Chapter 6 Wales and adjacent areas

Introduction

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Geological setting

In early Ordovician times Wales lay at a latitude of approximately 60°, in the southern hemisphere on the margin of a major continent, Gondwana (Cocks and Fortey, 1982; Torsvik and Trench, 1991). This continent was separated from two other major continents, Laurentia and Baltica, by the Iapetus Ocean and Tornquist Sea respectively. Active subduction of Iapetus oceanic lithosphere beneath the continental margin of Gondwana was associated with extension of the overlying crust and the generation of abundant magmatism (Bevins *et al.,* 1984; Kokelaar *et al.,* 1984b). This extension also led to the development of the Welsh Basin, a marine basin up to 150 km wide, which was to dominate the palaeogeography of Wales for over 100 million years. During mid-Ordovician times, Eastern Avalonia, a continental fragment or microcontinent, split away from Gondwana and drifted northwards, linked to continued subduction. Collision with Laurentia may have occurcd as early as Caradoc times in this sector of Iapetus. Wales was a part of this microcontinent (Soper, 1986) and the character and timing of igneous activity across the Welsh region was dictated by this subduction-dominated tectonic evolution, from the earliest activity in southern Snowdonia and north Pembrokeshire in Tremadoc times through to the last recorded major activity in southern Pembrokeshire, of Llandovery age.

Sedimentation throughout the region was largely of marine character; for long periods of time, black muds accumulated in deep waters, interrupted periodically by incursions of coarser sediment, transported by gravity flows. At the margins of the Welsh Basin shallower water conditions prevailed, and periodically the Midland Platform to the SE of the basin was emergent. Sedimentation was also strongly influenced by relatively short-lived volcanic episodes, when large volumes of coarser detritus were available for reworking in the marine environment (Kokelaar *et al.,* 1984b).

Kokelaar (1988) has argued convincingly that magmas in the Ordovician Welsh Basin were channelled up major fractures that cut through the crust, in an overall sinistrally transtensional tectonic environment. Major volcanism was restricted to narrow graben-like zones above the most important fractures, leading to the development of thick local accumulations. In some cases, as in central Snowdonia, extension was linked to caldera development (Howells *et al.,* 1991).

The geochemistry of the various Caledonian igneous rocks across Wales has been studied in considerable detail. The earliest lavas show a strong subduction-zone influence, being low-K tholeiitic to calc-alkaline in character (Kokelaar *et al.,* 1984b). Variations from basic to silicic composition have been identified, resulting from low pressure fractional crystallization (Kokelaar, 1986). Subsequent Ordovician events were characterized by bimodal sequences, showing a range of chemical affinities, from Mid-Ocean-Ridge Basalt (MORB) types through low-K tholeiites to calc-alkaline, some lava sequences showing more than one chemical type (Bevins, 1982; Bevins *et al.,* 1984; Smith and Huang, 1995). The origin of the silicic rocks has been a matter of considerable debate, linked variably to melting of the crust as the hot mafic magmas rose towards the surface (Kokelaar *et al.,* 1984b), to fractional crystallization of the mafic magmas (Bevins *et al.,* 1991), or to a combination of these processes (Leat *et al.,* 1986). Studies of the chemical variations seen within a single intrusion showing extreme compositional variation in South Wales (Bevins *et al.,* 1994), and also from detailed studies of a closely related suite of minor silicic intrusions and ash-flow tuffs in North Wales (Campbell *et al.,* 1987; Thorpe *et al.,* 1993b) favour the bulk of the silicic rocks being derived from more mafic compositions through fractional crystallization.

The chemistry of late Ordovician igneous rocks from Snowdonia suggest that subduction beneath Eastern Avalonia ceased during Caradoc times (Leat and Thorpe, 1989), although the effects of the subduction are still to be seen in later igneous rocks. An episode of igneous activity in South Wales during Llandovery times was more alkaline in composition than earlier episodes, with the eruption of basalts, hawaiites and mugearites, as well as peralkaline rhyolitic rocks (Thorpe *et al.,* 1989). These lavas still, however, show a chemical signature related to the modification of mantle-derived

magmas most probably by fluids driven off from subducted oceanic crust.

The igneous sequence

The sites selected to represent the Caledonian igneous history of Wales are located on (Figure 6.1). A general stratigraphical representation of the main volcanic events is presented in (Figure 6.2). An overall review is presented in this section, followed by individual site reports.

Tremadoc

The earliest expressions of Caledonian igneous activity in the Welsh region are represented by the Treffgarne Volcanic Group, exposed in north Pembrokeshire (Bevins *et al.,* 1984) (not formally represented in the GCR at the time of writing), and the Rhobell Volcanic Complex, exposed in southern Snowdonia (Kokelaar, 1979, 1986) at the Rhobell Fawr GCR site. Here, basic lavas and related high-level basic, intermediate and silicic intrusions are thought to represent the eroded remnants of a calc-alkaline volcano linked to the first stages of subduction of Iapetus oceanic crust. Rare cumulate blocks, unique in the British Caledonide region, provide critical evidence for the petrogenesis of the various rock types present. The Rhobell igneous rocks have low-K tholeiitic to calc-alkaline geochemical affinities.

Arenig to Llandeilo

Following the localized igneous activity in Tremadoc times, Arenig to Llanvirn times, in contrast, saw widespread volcanism across Wales, from Pembrokeshire in the south, through southern Snowdonia, to Ll■n in the north, with the first activity also seen in the Welsh Borderland.

In north Pembrokeshire (Figure 6.3), a major volcanic centre developed during latest Arenig to Llanvirn times in the vicinity of Fishguard (Bevins, 1979; Bevins and Roach, 1979a), characterized by the predominantly bimodal basic–silicic volcanic rocks exposed at the Pen Caer GCR site. Here, up to 1800 m of basaltic lavas and relatively minor rhyolitic lavas and ash-flow tuffs, which make up the Fishguard Volcanic Group, represent the most important Ordovician volcanic centre in South Wales. The sequence developed entirely in a submarine environment and the sequence of pillow lavas exposed around the Pen Caer coast is among the finest seen anywhere in Great Britain. At the base of the succession, in the Porth Maen Melyn area, dacitic to rhyodacitic lavas exhibit elongate flow tubes developed at a steep flow front (Bevins and Roach, 1979b); flow phenomena of this type are rarely developed in lavas of such silicic compositions and hence the features are of international significance. The basic lavas show a tholeiitic chemistry of N-type (normal) MORB character, with a minor subduction zone influence (Bevins, 1982), although the dacitic lavas and high-level intrusions at the base of the sequence have calc-alkaline affinities (Bevins *et al.,* 1992).

