Caledonian Igneous Rocks of Great Britain

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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 occured 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.

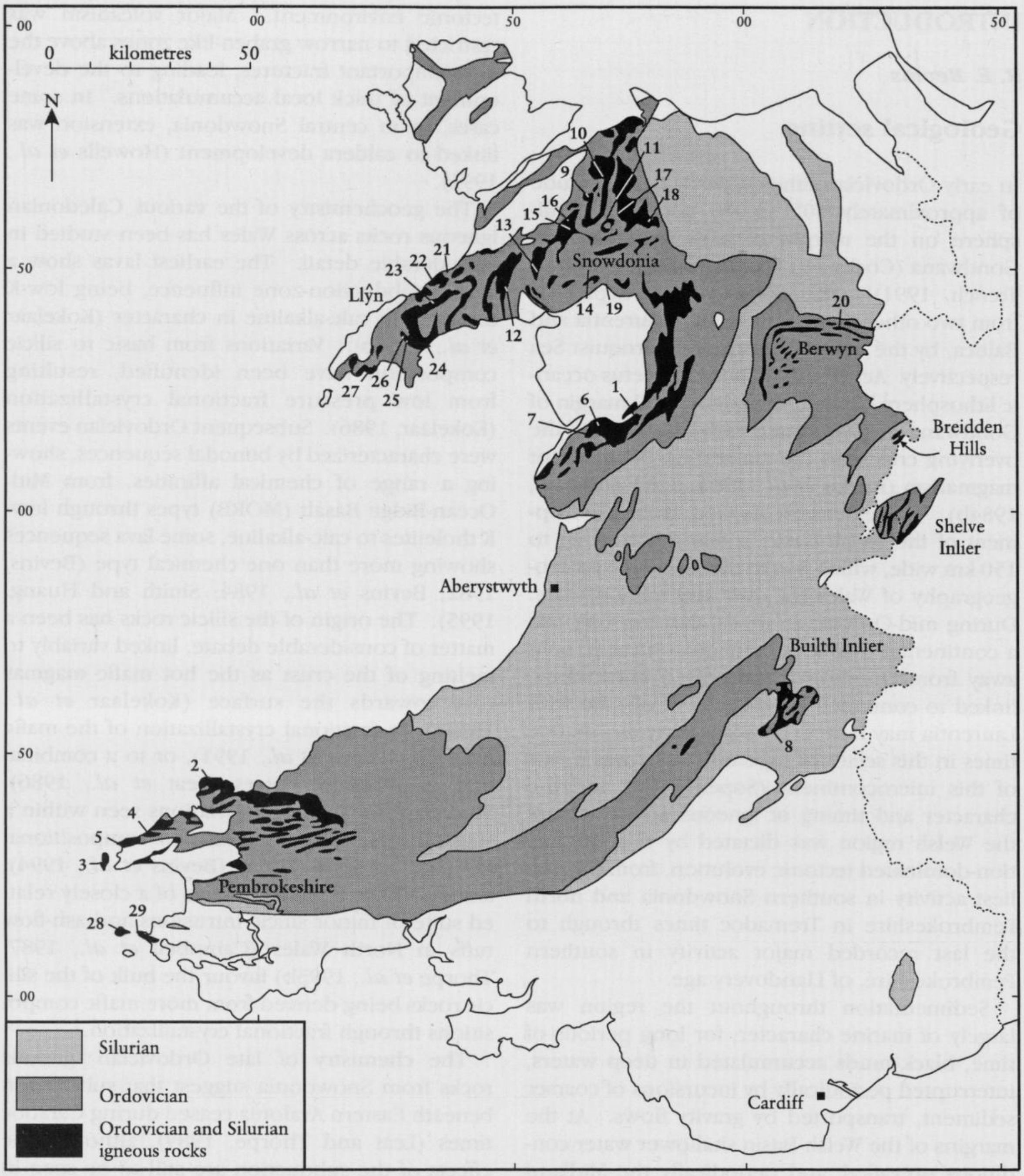


Figure 6.1 Distribution of Ordovician and Silurian igneous rocks in Wales, and the location of GCR sites. 1, Rhobell Fawr; 2, Pen Caer; 3, Aber Mawr to Porth Lleuog; 4, Castell Coch to Trwyncastell; 5, St David's Head; 6, Cadair Idris; 7, Pared y Cefn-hir; 8, Carneddau and Llanelwedd; 9, Braich tu du; 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.

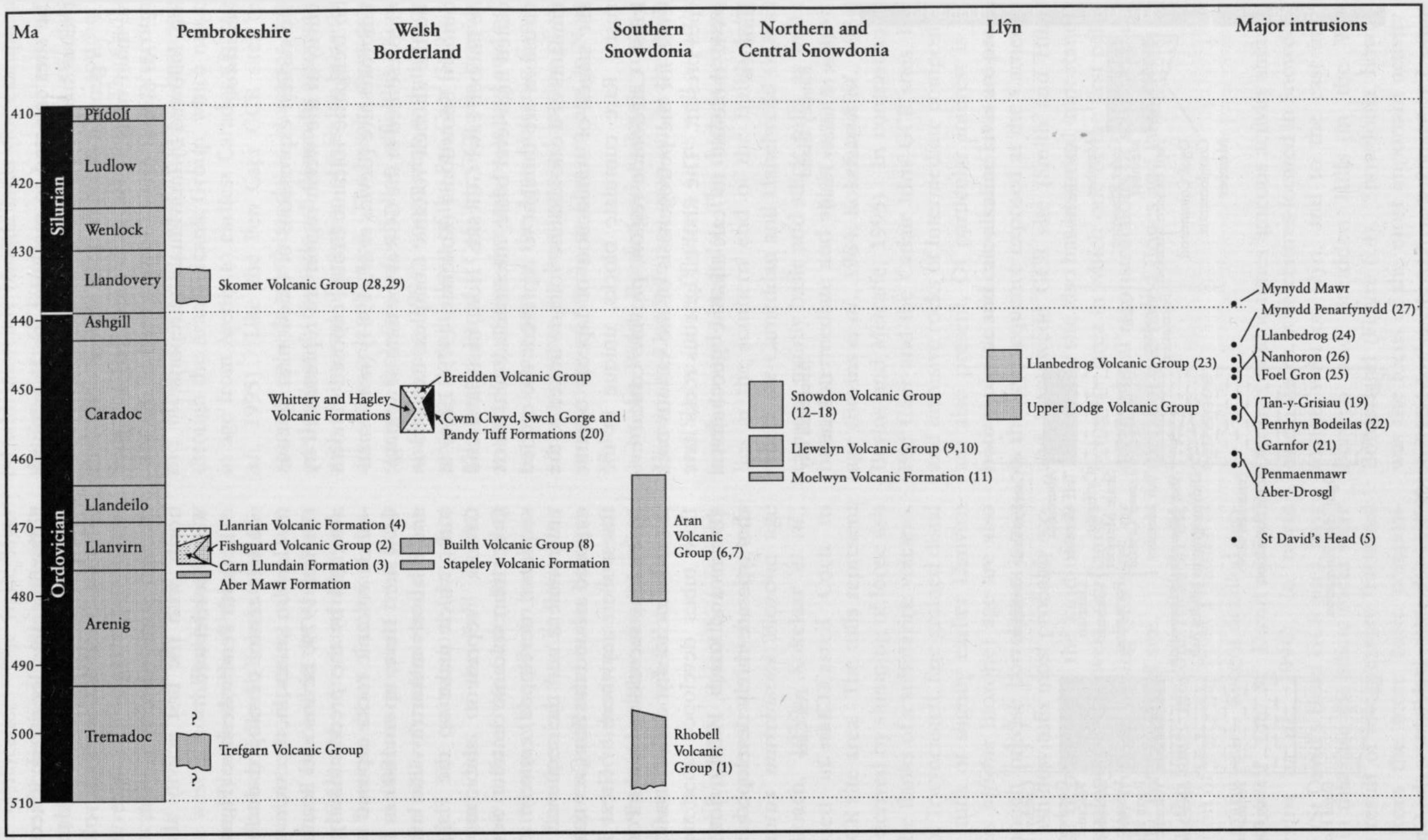


Figure 6.2 Generalized stratigraphical successions of the Lower Palaeozoic sequences of Wales, highlighting the major volcanic episodes. GCR sites are numbered and listed on Figure 6.1.

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 Llŷn 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

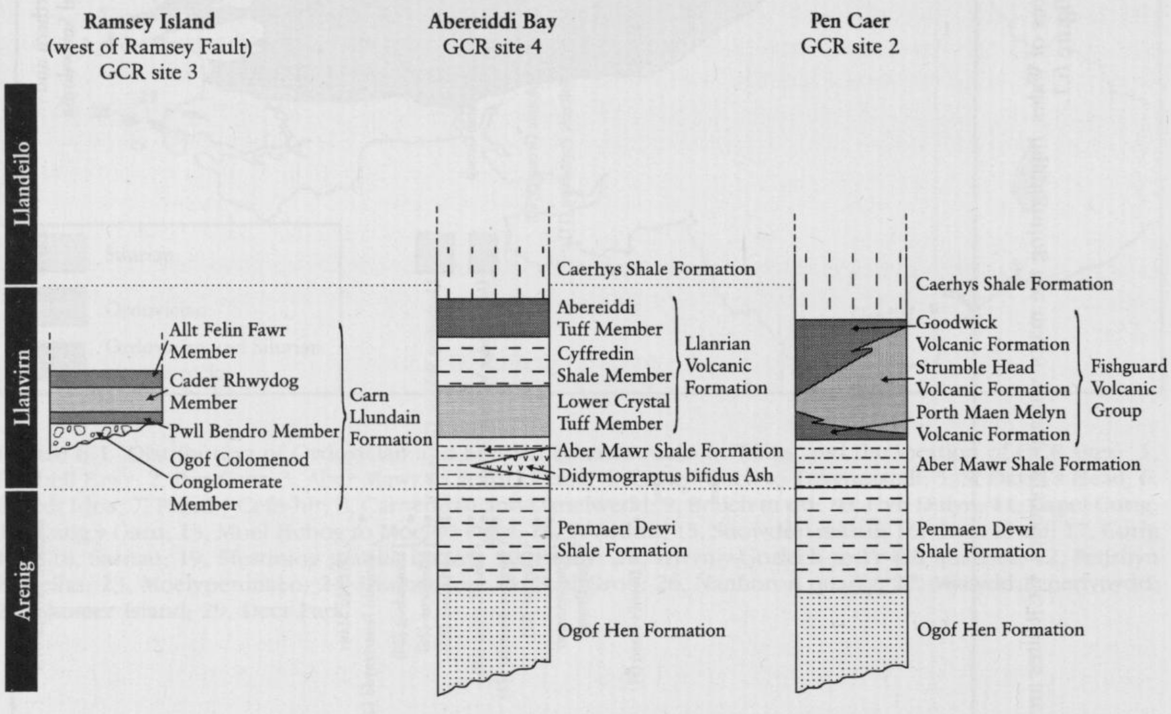


Figure 6.3 Simplified geological successions of north Pembrokeshire, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.

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 Inlier, 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 Llŷn, 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

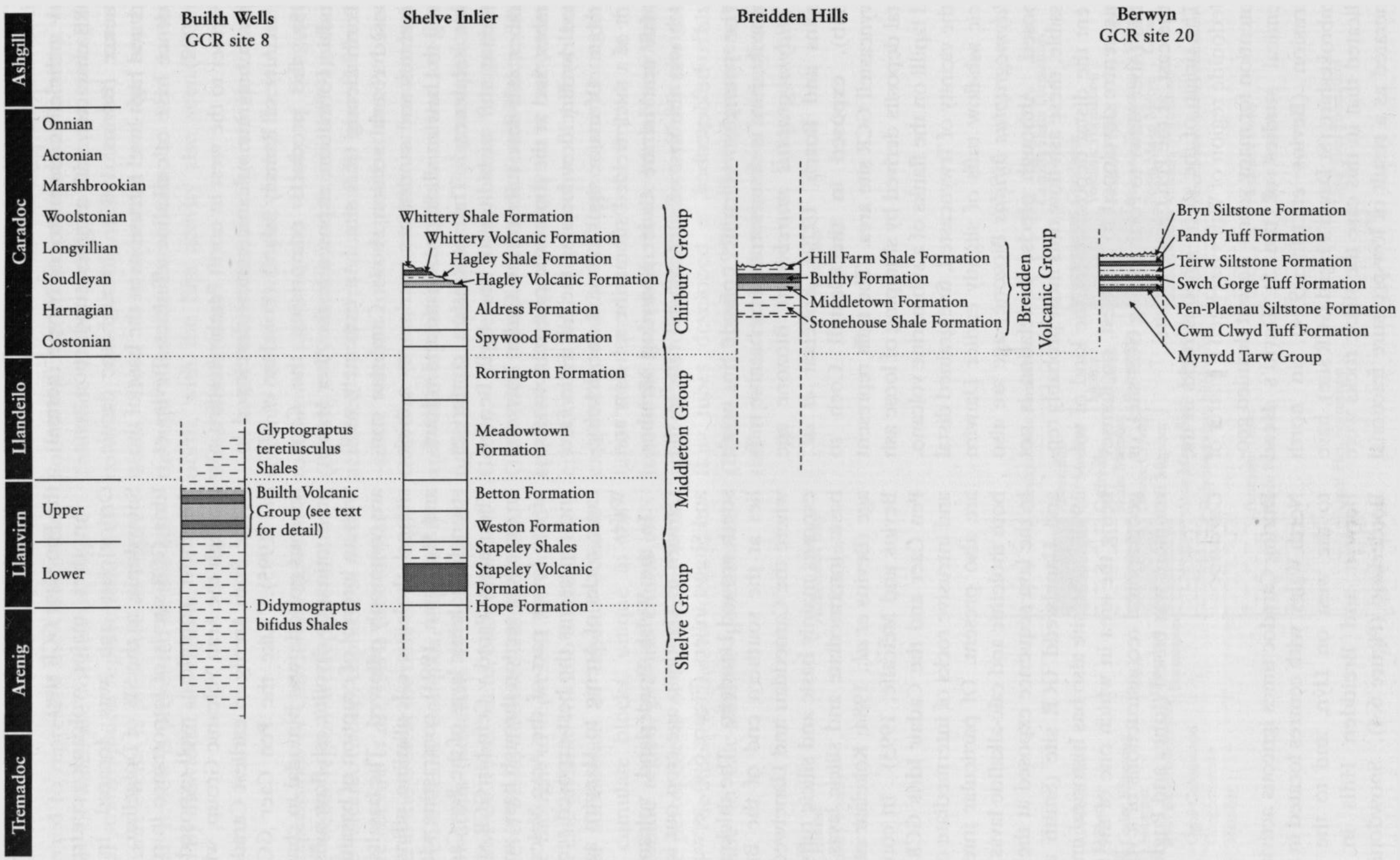


Figure 6.4 Simplified geological successions of the Welsh Borderland, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.

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 Peléan 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, multi-disciplinary investigation of the Caradoc volcanism, co-ordinated 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 siliciclastic 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 pillowed 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 evolu-

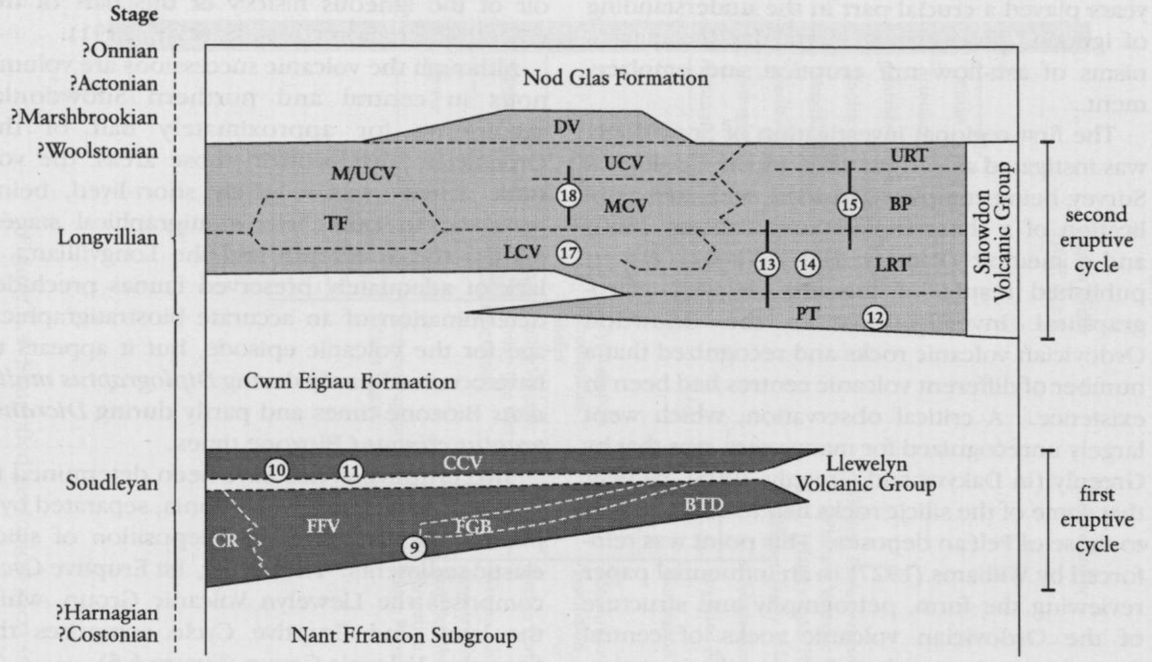


Figure 6.5 Simplified geological successions of northern Snowdonia, highlighting the Ordovician volcanic sequences, in particular the Llewelyn Volcanic Group of the 1st Eruptive Cycle, and the Snowdon Volcanic Group of the 2nd Eruptive Cycle. GCR site numbers are listed on Figure 6.1. BP, Bedded Pyroclastic Formation; BTD, Braich tu 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.

tion 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 subaerial setting. This intracaldera facies of the Pitts Head Tuff is exposed at the Craig y Garn 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 peralkaline 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 Llŷn (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 Llŷn, 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 Llŷn. 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 Llŷn. 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

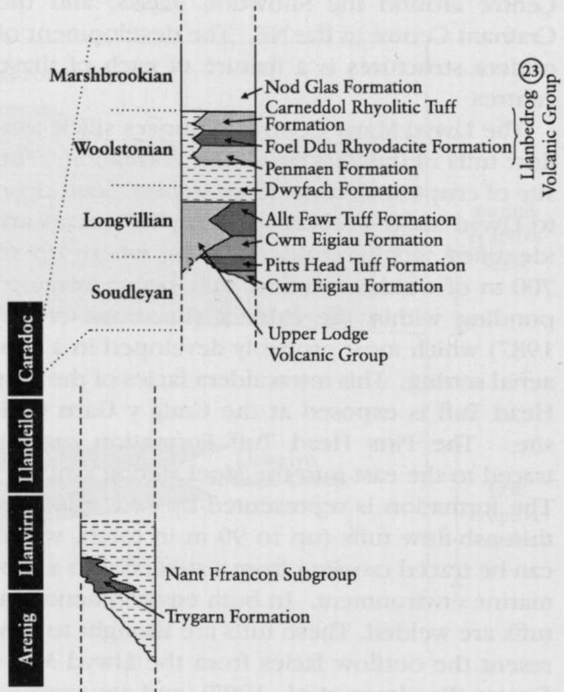


Figure 6.6 Simplified geological successions of Llŷn, highlighting the Ordovician volcanic sequences. GCR site numbers are listed on Figure 6.1.

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 Llŷn. 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 Llŷn 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 Penarfynydd 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, tuffs 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 Přídolí 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.

RHOBELL FAWR (SH 787 257)

R. E. Bevins

Introduction

Early Ordovician basic volcanic rocks and associated high-level basic, intermediate and silicic intrusions, comprising the Rhobell Volcanic Complex, are exposed in a remote tract of country on the eastern side of the Harlech Dome, in southern Snowdonia, centred around Rhobell Fawr (Figure 6.7). The site is of importance as a representative of the only substantial remnant of the early arc igneous episode in Wales, linked to subduction of Iapetus oceanic lithosphere beneath the Welsh Basin. Rare cumulate blocks in the basaltic lavas provide critical evidence for petrogenesis of the various igneous rocks, related to processes occurring in a thermally and compositionally stratified magma chamber. This is the only record of such cumulate blocks in the Caledonides of the British Isles.

The first detailed description of the volcanic sequences exposed around Rhobell Fawr was provided by Wells (1925). In the mid to late 1970s there was a resurgence of interest in the various Ordovician volcanic sequences across Wales, following the work of Fitton and Hughes (1970) who linked their origin to subduction of oceanic crust beneath the Welsh Basin. The area of Rhobell Fawr was studied in detail by Kokelaar (1977), including a detailed investigation of the petrology, geochemistry and petrogenesis (see Kokelaar, 1986).

The Rhobell Volcanic Group lies with marked unconformity on folded sedimentary rocks of Cambrian and earliest Tremadoc age. A maximum vertical thickness of 260 m of lavas, chiefly

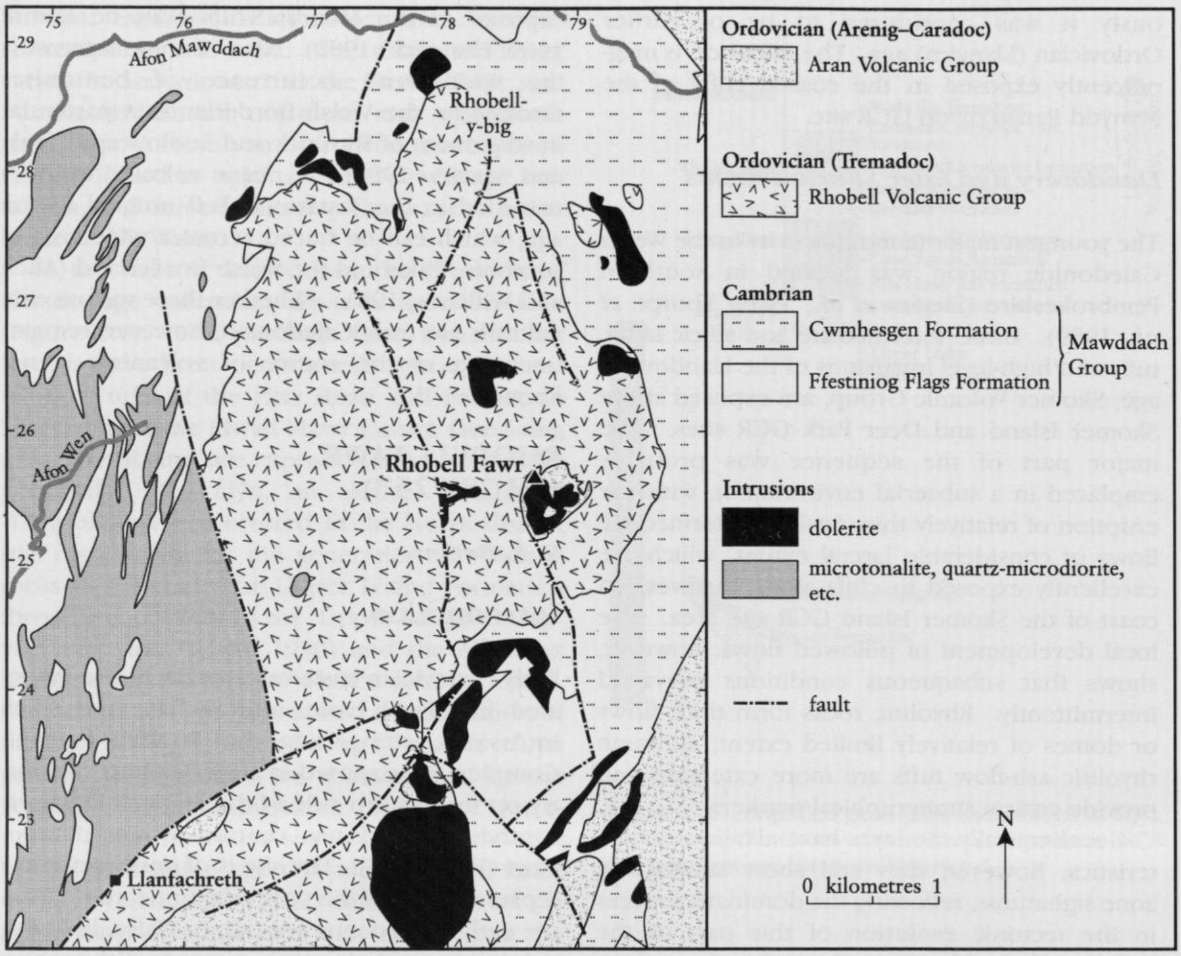


Figure 6.7 Map of the Rhobell Fawr GCR site, adapted from Kokelaar (1977).

plagioclase-clinopyroxene-phyric basalts, is exposed around Rhobell Fawr, although Kokelaar (1986) estimated, from structural considerations, that originally up to 2 km of basalts were erupted. K-Ar age determinations on pargasites from basalt lavas of the complex give an age of 508 ± 11 Ma (Kokelaar *et al.*, 1982).

A N–S fault zone, termed the Rhobell Fracture, appears to have strongly influenced development of the volcanic pile, as well as defining the eastern margin of an upfaulted horst of Cambrian rocks, known as the Harlech Dome. Indeed, further movements along the Rhobell Fracture in late Tremadoc times led to folding, faulting and erosion of igneous rocks of the Rhobell Volcanic Complex, such that today they are overlain by lowest Arenig strata with marked unconformity.

Description

Kokelaar (1977) divided the Rhobell Volcanic Group into four formations:

1. Ffridd Graig-wen Formation (youngest)
2. Eglwys Rhobell Formation
3. Rhobell Ganol Formation
4. Blaen-y-Glyn Formation (oldest)

These formations successively overlap to the east. The four formations are composed almost entirely (99%) of plagioclase-clinopyroxene-phyric lavas. Rare pargasite-bearing lavas are found chiefly in the Blaen-y-Glyn Formation (Figure 6.8), while porphyritic basalts are present mostly in the Eglwys Rhobell Formation. Variations that are present in the succession are considered by Kokelaar (1986) to reflect changes

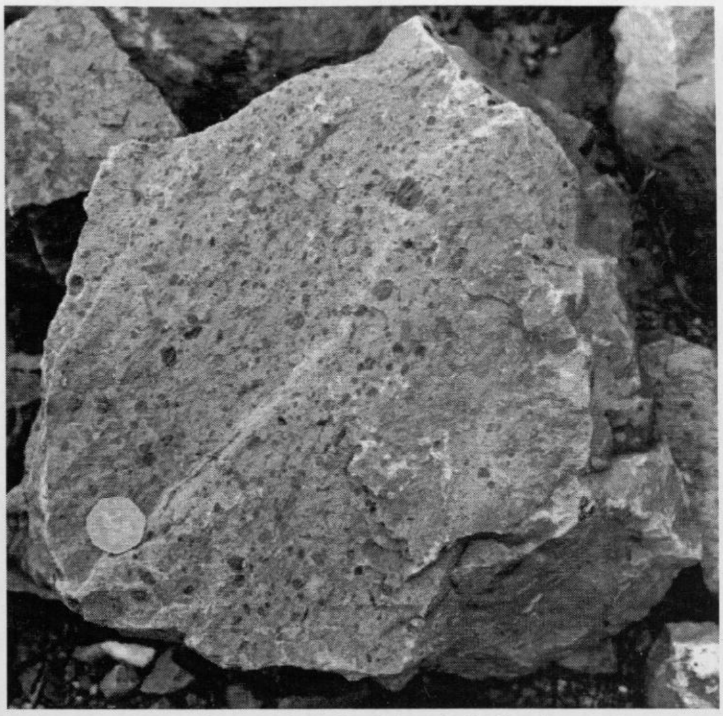


Figure 6.8 Porphyritic pargasite-bearing basalt of the Rhobell Volcanic Complex, Rhobell Fawr. (Photo: BGS no. L 1274.)

in effusion rates. Breccias occurring in intimate association with the lavas are thought to be autoclastic in origin, while minor volcaniclastic units are possibly water-reworked deposits.

