Precambrian Rocks of England and Wales

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Chapter 6

Wales, south and east of the Menai Strait

INTRODUCTION

J. M. Horák and W. Gibbons

The two sites covered by this chapter lie to the south-east of the Menai Strait Fault System (Figure 6.1), which is a major Precambrian crustal boundary (Figure 1.1). In contrast to sites dealt with in Chapter 7, which include outboard components of the Avalonian subduction system, such as blueschists, this chapter deals with rocks formed within a magmatic arc located inboard of the former subduction zone (Figure 1.4). The sites cover volcanic and volcaniclastic sequences belonging to the Pebidian Supergroup (St David's Peninsula GCR sites) and the Arfon Group (the Llyn Padarn GCR site), which are the principal outcropping representatives of the Cymru Terrane (see Chapter 1).

Geochemical studies reveal that the Arfon Group and Pebidian Supergroup rocks both possess similar calc-alkaline signatures (Bevins *et al.*, 1995), supporting their joint placement within a single terrane. That the magmatism of the two sequences was broadly contemporaneous is further suggested by U-Pb zircon ages, of 614 ± 2 Ma for the Arfon Group (Tucker and Pharaoh, 1991) and 587 $^{+25}_{-14}$ Ma for the St David's Granophyre, which is the youngest Pebidian component (Patchett and Jocelyn, 1979). Such ages place these igneous rocks within the main phase of Avalonian arc magmatism, as described by Gibbons and Horák (1996), identifiable in southern Britain and more extensively in the Avalonian of Maritime Canada. The two sites, however, show several contrasting features, the most notable of which is the fact that Arfon Group magmatism is dominated by acidic ash-flow tuffs, whereas the Pebidian Supergroup is predominantly composed of basic volcanic rocks.

There are important geochemical differences between the Pebidian Supergroup, the Coomb Volcanic Formation of the Llangynog site and the Johnston Diorite–Benton Volcanic Group, as summarized by Bevins *et al.* (1995) and discussed further in the introduction to the St David's site. Whereas the former is calc-alkaline, the latter two form part of a bimodal magmatic suite with a more pronounced within-plate component. Such geochemical differences are the basis for suggesting that the Coomb Volcanic Formation and the Pebidian Supergroup may belong to different terranes within the Avalon Composite Terrane (Chapter 1). The putative terrane boundary is taken as the south-western extension of the Welsh Borderlands Fault System (Figure 6.1).

It should be noted that there are two possible occurrences of Arfon-type pyroclastic rocks on Anglesey, these being the welded, acidic ash-flow tuffs of the Bwlch Gwyn Tuff and Baron Hill Formation (Reedman *et al.*, 1984). According to Gibbons and Horák (1996) these rocks, which occupy isolated exposures within the Berw Shear Zone (Figure 7.1), represent fragments of the Cymru Terrane that were tectonically interleaved with the Monian Composite Terrane following cessation and dismemberment of the Avalonian arc (Figure 1.4).

The Sarn Complex and Parwyd Gneiss are further components of the Cymru Terrane but they occur in tectonic contact with the Monian Gwna Group in the Llŷn area and are for convenience described in Chapter 7. The Parwyd Gneiss is represented at the Braich y Pwll to Parwyd GCR site by a single exposure of heavily retrogressed garnet amphibolite and felsic gneisses within the Llŷn Shear Zone (the south-western extension of the Menai Strait Fault System traversing Llŷn, Figure 7.1). The metamorphic or igneous protolith age of the gneiss is unknown, and although Beckinsale *et al.* (1984) undertook Rb-Sr analysis on samples from this outcrop, the result that was obtained, of 542 ± 17 Ma, represents the age of low-grade retrogression of the gneiss. Beckinsale *et al.* (1984) considered the gneisses and the adjacent Sarn Complex to the south-east to be separate entities, whereas Gibbons (1980), Gibbons and Horák (1990, 1996) and Horák (1993) grouped these two units together as the Sarn Complex. The Sarn Complex includes poorly exposed, highly heterogeneous, calc-alkaline plutonic rocks ranging from gabbros to evolved leucogranites, some of these lithologies being seen at the Penrhyn Nefyn GCR site. Horák (1993) has confirmed the magmatic age of this igneous suite as 615 ± 2 Ma, on the basis of U-Pb zircon data, and suggested that it represents the most north-westerly occurrence of the main Avalonian arc (i.e. the Cymru Terrane) in southern Britain.

The main value of the two sites that are featured in this chapter rests upon the record they provide of some of the oldest geological events in southern Britain. Together with the evidence from the Coomb Volcanic Formation of the Llangynog site, they show how the Avalonian