Farther to the west in north Pembrokeshire, a major submarine volcanic centre developed in the vicinity of Ramsey Island (Kokelaar *et al.,* 1985), the products comprising the Carn Llundain Formation, exposed in the Aber Mawr to Porth Lleuog GCR site. An extremely well-exposed coastal section shows Cambrian conglomerates and sandstones overlain by a thick Arenig to Llanvirn silicic pyroclastic and volcaniclastic sequence. The succession comprises abundant tuff turbidites of the Pwll Bendro Member, ash-flow tuffs of the Cader Rhwydog Member, and at the top of the pile an autobrecciated rhyolitic flow forming the Allt Felin Fawr Member. Of major significance is the development of a thick welded submarine ash-flow and ash-fall unit in the Cader Rhwydog Member, which was the first of such ash-fall tuffs in the world to be described.

The youngest volcanic episode in north Pembrokeshire is demonstrated by basaltic tuffs of *Didymograptus murchisoni* Biozone age (Bevins and Roach, 1979a; Kokelaar *et al*., 1984b), exposed in the Castell Coch to Trwyncastell GCR site area. The tuffs represent distal deposits derived by slumping of loose ash and lapilli on the flanks of a submarine volcano. In the vicinity of Trwyncastell, fine-grained distal silicic ash-flow tuffs of slightly earlier Llanvirn (*Didymograptus bifidus* Biozone) age are also exposed. Although precise correlation is not possible, these ash-flow tuffs most probably represent the distal deposits from the kind of volcanic centre developed to the west, on Ramsey Island (Aber Mawr to Porth Lleuog GCR site), or to the east, at the Pen Caer GCR site.

The origin of the silicic igneous rocks in the Caledonide region of Wales has been a matter of contention for many years. Recent detailed geochemical studies of the St David's Head Intrusion (Bevins *et al.,* 1994), in north Pembrokeshire (St David's Head GCR site), have indicated that in this case the silicic rocks were generated as a result of low-pressure fractional crystallization from the more basic compositions, providing a model for the generation of some of the Ordovician rhyolitic rocks associated with tholeiitic basaltic lavas (for example at the Pen Caer GCR site).

Another major volcanic centre of early Ordovician age was located in southern Snowdonia, to the SW of Dolgellau. The Cadair Idris GCR site is of importance in representing the most complete, well-exposed sequence through the Aran Volcanic Group, which ranges in age from Arenig to earliest Caradoc (Pratt *et al.,* 1995). Like the Pen Caer GCR site, the igneous episode was bimodal in character, with predominantly rhyolitic ash-flow tuffs associated with an interval of eruption of basaltic lavas that are commonly pillowed. The basalts show transitional tholeiitic-calc-alkaline affinities (Kemp and Merriman, 1994), contrasting with the more strongly tholeiitic lavas of the Pen Caer GCR site. The nearby Pared y Cefn-hir GCR site provides an excellent section through basic and acid tuffs of the lower part of the Aran Volcanic Group, and represents the best-exposed section of volcanic rocks of Arenig to Llanvirn age in North Wales.

In the Welsh Borderland, volcanic rocks of Llanvirn to Llandeilo age crop out in the Builth and Shelve inliers (Figure 6.4), as well as farther south around Llandeilo. The thickest sequence lies at the southern end of the Builth where the Carneddau and Llanelwedd GCR site exposes mainly basic and silicic tuffs, as well as basic, intermediate and silicic lavas of Llanvirn age (Bevins *et al.,* 1984; Kokelaar *et al.,* 1984b; Bevins and Metcalfe, 1993). In contrast to the Pen Caer and the Cadair Idris GCR sites, lavas and intrusive rocks of intermediate composition are also present. Of particular interest is that both tholeiitic and calc-alkaline lavas are present in the lava sequence exposed at the Carneddau and Llanelwedd GCR site (Smith and Huang, 1995). The site also has historical importance in being the area in which one of the first palaeogeographical reconstructions of a volcanic environment was based (Jones and Pugh, 1949).

Caradoc

During Caradoc times igneous activity shifted to North Wales, with centres located in Snowdonia, to the west on Ll■n, and to the east in the Berwyn and Breidden Hills in the Welsh Borderland (Figure 6.4). Snowdonia, however, was the focus of the most important activity in the Welsh Caledonide region and has for many years played a crucial part in the understanding of igneous processes, in particular the mechanisms of ash-flow tuff eruption and emplacement.

The first regional investigation of Snowdonia was instigated as early as 1846 by the Geological Survey, being completed in 1852, with later publication of a sheet explanation (Ramsay, 1866) and a memoir (Ramsay, 1881). Harker (1889) published results of the first detailed petrographical investigations of the Snowdon Ordovician volcanic rocks and recognized that a number of different volcanic centres had been in existence. A critical observation, which went largely unrecognized for many years, was that by Greenly (in Dakyns and Greenly, 1905), namely, that some of the silicic rocks had textures similar to those of Pelean deposits. This point was reinforced by Williams (1927) in an influential paper reviewing the form, petrography and structure of the Ordovician volcanic rocks of central Snowdonia. A crucial stimulus to the investigation of the volcanic history of Snowdonia, however, was provided by Oliver (1954) and later by Rast *et al.* (1958), who recognized that many of the silicic volcanic rocks were in fact welded ash-flow tuffs. At the time it was assumed that such tuffs could only be generated in subaerial environments and hence palaeogeographical reconstructions were revised to take account of substantial, periodic rises and falls in sea level, with the environment periodically changing from subaerial to submarine. Consideration of these environmental changes led to the proposal of a major subaerial volcano and related caldera structure (Bromley, 1969; Rast, 1969; Beavon, 1980).

