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Evidence for gold mineralisation in the Lower Palaeozoic and Precambrian rocks of south-west Wales

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Winter Landsat TM image
(bands 4, 5, 7) south-west Wales.
Survey area is outlined in red.

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SUMMARY

This report describes geochemical surveys across an area of 400 km^2 in south-west Wales, carried out to investigate alluvial gold occurrences reported by the BGS Geochemical Baseline Survey of the Environment (G-BASE). Drainage, rock and overburden samples were collected, and the survey comprised (i) an orientation study to provide information on the occurrence of gold in drainage, (ii) rock sampling to provide baseline information on the composition of catchment rocks and stream clasts, (iii) follow-up drainage sampling to supplement the G-BASE coverage, (iv) detailed drainage sampling in three gold-bearing catchments between Narberth and Haverfordwest, and (v) overburden sampling in these three catchments.

The orientation survey indicated that gold occurs in different grain sizes in different catchments and that fine gold may be present locally. Grain morphology varies from angular to well rounded; some grains are likely to be of very local origin. Chemical analysis for a wide range of elements revealed no clear pathfinder elements for gold in this area. Mineralogical examination showed that cassiterite is present locally, indicating the presence of tin mineralisation and reducing the use of tin values in drainage samples as a guide to contamination. Native mercury was identified at one site, but it is not clear whether or not this is the product of contamination.

Follow-up sampling reinforced the findings of the orientation survey and indicated that geochemical variation in the stream-sediment and panned-concentrate samples could be related to (i) gold mineralisation, (ii) black shales, (iii) limestones, (iv) mafic (chloritic) rocks, (v) contamination and (vi) nodular monazite. Several gold-bearing prospective catchments were identified, separated by distances of up to 15 km. They include the Afon Marlais, Deepford Brook, Fenton Brook and streams south of New Moat. Overburden sampling and panning from pits close to some of the anomalous drainage sites showed that the methodology was potentially useful. Gold was recorded in three of these samples. Desk studies of available geophysical data indicated that anomalous gold concentrations appeared to be spatially related to regional magnetic features, which suggested an association between the occurrence of gold and shallow (magnetic) basement or major faults controlling depth to basement.

Gold grains from the orientation and follow-up surveys were subjected to detailed electron microprobe analysis and were classified on the basis of their chemical composition. Four types were identified, of which the commonest suggested the metallogenetic involvement of granitic rocks. No such rocks are exposed in the survey area, but they exist to the west, predominantly in the late Precambrian, so it was most likely that this type of gold originated in those rocks. Evidence from other sources, including the presence of a distinctive type of gold in the Llandeloy area probably derived from the porphyry-style copper mineralisation in the area, indicated that fluvio-glacial transport was unlikely to be a major factor.

Analysis of all the available data led to the conclusion that there are probably three principal sources of the alluvial gold found in south-west Wales: (i) palaeoplacers; (ii) porphyry-style copper-gold mineralisation, and (iii) black-shale/shear-zone mineralisation. The first of these, most probably in the uppermost Ashgillian rocks, is probably responsible for most of the alluvial gold but it is the last which is more likely to have economic potential in view of similarities with the Ogofau deposit in south-central Wales. Further work is merited to investigate the association of gold with black shales and major fracture zones.

INTRODUCTION

This report describes the results of desk studies, field surveys and laboratory analysis, based largely on geochemical and mineralogical methods, for an area in south-west Wales where gold had been observed in panned stream sediment during the collection of samples and data for the BGS Geochemical Baseline Survey of the Environment (G-BASE). The work was carried out under the DTI-funded Mineral Reconnaissance Programme (MRP) which ended in 1997. This report was completed for the Minerals Programme which succeeded the MRP. The objective of the work was to provide further information on the occurrence of alluvial gold in the area and its possible sources, and to assess whether these sources might include a deposit with economic potential.

The area investigated covers 400 km^2 straddling east Pembrokeshire and west Carmarthenshire (Figure 1). It is composed principally of sedimentary and volcanic rocks deposited in the Lower Palaeozoic Welsh Basin, unconformably overlain by Devonian and Carboniferous sedimentary rocks at the southern margin. In the north-west and to the west of the area, inliers of the late Proterozoic basement are exposed (Figure 2).

Previous work in south-west Wales

G-BASE sampled south-west Wales in the summers of 1992 and 1993. Drainage sampling was carried out at a density of approximately 1 sample/km^2 and observations of panned gold were recorded from sites over a wide area to the west of Carmarthen, largely underlain by Ordovician and Silurian mud-dominated, sedimentary rocks deposited at the south-west margin of the Welsh basin. These observations, coupled with the attractive geological setting, were largely responsible for the instigation of the work contained in this report. The field and analytical data for the G-BASE and MRP samples are available from the BGS.

There has been little recent published geological mapping in south-west Wales. Most of the BGS maps at 1: 50 000 scale, which cover the southern part of the survey area, are based on work carried out in the early part of the century (Cantrill et al., 1916; Strahan et al., 1909, 1914). The recently published St. David’s 1: 50 000 scale sheet is a compilation from a desk study of available data (British Geological Survey, 1992). There are no published geological maps at this scale for the northern part of the area, but a new 1: 250 000 scale sheet for the whole of Wales provides useful regional-scale information (British Geological Survey, 1994), and more detailed information for some small areas is provided in the publications of individual researchers.

The Palaeozoic stratigraphy and sedimentology of the rocks in this area have been the subject of many studies, which are summarised in a number of overviews (e.g. Wood, 1969; Owen, 1974; Bassett, 1980). The structure of the Lower Palaeozoic rocks and effects of the Caledonian orogeny have been described at a regional level, while the impact of the Variscan orogeny on the Caledonian rocks and structures is summarised by Hancock et al. (1981).

Geochemical studies of rocks in south-west Wales have concentrated primarily on the petrogenesis of the volcanic and plutonic rocks, particularly the Fishguard Volcanic Group (Bevins, 1982; Bevins et al., 1989, 1991, 1992, and 1995; Lowman and Bloxam, 1981; Patchett and Jocelyn, 1979; Thorpe, 1970). The sedimentary rocks have received little attention. The few exceptions include a chemical analysis of the equivalent of the Nod Glas Formation of North Wales from near Whitland (Temple and Cave, 1992) and 20 analyses of mudrocks from around Newcastle Emlyn, which have much higher P_2O_5 and Ba contents and lower Mn and Co than similar rocks from mid-Wales (Ball et al., 1992; Smith et al., 1994).

Regional aeromagnetic and gravity survey data for Wales are available from the BGS. These data show anomalously high areas in both parameters on the south-east margin of the Welsh Basin, which have been attributed to blocks of basement at depth that may have controlled faulting and subsequent sedimentation within the basin during the Palaeozoic. It has been suggested that the regional data show that the basement blocks are offset in a sinistral sense along north-east-trending deep structures (McDonald et al., 1992).

Several on- and off-shore seismic lines have been shot in the area (Brooks et al., 1983). Most significantly for this study, a line from north to south across Pembrokeshire indicated that autochthonous basement was present at surface in the Hayscastle anticline, but that the Precambrian outcrops of the Johnston complex and Benton Volcanic Group in southern Pembrokeshire are merely thin slices of basement thrust over underlying Palaeozoic sedimentary rocks, confirming the interpretation of sedimentological rock data by Sanzen-Baker (1973).

Mineral occurrences and past mining activities, all on a very small scale in south-west Wales, have been reviewed by Hall (1971) and Foster-Smith (1981). Except for the work of the MRP, little modern mineral exploration work has been carried out in south-west Wales. In the 1970s the MRP carried out an appraisal of the mineral potential of south-west Wales based on the (then new) geological models relating styles of mineralisation to plate-tectonic setting (e.g. Mitchell and Garson, 1976). This work included a literature survey which revealed references to several sulphide-bearing localities recorded during geological mapping and other activities. The results of the appraisal and recognition of the metallogenic potential of south-west Wales led to four surveys: (i) a reconnaissance drainage survey of the Preseli Hills (Cameron et al., 1984); (ii) an investigation of high-level intermediate intrusions in the Llandeloy area for porphyry-style copper mineralisation (Allen et al., 1985); (iii) an examination of the sedimentary and volcanic rocks of the Roch Rhyolite Group for indications of stratabound volcanogenic base-metal mineralisation (Brown et al., 1987); and (iv) a detailed low-level airborne geophysical survey of northern Pembrokeshire (Cornwell and Cave, 1986). Further information on the first three of these surveys is provided in the mineralisation section of this report.

The helicopter-borne geophysical survey was carried out over an area of 670 km^2 extending from St. David's to the Preseli Hills (Figure 3). Unfortunately, except for the north-west, the present survey area was not covered. Magnetic, VLF-EM and radiometric data were collected over rocks ranging in age from Precambrian to Carboniferous and some ground follow-up was undertaken. No features solely attributable to mineralisation were found, but interpretation of a number of features provided geological and structural information that could be useful when seeking a number of types of mineralisation (Cornwell and Cave, 1986).

Selection of the survey area

The area investigated was chosen from the records of gold grains seen in panned stream sediments collected by G-BASE field parties. These data, on open file and available from the BGS, show several features of interest, including:

(i) A group of sites around Llandeloy that might be related to porphyry-style copper mineralisation or copper-rich Tertiary or glacial deposits previously identified by the MRP (Allen, 1981; Allen et al., 1985).

(ii) An elongate east–west zone of sites extending 35 km from the coast at Druidston Haven to Whitland (Figure 1) to west of St. Clears, over the outcrop of Upper Ordovician to Lower Silurian sedimentary rocks. The zone is roughly parallel to and close to the Hercynian Front, and the Lower Palaeozoic rocks are at least locally tectonised with thrusts, tight folds and cross-cutting faults evident on maps.

(iii) Sites that may be associated with Lower Ordovician volcanic sequences and associated intrusions.

(iv) Sites to the south of the Variscan Front, on outcrops of Upper Palaeozoic rocks, including Coal Measures.

It was considered that, because of the large number of sites where gold was seen in the panned concentrates and the geological setting (see below), the occurrences over the Upper Ordovician and Lower Silurian rocks, i.e., case (ii) above, merited most attention. Consequently, the area outlined in Figure 1 was selected for more detailed investigation. A small amount of work (drainage and rock sampling) was also carried out peripheral to this area to provide additional information that would aid interpretation of the data collected. The occurrence of gold in the volcanic rocks was largely covered by the results of a lithogeochemical reconnaissance described in MRP Report 137 (Colman et al., 1995).

The gold occurrences over the Upper Ordovician and Lower Silurian rocks were selected for more detailed investigation because of similarities with slate-belt gold provinces, for example, well-described mineralisation in Victoria, Australia (Sandiford and Keays, 1985), at Banjas in the Valongo-Gondomar belt in northern Portugal (Gunn et al., 1995), or most closely relevant to south-west Wales, the Meguma slate terrane in Nova Scotia (Graves and Zentilli, 1982; Haynes, 1985; Kontak et al., 1990). In these areas, a Lower Palaeozoic succession of slates and greywackes, with or without volcanics, shows later deformation, metamorphism and intrusion of granitoids. The intrusions are thought to act largely as controls on deformation, not as sources for the mineralising fluids. The slate-belt-type gold deposits are found in a wide variety of host lithologies and structural settings, but genetic emphasis is put on faults cutting chemically favourable horizons and anticlines, both of which behave as zones for the transport and deposition of gold. The structural level of the sequence is also seen as an important control, with higher levels, and hence lower-grade metamorphism, being most prospective for disseminated mineralisation, and deeper structural levels favouring vein-hosted deposits. About 30 km to the north-east of the survey area, at Pumpsaint, a turbidite-hosted slate-belt-type gold deposit was worked intermittently from Roman times until 1938. In this deposit gold occurs disseminated in tightly folded and sheared, pyritic mudstones and in veins and saddle reefs (Annels and Burnham, 1986; Annels and Roberts, 1989).

Minerals planning and development framework

The principal survey area is free of major designated planning constraints. The Pembrokeshire Coast National Park lies to the north, west and south. Land use is dominated by mixed agriculture with small areas of woodland and rough grassland. There is little industry in this essentially rural area. Road and rail communications are good, the A40 trunk road and London to Fishguard railway line passing through the area (Figure 1).

GEOLOGY

The geological map of south-west Wales (Figure 2) shows the presence of rocks which range from late Precambrian (Neoproterozic) to late Carboniferous in age. Isolated pockets of possible Tertiary sediment predate glacial and post-glacial Quaternary drift deposits, which are distributed throughout the region. Although drift coverage is generally thin, exposure is poor and it is likely that the geology is more complex than that mapped. The pattern of outcrop of the solid strata reflects the complex geological history of the region and owes its form to several phases of subsidence and deposition, separated by episodes of deformation, uplift and erosion. The Lower Palaeozoic sequences principally relate, (i) to the rifting and northward drift of Avalonia, a microcraton derived from the contemporary supercontinent of Gondwana, (ii) to the progressive closure of the Iapetus ocean, and (iii) to the subsequent collision of

Avalonia with the northern continent of Laurentia. The last event caused the diachronous deformation known as the Caledonian Orogeny. The Upper Palaeozoic sequences reflect the various extensional and compressive events which attended the complex convergence of the enlarged Laurentian plate (Laurasia) with Gondwana and which culminated in the Variscan (or Hercynian) Orogeny in Europe. Mesozoic and Tertiary deposits are absent from the region, though they are preserved off-shore. Nevertheless, the major fractures which traverse the area may have moved during these intervals as they responded to regional stresses linked to the Alpine Orogeny in Europe and attendant to the opening of the Atlantic Ocean.

South-west Wales can be broadly divided into three, east−west trending, structural blocks: a Northern Block, a Southern Block and an intervening Central Block (Figure 2). In the Northern Block, predominantly deep-water late Ordovician and early Silurian sequences accumulated within the Lower Palaeozoic Welsh Basin. The north-east-trending folds and cleavage which pervasively affect these strata were imposed principally during the Caledonian Orogeny which, in Wales, reached its acme in the middle Devonian. In the Southern Block, terrestrial, deltaic and shallow marine facies of predominantly Devonian and Carboniferous age are disposed in a series of east-south-east-trending synclines and anticlines formed during the compressional culmination of the Variscan Orogeny, in late Silesian times. In the complex Central Block, severe faulting affecting volcanic strata and marine sediments of late Precambrian to Silurian age reflects a setting astride the rifted southern margin of the Welsh Basin. Caledonian cleavage fails southwards within this region and contemporary folds and faults swing into an east–west trend. In the south-east of the area, late Silurian to early Devonian red beds (Old Red Sandstone facies) overstep the earlier Lower Palaeozoic divisions. These, in turn, are overstepped by Carboniferous strata. The unconformity developed at the base of the Carboniferous between Pendine and St. Brides Bay serves as a convenient southern limit to the Central Block. This southern edge broadly coincides with the northern limits of intense Variscan deformation in Pembrokeshire, the so-called Variscan Front, though fractures throughout the region undoubtedly suffered substantial Variscan (and probably subsequent) reactivation. The areas of detailed investigation considered in this report are sited within this Central Block and it is principally the stratigraphy, structure and geological history of this region which are set out in greater detail below (Figure 4).

Precambrian

In the Central Block, Precambrian rocks outcrop in east Pembrokeshire and in Carmarthenshire. Precambrian inliers also occur in the Southern Block (Figure 2). The Precambrian rocks of the region are predominantly of igneous derivation and essentially unmetamorphosed, preserving many of their original textures.

The Pebidian Supergroup of east Pembrokeshire comprises a succession of acid to intermediate tuffs, lavas and tuffaceous sediments of late Precambrian age (Thomas and Jones, 1912; Williams, 1933; Shackleton, 1975; Davies and Bloxam, 1990) with subduction-related geochemical characteristics (Bevins et al., 1995). These are intruded by quartz porphyry and granophyric granite bodies (the 'Dimetian' of Hicks, 1877), including the St. David's Granite which has provided a radiometric date of 650–570 Ma (Patchett and Jocelyn, 1979; Bloxam and Dirk, 1988). Porphyry-type copper mineralisation is associated with at least one of the intrusions in the Llandeloy area, which Allen et al. (1985) suspected might be of Lower Palaeozoic (Cambrian) age. A number of later Precambrian dolerite dykes also cut the sequence.

The Llangynog inlier of Carmarthenshire, exposes the Coomb Volcanic Formation (Cantrill and Thomas, 1906; Cope and Bevins, 1993; Bevins et al., 1995), a succession of late Precambrian flow-banded and brecciated rhyolitic lavas, interbedded tuffs and volcaniclastic sediments, with doleritic and dacitic intrusions. An Ediacaran fauna has been obtained from the sediments (Cope, 1983). The formation has been tentatively correlated with the Pebidian rocks of north Pembrokeshire (Cope and Bevins, 1993).

In the Southern Block, the Precambrian comprises two groups of igneous rocks, which are locally strongly deformed within a complex thrust belt close to the northern margin of 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 (Thorpe, 1970, 1982; 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; Baker, 1982). Quartz-dolerite dykes also intrude the complex. The poorly exposed Benton Volcanic Group contains spherulitic and autobrecciated lavas of sodic rhyolite and trachyte, with subordinate red and green tuffs, resembling those of the Pebidian Supergroup (Strahan et al., 1914; Cantrill et al., 1916). They outcrop within a major Hercynian structure, the Johnston-Benton Thrust Zone (Duff and Smith, 1992).

It is difficult to interpret the relationships between the Precambrian igneous complexes of Pembrokeshire and Carmarthenshire (and elsewhere), due to the dislocated nature of their outcrops. A genetic relationship between the Pebidian volcanics and Dimetian intrusions is suggested by their compositional similarities (Baker, 1982), and it is possible that the Benton Volcanic Group is likewise related. Thorpe et al. (1984) suggested that these Na-rich, K-poor associations had island-arc affinities, and considered that the calc-alkaline Johnston intrusives were characteristic of volcanic arcs formed and accreted during late Precambrian subduction of the Iapetus oceanic lithosphere beneath Britain. Bevins et al. (1995) reached similar conclusions from more comprehensive data, suggesting that the geochemical data are consistent with the area being on the site of subduction-related igneous activity at the margins of Gondwana in the late Proterozoic.

Cambrian

The Cambrian succession of north Pembrokeshire flanks the faulted Precambrian inliers in the area around St. David’s and Treffgarne. It principally comprises a transgressive, deepening upwards, marine sequence which was deposited unconformably over eroded and weathered Precambrian igneous terrain. Cambrian deposition here and throughout Wales records a period of extension and subsidence which has been related to rifting precursive to the separation of the Avalonian microcraton from Gondwana.

The local Cambrian succession has been subdivided into three major groups which in total exceed 1600 m in thickness (Williams and Stead, 1982). In the Lower Cambrian (Comley Series) Caerfai Group, which correlates with the Welsh Hook Beds of Treffgarne, basal conglomerates containing pebbles derived from the earlier Precambrian strata, give way to a sequence of feldspathic and micaceous sandstones with subordinate purple mudstones. Sedimentary structures and trace fossils testify to shallow marine deposition.

Sandstone-dominated, purple and green, shallow marine facies persist in the succeeding Solva Group (Williams and Stead, 1982) though the proportion of intercalated siltstone and silty mudstone is greater. Conglomeratic levels in the lower and middle part of the group include igneous, metamorphic and sedimentary clasts. Bioturbated levels with *Skolithus* burrows and beds rich in sponge spicules are also present in the group, as are trilobites and acritarchs which indicate a possible Middle Cambrian (St. David’s Series) age (Rushton, 1974). In the upper part of the group, intercalated bioturbated sandstones and mudstones with rusty-weathering concretions mark an upward passage into the deeper water, turbiditic facies of the Menevian Group, also of Middle Cambrian age. In the latter, black, pyritic laminated hemipelagic mudstones, thinly interbedded with paler, turbiditic silty mudstones record anoxic accumulation during the acme of the Cambrian transgression. Thin, lenticular sandstones, associated with thin tuffaceous bands and phosphate nodule horizons, appear in the middle part of the group (Rushton, 1974). In the upper part, are massive coarse-grained, dark grey sandstone turbidites.

The informally named “Lingula Flags” and the equivalent Treffgarne Bridge Beds conformably overlie the Pembrokeshire Menevian sequence, but record a marked shallowing of the depositional environment in Upper Cambrian (Merioneth Series) times. Siliceous and feldspathic siltstone beds are thinly interbedded with greenish grey micaceous shaly mudstones, and locally with beds of coarse and conglomeratic sandstone. Coquinas of *Lingulella davisii* are common at several horizons. A range of sedimentary structures suggests that the sequence was derived from the south (Crimes, 1969) and relates to the reactivation basin-margin faults.

The Cambrian succession of the Llangynog area (Cope and Rushton, 1992), although much faulted, unconformably overlies Precambrian volcanic rocks. The Lower Cambrian Allt y Shed Sandstone comprises shallow marine, quartzose siltstones and sandstones, with a basal conglomerate similar to that of the St. David’s area. The base of a younger, Upper Cambrian sequence is either unconformable or faulted. Based on both faunal and lithological criteria, these strata have been assigned, in ascending order, to the Treffgarne Bridge Beds (see above), and to the Ffestiniog Flags and Dolgellau formations (Cope and Rushton, 1992). Together these divisions define a fining-upwards sequence. Storm-sheet sandstones present in the Ffestiniog Flags are absent from the Dolgellau Formation, which marked a return to deeper-water, largely hemipelagic, dark-mudstone deposition.

Ordovician

The Ordovician period saw major changes in the tectonosedimentary regime operating in south-west Wales coincident with the onset of volcanism throughout the principality. The earlier rifting regime gave way to one consequent southerly-directed subduction and marginal basin development at the northern edge of the Avalonian microcraton (Kokelaar et al., 1984; Traynor, 1988). The tectonic evolution is charted by the changing chemistry of local volcanism. Thus, the andesitic lavas of the local Treffgarne centre (Treffgarne Volcanic Formation), believed to be of Tremadoc age and comparable and contemporary with those of Rhobell Fawr in North Wales (Bevins et al., 1984), record an episode of subduction-related, island-arc volcanism (Kokelaar, 1988). Intermediate volcanism in Pembrokeshire persisted into the Arenig (Llandeloy Ashes), though local acidic eruptions (Roch Rhyolite Group) may also have occurred during this interval (Brown et al., 1987; Colman et al., 1995). Subsequently, in the Llanvirn, large volumes of lavas, volcanic breccias and tuffs, of both acidic and basic composition, were erupted from a series of related centres in northern Pembrokeshire. Their products comprise the Sealyham and Fishguard volcanic groups and the Llanrian Volcanic Formation (e.g. Bevins et al., 1989, 1992; British Geological Survey, 1992). The onset of such bimodal volcanism, here and at contemporary centres in both North Wales and the Welsh Borders, signalled the transition from an arc setting into a back-arc, marginal basin (Kokelaar et al., 1984; Kokelaar, 1988). Ridge-trench collision during the late Caradoc brought Ordovician volcanism in Wales to a close and sedimentation was subsequently influenced by oceanographic and sea-level changes attendant to the contemporary glaciation of Gondwana (Brenchley, 1988). The geochemistry and mineral potential of the various Ordovician volcanic sequences in south-west Wales have been assessed in detailed by Colman et al. (1995), and references therein, and need not be repeated here.

Dated Tremadoc sediments within the area are only known in the Llangynog Inlier, where Cope and Rushton (1992) report fossiliferous siltstones and shales which disconformably overlie the local Cambrian succession. Elsewhere, a varied sequence of Arenig littoral and shoreface sandstones and mudstones, known as the Ogof Hen Formation in west Pembrokeshire and the Blaencediw Formation in the Carmarthen area, overstep on to the local Cambrian successions of the region (Fortey and Owens, 1987; Traynor, 1988). Succeeding deeper water, locally turbiditic Arenig facies, strata previously known as the *Tetragraptus* Beds or Shales (e.g. Strahan et al., 1914), are represented by the Penmaen Dewi Shale Formation of Pembrokeshire. Equivalent strata further east are represented by the Afon Ffinnant Formation of Fortey and Owens (1987). Pale mudstones containing trilobites of late Arenig and early Llanvirn age comprise the Llanfallteg Formation, and record local shallowing in the Carmarthen region.

The black, graptolitic, Llanvirn mudstones of the *Didymograptus bifidus* Beds are of deeper-water aspect, but also yield a varied assemblage of trilobites and include tuffaceous levels (Strahan et al., 1909, 1914) which are related to the Fishguard Volcanic Group (Kokelaar et al., 1984). In west Pembrokeshire, equivalent strata have been renamed the Aber Mawr Shale Formation (British Geological Survey, 1992). The late Llanvirn *Didymograptus murchisoni* Beds of north Pembrokeshire and the Carmarthen district are absent from the Haverfordwest area, where limestones and calcareous mudstones of Llandeilo and Caradoc age, in part equivalent to the Mydrim Limestone, are disconformable. Calcareous facies are widespread at this general level and may record a period of marine regression. The succeeding Mydrim (or *Dicranograptus*) Shales marked a resumption of black, pyritic and graptolitic mudstone deposition, much of it hemipelagic in character, which continued throughout the remainder of the Caradoc. Zalasiewicz et al. (1994) have suggested that low-diversity graptolite assemblages from the upper parts of this sequence, near Whitland, reflect the onset of a shallowing and/or cooling event. They also question whether the succeeding early Ashgill (Cautleyan) shelly limestones, variously known as the Shoalshook Limestone and Robeston Wathen Limestone, are disconformable despite evidence of a faunal hiatus. Irregular, iron-impregnated tops to the lowest limestone beds provide the only evidence of sedimentary omission within an otherwise gradational passage.

The younger Ashgill Slade and Redhill Beds, though depicted as a single stratigraphical division on the BGS 1: 50 000 geological maps of the region, were originally defined as two distinct units by Marr and Roberts (1885). The Slade Beds appear to succeed Redhill Beds facies in their type area near Haverfordwest, but to pass laterally into them northwards (Strahan et al., 1909). In the Redhill Beds, sharp-based sandstones with basal shell lags and bioturbated tops, interbedded with grey, silty mudstones, represent storm-event beds deposited in a distal shelf setting. In the more proximal Slade Beds, the frequency and thickness of these beds is greater and the associated mudstones are more fossiliferous. Thus, the distribution of the two facies appears to reflect a shoaling upwards and northward prograding sequence. Overlying strata, a sequence of dark mudstones with thick conglomerates and a quartzitic sandstone unit (the Cethings Sandstone), though depicted on the published maps as basal Llandovery and grouped together in the contemporary memoir as Basement Beds (Strahan et al., 1914), are now known to be of Ashgill age, since shelly mudstones which overlie them (the St. Martin's Cemetery Beds), contain a Hirnantian fauna (Ingham and Wright, 1970). Collectively, these reassigned strata record facies changes attendant to the major, late Ashgill, glacio-eustatic regression (Brenchley, 1988). The overlying Cartlett Beds, a succession of poorly fossiliferous mudstones now known to span the Ordovician (Hirnantian) − Silurian (Rhuddanian) boundary (Cocks, 1968), were deposited during the subsequent world-wide post-glacial transgression.

Silurian and Devonian

The Silurian sequences of the Central Block are seen principally in the Haverfordwest district (Strahan et al., 1914). In common with the preceding Ashgill, early Llandovery sedimentation within the Welsh Basin and across its margins was principally influenced by widely recognised movements in contemporary sea-level. From late Llandovery (Telychian) times onwards, these eustatic controls were being over-ridden by tectonic events related to the closure of Iapetus and the progressive collision of Avalonia with Laurentia (Soper and Woodcock, 1990).

The Cartlett Beds (see above) and the succeeding, more fossiliferous, bioturbated and sandy Gasworks Mudstones together comprise the Haverford Mudstone Formation of Cocks and Price (1975). They represent a coarsening-upwards sequence of Rhuddanian marine shelf facies. Deposition of the succeeding Gasworks Sandstone, of Aeronian age, equates with a widely acknowledged marine regression (Davies et al., 1997). Green and locally maroon-coloured mudstones characterise much of the Telychian Uzmaston Beds. The entry of coarser terrigenous detritus, as evidenced by a sandy and pebbly middle division, may equate with the introduction and expansion of collision-zone-derived sandy turbidite facies in the basin centre further north (Davies et al., 1997). The darker, possibly disconformable mudstones of the Caniston Beds are also thought to be of Telychian age. The Uzmaston and Caniston beds together comprise the Millin Mudstone Formation of Cocks and Price (1975).

Marine shelf, sandstone facies of Wenlock age are preserved in inliers in the Southern Block, but in the Central Block these have been overstepped by facies of the Old Red Sandstone. Whether the latter is in part Ludlow, or ranges from Pridoli to Devonian in age is debated (Cocks et al., 1971). In the Green Basal Beds (Strahan et al., 1914), the mudstones which succeed a locally developed basal conglomerate, include separate levels with *Lingula* and with calcrete, and record deposition on a frequently submerged coastal plain. The succeeding Red Marls, equivalent in part to the Raglan Marls and St. Maughan's Group of other areas (Allen, 1977), with common calcretes and some channel sandbodies, point to deposition in a more fully terrestrial river-flood-plain setting, though trace fossil assemblages preserved beneath volcanic-tuff marker beds suggest that quasi-marine conditions were, at times, re-established (Allen and Williams, 1981). Approaching a kilometre in thickness in the Central Block, the accumulation of this largely Lower Devonian red-bed sequence marked a period of pronounced subsidence affecting the earlier basin margin. South-west Wales, during this interval, can be viewed as part of a developing foreland basin receiving distal post-orogenic molasse sourced from the recently formed and still rising Caledonian uplands of northern Britain (King, 1994).

A conformable contact between Upper Devonian Old Red Sandstone fluvial facies (Skrinkle Sandstone) and transgressive Dinantian marine mudstones and limestones (Lower Limestone Shales), in the south of the southern Block, contrasts with the strongly overstepping and onlapping relationship of the Dinantian succession along the southern margin of the Central Block. Here neither Middle nor Upper Devonian facies are preserved (Allen, 1977). The two areas clearly lay either side of an important structural divide which is manifest today as the Ritec Fault and its attendant fractures. Variations in Lower and Middle Devonian facies on either side of this structure point to contemporary and periodic reversals of movements throughout this period (Williams et al., 1982), but the net effect of Upper Devonian activity was to promote subsidence and preservation to the south, in contrast to uplift and deep erosion to the north.