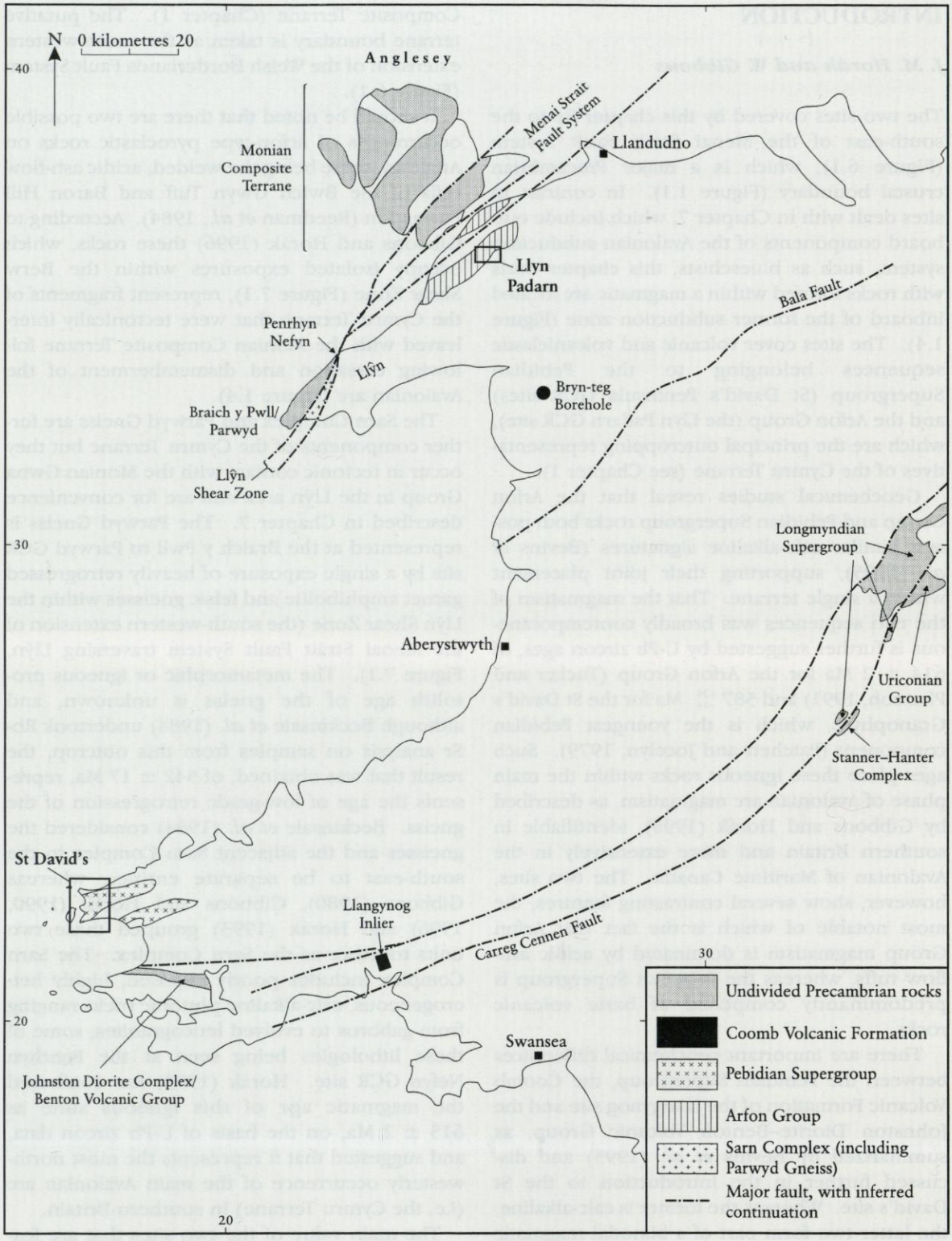

Figure 6.1 Geological map showing the relationship of the St David's and Llyn Padarn sites to other Precambrian outcrops.

Precambrian arc changed with time, from one with a typical calc-alkaline signature to one involving a more complex, intraplate-type chemistry during later rifting of the arc. Such characteristics record the transition from steady-state subduction to extreme oblique subduction leading eventually to arc dissections (Figure 1.4), processes that are observed in modern and recent arc systems.

ST DAVID'S PENINSULA

R. E. Bevins and J. M. Horák

Introduction

This site encompasses part of the rugged coastline and small inland exposures of the St David's Peninsula (Figure 6.2). It provides some of the most extensive sections through Precambrian volcanic rocks and associated intrusions, in particular the St David's Granophyre, to the south-east of the Menai Strait Fault System. In addition to the completeness of the stratigraphical section, this site records the relationships between the overlying Cambrian sedimentary rocks and both the volcanic sequence and the St David's Granophyre.

The volcanic sequence represented is the Pebidian Supergroup of Pharaoh and Gibbons (1994), which comprises basic and acidic lavas, tuffs and minor intrusions. The lavas were originally interpreted as being dominantly andesites, but recent investigations have shown that they are chiefly of basic composition (Bevins *et al.*, 1995).

The St David's site is important for a number of reasons. Stratigraphical relationships in this area were at the centre of one of the greatest controversies in the history of British geology, the debate revolving around the relative ages of the St David's Granophyre and the surrounding rocks. Hicks (1877, 1878) mapped the area in considerable detail and was convinced that the granophyre was of Precambrian age; in contrast, Sir Archibald Geikie, representing the Geological Survey, considered the Pebidian sequence to be Cambrian in age, therefore making the St David's Granophyre a post-Cambrian intrusion. The matter was settled finally by Green (1908), who excavated a trench a short distance to the south of St David's, which clearly demonstrated an unconformable relationship between underlying granophyric rocks and an overlying basal Cambrian conglomerate. Although the trench is now obliterated, a new track-side exposure in the same area provides the critical field evidence today and is described below.

Hicks (1877, 1878) coined the terms 'Dimetian' and 'Pebidian' respectively for the granophyre and the volcanic rocks of the St David's area. Green (1908), however, undertook the first detailed stratigraphical investigation of these rocks, recognizing four divisions within the Pebidian, namely, from bottom to top of the succession: the Penrhiw, Treginnis, Caerbwdy and Ramsey Sound Series. This stratigraphy remained until publication of the 1:25 000 St David's geological map (Institute of Geological Sciences, 1973). This work revised the stratigraphy, adding two 'Groups', namely the Ogofgolchfa Group, at the top of the succession, and the Rhosson Group, lying immediately below the Ogofgolchfa Group. These changes resulted from a reconsideration by Green (in Cox *et al.*, 1930) that Carn Rhosson (SM 728 252) and adjacent crags were not dolerite intrusions but in fact basic lavas and breccias. A similar scheme was adopted for the recent 1:50 000 geological map (British Geological Survey, 1992), although the lower series were grouped together as Lower Pebidian (undivided).