The plagioclase-clinopyroxene-phyric basalts are extensively altered, with a range of secondary minerals characteristic of the prehnite-pumpellyite and lower greenschist facies. Euhedral plagioclase phenocrysts, almost always albitized, form up to 40% of the mode, and commonly show evidence of normal or oscillatory zoning, or contain concentric zones of inclusions towards their margins. Clinopyroxenes are more commonly fresh, and have augitic compositions. These also show normal and oscillatory zoning, and inclusion-rich zones occur towards the crystal margins. Groundmass in the basalts is invariably altered.

Pargasite-bearing basalts form a minor component of the Rhobell lavas. Typically pargasite phenocrysts form 1–5% of the mode, and reach up to 4 cm in length. Both oscillatory zoning and zones at crystal margins rich in inclusions are present, sometimes both being sharply truncated by later crystal growth. Clinopyroxenes range up to 4% of the mode, and reach up to 7 mm in diameter. Both normal and oscillatory zoning are present, and margins to crystals are inclusion-rich. Clinopyroxenes are augitic in composition. Plagioclase phenocrysts, up to 2 mm in length, form up to 20% of the mode; typically they are altered. The groundmass is fine grained and altered.

Locally the lavas are cumulo-phyric, with cumulus ferromagnesian phenocrysts forming up to 50% of the mode. In the cumulo-phyric basalts pargasite forms up to 47% of the mode, while clinopyroxenes form up to 10%, and are diopsidic in composition. Plagioclase is typically absent from the cumulo-phyric basalts.

Rarely cumulo-phyric lavas of the Eglwys Rhobell Formation contain cognate cumulate blocks which reach up to 10 cm in diameter (Figure 6.9). Kokelaar (1986) reported the presence of two classes of cumulate blocks, namely pargasite mesocumulates and adcumulates, and pargasite-salite (augite) mesocumulates and adcumulates. The former class of block, which is the most common type found, contains pargasite, up to 1.5 cm in diameter, as the only cumulus phase, with variable amounts of post-cumulus material, possibly showing fine-scale grain size and textural lamination. Small inclusions are present in many of the pargasite crystals. The pargasite-augite cumulate blocks are similar to the pargasite cumulate blocks but contain up to 20% modal augite. Some of the augites contain minor chlorite inclusions, possibly after

Figure 6.9 Cognate cumulate block in basalt lava of the Rhobell Volcanic Complex, Rhobell Fawr. (Photo: R.E. Bevins.)

glass.

Intrusions associated with the Rhobell Volcanic Group comprise basic, intermediate and silicic varieties. Although sheet-like with respect to the Cambrian strata within which they are contained, they are dyke-like with respect to the base of the volcanic pile. Basic varieties are doleritic, typically dominated by clinopyroxene and plagioclase; leucodoleritic varieties contain only sparse clinopyroxene. Intrusions of intermediate composition (not exposed in the GCR site area) are represented by porphyritic microdiorites, which contain plagioclase and hornblende phenocrysts (up to 40% and 3% of the mode respectively), the former showing normal and oscillatory zoning. In the more silicic (microtonalitic) intrusions, the modal proportion of hornblende decreases (to *c.* 1% of the mode) while that of quartz, present both as phenocrysts and in the groundmass, increases. The phenocrysts reach up to 0.4 mm in diameter, and form up to 5% of the mode.

Interpretation

Basaltic rocks of the Rhobell Volcanic Complex are thought to reflect a subaerial sequence of lavas which produced a volcanic pile up to 2 km thick around a fissure zone, now represented by an intense swarm of dykes. In the central zone of the swarm, intervening screens of sedimentary rocks are absent, and up to 1 km of E–W dilation across the Rhobell Fracture Zone has been estimated (Kokelaar, 1986). Activity was focused along this zone for up to 24 km in a N–S orientation, most probably with other volcanic piles developing locally. The abundant clasts of porphyritic igneous rock and the feldspar-rich nature of many sandstones in the Arenig of this part of the Welsh Basin support such a contention.

Textures in the cumulate blocks, in particular the inclusion-free and inclusion-rich zones, have been interpreted by Kokelaar (1986) as reflecting varying conditions of crystal growth, especially variations in temperature within a magma chamber, coupled possibly with variations in composition. Crystals that grew and accumulated in this magma chamber were periodically disturbed, as is shown by the presence of oscillatory zoning and by the sharp terminations to growth patterns in crystals. Disrupted crystals or blocks were incorporated into erupted magmas.

Kokelaar (1986) provided extensive whole-rock and mineral geochemistry for samples from the Rhobell Volcanic Complex and combined these data to present a petrogenetic model to explain the diverse rock types present. Geochemical and mineralogical constraints suggest that the variety of igneous rocks present in the Rhobell Volcanic Complex was derived by fractional crystallization from a basic parent. The fractionation process was heavily influenced by pargasite in the early stages, along with clinopyroxene. Geochemically, the rocks show calc-alkaline affinities, characteristic of destructive plate margins, which supports the suggestion that these rocks were generated as a result of the subduction of Iapetus oceanic lithosphere beneath the Welsh Basin in early Ordovician times (Bevins *et al.,* 1984; Kokelaar *et al.*, 1984b).

Conclusions

Basic, intermediate and silicic rocks of the Rhobell Volcanic Complex represent the extrusive and high-level intrusive products of a calc-alkaline volcanic episode which developed over a major fracture, the Rhobell Fracture, in early Ordovician times. Dyke rocks were emplaced as a swarm along the central zone of the fracture, reflecting up to 1 km of crustal extension in an E–W direction.

The majority of the lavas are basaltic, rarely containing amphibole phenocrysts and blocks of amphibole-pyroxene-rich rock that are unique in the British Caledonides and which provide important constraints on the origin and evolution of the magmas. Textures in the blocks imply crystal accumulation, under varying temperature conditions, in a compositionally varied magma chamber. Periodically this chamber was disturbed, releasing crystals and blocks into the erupting magmas. The various igneous rocks were generated from a basic parental magma, by crystal fractionation, dominated by the removal of the amphibole crystals from the magma.

The rocks show calc-alkaline affinities, in keeping with suggestions that these Ordovician volcanic rocks were derived as a result of the subduction of Iapetus oceanic lithosphere beneath Wales. Indeed, they represent the only substantial remnant of an early volcanic-arc episode in Wales. Following eruption of the Rhobell lavas, the character of magmatism changed, with the later eruption of magmas more typical of a back-arc basin environment (see, for example, the Pen Caer GCR site report).

PEN CAER (SM 887 391–909 409, 937 404–952 402)

R. E. Bevins

Introduction

The Pen Caer Peninsula, located to the west of Fishguard in north Pembrokeshire, largely comprises Ordovician lavas and related intrusive rocks, chiefly of bimodal basic and silicic compositions, but rarely of intermediate composition. These are associated with pyroclastic and sedimentary volcaniclastic rocks and argillites, the latter reflecting the background sedimentation that was punctuated by the relatively short-lived volcanic inputs.

The site is of importance in view of the excellent coastal exposures, which demonstrate the nature of subaqueous extrusive and related high-level intrusive igneous processes in the southern part of the Welsh Basin in early Ordovician times. In addition, the geochemistry of the igneous rocks has been used to establish the ensialic marginal arc-basin setting in which these various extrusive and intrusive rocks were emplaced (Bevins *et al.*, 1984; Kokelaar *et al.*, 1984b).

The extrusive volcanic rocks, up to 1800 m thick, belong to the Fishguard Volcanic Group of Llanvirn age, and were emplaced entirely in a submarine environment. They show a range of forms related to their mode of eruption and emplacement, which included the quiet effusion of basic sheets and pillowed flows and silicic dome-producing extrusions, the dramatic effects of thermal shattering and breccia production, and the explosive eruption associated with the generation of hyaloclastites and silicic ash-flow tuffs.

Basic intrusive sheets show a variety of forms, directly related to depth of emplacement. Those emplaced at some depth in the sequence show parallel tops and bases and relatively coarse-grained textures. At higher levels, however, the intrusions invaded still-wet sediments, their contacts are irregular, sometimes with flame structures at the sediment–igneous contact, and textures are those characteristic of rapid quenching.

The extrusive products were subject to rapid reworking, and volcaniclastic rocks were generated. For the most part, however, the lava pile must have been well-below wave-base, as such rocks are relatively rare. More common are mudstone intercalations, which reflect temporary cessations in the volcanic activity and a return to 'normal' background sedimentation.

The first detailed description of the igneous rocks of the Pen Caer Peninsula was by Reed (1895). This study was extended subsequently by Cox (1930), and later by Thomas and Thomas (1956). The most recent investigations are those of Bevins (1979) and Bevins and Roach (1979a, 1979b). Bevins (1982) described aspects of the petrology and geochemistry of the volcanic and related intrusive rocks of the Fishguard Volcanic Complex. A detailed description of parts of the site area appears in the field guide of Kokelaar *et al.* (1984a).

Description

The Fishguard Volcanic Group in the Pen Caer area comprises three formations, namely:

1. Goodwick Volcanic Formation (youngest)
2. Strumble Head Volcanic Formation
3. Porth Maen Melyn Volcanic Formation (oldest)

The Porth Maen Melyn Volcanic Formation is exposed to the north of the bay known as Porth Maen Melyn (Figure 6.10), to the south of Strumble Head. The lowermost unit of the formation comprises 10 m of extensively recrystallized bedded rhyolitic tuffs that show evidence of shardic textures. The tuffs appear to be non-welded, silicic ash-flow tuffs, emplaced subaqueously. This unit is overlain by two units, 35 m thick in total, of lithic-crystal-vitric breccias and crystal-vitric tuffs. The lower unit shows a fining upwards through the lowermost 50 cm. Clasts in the breccias are chiefly of angular to sub-rounded rhyolitic lava, sometimes with a perlitic texture, although in the lower part of the sequence basic lava and dolerite are common. Crystals, chiefly bi-pyramidal quartz and plagioclase, are prominent in the fine-grained basal part of the sequence. Pumice clasts are represented by weathered-out streaks in the tuffs, while shardic fragments are seen in thin section. These tuffs are thought to be sediment-gravity flow deposits, derived from the reworking of primary silicic eruptive volcanic detritus. The basic clasts were most probably eroded from wall rocks in the volcanic edifice during eruption. Overlying these breccias and tuffs is a rhyodacitic lava flow up to 40 m thick; to the east it is massive, while traced westwards it becomes pillowed, showing elongate flow tube structures, associated with inter-pillow breccias. The flow is quenched and shows a perlitic texture, reflecting the recrystallization of a glass. The top of the flow is autobrecciated. The tubes and pillows are thought to result from the rapid effusion of hot magma at the steep front of a lava flow, as described by Bevins and Roach (1979b).

The Strumble Head Volcanic Formation con-

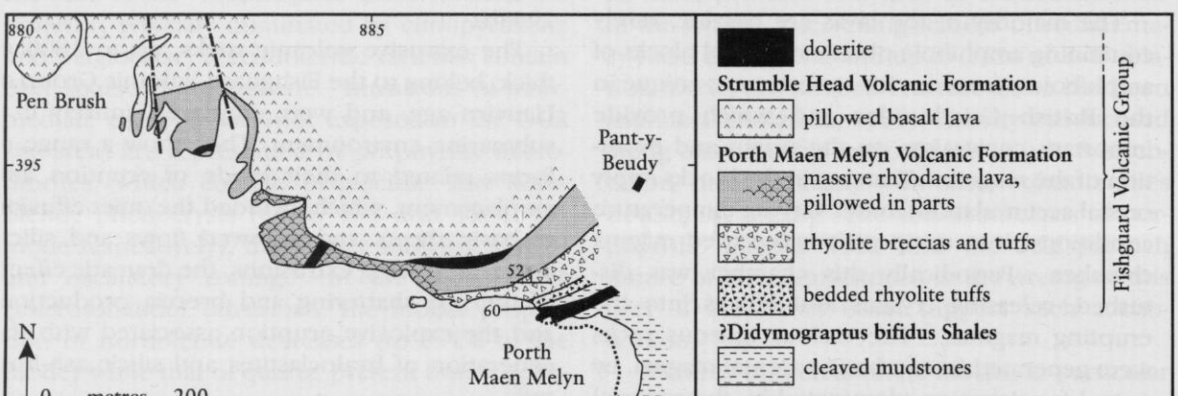


Figure 6.10 Map of the Porth Maen Melyn area, Pen Caer GCR site (after Kokelaar *et al.*, 1984a).

Figure 6.11 Pillow lava from the Fishguard Volcanic Group, Strumble Head. The pillow in the centre of the photograph is 75 cm across (long axis). (Photo: R.E. Bevins.)

formably overlies the Porth Maen Melyn Volcanic Formation, a contact well exposed in the steep cliffs on the north side of the bay. Immediately overlying the contact are classic pillowed basaltic lavas, individual pillows typically reaching up to 40 cm in diameter (Figure 6.11). Such lavas form the bulk of the succession exposed from Porth Maen Melyn northwards to Strumble Head and then eastwards to the extremity of the outcrop of the Strumble Head Volcanic Formation at Carnfathach. The pillowed flows commonly show well-developed inter-pillow breccias, while intercalations of isolated pillow breccias and hyaloclastites are sporadically developed. Locally, elongate, steeply inclined lava tubes are developed, as are classic necking structures. Intercalated with the pillowed lavas are massive, commonly lensoid lava sheets, as well as high-level intrusive basaltic sheets. Some intrusive sheets show pillowed forms at their base, while the thicker sheets commonly possess well-developed columnar jointing.

The top of the chiefly basaltic Strumble Head Volcanic Formation and the base of the overlying chiefly silicic Goodwick Volcanic Formation is marked by a complex interdigitation of lavas and high-level intrusions (Figure 6.12). The various facies of a thick rhyolite flow or dome at the base of the Goodwick Volcanic Formation are excellently exposed on Penfathach. The lowermost facies, a breccia, comprises 4–5 cm-diameter clasts of flow-banded rhyolite showing little to no post-brecciation rotation. This passes upwards into rhyolites with excellent large- to small-scale flow-folding, and locally with well-developed columnar jointing. Locally, perlitic textures are preserved. Contact with the overlying autobrecciated carapace is gradational. To the east, basaltic tuffs are exposed at the foot of cliffs at Porth Maen. These tuffs are generally parallel-bedded, and show both normal and inverse grading. Clasts are typically 2–3 mm in diameter, reaching up to *c.* 1.5 cm. Offsets to bedding probably relate to soft sediment faulting. These tuffs are thought to be sediment-gravity flows slumping off the flanks of a submarine, possibly shallow-water volcano. Farther to the east, and up-section, coarse lithic-rich ash-flow tuffs are exposed. These are overlain by fine-grained silicic tuffaceous sedimentary rocks that have been intruded by a basic sill. This sill shows bulbous protrusions at its base, indicative

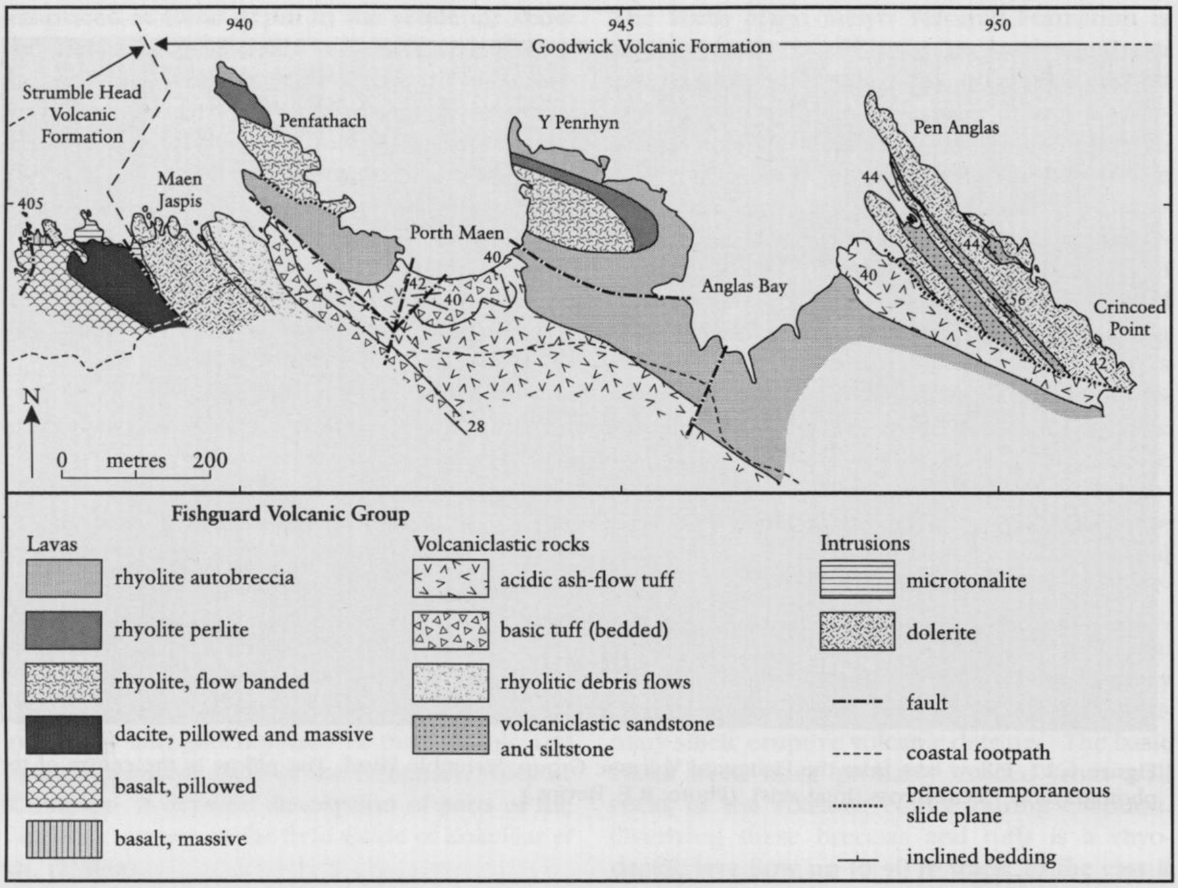


Figure 6.12 Map of the north-eastern part of the Pen Caer GCR site (after Kokelaar *et al.*, 1984a).

of wet sediment–magma interactions. The top of a higher basic intrusion, exposed on Pen Anglas, has particularly well-developed columnar jointing, yet is pillowed at its top, again indicative of intrusion of magma into wet sediment (Figure 6.13).

Interpretation

This site demonstrates the complex facies developed in extrusive and high-level intrusive rocks associated with the generation and evolution of a submarine volcanic complex, with compositions ranging from basic through intermediate to silicic.

Classic pillowed and sheet-like forms are developed in the basic lavas, along with inter-pillow and isolated-pillow breccias. In critical sections, elongate, steeply dipping lava tubes can be seen. Unconsolidated tuffs, probably generated in relatively shallow-water environments, were reworked locally and led to the generation of bedded basaltic volcaniclastic sediments.

Some basic magmas failed to reach the seawater–sediment interface, and were intruded at a high level. At deeper levels in the sequence the intrusions are relatively thick, typically coarse-grained, and show sharp concordant contacts. At shallower levels, the intrusions are thinner, finer grained, even quenched, and show irregular, sometimes flamed or pillowed, contacts.

More silicic, dacitic, magmas produced a 40 m-thick flow that erupted onto the sea floor. Part of the exposure reveals a massive, central facies with an autobrecciated flow top; at the steep front of the flow, however, elongate flow tubes developed, associated with inter-pillow breccias. The flow appears to have been glassy throughout. Such flow features in dacitic lavas are extremely rare, making this site of interna-

Figure 6.13 Magma-wet sediment relationships at the base of a high-level basic intrusion, Pen Anglas. Magma has injected and loaded down into unlithified tuffaceous sediment, while the wet sediment has locally flamed up into the magma. Lens cap for scale. (Photo: R.E. Bevins.)

tional significance in terms of understanding eruptive igneous processes.

Silicic magmas were emplaced as extrusive domes on to the sea floor, with well-developed autobrecciated carapaces and showing magnificent flow-folding phenomena. In addition, explosive eruptions produced deposits of ash, pumice, glass shards and lithic fragments; some deposits were derived from primary ash-flows, in other cases they represent the slumping of previously deposited debris on the unstable flanks of submarine volcanoes and domes.

Bevins (1982) investigated the geochemistry of the basaltic rocks of the Fishguard Volcanic Group. He reported that they show close similarities to N-type (normal) Mid-Ocean-Ridge Basalt (MORB), but were slightly enriched in the light rare earth elements and Th, coupled with a marked depletion in Nb. Such features are thought to reflect a minor subduction zone influence in their genesis and are characteristic of basalts erupted in back-arc or marginal basins. This is consistent with the Welsh Basin occupying a tectonic position at the margin of Gondwana during early Ordovician times, and with subduction of the Iapetus Ocean crust beneath the continental margin.

Conclusions

This site provides excellent coastal exposures through a submarine volcanic pile, showing a range of extrusive and intrusive igneous phenomena. The products provide critical evidence for the nature of submarine volcanism and the processes involved in the development of a submarine volcanic complex. It is one of the classic sites in the British Isles for pillowed basaltic lavas and related tuffs and breccias. Of international note, however, are exposures through a dacite lava that shows a transition from a massive centre to a flow front with elongate flow tubes; such phenomena are extremely rare in lavas of such silicic composition. Also, the nature of the growth and development of rhyolitic domes on the sea floor is demonstrated, associated with the products of more explosive activity and the subsequent reworking of loose debris in the submarine environment. Finally, the geochemistry of the basalts indicates that the lavas were erupted in a marginal basin environment linked to subduction of Iapetus Ocean crust beneath Gondwana in Ordovician times.

ABER MAWR TO PORTH LLEUOG (SM 698 240–700 231)

R. E. Bevins

Introduction

The volcanic and intrusive rocks of Ramsey Island form part of a belt of bimodal basic–acidic Ordovician igneous rocks in north Pembrokeshire, interpreted as having been emplaced in a marginal basin related to closure of the Iapetus Ocean. The site is of importance in providing important exposures of silicic volcanic and related rocks in the southern part of the Welsh Basin, and in a wider context it provides critical insight into the nature of submarine explosive eruptions and the emplacement of welded ash-flow and ash-fall tuffs.

Ramsey Island is composed of a sequence of rocks ranging from mid-Cambrian through to Ordovician (Llanvirn) in age, in part sedimentary but mainly igneous. The igneous rocks are entirely Ordovician, and are chiefly silicic pyroclastic and volcaniclastic rocks, associated with relatively minor silicic extrusive and intrusive equivalents. The rugged coastline provides excellent exposures and presents detailed sections through the succession.

Early studies of the geology of Ramsey Island concentrated on establishing the age and stratigraphical relationships of the various lithological units. Those by Pringle (1914, 1915, 1930) are particularly important in providing the first detailed account and geological map of the island. Later investigations by Bevins and Roach (1979a), Kokelaar (1982), and Kokelaar *et al.* (1985) presented an interpretation of the various pyroclastic and volcaniclastic rocks. In particular, the studies of Kokelaar *et al.* (1985) have provided an insight into the processes related to the submarine eruption of silicic magmas and their subsequent reworking.

A major N–S fault divides Ramsey Island into two, with contrasting stratigraphies and geological evolutions. The GCR site covers the area to

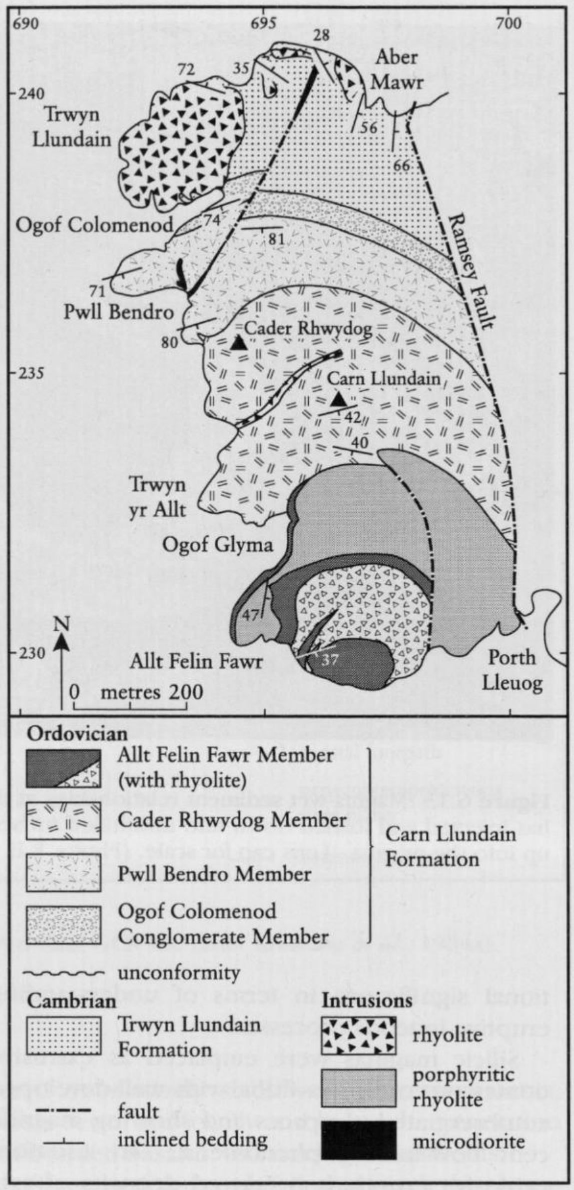


Figure 6.14 Map of the Aber Mawr to Porth Lleuog GCR site, Ramsey Island (after Kokelaar *et al.*, 1985).

the west of the Ramsey Fault.

Description

The succession to the west of the Ramsey Fault is dominated by silicic pyroclastic rocks of Llanvirn age, comprising the Carn Llundain Formation (Figure 6.14). The lowermost rocks, buff-coloured sandstones, are thought to be of mid-Cambrian age. A spectacular 35 m-thick, poorly bedded conglomerate, the Ogof

Figure 6.15 Ragged, elongate pumice fragments up to 12 cm in length in the Cader Rhwydog Tuff, Cader Rhwydog, Ramsey Island. (Photo: R.E. Bevins.)

Colomenod Conglomerate Member, overlies these sandstones with marked unconformity and represents the lowermost member of the Carn Llundain Formation. The conglomerate is poorly sorted, with rounded cobbles and pebbles of rhyolite, set in a finer matrix of rhyolite and rhyolitic sandstone.