This palaeogeographical reconstruction for Snowdonia was challenged and substantially revised following the crucial identification in Snowdonia of ash-flow tuffs that had welded in the submarine environment (Francis and Howells, 1973; Howells *et al.,* 1973). This work, of major international significance, stimulated a thorough reinvestigation of the Ordovician volcanic rocks of northern and central Snowdonia, based on detailed field mapping by officers of the British Geological Survey. Most recently the area has been the subject of a comprehensive, multidisciplinary investigation of the Caradoc volcanism, coordinated by the British Geological Survey but also involving researchers from other institutions. The culmination of this project was the publication of a definitive memoir of the igneous history of this part of the Caledonide region (Howells *et al.,* 1991).

Although the volcanic successions are voluminous in central and northern Snowdonia, accounting for approximately half of the Ordovician succession in those areas, the volcanic activity was relatively short-lived, being restricted to two chronostratigraphical stages, namely the Soudleyan and the Longvillian. A lack of adequately preserved faunas precludes determination of an accurate biostratigraphical age for the volcanic episode, but it appears to have occurred partly during *Diplograptus multidens* Biozone times and partly during *Dicranograptus clingani* Biozone times.

Two eruptive cycles have been determined in northern and central Snowdonia, separated by a period of quiescence and deposition of silici-clastic sediments. The earlier, 1st Eruptive Cycle comprises the Llewelyn Volcanic Group, while the later, 2nd Eruptive Cycle comprises the Snowdon Volcanic Group (Figure 6.5).

The Llewelyn Volcanic Group comprises five formations that are exposed in a NE-trending tract of country across northern Snowdonia, with distal facies locally reaching central Snowdonia. The first four formations represent an earlier phase of activity, the formations being in part contemporaneous. The eruptions occurred from four different centres, with deposition being strongly controlled by contemporaneous faults; hence thicknesses vary rapidly. The most northerly formation, the Conwy Rhyolite Formation, is exposed to the SW of Conwy, and comprises flow-banded rhyolitic lavas and ash-flow tuffs (Howells *et al.,* 1991). To the SW, the Foel Fras Volcanic Complex is composed chiefly of trachyandesitic lavas and ash-flow tuffs and associated high-level intrusions (Howells *et al.,* 1983; Ball and Merriman, 1989), with the maximum thickness being developed Within a caldera structure at the centre of eruption. The Foel Grach Basalt Formation is exposed farther to the SW again, with deposition of massive and pil-lowed basalts and hyaloclastite breccias in two separate basins which, considering thickness variations, had the form of half-graben. Magma ascent most probably took place up the bounding faults (Howells *et al.,* 1991). The most south-westerly formation of the early phase of the 1st Eruptive Cycle is the Braich tu du Formation, composed mainly of rhyolitic lavas and tuffs. The Braich tu du GCR site exposes sequences that demonstrate the volcanic evolution of the three most south-westerly formations described above.

The final volcanic episode of the 1st Eruptive Cycle is represented by the Capel Curig Volcanic Formation, exposed across northern and eastern Snowdonia (Howells *et al.,* 1979; Howells and Leveridge, 1980). The formation chiefly comprises ash-flow tuffs, both welded and non-welded in character. These tuffs were erupted from three volcanic centres; two located in the north were in a subaerial environment, the third in the south in a submarine environment. Howells and Leveridge (1980) demonstrated, on the basis of the various facies of the tuffs, that the ash-flows passed from the subaerial to the submarine environment. The Llyn Dulyn GCR site illustrates the subaerial character of the Capel Curig Volcanic Formation ash-flow tuffs while the Capel Curig GCR site, in contrast, is of importance in being representative of the submarine facies of the ash-flow tuffs. Critically, the tuffs are welded in close contact with the adjacent sedimentary rocks (Francis and Howells, 1973), and this is interpreted as representing welding of the ash-flow tuffs in a submarine environment. This site is of international importance in representing the first location where the welding of tuffs in a submarine situation was identified.

The Snowdon Volcanic Group, representing the 2nd Eruptive Cycle, comprises a complex sequence of silicic ash-flow tuffs, rhyolitic and basaltic lava flows and hyaloclastites emplaced in a shallow to offshore marine environment. Contemporaneous high-level silicic intrusions are abundant. The group crops out across Snowdonia, trending from the NE to the SW over a distance of some 45 km. Three centres of activity have been defined (Howells *et al.,* 1991), the Llwyd Mawr Centre in the SW, the Snowdon Centre around the Snowdon Massif and the Crafnant Centre in the NE. The development of caldera structures is a feature of each of these centres.

The Llwyd Mawr Centre comprises silicic ash-flow tuffs of the Pitts Head Tuff Formation. The site of eruption is considered to have been close to Llwyd Mawr (Roberts, 1969). Two facies are identified, an intracaldera facies, where up to 700 m of welded ash-flow tuffs occur owing to ponding within the caldera (Reedman *et al.,* 1987) which most probably developed in a sub-aerial setting. This intracaldera facies of the Pitts Head Tuff is exposed at the Craig y Gam GCR site. The Pitts Head Tuff Formation can be traced to the east into the Moel Hebog syncline. The formation is represented by two, relatively thin ash-flow tuffs (up to 90 m in total), which can be traced crossing from a subaerial to a submarine environment. In both environments the tuffs are welded. These tuffs are thought to represent the outflow facies from the Llwyd Mawr Centre (Reedman *et al.,* 1987), and are exposed in the Moel Hebog to Moel yr Ogof GCR site area.

Activity linked to the Snowdon Centre was dominated by the eruption of voluminous acidic ash-flow tuffs linked to major caldera collapse. The earliest activity from this centre, which occurred prior to development of the caldera, led to the accumulation of 180 m of welded ash-flow tuffs, the Yr Arddu Tuffs, erupted along a NNE-trending fissure (Howells *et al.,* 1987). The deposits from this phase of activity are exposed in the Yr Arddu GCR site area.