Davies and Bloxam (1990) modified this stratigraphy by: placing the Rhosson Series at the base of the succession; renaming the Treginnis Series the Pen Pedol Series; and including the Penrhiw Series with their Ramsey Sound Series. The ascending order of the stratigraphy was redefined as the Rhosson, Treginnis (Pen Pedol), Ramsey Sound and Caerbwdy series. The British Geological Survey (1992) subsequently made further alterations to this stratigraphy and upgraded the series to group status. The latter stratigraphical sequence has been used in this work and is detailed below:

- Ogofgolchfa Group
- Rhosson Group
- Ramsey Sound Group
- Caerbwdy Group
- Lower Pebidian (undivided Treginnis, Treglemais and Penrhiw groups)

Recent work on the rocks within this site includes isotopic dating of the main intrusion and geochemical studies of both intrusive and extrusive components. Patchett and Jocelyn (1979) published a U-Pb zircon age from the St

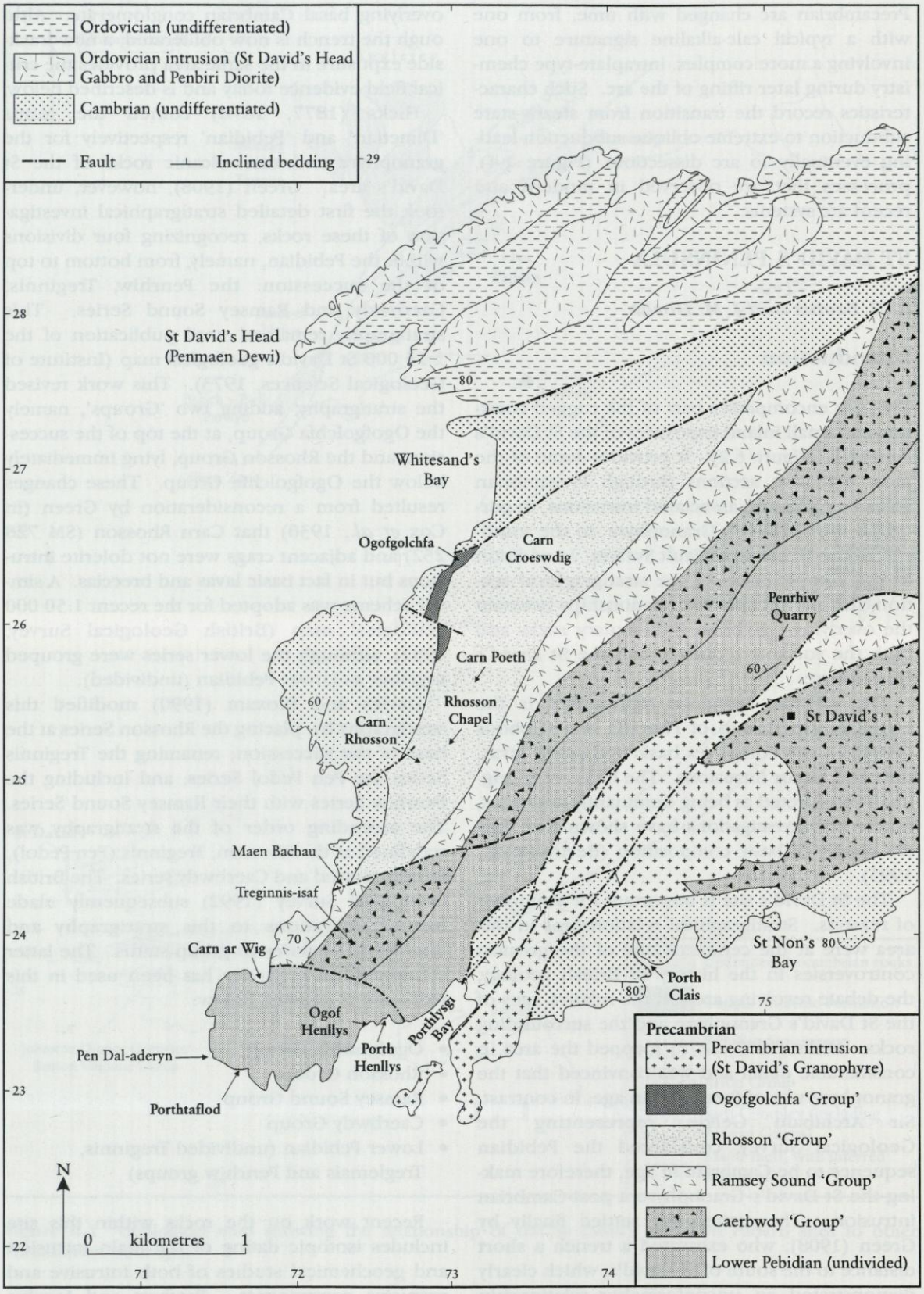

Figure 6.2 Geological map and locality index to the St David's site (based on the British Geological Survey Sheet 209, St David's 1:50 000 provisional sheet). Localities referred to in the text are in bold.

David's Granophyre of 587 $^{+25}_{-14}$ Ma, proving it to be late Precambrian and providing a minimum age for the Pebidian Supergroup. The study also permitted correlations to be made with other Avalonian rocks both within and outside Britain and in Maritime Canada.