Carboniferous

Sedimentation in the region resumed during the Lower Carboniferous (Dinantian), prompted by a major marine transgression and associated with Variscan extension of the British Isles (Leeder, 1988). Aside from basal and capping mudstone-rich divisions, the Lower and Upper Limestone Shales respectively, the disconformable and onlapping Dinantian sequence is composed predominantly of shallow-marine limestones of oolitic and shelly varieties. Internal non-sequences are revealed by karstic and pedogenic features and coincide with faunal hiatuses (George et al., 1976).

Variscan earth movements, possibly related to strike-slip displacements on pre-existing basement fractures, were responsible for localised uplift and erosion in South Wales during the late Dinantian and early Silesian (Kelling, 1974; Wilson et al., 1988), and these are evidenced in this area by the progressive westward overstep of Dinantian divisions by Namurian strata (Strahan et al., 1914). Early Namurian ammonoid- and bivalve-bearing marine and coastal siliciclastic facies, sourced from still emergent Caledonian uplands to the north (St. George's Land), were over-ridden and incised by late Namurian, fluvial sandstones (Farewell Rock), also of northerly derivation. During the Westphalian, these gave way to the southerly supplied Coal Measure deltaic facies of the Pembrokeshire Coalfield.

Intrusive igneous rocks

Aside from those associated with the Precambrian inliers of the region (see above), intrusive igneous bodies are principally confined to the Preseli Hills, in the northern part of the Central Block. A series of dolerite sills are emplaced into Ordovician strata of Arenig and Llanvirn age (Evans, 1945). They probably relate to the eruption of the Fishguard Volcanic Group, into the lower part of which the thickest and most extensive dolerite bodies where intruded (Bevins et al., 1989). Coeval dolerites, as well as diorites, micrograrites and microtonalites, intrude higher levels of the group. The gabbroic intrusions of Carn Llidi and St. David's Head have also been linked to this volcanic episode (Bevins and Roach, 1982).

A quartz-dolerite dyke some 40 km in length and 15 m in width has been traced from near Mathry to Llanboidy, largely from detailed airborne magnetic survey data (Cave et al., 1989). It runs across the northern part of the survey area in an east-south-easterly direction from south of Maenclochog to north of Login. The dyke cuts across the strike of the Caledonian host rocks but is parallel to the line of the Hercynian Front to the south. It is probably Carboniferous in age.

Structure

The principal structural features of the survey area are shown in Figure 4. The complex outcrop patterns of Lower Palaeozoic formations principally reflect the affects of Caledonian folding and faulting. The folds affecting these rocks comprise a series of major, east-west-trending, periclinal, asymmetric anticlines and synclines with steep, northerly dipping axial planes. The periclines plunge both eastward and westward by up to 12°; their amplitudes range from 1.8 to 2.8 km. Coaxial mesoscale folds, with amplitudes of between 0.5 and 1 km, affect the limbs of these major structures, and still smaller-scale folding is widely observed. Within the anastomosing pattern of faults which affect the Lower Palaeozoic succession, steep, northward-dipping, reverse faults predominate, with southerly downthrows of up to 760 m reported for individual faults (Strahan et al., 1914). Though on a local level the pattern of fracturing appears complex, regionally the faults can be viewed as elements of an east—west belt of dislocation broadly co-linear with the folds of the area. It seems clear that both the folds and the faults were the synchronous products of the same compressive event; their overstep by Old Red Sandstone facies of Pridoli age pointing to an intra-Silurian, possibly Ludlow deformation.

The effects of Devonian faulting in south Pembrokeshire, along the line of the Retic Fault and its contiguous fractures (see above), are not obviously reflected by displacements on parallel fractures further north. In contrast, off-sets of Caledonian fold axes and faults across the sinuous west-south-west-trending Develidge Disturbance and the contiguous Eastern Cleddau Disturbance are cited as evidence for a sinistral strike-slip displacement which post-dated the deposition of the Lower Old Red Sandstone (Strahan et al., 1914). However, dextral shifts in the base of the Old Red Sandstone and overlying Carboniferous sequences demonstrate a subsequent, probably late Carboniferous, reversal of movement along this fracture belt.

Pervasive deformation related to the Variscan Orogeny, principally folding and northward-directed thrusting, is confined to south Pembrokeshire and to the Carboniferous rocks of the Pembrokeshire Coalfield (Hancock et al., 1981). Further north, beyond the Variscan Front, 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 such late Carboniferous movements cannot separately be distinguished, but where these earlier fractures underlie Upper Palaeozoic formations their Variscan activity is manifest as narrow fold and fracture belts affecting these younger strata. Such belts include the Red Roses Disturbance (5 km south of Whitland), and the Eastern Cleddau Disturbance and the Haverfordwest Disturbance (Figure 4).

Tertiary and Quaternary

Deposits of white clay with subordinate quartz gravels recorded at Flimston in south Pembrokeshire are thought to be of Tertiary (Palaeogene or early Miocene) age (Dixon, 1921; George, 1974). They are preserved within a solution hollow or pipe developed in the local Carboniferous limestones. Drilling in the Llandeloy area (Allen et al., 1985) revealed a locally thick (over 20 m) sequence of well-bedded feldspathic sands and white clays which Allen (1981) suggested might also be of Tertiary age.

The Quaternary deposits of south-west Wales, principally of glacial or periglacial origin, relate to at least two periods of ice-sheet advance. Much of the region lay beyond the limits of the most recent, Devensian glaciation and here degraded drift deposits and landforms date from one or more earlier glacial episodes, possibly the widespread Anglian and earlier glaciations (Campbell and Bowen, 1989). During the earlier ice advances, as well as during the Devensian, much of the area was unaffected by land-based Welsh ice sheets; instead, it formed part of a tract of country which was over-ridden by ice masses which had advanced southwards via the Irish Sea basin. Within the region of interest of this report, the residual deposits of these early Irish Sea ice sheets are more prevalent in the north, where patches of till (boulder clay) are subordinate to spreads of glacial sand and gravel. Amongst the assemblage of glacial erratics reported from the Haverfordwest district, dolerites from the Preseli Hills and gabbros from St. David’s Head are common, but far-travelled boulders of several different Scottish granites are also represented (Strahan et al., 1914). Thick regrowth profiles are a ubiquitous feature of the areas of rock outcrop and testify to protracted periglaciation and weathering consistent with a setting which escaped Devensian glacial scour.

Only in the northern and westernmost parts of Pembrokeshire and in the Carmarthen area, where areas of Devensian till and sand and gravel are preserved, were the products of the earlier glaciations destroyed or reworked during the last period of ice advance. Raised beach deposits, locally preserved along the coast and estuaries of south-west Wales (Strahan et al., 1914; Dixon, 1921), predate widespread Devensian periglacial deposits (head) (Bowen, 1974; Campbell and Bowen, 1989). These littoral facies record deposition during the sea-level highstand of a preceding interglacial episode and are conventionally regarded as Ipswichian.

Extensive post-glacial deposits are principally confined to the alluvial tracts of the main river valleys.

MINERALISATION

Wales has long been considered a metalliferous province in both base and precious metals, but few metalliferous occurrences are recorded in the survey area and none have been worked. Peripheral to the survey area there are a number of old trials and workings for metalliferous mineralisation. Those to the west of Carmarthen are listed in Table 1 and their location shown on Figure 3. All the trials and workings exploited vein-style mineralisation, most in rocks of Precambrian to Ordovician age. The largest workings were the Llanfyrnach and Carmarthen United mines. Galena, extracted for lead and silver, was the only economic product of note, although small amounts of zinc (sphalerite) and copper (chalcopyrite) ore were also produced.

Table 1 Trials and workings for metalliferous minerals in south-west Wales (west of grid line 240000)

Name	Grid Reference	Metals	References
1. Carmarthen United (Santa Clara, Trelach)	2263 2282	Pb	Hall, 1971; Foster-Smith, 1981
2. Castell Gorwyn	2312 2257	?Pb	Hall, 1971; Foster-Smith, 1981
3. Dale	Uncertain	Cu	Hall, 1971
4. Fron-Las	2166 2340	Cu, Au?	Hall, 1971; Foster-Smith, 1981
5. Fron-Lwyd	2178 2339	Pb, Cu	Hall, 1971; Foster-Smith, 1981
6. Linney Head	1883 1960	Pb	Foster-Smith, 1981
7. Llanfern-nant-gwyn	Uncertain	?	Hall, 1971
8. Llanfyrnach	2225 2317	Pb, Ag	Hall, 1971; Foster-Smith, 1981
9. Llanglydwen (Minefields)	2175 2268	?	Hall, 1971; Foster-Smith, 1981
10. Llwyn-yr-Hwrdd	2225 2324	Pb	Foster-Smith, 1981
11. Llwyncelyn	2232 2314	Pb	Hall, 1971; Foster-Smith, 1981
12. Minwear	2040 2130	Au	Hall, 1971
13. Mydrim (Gellywen)	2278 2237	Cu, Pb	Hall, 1971; Foster-Smith, 1981
14. Nant-y-Cerni	2335 2284	?	Hall, 1971
15. Nant-y-Garreg	2369 2365	?Pb	Hall, 1971; Foster-Smith, 1981
16. Pont-y-gafel	2192 2300	?	Hall, 1971
17. Ramsey Head	1715 2235	Cu	Hall, 1971; Foster-Smith, 1981
18. Rose Hill	2180 2264	Pb	Hall, 1971; Foster-Smith, 1981
19. St. Elvis	1813 2231	Pb	Hall, 1971; Foster-Smith, 1981
20. Treffgarne	1961 2236	Au, Cu	Davies, 1948

Numbers refer to the locations shown on Figure 3.

Three historical records of gold discoveries are known from south-west Wales. Firstly, at Treffgarne (Table 1, No. 20) trials for gold are said to have been dug in the gorge and, when the railway was constructed here, a gold-bearing vein is said to have been cut (Davies, 1948). These reports could be dismissed, as no subsequent working on a vein is known to have taken place. However, the hydrothermally altered and veined volcanic rocks of the Roch Rhyolite Group that form the most precipitate part of the gorge represent a favourable host, and recent MRP work indicated some gold potential (see below). The second record is a reference to unsuccessful trials for gold at Minwear

(Table 1, No. 12), but Hall (1971) noted that this may be solely the result of a corruption of the place name. Lastly, there is a record of visible gold in a lode cut in the south level of the trials at Fron-las in 1865 (Table 1, No. 4).

Two features of mineralisation in the Welsh basin to the east of Carmarthen are worthy of note here: the occurrence of baryte near Carmarthen and the presence of typical slate-belt-type gold mineralisation at Ogofau near Pumpsaint, about 30 km to the north-east of the survey area.

Baryte mineralisation, which is relatively rare in Wales and whose distribution is not clearly understood, occurs in a number of veins in an area two miles to the east of Carmarthen. The veins occur within the Ordovician mudstone to sandstone succession of the Welsh Basin and were tried or worked at a number of sites, notably the Vale of Towy and Cystanog mines (Strahan et al., 1909). Besides baryte, lead (galena, pyromorphite) and zinc (sphalerite) minerals are present in the veins, and all three commodities were extracted for profit during the eighteenth and nineteenth centuries. Other minerals recorded include quartz, calcite, pyrite, chalcopyrite and chalybite. Details of the workings are given by Hall (1971).

Gold mineralisation at Ogofau has been exploited intermittently since pre-Roman times, with the last mining taking place in 1939. The mine workings, also known as Roman Deep or Pumpsaint, and their history are described by Hall (1971) and Annels and Burnham (1986). A modern account of the mineralisation is provided by Annels and Roberts (1989). Production records are poor, but one estimate placed the gold extracted as high as 1 million ounces from half a million tonnes of ore. This appears optimistic, particularly with respect to grade, and perhaps a tenth of the gold figure is more likely.

The gold mineralisation at Ogofau is typical turbidite-hosted, slate-belt type. It is hosted by mudrock-dominated turbidite deposits laid down near the southern margin of the Lower Palaeozoic Welsh Basin during the Upper Ordovician and earliest Silurian. The sedimentary succession was deformed into a series of asymmetrical, commonly overturned, tight south-east-facing folds with associated cleavage during the Caledonian orogeny. Reverse dip-slip faulting associated with the steeper or overturned fold limbs accompanied folding, and later tensional faults are also present. Metamorphism locally reached lower greenchist facies. Hydrothermal alteration is closely associated with thrusting, and mineralisation is clearly controlled locally by the Caledonian structures and host-rocks. Regional-scale controls are less obvious, but the stratigraphic level, deep-seated structures, including step-like basin-margin feature, and unseen igneous activity have all been suggested as influential. Gold occurs at a number of locations, principally in (i) folded and sheared pyritic shales, (ii) a flat-lying auriferous quartz reef termed the Roman lode, (iii) quartz-carbonate stringer veins in the footwall to the Roman lode, (iv) veins associated with shear zones, and (v) planar quartz veins associated with up-dip axis of the Roman lode. The mineralogy is relatively simple with, besides gold, arsenopyrite, pyrite, ankeritic carbonate, hydromuscovite, cookeite (lithium silicate), quartz, argentiferous galena, chalcopyrite and sphalerite. Several of these are considered to be mainly the product of late-stage events accompanying high-angle reverse and normal faulting. Gold generally occurs locked in sulphide grains and reaches its highest concentration in mudstones containing sulphides. Fluid-inclusion studies indicate a mineralisation temperature of 345–450°C coincident with the principal Caledonian deformation, placed at c. 400 Ma.

Work by the MRP has found evidence of gold and base-metal mineralisation in south-west Wales close to the survey area. In the Middle Mill and Llandeloy areas (Figure 3), geophysical and geochemical surveys followed by drilling identified porphyry-style copper mineralisation near Treffynnon. The mineralisation is associated with intermediate sheeted (tonalitic and dioritic) intrusions of possible late Cambrian age completely concealed by Tertiary to recent deposits up to 20 m thick and locally enriched in copper (Allen at al., 1985). Pervasive hydrothermal alteration of the intrusives over an area of at least 1 km^2, with patchy low-grade copper mineralisation reaching a maximum of 0.1% Cu over 3.4 m, was recorded in boreholes. The style of alteration (polyphase propylitic and locally potassic) and mineralisation is consistent with the deeper levels of a porphyry-copper system.

Gold was not determined at the time of the original investigations at Llandeloy, but subsequently 15 samples taken from six of the boreholes were analysed for gold and silver. These samples, all taken from the more highly altered and mineralised sections and containing 47–3515 ppm Cu, revealed a pervasive low-level enrichment in Au (range 5–139 ppb) and one sample containing 649 ppb Au. Overall, there is a rough positive correlation between the Au and Cu contents, except that the core section containing the highest concentration of Cu (3515 ppm) only contains a trace of Au (24 ppb). Silver concentrations are low in all samples (0.6–1.7 ppm) but a correlation with the Au content is evident at higher levels. These results, indicating that the porphyry-type mineralisation at Llandeloy is gold-bearing, extends the list of similarities with the more widely known Coed y Brenin deposit (Rice and Sharp, 1976).

A reconnaissance stream-sediment survey of 350 km^2 of the Preseli Hills by the MRP covered the main outcrop of the Fishguard Volcanic Group and peripheral Ordovician black shales and mudstones. The results provided some evidence of sulphide mineralisation but only recorded gold in panned concentrates from two sites (Cameron et al., 1984). A single grain, accompanied by pyrite and metallic contaminants, was seen in the pan taken from a stream between Carn Slanney and Mynydd Dinas [19972 13763] and another grain was seen in a sample collected from a stream near Pentre Ifan [20983 23705]. In both cases the catchments consisted of Fishguard Volcanic Group acid lavas and tuffs and dolerite intrusions. The report describing this work concluded that there was some potential for gold and base-metal mineralisation associated with the Fishguard Volcanic Group and overlying *D. Murchisoni* mudstones (Cameron et al., 1984). There was also some evidence of metal enrichments associated with the Hendre and *Dicranograptus* shales, mudrocks of Ordovician (Llandeilo–Caradoc) age.

Descriptions of abundant pyrite and traces of copper in the Nant-y-Coy Formation (Roch Rhyolite Group) around Treffgarne (Thomas and Cox, 1924) led to reconnaissance geochemical and geophysical studies of the area. Strong IP chargeability anomalies, accompanied by weak geochemical anomalies in overburden, were found and used to site three boreholes. These revealed extensive hydrothermal alteration and strong pyrite mineralisation with some baryte (up to 3.9% Ba over 4.5 m) in volcanic rocks and mudstones, but no significant base-metal mineralisation was encountered. It was concluded that the locally highly altered rocks with thrust-faulted boundaries are probably of early Ordovician age, and not Precambrian as suggested by earlier work. Alteration and mineralisation is consistent with an exhalative volcanogenic model, but the potential for volcanogenic massive-sulphide mineralisation may be limited by the probable magma source. Gold was recorded in a few of the samples analysed and it was concluded that there is some potential for epithermal gold mineralisation associated with the hydrothermal activity (Brown et al., 1987; Colman et al., 1995). A reconnaissance survey of other volcanic rocks in south-west Wales carried out in concert with this work suggested that, besides the Roch Rhyolite Group, the Sealyham Volcanic Group, had the greatest mineral potential (Colman et al., 1995).

ROCK GEOCHEMISTRY

Exposure is poor across the survey area, except for new road sections such as the A40 road cutting west of Whitland [2216 2217], quarries and a few stream sections. Unfortunately many small quarry exposures described in the Haverfordwest memoir (Strahan et al., 1914) have been filled, but several new small quarries in ‘rab’ (shales of the Slade and Redhill Beds) have since been dug by farmers for use on farm tracks. Most streams in the south of the area are of low energy and fail to cut bedrock.

To establish baseline levels of element concentrations in the rocks of the area and aid interpretation of the drainage data, rock samples were taken for analysis from key sections of all lithologies. Geological descriptions of these sections are given in Appendix 1 and include some from outside the confines of the survey area due to the lack of suitable exposures within it.

Samples of any altered and mineralised rocks encountered during drainage sampling, including some stream clasts, were also collected to determine whether any metal enrichments were present and help to clarify the source of drainage anomalies. A total of 92 rock samples were collected.

Sample preparation and analysis

Rock samples were jaw crushed, the entire sample mixer milled and then sub-samples taken for chemical analysis.

Gold was determined on a 20 g sub-sample by graphite-furnace atomic absorption spectrophotometry (GF-AAS) following aqua regia digestion and MIBK extraction at Acme Analytical Laboratories Ltd, Vancouver (AALL). Another 12 g sub-sample of each rock powder was mixed with elvacite binder and ball-milled prior to pelletising and analysis by X-ray Fluorescence Spectrometry (XRFS) at the BGS Laboratories, Keyworth (BGSL): Mn, Fe, Cr, Ba, Cu, Zn, As, Mo, Pb, Bi and Sb were determined on most samples, and additionally Mo, Sn, Ag, Cd, Ca, Co, Ni, Ti and Zr on some. Another sub-sample was analysed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for 30 or 35 elements at AALL, following digestion in 3-1-2 HCl-HNO_3-H_2O at 95°C for one hour. The leach is partial for Mn, Fe, Sr, Ca, P, La, Cr, Mg, Ba, Ti, B and W and limited for Na, K and Al. Other elements determined were Ga, Tl, Se, Te, Hg, Mo, Cu, Pb, Zn, Ag, Ni, Co, As, U, Th, Cd, Sb, Bi and V. A number of duplicate and standard analyses were completed for quality-control purposes.

Results

Except for *Dicranograptus* Shales, the number of samples of unaltered individual lithologies collected is small, but the median values of the analyses of each group provide a good indication of background levels of metallic elements in these rocks (Table 2). Summary statistical data for the *Dicranograptus* Shales is given in Table 3.

The median values illustrate a number of features, notably the enrichment of Ba in mudrocks, particularly from the Llandeilo and *Dicranograptus* shales, and the general enrichment of metals in the *Dicranograptus* Shales. These contain the highest levels recorded in any of the rocks samples for several elements including Ag, As, Ba, Cu, Hg, Mo, Ni and U. There is, however, no enrichment of Au evident in the mudstones. The only rocks which show any significant Au enrichment are the coarse clastic Ashgillian deposits (see below).

Mineralised samples

The *Dicranograptus* Shales exposure at Druidston Haven (Figure 1) contains visible mineralisation and some of the highest base-metal values. A sample of massive pyrite from this locality (PWR4 [18610 11729]) is enriched in As (120 ppm), Cu (345 ppm), Pb (93 ppm), Ag (500 ppb) and Zn (186 ppm). Another sample of intensely veined black shale with lenses of pyrite (PWR23 [18606 21732]) has similarly high values (195 ppm As, 243 ppm Cu, 200 ppm Pb, 1400 ppb Ag). Some other samples of mudstone and siltstone with metal enrichment were collected during the follow-up of drainage anomalies, and these are described with the drainage anomalies.

Table 2 Median values for the metal content of rock samples classified by lithology and age

Group	No.	Au	Ag	As	Hg	Cu	Pb	Zn	Ba	Sn
Arenig shales	5	<1	n.a.	<5	n.a.	17	14	49	162	<5
Llandeilo limestone	3	4	<30	<5	10	4	4	11	122	<5
Llandeilo shales	3	3	300	15	n.a.	21	13	87	3122	n.a.
Ashgill conglomerate	3	3	n.a.	<5	n.a.	8	11	31	196	<5
Ashgill grits	2	10.5	51.5	11	n.a.	10	7	24	139	<5
Ashgill sandstones	5	4	<30	6	13	9	7	35	122	<5
Ashgill siltstone	5	1	<30	12	<5	9	12	47	630	<5
Llandovery shale	2	3	<30	n.a.	<5	14	12.5	39	187	<5

Ag and Hg analysed by ICP; Au by GF-AAS; remaining elements by XRFS.
Au, Ag and Hg values in ppb; remaining elements in ppm.
n.a.: not analysed.

Table 3 Summary statistics for the metal content of 25 samples of *Dicranograptus* Shales

	Mo	Ag	Hg	Au	Cu	Zn	As	Pb	Sn	Ba
Mean	8.6	145	57	2.8	38	53	30.6	22.7	<5	2384
Median	7	57	23	3	25	51	14	18	<5	1396
Minimum	0.6	<30	11	<1	<3	3	<5	<2	<5	154
Maximum	33.6	1400	340	7	243	104	195	200	<5	12789

Mo, Ag and Hg analysed by ICP; Au by GF-AAS; remaining elements by XRFS.
Au, Ag and Hg values in ppb; remaining elements in ppm.

The two samples with the highest levels of Au in rock are both gritstone stream clasts probably derived from the coarse sandstone or conglomerate at the top of the Slade and Redhill Beds, close to the Ashgill–Llandovery boundary. One (PWR1506) was collected from a north flowing tributary of Church Hill Brook [20268 21944] and the other (PWR12) from an easterly flowing tributary of the Afon Marlais near Pan-teg [21610 21635] (see drainage geochemistry section). Levels of gold are low (14 and 20 ppb respectively), but higher than in any other rocks and suggest that the coarser detrital sedimentary rocks may represent a source.

SATELLITE IMAGERY

A Landsat Thematic Mapper (TM) image of the area west of easting 250000 was analysed, principally to look for indications of fractures that might have controlled the occurrence of gold mineralisation.

Features, mainly linears, were abstracted, and classified into three groups according to their probable origin: (i) those related to the geological strike (bedding and cleavage); (ii) those which may be fracture controlled, normally cross-cutting the strike, and (iii) those related to superficial deposits. The principal linears in groups (i) and (ii), omitting short strike-related lines, are shown in conjunction with geophysical linears against a geological background for the project area in Figure 5.

In northern Pembrokeshire the image shows relatively few features, partly due to the cover of superficial deposits, partly due to the massive nature of some of the rocks, notably the igneous rocks of the Preseli Hills, and partly due to the sun angle. The extent of drift coverage can be estimated by the texture of the geomorphology and the depth of incision of the post-glacial drainage. This correlates with the extent of the Devensian glaciation determined from ground observations. Glacial outwash channels are particularly well defined.

Features related to the geological strike trace out the main Caledonian and Variscan structure of the region and are particularly clear in the south and south-east, where major and minor east-trending features are prominent.

Four principal directions cross-cutting the regional trend are evident, north-east, north-north-east, north-north-west and north-west. Perhaps significantly, these cross-cutting linears are well seen in the area to the north of a line between Carmarthen and Narberth, in part coincident with the area containing many of the gold-bearing drainage sites. North to north-east features are dominant and these may be related to joint sets within the Lower Palaeozoic lithologies preferentially eroded by glacial melt water, and later drainage systems. There are few north-westerly trending features evident in the main survey area (Figure 5), most occurring in the north of the south-west Wales region.

The data suggest that the Narberth–Carmarthen area may provide suitable dilational zones for the transport and deposition of metals in hydrothermal fluids, thereby increasing its potential for gold mineralisation as, according to some models, late-stage brittle faulting is integral to the transport and deposition of gold. Their relationship to geophysical features is described below.

REGIONAL GEOPHYSICS

Regional gravity and aeromagnetic data have frequently proved of use in understanding the distribution of gold-producing areas, notably by defining large-scale lineaments (e.g. Whitaker, 1992) or by locating mineralised granitoids (e.g. Leaman, 1992). The south-west Wales area has been covered by BGS regional gravity and aeromagnetic surveys and the digital data are available from BGS databases.

Sources of regional geophysical data

The aeromagnetic data were acquired in 1960 at a mean terrain clearance of 305 m along north–south flight lines 2 km apart. The north-western part of the area was covered by a detailed, low-level helicopter survey (the south-west Dyfed survey) as part of the MRP programme in 1978, and digital data were recorded along 250 m spaced flight lines using magnetic, VLF-EM and radiometric instrumentation (Cornwell and Cave, 1986). The regional gravity data coverage for the area has an average station density of about 1 per 1.3 km^2. Physical property data were acquired during previous MRP studies in South Wales, most recently during the work reported in Colman et al. (1995).

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

Regional geophysical anomalies

The aeromagnetic map of south-west Wales is dominated by a series of east-north-east-trending highs, which appear to be truncated to the south by the Variscan Front (Figure 6). Their source is unknown but their interpreted depths indicate that Precambrian rocks are responsible. This interpretation is supported by the existence of more local anomalies over the exposed Precambrian rocks of the St. David's and Hayscastle anticlines, where the volcanic rocks provide the main magnetic sources. The east-north-east-trend of all these major anomalies represent a continuation of the Caledonian trend observed in central Wales, although the near surface geological strike has a more east–west trend where it abuts the Variscan Front. In the north, a belt of anomalies is associated with the Fishguard Volcanic Group. The low-level airborne survey provides a detailed map of their distribution and, together with susceptibility measurements, indicates that the anomalies are associated with basic lavas in the sequence (Strumble Head Volcanic Formation) and dolerite intrusions. Similarly, the Skomer Volcanic Group generates aeromagnetic anomalies in the west of the area. In the east, an anomaly near Kidwelly, has a clear relationship with the Careg Cennen disturbance and has also been interpreted as evidence of a palaeohigh which controlled sedimentation in Dinantian times (Ramsay, 1991). A linear feature, not evident on Figure 6 but detected by the low-level survey, led to the discovery of a 45 km long basic dyke of possible Carboniferous age (Cave et al., 1989).

The Bouguer anomaly map of south-west Wales is dominated by the regional increase of values towards the St. George's Channel, reflecting density changes at mid- to deep crustal levels (see Figure 4 in Colman et al., 1995). Superimposed on this are gravity lows associated with a Precambrian acid intrusion in the Hayscastle Anticline and extrusive rocks within the Ordovician sedimentary sequence.

The south-west Wales area was included in a structural interpretation of the gravity and aeromagnetic data for Wales (McDonald et al., 1992) based on image processing and automated interpretation techniques. A series of major lineaments were identified, many of which are related to known faults and tectonic disturbances, forming a pattern which is interpreted as a result of sinistral strike-slip displacement along north-east-trending structures. Two of these linears, both east–west oriented, cross south-west Wales in the vicinity of the survey area. The more northerly runs from just north of St. David's, across the northern limit of the survey area to north of Carmarthen, while the more southerly runs along Milford Haven and out to sea near Tenby.

The survey area

The regional geophysical data were processed to highlight gradient zones and shorter wavelength components of the fields which should be associated with density/magnetic property changes of rocks nearer the surface. In addition, modelling was carried out for a profile in 2.5D and in 3D for the entire aeromagnetic anomaly. Selected results are presented in Figures 7−11, together with the location of gold observations in panned heavy-mineral concentrates.

Aeromagnetic data

The area is dominated by the large east-north-east-trending high, referred to as the Haverfordwest anomaly (HFW), which forms one of the series abutting the Variscan Front in South Wales. The anomaly (Figure 7) is interpreted as indicating magnetic Precambrian rocks rising to an estimated depth of less than 3 km. The contour pattern indicates that the overall form of the source is modified by elongations to the east-north-east (in the east) and to the south-west (in the west). The main anomaly is flanked to the south-east by a local high centred at [211 218], here referred to as the Narberth anomaly. This anomaly is not closely defined by the data from the 2-km-spaced flight lines of the aeromagnetic survey.

The 2.5D model prepared for the Haverfordwest anomaly (Figure 8) assumes that the main source is a magnetic body with a limited strike extent and a susceptibility of 0.025 SI units, set in a less magnetic basement which disappears to the north-west. The flanks of the body dip at angles of up to 45°, suggesting that it might be a separate intrusion, rather than being simply a basement high. The 3D model, based on the interpretation procedure of Rollin (1993) using a single magnetisation and a lower depth limit of 12 km, emphasises the flat-topped form of the body (Figure 9). The modelling assumes that the source of the Narberth anomaly is the same as that of the main anomaly and produces a circular conical form. More detailed modelling could be used to define its upper limit more accurately.

Gravity data

The main gravity anomalies in the survey area comprise a major high to the north-east, which extends to the west-south-west as a ridge (Figure 10). A gravity low to the west reflects the presence of low-density acid intrusions in the Hayscastle Anticline, and a second low to the south-east is associated with lower-density sedimentary rocks of Devonian and younger age (Figure 10).