The Pwll Bendro Member, comprising 165 m of silicic lapilli-tuffs and fine-grained typically massive tuffs, overlies and grades up from the underlying conglomerates. These tuffs are poorly sorted and poorly bedded, with individual tuff beds ranging from a few centimetres to 20 m in thickness, although typically they are in the range 1–2 m. They chiefly comprise lapilli of rhyolite, tube pumices, plagioclase and quartz crystals, and glass shard fragments. The tuffs are non-welded. A sequence of three ash-flow tuffs, the Cader Rhwydog Tuff (CRT), the Trwyn yr Allt Tuff (TAT) and the Ogof Glyma Tuff (OGT), comprise the overlying Cader Rhwydog Member, totalling some 223 m in thickness. The lowermost tuff, which is 186 m thick, dominates the succession, the other tuffs being 22 and 15 m thick respectively. The CRT is excellently exposed about Carn Llundain. The base is slightly unconformable in relation to the underlying tuffs and shows slight down cutting. A deeply incised 'palaeo' gulley is also seen. Near the base the CRT includes rounded pebbles and granules of rhyolite, angular clasts of rhyolite, and mudstone clasts. The main part of the CRT, however, contains ragged, commonly elongate, tube pumices (Figure 6.15), up to 32 cm, along with rhyolite fragments, and whole and broken quartz and plagioclase crystals. The pumice fragments are commonly flattened and in places are moulded around rhyolite clasts. Flattened

Figure 6.16 Wet sediment disturbance in thinly laminated turbiditic tuffs at the top of the Trwyn yr Allt Tuff, Cader Rhwydog Member, Carn Llundain, Ramsey Island. (Photo: R.E. Bevins.)

porphyritic rhyolite fiamme are also present. Poorly developed columnar jointing is seen extending upwards from the base for around 100 m. The uppermost 25 m or so of the CRT shows a marked fining, passing eventually into very fine-grained vitric tuffs. The TAT succeeds the CRT conformably, and comprises massive rhyolitic lapilli-tuffs with pumice clasts and quartz and plagioclase crystals. At the top these pass into thinly laminated turbiditic tuffs showing evidence of wet-sediment disturbance (Figure 6.16). The overlying OGT is similar to the TAT, but it also contains streaky, flattened pumices.

The Cader Rhwydog Member is succeeded conformably by several metres of thinly bedded and laminated tuffs of the Allt Felin Fawr Member, although the succession is complicated by a slightly discordant, cross-cutting porphyritic rhyolite intrusion, which shows irregular bulbous and peperitic margins. A maximum of 25 m is exposed beneath the sill with a further 8 m above the sill. The tuffs are silicic, containing rhyolite and pumice lithic clasts and quartz and plagioclase in a fine-grained siliceous matrix. The tuffs are well bedded, fine upwards and show loading structures at the base of individual beds. In the finer-grained tuffs, ripple drift cross-lamination, soft-sediment disruption and convolute lamination are all seen. This sequence is partly repeated by sliding. A large channel structure, up to 20 m wide and 6 m deep, is seen on a small headland to the SE of Allt Felin Fawr. Above this lies a poorly sorted heterolithic deposit, 3 m thick, which contains clasts of pumice, porphyritic rhyolite, rhyolite, fine-grained silicic tuff, and crystals set in a fine-grained silicic matrix. This unit is followed by a thin (0.5 m) conglomerate bed, poorly sorted heterolithic deposits (1.5 m), and then 2 m of laminated and thinly bedded silicic tuffs.

Overlying these various units is an autobrecciated rhyolite exposed to the east and south of Allt Felin Fawr. In the east the lava reaches up to 35 m in thickness, but to the SW the flow becomes compound, as two tuffaceous wedges come in. In the lowermost tuffaceous wedge a thin sequence of turbiditic tuffs occurs, which is overlain by an ash-flow tuff containing rhyolite and pumice lapilli in a vitric matrix with quartz and plagioclase crystals. The top grades sharply into fine tuffs. Towards the SW a flattening fabric is seen and the tuff contains randomly orientated slabs (1 m thick and 10 m in length) of laminated pumice- and crystal-bearing tuffs, in addition to an individual block (2.1 m in diameter) of porphyritic rhyolite with peperitic and lobate margins. A 0.5 m-thick, chaotic unit, containing rhyolite clasts and crystals in a mudstone matrix, lies between the ash-flow tuff below and a further ash-flow tuff above. Similar to the lower ash-flow tuff, this upper unit contains further contorted slabs of laminated fine tuffs. In places this ash-flow disrupts the thin chaotic unit below, with flames of muddy material penetrating up to 2 m into the ash-flow tuff. To the SW the ash-flow tuff is completely broken up into sac-like masses separated by thin veneers of the chaotic muddy deposit.

The upper wedge in the rhyolite lava flow comprises 20 m of medium- to fine-grained silicic tuffs, which wedge out against the rhyolite. The coarser tuffs show erosive bases, normal grading of the lithic component, and loading structures. The uppermost unit of these tuffs comprises the youngest strata exposed of the Carn Llundain Formation.

Interpretation

The entire sequence of Ordovician volcanic rocks exposed on Ramsey Island is considered to have been erupted and emplaced in a submarine environment, and those of the GCR site are considered to be of proximal origin. Uplift prior to the onset of deposition of the Carn Llundain Formation is represented by the marked unconformable relationship at the base of that formation and is probably related to intrusion at a high level of significant volumes of silicic magma.

The lowest conglomerates of the Ogof Colomenod Member are thought to result from a series of sediment-gravity flows, generated perhaps by volcanotectonic instability and derived from a littoral or supralittoral environment, possibly linked to a rhyolitic volcanic island, but emplaced in deeper water.

Tuffs of the Pwll Bendro Member are considered to have been generated essentially from cold high-density turbidity currents, with the thinner-bedded units resulting from less dense turbidity currents. Eruption of the primary ashes must have been rapid because of the lack of any intercalated background sediments. However it is difficult to establish whether this was in a subaerial or a submarine environment, although Kokelaar *et al.* (1985) favoured a submarine eruptive column as the source. In comparison with tuffs higher in the sequence this source seems to have been at some distance from the site area. They are most probably derived from the slumping of debris immediately following accumulation on the flank of a submarine volcano.

The overlying tuffs of the CRT show crucial evidence for heat retention following emplacement, including the flattening of pumices and the moulding of pumices around lithic clasts. This tuff is interpreted as having been erupted from a major, single, entirely submarine eruption, emplaced as a hot ash-flow tuff with associated ash-fall. A totally subaqueous environment is supported by the presence of soft-sediment convolutions in the overlying fine tuffs. These tuffs are thought to be of proximal origin.

The TAT largely comprises turbiditic tuffs, again thought to be derived from the reworking of unconsolidated ash deposits derived from explosive, most probably submarine, rhyolitic volcanism. Tuffs of the OGT, however, show welded shardic fragments, implying the welding of hot juvenile fragments, suggestive of a very proximal environment.

The Allt Felin Fawr Member is characterized by deposits derived from turbidity currents, which are invaded by a rhyolitic intrusion showing evidence of emplacement into wet, poorly consolidated tuffs, associated with fluidization. This had a catastrophic effect on the overlying tuffs, which were slumped away, exposing the rhyolite at the sea bed, to suffer later reworking into younger debris-flow deposits. Slumping of the tuffs resulted in their repetition in the stratigraphical succession.

The rhyolite appears to have been an autobrecciated lava erupted on to the sea floor, with very shallow (*c.* 6°) slopes. The two wedges intercalated with the rhyolite in the west of the outcrop were derived from the slumping of primary rhyolitic ash-flow tuffs, the extrusive rhyolite providing a topographic restriction to the distribution of the reworked tuffs. The contained contorted slabs are thought to represent turbiditic and ash-fall deposits genetically associated with the ash-flow tuffs but incorporated later, following slumping and mass-gravity flow. The contained block of porphyritic lava from the immediately subjacent sill is considered to reflect the contemporaneous nature of the intrusive activity, the explosive silicic volcanism and the quiet effusion of rhyolitic lavas, all in a submarine environment.

Conclusions

The rugged coastline and crags of Ramsey Island provide magnificent exposures through rhyolitic volcanic rocks that were erupted and emplaced close to their source, entirely in a submarine environment. A variety of processes are demonstrated, including the eruption of rhyolitic lava on to the sea floor, and the emplacement and reworking of silicic ash-flow and ash-fall deposits.

These exposures provide one of the most crucial sites in the British Isles for the interpretation of submarine silicic volcanic processes, and indeed are of international importance in demonstrating the submarine emplacement and welding of a silicic ash-flow tuff and related ash-fall derived from a major submarine explosive eruption. This account is the first record of such welded ash-fall tuffs in the world.

CASTELL COCH TO TRWYNCASTELL (SM 775 303–796 316)

R. E. Bevins

Introduction

Volcanic rocks are exposed extensively in the north Pembrokeshire region. The major activity, for example around Fishguard, appears to have occurred during Llanvirn times, chiefly during *Didymograptus bifidus* Biozone times. In the Abereiddi area, volcanic rocks of the Llanrian Volcanic Formation (of Hughes *et al.*, 1982) are exposed on the north and south sides of the bay, on opposing limbs of the Llanrian Syncline. On the south side of the bay, between Castell Coch in the west and Melin Abereiddi in the east, basaltic tuffs of the Didymograptus Murchisoni Ash of Cox (1915), or the Abereiddi Tuff Member of Hughes *et al.* (1982), are of *Didymograptus murchisoni* Biozone age. On the north side of Abereiddi Bay, silicic tuffs of *Didymograptus bifidus* Biozone age, are exposed; these are the Llanrian Volcanic Group of Cox (1915), or the Lower Crystal Tuff Member of the Llanrian Volcanic Formation of Hughes *et al.* (1982).

The first important description of these tuffs was by Cox (1915). Bevins and Roach (1979b) provided an initial interpretation of the environment and the depositional processes responsible for the genesis of the various tuffs. This was expanded upon by Kokelaar *et al.* (1984a). The geochemistry of tuffs belonging to the Abereiddi Tuff Member was described by Bevins *et al.* (1992).

Tuffs belonging to the Abereiddi Tuff Member represent the youngest Ordovician volcanic rocks exposed in the southern part of the Welsh Basin.

Description

The Ordovician sequence in the area around Abereiddi contains significant volcanic and volcaniclastic rocks, exposed in two E–W coastal sections. These rocks are interbedded with strongly cleaved mudstones that reflect the character of the background sedimentation which was punctuated periodically by short-lived volcanic events.

At the western end of the cliffs forming the south side of Abereiddi Bay (Figure 6.17), the Abereiddi Tuff Member is well exposed to the NE of Aber Creigwyr. The tuffs dip to the north at around 45°, and are represented by two fining-upwards sequences, 95 m thick in total. The upper tuff unit lies conformably on the lower, and the base of each unit is sharp and planar.

The lower tuff unit is poorly to moderately bedded, with successively higher beds becoming overall of finer grade and showing more clearly defined coarse-grained bases (coarse-tail grading). The upper unit, in contrast, is not obviously bedded, although it does show evidence of grading. The tuffs are composed of angular, scoriaceous basalt lapilli and sparsely vesicular blocks and bombs, up to 40 cm in diameter, set in a fine-grained tuffaceous matrix (Figure 6.18).

To the east, in the area around Melin Abereiddi, the tuffs are thinner (around 60 m). The tuffs of the lower unit rest conformably on tuffaceous mudstones, and are poorly sorted, with crude coarse-tail grading and ill-defined bedding. Upwards the tuffs of the lower unit become more thinly bedded and finer grained. The upper unit, which has a distinctive lapilli-tuff at its base, shows a coarser grain-size. These

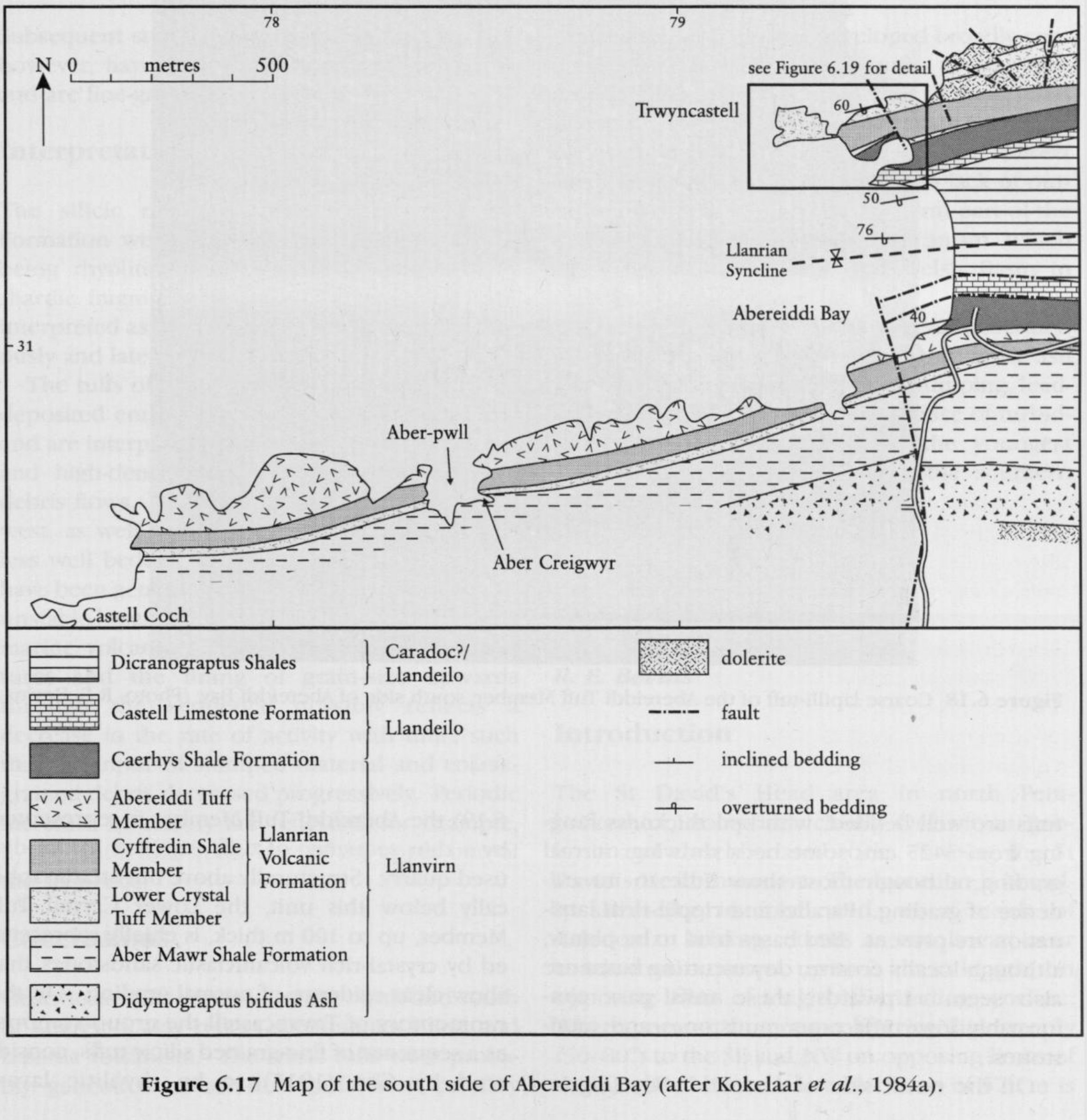


Figure 6.17 Map of the south side of Abereiddi Bay (after Kokelaar *et al.*, 1984a).

Figure 6.18 Coarse lapilli-tuff of the Abereiddi Tuff Member, south side of Abereiddi Bay. (Photo: R.E. Bevins.)

tuffs are well bedded, with bed thickness ranging from 3–25 cm; some beds showing normal grading, although most show little to no evidence of grading. Parallel and ripple drift lamination are present. Bed bases tend to be planar, although locally erosive, down-cutting bases are also seen. Upwards, these tuffs pass conformably into tuffaceous mudstones and mudstones.

On the north side of Abereiddi Bay (Figure 6.19) the Abereiddi Tuff Member is represented by a thin sequence of tuffs exposed in the disused quarry. Structurally above but stratigraphically below this unit, the Lower Crystal Tuff Member, up to 100 m thick, is chiefly represented by crystal-rich volcaniclastic sandstones that show clear evidence of normal grading. On the promontory of Trwyncastell the group comprises a sequence of fine-grained silicic tuffs, considered by Cox (1915) to be rhyolitic lavas.

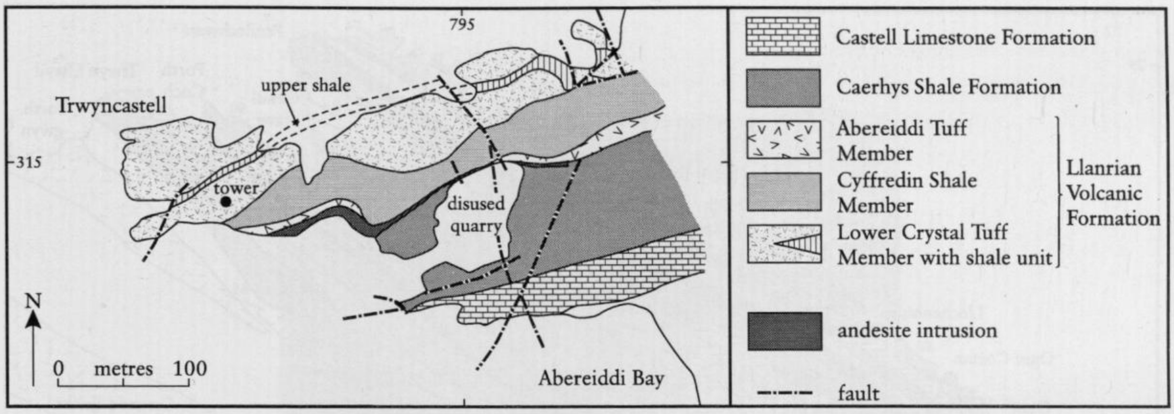


Figure 6.19 Map of the north side of Abereiddi Bay (adapted from Hughes *et al.*, 1982).

Subsequent studies (Bevins and Roach, 1979a), however, have shown that they contain shards and are fine-grained, silicic tuffs.

Interpretation

The silicic rocks of the Llanrian Volcanic Formation were interpreted by Cox (1915) as being rhyolitic lavas. However, they contain shardic fragments, along with crystals and are interpreted as ash-flow tuffs, emplaced subaqueously and later extensively recrystallized.

The tuffs of the Abereiddi Tuff Member were deposited entirely in a submarine environment and are interpreted as deposits chiefly from low- and high-density turbidity currents and from debris flows. They become thicker towards the west, as well as becoming coarser grained and less well bedded. The sequence is thought to have been generated by the periodic slumping of unstable basaltic debris down the flanks of a submarine volcano. The increase in bedding features and the fining of grain-size upwards through the sequence possibly reflects a decrease in the rate of activity with time, such that the input of slumped material and coarse-grained debris decreased progressively. Periodic increases in activity are reflected, for example, by the lapilli-tuffs at the base of the upper unit of the sequence.

Conclusions

Ordovician tuffs exposed to the north and south of Abereiddi Bay reflect subaqueous silicic and basaltic volcanism. The silicic tuffs were probably generated as ash-flow tuffs from primary explosive eruptions and developed broadly contemporaneous with similar tuffs to the east around Fishguard (at the Pen Caer GCR site) and to the west in the vicinity of Ramsey Island (at the Aber Mawr to Porth Lleuog GCR site). Direct correlations are not possible due to lack of outcrop continuity, but they clearly form part of the major bimodal basic–silicic volcanism which characterized this part of the Welsh Basin in early Ordovician times.

Basaltic tuffs appear to have been generated on the flanks of a submarine volcano; loose ash and lapilli were reworked due to slumping, leading to the accumulation of a sequence of turbidity deposits. These tuffs are the youngest Ordovician volcanic deposits in the southern part of the Welsh Basin.

ST DAVID'S HEAD (SM 733 275–747 288)

R. E. Bevins

Introduction

The St David's Head area in north Pembrokeshire, comprises chiefly Ordovician gabbroic and closely related rocks, forming the St David's Head Intrusion. The intrusion is broadly sheet-like in form and, as a result of Caledonian folding, occurs as two linear, near continuous outcrops, up to 2 km in length, on opposing limbs of a tight NE-trending syncline. Where present, an igneous layering dips steeply (50–80°) to the SE and NW on opposing limbs of the syncline. A maximum thickness of 570 m is

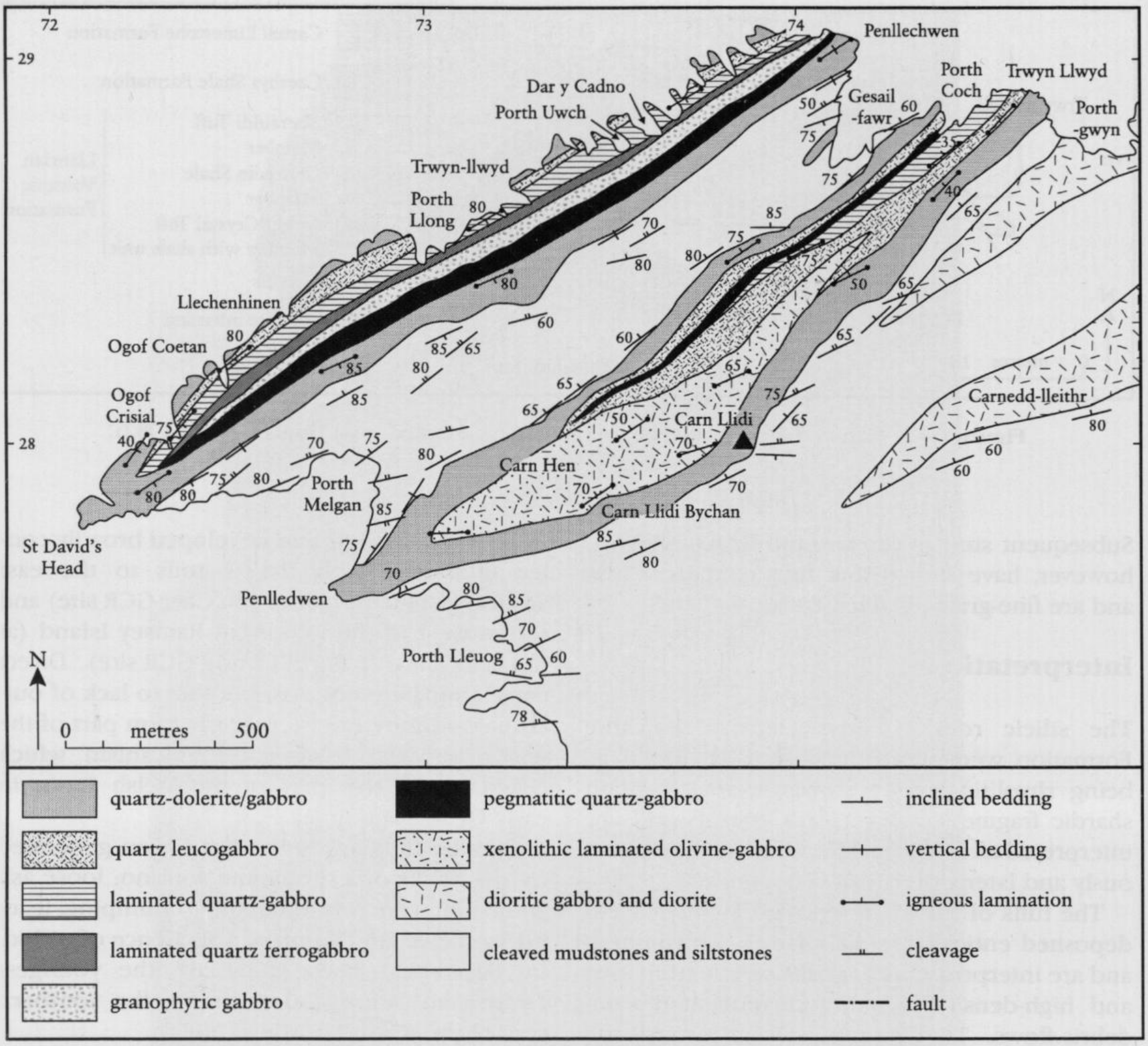


Figure 6.20 Map of the St David's Head Intrusion (after Bevins *et al.*, 1994).

seen on the south-eastern (Carn Llidi) limb, while only *c.* 385 m is exposed on the north-western (St David's Head) limb.

The intrusion invaded sedimentary rocks (mudstones to fine-grained sandstones) of Ordovician, probable Arenig, age prior to Caledonian (end-Silurian) folding. Contact metamorphic effects are seen in manganiferous siltstones, with the development of spessartine and cordierite porphyroblasts (now pseudomorphed).

The earliest studies on the St David's Head Intrusion were those by Elsden (1905, 1908), who described the presence of various norites, quartz-norites, and enstatite diorites, noting interbanding between and a regular distribution of the different rock types. Roach (1969) elaborated on the earlier work, identifying seven major petrological types in the intrusion orientated parallel to the contacts, in addition to minor, cross-cutting aplite veins. Roach (1969) considered that the two outcrops represent two separate sheets, while Bevins and Roach (1982) suggested that the two sheets are, in fact, opposing limbs of a synclinal structure. Bevins *et al.* (1991) presented geochemical data, highlighting the petrogenetic link between the basic and silicic rocks. Most recently, Bevins *et al.* (1994) provided a detailed petrological and geochemical description of the major rock types present in the intrusion, arguing for a complex evolution, linked to multiple magma injection and in-

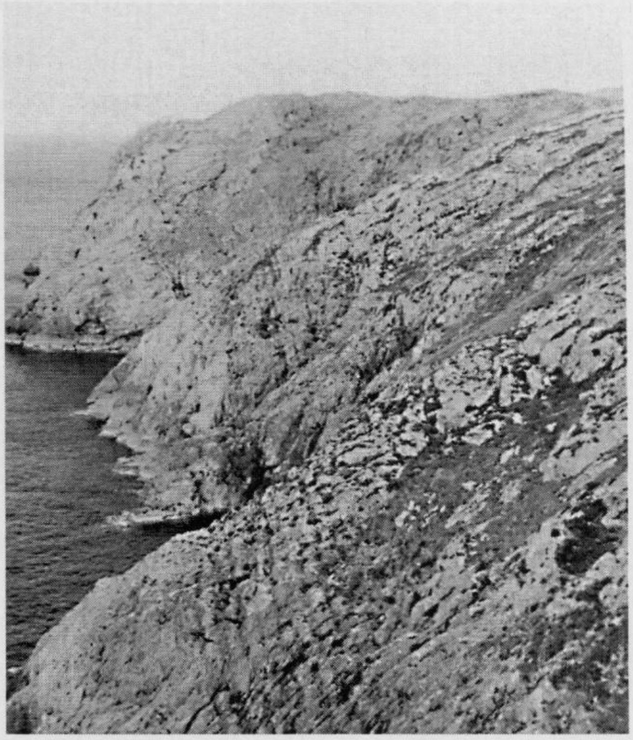


Figure 6.21 Macrorhythmic layering between laminated quartz-gabbro (lighter bands) and laminated quartz-ferrogabbro (darker bands), looking to the NE across Porth Llong, St David's Head Intrusion. (Photo: R.A. Roach.)

situ crystallization.

This is one of only two layered intrusions in the Caledonian sequences of Wales, and illustrates the complex nature of processes involved in the development of a layered intrusion, as well as providing critical evidence for the origin of contemporaneous, closely related silicic lavas and pyroclastic rocks.

Description

The St David's Head Intrusion is magnificently exposed in sea cliffs and adjacent exposures in the area to the north of Whitesand Bay. It occurs as two NE-trending outcrops, the north-western forming the coastal section from St David's Head to Penllechwen, the south-eastern forming the less well-exposed section between Penlledwen and Trwyn Llwyd, best exposed on the crags of Carn Llidi. Seven major petrological types are recognized in the St David's Head Intrusion (Figure 6.20), in addition to the relatively minor, cross-cutting aplite veins.

Quartz-dolerite and quartz-gabbro

Quartz-dolerite and quartz-gabbro form an outer unit to the intrusion, up to 100 m thick and best exposed in cliffs at the south-western extremity of the St David's Head outcrop. Here, intermittent centimetre-scale microrhythmic felsic–mafic segregations occur, passing in places into irregular pegmatitic patches. Mineralogically, the gabbros are dominated by plagioclase (max An_{65}) and clinopyroxene (cores $Ca_{40}Mg_{49}Fe_{11}$ to $Ca_{40}Mg_{43}Fe_{17}$; rims $Ca_{40}Mg_{47}Fe_{13}$ to $Ca_{40}Mg_{36}Fe_{24}$) along with minor altered olivine, orthopyroxene and ilmenite, and a quartz-feldspar mesostasis. Texturally, the gabbros are subophitic.