Following eruption of the Yr Arddu Tuffs, a major caldera-forming event in central Snowdonia occurred, associated with the eruption of a huge volume of acidic ash-flow tuffs, forming the Lower Rhyolitic Tuff Formation ¯(Howells *et al.,* 1986). The formation is up to 600 m thick and volume estimates range from 30 km^3 in the central area, to 20 km^3 away from this area. Marked variations in thickness define intracaldera and outflow facies. On the basis of such thickness and facies variations, the caldera has been calculated as being up to 12 km across. Intrusive rhyolites are particularly abundant within the caldera area, with five geochemically distinct groups being determined (Campbell *et al.,* 1987). The form of the caldera was strongly influenced by four NE- to NNE-trending basement fractures. The various lithologies and the different facies of this caldera-forming event are seen across central Snowdonia, in the Moel Hebog to Moel yr Ogof Snowdon Massif, and Cwm Idwal GCR site areas.

The caldera-forming event was followed by an episode of predominantly basic volcanic activity, and the Bedded Pyroclastic Formation is dominated by basic tuffaceous sedimentary rocks, basaltic lavas, hyaloclastites, and high-level basic intrusive rocks (Howells *et al.,* 1991). Kokelaar (1992) demonstrated the strong tectonic influence in the timing, location and style of the basaltic volcanism associated with development of the Bedded Pyroclastic Formation. The formation is exposed around the Snowdon Massif and the sequences are represented in the Moel Hebog to Moel yr Ogof, Snowdon Massif, and Cwm Idwal GCR site areas.

The final activity of the Snowdon Centre was the eruption of further silicic ash-flow tuffs of the Upper Rhyolitic Tuff Formation, possibly linked to the generation of another caldera structure. Eruption of the tuffs was associated with the development of high-level rhyolite intrusions, all of the silicic rocks being of peral-kaline composition. The Upper Rhyolitic Tuff is best exposed in the Snowdon Massif GCR site area.

Following eruption of the Upper Rhyolitic Tuffs of the Snowdon Centre, the focus of activity shifted to eastern and north-eastern Snowdonia, with eruptions from the Crafnant Centre. Activity was dominated by the eruption and emplacement of silicic ash-flow tuffs in a relatively deep marine environment. The earliest events were linked to the generation of three primary, non-welded tuffs, derived from a local source, which form the Lower Crafnant Volcanic Formation (Howells *et al.,* 1973), exposed at the Curig Hill GCR site area. Later activity shifted to the east, deposits from which are outflow tuffs of the Middle and Upper Crafnant ¯volcanic formations (Howells *et al.,* 1978), seen in the Sarnau GCR site area.

Most acidic intrusions in Snowdonia are closely related to the centres of eruption of the silicic ash-flow tuffs and the caldera structures. Two major acidic intrusions, however, fall outside of the caldera areas, namely the Mynydd Mawr and the Tan y Grisiau granitic intrusions. The character of the latter intrusion is demonstrated at the Ffestiniog Granite Quarry GCR site.

Volcanism during Caradoc times was not solely restricted to Snowdonia. To the east, in the Berwyn, explosive silicic volcanism occurred contemporaneous with the caldera-forming events in Snowdonia. At the Pandy GCR site, pumiceous ash-fall, ash-flow and pyroclastic surge deposits testify to short-lived subaerial volcanoes, linked to uplift associated with the volcanism, and demonstrate the character of activity across NE Wales.

To the west of Snowdonia, the products of Caradoc-age volcanism are also seen on Ll■n (Figure 6.6). The products from two distinct centres have been determined, although distal ash-flow tuffs of the Pitts Head Tuff Formation erupted from the Llwyd Mawr Centre (see Craig y Garn GCR site) are exposed in the east of the peninsula. On 14n, an earlier ?Soudleyan–Longvillian event centred in the Nefyn district was responsible for the generation of volcanic rocks that include the Upper Lodge Formation (broadly equivalent to the 'Upper Lodge Group' of Matley and Heard, 1930) and the Allt Fawr Rhyolitic Tuff Formation, while a younger event, of Woolstonian age, was linked to generation of the Llanbedrog Volcanic Group (Young *et al.,* in press). Both centres are characterized by the development of subvolcanic high-level intrusions. These intrusions were previously thought to be of Devonian age (Tremlett, 1962). Later studies by Croudace

(1982) and Young *et al.* (in press) have demonstrated convincingly that the volcanism and intrusions were contemporaneous.

Subvolcanic intermediate to silicic intrusions linked to the Upper Lodge volcanic rocks are exposed in northern Ll■n. The Trwyn-y-Gorlech to Yr Eifl GCR site provides excellent exposures through the Garnfor Multiple Intrusion, demonstrating a basic to acid evolution with time, possibly linked to the evacuation of a fractionating, layered magma chamber at depth. The nearby Penrhyn Bodeilas GCR site shows intermediate to silicic intrusive components of the contemporaneous Penrhyn Bodeilas Intrusion which contains co-magmatic mafic enclaves, also suggestive of high-level fractionation processes.

A major volcanic centre of Woolstonian age, linked to the generation of a caldera collapse structure, developed farther to the west on Ll■n. Basic to intermediate lavas were erupted while explosive activity produced a series of ash-flow tuffs. The high proportion of intermediate lavas seen in the group, for example at the Moelypenmaen GCR site, contrasts with the predominantly bimodal basic–silicic activity of the central Snowdonia centres (e.g. at the Cwm Idwal GCR site). Related high-level silicic intrusions again developed, and are well exposed at a number of sites in western Ll■n. At the Llanbedrog GCR site the Mynydd Tir-y-cwmwd Porphyritic Granophyric Microgranite is thought to be a subvolcanic intrusion associated with the Carneddol Rhyolitic Tuff Formation (of the Llanbedrog Volcanic Group). Other intrusions linked to the Llanbedrog group, and occurring along its western margin, are of particular interest in being peralkaline in character, such as the Foel Gron Granophyric Microgranite (exposed at the Foel Gron GCR site) and the Nanhoron Granophyric Microgranite (exposed at the Nanhoron Quarry GCR site).

