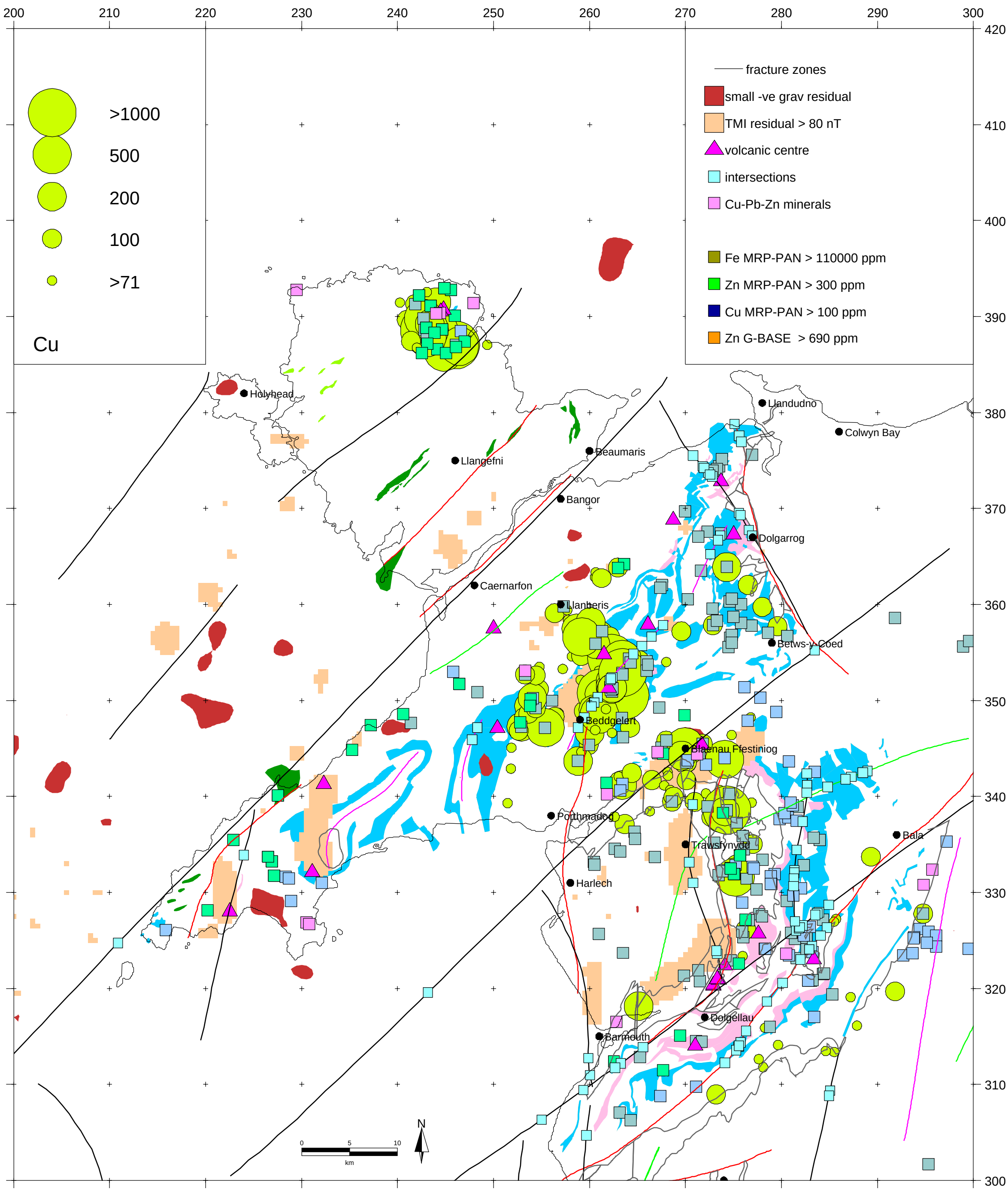

Figure 29A Detail of data layers for VMS prospectivity analysis, North Wales