Lineament interpretation

Geophysical lineaments were defined on the basis of processed data, such as derivative and short wavelength components of the observed fields; the main lineaments abstracted are shown on Figure 5 with those derived from the satellite imagery.

The major magnetic high has a pronounced east-north-east trend and its southern margin is most clearly defined by the maximum gradient (A–A' on Figure 5). Linear E–E' forms the western margin of the main magnetic high. Unlike the magnetic anomalies in the St. David's and Hayscastle areas, which are clearly congruent with, and related to the surface geology, these anomalies show little relationship or obvious influence upon the rocks or structures mapped at surface, implying a major discordance at less than 3 km depth.

A short gravity lineament (C–C') runs parallel with the major magnetic feature (A–A') and appears from magnetic (forms eastern margin of the local high) and gravity evidence to be interrupted by a linear (D–D').

The position of lineament A–A' is difficult to define exactly; an examination of the relationship between the Kidwelly anomaly, to the east, and the associated Careg Cennen disturbance shows that this major fault zone at the surface lies along the northern margin of the anomaly. This would indicate that the equivalent for the Haverfordwest anomaly is the mapped east-north-east-trending fault running north of Walton, east and south of New Moat.

Relationship with gold occurrences

There appears to be a relationship between the occurrence of gold in panned concentrate (see below) and the magnetic features. The coincidence of gold occurrences with the main Haverfordwest magnetic anomaly is apparent on the observed data, but processed data indicate a relationship to the Narberth anomaly as well (Figure 11). Although the gold-occurrence data is highly biased by the large number of samples collected in a few catchments during follow-up work (see below), these catchments were chosen as they contained appreciable gold, and it appears safe to conclude that there is a general relationship between the presence of shallow magnetic basement and the alluvial gold occurrence, i.e. there is a basement control on the source or source(s) of gold in this area.

DRAINAGE AND OVERBURDEN GEOCHEMISTRY

The drainage and overburden sampling comprised four activities:

1. An orientation study to provide information on the occurrence of gold in drainage (size distribution, geochemical and mineralogical associations) and the optimum sampling methods.
2. Follow-up drainage sampling to supplement the G-BASE coverage.
3. Detailed drainage sampling in three gold-bearing catchments between Narberth and Haverfordwest.
4. Overburden sampling in these three catchments.

All the data collected are available from the BGS Geochemistry Database.

Orientation study

This consisted of two parts. Firstly, 16 stream sites were sampled, including several at which gold was seen during the G-BASE work. This included some sites to the west of Haverfordwest. A few samples were also collected at sites with no previously observed gold, to test the reproducibility of the G-BASE observations. Panned heavy-mineral concentrates made from the <2 mm fraction of stream sediment were collected at every site and at four sites a fine fraction (<150 µm) stream sediment was also taken to test for the presence of fine gold. The sampling methods used were those developed by the BGS and described in detail elsewhere (Darnley et al., 1995). Duplicate panned concentrates were taken at two stream sites (PWP112A, B and C, and PWP115A and B) to provide information on within-site sampling variation.

Secondly, bulk stream-sediment samples were taken at three sites in different geographical and geological environments where gold had been observed during the G-BASE work. The samples consisted of approximately 10 litres of <2 mm stream sediment dug from as deep as possible in the stream bed. These sites were:

(i) North-east of Narberth [21194 21586], site PW112. The site is located on a high-energy first-order stream draining folded and faulted Llandeilo to Ashgill sedimentary rocks. Quartz-veined and silicified clasts are abundant in the stream. These contain no visible mineralisation but eight grains of gold were recovered from initial panning, and native mercury was noted in the pan.

(ii) South-east of Clarbeston [20706 21989], site PW114. The site is in a third-order stream draining predominantly *Dicranograptus* Shales, which are abundant as stream clasts. Angular quartz-vein material is also common, and initial panning suggested the presence of fine gold.

(iii) North of Haverfordwest [19405 21822], site PW116. This site is located on a first-order stream draining sedimentary rocks of Ashgill age. The stream contains clasts of quartz-vein material and reddened silicified rock, but no gold was seen during panning.

Sample preparation and analysis

The bulk stream-sediment samples were sieved at 500, 250, 125 and 63 µm. If there was sufficient material, the four coarser fractions were split into sub-samples, and each sub-sample panned to approximately 30 ml. Each panned concentrate was examined, and gold grains and associated ore minerals extracted for mineralogical study. If there was insufficient material to pan, then the total sub-sample was examined mineralogically. These fractions were not analysed for Au. The <63 µm fractions were sub-sampled and analysed for Au but not examined mineralogically.

The panned concentrate (<2 mm) and stream sediment (<150 µm) samples collected from all localities were riffle split and a large sub-sample milled. Gold was determined on a 20 g sub-sample of the resulting powder by GF-AAS following aqua regia digestion and MIBK extraction at Acme Analytical Laboratories Ltd (AALL), Vancouver. ICP-OES analysis for 30 elements at the same laboratories followed digestion of a 0.5 g sub-sample of the milled powder with 3 ml 3-1-2 HCl-HNO_3-H_2O at 95°C for one hour and dilution to 10 ml with water. The leach is partial for Mn, Fe, Sr, Ca, P, La, Cr, Mg, Ba, Ti, B and W and limited for Na, K and Al. Other elements determined were Mo, Cu, Pb, Zn, Ag, Ni, Co, As, U, Th, Cd, Sb, Bi and V. Pelletised 12 g milled powder sub-samples were analysed by XRFS at the BGS Laboratories (BGSL), Keyworth for Ca, Mn, Fe, Cr, Co, Ba, Ni, Cu, Zn, As, Mo, Pb, Bi, Ag, Cd, and Sb. Panned concentrates were analysed for Sn by XRFS in addition to these other elements.

To provide information on sub-sampling and analytical variation, a number of sub-samples were generated and repeat analyses carried out. One panned concentrate was split prior to milling and the two halves analysed separately (PWP114A and B). One stream sediment (PWC116) was sub-sampled after milling and each split was analysed by AALL and BGSL independently. AALL also repeated the analysis of PWC116B and analysed three BGS standards, as well as providing data on their internal standards.

Results

Visible gold was recorded at six of the ten G-BASE sites that were resampled. The variation in the number of grains in the duplicate samples from the same sites (PW112 and 115, Table 4) indicates the extent of sampling variation produced by the 'nugget effect'. The gold grains varied in size and shape, both between and within sites; for example, at site PW112, a large flattened grain (c. 1 mm diameter) was accompanied by five smaller, more rounded grains.

In addition to gold, mineralogical inspection in the laboratory showed the presence of galena, chalcopyrite, sphalerite and baryte grains in the samples from site PW115 [19094 21718], which were removed prior to chemical analysis. Samples PW106 [19206 21919] and PW107 [19194 21904] contained abundant pyrite.

Clast lithologies at each site almost exclusively represented the catchment geology, indicating that most of the stream sediment is locally derived. The only exception was the stream draining black shales near Druidston Haven (PW101 at [18628 21726]) where the clasts were extremely varied. The central part of the Haven is filled by six generations of till, raised beaches, fluvioglacial deposits and head that have been interpreted as glacial melt-water channel deposits (Campbell and Bowen, 1989) and this is probably the source of the exotic sediment.

<u>Panned concentrates.</u> The analytical data (Table 4) show that there is Au in the panned concentrates in addition to that in the visible gold grains. For example, samples from sites PW106 [19206 21919] and PW107 [19194 21904] contained appreciable analytical Au despite the lack of visible gold grains. At both of these sites, which are underlain by *Dicranograptus* Shales, abundant coarse and fine pyrite was observed in the pan (over 10%), and it is possible that gold is present within the pyrite or was not observed due to the abundance of pyrite. These samples also show substantial enrichment in Ba: this is commonly observed over anoxic black shales, which rock analyses show may contain over 1% Ba (Table 3).

Table 4 Visible gold grains and selected chemical analyses for panned concentrates collected in the orientation survey

Sample number	Panned gold grains	Au ppb	Cu ppm	Zn ppm	As ppm	Pb ppm	Bi ppm	Sn ppm	Sb ppm	Ba ppm
101	0	3	95	103	53	142	<1	107	4	181
102	4	1130*	7	45	6	35	<1	44	<1	143
103	0	10	11	82	12	34	<1	24	3	341
104	0	4	7	42	7	16	<1	22	7	539
105	0	260	12	171	7	26	<1	43	3	562
106	0	1210	47	169	23	18	<1	10	<1	15456
107	0	420	48	381	58	18	<1	25	<1	16914
108	0	7	23	132	10	80	<1	57	<1	305
109	1	720	48	137	8	249	<1	153	2	263
110	0	550	5	40	3	11	<1	12	5	150
111	0	17	55	89	9	14	<1	16	<1	265
112A	4	930*	23	149	21	76	1	295	5	388
112B	0	3	13	84	15	30	<1	16	5	298
112C	2	2*	18	135	24	32	1	180	<1	365
113	2	44*	21	99	21	42	2	64	<1	183
114A	1	4*	14	54	11	21	<1	53	3	544
114B	0	1	12	61	8	26	<1	40	<1	517
115A	1	2*	7	58	9	23	<1	28	2	311
115B#	3	6260	9	529	14	66	<1	36	<1	306
116	0	20	10	86	12	26	<1	27	4	605

* analysed after visible gold grains had been extracted.
# analysed after coarse baryte, chalcopyrite, sphalerite and galena grains removed.
Au analysis by GF-AAS, other elements by XRFS.

The data did not indicate the presence of any useful Au pathfinder elements. Arsenic, the most commonly used pathfinder, shows no close correlation with Au enrichment (Table 4). The highest As value is low (58 ppm) compared with areas containing arsenic mineralisation and the slight enrichment at this site (PW107 at [19194 21904]) is probably due to traces in the abundant pyrite. Silver shows slight enrichment (up to 8 ppm by XRFS) but no correlation with Au content. Bismuth and Sb are notable only for their low concentrations. Amongst other chalcophile elements, Cu and Pb are generally low with only weak enrichment in a few samples. Zinc is high in two samples, (Table 4, PW107 and PW115), and mineralogical examination revealed that this is probably due to the abundant pyrite in the former and to fine-grained sphalerite in the latter.

Tin in panned concentrate can often be used as a measure of contamination if the area is free of Sn mineralisation (Cooper and Thornton, 1994), but at site PW112 [21194 21586] there are anomalous Sn values which mineralogical examination found to be due to the presence of cassiterite.

The duplicate samples show considerable variation in those elements which occur principally in a few heavy-mineral grains. This ‘nugget effect’ is most obvious in the Au data, with duplicate samples from the same site giving analytical values that vary by orders of magnitude, but Sn, Pb and Zn are also affected (Table 4).

Stream sediments. A maximum of only 8 ppb Au was recorded in the samples of <150 μm stream sediment, despite the presence of panned gold at the sites (cf. Table 4 and Table 5). This suggests that the gold is predominantly coarse grained, but the presence of analytical gold in panned concentrates from some sites where no fine sediment was collected and no gold was seen in the pan (e.g. PW106, 107 and 110) suggests that fine-grained gold may be present locally.

Levels of base metals, in the sediment samples are low but in two samples levels of Ba (>1500 ppm) are recorded that are much higher than the values in the panned concentrate taken from the same sites (PW112C and 114A, Tables 4 and 5), suggesting that the source rocks are rich in a light Ba-rich mineral, possibly a feldspar or mica. Geochemical analyses of Ordovician rocks from this area suggests that *Dicranograptus* Shales are the probable source (see below).

Table 5 Analyses of gold and other elements in stream-sediment samples collected in the orientation survey

Sample number	Au ppb	Cu ppm	Zn ppm	As ppm	Pb ppm	Bi ppm	Sb ppm	Ba ppm
112C	8	23	142	19.0	30	<1	2	1864
114A	2	22	126	14.0	23	<1	<1	4045
115A	<1	11	93	12.0	21	<1	6	577
116A	1	11	93	8.0	21	<1	3	727
116B	<1	10	89	7.0	19	<1	4	686

Bulk samples. Detailed mineralogical work on the three bulk samples, together with compositional and mineral-inclusion characterisation of the gold grains extracted from the panned concentrates, showed that each of the sites has different mineralogical characteristics (Table 6).

Most gold grains from site PW112 [21194 21586] have well-rounded morphologies and occur in the coarsest fraction (13 grains in the 500–2000 μm fraction), with a smaller number (4 grains) in the 63–150 μm fraction (Table 6). The gold grains have a wide range of Ag contents, from 0 to 45.9% (both grains with extreme compositions from PWP112A). Tin minerals are present, both as inclusions within the gold (stannite and stannoidite) and as discrete phases (cassiterite). The cassiterite appears to be visually identical to that found in south-west England (Bland, 1995). Other minerals found at this site included galena, chalcopyrite and monazite (both authigenic and igneous). Galena and chalcopyrite were also present as inclusions within the gold grains.

The bulk sample from site PW114 [20706 21989] yielded over forty grains of gold, predominantly between 250 and 500 μm in size, with some in the ranges 150–250 μm and 500–2000 μm. The finest size fractions contained very little gold (Table 6). The silver content of the grains between 250 and 500 μm is tightly constrained around a mean of 6.1% Ag. The grains are characterised by As, Hg and ?Cu telluride inclusions (petzite, coloradoite, ?vulcanite), probably indicative of high-temperature mineralisation. These grains are generally very angular, and have telluride minerals attached to the surface of the grain.

Therefore, they have probably not travelled far from source, which could be associated with *Dicranograptus* Shales and/or a major east–west structure to the north of Clarbeston.

Table 6 Analytical and mineralogical data for size fractions of the bulk samples

No.	Sub-sample	Size fraction (µm)	Panned gold grains	Au ppb	Other minerals	Range Ag %	Inclusions
112	D1–D7	500–2000	13	n/a	cassiterite, monazite, mercury, galena	7.2–29.5	galena, stannoidite, chalcopyrite stannite
112	E1	250–500	0	n/a			
112	G1	150–250	0	n/a			
112	F1	63–150	4	n/a			
112	H1–H2	<63	n/e	4.5			
114	C1–C6	500–2000	4	n/a		10.8–18.6	
114	D1–D2	250–500	38	n/a		1.4–7.9	petzite, pyrite, pyrrhotite, ?vulcanite, coloradoite
114	E1	150–250	6	n/a		5.5–19.6	
114	F1–F2	63–150	0	n/a			
114	G1–G4	<63	n/e	2.5			
116	C1–C2	500–2000	0	n/a	mercury, galena, pyrite		
116	D1	250–500	1	n/a	arsenopyrite	29 (1 grain)	
116	E1	150–250	0	n/a			
116	F1	63–150	0	n/a			
116	G1–G2	<63	n/e	5.5			

n/a: not analysed. n/e: not examined.

The sediment from site PW116 [19905 21822] yielded only one grain of gold, with associated mercury, galena, pyrite and arsenopyrite. There was little gold in the <63 µm fraction. The Ag content of the gold grain is quite high (29% Ag, Table 6). No inclusions were present in the grain and the small number of gold grains from this site precludes any detailed mineralogical interpretation with respect to probable source.

Conclusions

1. The orientation study validated the G-BASE findings, and indicated that gold of a number of types was present, possibly derived from different sources. Gold occurs at different grain sizes in different catchments, and fine gold may be present locally. Grain morphology is variable from angular to well rounded; some angular grains with tellurides on the outer surfaces are likely to be of very local origin.

2. The composition of the gold grains from all the bulk sites was predominantly Au–Ag, with little or no Pt, Cu or other elements. Gold inclusion compositions are diverse, reflecting several potential sources of bedrock mineralisation including black shale, shear zone and granite-related. The absence

of any granitic rocks at surface in the area would seem to preclude a local origin for this type of gold unless it is an inherited from a palaeoplacer deposit.

3. Chemical analysis revealed no clear pathfinder elements for gold in this area. This is likely to be due to the presence of gold of a number of types from different sources. There is some indication of chemical associations of individual types; for example, gold-bearing sites located on or close to the *Dicranograptus* Shales show enrichment in Ba, with weaker As and Zn.

4. Traces of Sn mineralisation are present locally and this prevents the unconstrained use of Sn values in drainage samples as a guide to contamination. Native mercury was identified at two sites and it is not clear whether or not this is the product of contamination. Mercury inclusions occur in some gold grains and its presence led to the determination of this element in all follow-up samples.

Follow-up drainage geochemistry

Streams between Cartlett Brook [easting 200000] and the Eastern Cleddau [easting 212000] were sampled south of northing 227000 to provide panned heavy-mineral concentrates from the main area of G-BASE gold observations in catchments composed of Ordovician and Silurian rocks. Samples were normally collected at 800 to 1000 m linear stream-length intervals. In addition, a few samples were collected outside this area to provide additional information on gold that may be related to other lithologies, notably the porphyry-style copper mineralisation near Llandeloy.

Three catchments were sampled in detail because of the known occurrence of gold and possible presence of shear-zone-hosted deposits in black shales. These were: the Afon Marlais, north-east of Narberth; Deepford and Church Hill brooks south-east of Clarbeston Road; and Fenton Brook, north-east of Haverfordwest (Figure 13). In these catchments samples were taken undertaken at approximately 250 to 300 m intervals.

Sampling and analysis

The methods used during the orientation survey were employed with little modification. The principal differences were that (i) a <150 μm stream-sediment sample was collected at all sites except three, and (ii) at most sites a full pan (4 to 5 litres) of <2 mm stream sediment was split into two equal amounts and each split panned separately to yield two concentrates of approximately 50 ml. This procedure improved recovery of heavy minerals due to more efficient panning. At five sites (PW219, 302, 313, 439 and 542) only one pan was taken. This was due to dry streams and/or lack of stream sediment. At three sites more than two pans were taken to test the efficiency of the Henderson pump (PW301: 4 samples), or to collect a large population of gold grains for mineralogical analysis (PW231: 6 samples; PW531: 4 samples). In total, 405 panned concentrates and 198 stream sediment samples were collected from the 201 sites visited.

A wide range of information was recorded about each site, with particular attention given to stream clasts and any rock exposures. Mineralised, altered or unusual rocks were collected for analysis. The number, size and shape of visible gold grains in each pan were recorded, together with any associated minerals.

Panned concentrates from sites with more than 3 grains of visible gold were dry sieved at 500 μm and the gold grains removed by superpanning the <500 μm fraction. The >500 μm fraction was examined visually and any gold grains removed. The two fractions were then recombined prior to milling. The extracted gold grains were weighed prior to mounting for mineralogical examination. The weight of the gold grains relative to the size of the total sample was added to the determined analytical value for Au. Panned concentrates with 3 or fewer grains of visible gold were sent directly for milling.

One of the panned concentrates from each site (average weight 46 g) was mixer-milled in toto, to minimise sub-sampling due to the 'nugget effect', prior to splitting. From sites with high numbers of observed gold grains or with unusual mineralogy, the second panned concentrate was sieved at 500 µm and superpanned to extract gold grains and associated minerals for detailed study. The intact second panned-concentrate samples were retained for reference.

Each dried stream-sediment sample was lightly disaggregated, and riffle split to give a c. 50 g sub-sample of material, which was reduced to powder using an agate ball mill. Splits of the powdered material were taken from both sample types for chemical analysis and the remaining material archived.

Gold was determined on a 20 g sub-sample of the milled powder from both sediments and concentrates by GF-AAS, following aqua regia digestion and MIBK extraction at AALL. Cu, Zn, Pb, As, Bi, Sn, Sb, Fe_2O_3, Ba and Cr were determined by XRFS at the BGSL, on a second split of milled samples from all sites. Arsenic was also determined on the panned-concentrate samples. A further 15 g sub-sample of powder from 171 of the panned concentrates and 168 of the stream sediments was analysed for 35 elements by ICP-OES at AALL following digestion in 90 ml 3-1-2 HCl-HNO_3-H_2O at 95°C for one hour. This leach is partial for Mn, Fe, Sr, Ca, P, La, Cr, Mg, Ba, Ti, B and W and limited for Na, K, Ga and Al. Mo, Cu, Pb, Zn, Ag, As, Cd, Sb, Bi, Tl, Hg, Se, Te and Ga were extracted with MIBK prior to analysis. Other elements analysed were Ni, Co, U, Th, and V.

Results: field observations

Samples were collected at 201 sites. At approximately two thirds of these, one or more gold grains were seen in the panned concentrates. The spatial distribution of panned gold shows that it is widely dispersed in small amounts; samples with more than five gold grains occur in six catchment areas (Figure 12). These are Deepford Brook, Fenton Brook, Afon Marlais two tributaries of the Afon Syfynwy draining southwards from New Moat, the Afon Conyn to the north-west of Clunderwen, and a tributary of Cartlett Brook to the east-north-east of Clarbeston Road.

The size of gold grains in the pans varied considerably. The largest (from site PW444 [20030 22361]) is coarsely dendritic and approximately 4 mm long. Many other grains measured over 500 µm, particularly in the Deepford/Church Hill Brook catchment. In the Fenton Brook catchment, the observed gold is generally much finer, although the site with the most gold (PW232) produced grains up to 1.2 mm in length. Most of the grains are rounded but some are very angular, suggesting a local source.

Sulphide minerals were also seen in the panned concentrates, but there was no obvious connection between their presence and visible gold. Pyrite (and possible minor chalcopyrite or arsenopyrite) occurs in very large amounts (>10% of the concentrate) in streams draining *Dicranograptus* Shales, but is rarely associated with visible gold. Iron oxides (hematite and magnetite) and zircon were the most abundant heavy minerals observed in the pans, although monazite and baryte were also seen locally.

Stream clasts were mostly angular or sub-angular and locally derived. Much quartz-vein material is present throughout the area and, in places, occurs as well-rounded cobbles which may be derived from conglomerates and coarse grits within the Ashgill/Llandovery sedimentary sequence. Clast lithologies unrelated to the mapped bedrock were commonly recorded. These lithologies included silicified and often pyritic ashes or lavas, coarse-grained mafic igneous rocks and silicified grits. Although some may be locally derived, possibly from the conglomerates, it is most likely that many have been transported from the north (see Strahan et al., 1914, p.216 ff.).

Results: analytical data

Summary statistics of the analytical results for selected elements in panned concentrates are shown in Table 7 and for stream sediments in Table 8.

Levels of Au in the panned concentrates are high (Table 7), but a cumulative frequency plot revealed no distinct populations except for an ill-defined background group below 10 ppb. Gold values are considerably lower in the <150 µm stream sediments (Table 6), but their cumulative distribution plot revealed a threshold value of 10 ppb between background and anomalous populations, corresponding to 91.2% of the analysed samples.

Table 7 Summary statistics for selected elements in panned-concentrate samples

	Mo ppm	Ag ppb	Hg ppb	Te ppm	Cu ppm	Zn ppm	As ppm	Pb ppm	Sn ppm	Sb ppm	Ba ppm	Au* ppb	Gold grains
No.	191	191	171	171	221	221	221	221	221	82	221	191	221
Min.	<0.1	<1	<5	<0.1	<3	20	<5	7	<5	<1	<1	<1	0
Max.	17.3	12647	2455	0.9	960	666	94	1500	1865	42	19700	>99999	32
Mean	2.2	494	72	0.2	45	117	8	95	120	1	946	4278	3
90 %	5.6	1188	114	0.4	87	188	23	205	307	4	1322	10005	8
95 %	10.3	2114	332	0.5	136	316	27	354	402	5	3210	24180	14
Std. dev.	3.2	1167	214	0.2	85	98	13	146	175	5	2732	11321	5
Median	0.9	123	24	0.1	23	95	<5	49	61	<1	282	410	1

* includes gold grains extracted for mineralogical analysis.
All elements analysed by XRFS except for Mo, Ag, Hg, Te (ICP-OES) and Au (GF-AAS). These data include analyses of the samples collected for the orientation study.

Table 8 Summary statistics for selected elements in <150 µm stream-sediment samples

	Mo ppm	Ag ppb	Hg ppb	Te ppm	Cu ppm	Zn ppm	As ppm	Pb ppm	Sn ppm	Sb ppm	Ba ppm	Au ppb
No.	173	173	168	168	203	203	66	203	198	66	203	173
Min.	<0.1	3	15	<0.1	9	49	5	14	<5	<1	419	<1
Max.	49.3	647	1328	0.3	360	535	62	127	32	6	12000	1480
Mean	2.0	57	70	<0.1	23	136	15	28	<5	<1	1531	30
90 %	3.8	138	104	0.2	30	197	20	38	10	<1	4045	8
95 %	7.1	198	138	0.3	35	238	27	43	12	2	5800	130
Std. dev.	4.2	83.8	115.5	0.06	25.3	56.7	8.90	12.7	4.84	0.95	1726.4	148.8
Median	1	37	47.5	0.1	20	126	14	26	5	<1	959	1

All determinations by XRFS except for Mo, Ag, Hg, Te (ICP-OES) and Au (GF-AAS). These data include the analyses of samples collected for the orientation study.

The analytical values for Au in panned concentrates show a broad correlation with the number of grains observed in a pan (Figure 13). The outliers away from the main trend can be explained by variation in grain size: coarser grains yielding higher analytical values and finer grains not having been observed in the field. As was indicated by the orientation study, the 'nugget effect' will also have produced variation due to the heterogeneous distribution of gold grains in sub-samples. The correlation between Au in stream sediment and panned concentrate is poor (Figure 14). Although there is no doubt that sampling and analytical variation will account for some scatter, the absence of any clear association suggests different sources for coarse and fine gold.

Within-site variation proved large. For example, sites PW301, PW302 and PW303 were located within 10 m of each other in the same stream. PW301 was sampled upstream from a convex stream bend and was dug to 0.5 m. The first two pans yielded 5 grains of gold but only 581 ppb Au in pan A. PW302 was sampled 5 m away in the central part of a convex stream bend and yielded no grains of gold and 462 ppb Au in the pan. PW303 was dug on the down-stream end of the convex stream bend and also yielded no grains of gold and only 4 ppb Au. Besides the effects of within-site and between-sub-sample variation, greatest for elements concentrated in heavy minerals and in panned concentrates, variation in the geochemical data can be related to a number of geological and anthropogenic sources.

Results: geochemical associations

Precious-metal association: Au, Ag, (Sn). Gold does not show strongly significant positive correlations with any element determined except for Ag in panned concentrates. A weaker association with Sn in both sample media is also evident (Table 9). The latter may be due to a density-related heavy-mineral association produced by panning, or a palaeoplacer source, or a granite-related mineralised source. It reflects the presence of gold with cassiterite and other tin minerals noted during the orientation study. Weak associations of Au with Hg, Cu, Pb and Zn in stream sediment are present, but none of these are strong enough to provide reliable pathfinders. There is no correlation evident with As. The regional variation of these elements is illustrated in Figures 15–22 and described with respect to Au in the following sections.

Table 9 Spearman-rank correlation coefficients between Au and selected elements in stream sediments and panned concentrates

	Au in stream sediment	**Au in panned concentrate***
Mo	-0.025	-0.012
Ag	0.162	0.568
Te	0.094	0.097
Cu	0.237	0.098
Zn	0.211	0.002
As	0.079	-0.006
Pb	0.258	0.075
Sn	0.399	0.481
Hg	0.306	0.116
Bi	0.200	0.078
Sb	0.015	0.125
Ba	0.120	0.071

* Total 99% confidence level = 0.20

Black-shale association: Mo, Ba, As, Zn, (Cu, Cd, Pb, Se, Sr). A strong positively correlated group of elements all show high levels related to the presence of black shales, principally of *Dicranograptus* age. The strong spatial correlation between the principal elements in this group and the outcrop of these rocks is seen most clearly in the Deepford Brook area but is also evident elsewhere. The regional variation pattern, demonstrated clearly by the distribution of Ba (Figures 23 and 24) and Mo (Figure 25), indicates that the stream sediment is predominantly locally derived. It is seen in both the fine-fraction sediment and the panned concentrate for Mo, Ba, As and Zn, but principally in the panned concentrate for Cr, Se, Cd and Cu, and in the fine sediment for Sr. Some other elements, such as Hg, Fe, Ni and Pb, also show enrichment related to black shales, but the spatial distribution patterns and correlations of the elements are more disturbed by other sources of variation. Abundant fine and coarse pyrite was observed in panned concentrates at most sites overlying these rocks, and one of the sources of the co-variation is probably the substitution of minor amounts of some elements for Fe in pyrite. In detail, there are differences in the association in different catchments that are probably related to stratigraphical and lithological variations. Silver shows weak positive correlation in the stream sediment, with a number of elements in the black-shale association (Ba, As, Cu, Mo, Sb) providing a weak link between precious-metal mineralisation and this black-shale association.

<u>Limestone association: Ca, (Sr, P)</u>. Limestones in stream catchments give rise to this association in stream sediments and panned concentrates. It is clearest for Ca, as variation in Sr in stream sediment is in part related to the presence of black shales and that of P to the presence locally of significant amounts of monazite. The limestone association is most evident in the Afon Marlais catchment, where limestones of Llandeilo age are common.

<u>Chlorite (mafic igneous) association: Mn (Zn, Ni, Fe, Cr, V, Co).</u> Sites in the north of the area overlying Arenig or Llanvirn rocks are characterised by a distinct geochemical signature most notable for enrichment in Mn in panned concentrates and stream sediment. Zn, La, Ni and Fe are high in stream sediments and Cr in panned concentrates. Correlations also indicate links with Mg, K, Al and, in sediment, La and Th. This is tentatively attributed to the presence of chlorite and perhaps other minerals derived from the Lower Ordovician rocks or basic intrusions that outcrop in the north of the survey area. Variation, relatively minor compared with more mountainous areas of Wales, due to secondary precipitation of hydrous Fe and Mn oxides may also be incorporated here. In sediment, there appears to be an antipathetic relationship between some elements in this group and those concentrated in limestones.

<u>Monazite: La (Th, P).</u> High levels of La (up to 4264 ppm) in panned concentrates from the north of the area, south-east of Maenclochog and sporadically elsewhere, are due to the presence of nodular grey authigenic monazite (Cooper et al., 1983; Smith et al., 1994). High La is accompanied by elevated levels of P and Th in panned concentrates due to the very strong upgrading of this heavy mineral in the pan (Smith et al., 1994). In the stream sediment, La and Th are, by contrast, correlated with a group of elements concentrated in clay/chlorite minerals and P is associated with limestones (Ca and Sr).