The final phase of volcanic activity on Ll■n is seen in the west of the peninsula, and occurred during Nod Glas (late Caradoc) times. Young *et al.* (in press) have linked the Mynydd Penar-fynydd Intrusion, one of the most spectacular layered mafic intrusions in the whole of the British Isles, to this episode of volcanism; previously it was considered to be of earlier Ordovician (Llanvirn) age. The intrusion is magnificently exposed in the coastal cliffs of the Mynydd Penarfynydd GCR site.

Llandovery and later Silurian events

The youngest major igneous activity in the Welsh Caledonide region was located in southern Pembrokeshire (Ziegler *et al.,* 1969; Thorpe *et al.,* 1989). Basic, intermediate and silicic lavas, ruffs and high-level intrusions of the Llandovery-age, Skomer Volcanic Group, are exposed at the Skomer Island and Deer Park GCR sites. The major part of the sequence was probably emplaced in a subaerial environment, with the eruption of relatively thin, basic to intermediate flows of considerable lateral extent, which are excellently exposed in cliffs along the western coast of the Skomer Island GCR site area. The local development of pillowed flows, however, shows that subaqueous conditions prevailed intermittently. Rhyolitic rocks form thick flows or domes of relatively limited extent, although rhyolitic ash-flow tuffs are more extensive and provide critical stratigraphical markers.

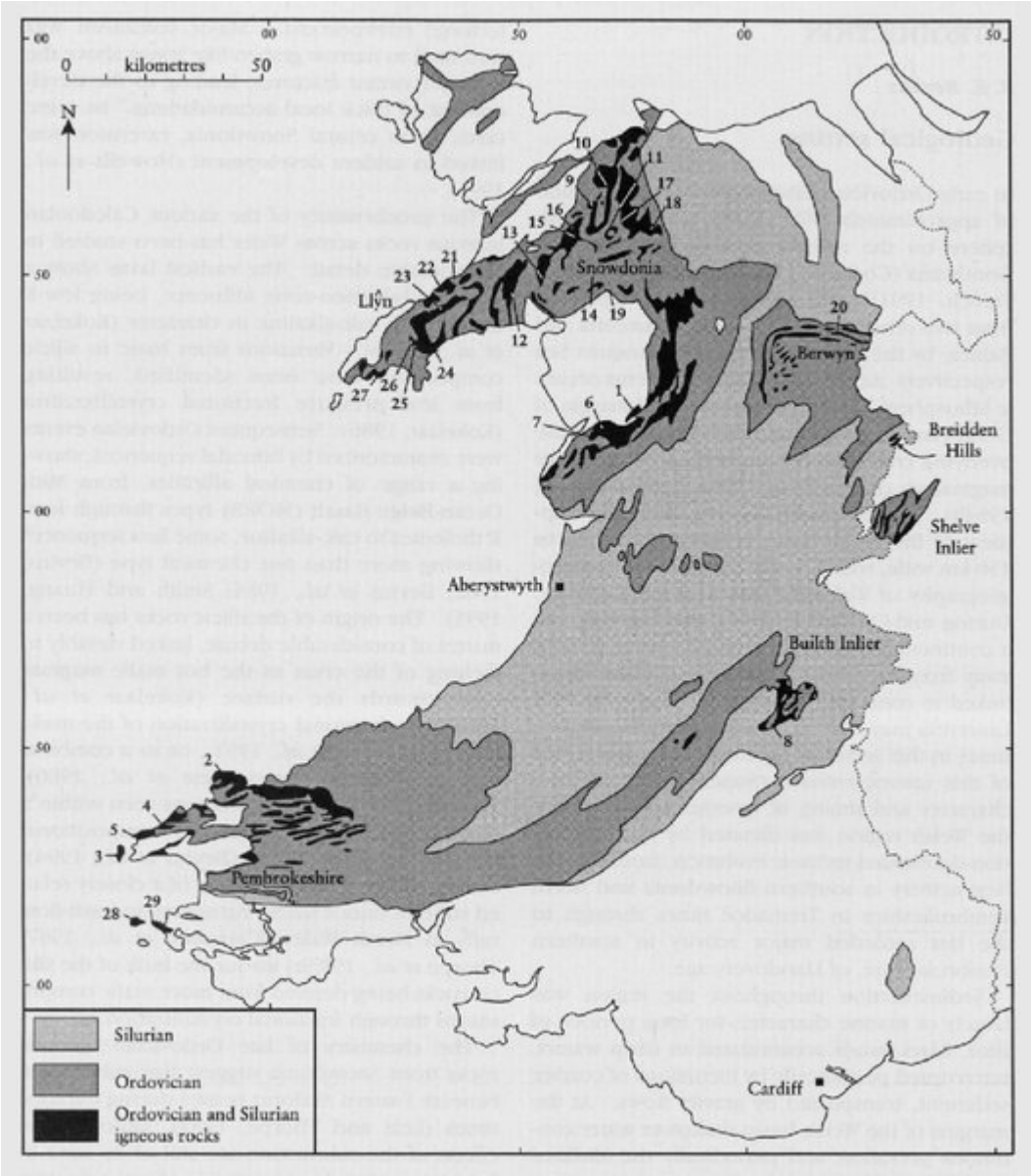
Geochemically the lavas have alkaline characteristics; however, they still show subduction zone signatures, reflecting the dominant process in the tectonic evolution of this part of the British Caledonides from Tremadoc through to Llandovery times. Two contrasting rhyolite groups in the Skomer Volcanic Group were previously considered not to be related geochemically (Thorpe *et al.,* 1989). Recent work, however, has suggested that they are linked through low-pressure fractional crystallization, with the contrasting trace element concentrations resulting from the precipitation of different minor mineral assemblages.

The Deer Park GCR site is located on the mainland adjacent to the Skomer Island GCR site. Although exposures are more difficult to access, the Deer Park GCR site is crucial in providing a diagnostic age constraint. Faunas within adjacent sedimentary rocks at Anvil Bay are indicative of an early Upper Llandovery ($C_{1–2}$) age for the Skomer Volcanic Group (Walmsley and Bassett, 1976; Bassett, 1982).