The geochemical investigations into the volcanic rocks and St David's Granophyre revealed the nature of their primary igneous compositions and the effects of element mobility and alteration (Bloxam and Dirk, 1988; Davies and Bloxam, 1990; Bevins *et al.*, 1995). The basic volcanic rocks have a clear calc-alkaline signature, demonstrated by a negatively sloping N-type MORB-normalized trace element pattern with slight Nb and Ta depletion and Th, Ce, P and Sm enrichment (Bevins *et al.*, 1995). Similarly, the Nb-Y tectonic classification diagrams of Pearce *et al.* (1984) show that both rhyolitic tuffs and the St David's Granophyre have a volcanic arc granite affinity (Bloxam and Dirk, 1988; Bevins *et al.*, 1995). The last-named workers discussed comparisons with other Precambrian occurrences and suggested that chemically these rocks are related to the Arfon Group of the Llyn Padarn GCR site, but differ considerably from the Coomb Volcanic Formation at Llangynog.

Description

A selection of some of the more important exposures along St David's Peninsula (Figure 6.2) is described here, with interpretations following in a later, amalgamated section.

St Non's Bay

At St Non's Bay (SM 725 242), the Caerbwdy Group is exposed in contact with basal conglomerates of Cambrian age, the contact being locally overturned. The group largely comprises fine- to coarse-grained silicic tuffs, however, and hence is difficult to distinguish from rocks belonging to the Ramsey Sound Group; indeed it is possible that they are equivalents. The tuffs are composed of varying proportions of crystals and lithic fragments, and in places show a fine-scale layering. Locally, they are thoroughly recrystallized, and were termed 'halleflinta' or 'porcellanite' in the early literature.

Treginnis–Porthtaflod

These localities constitute the chief exposures of the Lower Pebidian sequence. It is shown undifferentiated on the most recently published map (British Geological Survey, 1992), but comprises the Treglemais, Penrhiw and Treginnis groups of the earlier literature. This sequence shows a wide variety of lithologies, although not all are represented in the GCR site areas.

The basic composition of rocks comprising the Treginnis Group is well illustrated, for example, by the exposures near Pen Dal-aderyn (Figure 6.2; SM 715 233). They show well-developed columnar jointing in places, such as to the south-west of Porth Henllys (SM 724 233), as well as autobrecciated horizons, seen in the area around Porthtaflod (SM 718 232). Also, green and purple basaltic tuffs are widespread in the tract of country to the south-west of Treginnis-isaf (SM 724 239). These tuffs are characterized by abundant, flattened basaltic scoriaceous clasts, accompanied invariably by broken crystals and rare clasts of silicic, shardic tuff. In the coastal section immediately east of Pen Dal-aderyn, basaltic lava and metabasic tuffs overlie a sequence of pink to purple, rhythmically bedded tuffaceous siltstones and mudstones (Figure 6.3). Although silicic rocks are rare in the Treginnis Group, a thin (< 2 m) silicic ash-flow tuff unit, containing prominent rhyolite lithic clasts up to 6 cm, occurs interbedded with metabasic tuffs at Ogof Henllys (SM 725 235).

The Treglemais Group is named for the outcrops at Treglemais (SM 816 281), to the east of the area shown in Figure 6.2, where it comprises non-welded silicic ash-flow tuffs, composed of broken quartz and feldspar crystals, rhyolitic and (rarer) basaltic lava clasts, fragments of shardic tuff, pumice, and recrystallized glass shards. The Penrhiw Group, at the type locality at Penrhiw Quarry (SM 751 258), comprises a similar but more altered lithological assemblage, and the two groups may be lateral equivalents.

Carn ar Wig and Porthlysgi Bay

These localities provide exposures of the Ramsey Sound Group, made up of silicic pyroclastic rocks. Extensive recrystallization has unfortunately destroyed many of the original textures. However, sufficient details remain to suggest that these rocks were composed originally of varying proportions of crystals, lithic fragments, pumice and shards. Locally, as at Carn ar Wig (SM 719 239), eutaxitic textures are preserved. At Porthlysgi Bay (SM 730 236), tuffs

Figure 6.3 Well-bedded, possible airfall tuffs overlain by basalt lava; Treginnis Group east of Pen Dal-aderyn, St David's Peninsula, Pembrokeshire. (Photo: J.C.W. Cope.)

of the Ramsey Sound Group are intensely sericitized and many primary textures have been obliterated. In some cases, however, the presence of pumice, shards, lithic fragments and broken crystals can be determined; original eutaxitic fabrics can also be discerned.

Rhosson and environs

This large area contains a number of localities exposing the Rhosson Group. According to the British Geological Survey map (1992), this comprises andesitic and trachytic tuffs and lavas. Petrological and geochemical analyses (Davies and Bloxam, 1990; Bevins *et al.*, 1995) suggest, however, that the rocks are of basaltic affinity, and that the various tuffs are autobrecciated lavas and scoriaceous debris.

The Rhosson Group is best exposed on Carn Rhosson (SM 7275 2513). The lavas are commonly vesicular, and carry phenocrysts of olivine and plagioclase, although both these minerals are altered; fresh clinopyroxene is, however, present in some samples. Almost all samples show the presence of epidote, some lavas being pervasively epidotized, for example in the vicinity of Carn Croeswdig (SM 738 263) and Carn Poeth (SM 732 257). Near to Maen Bachau (SM 732 257), the lavas are silicified; the presence of abundant olivine pseudomorphs, however, points to their original basic composition. Some lavas show evidence of autobrecciated horizons, whereas other breccias appear to be accumulations of scoriaceous material, commonly containing angular quartz crystals and in one case, 150 m to the south-east of old Rhosson Chapel (SM 729 251), a clast of silicic welded ash-flow tuff.