Xenolithic laminated olivine-gabbro

The xenolithic laminated olivine-gabbro unit is up to 200 m thick, being exposed only on the south-eastern limb of the intrusion and with the best exposures present in the steep crags of Carn Llidi. This unit is characterized by the pres-

Figure 6.22 Granophyric gabbro from the St David's Head Intrusion, showing slight variations in felsic components, east of St David's Head. (Photo: R.A. Roach.)

ence of mafic and felsic cognate xenoliths up to 1 m in length. The host gabbro is poorly laminated and is characterized by plagioclase, clinopyroxene, orthopyroxene (typically pseudomorphed), altered olivine and minor Ti-rich biotite and hastingsitic amphibole. The mafic xenoliths are predominantly composed of clinopyroxene, pseudomorphed orthopyroxene and pseudomorphed olivine. Clinopyroxenes are the most Mg-rich in the intrusion, with compositions in the range $Ca_{42}Mg_{47}Fe_{11}$ to $Ca_{40}Mg_{45}Fe_{15}$; orthopyroxenes show very restricted compositions, from $Ca_4Mg_{72}Fe_{24}$ to $Ca_4Mg_{68}Fe_{28}$. Plagioclase compositions reach An_{71}, the most Ca-rich feldspars in the intrusion.

Quartz-leucogabbro

Quartz-leucogabbro units are present in both outcrops of the intrusion. These gabbros are characterized by relatively high modal proportions of plagioclase relative to the mafic minerals. Clinopyroxenes are similar in composition to those in the xenolithic laminated olivine-gabbro unit, while plagioclases reach An_{61}, although generally they are albitized. Minor ilmenite and quartz are also present.

Laminated quartz-gabbro

Quartz-gabbros showing a pronounced mineral lamination are best exposed in the vicinity of Ogof Crisial. Locally, these gabbros are interlayered with laminated quartz-ferrogabbros (Figure 6.21). The lamination is due to the alignment of the major mineral phases, namely tabular plagioclase, elongate, prismatic clinopyroxene (and rarer altered orthopyroxene) and elongate ilmenites. Clinopyroxenes show a restricted range of compositions from $Ca_{43}Mg_{39}Fe_{18}$ to $Ca_{42}Mg_{33}Fe_{25}$. Plagioclase compositions reach a maximum calcic component of An_{58}. Commonly, the plagioclases show strong compositional zoning.

Laminated quartz-ferrogabbro

A relatively thin unit of laminated quartz-ferrogabbro in the St David's Head outcrop is best exposed on the north-eastern side of Porth

Llong. Towards the south-western end of the outcrop laminated ferrogabbros, up to 1 m thick, are spectacularly interlayered on a macrorhythmic scale with laminated quartz-gabbros. The lamination is similar to that in the laminated quartz-gabbros, except that ilmenite is more abundant in the ferrogabbros. Mineral compositions are nearly identical to those in the laminated quartz-gabbros.

Granophyric gabbro

The principal exposures of granophyric gabbro occur in the north-western outcrop of the St David's Head Intrusion, for example in the cliff-top crags above Porth Llong, although coarse pegmatitic to granophyric gabbros are also present in the Carn Llidi outcrop. These gabbros are isotropic, dominated by plagioclase (altered), with relatively minor clinopyroxene (the most Fe-rich in the St David's Head Intrusion, reaching $Ca_{42}Mg_{27}Fe_{31}$), orthopyroxene, and ilmenite. Apatite, as stout prisms up to 2 cm long, is abundant and of probable cumulus origin. These gabbros are characterized by interstitial quartz-alkali feldspar granophyric intergrowths (Figure 6.22).

Pegmatitic quartz-gabbro

Distinctive pegmatitic quartz-gabbros are present in both outcrops, towards the top of the intrusion. Geochemical evidence presented by Bevins *et al*. (1994) suggests that these gabbros are in fact coarse-grained equivalents of either quartz-gabbro, leucogabbro or granophyric gabbro. Distinctive in these pegmatitic quartz-gabbros are prismatic clinopyroxene crystals up to 12 cm in length.

In addition to the seven main petrological units, thin (up to 30 cm wide) cross-cutting aplite veins are particularly well developed in the vicinity of Ogof Crisial. The aplites are dominated by albite and quartz, associated with minor ilmenite, amphibole, apatite, titanite and zircon.

Contact relationships and layering

Contacts between the petrological units vary from sharp to gradational, while certain units are interbanded. Relationships are described in detail by Bevins *et al*. (1994). The nature of the contacts is crucial in establishing the history of the intrusive events. In addition, the St David's Head Intrusion shows three types of mineral and compositional layering within the individual petrological units, namely:

1. Mineral layering in the more evolved laminated quartz-gabbros and laminated quartz-ferrogabbros, related to the parallel alignment of tabular plagioclase, pyroxene and ilmenite crystals.
2. Macrorhythmic modal layering, up to 1 m thick, related to an alternation of laminated quartz-gabbro and laminated quartz-ferrogabbro units.
3. Centimetre-scale, felsic-mafic, microrhythmic modal layering in the quartz-gabbro unit.

Geochemistry

Bevins *et al*. (1994) provided the first detailed geochemistry for the full range of gabbroic and related rocks of the St David's Head Intrusion. Roach (1969) had previously presented major element analyses for a small number of samples from the quartz-dolerites and quartz-gabbros, while Bevins *et al*. (1991) had used the geochemistry of the silicic (aplitic) derivatives of the St David's Head rocks to speculate on the origin of silicic eruptive rocks associated with the neighbouring Ordovician volcanic centres (e.g. the Pen Caer GCR site). The apparent link by fractional crystallization between the St David's Head aplites and the more basic gabbros led Bevins *et al*. (1991) to suggest that many of the rhyolitic lavas and ignimbrites in the adjacent sequences were similarly derived from more basic compositions by fractional crystallization.

Interpretation

The petrological varieties present in the St David's Head Intrusion and their contact relationships reveal a complex origin, thought to relate in part to in-situ fractionation and in part to multiple events of magma injection. For example, interbanding relationships between leucogabbro and laminated quartz-gabbro at Ogof Crisial imply that the leucogabbro was intruded later than the crystal accumulation that gave rise to the laminated quartz-gabbro, indicating separate intrusive events. In contrast, the lamination in the laminated quartz-gabbros and the laminated quartz-ferrogabbros is thought to be of cumulus origin, resulting from the periodic sedimentation and accumulation of ilmenite crystals. The presence of mafic (olivine +orthopyroxene+clinopyroxene) cognate xenoliths in the xenolithic gabbros has been taken as evidence for the existence of high-level magma chambers in which these mafic minerals accumulated, prior to incorporation in later basic magmas and transport to higher crustal levels.

The geochemical data set of Bevins *et al.* (1994) confirmed the earlier proposals of Bevins *et al.* (1991) that the various petrological types are related through crystal fractionation. In particular, strong correlations between highly incompatible elements demonstrate that all the different rock types present in the intrusion, from basic through to silicic compositions, are petrogenetically linked, while plots of highly compatible elements versus incompatible elements illustrate the role of clinopyroxene and olivine in the fractionation process. Not all of the chemical variations determined, however, can be explained by crystal fractionation. Certain major and minor element variations suggest the importance of cumulate processes, in particular accumulation of olivine-orthopyroxene, ilmenite, and of apatite.

Conclusions

The St David's Head Intrusion is one of only two layered intrusions in the Caledonides of Wales, and provides evidence for a variety of high-level igneous processes. A great variety of rock types are present, resulting in a number of different rock units, ranging from basic through to silicic composition. Evidence from the field relationships between these different units, afforded by magnificent coastal exposures, combined with geochemical evidence, suggests that the units are all related to each other magmatically, but that a variety of igneous processes have operated, leading to the variety of compositions exposed today. These include in-situ fractional crystallization, the incorporation of crystalline material (cognate xenoliths) from an underlying high-level magma chamber, and the injection of different magma batches of contrasting compositions at slightly different times. The geochemical variation present in the intrusion provides critical evidence for the origin of rhyolitic lavas and ash-flow tuffs exposed elsewhere in the Ordovician sequences of Pembrokeshire.

CADAIR IDRIS (SH 750 149, 667 133, 712 148–711 100)

D. G. Woodhall

Introduction

The Cadair Idris GCR site comprises a well-exposed succession of acid and basic volcanic rocks of Llanvirn to basal Caradoc age, belonging to the Aran Volcanic Group (Figure 6.23). The latter comprises up to 2 km of volcanic and sedimentary rocks of Arenig to Caradoc age, that crop out around the southern and eastern parts of the Harlech Dome. At the Cadair Idris GCR site, subaqueously emplaced silicic ash-flow tuffs in the lower and upper parts of the succession, are separated by a thick series of submarine basalt lavas with interbedded tuffs and mudstones. A number of dolerite sills, and a thick microgranite sheet, are also well exposed. The whole succession dips to the south or south-east.

The first detailed descriptions of the igneous rocks of Cadair Idris were given by Cox (1925) and Cox and Wells (1927) in their accounts of the stratigraphy, tectonics and intrusive igneous rocks of the Dolgellau area. Some of the intrusions within the site have been the subject of detailed structural, petrographical and geochemical studies. Lake and Reynolds (1912) described the structure of the Mynydd y Gader dolerite, which lies in the northern part of the site area, while Davies (1955, 1956, 1959) described the petrology, geochemistry and contact metamorphism associated with the Cadair Idris granophyre (now classed as a microgranite) and the Pen-y-gader dolerite, both of which crop out extensively. The site area was included in a recent resurvey of the Cadair Idris district by the British Geological Survey (Pratt *et al.*, 1995), which involved a geochemical study of the igneous rocks by Kemp and Merriman (1994).

Exposures of the Aran Volcanic Group in the Cadair Idris GCR site area represent products of the most voluminous early Ordovician igneous episode in southern Snowdonia.

Description

The stratigraphical succession established most recently by the British Geological Survey (Pratt *et al.*, 1995) is presented below (Table 6.1), along

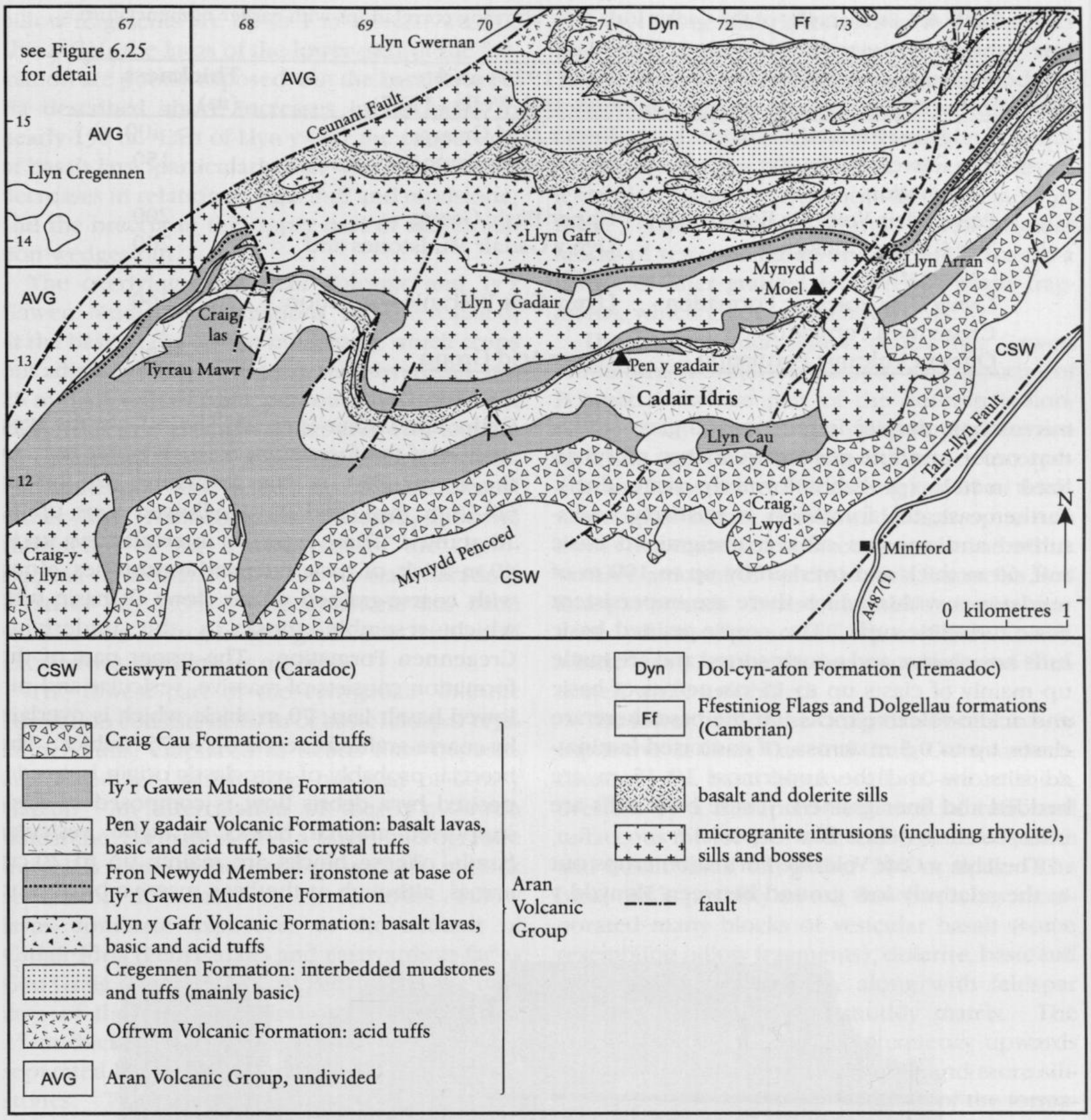


Figure 6.23 Map of the Cadair Idris area.

with the earlier terminology of Cox (1925) and Cox and Wells (1927).

Silicic ash-flow tuffs of the Offrwm Volcanic Formation crop out on Mynydd y Gader to the north of the site area, where they are intruded by the Mynydd y Gader dolerite sill (Lake and Reynolds, 1912). In contrast to the Pared y Cefn-hir GCR site, at Cadair Idris there are no interbedded mudstones, although the tuffs are petrographically similar and display microscopic evidence of welding. Bedded tuffs up to 3 m thick occur locally at the top of the formation.

The overlying Cregennen Formation consists of interbedded tuffs and mudstones, which crop out along the south side of Mynydd y Gader. In the west of the area, relationships are complex as a result of slumping and later intrusions, and therefore correlation with the Pared y Cefn-hir GCR site has proved difficult (Pratt *et al.*, 1995). The upper part of the formation, in the vicinity of the Penrhyn-gwyn slate quarries, includes a silicic ash-flow tuff up to 25 m thick, which is possibly equivalent to a similar tuff seen on Pared y Cefn-hir itself. This tuff is composed of

Table 6.1 Stratigraphy of the Cadair Idris area, showing correlations with earlier nomenclature.

Pratt *et al.* (1995)	Cox (1925) and Cox and Wells (1927)	Thickness (m)
Craig Cau Formation	Upper Acid Group	> 400
Ty'r Gawen Mudstone Formation	Llyn Cau Mudstone	150
Penygadair Volcanic Formation	Upper Basic Group	200
Ty'r Gawen Mudstone Formation	Llyn y Gadair Mudstones and ash	200
Llyn y Gafr Volcanic Formation	Llyn y Gafr Volcanic Formation	360
Cregennen Formation		160
Offrwm Volcanic Formation	Lower Acid Group	80

microscopic pumice fragments and glass shards that occur in a fine-grained quartzose recrystallized matrix (probably formerly vitric dust). Farther east, the formation is relatively undisturbed and consists of a coarse-grained basic tuff, 60 m thick and overlain by up to 100 m of mudstones within which there are impersistent basic turbiditic tuffs. The coarse-grained basic tuffs are massive and poorly sorted and are made up mainly of clasts up to 15 cm across of basic and acidic volcanic rocks. At the base there are clasts, up to 0.5 m across, of contorted laminated siltstone and the uppermost 10–15 m are bedded and finer grained. These basic tuffs are interpreted as debris flow deposits.

The Llyn y Gafr Volcanic Formation crops out in the relatively low ground between Mynydd y Gader and Cadair Idris. At Llyn y Gafr, the type section of the formation, massive basalt lavas in the lower part of the formation are up to 60–70 m thick and have pillowed tops up to 10 m thick. There are a few intercalations, up to 40 m thick, of basic tuffs and mudstones, along with coarse-grained debris flows of basic tuffs which resemble those in the underlying Cregennen Formation. The upper part of the formation consists of massive, vesicular and pillowed basalt lava, 70 m thick, which is overlain by coarse-grained breccia up to 75 m thick. The breccia, probably of pyroclastic origin but redeposited by a debris flow, is composed of clast-supported angular blocks of highly vesicular basalt. These blocks are mainly up to 20 cm across, although at the base massive basalt and

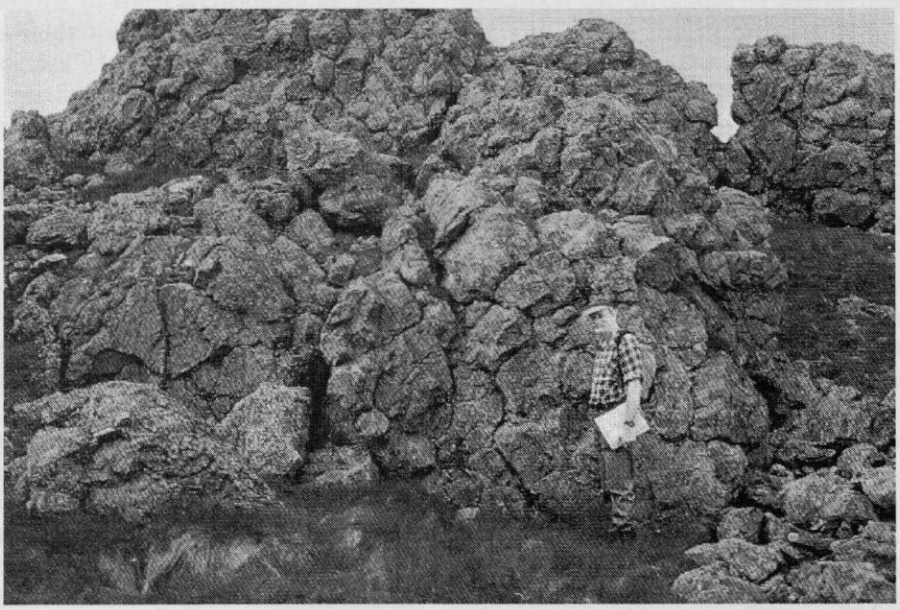


Figure 6.24 Pillowed basalts from the Penygadair Volcanic Formation, SW of Penygadair summit. (Photo: D.G. Woodhall.)

pillow fragments are up to 1 m across. West of Llyn y Gafr the lavas of the lower part of the formation are poorly exposed, but the basaltic breccia described above increases in thickness to nearly 150 m. East of Llyn y Gafr the proportion of basalt lava, particularly that which is massive, decreases in relation to basic tuff and mudstone, and the breccia in the upper part of the formation wedges out.

The overlying Penygadair Volcanic and Ty'r Gawen Mudstone formations are intercalated. At the base of the lowest mudstone, which crops out adjacent to Llyn y Gadair and Llyn Arran, is a 25 m-thick unit of black pyritous mudstone with numerous phosphatic nodules and with lenticular oolitic and pisolitic ironstone up to 2 m thick. The mudstone has yielded fossils indicative of either the *Nemagraptus gracilis* Biozone (Llandeilo) or the lowest part of the *Diplograptus multidens* Biozone (basal Caradoc) (Pratt *et al.*, 1995). The ironstone has been worked as a source of low grade ore, with small excavations marking its outcrop.

The lowest part of the Penygadair Volcanic Formation consists of 10 m of basic feldspar crystal-rich tuffs, emplaced as debris flow deposits and turbidites, which crop out east of Llyn y Gadair. An intercalation of the Ty'r Gawen Mudstone Formation and a large microgranite intrusion separate these tuffs from a 200 m-thick succession dominated by basalt lavas. Pillow lavas dominate exposures at the summit of Cadair Idris (Penygadair) and eastwards as far as Gau Graig (Figure 6.24). At Penygadair, the type area of the formation, individual flows up to 15 m thick are locally apparent where they are separated by thin intervening tuffs and/or mudstones. The thicker flows are massive at the base, with some incipient columnar jointing, but are pillowed at the top. The pillows are closely packed with little or no interpillow sediment and tend to decrease in size upwards within a flow from about 2 m across to about 0.2 m. They display radial and concentric fractures and most have quartz-filled amygdales. There are rare lava tubes up to 10 m across infilled with flow-banded basalt, and locally hyaloclastite occupies depressions on flow surfaces. At Penygadair there are two interbedded silicic ash-flow tuffs each about 15 m thick and composed of quartz, recrystallized pumice fragments, and glass shards along with feldspar crystals. There is microscopic evidence for welding. The lower of the two silicic ash-flow tuffs is the most persistent, extending from Tyrrau Mawr in the west to Gau Graig in the east. Between Penygadair and Tyrrau Mawr the basalt lavas wedge out and the formation consists of silicic ash-flow tuffs with interbedded tuffaceous sandstones and mudstones, altogether 65 m thick, overlain by a lenticular basaltic (?)pyroclastic breccia, 3 m thick. The breccia is composed of angular blocks of vesicular basalt up to 0.2 m across in a matrix of finer grained scoriaceous basalt fragments, which grade into glass shards.

The highest intercalation of the Ty'r Gawen Mudstone Formation crops out south of Penygadair, where part of the outcrop is concealed by Llyn Cau. In the steep slopes between Llyn Cau and Craig Cau the mudstones incorporate an olistostrome, 200 m long and 20 m thick, made up of blocks of pillowed basalt up to 4 m across in a matrix of tuffaceous mudstone with a variable amount of volcanic rock fragments and feldspar crystals. It also contains irregular contorted clasts of green tuff, up to 0.3 m across, which were probably incorporated and deformed while unlithified.

The lower part of the Craig Cau Formation, in exposures at Craig Cau and Craig Cwm Amarch, consists of a basal blocky tuff, 20–40 m thick, overlain by a disrupted sequence of tuffs and tuffaceous mudstones with lenticular mudstones and basalt lavas, altogether 200 m thick. The basal tuff is possibly an ash flow but it has incorporated many blocks of vesicular basalt (some resembling pillow fragments), dolerite, basic tuff and more rarely rhyolite, along with feldspar crystals, in a dark-green muddy matrix. The blocks decrease in size and frequency upwards and the top is relatively block-free and more silicic in appearance. The upper part of the formation consists of an ash-flow tuff, 180 m thick, with up to 10 m of bedded tuffs at the top. The ash-flow tuff is non-welded and feldspar crystal-rich in the basal 2–3 m, although above the tuff is strongly welded with a contorted welding fabric indicative of rheomorphic folding. This becomes less evident upwards as the attitude of the welding fabric becomes approximately bedding parallel. The overlying bedded tuffs are fine grained and include laminated tuffs and thin intercalations of mudstone.

Most of the igneous intrusions within the site area are dolerite sills, up to 200 m thick, of which the Mynydd y Gader dolerite (Lake and Reynolds, 1912) and the Penygadair dolerite (Davies, 1956) are the most extensive. The

Cadair Idris microgranite, previously referred to as 'granophyre' (Davies, 1959), is for much of its outcrop a sill up to 600 m thick. It forms a prominent escarpment immediately north of Cyfrwy, Penygadair and Mynydd Moel, with columnar jointing evident in the escarpment cliffs. At Mynydd Moel the sill becomes a highly discordant boss, within which the microgranite becomes fine grained and grades into rhyolite. Whereas the sill is emplaced into the lowest part of the Ty'r Gawen Mudstone Formation, the boss has intruded overlying formations as high as the upper part of the Craig Cau Formation. Here it loses its identity as a result of the lithological similarity between recrystallized ash-flow tuff and rhyolite (Davies, 1959; Pratt *et al.*, 1995).

Interpretation

The tuffs of the Offrwm Volcanic and Cregennen formations are interpreted as the subaqueous products of contemporaneous acid and basic explosive volcanism at both the Cadair Idris and the Pared y Cefn-hir GCR sites. However, the absence of interbedded mudstone in the Offrwm Volcanic Formation on Mynydd y Gader suggests that the formation is represented here by a single thick ash-flow tuff, which was possibly emplaced into shallower water than the tuffs of this formation at the Pared y Cefn-hir GCR site. The scarcity of mudstone at the base of the Cregennen Formation along the central part of Mynydd y Gader indicates that shallow-water conditions persisted during the emplacement of the lowest basic tuffs by one or more debris flows. However, the mudstone-dominated succession above indicates the establishment of deeper water conditions in which relatively fine-grained turbiditic tuffs were deposited.

The basalt lavas of the Llyn y Gafr and Penygadair volcanic formations are the products of effusive volcanism from an unknown source area. The basalt breccias possibly represent coarse pyroclastic material that accumulated close to a vent, but it is possible that the breccias represent accumulations of pyroclastic material redeposited by debris flows at greater distances from the source vents. The mudstone intercalation that separates the two formations indicates a hiatus in volcanism. The pyritous mudstones and ironstones are interpreted as the result of low sedimentation rates during this hiatus (Pratt *et al.*, 1995).

The presence of the few silicic ash-flow tuffs in the Cregennen and Penygadair Volcanic formations indicates that explosive silicic volcanism was only intermittent. However, during the emplacement of the Craig Cau Formation the situation was very different. The basaltic material incorporated in the ash-flow tuffs and other deposits in the lower part of the formation is consistent with sporadic basaltic volcanism. The lack of such material higher up in the formation suggests that basic volcanism had died out before the subaqueous emplacement of the thick silicic ash-flow tuffs that dominate the upper part of the formation. It has been suggested that the boss of the Cadair Idris microgranite lies close to the source of the silicic tuffs of the Craig Cau Formation (Cox and Wells, 1927; Davies, 1956, 1959; Pratt *et al.*, 1995).

Geochemical analyses (Kemp and Merriman, 1994) confirm the existence of bimodal basaltic and rhyolitic lavas and tuffs, and suggest that the associated dolerite and microgranite intrusions are probably cogenetic. The rocks evolved largely by crystal fractionation of transitional tholeiitic/calc-alkaline magmas emplaced into thinned continental lithosphere, probably in an extensional marginal basin. The magmas are believed to have been generated in the mantle by the melting of subduction-modified N-type (normal) Mid-Ocean-Ridge Basalt (MORB).

Conclusions

The Cadair Idris GCR site represents the most important episode of Ordovician volcanism in southern Snowdonia. The well-exposed volcanic and associated intrusive rocks of the site area include examples of a subaqueously emplaced volcanic succession dominated by basaltic pillow lavas and silicic ash-flow tuffs.

Evidence for welding in the silicic tuffs at the base and top of the volcanic succession indicates that they were emplaced as hot ash-flow tuffs contemporaneous with explosive volcanism. However, the mode of emplacement of the basic tuffs and their association with contemporaneous volcanism is less clear. The existence of well-exposed pillow lavas provides clear evidence that effusive basaltic volcanism took place and it is likely that there was associated explosive volcanism. Many of the basic tuffs display evidence of mass-flow emplacement, suggesting that the products of this explosive volcanism were dispersed in debris flows and turbidity currents.