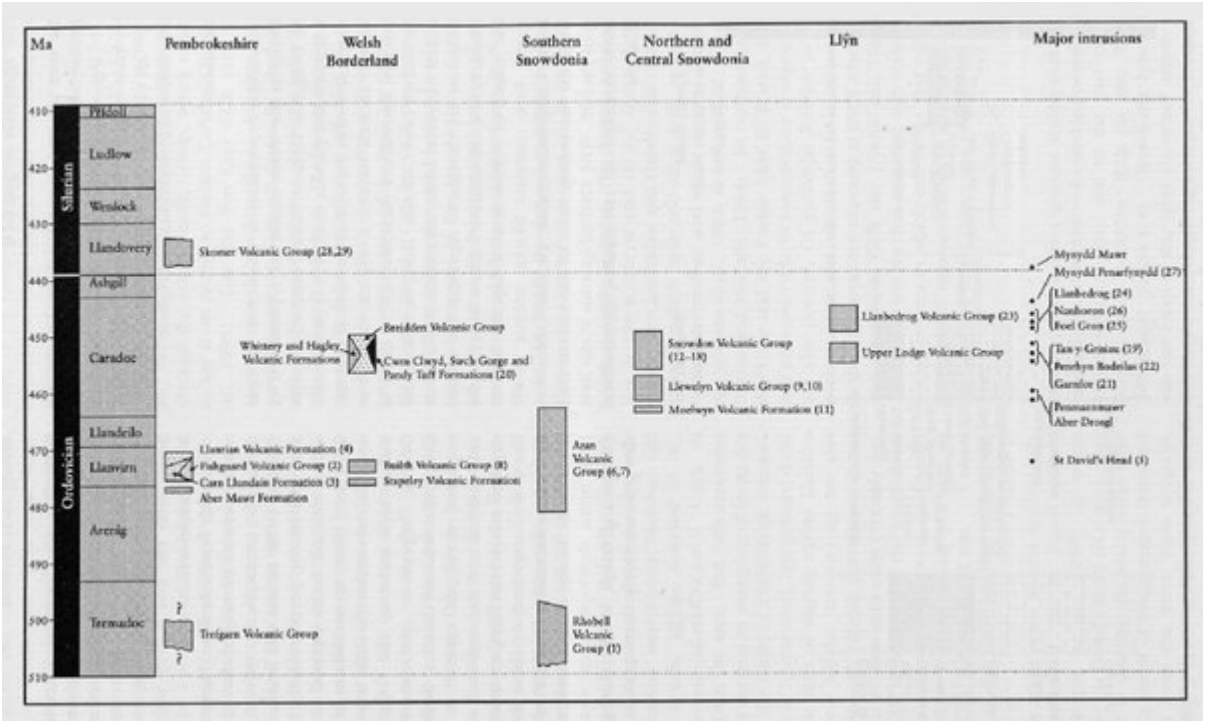
Silurian volcanic rocks in areas of England close to South Wales, include basaltic lavas of Llandovery age that crop out in the Tortworth area (Van de Kamp, 1969; Cave, 1977), and andesites and andesitic tuffs of Wenlock age exposed in the Mendip Hills (Van de Kamp, 1969; Hancock, 1982). Also of some interest is the widespread occurrence of bentonites

throughout the Welsh Borderland, in particular in sequences of Wenlock and Ludlow age (Teale and Spears, 1986). A major volcanic event is recorded in the Townsend Tuff unit, of P■ídolí age, which can be traced across a wide area of southern Wales and the Welsh Borderland (Allen and Williams, 1981). Whether these various ash-fall tuffs are truly Caledonian, however, remains uncertain as the source of volcanism is not known.