Ogofgolchfa

This locality (SM 7303 2643) contains exposures representative of the Ogofgolchfa Group, and its marked unconformity with a basal conglomerate belonging to the Caerfai Group, of lowermost Cambrian age. The Ogofgolchfa Group comprises green, chloritic tuffaceous rocks and purple slates, the latter showing extreme stretching of lithic fragments. A thin basic sheet intrudes these rocks. This section is important as it clearly demonstrates that the Pebidian Supergroup is of Precambrian age.

Porthlysgi Bay and Porth Clais

These localities contain some of the most informative exposures of the St David's Granophyre. On the eastern side of Porthlysgi Bay (SM 732 236), the granophyre is seen in fault contact with the Pebidian Supergroup. The granophyre becomes finer grained towards its margin, but is typically medium-grained and highly leucocratic. In thin section it shows a simple assemblage dominated by quartz and plagioclase, with classic granophyric textures locally showing an almost graphic form. Alkali feldspar is restricted to groundmass crystals, whereas both plagioclase and quartz form phenocrysts. This assemblage is variably hydrated, with plagioclase alteration ranging from clouding to extensive replacement by sericite. Ferromagnesian minerals are restricted to biotite, but this is totally replaced by chlorite. Both epidote and clinozoisite are present, although not noticeably pseudomorphing primary phases. Bloxam and Dirk (1988) have classified this intrusion as a trondhjemite on the basis of its low content of alkali feldspar and ferromagnesian minerals.

To the north-west of Porth Clais (SM 742 238) lies the famous site where Green (1908) dug a trench to demonstrate the unconformable relationship between the St David's Granophyre and the overlying Cambrian succession. As the trench no longer permits the observation of this key piece of stratigraphical evidence, a new exposure, approximately 40 m to the south-west, was created in 1997. The exposure (Figure 6.4) lies on the edge of a small farm track (SM 7388 2430). It shows the unconformity dipping at 75° to the north-west, separating highly weathered, locally iron-stained granophyre, cut by minor faults, from overlying Cambrian conglomerates of the Caerfai Group. The conglomerates contain rounded pebbles and sporadic cobbles chiefly of colourless to liver-coloured quartz.

Interpretation

Geochemical studies of the igneous rocks from the St David's site, discussed in the introduction to this chapter, show that they can all be interpreted as the products of subduction zone magmatism (Bloxam and Dirk, 1988; Bevins *et al.*,

Figure 6.4 Unconformable contact between the St David's Granophyre (Precambrian) below and conglomerates of the Caerfai Group (Cambrian) above, exposed in a farm track to the north-west of Porth Clais, St David's Peninsula, Pembrokeshire. The level of the unconformity lies at the position of the hammerhead. (Photo: S. Howells.)

1995). The compositional range of these rocks is typical of many volcanic arc sequences and is particularly emphasized within the Lower Pebidian, which includes basaltic lava and tuff sequences, the latter with interbedded silicic pyroclastic rocks. In the Ramsey Sound Group, these latter silicic rocks are dominant, their content of broken crystals, lithic fragments, pumice and shards leading to the conclusion that they were originally ash-flow tuffs. Original eutaxitic fabrics, characteristic of welded ash-flow tuffs, can also be discerned.

The Rhosson Group was interpreted in an earlier survey to comprise andesitic and trachytic tuffs and lavas. Petrological and geochemical analyses (Davies and Bloxam, 1990; Bevins *et al.,* 1995) suggest, however, that together with the overlying Ogofgolcha Group it marks a reversion to basaltic volcanism, the various tuffs being interpreted as autobrecciated lavas and scoriaceous debris related to lava effusion. The occurrence of silicic welded tuff clasts demonstrates further that acidic volcanic activity predated the eruption of these basic lavas.

Bevins *et al.* (1995) have contrasted the chemistry of the volcanic rocks from the St David's Peninsula site with those of the Coomb Volcanic Formation and Johnston Complex –Benton Volcanic Group, which lie to the south and are of 'Uriconian' affinity. Such studies have furnished important evidence for the existence of separate Precambrian terranes in the local basement, as discussed in the introduction to this chapter.

Although the Pebidian Supergroup has been widely correlated with other Precambrian volcanic successions in southern Britain, the geochemical characterization of the Pebidian Supergroup and St David's Granophyre now allow more valid correlations to be made. The U-Pb zircon age date (within error) allows these intrusive and extrusive rocks to be placed within Avalonian Event 2, at 630–600 Ma, which has been interpreted by Gibbons and Horák (1996) as the main phase of Avalonian magmatism. The Pebidian Supergroup and associated intrusives can therefore be categorized in terms of the Avalonian crustal evolution of southern Britain. They can also be more broadly correlated with components of the Avalonian basement in eastern Canada, and thus provide evidence of the extent and nature of magmatism in this complex, multiple-arc system. In addition, these rocks, together with those of the Arfon Group at the Llyn Padarn GCR site, provide insight into the likely nature of the pre-Palaeozoic basement below much of the Welsh Basin.

The Precambrian igneous sequences of the St David's Peninsula also provide evidence for a discordant, unconformable contact with overlying Cambrian strata.

Conclusions

The Pebidian Supergroup exposures at this site exemplify the diversity of rock types formed within a late Precambrian volcanic arc. They are volcanic rocks such as basaltic lavas and tuffs, which are in places interleaved with ash-flow tuffs derived from a contemporary, more silica-rich and explosive style of volcanism. The final stage of magmatism involved the intrusion of granophyre, as is also seen in the Precambrian suites of Charnwood Forest (Chapter 2) and the Uriconian Group of The Wrekin (Chapter 4). These rocks contribute much evidence about the nature, evolution and extent of Precambrian Avalonian arc magmatism in southern Britain and its correlation with the well-documented events of similar age in eastern Canada. Regionally the St David's Peninsula occurrences are significant in that they represent parts of the 'basement' that lies unconformably beneath Palaeozoic sedimentary rocks of the Welsh Basin.