<u>Contamination: Pb, Sn, Sb.</u> These three elements show an association in panned concentrates that is related to the presence of metallic contamination. Cu, Hg and Zn may also be involved, though much of their variation is related to other sources. In many areas, Sn concentrations, particularly in panned concentrates, are a reliable indicator of contamination, but natural Sn minerals are known to occur in this area and Sn variation is in part related to precious-metal mineralisation. Lead variation also has other sources, so it is difficult to assess which anomalies are related to mineralisation and which are due to contamination. Also, high levels of these metals in a single sample may be the product of more than one source. Mineralogical examination of the concentrate is required to identify the sources, but site observations provide a guide, and very high levels of Sn and Pb or Sb are particularly likely to be caused by contamination. For example, at site PW420 [20710 21982] on a small tributary of the Afon Syfni draining Shipping Cwm Farm, extremely high levels of Sn (1865 ppm), Pb (1500 ppm), Cu (399 ppm) and Hg (361 ppb) are associated with copper wire and lead seen in the stream (Figures 18–21).

Base-metal mineralisation: Cu, Pb, Zn, As, Sb. There is no clear base-metal-mineralisation signature evident in the drainage-geochemistry data. A weak signature may be obscured by the dominant variation related to black shales. The 95th percentile levels and maximum values for all the base metals, particularly in panned concentrates (Tables 5 and 6), are not particularly high when compared with areas containing base-metal mineralisation, but some samples contain much higher levels of a metal in the concentrate than the sediment from the same site, indicating the presence of a heavy-metallic mineral phase. In some cases this may be due to abundant pyrite or contamination, but there are also some sites where enhanced levels of these metals may be indicative of minor base-metal mineralisation (see below).

Sandstones. Variation due to the presence of sandstones was not well defined due to the absence of suitable analyses such as SiO_2 and Zr in sediment. Some variation in elements locally concentrated in heavy minerals, for example Cr, La and Th, is however believed to be related to the presence of these rocks.

Results: regional distribution of anomalies

Samples containing the most Au in panned concentrate (>24 ppm, 95th percentile) occur in three catchments sampled in detail (Deepford Brook, Afon Marlais and Fenton Brook) and a number of other sites described below (Figure 15).

The site with the highest Au content (>99.999 ppm, PW377 at [20618 22438]), lies in a southward-draining stream 1 km south of New Moat (Figure 15). The stream drains a Llanvirn succession and an area of poorly known Arenig rocks, possibly akin to the turbiditic and volcaniclastic Afon Ffinnant Formation (Fortey and Owens, 1987), cut by several faults. Only three grains of gold were observed in the pan from this site and no other elements are anomalous except for Ag (13 ppm). This implies that the gold is either fine or contained in other minerals and so was not observed, and/or there is large sampling variation. Inspection of the upstream section revealed nearly continuous exposure of variably cleaved and disrupted grey-black shales cut by quartz veins up to 30 cm wide with occasional pyrite. The zone of disturbance is perhaps 100 m from south to north and could be a source for the panned gold observed downstream. Although none of the rock samples collected contained metal enrichments above the levels typical of these lithologies, the fault zone may represent a major east-north-east-trending structure inferred from interpretation of the Haverfordwest magnetic anomaly as running north of Walton East and south of New Moat (see above).

A site along strike in a parallel stream 0.5 km to the west (PW363 at [20550 22446]) is also highly anomalous (49 ppm Au and 3.2 ppm Ag) and may be related to the same structure. Several other sites in the area contain lesser but still appreciable levels of Au and Ag. These sites show no substantial enrichment in other elements in panned concentrates, but two sites adjacent to PW363 show weak As enrichment (27 and 50 ppm) in the stream sediment. To the south-east, a site in the Rhyd y Brown Brook (PWP360 at [20690 22225]) is not anomalous in Au, but does have enhanced levels of Sn (432 ppm) and Hg (644 ppb) in the panned concentrate.

Moderate Au enrichment is also recorded in panned concentrates from the upper reaches of Cartlett Brook, north-west of Walton East (Figure 15) and close to the same east-north-east-trending structure. Up to seven grains of gold were recorded in a pan (PW443 at [20040 22353]), and chemical analysis shows accompanying enrichment in Ag (up to 0.6 ppm).

In the north-east of the survey area, 24.2 ppm Au was recorded in a panned concentrate from a site (PW336 at [20919 22224]) on the Afon Rhyd. Besides Au, only Hg in stream sediment is anomalous in the samples from this site, but 1 km upstream is another site (PW335 at [20860 22320]) with high Au in the panned concentrate. This reinforces the significance of this catchment which cuts faulted components of the Arenig and Llanvirn successions and of the east-north-east-trending fault zone south of New Moat, which also passes through the upper part of this catchment.

The Afon Conyn, north-west of Clunderwen, yielded anomalous values of Au at one site (PW333 at [21106 21968]). There were accompanying high levels of Zn, Pb, Ag and Sn in the panned concentrate, but no high levels of metals in the stream sediment. Another site downstream (PW533 at [20949 21988]) yielded seven grains of gold and minor Zn in the panned concentrate, together with anomalous levels of Au (130 ppb) in stream sediment. Both of these sites are directly along strike to the east of the Deepford Brook area and any east-trending fault or stratigraphically controlled mineralisation source is likely to be common to both catchments.

A site (PW370 at [20010 22122]) on a small tributary of Cartlett Brook west of Clarbeston Road and Deepford Brook yielded visible and anomalous analytical gold in the panned concentrate, together with high Ag, Sn, Sb Hg and Pb values. No elements were enriched in the stream sediment. A zone of brecciation and veining is exposed within black shales of probable Caradoc age in the stream, and a one-metre-thick altered ash horizon outcrops 2 m downstream from the most intensely veined section. The shales adjacent to the ash are bleached and the black shales downstream of this outcrop have abundant disseminated pyrite. Adjacent sites show enrichment in Hg and Zn in both panned concentrates and stream sediments. The geology of the area is similar to the nearby Deepford Brook catchment, and, notably, the major east-trending reverse fault which downthrows Caradoc *Dicranograptus* Shales to the south against the Llanvirn *Didymograptus bifidus* Beds in the Deepford Brook also crosses this area. Here the fault has largely cut out the Caradoc sequence, and Redhill Beds type outcrop a short distance to the south, but any fracture-controlled mineralisation may be common to the two catchments.

In Church Hill Brook, the catchment immediately south of Deepford Brook (Figure 15) a site (PW310 at [20380 21960]) returned high levels of Au in the panned concentrate, but no associated element enrichments, although the concentrate collected 1 km upstream (PW313 at [20284 21987]) contains anomalous Cu, Pb and Zn and a further site downstream (PW510 at [20469 21945]) produced anomalous panned Au. The sporadic distribution of element enrichments in this catchment suggests that it may be peripheral to the source of the Deepford Brook mineralisation. A gritstone clast sample collected from a northward-flowing tributary to Church Hill Brook [20268 21944], and probably derived from the coarse sandstone or conglomerate at the top of the Slade and Redhill Beds, contained 15 ppb Au, suggesting a possible source in the coarser detrital sedimentary rocks of the area.

The only other site with a high level of analytical Au in panned concentrate was from the Llandeloy area (PW231 at [18524 22722]), where 27 grains of gold were collected from six pans for gold characterisation studies. This site also yielded anomalous Au in stream sediment, together with Sn and Ag. This was one of two samples taken from streams with observed G-BASE gold in this area and is underlain by intermediate intrusions that host an eroded copper porphyry system (Allen et al., 1985).

Gold grains (up to 5), accompanied by anomalous Au in stream sediment, are recorded from sites in the Afon Daulan and its tributaries east of Clunderwen (Figure 16). The gold is accompanied by a modest Hg enrichment (141 ppb) at one site (PW329 at [21522 21898]), and an adjacent site (PW328 at [21511 21894]) has enrichments of Ba (2179 ppm) and Sn (338 ppm). Upstream, at site PW331 [21310 21894] there is enrichment of Au (5.3 ppm), Sn (317 ppm), Cr (3515 ppm) and Ag (1418 ppb) in the panned concentrate, and Zn (435 ppm) with slightly elevated levels of Fe, As and Sn in the stream sediment. The catchment is composed largely of *Dicranograptus* Shales, and the stream runs along a faulted contact with Llanvirn and Ashgill sediments. These could be sources of gold, but there is a large tract of fluvio-glacial sands and gravels in this area, exposed in a farm quarry north of Glan Rhyd and proved in boreholes near Gower Villa, and the association between Au, Sn, Cr and Ba in panned concentrates could indicate a heavy-mineral accumulation in superficial deposits. However, there is a railway running by the stream and some of the metal levels may be caused by ballast or other contaminants.

Sites at which gold is only recorded in the stream sediment are widely spread (Figure 16). One site (PW344), which also shows minor enrichments of Sn, Cu, Zn and Ag, in the north-east of the survey area [21096 22630] is notable for the absence of panned gold in the vicinity. There are minor enrichments of Cu, Pb, Zn and As in a stream sediments from a site upstream and a parallel south-draining stream to the west shows similar enrichments. These may be indicative of mineralisation, as a siltstone stream clast collected to the west of Ffynnon Samson Farm [21190 22507] contains elevated levels of Pb (453 ppm) and Zn (263 ppm). The siltstone, of probable Arenig age, contains disseminated pyrite and provides evidence of weak base-metal mineralisation in the rocks of this area.

Afon Marlais catchment

This catchment occupies much of the ground between Narberth and Whitland. Only the upper part of the catchment near Narberth was sampled in detail and this forms the south-east corner of the survey area.

<u>Geology.</u> The main water course flows eastwards along the axis of the westward-plunging, Lampeter Vale Anticline (Figure 4). The structure is cored by the dark, graptolitic *Didymograptus bifidus* Beds which, in the east, contain one or more volcanic tuff horizons. Down plunge and along both flanks of the structure, these Llanvirn strata are succeeded, probably disconformably, by a sequence of nodular and argillaceous limestones, weathering to fossiliferous rottenstone, of Llandeilo and Caradoc age; the lateral equivalent of the Mydrim Limestone of Camarthenshire. During drainage sampling, beds of shelly limestone were observed and fossils in stream clasts (*Flexicalymene cambrensis, Basilicus tyrannus*) have since confirmed a Llandeilo age for these rocks (A.W.A. Rushton, personal communication).

The nose and northern flanks of the anticline, including the area of the detailed drainage sampling, are affected by faults which are contiguous with, and may represent the eastward continuation of, the Robeston Wathen Fault (Strahan et al., 1914). A locally developed fracture cleavage is developed in the vicinity of these structures. Displacement on these and other unrecognised fractures is likely to account for an apparent attenuation of the black-shale sequence (*Dicranograptus* Shales) and the absence of the Shoalshook Limestone within this area. The earlier suggestion, that this was evidence of a surface of disconformity (Strahan et al., 1914), is now difficult to reconcile with the faunal studies of Zalasiewicz et al. (1994). Younger Ashgill strata in the area are of the Redhill Beds facies. These are succeeded, in the north of the area and to the west, by Hirnantian feldspathic, clast supported conglomerates and sandstones. Vein quartz and a variety of lithic pebbles, including igneous clasts, are reported from the conglomerates.

Mapped superficial deposits within the area include a small area of glacial sand and gravel at Stonyford, alluvial deposits in the stream valley and, locally, patches of boulder clay.

<u>Drainage results.</u> The Afon Marlais contains two sites which returned high Au in panned concentrate (PW307 at [21258 21537] and PW203 at [21258 21537], Figure 15). The samples do not contain other anomalous elements, except for a moderately high value for Mo in the pan from site PW203. At two sites upstream from site PW307, which drains the northernmost part of the catchment, there are high values for As, Cu and Pb which are probably derived from the *Dicranograptus* Shales or minor mineralisation associated with an east-trending fault.

Several samples from the Afon Marlais show evidence for base-metal mineralisation or contamination (Figures 17–22) In the north of the catchment at [21162 21614], site PW207 shows strong base-metal enrichment in the panned concentrate (12200 ppm Ba, 160 ppm Cu, 666 ppm Zn, 25 ppm As). Abundant pyrite was observed in the pan but no gold was seen. 50 m upstream from the site, a brecciated outcrop of Llandeilo limestones and Caradoc shales can be seen, and is probable that there is minor base-metal mineralisation along a small fault that runs through this stream. A site in an adjacent tributary (PW208 at [21184 21624]) also shows enrichment in base metals (2362 ppm Ba, 120 ppm Cu, 543 ppm Zn) which may have a similar source. To the south, site PW418 [21214 21595] near Stonyford shows a similar association of metals (278 ppm Cu, 855 ppm Pb, 500 ppm Zn, 425 ppb Hg, 460 ppm Sn, 5.9 ppm Mo) which may be the product of contamination and the same type of mineralisation on a parallel fault.

The most notable metal anomalies are at site PW407 [21219 21498] in the south of the catchment, where there is enhanced Sn, Pb, Zn, Cu, As, Hg and Mo in the panned concentrate and Sn and Pb in the stream sediment. This site is downstream of Narberth Station, copper wire was seen at site, and it is not clear what are the relative contributions of contamination and natural sources to these anomalies.

Site PW205 [21291 21555] has enhanced Au and Ag in the stream sediment, but had no anomalous concentrations of other elements in either the panned concentrate or the stream sediment. Six grains of gold were panned at this site, which receives material from the southern side of the catchment, formed of folded and faulted Ashgill and Lower Silurian rocks. A black-shale stream clast of probable Llanvirn age collected up stream of here near Whitley Farm [21258 21537] contained 2 mm thick quartz veins and occasional pyrite grains on joint surfaces (PWR1201). This sample gave a weakly anomalous level of Zn (212 ppm).

Another source of gold in this area is provided by the coarse sandstone and conglomerate at the top of the Slade and Redhill Beds, as a gritstone clast (PWR12) from an easterly flowing tributary of the Afon Marlais near Pant-teg [21610 21635] contained 20 ppb gold.

Deepford Brook

This catchment, running east–west across the centre of the survey area, east of Clarbeston Road, contained a number of gold-bearing sites (Figures 13, 16, 17).

Geology. The stream drains a predominantly southward-younging succession of Llanvirn to Llandovery age. In the south of the area, northward-draining tributaries traverse the eastern continuation of the Wiston Syncline (Figure 4). In the north, *Didymograptus bifidus* Beds, including a thick volcanic tuff sequence, are separated from Caradocian *Dicranograptus* Shales by a major, northward-dipping, reverse fault. Two anticlinal inliers of Llandeilo limestones and mudstones are present within the Caradoc outcrop, one to the west of Bletherston and another west of Bullhook, where the limestones exhibit conspicuous calcite veining. South of Deepford Brook, Ashgill strata of Redhill Beds facies directly succeed the Caradoc sequence. The Shoalshook Limestone, seen elsewhere at this level, is absent. Conglomerates, included in the local Ashgill succession, are reported from Cotland Mill Quarry [2053 2194] where they have yielded a reworked Caradoc graptolite fauna (Strahan et al., 1914). The Hirnantian and Llandovery facies of the Wiston Syncline are identical and contiguous with those described from the Fenton Brook area. These strata are also affected by the east–west faults trending from around Llawhaden.

Extensive spreads of glacial sand and gravel are present in the northern part of the area around Clarbeston. In the south of the catchment, northward-flowing tributaries with sources to the east of Wiston drain a large area of boulder clay.

Drainage results. This catchment includes the bulk-sample orientation-study site (PW114) containing gold with associated telluride minerals (see above). Three other sites with anomalous panned gold in Deepford Brook catchment lie along the main stream and thus are close to the upper boundary of the Dicranograptus Shales. These are sites PW421 [20681 21995] with anomalous Cu (960 ppm) and Zn (314 ppm), site PW210 [20604 21982], which is only anomalous for Au in the panned concentrate but has Ag, Ba and Mo enrichments in the stream sediment, and site PW212 [20546 21993], which has enhanced values of Sn and Zn in the panned concentrate, and Au and minor Ba enrichment in the stream sediment.

Several sites along the stream and its tributaries have multi-element anomalies in both the panned concentrate and the stream sediment for some of Au, Ag, Hg, Te, Cu, Zn, Mo, Ba and Sn. For example, in the stream sediment from site PW213 [20513 22086] Mo (49.3 ppm), Ba (12000 ppm) and Ag (492 ppb) are highly anomalous (>98th percentile), with Hg (153 ppb), Cu (85 ppm) and Zn (320 ppm) also above the 95th percentile. Ba, Te and Mo were all above the 95th percentile in the panned concentrate, and one grain of gold was panned at this site. Syngenetic concentrations in black shales are no doubt responsible for many of these anomalies. For example a black-shale sample (PWR1502) collected from exposure in a southward-draining tributary of Deepford Brook to the east of Clarbeston Road [20272 22120] has high values of Mo (33.6 ppm), Ag (242 ppb), Hg (340 ppb) and Ba (4304 ppm). None of the black-shale samples analysed contained Au enrichments (Table 3) but this does not preclude the possibility of black-shale and shear-zone hosted precious-metal and perhaps polymetallic mineralisation in this catchment. The presence of fine and coarse gold in the same samples may indicate that either these sites are close to source, since no sorting of fine gold from coarse gold has occurred, or that there is more than one source of gold.

Sites at which both coarse and fine gold are found include two in the main northward-flowing tributary to Deepford Brook, north west of Llawhaden (PW318 at [20480 21812] and PW424 at [20220 21665]). One of these is also anomalous in Sn and Ag in the stream sediment and in Ag in the panned concentrate. There is also a site containing Au in stream sediment in this area (PW225 at [20470 21803]) and another (PW317 at [204935 21829]) in a tributary stream draining land to the east around Cotland from where anomalous Au and Hg were recorded in the panned concentrate. These northward-flowing tributaries drain a large area of boulder clay, which is likely to have been the initial source of a stream sediment.

The stream sediment from site PW530, also in a northward flowing tributary to Deepford Brook [20536 21940], contains 658 ppb Au and weak Hg enrichment (140 ppb). The site is located close to outcrop of a Ashgill conglomerate at Cotland Mill [20540 21935] which contains eroded clasts of *Dicranograptus* Shales (Strahan et al., 1914) and it is possible that there may have been some redistribution of fine gold within the Upper Ordovician.

Fenton Brook area

This westward-draining catchment lies to the east of Haverfordwest on the western margin of the survey area.

Geology. The catchment lies within the east–west trending Llawhaden Anticline (Figure 4). The brook and many of its tributaries are underlain by Ashgill strata, which occupy the core of the structure. In the east and north of the catchment these are predominantly of the Redhill Beds type, but in the south-west, around Fenton, they give way to Slade Beds facies. To the north, in the Wiston Syncline, the succeeding Hirnantian sandstones occupy a broad outcrop. The sandstones are coarse grained and locally pebbly and conglomeratic in their lower part, becoming finer upwards as they grade into the overlying Haverford Mudstone Formation. A comparable succession is encountered on the southern limb of the Llawhaden Anticline, though here mudstones intercalated within the Hirnantian sandstone sequence allow the quartzitic Cethings Sandstone to be separately distinguished. A complete, largely Llandovery, Haverford Mudstone Formation sequence, including the Cartlett Beds and Gasworks Mudstones divisions of Strahan et al. (1914), is succeeded by the Gasworks Sandstone. Faults known to affect both flanks of the anticline in the east of the area form part of the complex and laterally extensive fracture belts recognised in Robeston Wathen and Llawhaden areas further east. They possibly extend further west than depicted on the published map and may disrupt the poorly exposed Ashgill sequence within the core of the Llawhaden Anticline. The potentially complex nature of the anticlinal core is demonstrated at Shoalshook [1968 2170], beyond the western edge of the area, where, in a faulted inlier, the Shoalshook Limestone and underlying Llanvirn mudstones are thrust over Ashgill rocks (Strahan et al., 1914).

Glacial deposits, mainly sand and gravel, are present as isolated patches in the west of the area, notably around Crundale Hook [1980 2197] and east of Shoalshook [1975 2168].

Drainage results. Two sites in the lower part of the Fenton Brook catchment yielded gold grains (Figure 12). One of these sites, which receives sediment from much of the catchment, also showed anomalous concentrations of As, Cu, Sn and Zn in the panned concentrate, but neither site had any enrichment in elements in the stream sediment. The second drains a small area north of the A40 road cut by the Ordovician–Silurian boundary but contains no rock exposures except near to the northern limit of the catchment. Stream clasts are extremely variable, and are covered in a heavy brown Fe-Mn precipitate. The low flow of this stream and the lack of exposure suggest that most of the stream clasts have been eroded from superficial deposits. No evidence for the Cethings Sandstone, black shales or mapped fault could be seen, and in two pits dug by the farmer for rough stone and rubbish disposal in the field to the west of Good Hook Cottage the rocks are grey mudstones, not unlike the Ashgill rocks exposed in the small quarry to the south of Wiston [2014 2171].

Approximately 4 km upstream from these two sites, south of Wiston, is another site (PW428 at [20178 21732]) only anomalous for Au. Here the bedrock comprises Upper Ordovician and lower Silurian rocks. Adjacent sites are not anomalous, but to the east further anomalies are recorded in the northward-flowing tributaries to Deepford Brook. Elsewhere along Fenton Brook several samples returned small but above background levels of Au (Figures 12, 15 and 16).

Discussion

The drainage results confirm the presence of gold in streams over much of the area and indicate a number of prospective catchments from which drainage samples consistently return appreciable levels of Au in panned concentrate, often accompanied by Au in stream sediment. The most prospective areas include parts of the four catchments sampled in some detail: Afon Marlais, Deepford Brook and Fenton Brook, and the area south of New Moat. Gold in streams adjacent to these are in many cases likely to represent extensions of the same sources of mineralisation that are responsible for the principal anomalies.

On the basis of the magnitude and number of anomalous sites, the most prospective catchment would appear to be Deepford Brook. Here high panned Au values are often accompanied by high values of base metals in both stream sediment and panned concentrates that at least in part are probably related to the presence of Caradocian black shales. A major east–west geophysical linear (Figure 5) roughly follows the line of the brook. Several major east–west faults cross the area and, together with the black shales, could control the location of precious-metal mineralisation. The size of the prospective area is approximately 7 km east–west by 2 km north–south, and represents a large target that merits more detailed evaluation.

Catchments containing anomalies lie along strike from Deepford Brook, including Cartlett Brook west of Clarbeston Road, and the Afon Conyn and the Afon Daulan to the east and west of Clunderwen respectively. These show geological and geochemical similarities with the Deepford Brook area, and the drainage anomalies may have the same sources.

The area south of New Moat is also considered prospective. The geology is less well known in this area, but the geological setting has features in common with the Deepford Brook area, the Arenig and Llanvirn succession containing black shales and cross-cut by a major east–west fault structure. In contrast to much of the southern part of the survey area, including Deepford Brook, many of the anomalous streams here cut to bedrock, aiding any follow-up work.

The upper part of the Afon Marlais catchment, east of Narberth, also has potential for gold mineralisation but the anomalies in this catchment are sporadic and, at least locally, base-metal values are influenced by contamination. However, the presence of complex anticlinal and synclinal structures cut by faults and a succession of Llanvirn to Llandovery rocks are favourable features for gold mineralisation. Two major geophysical linears also cross the area (Figure 5).

The Fenton Brook catchment, to the east of Haverfordwest, is a relatively compact target area with some characteristics features, notably the Upper Ordovician to Lower Silurian age of the rocks, the lack of mapped major faults and the lack of anomalies in the fine sediment. Major geophysical and satellite imagery linears appear to terminate in this area (Figure 5).

The presence of gold in a number of catchments separated by distances of up to 15 km and characterised by different geology and structure suggests more than one source. This is supported by the mineralogical studies carried out on the bulk samples collected for the orientation study and the absence of a clear geochemical mineralisation signature, gold showing few highly significant correlations with other elements determined. The clearest associations are with Sn and Ag, weaker associations are evident with Hg and a range of base-metals. Looking more closely at individual catchments, an association with black shales and elements concentrated in them is evident, notably with those of Caradoc age in Deepford Brook, but also with older rocks, such as in the area south of New Moat. In both areas shear zones cutting the folded sedimentary sequence, could provide an Ogofau-type anticlinal or fault-related mineralised source. The association with Sn and the mineral cassiterite suggests granite-related mineralisation which is unknown in south-west Wales and leads to the possibility that it is an inherited signature related to gold in palaeoplacers, probably within coarse clastic rocks of the Ashgill/Llandovery succession which are known locally to contain reworked black-shale clasts from the Caradoc.

Gold may have been redistributed and concentrated in fluvio-glacial sediments, but in at least some areas such as Deepford Brook, it appears from its morphology and associated metal enrichments to be locally (< 1 km) derived.

To provide additional information on the source(s) of gold and a foundation for follow-up work, a limited number of overburden samples were collected and additional gold-grain characterisation studies carried out.

Geochemical overburden survey

Two well-constrained areas were selected for a short programme of overburden sampling: the Afon Marlais catchment to the north-east of Narberth, and the Fenton Brook catchment to the south and south-west of Wiston. The Deepford Brook and New Moat areas were not selected for follow-up because of the size of the prospective area with respect to the resources available.

Nine pits were dug in the Afon Marlais catchment and 16 in the Fenton Brook area (Figure 26). Two further pits were dug close to two other gold-bearing drainage sites. These were on the south side of Deepford Brook (PW532 at [20526 21985]) and by the Afon Conyn, north-west of Clunderwen (PW534 at [20950 21911]). A third pit was excavated at the site of a suspected ?"old level" noted on the 1911 geological field slips on the south side of Church Hill Brook [20314 21974].

In the Fenton Brook area the pits extended from Slade Bed facies Ashgill rocks in the north, across the Cethings Sandstone, onto the lowermost rocks of the Llandovery age Haverford Mudstone Formation in the south. The glacial sand and gravel mapped east of Shoalshook was encountered in the north.

In the Afon Marlais area, mapped superficial deposits include a small area of glacial sand and gravel at Stonyford [2122 2158] where an overburden sample was collected. A second sample, to the north, was sited on the Mydrim Limestone. The main traverse sampled, still further north, traversed an area underlain by boulder clay, *Dicranograptus* Shales and Redhill Beds facies Ashgill, and crossed the main fault affecting the northern limb of the anticline. This area also includes the bulk site containing tin minerals (site PW112).

Sampling and analysis

Pits were dug manually to depths of up to 1.4 m, where possible on convex slopes 30–50 m from the sides of the anomalous streams (Figure 26). Pits were generally dug to the B or C horizon, and bedrock was reached in one pit (PW601 at [21224 21643]). Much of the sampled material was clast-rich and of local derivation. Material was taken from the bottom of each pit, washed, sieved at 2 mm, and the undersize fraction panned to yield a concentrate of approximately 60 g. The total initial volume of material varied due to the different grain sizes of the soils. For example, larger amounts of material (up to 50 litres) were taken if the soil was either clast-rich or clay-rich in order to provide sufficient material to pan after washing and sieving. The average initial volume was 26 litres. Any mineralised clasts were sampled and analysed. An unprocessed overburden sample of approximately 500 g and a selection of clasts were also taken at each site and retained as reference material.

In the laboratory the overburden panned concentrates were prepared for analysis by the same method as that used for the drainage panned concentrates. The samples were analysed by ICP-OES for Au and the same range of other elements as the drainage panned concentrates at AALL, Vancouver, and by XRFS in the BGSL for Cu, Zn, As, Pb, Bi, Sn, Sb, Fe, Cr and Ba. The concentrate from site PW532, containing visible gold, was examined mineralogically and the gold extracted but not analysed. The two other samples containing visible gold (PW534 and 624) were sieved at 500 μm, superpanned and the gold grains removed prior to milling and analysis.

Results

<u>Field observations.</u> Where sampled, it appears that the drift cover on convex slopes is generally thin (< 2 m). Exposures of drift in stream banks typically show two layers of superficial deposits: a thin gravelly clay with angular clasts of local bedrock (commonly grey coloured), and a thicker (up to 2 m) orange clay with sparse, rounded, exotic clasts (e.g. silicified tuffs, granodiorite, dolerite).

On the Fenton Brook traverse, the geological map indicates the presence of glacial sand and gravel, but no superficial deposits of this type were encountered in any of the pits. Till was found in three pits (PW612, 613 and 622) and some others contained clay-rich horizons with abundant locally derived clasts.

The samples taken from the Afon Marlais traverse were quite variable. Most consisted of silty clay B/C horizon soils, but the two pits to the east of Pant-y-gorphwys had till horizons (PW604 and 605), which verifies the mapped geology, and the two pits to the south of Orielton-Fach contained more loamy soils.

At most sites the panned overburden from all the sampled areas was poor in heavy minerals, with only minor iron oxides and zircon observed. Oxidised pyrite was seen in a few pans and a possible grain of cerussite was noted in a pan from the Fenton Brook traverse (PW615). A pit from the south bank of Fenton Brook, which may contain alluvial sediment (PW624 at [19787 21724]), yielded six grains of gold.

The pit dug on the south side of Deepford Brook, approximately 150 m upstream from a gold-rich site (PW212) bottomed at 80 cm in clast-rich clay on bedrock. From 14 litres of material, 2 litres of <2 mm fraction was panned to approximately 40 ml and yielded four grains of angular gold up to 3 mm across. No other heavy minerals were observed except for moderate amounts of magnetite. The overburden in this pit was mostly locally derived, with clasts of sandstone, siltstone and vein quartz in a yellow-grey clay matrix. The occurrence of gold in the panned overburden at this site suggests that the gold is not derived from exotic drift clasts and confirms that detailed overburden sampling in this area would be merited.

At the site of the ?“old level” by Church Hill Brook, there is no visible sign of any excavation now, but there were abundant angular quartz clasts present in the soil; no heavy minerals were seen in the concentrate.

The panned concentrate taken from the pit on the bank of the Afon Conyn downstream of a gold-bearing site yielded one grain of gold. The river bank exposed a good section through 1.5 m of grey, locally derived till overlying a 15 cm thick gravel bed rich in small angular quartz clasts on top of Caradoc mudstone bedrock.