Some of the numerous dolerite sills display evidence of intrusion contemporaneous with the basaltic volcanism and it also seems likely that the silicic magma that produced the Cadair Idris microgranite was closely related to that which generated the silicic ash-flow tuffs of the Craig Cau Formation.

PARED Y CEFN-HIR (SH 666 152)

D. G. Woodhall

Introduction

The Pared y Cefn-hir GCR site (Figure 6.25) incorporates the best-exposed succession of volcanic rocks of Arenig to Llanvirn age in North Wales. The succession forms the lowest part of the Aran Volcanic Group.

A notable aspect of the site is the strong topographical expression of certain volcanic units and igneous intrusions. These form a series of NE-trending ridges, of which Pared y Cefn-hir itself is the most prominent (Figure 6.26). Intervening depressions are formed of less-resistant grey mudstones. The volcanic rocks consist mostly of acid and basic tuffs, all emplaced subaqueously, some as ash-flow tuffs. There are subordinate basaltic pillowed lava flows. The igneous intrusions consist of sills of dolerite and microgranite, some with well-exposed chilled margins and contacts with country rocks.

The first detailed description and map of the igneous rocks of the Pared y Cefn-hir area was that of Cox and Wells (1921), in their account of the stratigraphy, structure and intrusive igneous rocks of the district between Arthog and Dolgellau. The petrography of certain intrusive igneous rocks was also described. The site was re-examined during the recent resurvey of the Cadair Idris district by the British Geological Survey (Pratt *et al.*, 1995), which included a petrological and geochemical study of the igneous rocks by Kemp and Merriman (1994) (see the Cadair Idris GCR site report).

Description

The stratigraphy of the Pared y Cefn-hir area presented below (Table 6.2) is based on the recent

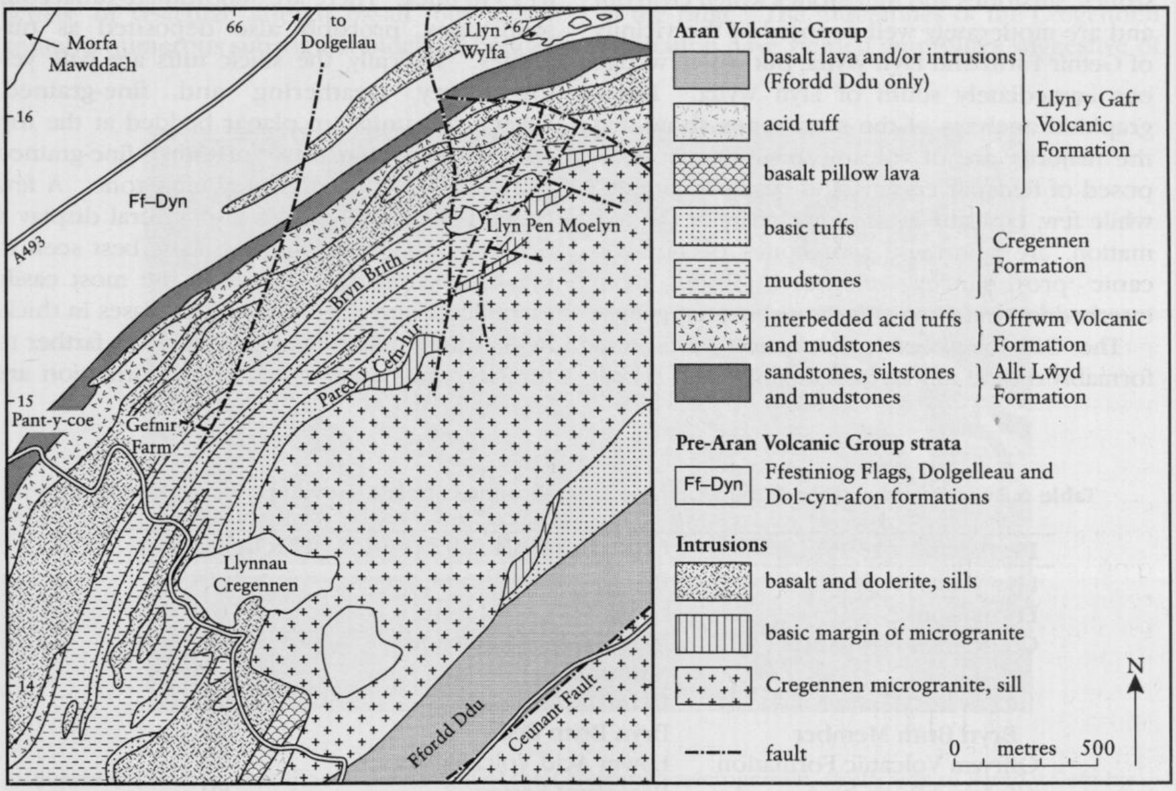


Figure 6.25 Map of the Pared y Cefn-hir area.

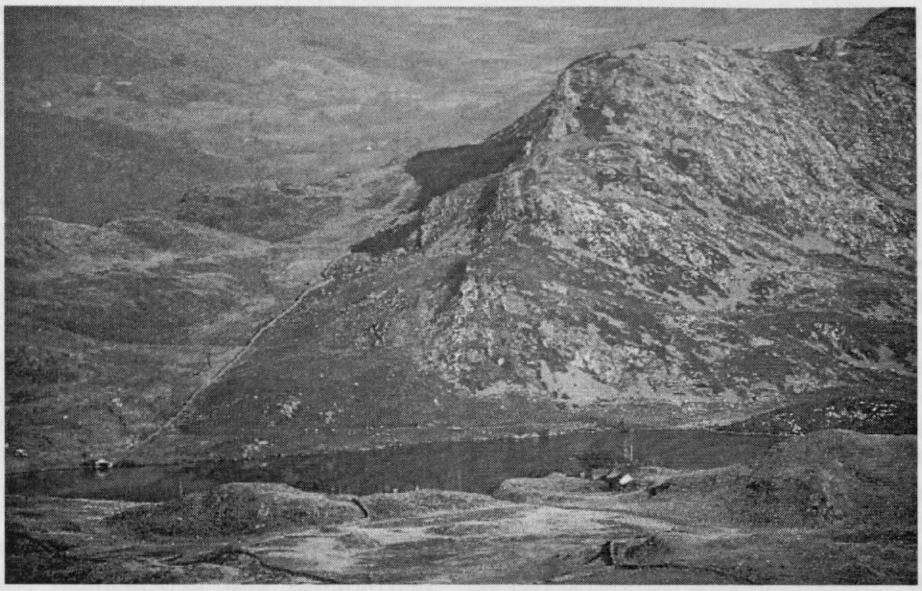


Figure 6.26 View of the Pared y Cefn-hir area from the SW. The prominent ridge is formed by the Cefn-hir Member and the rocky slopes to the right are in the Cregennen microgranite. (Photo: D.G. Woodhall.)

resurvey by the British Geological Survey (Pratt *et al*., 1995), with the earlier terminology of Cox and Wells (1921) for comparison.

The Allt Lŵyd Formation consists of sandstones, siltstones and mudstones which crop out and are moderately well exposed in the vicinity of Gefnir Farm and Llyn Wylfa, but which wedge out immediately south of Llyn Wylfa. Petrographical analyses of the sandstones show that the majority are of volcanic provenance, composed of feldspar crystals and basalt fragments, while few, typically in the lower part of the formation, are quartzose sandstones of non-volcanic provenance. Acritarch floras from interbedded mudstones indicate an Arenig age.

The Offrwm Volcanic Formation rests conformably on the Allt Lŵyd Formation and is best exposed immediately north of Gefnir Farm. Here, it consists of units 1–15 m thick of silicic ash-flow and turbiditic tuff, most of which are separated by intervals of dark-grey mudstone up to 25 m thick. There are subordinate tuffaceous sandstones, probably also deposited as turbidites. Typically, the silicic tuffs are pale yellowish-grey weathering and fine-grained. Several tuff units are planar bedded at the top and some contain clasts of either fine-grained silicic tuff or contorted grey mudstone. A few contain siliceous nodules and several display a bedding-parallel welding foliation, best seen in the highest tuff unit, which is the most easily identifiable and persistent. It increases in thickness, from 8 m at Gefnir Farm to 15 m farther to the NE. Tuff units lower in the formation are

Table 6.2 Stratigraphy of the Pared y Cefn-hir area, showing correlations with earlier nomenclature.

Pratt *et al*. (1995)	Cox and Wells (1921)	Thickness (m)
Llyn y Gafr Volcanic Formation	Lower Basic Volcanic Series	> 100
Cregennen Formation	Moelyn, Crogenen and Bifidus slates	225
Cefn-hir Member	Cefn Hir Ashes	45
Bryn Brith Member	Bryn Brith Beds	55
Offrwm Volcanic Formation	Lower Acid Volcanic Series	90
Allt Lŵyd Formation	Basement Series	80

probably also persistent but are difficult to distinguish from each other owing to intermittent exposure and numerous dolerite sills that complicate the succession. Thin sections show abundant glass shards and minute pumice fragments intensely altered to, and in many instances greatly obscured by, a microcrystalline quartzo-feldspathic aggregate. Feldspar crystals are abundant in some of the lowest tuffs. The interbedded mudstones are dark-grey and strongly cleaved. Graptolite faunas from a number of localities within the site area indicate the *Didymograptus artus* Biozone (early Llanvirn) (Pratt *et al.*, 1995).

The Cregennen Formation comprises 60 m of mudstone at the base, which crops out, but is poorly exposed, immediately NW of Bryn Brith where it rests sharply on the upper acid tuff of the underlying Offrwm Volcanic Formation. Basic tuffs in the middle of the Cregennen Formation constitute the Bryn Brith Member and are particularly well exposed on Bryn Brith. Here a single unit of massive, coarse-grained, poorly sorted basic tuff, 55 m thick and probably emplaced from debris flows, passes upwards into 10 m of finer grained, planar-bedded turbiditic tuff. The massive tuff is composed chiefly of abundant ragged fragments, up to 5 mm across, of vesicular, altered basalt, but it also contains numerous subangular blocks of bedded basic tuff up to 30 cm across, the bedding of which is highly contorted, indicating incorporation in an unlithified state. The Bryn Brith Member is overlain by 65 m of mudstone, which is poorly exposed in the low ground between Bryn Brith and Pared y Cefn-hir. The Cefn-hir Member lies at the top of the formation and is well exposed on the central and southern parts of the prominent ridge of Pared y Cefn-hir. On the southern part of the ridge a 2 m-thick bed of silicic ash-flow tuff lies in the middle of the member but underlying beds of basic tuff, 1–15 m thick, wedge out north-eastwards. Consequently, on the central part of the ridge the silicic tuff lies at the base of the member. Here, it is overlain by 2–3 m of mudstone followed by 25 m of massive, coarse-grained, blocky and poorly sorted basic tuffs, which form a series of debris flow units 1–10 m thick. Each unit has finer grained, planar bedded, turbiditic tuff at the top, in some cases up to 2 m thick. The basic tuffs are petrographically similar to those of the Bryn Brith Member but feldspar crystals are more common, and blocks of bedded basic tuff are accompanied by those of basalt, silty mudstone and acid volcanic rock. Basaltic pillow lavas, up to 5 m thick, occur locally near the top of the member at the SW end of the ridge. The mudstones of the Cregennen Formation have yielded graptolites suggestive of

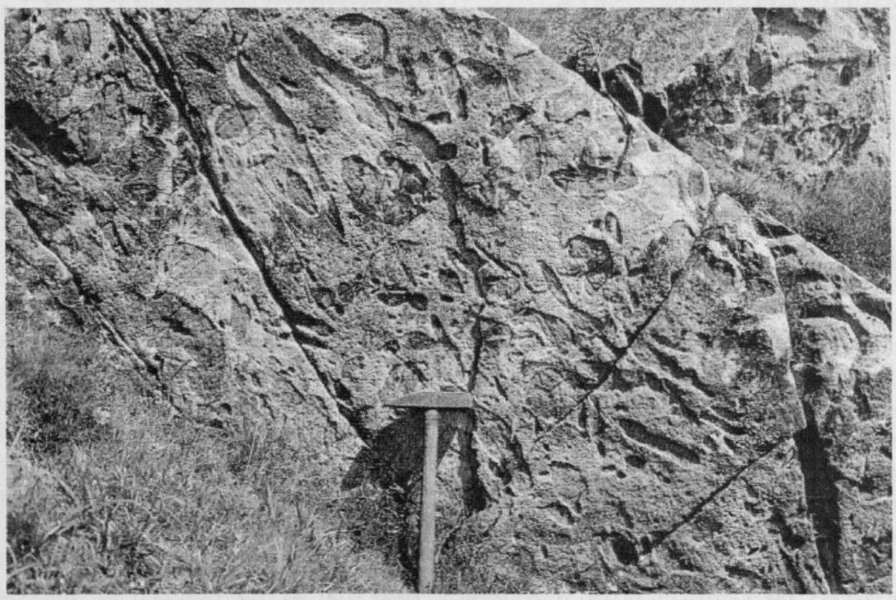


Figure 6.27 Basic xenoliths in the margin of the Cregennen microgranite, south side of Pared y Cefn-hir (6651 1506). (Photo: D.G. Woodhall.)

the *Didymograptus artus* Biozone, and fragmentary trilobites obtained from mudstone within the Bryn Brith Member SW of Bryn Brith suggest a similar early Llanvirn age (Pratt *et al.*, 1995). Basaltic pillow lavas of the overlying Llyn y Gafr Volcanic Formation are locally well exposed immediately south of Llynnau Cregennen.

The igneous intrusions are mostly dolerite sills which range in thickness from a few metres to *c.* 100 m. They occur typically within mudstones, which most probably facilitated intrusion. Dolerite exposures near Llyn Wylfa and Gefnir Farm display narrow (up to 0.5 m) chilled margins against mudstone country rocks. In each case mudstone 'flames' penetrate from 2 cm to as much as 1 m into the sill, and indicate that the sediment was unlithified at the time of intrusion. The dolerites are typically composed of plagioclase, clinopyroxene, iron-oxide and accessory apatite. Extensive alteration has produced a range of secondary minerals; albite replacing plagioclase, actinolite (along with chlorite) replacing pyroxene, titanite replacing iron-oxide, and intergrowths of chlorite, epidote, quartz and stilpnomelane replacing the groundmass of porphyritic rocks. In spite of the alteration, primary subophitic and ophitic igneous textures are preserved. The chilled margins tend to be vesicular and porphyritic with feldspar phenocrysts in a groundmass of feldspar microlites and chlorite.

The Cregennnen microgranite sill, which is 500 m thick, crops out extensively in the eastern part of the site. It has intruded the Cregennen and Llyn y Gafr formations. It is particularly well exposed on the eastern side of Pared y Cefn-hir where there is a distinct lower marginal facies developed up to 10 m from the contact. The microgranite proper is characterized by granophyric intergrowths of feldspar and quartz, but there are some alkali feldspar phenocrysts and accessory amounts of apatite and zircon. The feldspars have been altered to epidote and pumpellyite, and late stage stilpnomelane crystals are common. The marginal facies has abundant hornblende and biotite, but geochemically it is similar in composition to the microgranite (Kemp and Merriman, 1994). The contact between the basic margin and microgranite proper is marked by a conspicuous xenolithic zone several metres thick (Figure 6.27). This zone is interpreted as earlier, partly crystalline magma that was disrupted by the intrusion of the main part of the microgranite (Pratt *et al.*, 1995).

Interpretation

The sandstones of the Allt Lŵyd Formation are interpreted as shallow-marine deposits (Pratt *et al.*, 1995), with a volcaniclastic component derived from the contemporaneous erosion of pre-existing volcanic rocks, most probably of the Rhobell Volcanic Group (Kokelaar, 1979).

The absence of sandstones and shallow-water bedforms in the Offrwm and Cregennen formations suggests deeper-water conditions, possibly established by marked local subsidence. The tuffs of these formations are the products of contemporaneous explosive acidic and basaltic volcanism. This is clearly indicated by the presence of welding fabrics in silicic ash-flow tuffs in the Offrwm Volcanic Formation, while the presence of unabraded glass shards and/or pumice fragments in both acid and basic tuffs is regarded as being further evidence for contemporaneous volcanism, even though they are present in debris flow deposits and turbidites. The latter formed by the resedimentation of pyroclastic material during or soon after explosive volcanism. The fact that these tuffs are interbedded with mudstones clearly indicates subaqueous emplacement. The source of this volcanism has not been identified (Pratt *et al.*, 1995), but the occurrence of basaltic pillow lavas near the top of the Cefn-hir Member and in the overlying Llyn y Gafr Formation suggests that the effusive basaltic volcanism took place at an unknown source possibly closer to the site area.

Conclusions

The well-exposed volcanic and intrusive igneous rocks of the Pared y Cefn-hir GCR site are of national importance as they represent the best exposures of the Aran Volcanic Group of Arenig to Llanvirn age. They are also of importance as a succession of subaqueously emplaced volcanic rocks and for the associated igneous intrusions. The exposures are easily accessible for educational purposes and the site complements the Cadair Idris GCR site.

The volcanic rocks consist of acid and basic tuffs that were emplaced subaqueously, some as ash-flows and others as debris flow deposits and turbidites. Ash-flow tuffs are only distinguishable where evidence of welding fabrics can be seen, with some difficulty and uncertainty, in some of the acid tuffs. The presence of abundant angular glass fragments in both the acid and basic tuffs suggests that they were a product of explosive volcanism. These deposits contrast with the sandstones derived from reworked volcanic material which dominate the Allt Lŵyd Formation. The site includes a number of dolerite sills, some showing evidence for emplacement into unlithified sediment, which in turn is evidence that intrusive activity was approximately contemporaneous with the volcanism. Silicic magmatism represented by the Cregennen microgranite sill however, is clearly later than that indicated by the silicic tuffs of the Offrwm, Cregennen and Llyn y Gafr formations.

CARNEDDAU AND LLANELWEDD (SO 050 520–075 549)

D. G. Woodhall

Introduction

The Carneddau and Llanelwedd GCR site lies at the southern end of the Builth Inlier of Ordovician (Llanvirn to Llandeilo) volcanic and sedimentary rocks (Figure 6.28). The volcanic rocks consist mainly of rhyolitic and basaltic tuffs, but there are basaltic, andesitic and dacitic lavas in various parts of the succession, most particularly at the top. Doleritic and dacitic intrusions also occur.

The history of research on the Builth Inlier extends back to general observations made by Murchison (1833, 1839, 1867, 1872) who noted that the largest 'trap' district in Radnorshire extends southwards from Llandegley to Builth Wells. The stratigraphy of the inlier was described by Elles (1940) but most emphasis in this work was on the sedimentary rocks. The detailed survey of Jones and Pugh (1941, 1949) was used by the Geological Survey in the compilation of a 1:25 000 scale geological map (1977). The whole of the Builth Inlier has recently been resurveyed by the British Geological Survey (BGS).

Petrological and geochemical studies of the volcanic rocks by Furnes (1978) and Smith and Huang (1995) indicated a range in composition, from basalt through andesite and dacite to rhyolite, which is wider than that which occurs gen-

Figure 6.28 Map of the southern part of the Builth Inlier.

erally in North Wales. The volcanic rocks appear to have mainly calc-alkaline geochemical affinities, although some tholeiitic flows are also present.

Description

The volcanic succession given in Table 6.3 is based on the recent BGS resurvey of the Builth Inlier, with the stratigraphical units of Jones and Pugh (1949) for comparison.

The volcanic succession is underlain and overlain by mudstone-dominated sedimentary successions which crop out outside of the site area. The entire succession lies within the *Didymograptus murchisoni* Biozone.

The silicic ash-flow tuff at the base of the volcanic succession crops out along the eastern side of the site where it forms a subdued east-facing escarpment and is repeatedly offset by major E–W faults. It is composed of pumice fragments up to 3 mm across, along with glass shards and feldspar crystals, which can still be seen under the microscope despite intense quartz- and/or chlorite-dominated alteration. Much of the tuff appears to be bedded, but this is interpreted as a secondary feature resulting from the development of massive, resistant layers formed by intense silicification, and fissile, less-resistant layers produced by chloritization. True primary bedding is evident locally, however, where the uppermost *c.* 5 m of tuff is reworked. Erosion of the ash-flow tuff generated tuffaceous sands, composed of rhyolitic rock fragments, up to 2 m of which are locally preserved in erosional hollows at the top of the tuff.

The silicic tuff is sharply overlain by up to 100 m of massive lapilli-tuffs, emplaced as a series of debris-flow deposits. The lapilli-tuffs are composed of abundant poorly sorted fragments of basic volcanic rock up to 3 cm across, with scattered rhyolite fragments up to 15 cm across. Individual debris flow units are difficult to distinguish owing to poor exposure but they appear to be separated either by bedded tuffs, or by interbeds of dark-grey siltstone less than 10 cm thick. The massive lapilli-tuffs pass upwards into a series of turbidites, altogether about 50 m thick, each of which consist of normally graded beds of lapilli-tuff and/or tuff and which are well exposed near Maengowan Farm. Individual turbidites are sharp-based and range in thickness from 0.5 m to at least 4 m. The turbidites are overlain by up to 65 m of mudstones within which there are a number of interbedded tuff turbidites each less than 1 m thick. Within the lapilli-tuffs, tuffs and mudstones there are scattered pods of dacite lava (keratophyres of the Geological Survey 1:25 000 map, 1977) some of which are associated with hyaloclastite breccias.

An impersistent silicic ash-flow tuff occurs in the middle of the volcanic succession and is overlain by more basic lapilli-tuffs and tuffs. These were also emplaced as debris-flow

Table 6.3 Stratigraphy and lithologies of volcanic rocks of the Builth Inlier.

Lithology	Stratigraphy (after Jones and Pugh, 1949)	Thickness (m
Silicic ash-flow tuff	Rhyolitic ash and ashy mudstones of the Cwmamliw Series	35
Sandstones and conglomerates of volcanic provenance	Sandstones of the Newmead Series, including the boulder beds	65
Feldspar-phyric basalt and andesite lavas, passing laterally into hyaloclastite breccia	Spilites, keratophyres and bouldery spilitic ash of the Builth Volcanic Series	250
Feldspar crystal-rich basic lapilli-tuffs and tuffs	Pebbly feldspar ash of the Builth Volcanic Series	50
Silicic ash-flow tuff		0–35
Basic lapilli-tuffs, tuffs and mudstones, with subordinate dacite and hyaloclastite	Red agglomerate, ash and shales of the Builth Volcanic Series	> 200
Silicic ash-flow tuff	Rhyolitic ash of the Llandrindod Volcanic Series	50

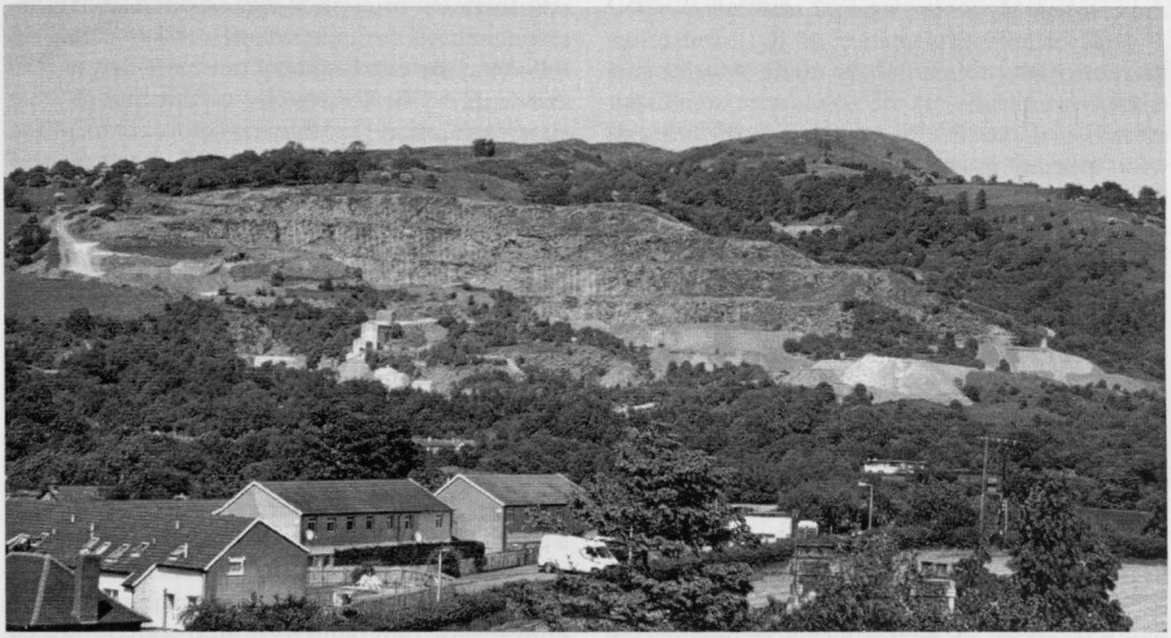


Figure 6.29 Llanelwedd quarries, Builth Wells, viewed from the south. Westerly-dipping basic lavas, belonging to the Builth Volcanic Group, comprise much of the quarry area. Other volcanic units form the prominent features in the hills behind the quarry, the slack ground being eroded into softer shales. (Photo: R.E. Bevins.)

deposits and turbidites, but they differ from those lower in the volcanic succession in that many individual flow units contain abundant feldspar crystals. Some of the tuffs are well bedded and display hummocky cross-stratification. An impersistent flow-banded dacite lava, 20 m thick, is well exposed immediately north of Caer Fawr.

The tuffs and dacite lava described above are sharply overlain by a series of feldspar-phyric basalt lavas, with subordinate andesite lava, lapilli-tuffs and tuffs. The lavas reach up to 250 m thick at Llanelwedd where they are well exposed in a series of quarries (Figure 6.29), but they are only 150 m thick immediately to the north of the quarries. The lavas in the lowest 30 m are microporphyritic and the basal flow can be seen resting sharply on tuffs in a small disused quarry immediately SE of the main working quarry. Individual flows are 10–20 m thick and include up to 5 m of brown-weathering, clast-supported flow surface breccia. These lavas wedge out immediately north of the main quarry. In the eastern part of the main quarry the microporphyritic lavas are overlain by a series of feldspar-phyric basalt lavas, 40 m thick, with some individual flows up to 12 m thick. Flow surfaces are either brecciated or highly vesicular, but a few flows are separated by several metres of lapilli-tuff. In the NW and western parts of the main quarry massive feldspar-phyric basalt displays no obvious flow surface features and may therefore be intrusive. Two such sheets, 35–50 m thick, are separated by up to 8 m of blocky lapilli-tuff. This deposit, probably emplaced as an ash-flow tuff, contains abundant blocks of feldspar-phyric basalt along with many of gabbro and rhyolite. In the extreme west of the main quarry feldspar-phyric basalt, considered to be extrusive, locally displays pillow-like structures up to 2 m across defined by concentric layers of amygdales. Similar structures are seen locally where the lavas crop out north of the quarries. The highest lava, 35 m thick, crops out immediately west of the main quarry and is andesitic in composition (Furnes, 1978). It is locally flow-banded and distinctly brownish-yellow weathering at the top. In the NW part of the site area the feldspar-phyric basalt lavas overlie, and interdigitate with, massive poorly sorted hyaloclastite breccia composed of angular blocks of massive and vesicular feldspar-phyric basalt up to 0.5 m across. The finest-grained material consists of basalt fragments and feldspar crystals;

the coarsest blocks are up to 2 m across.