LLYN PADARN (SH 550 630–590 610)

POTENTIAL GCR SITE

A. J. Reedman

Introduction

Llyn Padarn is situated within an area of spectacular scenery on the fringes of Snowdonia. It has been selected for the GCR independently for its Cambrian stratigraphy and is proposed as a Precambrian site because of its particularly good exposures of the Arfon Group, and also because of its accessibility (Howells *et al.,* 1985; Reedman *et al.,* 1984). These rocks crop out extensively on the south-eastern side of the Menai Strait between Caernarfon and Bangor, as shown in Figure 6.1. Llyn Padarn (Figure 6.5) includes the eastern part of the Arfon Group, which here is particularly well exposed in large crags and ice-moulded rocky knolls on the shores and nearby hills surrounding the north-western half of the lake. The lower part of the

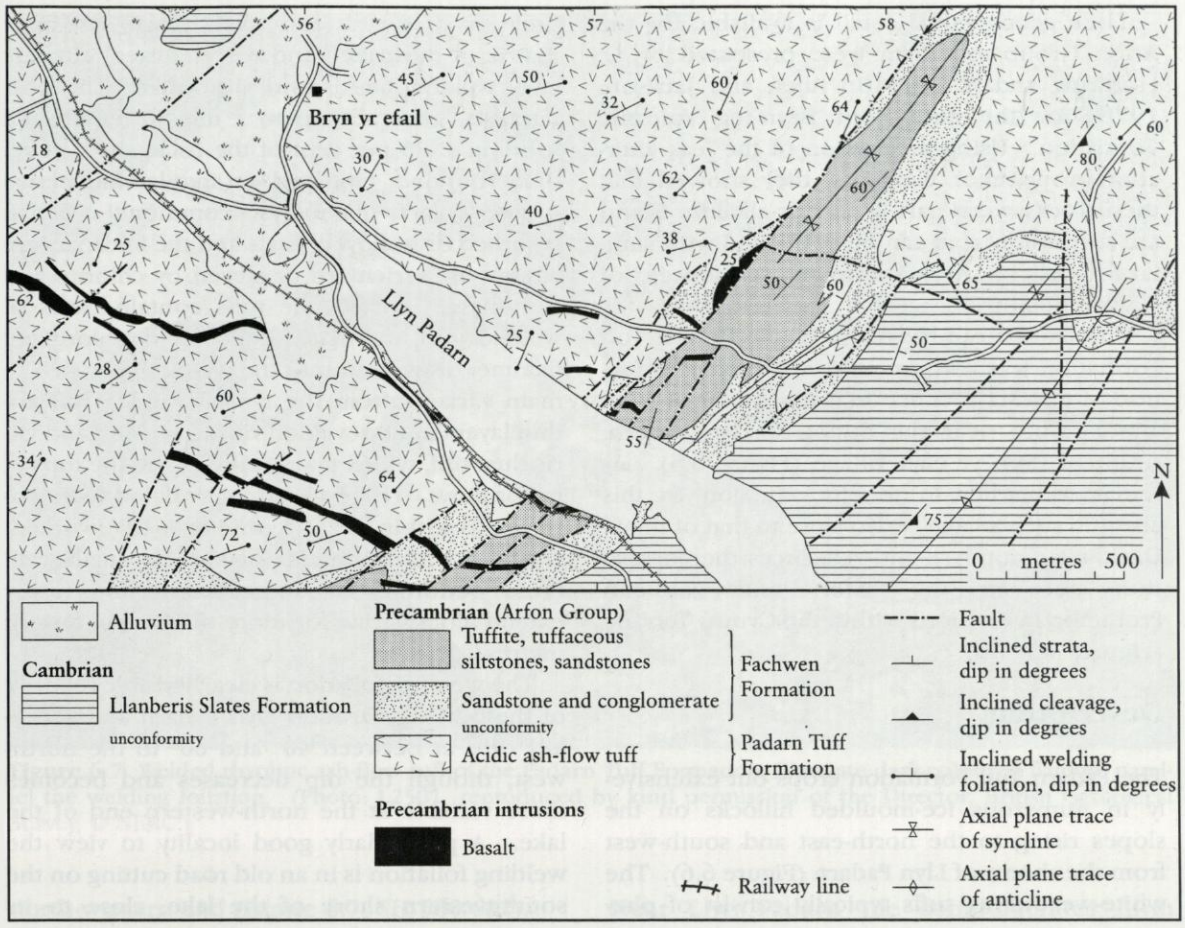

Figure 6.5 Simplified geological map of the Llyn Padarn site (based on BGS 1: 25 000 maps for parts of Sheets SH55 and SH56)

group comprises the Padarn Tuff Formation, dominated by acidic ash-flow tuffs (ignimbrites) and probably exceeding 1500 m in thickness. This is overlain by a further several hundred metres of clastic sedimentary rocks, the Fachwen Formation (Reedman *et al.*, 1984; Howells *et al.*, 1985).