Chemical analyses. Summary statistics for key elements are shown in Table 10. The highest values of many of the ore-forming elements (e.g. Mo, Hg, Cu, Zn, As, Sn, Bi but not Pb) occur at site PW609 on the south bank of the Afon Marlais [21250 21564]. The mapped geology at this location is Lower Llanvirn shales, and there is no significant mapped drift. The level of concentration of the metals is such that most of the anomalies could be explained by the presence of shales and some heavy minerals such as monazite, but the site is close to several stream sites with anomalous Au values and the possibility that mineralisation occurs locally cannot be ruled out. Site PW602 produced the only other pit sample with anomalous geochemistry in this catchment. It contains the highest Ba content (1297 ppm) recorded but, again, this level need not be the product of mineralisation.

Table 10 Summary statistics for all overburden samples (27)

	Mo ppm	Ag ppb	Hg ppb	Au ppb	Cu ppm	Zn ppm	As ppm	Pb ppm	Sn ppm	Ba ppm
Maximum	4.2	1578	94	8440	39	151	55	246	103	1297
Minimum	0.4	<30	<5	<1	6	25	<5	8	<5	37
Median	1	<30	21	3	18	66	25	24	5	548

Mo, Ag, Hg and Au analysed by ICP-OES at AALL; other elements by XRFS at BGSL.

The sites dug in the Fenton Brook catchment generally showed low values of all elements, with the exception of the site with visible gold (PW624) which had enhanced levels of Au (8440 ppm) and Ag

(1578 ppm) despite removal of coarse gold, suggesting that there is also fine gold present. Also in this catchment, site PW615 had slightly anomalous Pb (246 ppm) and Ag (31 ppb). Cerussite was observed in the panned concentrate from this site.

Samples from the sites dug near an old level by Church Hill Brook and the site dug in the bank side of the Afon Conyn showed no anomalous concentrations of ore-forming elements.

MINERALOGY

Mineralogy of panned concentrates

Six panned-concentrate samples from the orientation survey and 36 from the main and detailed follow-up drainage surveys were selected for mineralogical study on the basis of their gold, sulphide, or other heavy mineral content based on field observation and chemical analysis. The samples were sieved and the >500 µm fraction examined under a binocular microscope for visible gold, which was extracted for electron microprobe chemical analysis and characterisation studies.

Other grains of possible interest were extracted from the orientation samples and attached to microscope slides for later identification using an electron microprobe. The results of this exercise are reported in the orientation studies section.

Characterisation of gold grains

Alluvial gold grains frequently show internal heterogeneity in chemical composition of the gold and the presence of inclusions of other minerals. Recent work by the BGS using alluvial grains taken from many countries and geological settings has shown that the compositional and inclusion characteristics are very varied, but much can be deduced about the source of the grains from the composition of parts unaffected by subsequent replacement, deposition and leaching events and that grains can be related to the type of deposit from which they are derived. Consequently the study of alluvial gold grains provides valuable information on their bedrock source (e.g. Leake et al., 1993, 1997, 1998).

Electron-microprobe spot analyses indicate that elements other than Ag occur only rarely in the Pembrokeshire gold. There are three grains with a significant Pd content. These are from different areas, coming from sites in the Afon Marlais (PW203 at [21258 21537]), Afon Conyn (PW533 at [20949 21988]) and a tributary to the Cartlett Brook (PW444 at [20030 22361]). The grain from the latter site has a concentration (8.2% Pd) as high as the maximum found in grains from Devon (Leake et al., 1983). Also like the Devon grains, these are very low in silver (maximum 0.9% Ag). Although they form a very small percentage of the grains recovered, they can be identified and considered as a separate population of grains probably derived from ‘oxy-gold’ red-bed mineralisation.

The electron-microprobe spot analyses of the Ag content are plotted as cumulative curves for all grains at each site in Figure 27. Silver contents are variable and indicate multiple populations. The majority of gold grains are very similar in their median Ag levels and compositional range (see shaded area in Figure 27). However, there are two samples where the pattern of Ag distribution differs significantly from the others. The most noticeable difference is for grains from one of the samples collected during the orientation survey from just above the confluence of the Deepford Brook with the Afon Syfni (PW114 [20706 21989]) which consists of two populations marked by a sharp change in slope on the cumulative plot. The lower population has a sharply defined composition around the 6% Ag level while the upper probably corresponds to the predominant type in the area. Similarly, the shape of the cumulative plot of the Ag content of gold grains from the Llandeloy area is quite distinct.

Inclusions have been detected in gold grains from most of the areas but in highly variable amounts. The inclusion assemblage which characterises the majority of gold from the area comprises, in order of abundance, pyrite, galena, chalcopyrite, molybdenite and gersdorffite together with isolated grains of arsenopyrite, cobaltite and stannite. In sharp contrast the inclusion assemblage of grains from sample PW114 is characterised by the tellurides coloradoite, petzite and a Cu telluride, together with pyrite and pyrrhotite. Both the Ag levels and the inclusion assemblage indicate that the gold of this type is derived from an entirely different source from the majority of the gold across the rest of the area. There are insufficient inclusions in the gold from Llandeloy or Pant-y-gorphwys to define an inclusion assemblage.

Types of alluvial gold

From the composition and inclusion assemblages, four types of gold grains have been recognised in the samples examined. The predominant type, occurring widely, displays a very similar compositional range and inclusion assemblage. The inclusions consist, in decreasing order of abundance, of minerals containing the elements S, Fe, Pb, Cu, Mo, As, Ni, Co and Sn. The presence of Mo and Sn strongly points to acid granitic-type rocks, while the preponderance of Pb suggests either a granitic association or a shale association. This assemblage could, therefore, indicate mineralisation associated with a high-level granitic igneous body intruded into an ordinary sedimentary sequence. The absence of tellurides suggests that there is probably no magmatic component to the mineralisation but that the granite acts as an energy source for fluids in equilibrium with sedimentary rocks.

One sample (PW114) contains a well-defined type of gold with telluride inclusions. The preponderance of telluride inclusions suggests a primary igneous source and the coloradoite-petzite assemblage is similar to that found in the gold from the Afon Wen in the Dolgellau Gold Belt. The sample was taken from just above the confluence of the Deepford Brook with the Afon Syfni where there are no igneous rocks mapped so the source is not immediately obvious.

On the basis of the distribution of Ag, the gold in the Llandeloy area is probably derived from an entirely different source to the gold which predominates in the rest of the area. The most obvious source is the disseminated porphyry-type mineralisation and overlying alluvial deposits recorded here by previous MRP work (Allen et al., 1985).

In the Pant-y-gorphwys area there is likely to be a local source of gold of a different type, though inclusions from several grains would be required to establish the likely nature of the source material.

SOURCES FOR THE ALLUVIAL GOLD

There is a wide geographical distribution of gold in this area, and grain morphology suggests that at least some is locally derived. Besides its wide geographical distribution, there is evidence from the gold characterisation studies of more than one source. However, not all the sources indicated by the characterisation study appear to be present in the area. In particular there are no exposed granitic rocks at surface in the principal gold-bearing catchments to the east of Haverfordwest. There are, however, granitic and acid volcanic rocks in the Ordovician and Precambrian elsewhere in south-west Wales. The apparent enigma can therefore be explained if the gold is transported, either by glacial or fluvial action during the Quaternary or by erosion, transport and deposition to form palaeoplacers during much earlier events. The lack of association of the gold with sulphides and the absence of any clear pathfinder elements would also be explained if most of the gold was derived from palaeoplacers.

The possibility that gold in the main catchments east of Haverfordwest could at least in part come from drift derived from the late Precambrian succession and the acid intrusions to the west of Haverfordwest can be discounted (i) because of predominant glacial and fluvioglacial transport directions (Campbell and Bowen, 1989), (ii) because the presence of gold in locally derived overburden near Deepford Brook, and (iii) because alluvial gold from the Llandeloy area, probably derived from porphyry-type mineralisation associated with high-level acidic intrusions in this area, is of different character from that found in the survey area. An alternative source might be acidic igneous rocks associated with Ordovician volcanism exposed to the north, except that drainage sampling indicated that little gold is associated with these rocks (Cameron et al., 1984). However, it cannot be completely eliminated as a source because, for example, most gold in the west of the Fenton Brook catchment occurs close to pockets of glacial gravels which might contain lenses upgraded in gold from relatively weak or dispersed sources by fluvio-glacial action.

Gold is often seen in streams with abundant quartz-vein clasts; these are both angular and rounded and so could be derived from conglomerates or from local veining or both. The distribution of alluvial gold and the results of chemical analyses of rock samples both suggest that gold might be enriched in the coarse clastic rocks close to the Ashgill–Llandovery boundary. The proximal facies of the Redhill and Slade Beds are a possible source, but the most likely would appear to be the overlying sequence of dark mudstones with thick conglomerates and a quartzitic sandstone unit (the Cethings Sandstone). These are classified on published maps as basal Llandovery and grouped together as Basement Beds in the Geological Survey memoir (Strahan et al., 1914), but more recent work shows them to be Ashgillian (Ingham and Wright, 1970). Collectively, these strata record facies changes associated with the major, late Ashgill, glacio-eustatic regression. Uplift created high-energy environments and rapid erosion of the Midland Platform, which could have been favourable conditions for the erosion and deposition of gold-bearing palaeoplacers.

There is some evidence for the presence of disseminated fine-grained gold in rocks of the Lower Ordovician in the northern part of the study area. This association is not well defined, but may be widespread. The geology and structure in the area are not well known, but the deeply dissecting valleys could provide good exposure of potential host rocks.

The chemical analysis of Caradoc *Dicranograptus* Shales from the coastal section at Druidston Haven (Appendix 1) suggests that there is no gold associated with the sulphide mineralisation in these rocks. However, this lithology does contain higher concentrations of ore-forming elements and may act as a source for metals, or react chemically with hydrothermal fluids passing through fractures and cause the precipitation of gold. The apparent lack of correlation between the occurrence of gold in concentrates and elements concentrated in black shales would seem to preclude the black shales as a host, but the presence of telluride-bearing gold (similar to that from the Dolgellau gold belt) at site PW114 close to a major east-trending fault with *Dicranograptus* Shales on the north side may indicate the presence of shale-hosted mesothermal gold mineralisation nearby.

Although the Caradocian *Dicranograptus* Shales represent the major outcrop of black shales in the area, the youngest Ashgill and some of the older successions (Llanvirn and Llandeilo age) also contain mudrocks that may have a black-shale composition. Because of their physical properties they do not outcrop extensively, but in the north of the area east- or north-east-trending fault zones running north of East Walton and south of New Moat cut a poorly documented Arenig–Llanvirn succession known to contain quartz-veined and brecciated mudstones in one gold-bearing stream. A few analyses of the veined and brecciated rocks did not contain gold but such a geologically attractive target should not be written off on the basis of this scanty evidence. The Ashgill black shales are synchronous with the conglomerates that may contain palaeoplacers, and stratigraphically these are at the same level as the host rocks at Ogofau. This may therefore represent a prospective horizon, for two types of gold mineralisation, and is worth particular attention where cut by significant fault structures.

An unexplained feature of the alluvial gold in this area remains its apparent spatial relationship with the Haverfordwest and Narberth magnetic anomalies. These are interpreted as reflecting depth to an apparently structurally discordant basement and it is possible that the relationship is with major fault structures controlling the form of the magnetic anomaly rather than physical distance from the basement.

Although some gold may have been spread by glacial and fluvio-glacial activity, the available evidence leads us to favour palaeoplacers formed during eustatic uplift at the end of the Ashgill as a principal source of the alluvial gold found in this area. Other probable sources are black-shale-hosted shear-zone mineralisation, notably of Caradoc age and, adjacent to the survey area, porphyry-type mineralisation, of possible late Cambrian age. Late Variscan tectonic activity may have redistributed the gold from any these protoliths, possibly leading to local upgrading of the mineralisation. Of these sources, black-shale-hosted shear-zone mineralisation, perhaps similar to that at Ogofau, is likely to be of most economic interest and further work is merited to try and locate any such source.

CONCLUSION AND RECOMMENDATIONS

1. Alluvial gold occurs in many streams in south-west Wales, mostly with catchments in fine to coarse-grained sedimentary rocks of Lower Palaeozoic age.
2. The alluvial gold is probably derived from more than one source. The principal source in the survey area is likely to be palaeoplacers in coarse clastic deposits at the top of Ordovician, formed during glacio-eustatic regression at the end of the Ashgill, but some may be derived from black-shale-hosted shear-zone mineralisation. Adjacent to the survey area, porphyry-style copper mineralisation containing minor gold provides an additional source. Some gold may also be derived from fluvio-glacial deposits.
3. Further work is merited to try and locate black-shale-hosted shear-zone mineralisation. The two most favourable areas would appear to coincide with major east-trending fault structures running through Deepford Brook and south of New Moat.
4. Follow-up investigations should include traverse-based pit sampling and electron microprobe investigation of any gold found. Further rock sampling is merited and trial geophysical surveys should be carried out to determine their usefulness in precisely locating mineralised structures, though the combination of shear zones and black shales containing sulphides may generate results that are difficult to interpret.

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APPENDIX 1 Description of Key Rock Exposures

Whitland (Fron) road section [2170 2170]

This is the best section in the area, 3 km west of Whitland on the A40, providing excellent exposure 1.1 km long, through *Dicranograptus* (Caradoc) Shales, Bala limestones and Slade and Redhill Beds (Ashgill), dipping to the north-west. This section shows the debated junction between Caradoc and Ashgill sedimentation. The junction was considered by Strahan et al. (1914) to be unconformable on the basis of fossil occurrences, but the beds appear to have continuous sedimentation in this exposure: friable pyritic black shales become progressively more carbonate rich upwards into the Robeston Wathen Limestone of Bala age. The sequence is continuous and the perceived stratigraphical gap is due to changes in the sedimentary environment. The contact between the Slade and Redhill Beds and the underlying sequence is not seen. These Ashgill rocks consist of alternating decimetre scale distal turbidite sheets with distinct shelly lag bases, graded sandy beds, occasionally laminated upper sequences and bioturbated tops. These are interbedded with uniform grey shales.

There is minor, sporadic mineralisation visible in the section. In the *Dicranograptus* Shales, pyrite occurs as coarse (up to 3 mm cubes) joint coatings, and there is sparse pyrite within the black shales as cm-scale pods and disseminations. Towards the top of the sequence, decimetre-thick limestones (the Robeston Wathen limestones) appear and at the top of one of these beds is a cm-scale iron-stained horizon which consists of nodules of pyrite set in a dark grey mudstone matrix. The limestones are generally grey and dense with a few fossils but locally they are crosscut by coarse carbonate veining with euhedral calcite, pyrite and hematite. Similar mineral assemblages were seen in some panned mineral concentrates taken over the Slade Formation to the east of Haverfordwest. Veins in the limestone do not generally continue into the interbedded mudstones, probably as a result of differences in permeability and competence. Disseminated pyrite was also visible in the limestones. The overlying Ashgill sequence consists of grey mudstones and siltstones with mm-scale vertical quartz veining trending approximately north–south.

Stonyford, Narberth [2120 2159]

This easily accessible stream section, upstream from Stonyford, exposes a syncline in Llandeilo limestone and *Dicranograptus* Shales. The limestone is abundantly fossiliferous and veined in places. As in the Whitland section, the *Dicranograptus* Shales are black and pyritic and yield abundant graptolites. The shales are variably cleaved and this may be related to a fault, which is mapped parallel to the stream here, rather than to regional cleavage.

Canaston Bridge [2065 2152]

This road section, on the A40 near Canaston Bridge, cuts Llandovery rocks of the Haverford Mudstone Formation which are mostly grey mudstones with occasional gritty bands. Several sandy bands with laminated tops representing distal turbidite deposits are present. In the type Gasworks section in Haverfordwest, the beds are fossiliferous, but lower in the sequence they contain fewer remains and none were seen in this section.

Cotland Mill Quarry [2053 2194]

This quarry exposes sandstone and conglomerate within the Slade and Redhill Beds and received particular mention in the BGS memoir because the conglomerate contains large clasts of black shales of proven Glenkiln age, together with fossils of Ashgill age, thus indicating that denudation of Llandeilo/?Lower Caradoc rocks was occurring during Ashgillian times (Strahan et al., 1914). This locality is now largely overgrown, but clean faces still exist and clasts of a coarse fossiliferous sandstone can be found.

Longlands Quarry [2038 2186]

Exposure at this overgrown quarry in the basal conglomerate of the Llandovery is poor due to vegetation, but marked variation can be seen in lithology from coarse conglomerates through to grits and shales. Better exposure of the conglomerate can be seen in blocks in the barn wall at Longlands Farm. Here rounded cobbles of quartz-vein material and various other assorted clasts are set in a fine-grained matrix. The conglomerate is mainly clast supported, and graded beds can be recognised in some blocks. Examples of this conglomerate can also be seen in the walls of Wiston Castle [2022 2182], the stone for which was said to be taken from an old infilled quarry at [2026 2187].

Valley Farm Quarry, Wiston [2014 2171]

This small quarry in Upper Slade and Redhill Beds south of Wiston exposes fresh and near vertical beds of banded mudstones which are amongst the finest-grained Ashgillian sediments seen from the Welsh Basin. There is some bioturbation, but lamination is common and body fossils were not seen. Some small shears with ?gossanous/sericitised fault gouge are visible within the mudstones. The overburden is clearly shown here and is no more than 1 m thick. The top 0.5 m of the bedrock has been affected by soil creep and is bleached (?due to periglacial action).

Pant-y-gorphwys, Narberth [2115 2161]

A stream section between Pant-y-gorphwys Bridge and Blaenmarlais [2110 2116] exposes a faulted section of Llandeilo limestone and Caradoc shales with several crush zones and extensive quartz-carbonate veining.

Pwll-y-gors Hill [2055 2212]

Here slaty black Caradoc shales are faulted against Llandeilo limestone and Asaphus ash with associated quartz veining and brecciation.

Haverfordwest [19580 21540]

The type section for the Gasworks Mudstone and Sandstone (basal Llandovery) is on the north side of a minor road to the south-east of the railway bridge on the north bank of the Western Cleddau. Southward steeply dipping mudstones and fossiliferous sandstones are exposed.

Druidston Haven [186 217]

A horst of *Dicranograptus* Shales is faulted to the north and south against Coal Measures sandstones here [186 217]. The Ordovician rocks are structurally complex, with recumbent folding and several steep faults. Hancock et al. (1983) describes this section with respect to the overprinting of Variscan folding on the earlier Caledonian fabric. To the north of the outcrop, near Priest’s Vault, the shales are extensively quartz-carbonate veined. Hancock et al. (op. cit.) considered that this veining was Caledonian, and that in the northern part of the outcrop it had not been deformed by later Variscan movements. However, to the south these veins have been folded on a millimetric scale as a consequence of Variscan tectonics. The veining includes minor pyrite, chalcopyrite and ?arsenopyrite. The cliff face has a highly gossanous appearance, mostly due to the weathering of bedding-parallel pyrite comprising up to 20% of the rock by volume. The pyritous beds up to 4 cm thick are crosscut by the veining and in places folded and boudinaged. The Carboniferous strata to the north have some minor quartz veining, with possible disseminated pyrite of probable diagenetic origin. To the south of the outcrop, the quartz-carbonate veining in the black shales is less intense, but pyrite is still common. In addition, there are some carbonate-cemented decimetre-scale nodules within the black shale with disseminated pyrite, the sulphide concentration increasing to the centre of the nodule.

APPENDIX 2 BGS Reference Standards Analysed by Acme Laboratories Ltd

	Cu ppm	**Pb ppm**	**Zn ppm**	**Ag ppb**	**As ppm**	**Sb ppm**	**Bi ppm**	**Hg ppb**	**Te ppm**	**Au ppb**
KLR 1179	15.2	2.7	19.2	286	3.5	<0.2	0.8	<5	0.9	1328
	13.4	2.8	21.2	229	3.0	0.3	0.6	<5	0.6	1735
	12.7	2.7	19.5	207	3.2	<0.2	0.6	6	0.8	1721
	15.6	3.5	21.1	224	3.0	<0.2	0.5	18	0.7	2240
MHS 101	38744.1	31.0	85.9	748	463.2	57.8	13.4	2581	8.4	212
	42388.8	52.1	23.2	1744	534.0	60.1	2.0	1749	5.0	313
	39898.8	51.8	21.9	1616	512.7	64.0	57.2	2104	14.5	440
	37906.9	43.9	20.2	1155	472.7	40.2	3.0	1963	15.2	343
PGR 8108	3743.0	40.2	162.9	2029	0.6	<0.2	<0.1	13	0.7	10
	4235.7	51.5	204.0	2168	2.5	0.3	<0.1	56	1.2	10
	3914.2	52.0	186.1	4091	2.6	<0.2	<0.1	105	3.6	23
	1909.8	25.6	88.5	1189	<0.5	<0.2	<0.1	18	0.7	13

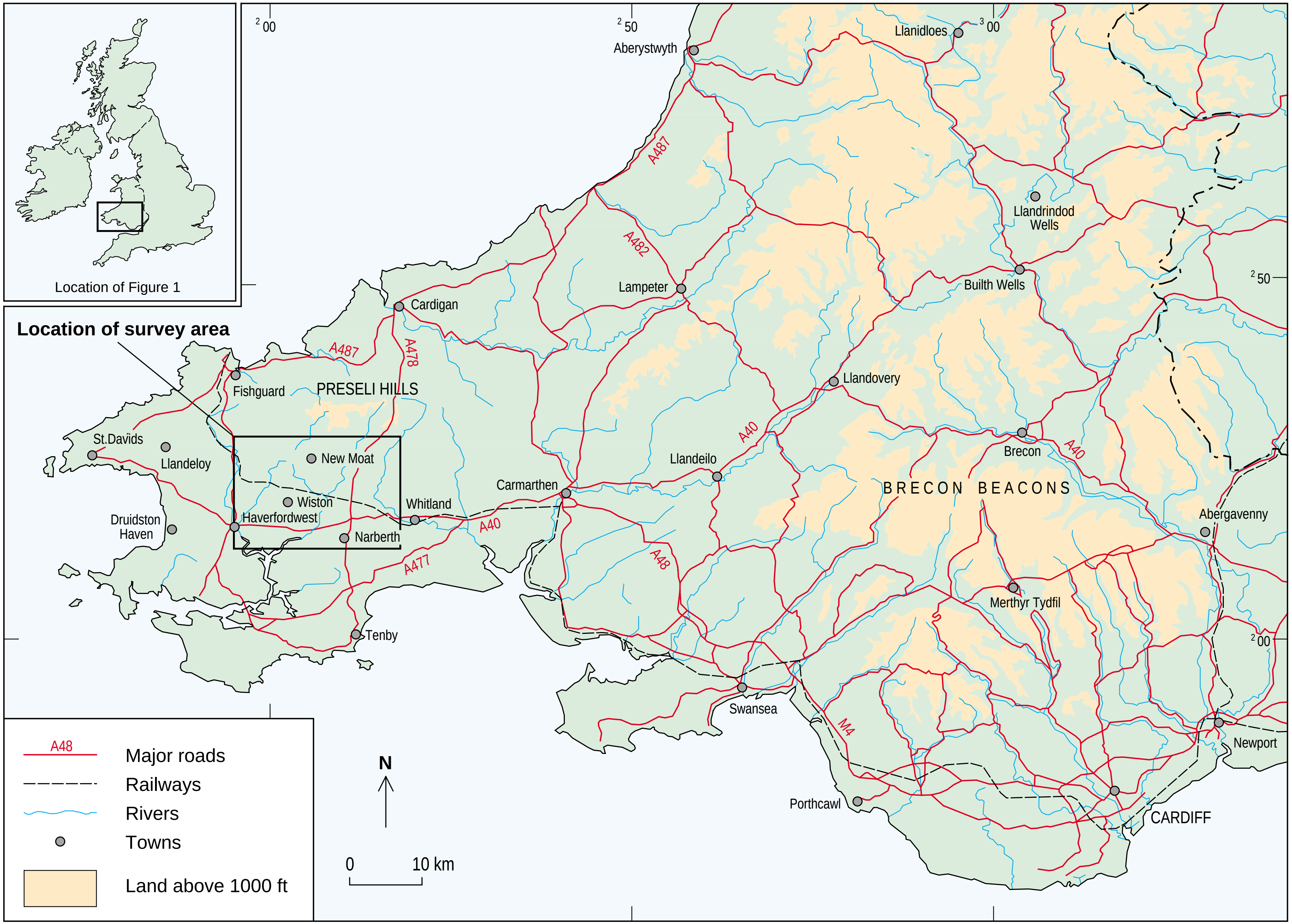

Figure 1 Location of the survey area

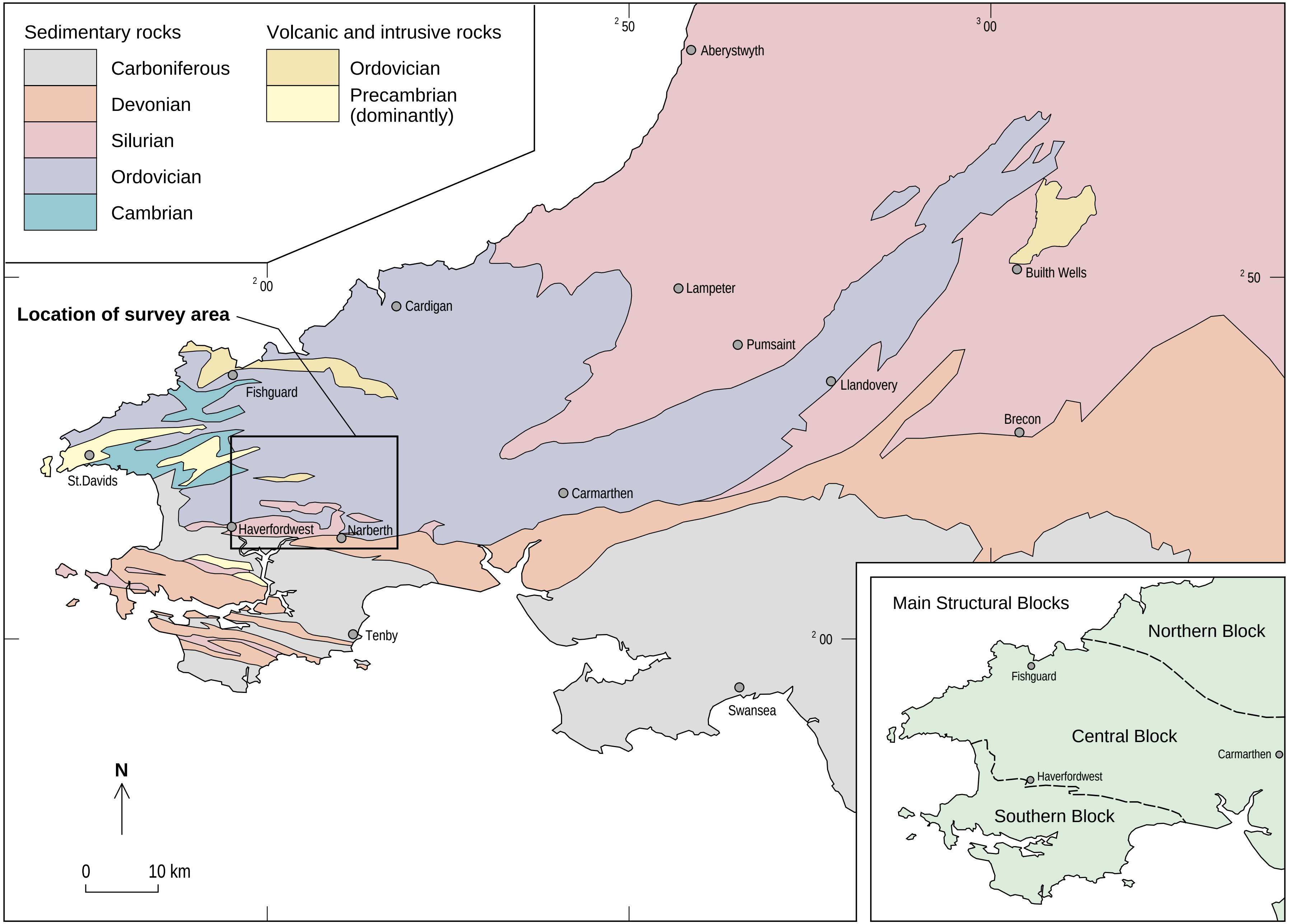

Figure 2 Simplified geological map of south-west Wales

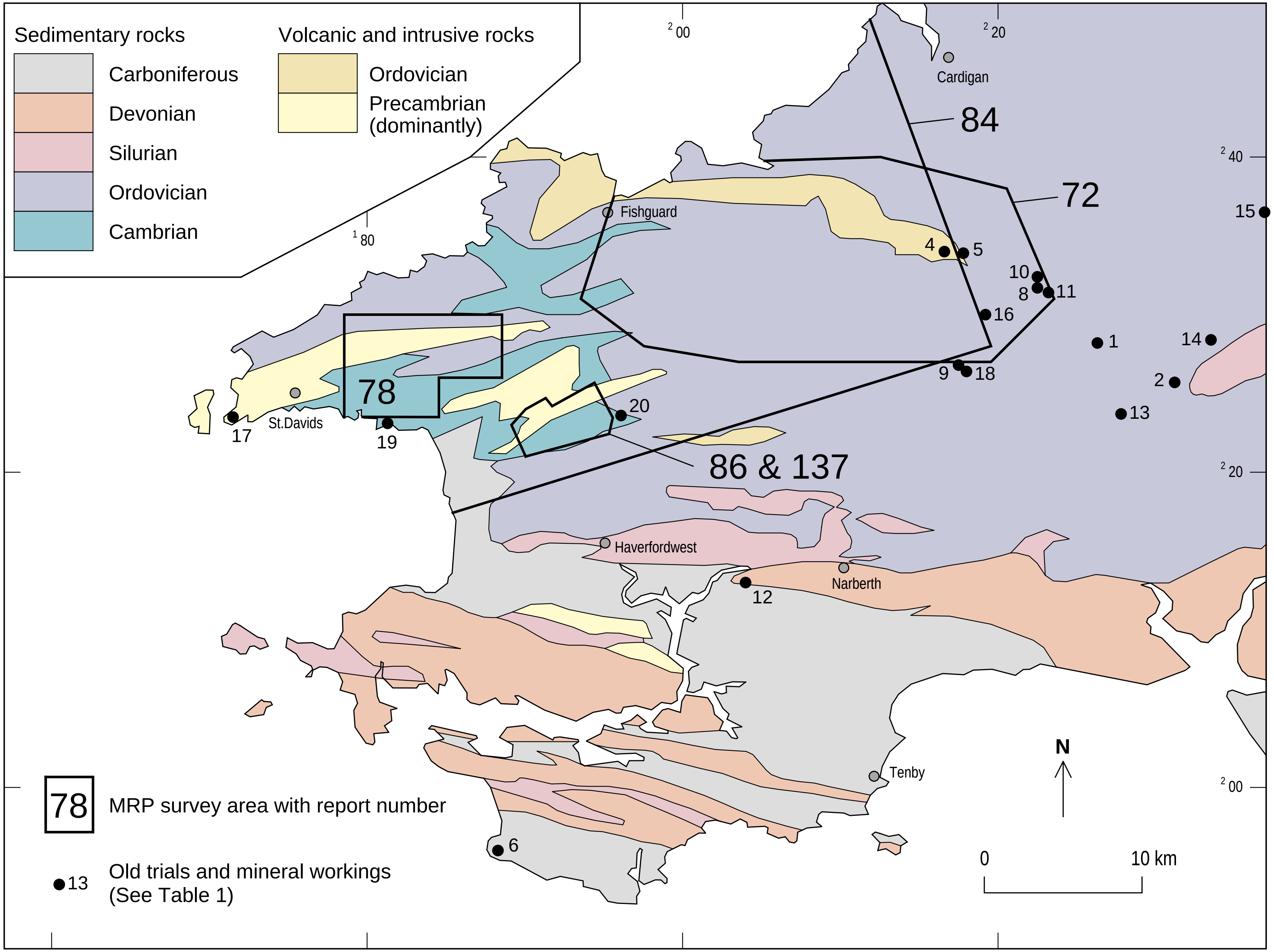

Figure 3 Location of MRP survey areas and old metalliferous mineral trials and workings west of Carmarthen. [72: Cameron et al. (1984), 78: Allen et al. (1985), 84: Cornwell et al. (1986), 86: Brown et al. (1987), 137: Colman et al. (1995)]