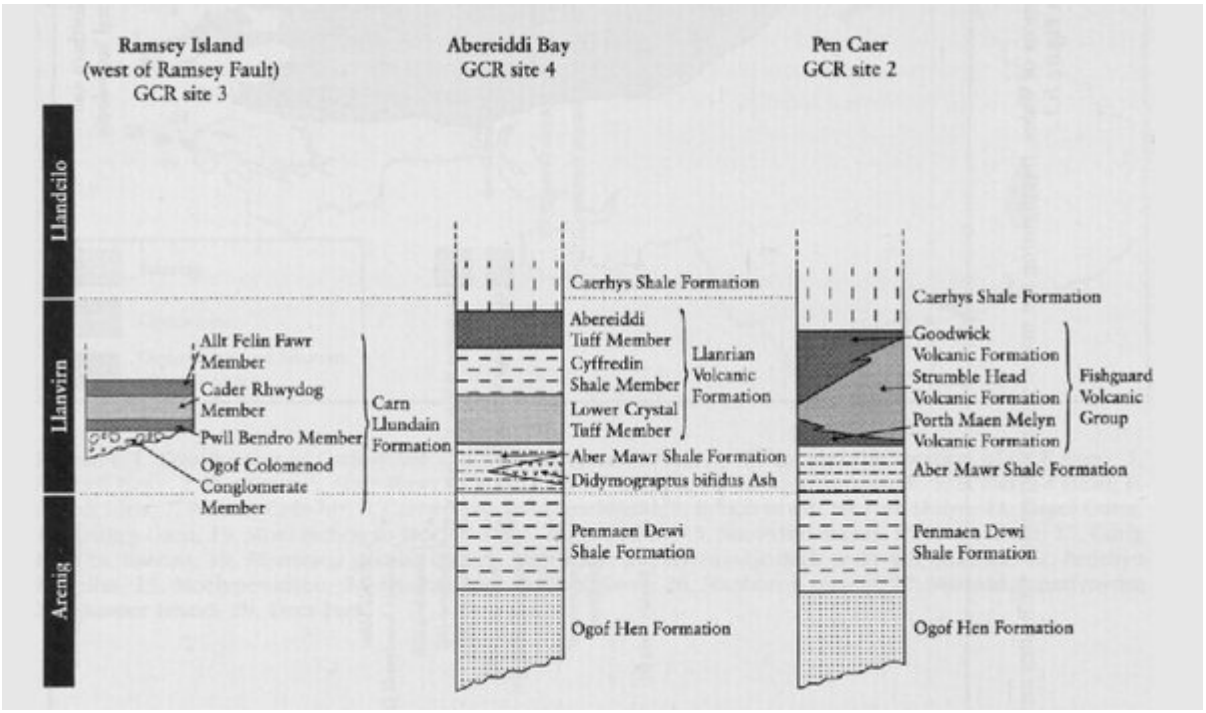
References



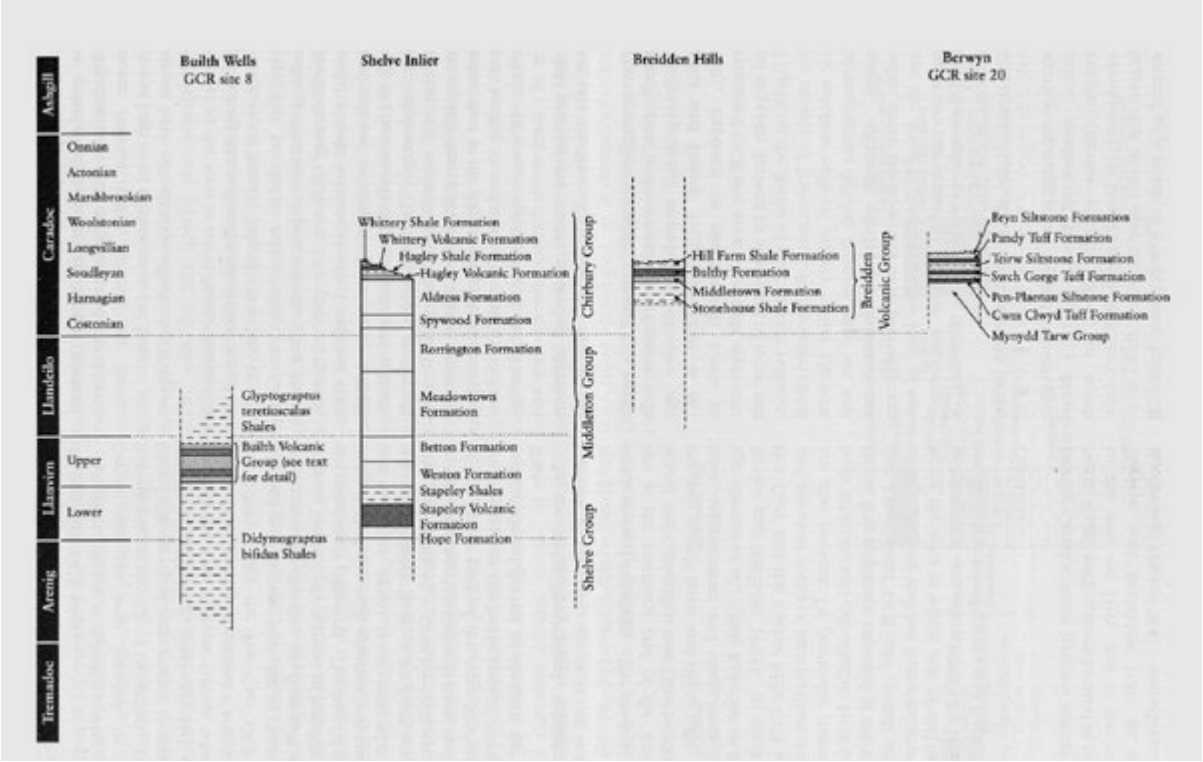
(Figure 6.1) Distribution of Ordovician and Silurian igneous rocks in Wales, and the location of GCR sites. 1, Rhobell Fawr; 2, Pen Caer; 3, Aber Mawr to Porth Lleuog; 4, Castell Coch to Trwyncastell; 5, St David's Head; 6, Cadair Idris; 7, Pared y Cefn-hir; 8, Carneddau and Llanelwedd; 9, Braich to du; 10, Llyn Dulyn; 11, Capel Curig; 12, Craig y Garn; 13, Moel Hebog to Moel yr Ogof; 14, Yr Arddu; 15, Snowdon massif; 16, Cwm Idwal; 17, Curig Hill; 18, Sarnau; 19, Ffestiniog granite quarry; 20, Pandy; 21, Trwyn-y-Gorlech to Yr Eifl quarries; 22, Penrhyn Bodeilas; 23, Moelypenmaen; 24, Llanbedrog; 25, Foel Gron; 26, Nanhoron quarry; 27, Mynydd Penarfynydd; 28, Skomer Island; 29, Deer Park.



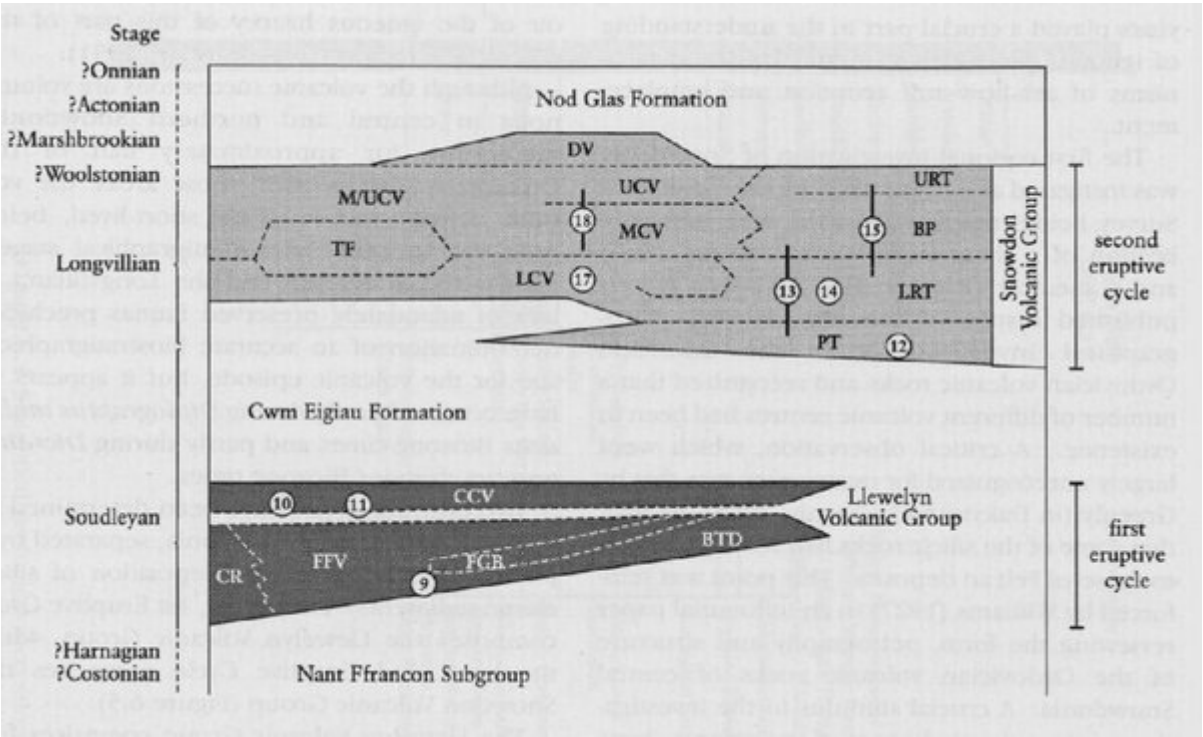
(Figure 6.2) Generalized stratigraphical successions of the Lower Palaeozoic sequences of Wales, highlighting the major volcanic episodes. GCR sites are numbered and listed on Figure 6.1.