The volcanic provenance of the sandstones and conglomerates at the top of the volcanic succession is indicated by the abundance of feldspar crystals and basalt clasts. The sandstones rest with marked unconformity on feldspar-phyric basalt and andesite lava. This unconformity was described in detail by Jones and Pugh (1949) who documented features such as fossil sea cliffs, stacks, wave-worn surfaces and screes, which they attributed to an ancient shoreline. Mapping of the unconformity clearly indicates that it has considerable relief. This may be at least 50 m in places, indicated by thickness variations across faults, notably the E–W Newmead Fault where the sandstones thin abruptly northwards from 85 m to 25 m. This may, however, be a result of contemporaneous faulting as well as relief on the unconformity. The lack of lavas or tuffs within the sandstones indicates that they are a product of post-volcanic sedimentation brought about by the erosion of pre-existing volcanic rocks.

There are few igneous intrusions within the site area. Many of the keratophyres shown on the 1:25 000 geological map (1977) have been re-interpreted during the recent BGS resurvey as dacite lavas, although the distinction between lavas and high-level intrusions has been difficult. A prominent E–W dolerite dyke adjacent to Tanlan cuts across feldspar-phyric basalt lavas and sandstones, and feeds a sill emplaced at the base of the overlying mudstones. The dyke increases in thickness to 80 m as it approaches the sill. The latter is exposed in a disused quarry at Tanlan where a concordant contact with the mudstones is seen.

Interpretation

The silicic ash-flow tuff at the base of the sequence was produced during a violently explosive volcanic eruption, and the ash-flow probably travelled many tens of kilometres from its source. The location of the source is not known, but a coarse-grained facies found in northern parts of the Builth Inlier (Davies *et al.*, 1996) is consistent with a source still farther to the north. Evidence for subaqueous emplacement, including contacts with underlying mudstones and fossiliferous reworked tuffs at the top, is present mainly in parts of the inlier outside of the site area. It is considered that emplacement took place into an open-shelf environment and brought about marked shoaling following the emplacement of up to 50 m of ash-flow tuff. This led to the establishment of a shoreface zone possibly no more than 20 m deep within which the top of the tuff was reworked.

The basic lapilli-tuffs and tuffs also represent the products of explosive volcanism but this was probably less violent. The emplacement of the fragmented (pyroclastic) material as debris flow deposits and turbidites was probably contemporaneous with the volcanism as suggested by the angularity of the fragments and preservation of delicate glass shard structures. The increasing frequency upwards of finer-grained tuffs and interbedded mudstones suggests that there was a gradual reduction in frequency and duration of successive volcanic eruptions. The dacite pods are interpreted as viscous magma bodies emplaced within unlithified mud and ash, which in at least some instances broke through to the surface. The associated hyaloclastites formed by non-explosive quench fragmentation of magma in wet sediment and/or water.

Some of the mudstones mentioned above possibly accumulated during a short hiatus in volcanism that was terminated by the emplacement of another subaqueous silicic ash-flow. The impersistence of this tuff within the site area is interpreted as a result of emplacement in a shallow-water high-energy environment, and it is thought likely that immediately following its emplacement the tuff was eroded by strong (?)tidal currents; the remaining occurrences are the result of preservation in sheltered sea-floor depressions. The overlying feldspar crystal-rich lapilli-tuffs and tuffs represent the products of further contemporaneous basic explosive volcanism. However the shallow-water bedforms in some bedded tuffs suggest shoaling brought about by the continued accumulation of debris-flow deposits and turbidites. Dacite magmatism persisted.

The shoreface environment established as a result of shoaling was displaced by the northward spread of feldspar-phyric basalt lavas. Pre-existing dacite lavas probably formed local topographical barriers limiting the extent of the earliest lavas. This is suggested by the abrupt termination of the basal microporphyritic lavas immediately north of the main quarry in proximity to a dacite lava. The feldspar-phyric basalt lavas have been interpreted as subaqueously emplaced (Jones and Pugh, 1949; Nicholls, 1958; Baker and Hughes, 1979; Metcalfe, 1990; Bevins and Metcalfe, 1993) on the basis of localized occurrences of interbedded black shales and pillows. However, they have also been interpreted as subaerial (Furnes, 1978), and this interpretation is preferred because of the nature of flow surfaces; lavas with brecciated surfaces are interpreted as aa flows, whereas those that are highly amygdaloidal at the top are interpreted as pahoehoe flows. In addition, the pillows are re-interpreted as cross sections through lobate pahoehoe lava on the basis of the presence of concentric zones of amygdales and the absence of prominent chilled margins and radiating fracture patterns. The massive feldspar-phyric basalt sheets which lack flow surface features are interpreted as high-level synvolcanic intrusions (sills). The hyaloclastite breccias in the north of the site area are thought to be the products of quench fragmentation of the lavas as they encountered relatively deep water; however, the poorly sorted nature of the breccia is consistent with debris-flow deposition. The fact that the breccia is first encountered immediately beneath feldspar-phyric basalt lavas suggests that the earliest breccias were over-ridden by later lavas.

The immediate post-volcanic period in the site area was marked by marine erosion, which was accompanied by sandstone deposition and possibly also by faulting. A combination of erosion and faulting may have produced a cliffed coastline, the ultimate burial of which by sands could account for the relief on the unconformity, most evident across the Newmead Fault. The latest volcanism to affect the Builth Inlier did not leave any deposits within the site area. This volcanism resulted in the subaqueous emplacement of a further silicic ash-flow tuff, comprising the Cwmamliw Series of Jones and Pugh (1949). The pile of feldspar-phyric basalt lavas appears to have acted as a barrier preventing the southward spread of this ash-flow tuff into the Carneddau and Llanelwedd site area.

Furnes (1978) investigated the geochemistry of the volcanic rocks of the site area, although this work remains unpublished. Kokelaar *et al.* (1984b) reported that the lavas have calc-alkaline affinities, while the more detailed investigations of Metcalfe (1990) and Smith and Huang (1995) identified the presence of tholeiitic lavas interbedded with those of calc-alkaline affinity.

Conclusions

The volcanic rocks of the Builth Inlier, most of which are seen within the Carneddau and Llanelwedd GCR site, are of national importance for their value in reconstructing the plate tectonic history of both Wales and the British Isles during Ordovician times. The extensive outcrops provide detailed successions through the thickest sequence of Ordovician volcanic rocks at the margin of the Welsh Basin. The sequence has mainly calc-alkaline affinities, in contrast to volcanic rocks of Llanvirn age in north Pembrokeshire (see the Pen Caer GCR site report), which are chiefly tholeiitic. Silicic ash-flow tuffs at the base and near the middle of the volcanic succession represent the onset of separate volcanic cycles characterized by more basic explosive activity and finally basaltic lavas. The best exposures are those of the late-stage lavas seen in the Llanelwedd quarries. The continued working of the main quarry, leading to constantly changing exposures, has resulted in divergent views as to the subaqueous or subaerial emplacement of the lavas.

Finally, the site is of historical interest in that it is in part the area studied in detail by Jones and Pugh (1949), which led to the presentation of one of the first detailed palaeogeographical reconstructions of an ancient volcanic environment.

BRAICH TU DU (SH 650 606–648 630)

M. Smith

Introduction

The steep western slopes of the ridge of Braich tu du, which form the eastern side of the Nant Ffrancon Pass, exhibit a classic condensed section up through a heterogeneous sequence of acid ash-flow tuffs, intrusions and marine sedimentary rocks. The section includes representatives of both the 1st and 2nd eruptive cycles of Caradoc caldera activity in North Wales as well as evidence for the background sedimentation, which provides valuable information on the general palaeoenvironment.

The site (Figure 6.30) lies on the north-western limb of a major synclinal structure, the Idwal Syncline. Moderate to gentle south-easterly dips

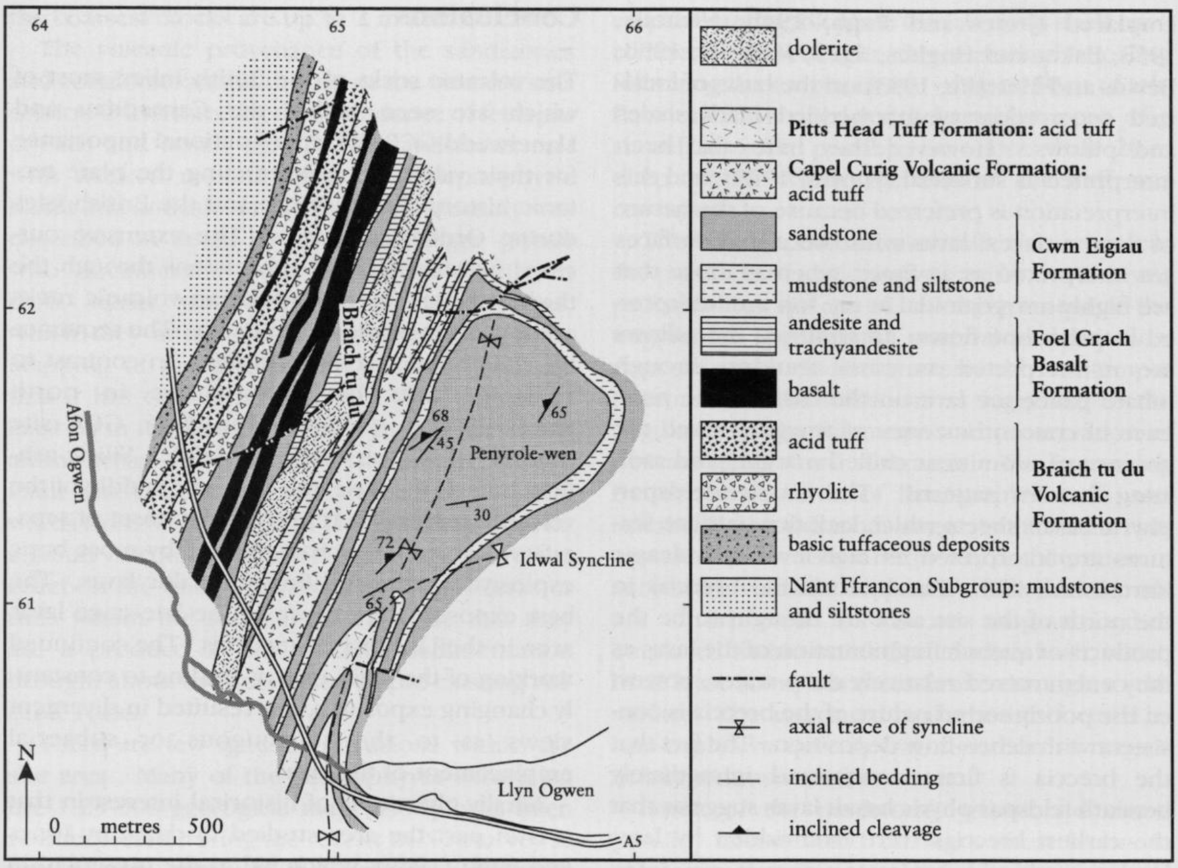


Figure 6.30 Map of the Braich tu du area. Adapted from BGS 1:25 000 Sheet 65/66 (1985).

expose up to 1000 m of section younging from NW to SE.

The area was included in the original primary geological survey completed in 1852 (Ramsay, 1881) and was resurveyed by the Geological Survey in 1968. It is included in the 1:50 000 scale Geological Sheet 106 (Bangor) (1985), although no detailed descriptions are available in the literature.

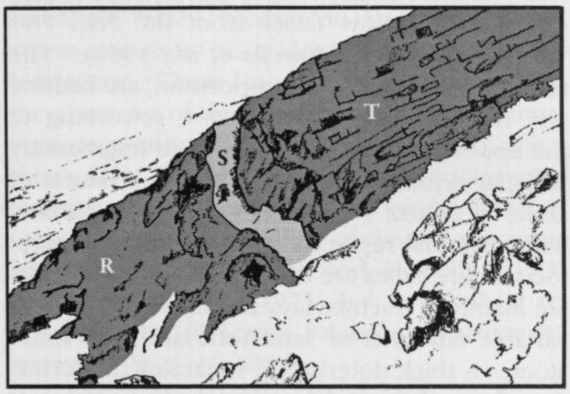
Description

The lower beds exposed at the north-western end of the GCR site comprise cleaved grey siltstones of the Nant Ffrancon Subgroup, which pass conformably into the overlying volcanic rocks of the 1st Eruptive Cycle belonging to the Llewelyn Volcanic Group (Soudleyan). This group comprises five formations, four of which are exposed in this section.

The Braich tu du Volcanic Formation is a heterogeneous sequence, up to 280 m thick, of rhyolitic flows and acid ash-flow tuffs, locally with basalt and basic tuffs. On the ridge of Braich tu du, the type locality for the formation, the sequence is dominated by two thick rhyolite flows separated by a welded ash-flow tuff with basalt lavas, basic tuffs and sedimentary rocks. The lower rhyolite, 60 m thick, is overlain by an intensely welded ash-flow tuff, up to 90 m thick (Figure 6.31). The tuff, characterized by small prismatic albite phenocrysts, has a weakly welded basal zone rich in lithic and cognate clasts. At 6–7 m above the base, welding is intense and chloritic clasts (up to 10 cm in length), representing flattened fiamme, are accentuated by quartzose recrystallization. Internally, the central part of the flow is characterized by highly contorted rheomorphic flow-folding and brecciation. The top is pervasively autobrecciated. The upper rhyolite is 45 m thick and, like the lower flow, displays excellent flow-banding and flow-folding with prominent columnar jointing and autobrecciation along the upper and lower contacts. Petrographically, the rhyolites contain up to 25% phenocrysts of sodic plagioclase and cryptoperthitic feldspar set in a devitrified groundmass of spherulitic intergrowths of quartz and feldspar.

Thin basalt lava flows and water-lain basaltic tuffs, associated with sandstones and siltstones, interdigitate throughout the sequence. The basalts and basic tuffs, originally considered by Howells *et al*. (1983) as part of the formation, have been re-interpreted as belonging to the Foel Grach Basalt Formation and indicate contemporaneity of the two formations (Howells *et al*., 1991).

The Foel Grach Basalt Formation generally overlies the Braich tu du tuffs along strike; interdigitation of the two formations shows them to be essentially contemporaneous. At Braich tu du up to 180 m of basalt lavas and tuffs are exposed, interbedded with marine sandstones and siltstones, but the formation wedges out rapidly to the south. The basalt flows are plagioclase-phyric, amygdaloidal and tend to have massive columnar-jointed cores with blocky brecciated carapaces. Primary flow alignment of phenocrysts and feldspar microlites is evident in



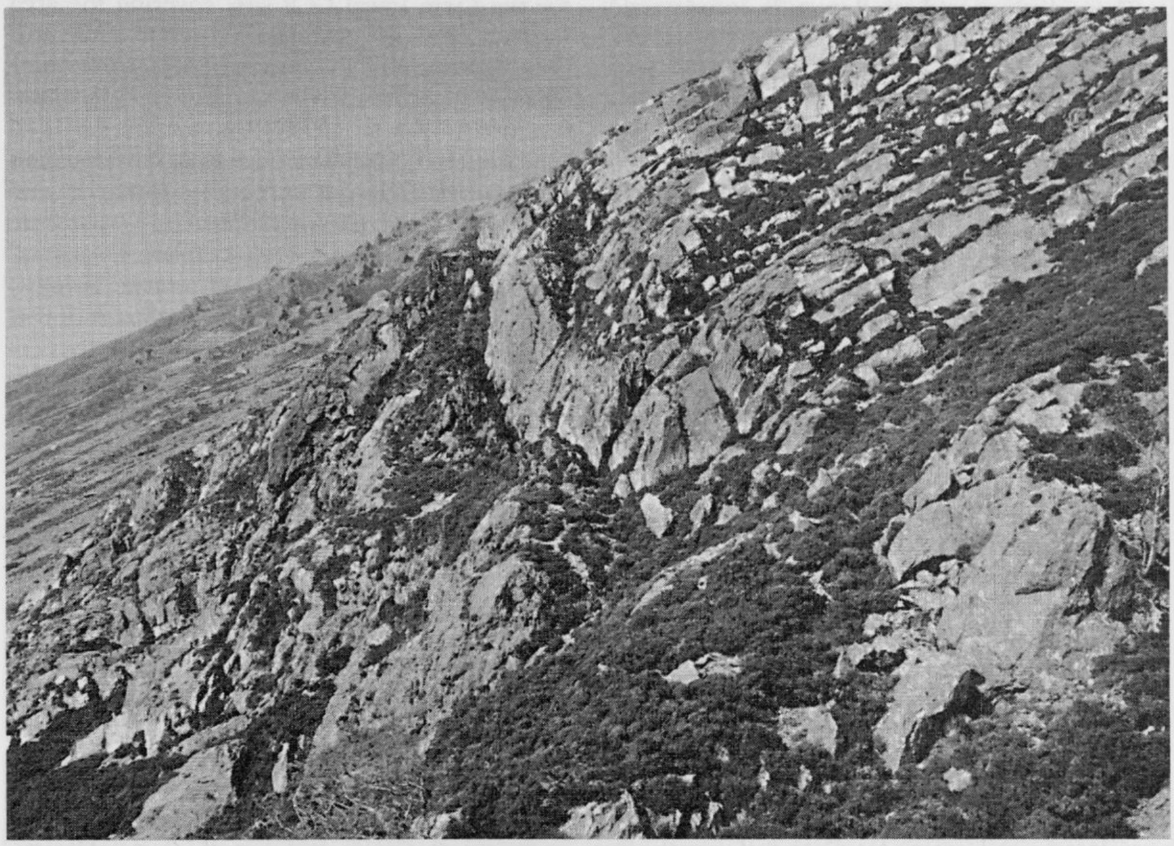


Figure 6.31 The lower rhyolite (R) and ash-flow tuff (T) members of the Braich tu du Volcanic Formation separated by a thin sequence of marine siltstone, sandstone and basic tuffaceous sedimentary rocks (S) on the NE slopes of Nant Ffrancon (SH 648 621). The columnar joints in the welded tuff (T) are perpendicular to its base, which dips steeply to the right. Reproduced from Howells *et al*. (1991).

thin section. The rocks are metamorphosed to lower greenschist facies grade with plagioclase phenocrysts altered to albite ± carbonate ± epidote ± white mica and hornblende to chlorite ± clinozoisite ± actinolite ± carbonate.

Two thin ash-flow tuffs, interlayered with sandstones and siltstones, comprise the Foel Fras Volcanic Formation at Braich tu du, and represent the outflow facies from the Foel Fras Volcanic Complex (Howells *et al.*, 1991). The tuffs, of trachyandesite composition, are bedded and non-welded, with extensive reworking of the upper contacts. They comprise fragmentary feldspar crystals and lithic clasts in a matrix of albite + quartz + sericite + calcite + anatase. Relict shards replaced by chlorite and cryptocrystalline silica are common. The lithic clasts are mainly of trachyte lava and microdiorite with variable amounts of sandstone and silty mudstone. A thick dolerite sill separates the formation from the overlying Capel Curig Volcanic Formation.

Three distinct acid ash-flow tuffs, interlayered with sedimentary rocks and belonging to the Capel Curig Volcanic Formation, are well exposed between Bwlch yr Ole Wen (6530 6206) and Clogwyn Llys (6500 6140). These tuffs, originally mapped as two separate units (the 1st and 4th members) by Howells and Leveridge (1980), are now considered to be entirely within the 4th member (Howells *et al.*, 1991). In marked contrast to the primary character of the Capel Curig tuffs in the Capel Curig and Llyn Dulyn districts (see the Capel Curig and Llyn Dulyn GCR site reports), the tuffs here show no primary characteristics and are composed entirely of slumped tuff, block-and-ash tuffs, debris-flow deposits, accretionary lapilli-tuffs and thin primary ash-flow tuffs. The lowermost unit is dominated by well-bedded, thin tuffaceous sedimentary rock and is underlain by up to 20 m of coarse sandstone, which wedges out along strike against a thick dolerite sill. Within the sequence, interlayered sandstones and siltstones contain a sparse shelly fauna dominated by the brachiopod *Dinorthis*.

Cessation of volcanic activity at the end of the 1st Eruptive Cycle saw a period of shallow to offshore marine sedimentation of the Cwm Eigiau Formation. Above the prominent ridge and summit area around Penyrole-wen (6534 6148), these strata are composed of well-bedded medium-grained fossiliferous sandstones with thin interlayers of siltstone and mudstone. These sedimentary rocks are described more fully in the Cwm Idwal GCR site account.

The 2nd Eruptive Cycle commenced with eruptive activity from the Llwyd Mawr Centre, with emplacement of acid ash-flow tuffs of the Pitts Head Tuff Formation. Along the lower slopes, north of Pont Pen-y-benglog, the northernmost expression of the Pitts Head Tuff Formation is exposed in the core of the Idwal Syncline. In contrast to the sections on Moel Hebog (see the Moel Hebog to Moel yr Ogof GCR site report) and Craig y Garn (see site report), the tuffs here are underlain and overlain by marine sedimentary rocks and deposition clearly took place in a submarine environment. The lower tuff, 30–40 m thick, has a thin non-welded base that grades up into white-weathering eutaxitically welded tuff with dark chloritic fiamme. Irregular zones of siliceous nodules are scattered throughout. More detailed descriptions of the formation and its confining sedimentary strata are provided in the description for the Cwm Idwal GCR site, covering the area located immediately to the south.

Interpretation

The Braich tu du Volcanic Formation has been interpreted as representing the outflow facies from small-scale caldera-like structures that were active prior to the main 1st Eruptive Cycle centres in northern Snowdonia. The laterally restricted, but locally thick, accummulations of the Braich tu du tuffs south of their eruptive centre at Foel Fras, and their interdigitation with the Foel Grach Basalt Formation are interpreted by Howells *et al.* (1991) to reflect topographically controlled deposition within a series of small fault-controlled troughs. Within the troughs, subsidence kept pace with accumulation of the volcanic deposits and basalt effusion was controlled by fissures located along the trough margins.

The overlying Capel Curig tuffs were emplaced and reworked in a submarine environment. The tuffs contain accretionary lapilli indicating that they are the products of subaerial eruptions probably from a centre located to the south (Howells *et al.*, 1991).

The sedimentary rocks above and below the Pitts Head tuff have been studied in detail by Orton (1988). Sedimentary features and bedform analysis suggest that the underlying sedimentary rocks reflect a shallow shelf environment with shelf–ridge sands and interbar silts and muds, with the thicker, coarser sand bodies marking interbar storm events. Above the tuffs there is a fining-up sandstone-dominated sequence with trough cross-bedding, parallel lamination and winnowed fossiliferous beds, which is interpreted as accumulating in a transgressive non-barred wave-influenced shoreline (Reedman *et al.*, 1987). The contained shelly faunas, dominated by *Dinorthis–Macrocoelia* communities, suggest water depths of less than 25 m (Pickerill and Brenchley, 1979). Thus, the Pitts Head tuffs were probably emplaced within a marine mid- to outer storm-dominated shelf environment. The tuffs clearly retained sufficient heat to weld upon emplacement and the streaming off of volatiles from the base of the tuffs facilitated the formation of irregular gas cavities and ductile deformation within the main body of the tuffs.

Conclusions

The GCR site at Braich tu du preserves an impressive section through a wide time-span of volcanic activity and sedimentation within the evolving Snowdon Graben. It contains representatives of most of the 1st Eruptive Cycle and the first major ash-flow tuff-forming eruptions related to the 2nd Eruptive Cycle. It is the type locality for the Braich tu du Volcanic Formation with excellent exposed examples of welded acid ash-flow tuffs.

LLYN DULYN (SH 703 661)

M. Smith

Introduction

The Llyn Dulyn GCR site lies within the main outcrop of volcanic strata of Caradoc (Soudleyan) age which forms a narrow strip trending NE–SW across northern Snowdonia. Originally mapped and described by the Geological Survey (Ramsay, 1881), the area was remapped by the Geological Survey in 1968–71 and is described in Howells *et al.* (1981). The site (Figure 6.32) provides excellent exposures of a part of the 1st Eruptive Cycle of early Caradoc volcanic activity and preserves the critical contact relationships between the ash-flow tuffs and their confining sedimentary rocks.

Three acid ash-flow tuffs, belonging to the Capel Curig Volcanic Formation, are distinguished and represent the emanations from a series of subaerial volcanic centres in North Wales (Howells *et al.*, 1991). These tuffs are in part correlatives to the three members described at the Capel Curig GCR site but with some important differences; the tuffs here have unwelded bases, contain no interlayered sediments and show no evidence for magma–water interaction. These features, in conjunction with the character of the adjacent sedimentary strata, indicate a subaerial emplacement of hot pyroclastic flow deposits and provide an important contrast with the subaqueous environment at Capel Curig. Recognition of these contrasting environments by Francis and Howells (1973) and Howells *et al.* (1973) led to a radical reinterpretation of Lower Palaeozoic palaeoenvironments in North Wales.

Description

The crags forming the south-western backwall to Llyn Dulyn (Figure 6.33) (between 7002 6632 and 7030 6631), expose a near-complete dip section through the Capel Curig Volcanic Formation and into the overlying sedimentary rocks of the Cwm Eigiau Formation. Three of the four members of the formation are present, in upward succession informally termed the 1st, 2nd, and 3rd members. They have a cumulative thickness of up to 180 m and characteristically comprise well-bedded, pale-grey, blocky and jointed fine-grained tuffs.

The lowest (1st) member, exposed in the western half of the site, is equivalent to the Garth Tuff farther south. It comprises a single cooling unit, 18 m thick, of a primary welded ash-flow tuff. The basal non-welded zone has an even, planar base with scattered tabular feldspar crystals, often pseudomorphed by sericite, and passes up into a welded central part with a eutaxitic foliation accentuated by concordant segregations of secondary quartz. The topmost 5 m is composed predominantly of non-welded shards and a well-defined zone of thin-walled siliceous nodules.

The 2nd or middle member, correlated with the Racks Tuff at Capel Curig, has a basal zone marked by a non-welded lithic crystal tuff and is overlain by strongly welded ash-flow tuff for 87 m. This thick unit comprises two separate cooling units. The lower tuff, 34 m thick, is rich

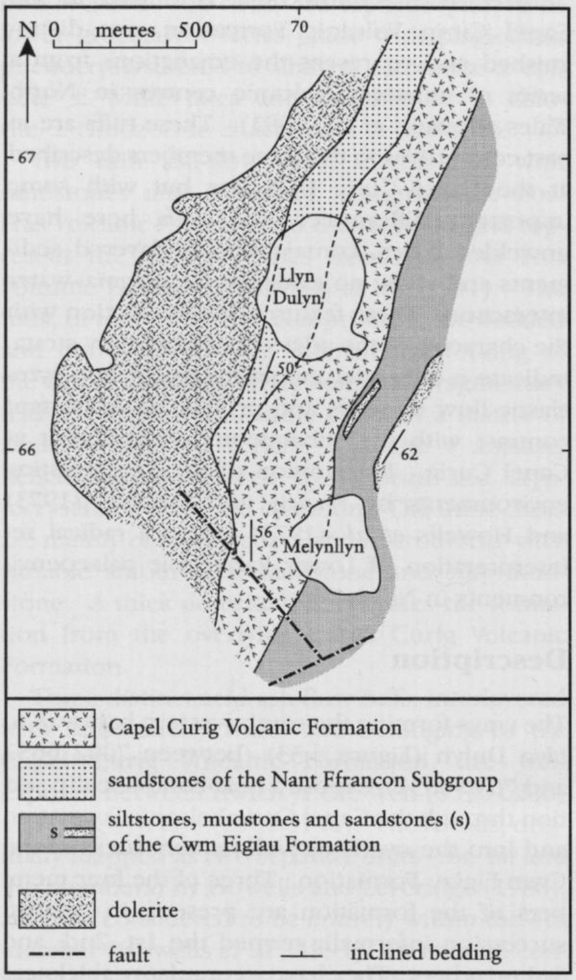


Figure 6.32 Map of Llyn Dulyn, after BGS 1:25 000 sheets 65/66 (1985) and 76 (1981).

in lithic clasts including mudstone, welded tuff, altered acidic and basic intrusive rock and feldspar crystals. In thin section, the crystals are of albite–oligoclase with rounded and resorbed textures and commonly are altered to sericite and carbonate. Delicate shards are scattered throughout, set in a matrix of sericite aggregates. The prominent eutaxitic foliation is defined by aligned, dark-green chloritic fiamme with ragged terminations consisting of chlorite flakes and sericite, which are interpreted as recrystallized pumice. Above 34 m from the base of the unit, feldspar crystals are notably less common and lithic clasts are absent. At 72 m, within the upper cooling unit, siliceous recrystallization along the foliation is distinctive and tends to obscure the eutaxitic foliation. The top part is characterized by a prominent bedding plane that can be traced throughout the immediate area.