Outcrops of the Arfon Group are restricted to North Wales in the vicinity of the Menai Strait and both geophysical and outcrop evidence suggest that the group thins rapidly to the south-east, where it is covered by the Lower Palaeozoic sequences of Snowdonia. Little therefore is known of its original lateral extent beneath these younger rocks towards central Wales. The Bryn-teg borehole (Allen and Jackson, 1978), however, penetrated through the Cambrian cover strata in the Harlech Dome region (Figure 6.1), and proved approximately 140 m of volcanic and sedimentary rocks beneath. These, named the Bryn-teg Volcanic Formation, occupy an apparently similar stratigraphical position and are correlated with the Arfon Group. The Bryn-teg sequence contains lithologies that include: andesite, dacite, tuffites, interbedded volcaniclastic mudstones, siltstones and sandstones and intrusive basalt. Allen and Jackson (1978) drew attention to the abundance of volcanic clasts in the basal conglomerates of the overlying, Cambrian-age Dolwen Formation. No evidence for an angular difference across the junction was found in the borehole, but Allen and Jackson (1978) nevertheless concluded that such an abrupt change in lithology meant that the Bryn-teg Formation and Dolwen Formation were unconformable and separated by an erosional interval. According to G. Hornung and A. Gray (in Allen and Jackson, 1978), the chemistry of the volcanic clasts in the Dolwen conglomerates is not of 'Bryn-teg'-type, but more in keeping with their derivation from Precambrian volcanic sequences such as that at Llyn Padarn.

Little geochemical detail is available for the Arfon Group, but data were presented by G. Hornung and A. Gray (in Allen and Jackson, 1978) for the equivalent Bryn-teg Volcanic Formation. Using a selection of the less alteration-prone trace elements, they showed that these rocks were part of a 'calc-alkaline island arc succession' that can be correlated with similar rocks in the Avalonian sequences of Newfoundland.

The late Precambrian age of the Padarn Tuff Formation was confirmed by a U-Pb determination of 614 Ma ± 2 Ma on rocks collected from an exposure near the outlet of Llyn Padarn, south of Bryn yr efail village (Figure 6.5). As remarked earlier in the introduction to this chapter, such an age is also close to that of the St David's Granophyre and reinforces the correlation between the Arfon and Pebidian Precambrian divisions within the Cymru Terrane (Figures 1.1, 1.2).

Description

The Padarn Tuff Formation crops out extensively in numerous ice-moulded hillocks on the slopes rising to the north-east and south-west from the shores of Llyn Padarn (Figure 6.6). The white-weathering tuffs typically consist of phenocrysts of quartz and sodic plagioclase in a matrix of devitrified and recrystallized, eutaxitically welded shards and vitric dust The phenocrysts, generally up to 2 mm in length and forming *c.* 25 per cent of the rock, show euhedral, rounded, embayed or angular fragmental forms. Quartz phenocrysts commonly occur as resorbed or hollow crystals and the feldspars are commonly sericitized or sieved by chlorite and carbonate. Locally the tuffs contain clasts of welded tuff, tubular pumice and chloritized fiamme, drawn out into the welding fabric. The main variants from the typical welded tuff are thin layers of non-welded vitroclastic tuff and vitric dust-tuff, which may locally define the tops of major flows. There are no intercalated sedimentary beds within the tuffs; thin beds of reworked, crystal-rich tuff debris, displaying small-scale cross bedding, are impersistent and rarely extend along strike for more than a few tens of metres.

The welding foliation is clearly visible in many of the outcrops around Llyn Padarn and generally dips at between 40° and 60° to the north-west, though the dip decreases and becomes more variable at the north-western end of the lake. A particularly good locality to view the welding foliation is in an old road cutting on the south-western shore of the lake, close to its

Figure 6.6 View to the north-east across Llyn Padarn with numerous outcrops of the Padarn Tuff Formation in the foreground. (Photo: L2244, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

Figure 6.7 Welded rhyolitic ash-flow tuff of the Padarn Tuff Formation. Elongate dark-coloured fiamme parallel the welding foliation. (Photo: L2501, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

north-western end (Figure 6.7; SH 560 622).

The most striking impression gained from an examination of the many outcrops of the Padarn Tuff Formation around Llyn Padarn is of its great uniformity of composition and texture. Furthermore, the overall north-westward dip of the welding foliation indicates that these tuffs accumulated to a great thickness, estimated to be at least 800 m in the vicinity of Llyn Padarn.

The Fachwen Formation occurs to the east of the Padarn Tuff Formation, its crop crossing the central part of Llyn Padarn. Locally its basal beds are seen overlying the Padarn Tuff Formation, either disconformably or unconformably, but commonly it is in faulted contact with the welded tuffs of the Padarn Tuff Formation. The basal strata are normally clast-supported conglomerates of angular to subrounded pebbles, cobbles and blocks of welded and non-welded acidic tuff and felsite. These are enclosed in a matrix of resorbed and hollow quartz and feldspar crystals, fine lithic grains and recrystallized vitric debris. Rounded clasts of basalt, jasper, quartzite, granite, siltstone and quartzose schist are rare near the base of the conglomerates, but become increasingly abundant in the upper part. Near Llyn Padarn the conglomerates form wedges up to 150 m thick which grade, both laterally and vertically, into coarse-grained, cross-bedded sandstones composed predominantly of quartz and feldspar crystals and grains of acidic tuff. At several localities a thin, welded, acidic ash-flow tuff is intercalated within the basal part of the formation.

Fine- to coarse-grained clastic sedimentary rocks, containing much reworked volcanic debris, make up the bulk of the rest of the formation. Lateral and vertical variation is rapid, but generally near Llyn Padarn, above the sandstones and conglomerates, the middle part of the sequence is dominated by laminated tuffaceous siltstones and tuffites, with sandstones becoming more abundant in the upper part.

The formation thickens markedly from east to west north of Llanberis; on Gallt y Foel (SH 585 620) it is represented by a single sandstone unit *c.* 40 m thick, whereas around Fachwen (SH 575 618) it is *c.* 450 m thick and increases to over 600 m near Moel-i-Ci (SH 590 661). Outcrops can conveniently be examined around Fachwen (SH 574 618) and along footpaths between Bigil (SH 579 623) and Deiniolen (SH 579 633).