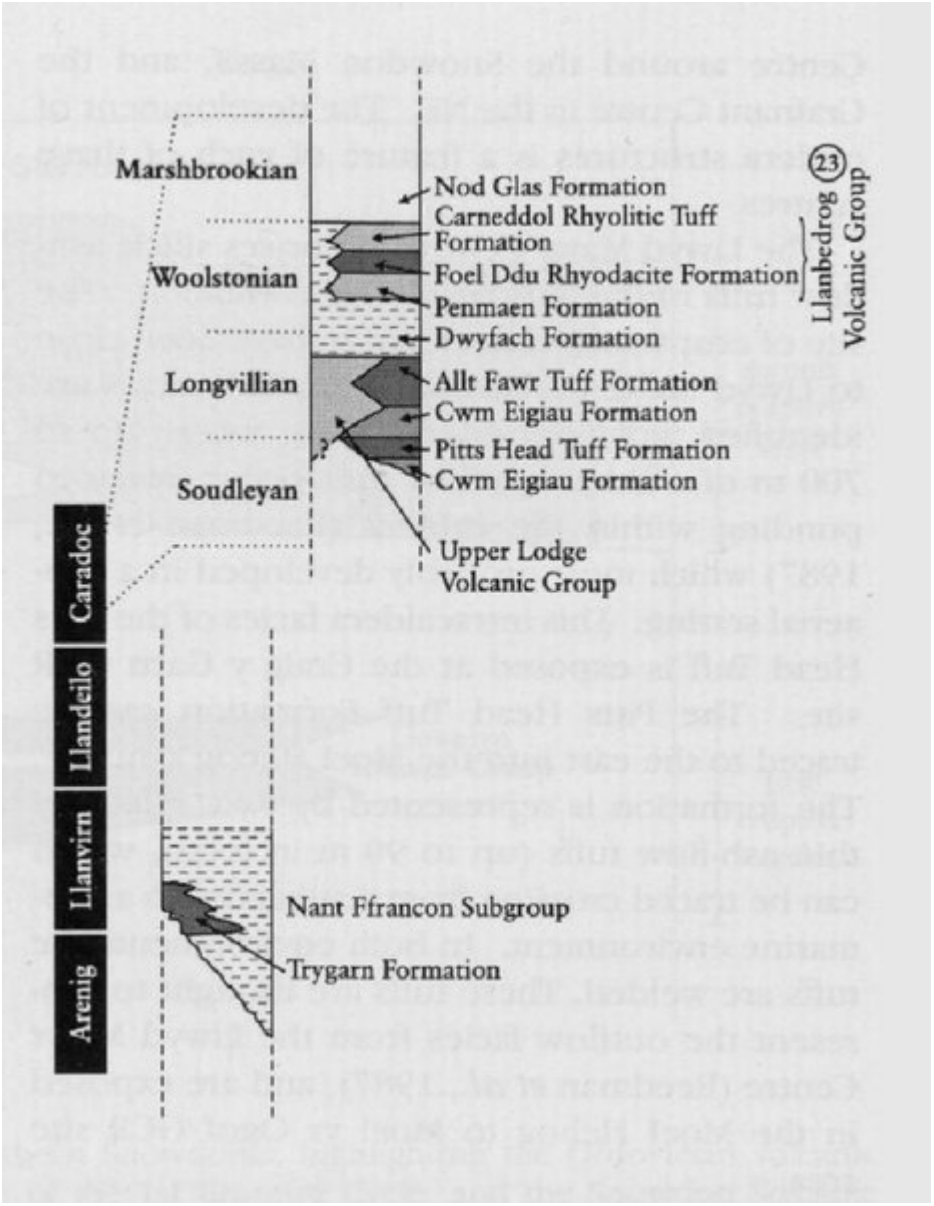
(Figure 6.3) Simplified geological successions of north Pembrokeshire, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.



(Figure 6.4) Simplified geological successions of the Welsh Borderland, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.



(Figure 6.5) Simplified geological successions of northern Snowdonia, highlighting the Ordovician volcanic sequences, in particular the Llewelyn Volcanic Group of the 1st Eruptive Cycle, and the Snowdon Volcanic Group of the 2nd Eruptive Cycle. GCR site numbers are listed on Figure 6.1. BP, Bedded Pyroclastic Formation; BTD, Braich to du Volcanic Formation; CCV, Capel Curig Volcanic Formation; CR, Conwy Rhyolite Formation; DV, Dolgarrog Volcanic Formation; FFV, Foel Fras Volcanic Complex; FGB, Foel Grach Basalt Formation; LCV, Lower Crafnant Volcanic Formation; LRT, Lower Rhyolitic Tuff Formation; MCV, Middle Crafnant Volcanic Formation; PT, Pitts Head Tuff Formation; TF, Tal y Fan Volcanic Formation; UCV, Upper Crafnant Volcanic Formation; URT, Upper Rhyolitic Tuff Formation.



(Figure 6.6) Simplified geological successions of Ll■n, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.