The 3rd member, which has no representative in the Capel Curig area, comprises up to 75 m of thinly banded welded tuff with distinctive layers of collapsed pumice and evidence of upward grading. Originally interpreted as a single unit by Howells *et al.* (1981), the fine-grained banding is interpreted here to represent a sequence of thin welded primary ash-flow tuffs. With thicknesses up to 4 m, the tuffs contain pumice-rich layers and locally graded concentrations of feldspar crystals towards the top. They are recrystallized with a platy quartzo-feldspathic mosaic obscuring the original shardic fabric. In the upper parts of the member, feldspar crystals up to 3.5 mm in diameter are common along

Figure 6.33 Moderately dipping welded ash-flow tuffs of the Capel Curig Volcanic Formation, SW side of Llyn Dulyn. (Photo: BGS no L1501.)

with segregations of quartz, sericite and chlorite. The uppermost beds are very fine grained with a pronounced penetrative cleavage.

The underlying sedimentary strata exposed in the extreme western part of the site comprise a heterolithic sequence of sandstones, conglomerates and siltstones which form part of the Nant Ffrancon Subgroup. The lower beds are coarse-grained sandstones and conglomerates in units up to 8 m thick and grading up into 2 m-thick cross-bedded sandstones. These coarse-grained beds are interlayered with thinner beds and lenses of laminated tuffaceous siltstone, which may also occur as irregularly orientated blocks. The upper beds are characterized by medium-grained graded sandstones and laminated tuffaceous siltstones. The sandstones are tabular and cross-laminated with symmetrical ripple marks.

The sedimentary rocks overlying the welded tuffs represent the local basal strata of the Cwm Eigiau Formation in the area. They crop out across the rounded shoulder SE of Llyn Dulyn and extend southwards to Melynllyn (Figure 6.32). Up to 12 m of grey siltstone are present immediately above the tuffs, passing upwards into fine-grained, cross-bedded sandstones.

Interpretation

Analysis of the regional thickness, lithological and textural variations, and volcanic features within the tuffs and adjacent sedimentary rocks of the Capel Curig Volcanic Formation were used by Howells and Leveridge (1980) and Howells *et al.* (1991) to identify the likely source areas for the individual eruptive events and the environments of deposition (Figure 6.34). The individual members of the Capel Curig Formation exposed at the Llyn Dulyn site are interpreted as massive acid ash-flows erupted from subaerial vents to the north (1st and 2nd members) and west (3rd member), travelling southwards and eastwards down the volcano flanks and onto a broad plain. The exceptional thin development (only 20 m) of the 1st member is interpreted by Howells and Leveridge (1980) to represent emplacement on a locally developed topographical high within this plain.

Features within the tuffs, including the presence of non-welded bases, normally graded lithic clasts and crystals, and the intense siliceous segregation accentuating the eutaxitic foliation, are all indicative of subaerial ash-flow emplacement. When combined with the sedimentary features in the underlying Nant Ffrancon Subgroup strata, which indicate shallow, lacustrine conditions succeeded by high-energy alluvial braided streams, they provide persuasive evidence for emplacement in a subaerial environment. This interpretation contrasts markedly with that of Capel Curig GCR site where the tuffs have extended into a shallow-marine environment (Figure 6.34).

Conclusions

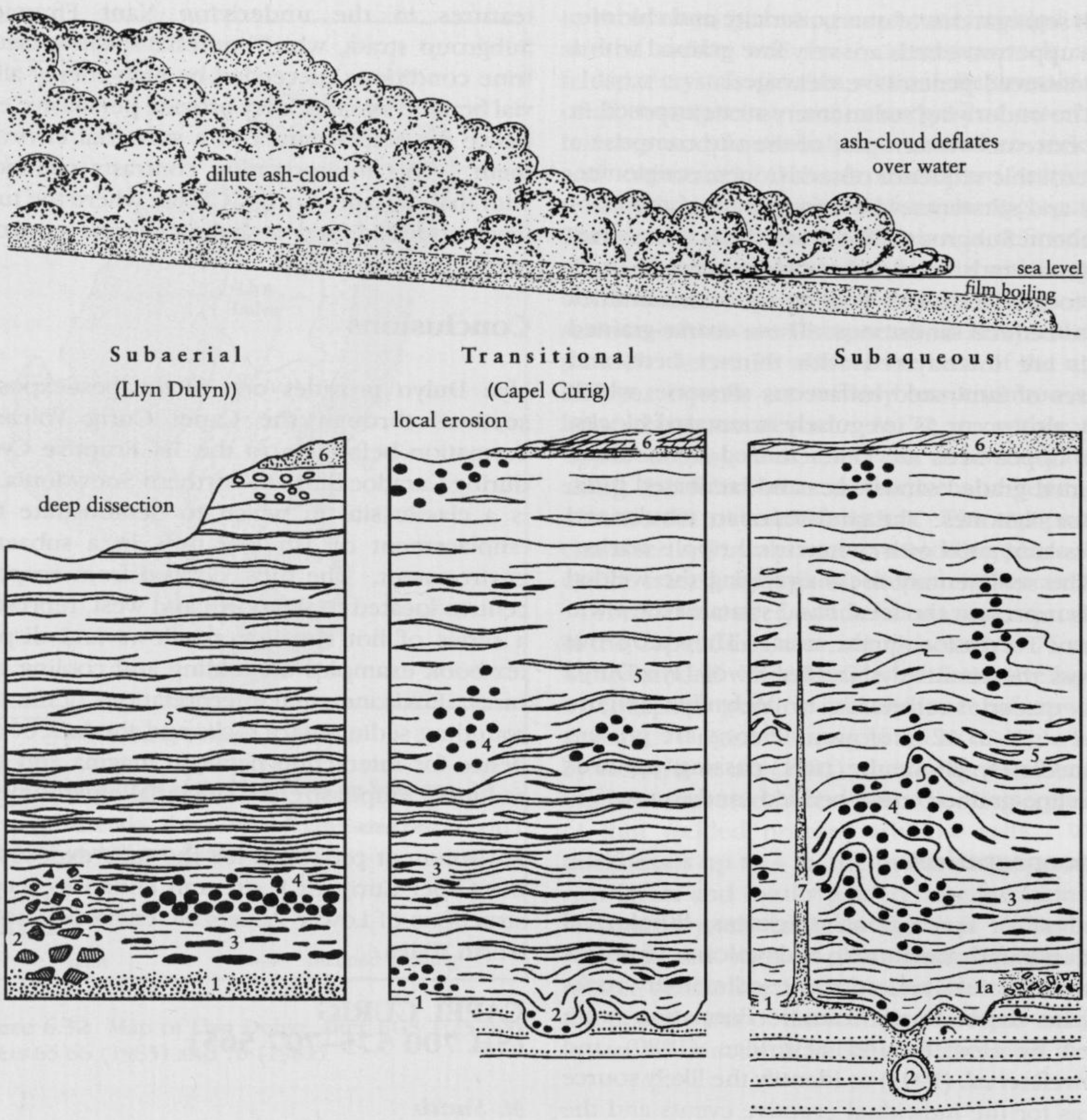
Llyn Dulyn provides one of the best-exposed sections through the Capel Curig Volcanic Formation belonging to the 1st Eruptive Cycle during Caradoc times in northern Snowdonia. It is a classic site in which to demonstrate the emplacement of ash-flow tuffs in a subaerial environment. The tuffs, derived from eruptive centres located to the north and west, represent a series of hot rhyolitic ash-flows and display textbook examples of welding and cooling textures. Environmental interpretations of the surrounding sedimentary rocks and the lack of evidence for interaction between magma and wet sediment emphasize the subaerial environment. This contrasts markedly with the submarine environment proposed for the tuffs exposed at the Capel Curig GCR site and enhances reconstructions of Lower Palaeozoic environments in North Wales.

CAPEL CURIG (SH 700 575–707 565)

M. Smith

Introduction

During Caradoc (Soudleyan) times, volcanicity in North Wales was characterized by a series of climactic acid ash-flow eruptions sourced from a number of subaerial volcanic centres in northern Snowdonia. These represent part of the 1st Eruptive Cycle of Howells *et al.* (1991). These ash-flow deposits, and their bounding sedimentary strata, provide important evidence for palaeoenvironment reconstructions and record a transgression from a subaerial environment across a shoreline into a subaqueous environment. Within this framework the exposures west of Capel Curig village are of international importance, as it was here that welded submarine ash-flow tuffs were first identified in ancient



1 Non-welded base	1 Welded to base	1 Welded to base 1a Crystal-rich, weakly welded basal zone (distal) incorporating sediment and shells
2 Normally graded lithic clasts	2 Irregular base	2 Detached pod of welded tuff
3 Fiamme near base	3 Fiamme developed where little or no silicification	3 Fiamme common
4 Siliceous nodules in zone parallel to base	4 Irregular clusters of siliceous nodules	4 Abundant swarms of siliceous nodules often associated with contorted welded foliation
5 Intense siliceous segregation accentuating the welding foliation	5 Siliceous segregation along the welding foliation	5 Siliceous segregation along the welding foliation poorly developed
6 Fine fall-out ash only locally preserved	6 Fine water-settled ash reworked at transgressive shoreface	6 Fine water-settled ash reworked above wave base
		7 Flame of fluidised sediment penetrating cooling joint

Figure 6.34 Model of ash-flow emplacement, and of contact and internal facies relations of welded ash-flow tuffs with respect to environment of deposition (after Howells *et al*., 1991).

rocks by Francis and Howells (1973) and Howells *et al.* (1973). The sections also provide classic examples of magma–sediment interaction and are pertinent to the continuing debate on subaqueous welding of ash-flow tuffs (see for example Cas and Wright, 1987, 1991; McPhie *et al.*, 1993).

The GCR site includes volcanic rocks and interlayered marine sedimentary rocks that form the type area for the Capel Curig Volcanic Formation. They lie within the core of the Capel Curig Anticline and are well exposed in the craggy ground to the NW and SE of Llynnau Mymbyr. Originally mapped and described by Ramsay (1881), the type area was remapped by Williams (1922) who interpreted most of the volcanic rocks as rhyolite lavas emplaced in a marine environment. Recognition by Oliver (1954) and Rast *et al.* (1958) that many of the 'rhyolite lavas' of North Wales are in fact welded tuff or ignimbrite radically changed views of the Caradoc palaeoenvironments. The latter authors considered that all of the ignimbrites were erupted and emplaced subaerially. Subsequent detailed mapping by Francis and Howells (1973) in the Capel Curig area convincingly demonstrated that some of the tuffs were emplaced in a submarine environment, work which provided a stimulus for further investigation and led to more realistic assessments of the palaeogeography (Howells *et al.*, 1979; Howells and Leveridge, 1980; Orton, 1988; Howells *et al.*, 1991). This site is complemented by the Llyn Dulyn GCR site, which demonstrates the lateral equivalents of these ash-flow tuffs emplaced in a subaerial environment (Figure 6.35).

Of the four volcanic members distinguished within the Capel Curig Volcanic Formation, three are present at the Capel Curig GCR site and in upward succession are the Garth Tuff, the Racks Tuff and the Dyffryn Mymbyr Tuff. Geochemical investigations indicate that the tuffs are rhyolitic to rhyodacitic in composition and are spatially and geochemically related to a series of subvolcanic intrusions (Howells *et al.*, 1991). The members may be distinguished by their trace element compositions and can be related by fractional crystallization, with the oldest (the Garth Tuff) being the least evolved.

Description

The Garth Tuff, forming the lower crags north of Llynnau Mymbyr (Figure 6.36), is a massive, cream to white, well-jointed unit, generally 10 m thick but increasing up to 40 m in the western part of the Capel Curig Anticline. It is massive and welded in the lower and middle parts, grading up through a zone with faint bedding planes into a reworked upper part, up to 20 m thick, with current bedding and ripples. A prominent eutaxitic foliation is always parallel to the regional dip except at the margins to the tuff. The top is concordant with the overlying sandstones. Lithic clasts, including devitrified perlitic glass and welded tuff, recrystallized shards, siliceous nodules, and isolated and fragmented albite phenocrysts are scattered throughout the unit. The fine-grained matrix is composed of sericite, chlorite, quartz and feldspar. On the south-eastern limb of the anticline, sections exposed above the A4086 road and in forestry cuttings (e.g. 7137 5732), show that the bedded top also contains accretionary lapilli. Here, the base is remarkably discordant, with flames of the underlying sediment penetrating deeply into the tuff. Tuff–sediment contacts at 90° to the regional bedding are not uncommon. The adjacent sedimentary strata are often highly disturbed and are interpreted as reconstituted bedded sandstones. Numerous small tuff apophyses penetrate the sediment and comprise admixtures of tuff and sediment, (e.g. at 7091 5665). Locally, these may be detached and resemble tuff-pipes at outcrop. Large detached bodies of tuff, up to 100 m × 250 m in plan, and surrounded by the underlying sandstones, are sporadically preserved. These bodies of tuff are lithologically identical to the main tuff.

The overlying strata, between the Garth and Racks tuffs, form part of the Cwm Eigiau Formation and comprise fine-grained pale-green sandstones with thin, impersistent, often disrupted, grey, cleaved mudstones and siltstones in the upper part. Poorly preserved fossiliferous bands are present in crags at 7095 5789 and a disused quarry at 7094 5784. Shelly forms dominate, and include *Dalmanella* sp., *Dinorthis* cf. *berwynensis*, *Howellites* sp. and *Macrocoelia* sp. (Howells *et al.*, 1978).

The Racks Tuff, lithologically comparable to the Garth Tuff, is well exposed on the south-eastern limb of the anticline, where it forms a well-bedded and non-welded unit up to 30 m thick. In contrast, on the northern crags (around 706 579) the tuff is thinner, massive and welded throughout with patches of siliceous nodules. The outcrop is discontinuous and podiform, with the tuff locally wedged out. The lower contact is highly irregular with large flames of mudstone transgressing the upper and lower tuff contacts (e.g. 704 578). The adjacent mudstones and sandstones are highly contorted and are penetrated by thin apophyses of tuff.

The Dyffryn Mymbyr Tuff is only present on the north-western limb of the anticline and thins markedly to the NE, grading from a coarse-grained lithic tuff containing accretionary lapilli to a tuffaceous mudstone.

Supplementary sites in the Lledr Valley (at 7656 5436 and at Rolwyd (765 512) to the SW of Capel Curig) provide additional evidence for the emplacement of isolated pods of tuff within unconsolidated marine sediments (Francis and Howells, 1973). A possible mechanism for the formation of these pods is described in Howells *et al.* (1991, fig. 27).

Interpretation

The presence of eutaxitic welding fabrics and relict shardic textures within the tuffs of the Capel Curig Formation, exposed on the flanks of the Capel Curig Anticline, are indicative of their formation as hot pyroclastic flow deposits. Regional lithological and geochemical studies show that these tuffs (the Garth and Racks tuffs) were erupted from subaerial centres in northern Snowdonia during Caradoc times and transported southwards. Changes in emplacement and cooling textures within the tuffs, combined with complex sediment–tuff relationships and studies of the adjacent sediment, indicate that the environment of deposition changed from subaerial

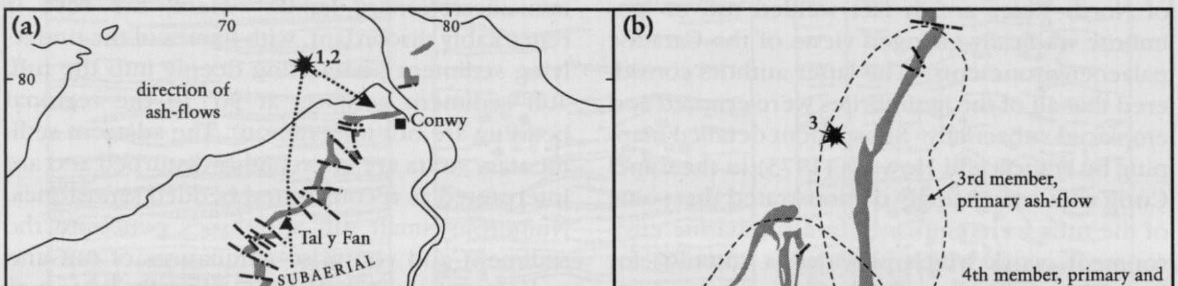


Figure 6.35 (a) Interpretation of the depositional environments of the 1st and 2nd members of the Capel Curig Volcanic Formation, showing flow directions and the distribution of isolated pods of the 1st Member. (b), (c) Distribution of the 3rd and 4th members of the Capel Curig Volcanic Formation. After Howells and Leveridge (1980).

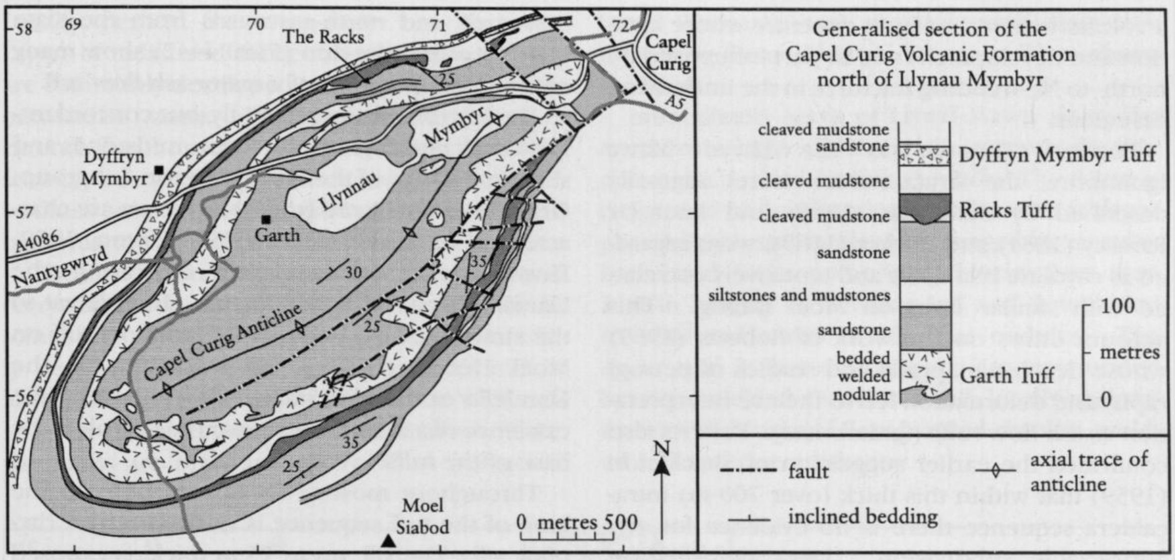


Figure 6.36 Map and vertical section of the Capel Curig Volcanic Formation in the Capel Curig Anticline (after Francis and Howells, 1973).

to submarine (Howells and Leveridge, 1980; Howells *et al.*, 1991). The outcrops around Capel Curig represent one of the key areas in this reconstruction, marking the shallow-water transition zone between a shoreline located just north of Capel Curig, and deeper basinal conditions farther south. This interpretation, supported by the sedimentary features and shelly faunas of the enclosing sediment and evidence for reworking of the upper parts of individual tuffs, contrasts markedly with the subaerial conditions at the Llyn Dulyn GCR site.

As the tuffs transgressed the shoreline into the submarine environment, the hot, gaseous and dense ash-flows interacted with the semi-lithified and water-saturated sediments on the sea bed. The remarkable irregularities of the lower tuff contacts may be attributed to the disturbance of the underlying wet unlithified sediments by the rapid emplacement of hot ash-flows on an uneven surface or to seismic shocks attendant on eruption (Francis and Howells, 1973). Either mechanism would induce the sediments to deform thixotropically and the ash-flows to collapse downwards by unequal loading to form irregular lobes and pipe-like masses, which in extreme cases may have become completely detached. Fluidization and magma–water interaction at the tuff–sediment contact probably facilitated these processes. Although still a matter of debate (see Howells *et al.*, 1991, pp. 163–5) water depths are generally assumed to be less than the thickness of the pyroclastic flow deposits (McPhie *et al.*, 1993).

Conclusions

The Capel Curig GCR site provides classic exposures exemplifying the delivery of subaerial pyroclastic flow deposits into a shallow-marine environment. As one of the first documented examples of this process in an ancient environment, the site is of historical as well as international scientific interest. The presence of a strong foliation within the tuffs and the interaction with the underlying fossiliferous marine sediments have been central to the arguments that the ash-flows crossed the shoreline hot and intact and continued across the sea bed, retaining sufficient heat to become welded when they stopped moving.

CRAIG Y GARN (SH 510 440–504 466)

M. Smith

Introduction

The Craig y Garn GCR site represents an important dip section through one of the main eruptive centres of the 2nd Eruptive Cycle of Caradoc volcanic activity in Snowdonia. It lies within the eastern half of an elongate synformal outlier of the main outcrop of the Snowdon Volcanic Group. This outlier is interpreted as the site of a volcanotectonic collapse structure whose location and development was in part influenced by north- to NE-trending fractures in the underlying basement.

Formerly known as the Llwyd Mawr Ignimbrite, the strata, which were originally described by Sedgwick (1843) and later by Ramsay (1881) and Harker (1889), were regarded as rhyolitic lava flows and tentatively correlated with similar lavas on Moel Hebog. This account draws on the work of Roberts (1969) whose detailed mapping and studies of petrography and deformation led to their re-interpretation as ash-flow tuffs (ignimbrites). Roberts also confirmed the earlier suggestion of Shackleton (1959) that within this thick (over 700 m) intra-caldera sequence there is no evidence for any appreciable subdivision. Later deformation studies by Roberts and Siddans (1971) used variations in the compactional strain, as seen in lithic clasts and pumice, to identify two separate eruptive pulses. However, a more recent geochemical study by Howells *et al.* (1991) shows little evidence for trace element compositional variation throughout the sequence and reconfirms the original suggestion that Llwyd Mawr represents one of the thickest accumulations of welded ash-flow tuffs related to an individual volcanic centre in Britain.

The Craig y Garn site includes the basal contact of the tuff sequence with marine mudstones of Llanvirn age. Elsewhere the tuff sequence is overlain by Longvillian age strata and thus an upper Soudleyan to Longvillian age is likely. In the northern half of the site intrusive rhyolite domes and a possible vent breccia may represent resurgent activity within the caldera. Lithological and geochemical studies (Howells *et al.*, 1991) include the Craig y Garn rocks within the Pitts Head Tuff Formation and confirm a correlation with the outflow facies on Moel Hebog (Reedman *et al.*, 1987), as described in the Moel Hebog to Moel yr Ogof GCR site report.

The site is partly included in the 1:50 000 scale Geological Sheet 119 (Snowdon) (1997) but has not been resurveyed in detail.

Description

The site encompasses some 3 km² along the western side of Cwm Pennant and includes the minor hills of Craig y Garn and Llywd Mawr (Figure 6.37). Scattered exposures extending eastwards and north-eastwards from the slate quarries at Hendre-ddu (5180 4442) show many of the features typical of a major ash-flow tuff.

The lower beds rest abruptly, but concordantly on dark bluish-grey micaceous mudstones and silty mudstones of the Nant Ffrancon Subgroup. Graptolites recovered from these strata are characterized by *D. murchisoni* (Shackleton, 1959; Howells and Smith, 1997) indicating the Llanvirn *D. murchisoni* Biozone. In contrast to the strata exposed beneath the ash-flow tuff on Moel Hebog there is no evidence for the Llandeilo or Caradoc stages, thus indicating the existence of a major volcanotectonic break at the base of the tuffs.

Throughout most of its eastern outcrop the base of the tuff sequence is underlain by a rhyolitic sill. The sill, up to 75 m thick, is exposed around the eastern flanks of Craig y Garn and comprises flow-banded and flow-folded rhyolite, locally autobrecciated and spherulitic at its lower contact. Contact metamorphism and alteration related to the intrusion of the sill has baked the overlying tuffs and protected them from cleavage development.

The sequence up through the tuff pile as exposed on Craig y Garn commences with a compact, silicified, blue-grey non-welded crystal-lithic-vitric tuff up to 3 m thick. The tuff contains a variety of clast types including rounded to weakly flattened pumice clasts, up to 10 cm in diameter, mudstone clasts, up 8 mm in length, and rare angular rhyolitic clasts, less than 2.5 cm, set in a devitrified matrix of glass shards, chloritized feldspar (mainly plagioclase and rarer anorthoclase), quartz crystals and dust. The mudstone clasts are common only in the basal 30 cm. The shards are typically well preserved and in thin section show Y-shaped or four-sided morphologies.

At about 4–5 m above the base the glass shards show increasing distortion and incipient welding, and a planar eutaxitic foliation is developed, although much of the foliation is obscured by spherulitic recrystallization. Quartz phenocrysts are rare above this level. The foliation dips consistently westwards and is concordant throughout. Above 10 m, spherulitic recrystallization reduces in intensity and welded textures are again evident. Shard distortion and collapse and flattening of pumice clasts and lapilli thereafter increases logarithmically upwards and at around 17 m above the base a strong parataxitic foliation defined by flattened shards is present.

Locally perlitic fracturing may be observed. Layers of radial and concentric siliceous nodules are commonly developed immediately below the parataxitic zone. The parataxitic foliation extends for the next 45 m. At 62 m, the tuff is strongly recrystallized; shards are flattened and outlines are completely destroyed. The textures continue to the top of the section.

The changes in the degree of deformation and recrystallization are matched by variations in joint style. Above the base, the joints are crudely perpendicular to the lower contact, and at about 18 m become crudely columnar with rectangular cross sections. At 18 m to about 58 m, the joints are platy and above 58 m polygonal forms dominate, with cross-sectional diameters increasing from 12 cm to 50 cm at 75 m above the base.

Immediately north of Llywd Mawr, along the northern margin of the site, an intrusive rhyolite dome can be seen cutting the tuffs. The dome is composed of flow-banded rhyolite with feldspar phenocrysts, and in places is fringed by an autobrecciated facies comprising blocks (less than 2 m in length) of flow-banded and flow-folded rhyolite and zones of siliceous nodules. The dome and its breccia carapace are surrounded by a non-welded vitroclastic tuff, locally agglomeratic with blocks of flow-banded rhyolite, welded tuff and rare mudstone.