Interpretation

The great thickness and the homogeneity of the Padarn Tuff Formation indicates rapid accumulation from pyroclastic flows restricted in a topographical depression. The current geometry of the formation suggests that the depression was a NE-trending graben, or half-graben, bounded on the west by the Dinorwic Fault. The voluminous eruption of ash-flow tuffs and the collapse of the fault-bounded depression were probably genetically linked.

A pronounced Bouguer gravity anomaly low, approximately coincident with the outcrop of the Padarn Tuff Formation, was originally described by Powell (1955) and subsequently modelled by Reedman *et al.* (1984). It provides additional evidence for the previous existence of an extensive topographical depression in which up to 2 km thickness of acid tuffs accumulated. This depression, some 15 km wide and possibly as much as 60 km long, can be compared to the Toba volcano-tectonic depression in Sumatra, Indonesia, a collapse structure associated with the voluminous eruption and accumulation of acidic ash-flow tuffs.

Following the accumulation of the ash-flow tuffs of the Padarn Tuff Formation, continued differential subsidence and uplift, accompanied by sporadic volcanism, erosion and the accumulation of a thick sequence of volcaniclastic sediments, characterized the further development of the Arfon Basin (Reedman *et al.*, 1984). In the east, lenses of conglomerate and coarse sandstone at the base of the Fachwen Formation represent alluvial fans and fluvial deposits that probably accumulated close to the fault system at the eastern margin of the structure, which restricted the Padarn Tuffs. Although acid tuff clasts predominate in these basal beds, rounded clasts of more distant provenance are also present. The Fachwen Formation conglomerates rest either disconformably or unconformably upon eroded ash-flow tuffs of the Padarn Tuff Formation. Around Llyn Padarn, variations in the angular relationships at these contacts take place abruptly across faults, suggesting rotation of the fault blocks prior to, and perhaps during, sedimentation.

To the west of Llyn Padarn, between Bangor and Caernarfon, there are extensive outcrops of the Arfon Group separated from the Llyn Padarn outcrops by the Aber-Dinlle Fault and an intervening tract of Ordovician strata (Bangor Sheet, 106). Here, in ascending order, the Arfon Group comprises: the Padarn Tuff, the Bangor and the Minffordd formations (Reedman *et al.*, 1984; Howells *et al.*, 1985). Around Bangor, the Minffordd Formation comprises conglomerates, sandstones, acid tuffs and tuffites, and rare basic tuffites. The higher beds in the formation display a westward overlap on to the Padarn Tuff Formation adjacent to the Dinorwic Fault, indicating continued fault activity which was accompanied by erosion of the Padarn Tuff Formation. As in the Padarn area, the polymict, ill-sorted, massive conglomerates are interpreted as small fans that accumulated adjacent to contemporaneous fault scarps. The Bangor Formation, restricted to a small area near Bangor (Reedman *et al.*, 1984), comprises similar lithologies to the Minffordd and Fachwen formations.

The distribution and composition of epiclasts in the conglomerates and sandstones of the Minffordd, Fachwen and Bangor formations reflect uplift and progressive stripping of the volcanic cover in the region adjacent to the basin. Initially, volcaniclastic debris of the Fachwen Formation was mainly derived from the irregularly faulted surface of the Padarn Tuff Formation within the basin, though in the east clasts of both metamorphic rocks and of basalt are found. The former are possibly derived from the pre-Arfon basement in the east and the latter from basalts locally erupted onto the Padarn Formation surface as at Coed Glanyrafon (SH 502 596), west of Betws Garmon. The Minffordd Formation shows a progressive increase in the ratio of basic to acidic detrital material during its accumulation. The acidic debris was probably derived mainly from the erosion of outflow deposits from the early Arfon Basin, and the basaltic material from lavas of undetermined provenance, which were progressively unroofed by uplift outside the basin. Further uplift and erosion of the basin margins in the west resulted in the supply of clasts of the pre-volcanic basement, including Penmynydd schists, to the proximal fan facies of the basal conglomerates of the Bangor Formation. Acidic volcanic debris continued to be supplied, but a sedimentary hiatus is suggested by the unconformity at the base of the Bangor Formation. This non-sequence could reflect uplift and erosion, removing the source of basaltic debris, or a change in topography, which prevented its incorporation in the Bangor Formation sediments.

In contrast to the Arfon Group, the

Precambrian rocks in the Bryn-teg borehole show a style of magmatism that gave rise to basic and intermediate volcanic products, most of the pyroclastic rocks being of basic composition. The depositional environment is believed to have been subaqueous (Allen and Jackson, 1978). Nothing is known of their lateral extent, but it is possible that both the Arfon Group and Bryn-teg Formation represent the broadly synchronous expression of volcanism and sedimentation dominated by contrasting volcanic centres within an extensive late Precambrian volcanic province.

Conclusions

The extensive outcrops of the Arfon Group are important for illustrating the development of a voluminous late Precambrian volcanic episode in the Cymru Terrane (Figure 1.1). The oldest rocks, of the Padarn Tuff Formation, represent perhaps as much as 500 km^3 of rhyolitic ash-flow tuff that was erupted explosively from volcanoes located within a region characterized by fault-controlled subsidence. The volcanism was succeeded by erosion, with the accumulation of conglomerates, sandstones, siltstones and tuffites making up the overlying Fachwen Formation. Initially its detritus was largely derived from the local volcanic terrain, but subsequently material was eroded from older sequences farther afield, at the margins of the Padarn Tuff depression. This progression indicates that the area continued to subside through repeated extension of the crust along major NW-trending faults.