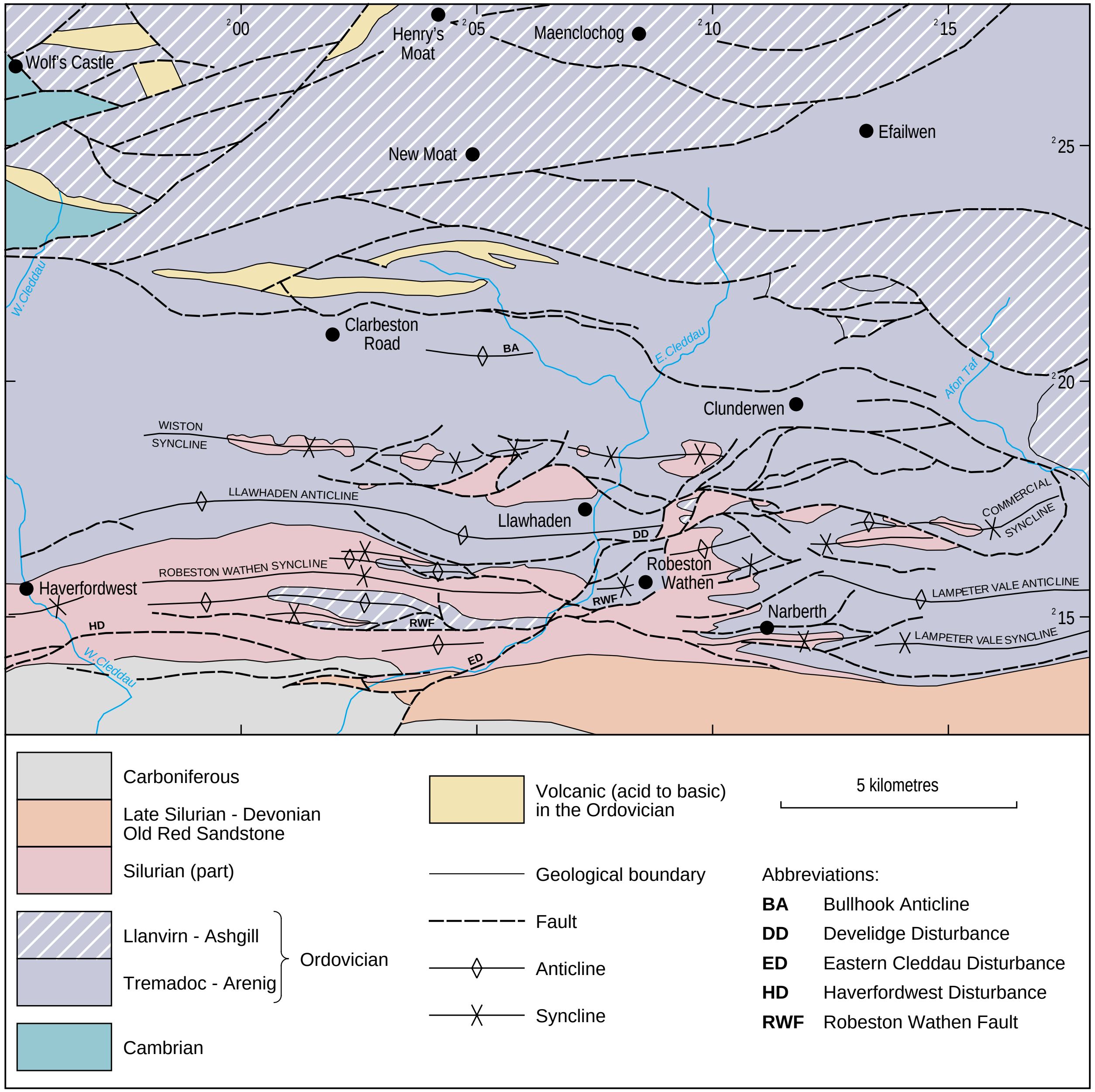

Figure 4 Simplified geological map of the survey area

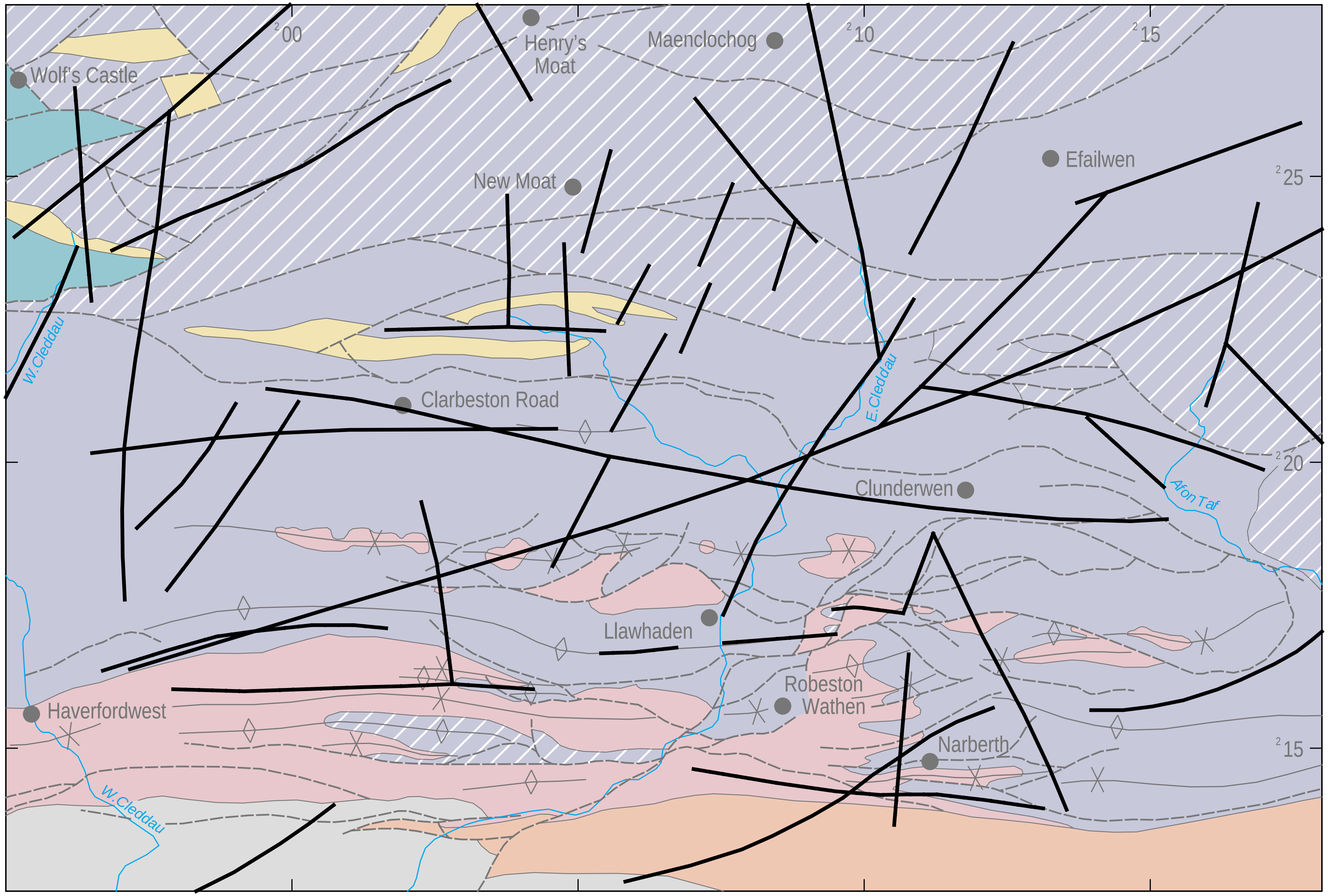

Figure 5 Principal linear features derived from TM imagery analysis and geophysical data analysis. Solid lines derived from geophysical data, pecked lines from TM imagery. The key to the background geological map is given in Figure 4

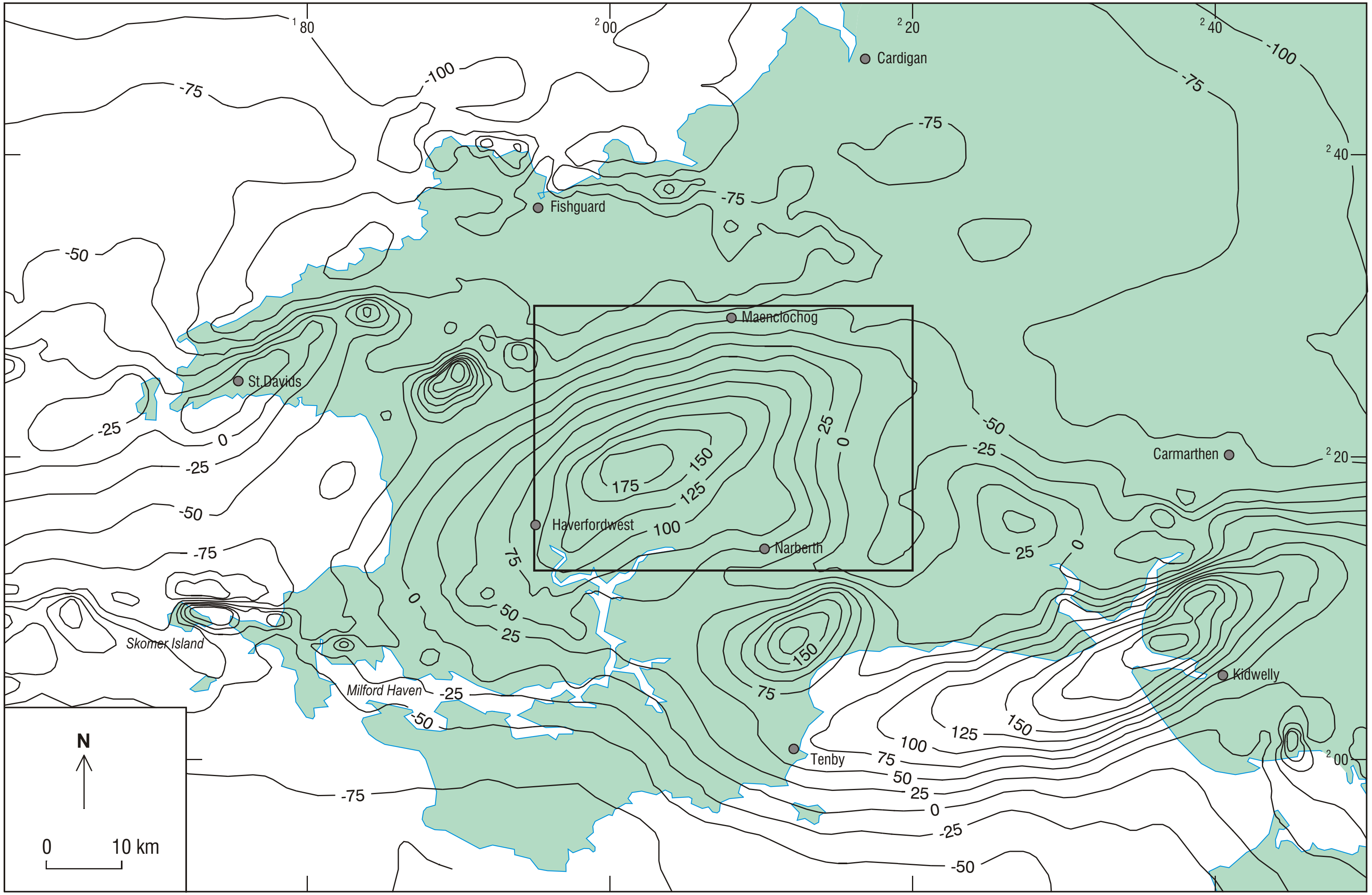

Figure 6 Aeromagnetic anomaly map of south-west Wales. Boxed area is shown in Figures 7 and 9-11

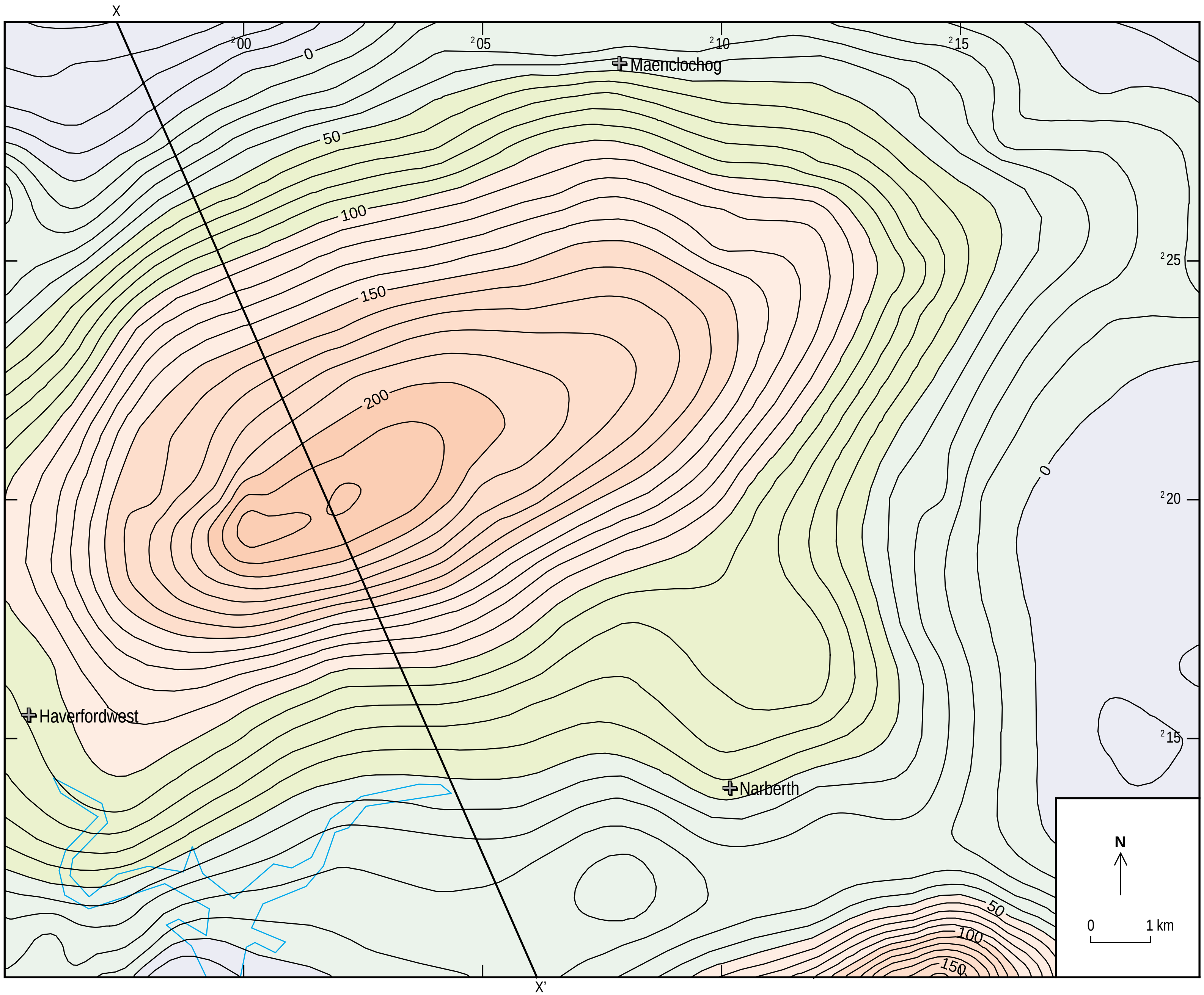

Figure 7 Aeromagnetic (reduced-to-pole) map for the survey area with contours at intervals of 10 nT, showing the location of profile X-X' (Figure 8)

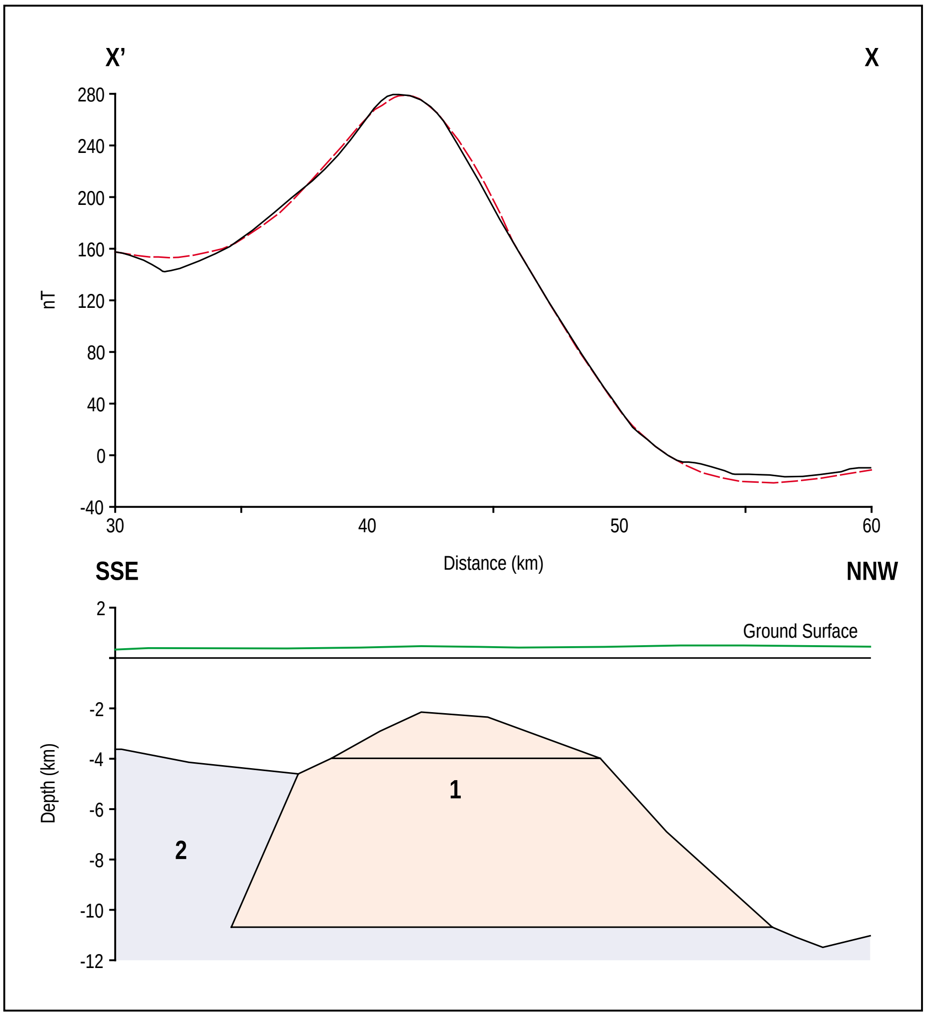

Figure 8 Aeromagnetic and Bouguer gravity anomaly profile X-X' (see Figure 7 for location) and model based on interpretation of the aeromagnetic profile. Magnetic susceptibilities (SI units) for model: 1 = 0.025, 2 = 0.015

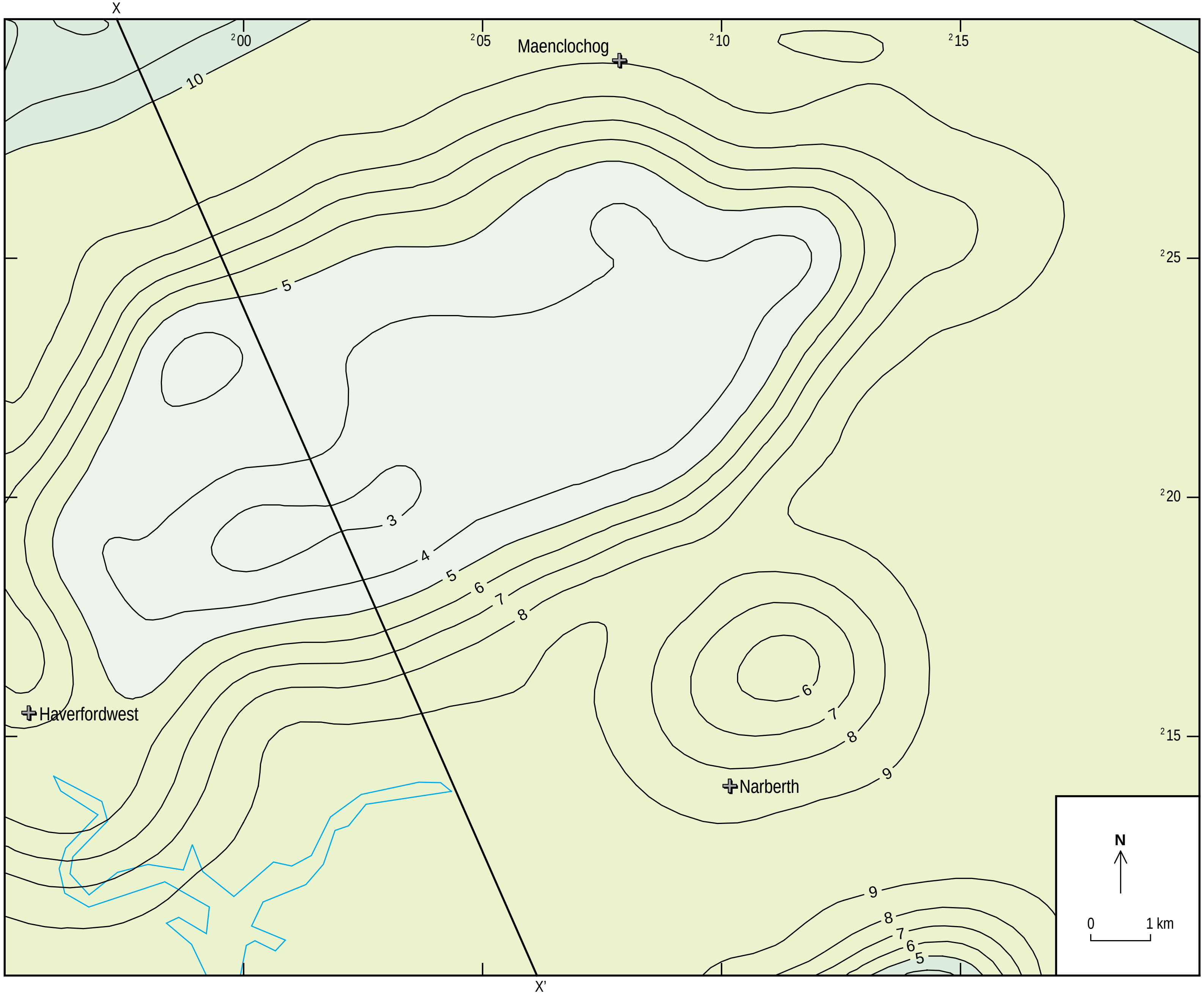

Figure 9 Interpretation of the Haverfordwest aeromagnetic anomaly with results presented as contours of the modelled upper surface of the 3D magnetic body. Slightly smoothed contours shown in km below OD (susceptibility 0.025 SI units)

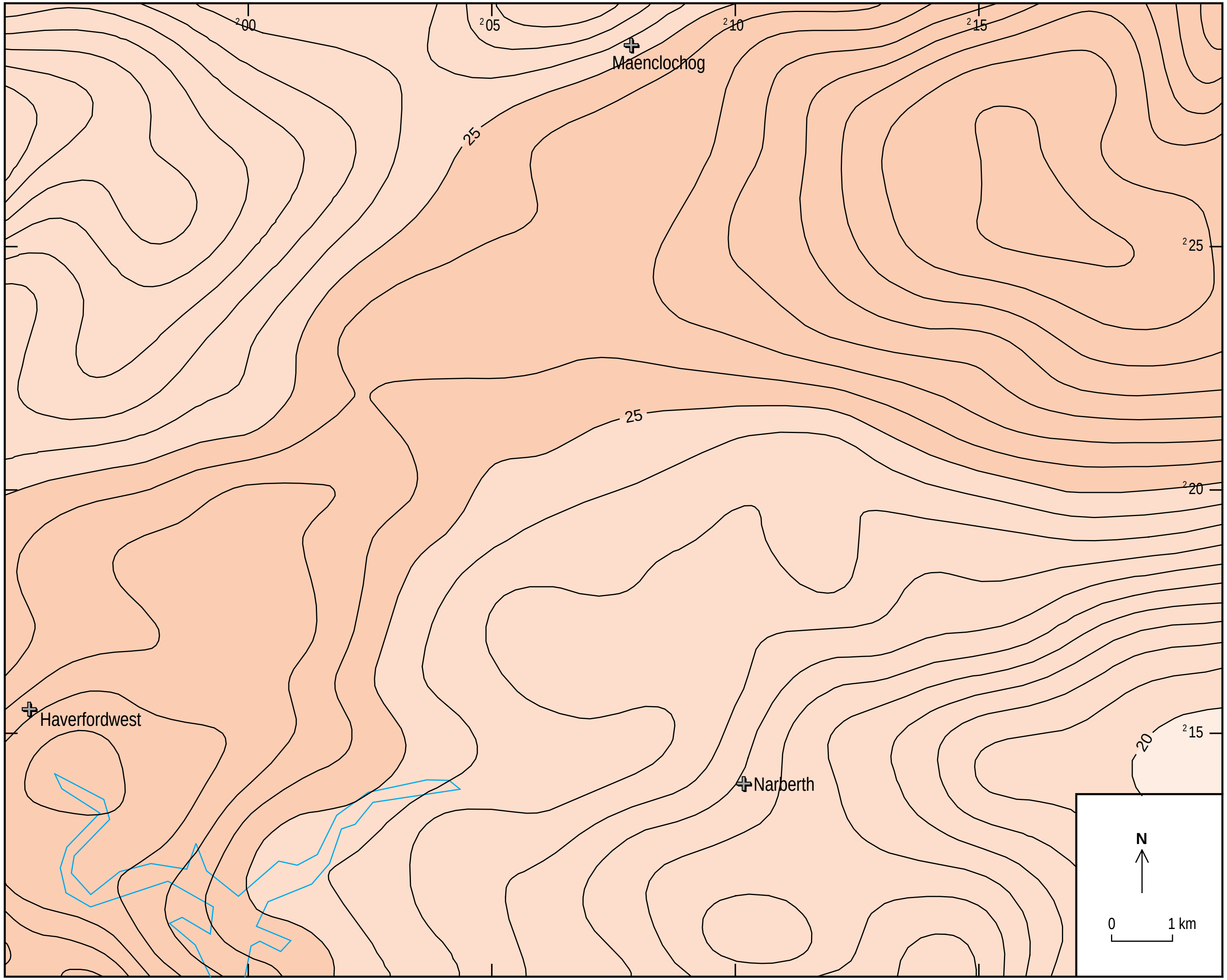

Figure 10 Bouguer gravity anomaly map for the survey area with contours at intervals of 0.5 mGal