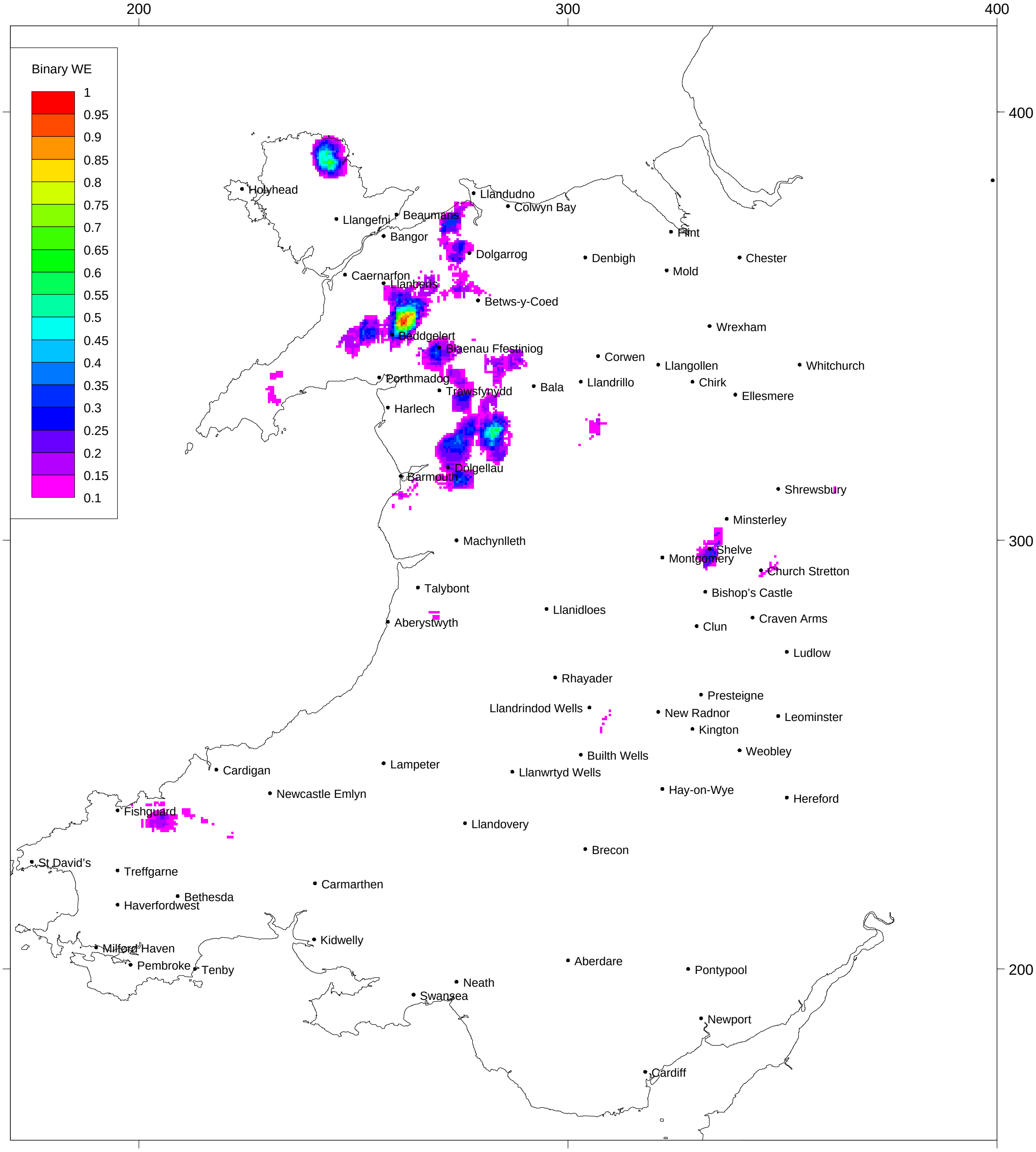

Figure 30 Binary weights of evidence VMS prospectivity map