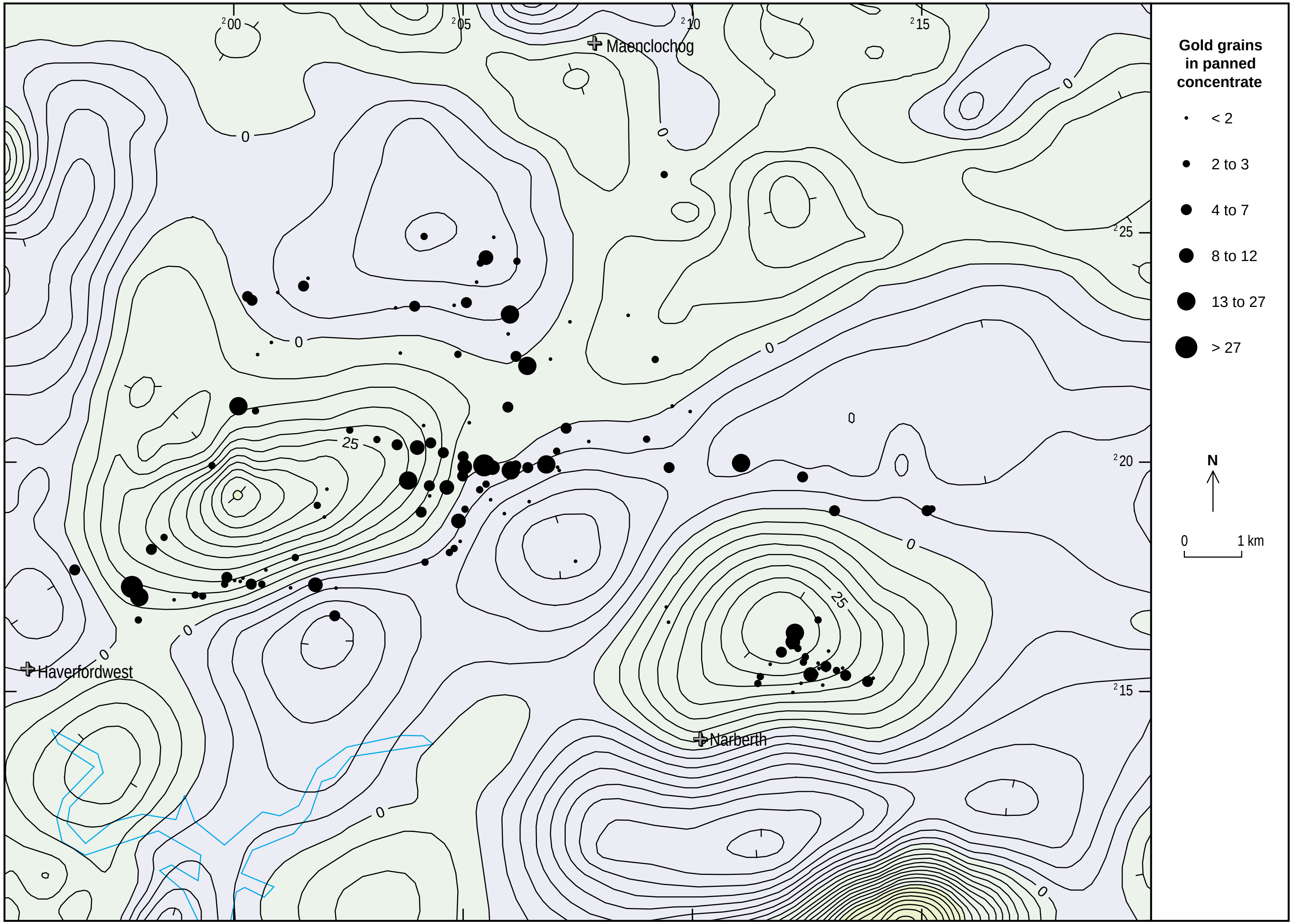

Figure 11 Filtered aeromagnetic data with contours at intervals of 5 nT showing components of anomalies with wavelengths of less than 10 km, and the location of alluvial gold from the present survey

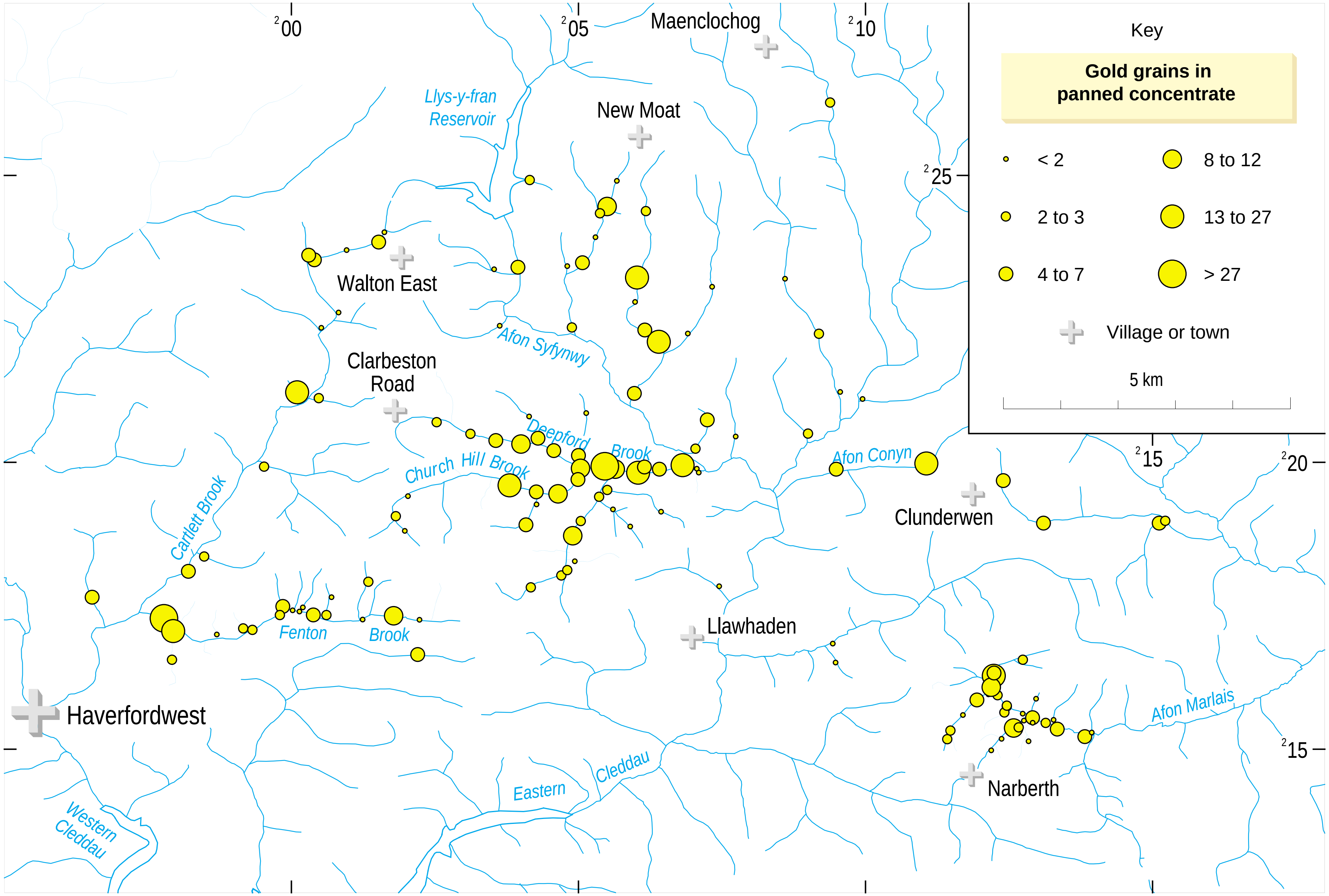

Figure 12 Areal distribution of gold grains in panned-concentrate samples from the present survey

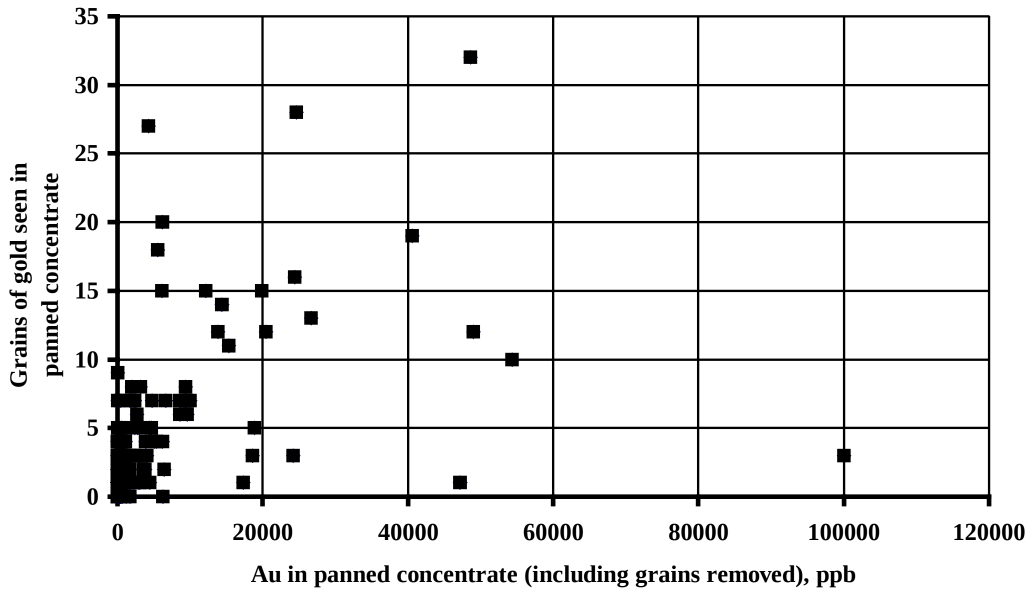

Figure 13 Relationship between visible gold grains and Au values in panned-concentrate samples

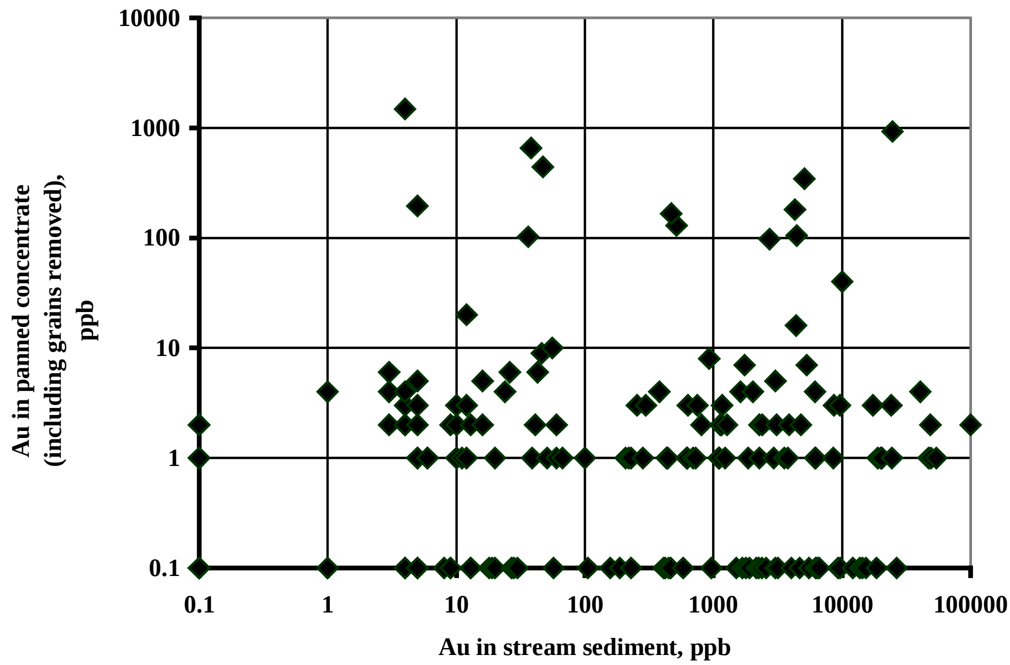

Figure 14 Relationship between Au in panned concentrate and in <150 µm stream-sediment samples