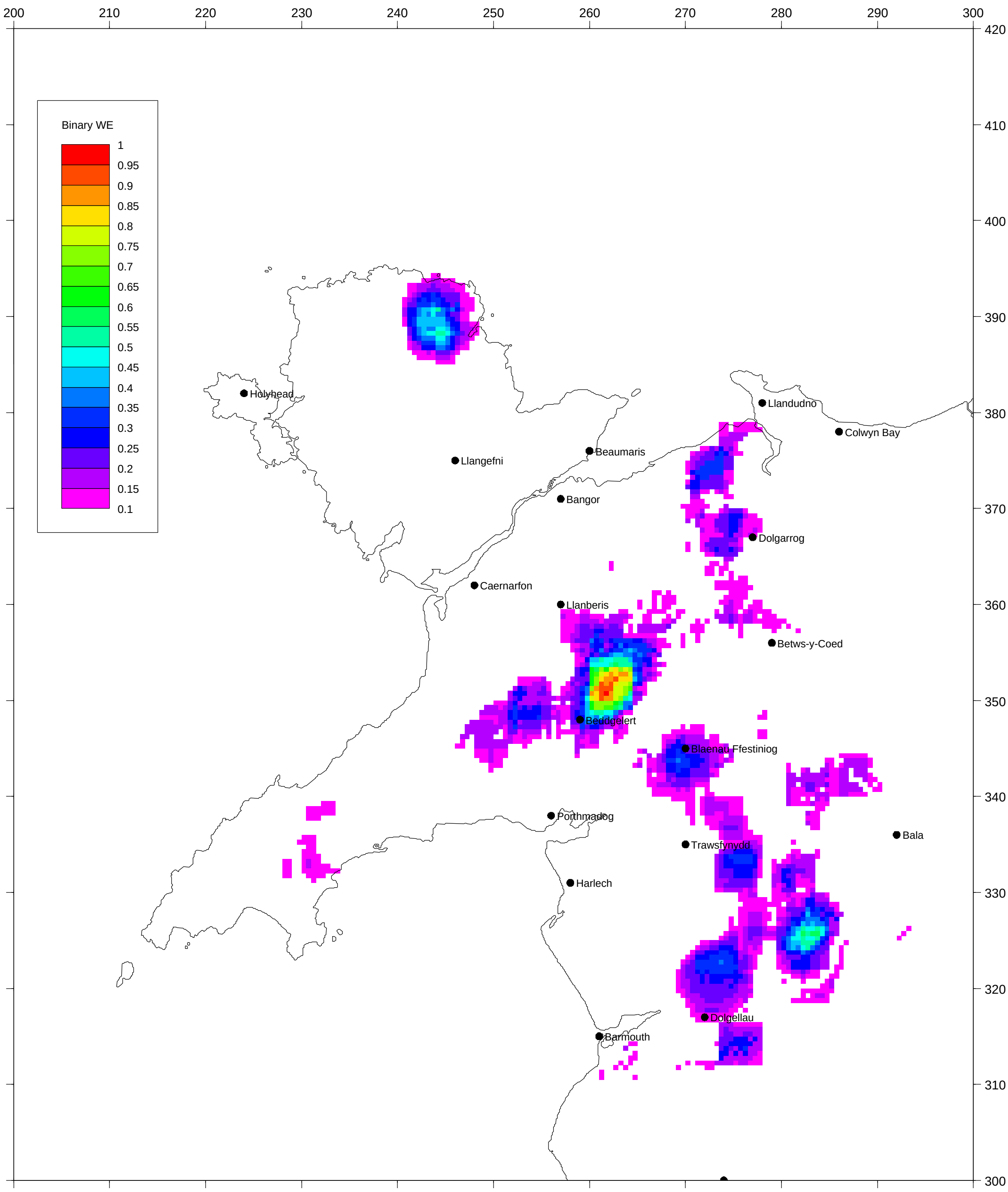

Figure 30A Detail of binary weights of evidence VMS prospectivity map, North Wales