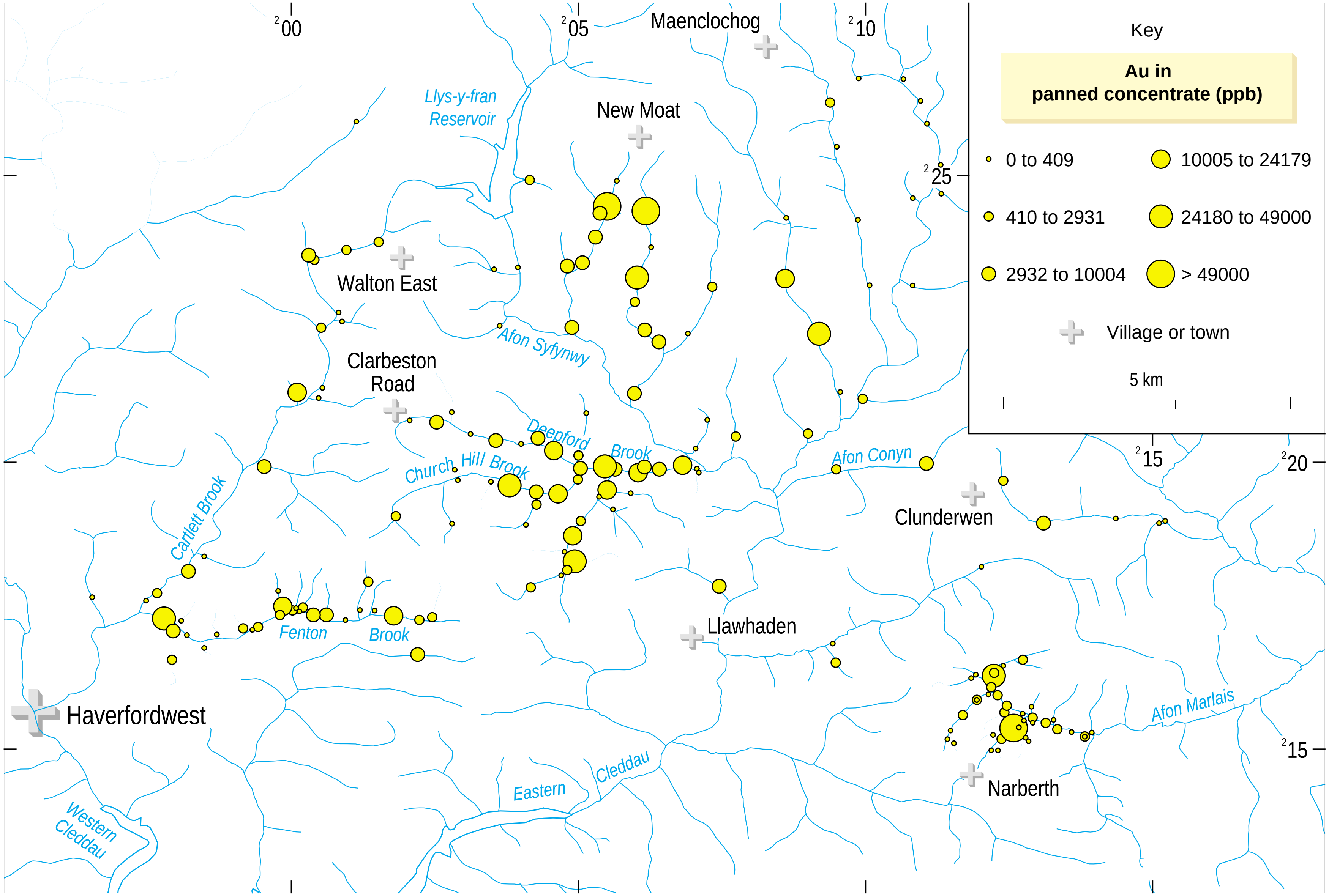

Figure 15 Areal distribution of Au in panned concentrate samples

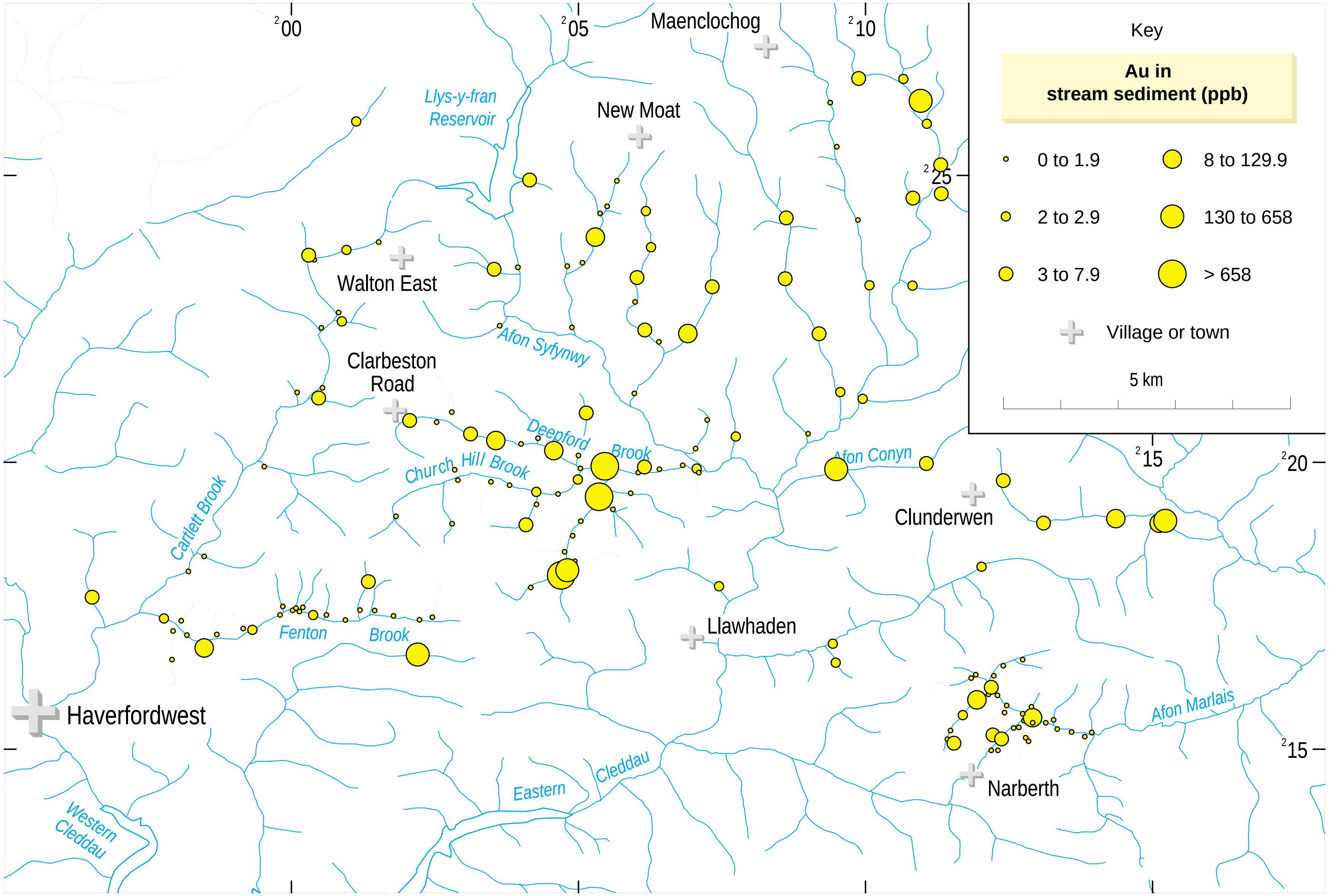

Figure 16 Areal distribution of Au in <150 μm stream-sediment samples

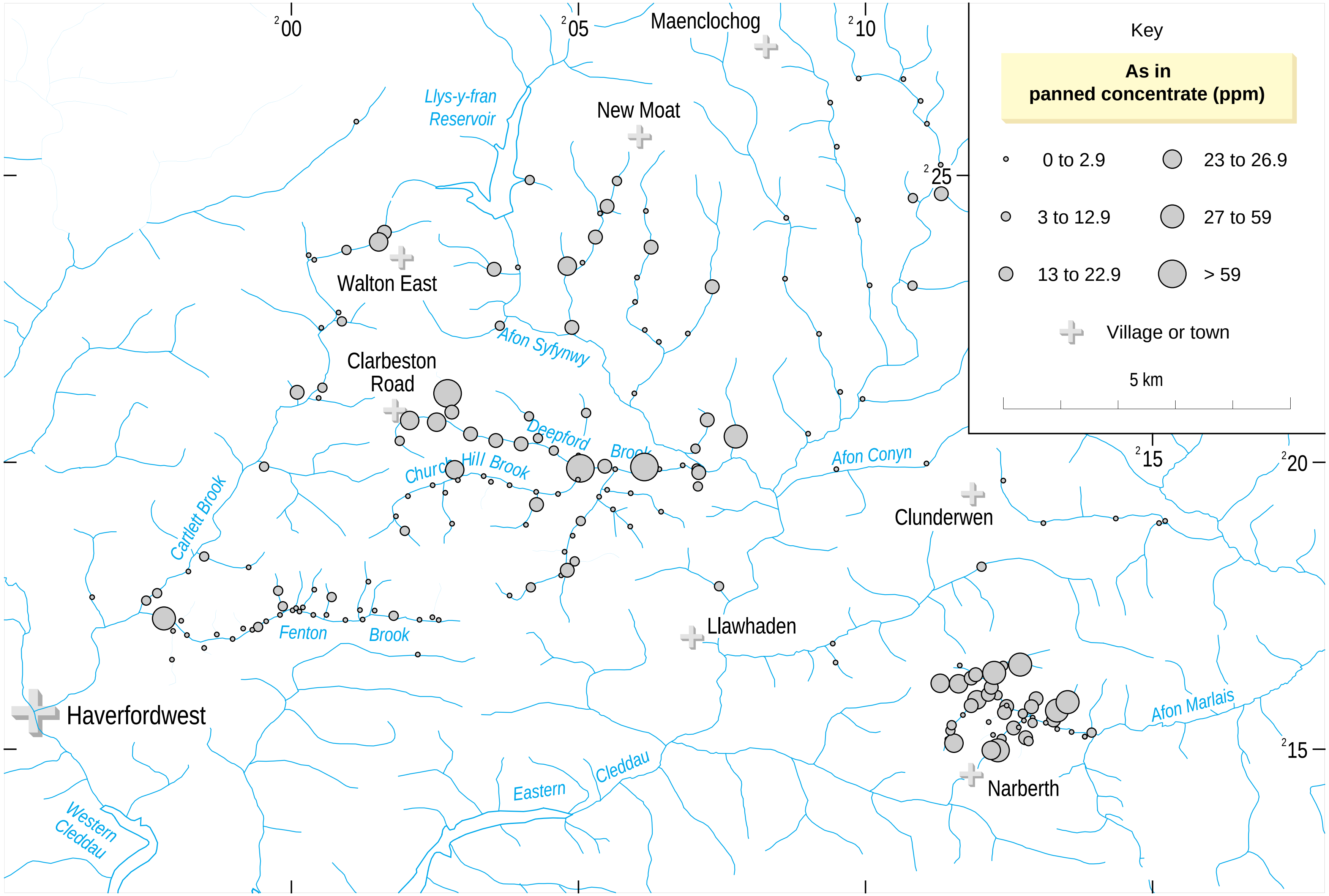

Figure 17 Areal distribution of As in panned-concentrate samples

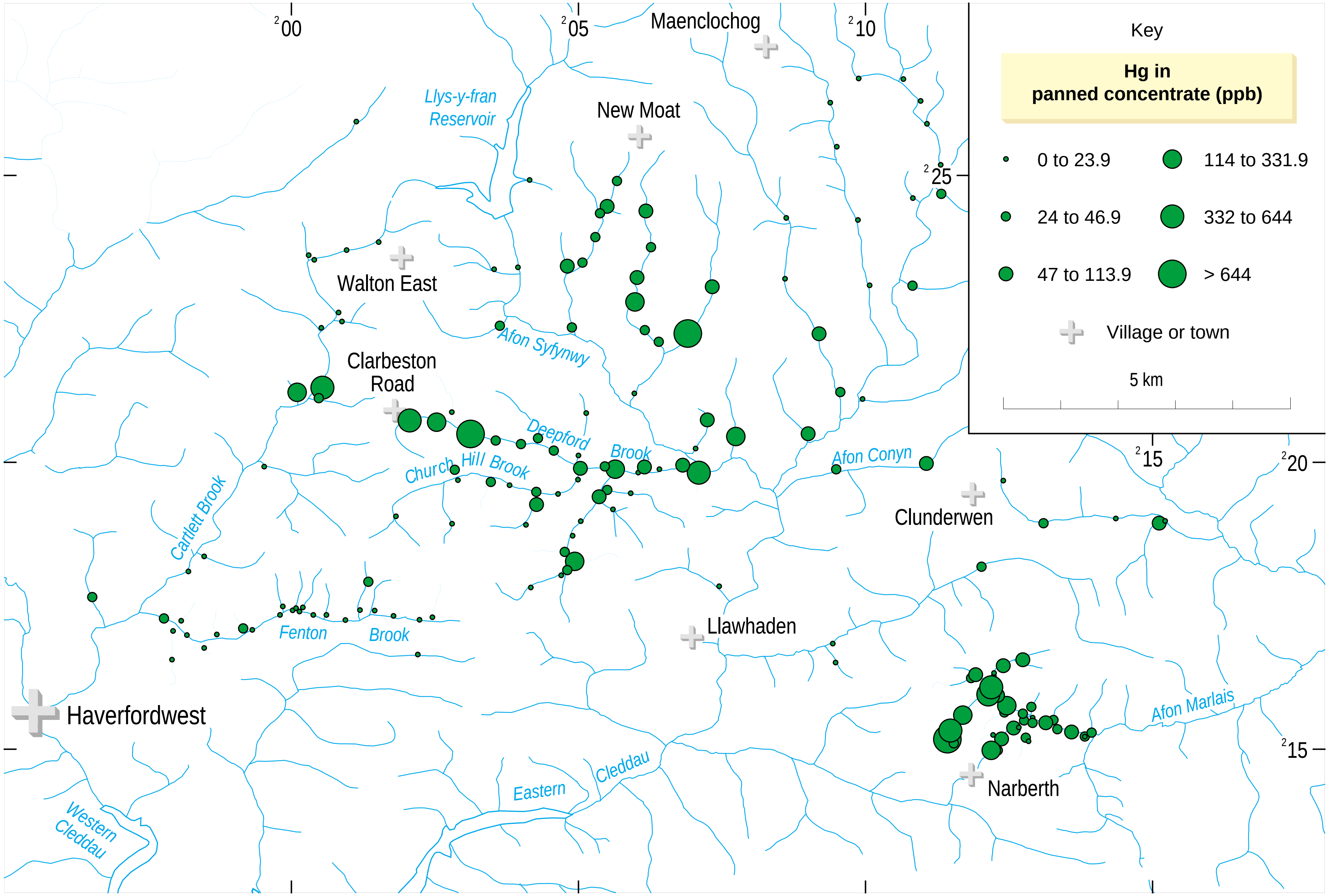

Figure 18 Areal distribution of Hg in panned-concentrate samples

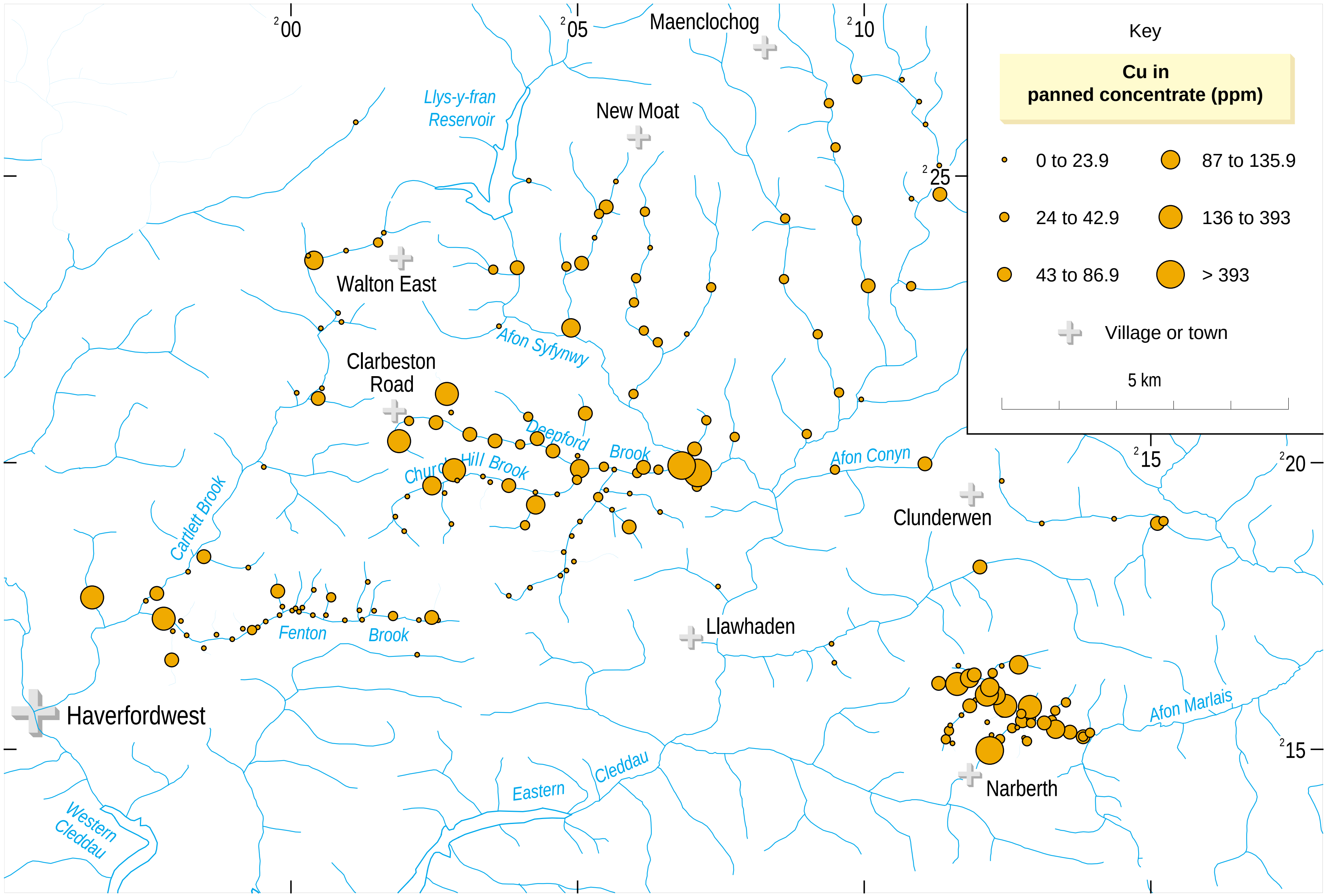

Figure 19 Areal distribution of Cu in panned-concentrate samples

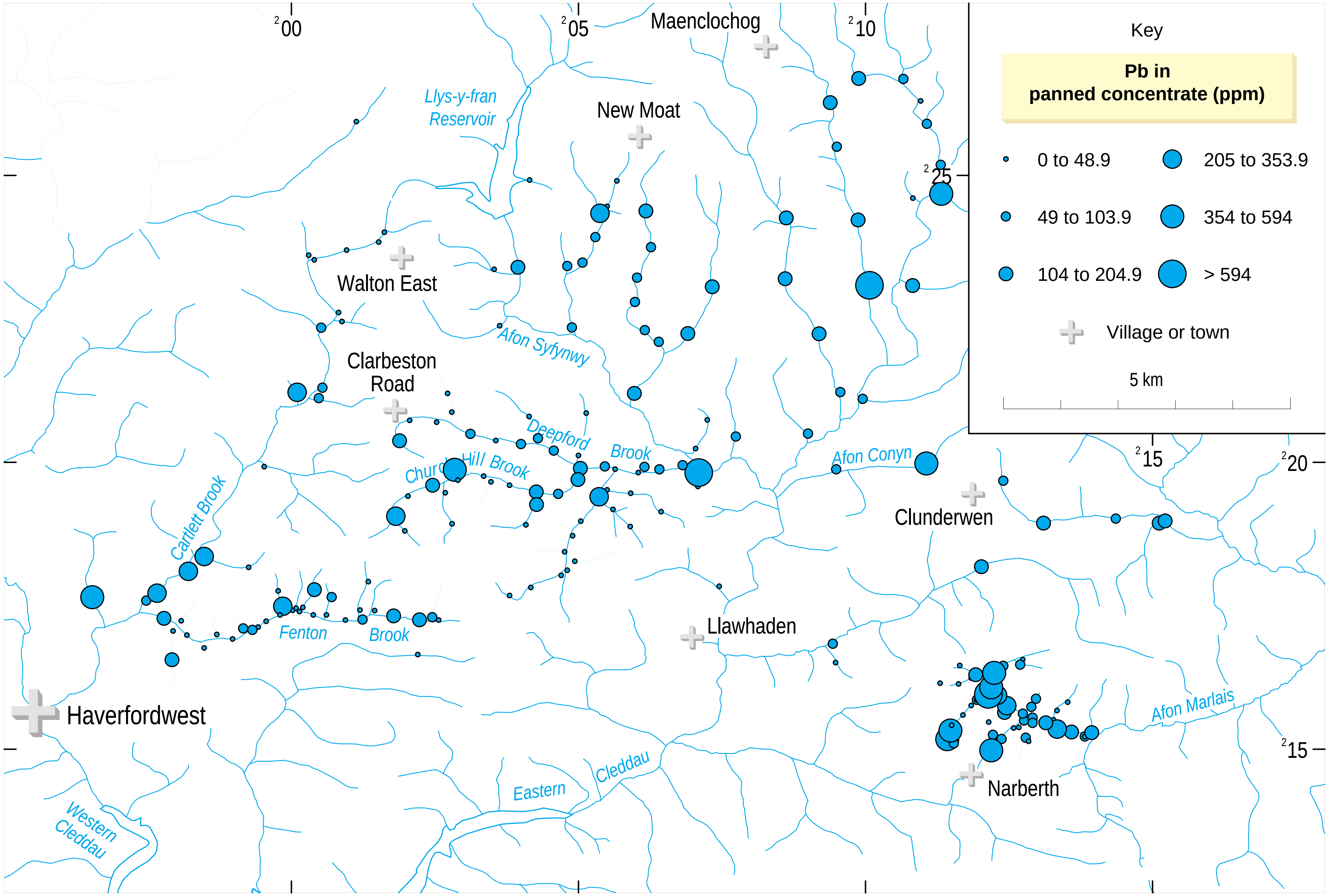

Figure 20 Areal distribution of Pb in panned-concentrate samples

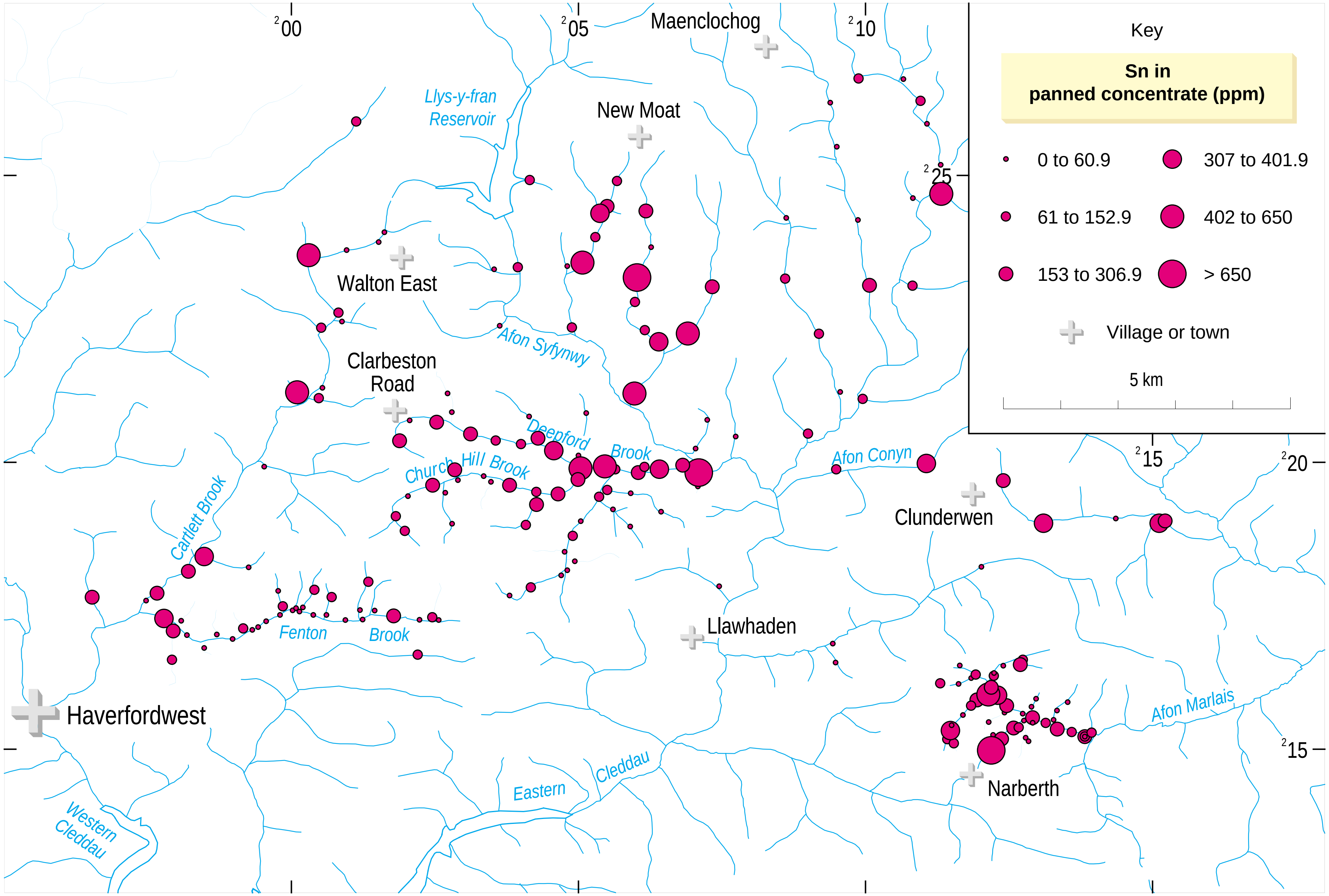

Figure 21 Areal distribution of Sn in panned-concentrate samples

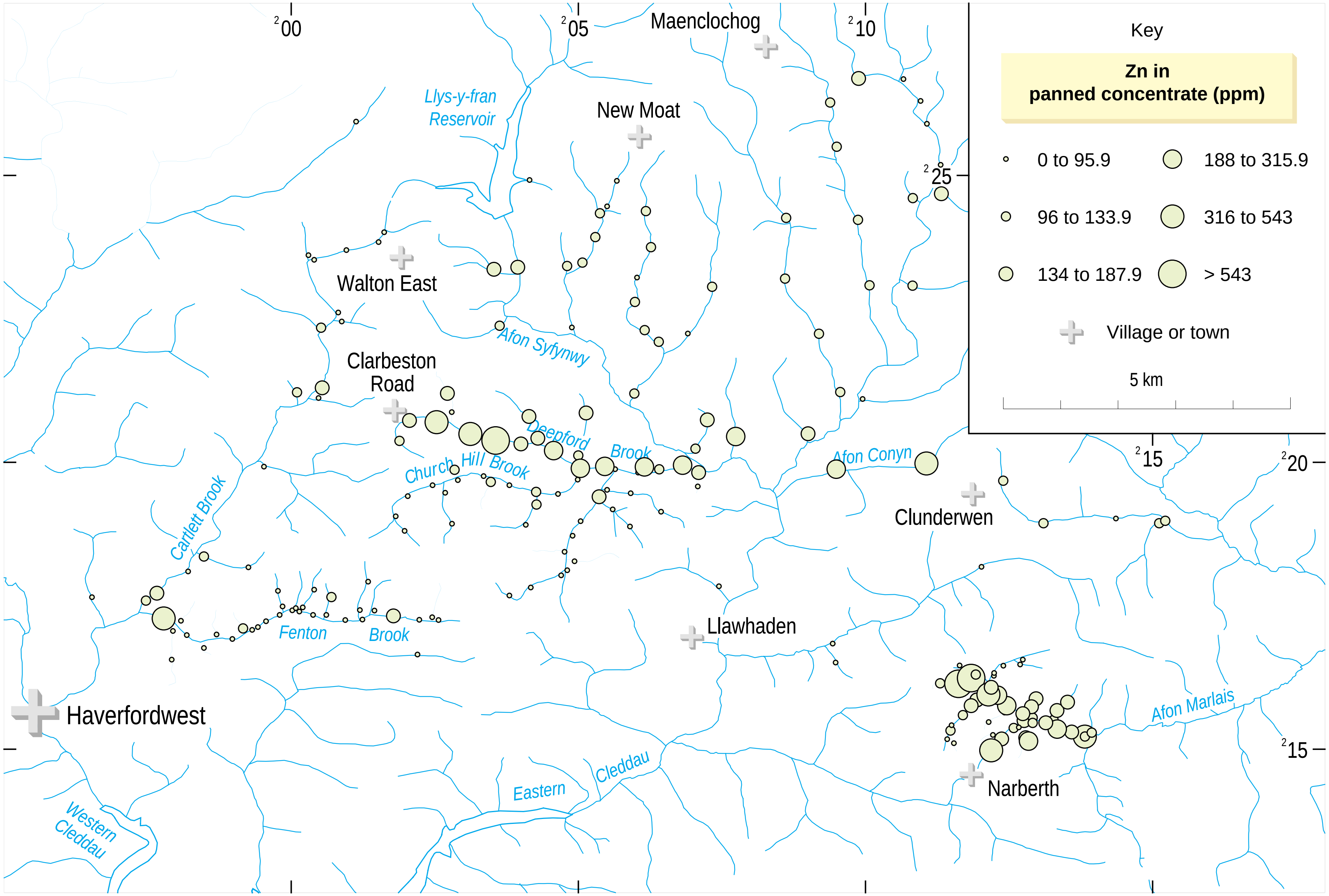

Figure 22 Areal distribution of Zn in panned-concentrate samples

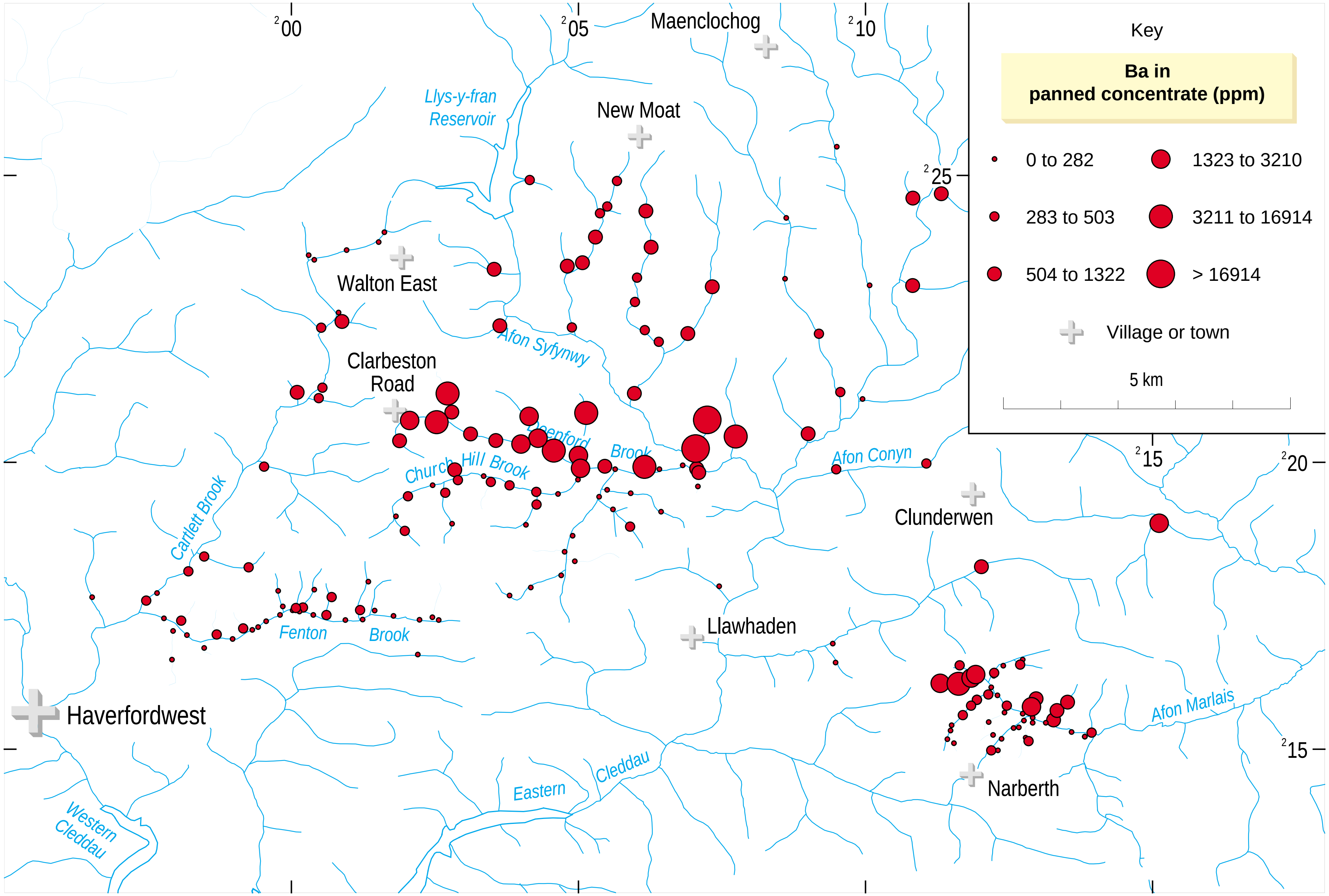

Figure 23 Areal distribution of Ba in panned-concentrate samples

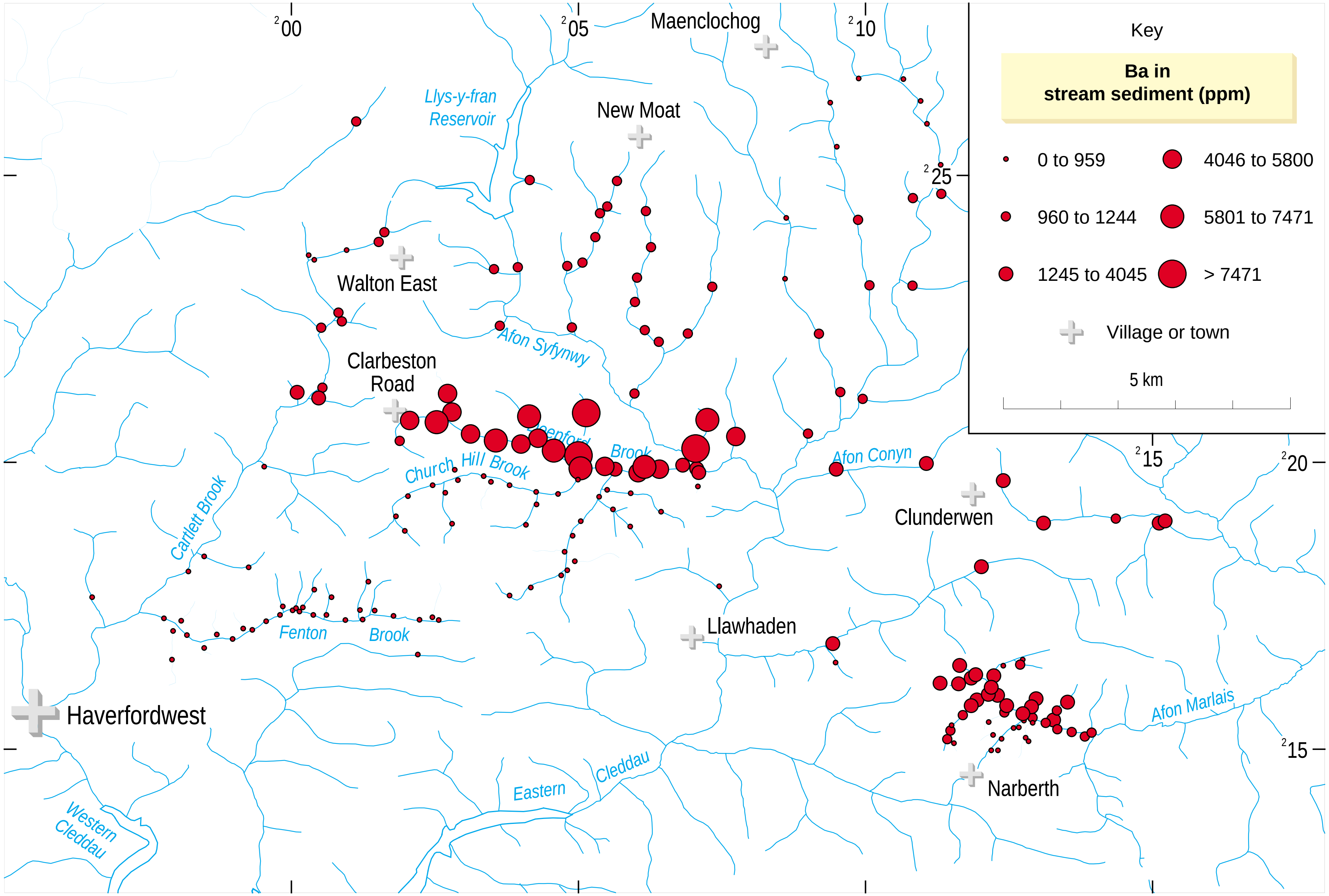

Figure 24 Areal distribution of Ba in <150 µm stream-sediment samples

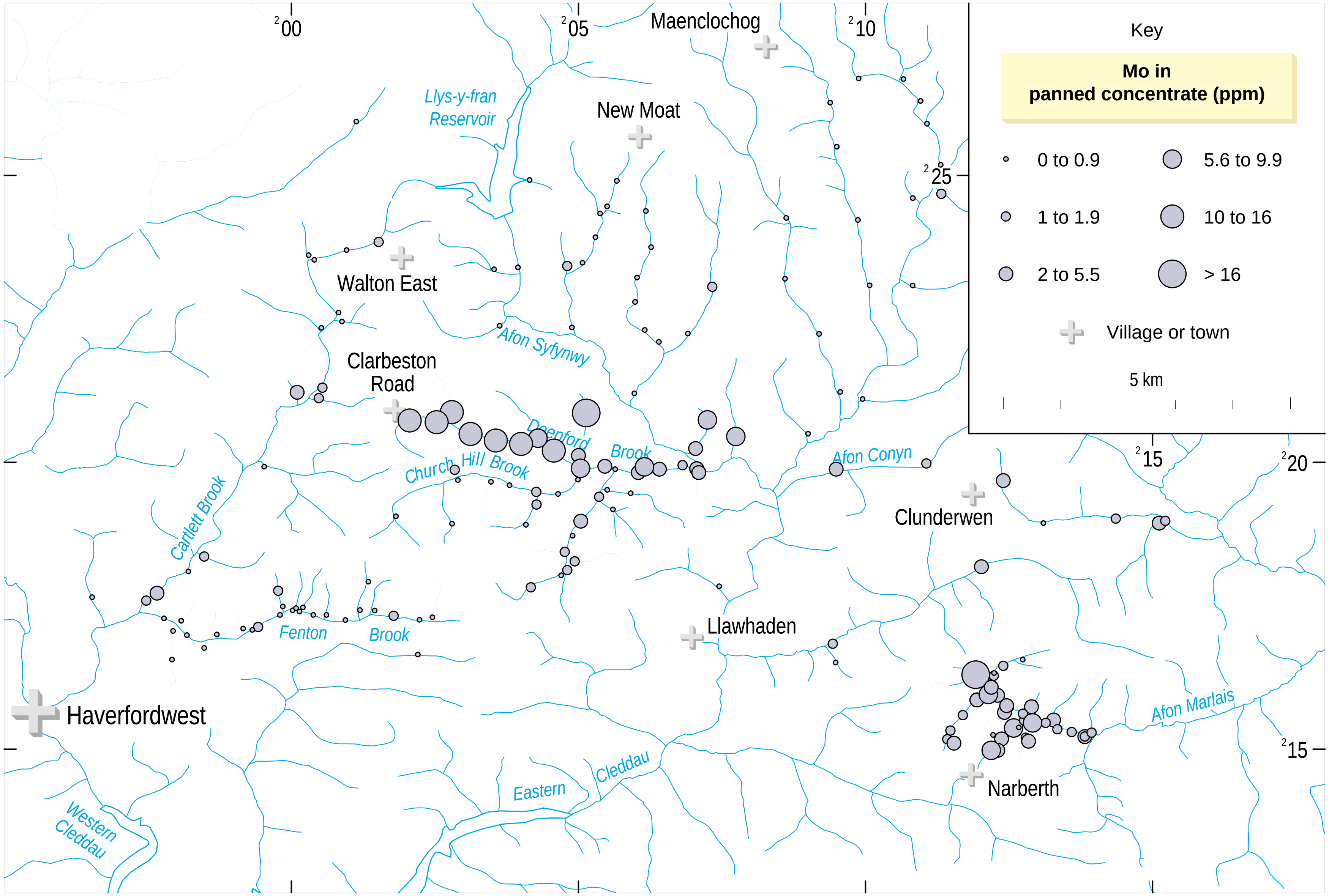

Figure 25 Areal distribution of Mo in panned-concentrate samples

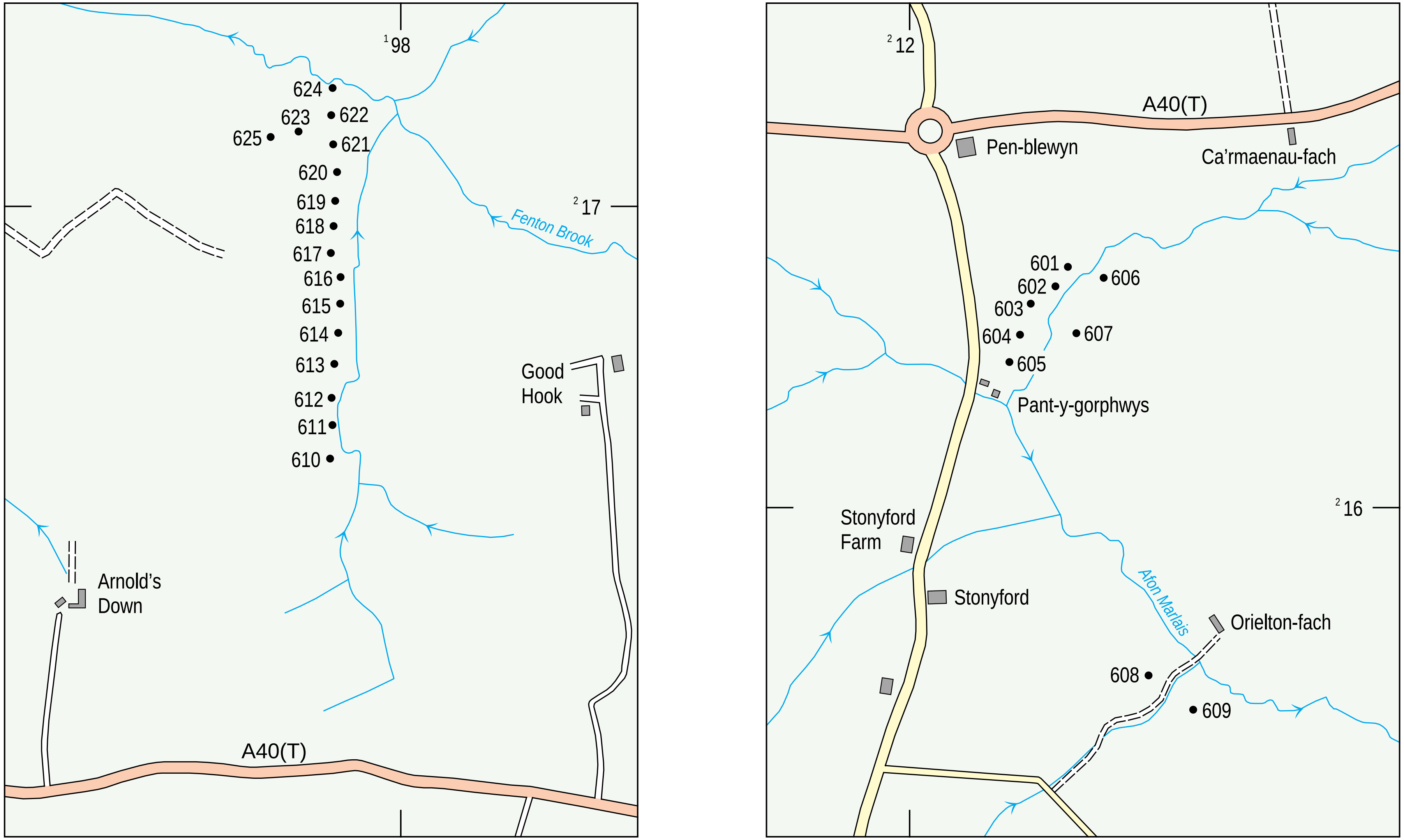

Figure 26 Location of pits in the Fenton Brook area (left) and Afon Marlais area (right)

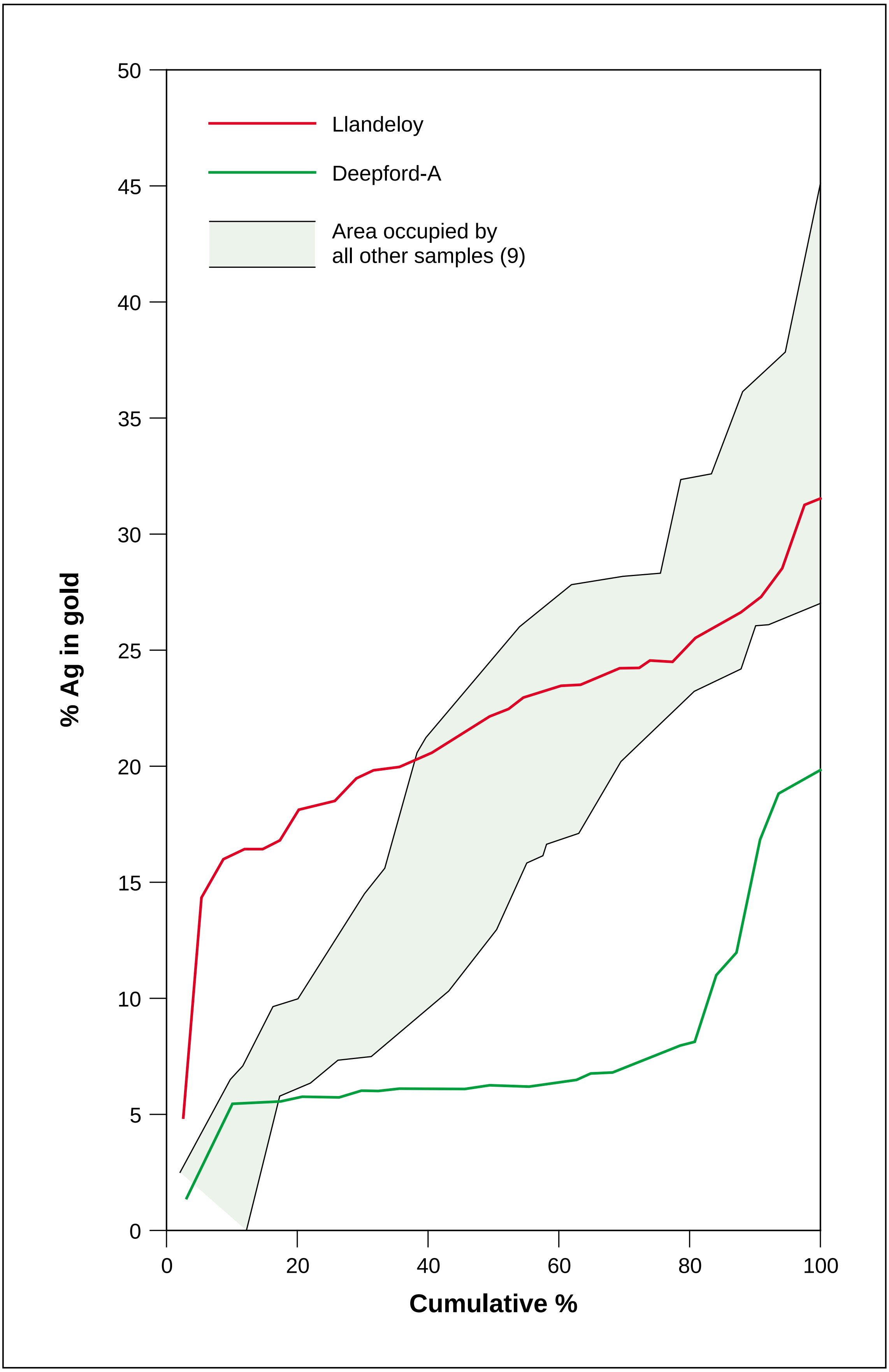

Figure 27 Cumulative Ag content in gold grains from the Llandeloy and Deepford Brook catchments, together with a generalised field for all other samples analysed