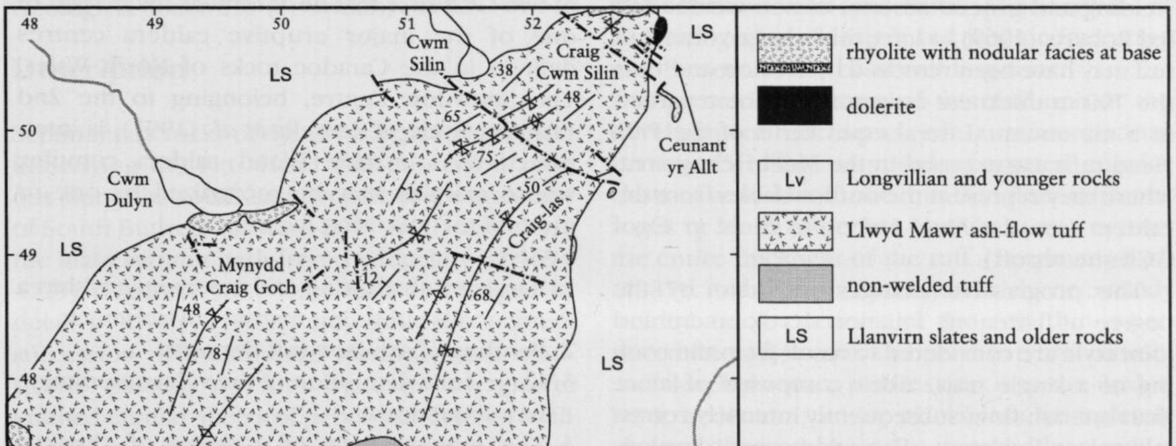


Figure 6.37 Map of the Llwyd Mawr Centre (after Roberts, 1969).

Interpretation

The textural and lithological characteristics of the Pitts Head Tuff Formation on Craig y Garn and the general absence of interaction with the enveloping marine sediments indicate that this impressive thick sequence of rhyolitic tuff was emplaced subaerially, probably within a subsiding volcanotectonic depression or caldera. A volcanotectonic break, of unknown magnitude, is indicated by the absence of Caradoc strata in the east and compares with a full sequence on the eastern side of Cwm Pennant at Moel Hebog. This implies uplift and erosion in the vicinity of the caldera prior to collapse (Howells *et al*., 1991). The lack of a decrease in the intensity of welding and general absence of non-welded tuff led Roberts (1969) to infer that a large volume of tuff may have been removed by erosion and thus the 700 m thickness estimate must be regarded as a minimum. Lateral equivalents of the Pitts Head tuffs are exposed in the Moel Hebog area, where they represent the outflow facies from the caldera (see the Moel Hebog to Moel yr Ogof GCR site report).

The progressive changes recorded by the degree of flattening, foliation development and joint style are considered to result from the cooling of a single unit, albeit composed of more than one ash-flow, subsequently intensely recrystallized and altered. The widespread development of spherulitic recrystallization beneath the main zone of development of a parataxitic fabric probably resulted from the trapping of volatiles exsolving from the basal non-welded tuff.

The latter stages of caldera evolution were marked by the forceful emplacement of rhyolitic domes and sills along the caldera margin and within feeder pipes or vents already choked with an agglomeratic vitric-clastic tuff in the centre of the caldera. Geochemically and petrographically comparable to the tuffs, these domes and sills may represent the late degassed equivalent of the tuff magma.

Conclusions

The Craig y Garn GCR site preserves one of the thickest and most complete sections through a Lower Palaeozoic caldera fill in Britain. In excess of 700 m of welded rhyolitic ash-flow tuff was ponded or entrapped within a major volcanic depression that formed within the Snowdon Graben and marked the initiation of the 2nd Eruptive Cycle across Snowdonia in Caradoc time. The site is important for the preservation of textures typical of welded ash-flow tuffs and for its correlation with tuffs present on Moel Hebog, which are considered to have emanated from the same caldera (see the Moel Hebog to Moel yr Ogof GCR site report).

MOEL HEBOG TO MOEL YR OGOF (SH 568 464–557 483)

M. Smith

Introduction

The Moel Hebog to Moel yr Ogof GCR site is one of two GCR sites that lie at or near the margin of one of the major eruptive caldera centres defined in the Caradoc rocks of North Wales. The Snowdon Centre, belonging to the 2nd Eruptive Cycle of Howells *et al*. (1991), is interpreted as a marine island caldera complex whose margins may be recognized by one or more of the following features:

1. Localized shallowing and emergence within a regionally subsiding marine environment.
2. Ponding of ash-flow tuff deposits.
3. Large-scale disruption of the volcanosedimentary sequences.
4. The emplacement of a series of rhyolitic domes and sills and basaltic magmas.

The complex geology displayed on Moel Hebog and Moel yr Ogof (Figure 6.38) shows many of the above features, including excellently exposed examples of subaerially emplaced acid ash-flow tuffs, primary and reworked intra-caldera tuffs, basic pillow lavas and spectacular large-scale disruption and slumping of blocks off the rim of the caldera.

The exposed strata comprise the Snowdon Volcanic Group which is divided into four formations. Only the three lowest formations are exposed at the Moel Hebog to Moel yr Ogof GCR site; the upper formation is seen at the Snowdon Massif GCR site. The lowest part of the succession crops out on the eastern side of Moel Hebog and includes marine sandstones of the Cwm Eigiau Formation overlain by acid ash-flow tuffs of the Pitts Head Tuff Formation, representing the outflow facies from the adjacent Llywd Mawr Centre (see the Craig y Garn GCR site report). These are in turn overlain by ash-flow tuffs representing the intracaldera facies of the Lower Rhyolitic Tuff Formation. The Bedded Pyroclastic Formation crops out at Moel yr Ogof and is interpreted as the site of an eruptive basic vent subsequently capped and intruded by rhyolite domes and sills.

The site area was originally described by Williams (1927) and Shackleton (1959), both of whom regarded the tuffs as extrusive rhyolites. They were subsequently shown to be welded ash-flow tuffs by Rast *et al.* (1958) and were remapped in detail at the 1:10 000 scale by the British Geological Survey between 1984 and 1985. Detailed descriptions are provided by Reedman *et al.* (1987) and Howells *et al.* (1991) and the site is included on the 1:50 000 scale Geological Sheet 119 (Snowdon) (1997).

Description

Sedimentary rocks of the Cwm Eigiau Formation underlying the Pitts Head Tuff Formation crop out along the south-eastern part of the site, east of South Buttress (around 5695 4671) and along the main summit path from Beddgelert (at 5694 4729) (Figure 6.38). Described and logged in detail by Orton (1988), they comprise a lower succession of interlayered siltstones and mudstones passing up into medium- to coarse-grained tabular sheets of pebbly sandstones with trough cross-bedding. Thin interlayers of white-weathering vitric tuff or tuffaceous sedimentary rock are developed sporadically. Debris flows and rapid variations in grain size characterize the uppermost units although bedding features are generally destroyed within 0.5 m of the overlying tuff.

The 2nd Eruptive Cycle of Caradoc volcanicity in Snowdonia, represented on Moel Hebog by the Pitts Head Tuff Formation, commenced with the eruption of ash-flow tuffs from the Llywd Mawr Centre. The intracaldera facies is described in the Craig y Garn GCR site report and is lithologically identical to the outflow facies on Moel Hebog, which is represented by two distinct layers of ash-flow tuff.

The lower tuff, up to 90 m thick, forms the lower parts of the crags immediately east of the summit of Moel Hebog (Figure 6.39), and is composed of welded and non-welded crystal-rich tuff. The basal contact appears conformable on the underlying sandstones. Locally, a distinctive unit, approximately 1 m thick, of thinly bedded non-welded vitroclastic tuff with polygonal jointing, intervenes between the main tuff and the underlying sandstones. The base of the main tuff unit is non-welded but grades rapidly up into strongly jointed welded tuff with chloritic fiamme and distinctive zones of siliceous nodules (Figure 6.40). These nodular zones are 1–3 m thick and individual nodules up to 40 cm in diameter are not uncommon; microscopically they comprise a quartz mosaic. Planar concordant siliceous segregations accentuate the strong parataxitic fabric in the remainder of the overlying tuff. The top of the tuff is irregular and eroded but locally a fine-grained top is preserved. The tuffs are devitrified and recrystallized and in thin section comprise aggregates of sericite, quartz, feldspar and chlorite. Shards are well defined and euhedral phenocrysts of albite–oligoclase feldspar and perlitic fracturing may be seen in the basal welding zone.

A prominent feature of this tuff unit is the development of areas of autobrecciation. Brecciated tuffs, composed of rotated angular clasts of welded tuff, occur as thin discontinuous zones or along joints but elsewhere may occupy the entire thickness of the tuff. Reedman *et al.* (1987) noted that the crystal-rich or weakly welded basal portions of the tuff thin when traced laterally to areas of pervasive brecciation, and develop lobate protrusions into the underlying sediment or in places are completely absent. These changes are matched by a reduction in the development of siliceous nodules close to the zones of brecciation. Where the breccia occupies the complete tuff it is markedly discordant with the underlying sediment. Locally, the upper parts of the brecciated tuff are disrupted and may occur as detached rafts and fragments within ash-flow tuff deposits of the overlying Lower Rhyolitic Tuff Formation (Figure 6.39). A subsidiary site located *c.* 800 m north of Moel Hebog, around Y Braich (5660 4785), displays more complex relationships between the Pitts Head and Lower Rhyolitic tuffs with large overturned rafts forming a volcanic megabreccia.

The upper tuff, up to 70 m thick, occupies the middle part of the Ladder Buttress (567 467) and differs from the lower flow in the absence of a basal nodular zone. It wedges out to the NE and is not present north of the summit of Moel Hebog. Geochemically, the upper tuff is distinguished by its lower TiO_2 content and enrichment in Nb relative to the lower tuff and the intracaldera tuffs on Llywd Mawr (Howells *et al.*, 1991).

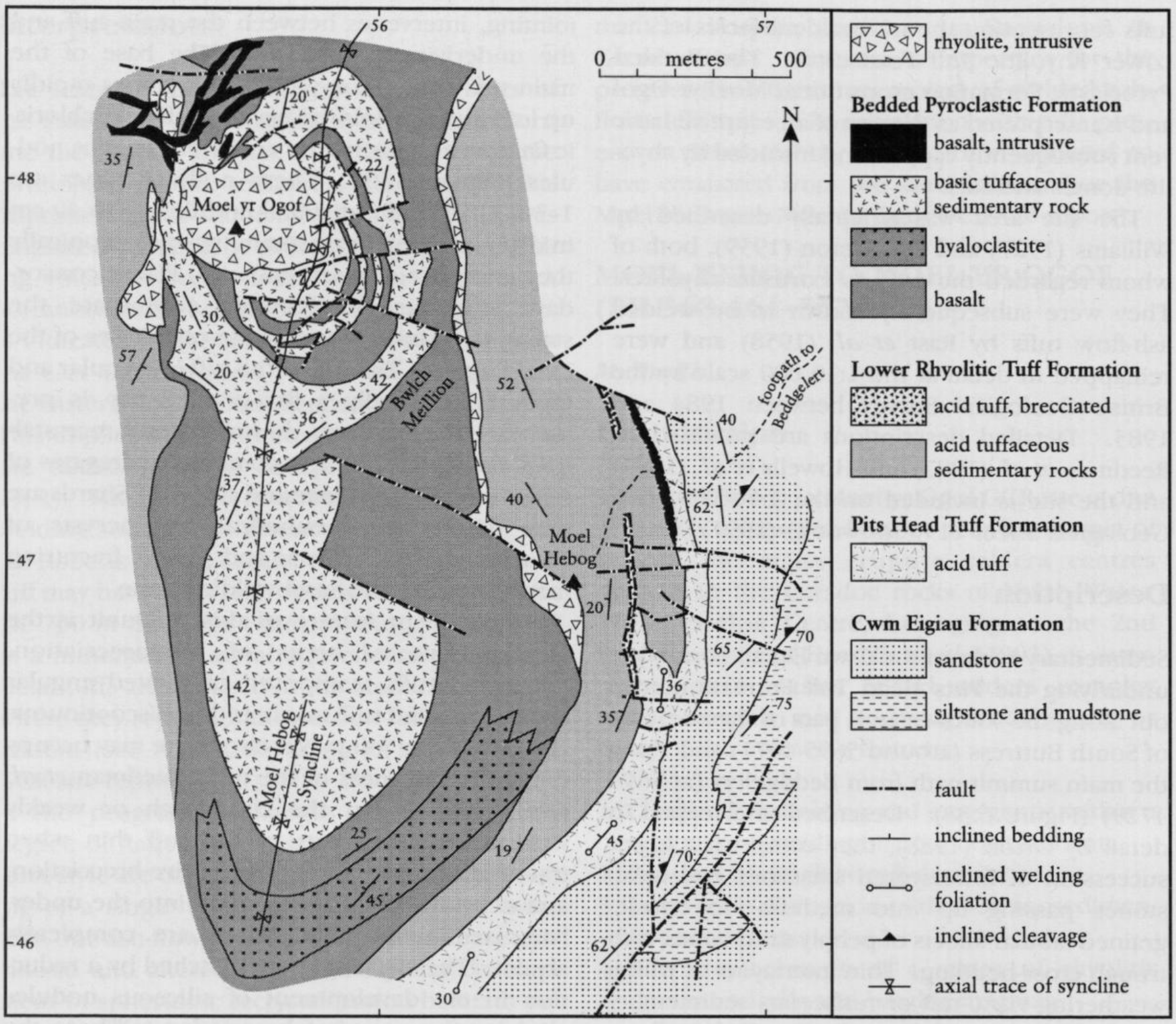


Figure 6.38 Map of the Moel Hebog and Moel yr Ogof area (after BGS 1:10 000 Sheet SH54NE).

The upper parts of the crags immediately east of the summit area are formed of primary and reworked ash-flow tuffs of the Lower Rhyolitic Tuff Formation. These tuffs rest unconformably on the underlying upper or lower units of the Pitts Head tuff. The lower, basal unit comprises up to *c.* 20 m of massive, brown-weathering primary welded lapilli-tuff with a well-developed eutaxitic foliation and is overlain by massive non-welded tuff and reworked tuffaceous sedimentary rocks. The reworked tuffs comprise planar-bedded tuffaceous siltstones and sandstones with 20–50 cm-thick tuff layers and contain numerous zones of hummocky cross-stratification and coarse-grained debris-flow conglomerates (Fritz *et al.*, 1990). The upper tuff is well bedded and displays trough cross-bedding. It is interlayered with tuffaceous sandstones and rare current-rippled vitric tuffs. Locally, the base is marked by a 1 m-thick clast-supported breccia containing pumice blocks and bombs and thin layers of parallel laminated tuff. Loading and irregular basal contacts to individual beds indicate deposition onto a semi-lithified substrate.

The later stages in the evolution of the main caldera phase at the Snowdon Centre were marked by an episode of basaltic volcanic activity. The deposits from this activity, known as the Bedded Pyroclastic Formation (Howells *et al.*, 1983), are widely dispersed across Snowdonia. In the north-western part of the GCR site the formation is superbly exposed in the crags surrounding the southern, eastern and northern flanks of Moel yr Ogof (5583 4767), which are

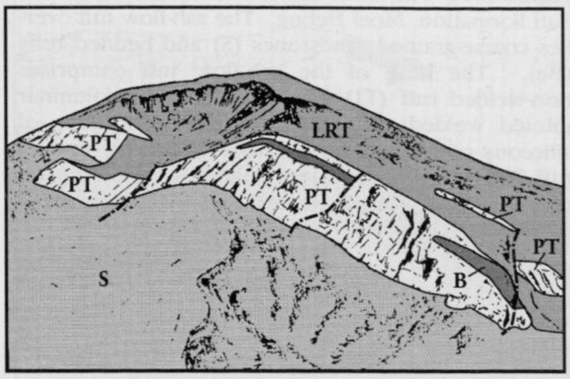
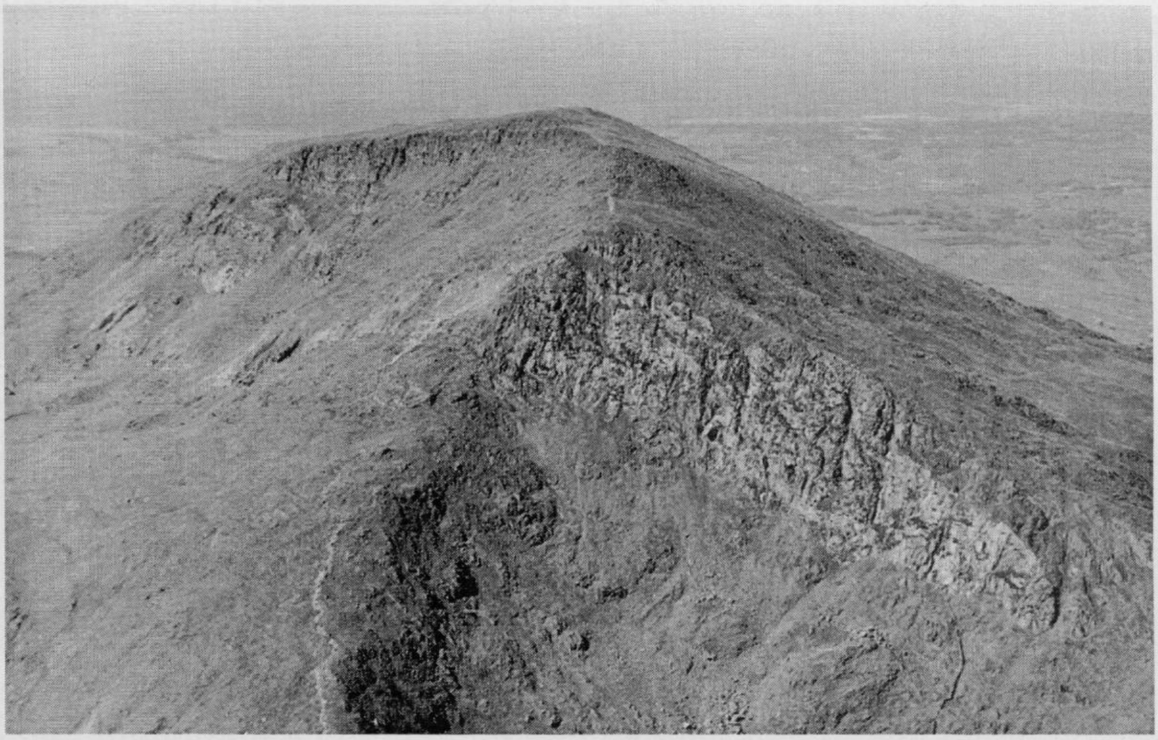


Figure 6.39 Moel Hebog, viewed from the NE, showing primary and reworked tuffs of the Lower Rhyolitic Tuff Formation (LRT) overlying and enclosing disrupted rafts and blocks of the Pitts Head Tuff Formation (PT) near the southern margin of the Lower Rhyolitic Tuff Formation caldera. The Pitts Head Tuff Formation is underlain by sediments (S) and intruded by basalt (B). Reproduced from Howells *et al.* (1991).



located within the core of the Moel Hebog Syncline. Well-featured ground rising up from Bwlch Meillionen (Figure 6.41) shows up to 230 m of extrusive basalts, variably pillowed with associated pillow breccias and hyaloclastites.

The lower beds within Bwlch Meillionen comprise a crudely bedded basaltic breccia with bombs and blocks of basalt, up to 50 cm in diameter, and lapilli in a matrix of basaltic tuff. These are interlayered with basic tuffs and thin rhyolitic vitric tuffs. Above, and to the north, the main crags show blocky basaltic lavas with pillow forms up to 1 m across. The pillowed basalt lavas can be traced laterally into pillow breccia deposits, hyaloclastites and well-bedded basaltic tuffs. With a decreasing frequency of basalt lava flows, the succession grades up into reworked basaltic tuffaceous and volcaniclastic sandstones with two prominent basalt lava flows. The tuffaceous rocks are generally well bedded, 1–10 cm thick with parallel- and cross-lamination. Transgressive basaltic sills and dykes occur within the succession and are particularly numerous to the north of Moel yr Ogof. These sills and dykes can be traced downward into a basalt/dolerite dyke feeder system exposed immediately to the west of the GCR site and

Figure 6.40 The lower outflow tuff of the Pitts Head Tuff Formation, Moel Hebog. The ash-flow tuff overlies coarse-grained sandstones (S) and bedded tuffs (Be). The base of the ash-flow tuff comprises non-welded tuff (T1) and is overlain by columnar jointed welded tuff (T2). A prominent zone of siliceous nodules (N) is overlain by densely welded tuff (T3) with a conspicuous, silicified, welding foliation (SH 5684 4694). Reproduced from Howells *et al.* (1991). (Photo: BGS no. A14658.)

down through the sedimentary rocks below the Pitts Head Tuff Formation to a massive dolerite sill.

Immediately south and west of the summit of Moel Hebog and on Moel yr Ogof, flow-banded and flow-folded autobrecciated rhyolite sills and domes cap the succession. These acid intrusive rocks form part of the second phase of rhyolite intrusions in Snowdonia (Campbell *et al.*, 1987) post-dating caldera subsidence, and were associated with resurgent activity broadly contemporaneous with the Bedded Pyroclastic Formation.

Interpretation

The bleached weathered appearance of the Pitts Head Tuff Formation makes it one of the most distinctive tuff sequences in Snowdonia. On Moel Hebog the formation is represented by two primary rhyolitic ash-flow tuffs. Lithological and geochemical similarities with the 700 m-thick intracaldera tuff sequence on Llywd Mawr support the interpretation that the Pitts Head tuffs are the outflow facies from the Llywd Mawr Centre, although detailed correlations with the

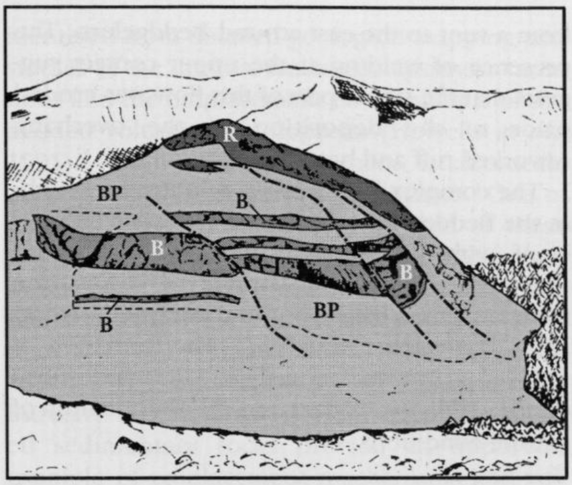


Figure 6.41 View, generally northwards, from Moel Hebog, showing broad features of geology on Moel yr Ogof (SH 556 478). Basaltic tuffs, hyaloclastites and volcaniclastic sediments (BP) and pillowed or massive basalts (B) of the Bedded Pyroclastic Formation are intruded by rhyolite (R). Reproduced from Howells *et al.* (1991). (Photo: BGS no. A14659.)

tuff sequence on Craig y Garn remain uncertain. Evidence from the south side of Moel Hebog and to the north indicates a considerable time gap between the upper and lower tuffs and therefore they must represent two distinct eruptive events. Facies and bedform analyses of the underlying sedimentary rocks have been interpreted by Orton (1988) to indicate alluvial plain and fan environments dominated by braided stream deposits derived from the W or SW.

These studies, combined with post-emplacement textures, thus support a subaerial emplacement for both tuffs. The non-welded, locally bedded base and the conspicuous zones of nodules marking the transition from non-welded to welded tuff probably resulted from the entrapment of volatiles near the zone of intense welding and growth during compactional welding and cooling, an interpretation supported by textural relationships. Above, the intense silicified planar parataxitic fabrics, with collapsed pumice clasts replaced by silica, indicate post-emplacement welding and compaction. In contrast, sections in the Pitts Head tuff farther north towards Snowdon show no siliceous nodule development and welding fabrics extend to the base of the flows. These changes correspond with a progressive north-eastward change to a submarine environment.

The evidence for post-emplacement brecciation and ductile flow of the Pitts Head tuff in a still plastic state and its presence as isolated rafts and blocks within tuffs of the Lower Rhyolitic Tuff Formation are distinctive and important features of the geology along the east side of Moel Hebog. These features have been interpreted as indicating instability and slope generation, probably by contemporary fault movements, post-Pitts Head tuff emplacement and during Lower Rhyolitic Tuff Formation times (Reedman *et al.*, 1987; Howells *et al.*, 1991). When this evidence is combined with the restriction of the upper Pitts Head tuff to the southern part of Moel Hebog and localization of acid and basic intrusive activity, it supports a model of fault-controlled topography along a caldera margin with the mass movement of welded tuff to form megabreccia deposits within a subsiding caldera.

The developing caldera was then infilled by the Lower Rhyolitic Tuff Formation with the widespread ponding and reworking of ash-flow tuffs and related mass-flow deposits within a shallow-marine environment. The basal welded unit is a primary ash-flow tuff possibly erupted from a vent to the east around Beddgelert. The presence of welding at the upper contact suggests that the upper part of this flow was eroded prior to the deposition of the overlying reworked tuff and breccia deposits.

The complex lateral facies relationships within the Bedded Pyroclastic Formation on Moel yr Ogof, with basaltic dykes and sills feeding up into basaltic pillow piles and lavas, suggest the formation of a basic vent and renewed activity along the caldera structure. The formation of pillows is inferred to reflect continued subsidence within the caldera and the continuation of marine conditions.

Conclusions

The Moel Hebog to Moel yr Ogof GCR site is a key site for the interpretation of the textures and emplacement mechanisms of acid ash-flow tuffs related to the 2nd Eruptive Cycle of Caradoc volcanic activity in Snowdonia, and in the identification of faulting and renewed volcanism along the caldera margin of an ancient submarine volcano. The Pitts Head tuffs represent the outflow from the caldera of the Llwyd Mawr Centre (see the Craig y Garn GCR site report). Their subaerial emplacement within an alluvial fan grading offshore into a shallow shelf provides an important contrast with marine conditions farther north. Subsequent fault-related activity along the south-western caldera margin of the Snowdon Centre and continued subsidence during the main phase of volcanic activity is graphically displayed in the brecciation, sliding and widespread disruption of previously emplaced ash-flow tuffs. Renewed basaltic activity and the intrusion of rhyolite domes serve to emphasize the importance of the caldera margin fracture in the channelling of magma to shallow crustal levels during later phases of resurgent activity.

YR ARDDU (SH 621 452–631 472)

M. Smith

Introduction

The present-day mountainous glaciated terrain of Snowdonia represents the deeply eroded roots to a series of large-scale (15–20 km in diameter) caldera-forming eruptive centres. These centres, of Caradoc age, have been largely identified from detailed geological mapping and studies of the internal facies and thickness variations and the emplacement environments of the bedded volcaniclastic deposits (Howells *et al.*, 1991). Within this environment, smaller-scale eruptive centres are surprisingly scarce. One of the best exposed and clearly defined of these smaller centres is that of Yr Arddu, interpreted as one of the earliest phases of activity related to the 2nd Eruptive Cycle of volcanic activity in Snowdonia in Caradoc times (Howells *et al.*, 1991). The well-exposed acid ash-flow tuffs, intrusive lava domes and breccias, and associated sedimentary rocks provide an important example of emplacement mechanisms and volcanic processes proximal to a fissure-controlled eruptive vent.

Originally mapped by the Geological Survey in 1851 as 'contemporaneous felsite', Yr Arddu was not described in detail until the work of Beavon in 1963. Beavon subdivided the tuff sequence on Yr Arddu into the Lower, Middle and Upper lapilli-tuffs, which he correlated with various outflow tuffs of the Lower Rhyolitic Tuff Formation on Moel Hebog and Snowdon. Shelly faunas in the subjacent sandstones were ascribed a Soudleyan age (Williams and Harper, in Beavon, 1963). Yr Arddu was later remapped by the British Geological Survey and was described by Howells *et al.* (1987). This work refuted the correlations proposed by Beavon, and showed that, geochemically, the Yr Arddu Tuffs form a distinctive group within the Lower Rhyolitic Tuff Formation with significantly lower Nb/Th ratios than other ash-flow tuffs of the formation (Howells *et al.*, 1991, figs 54 and 55).

The GCR site, which includes all of the main mass of Yr Arddu, covers an area of some 3 km^2 and includes the outcrop of the Yr Arddu Tuffs and the immediate underlying sedimentary strata (Figure 6.42). It is included in the geological 1:25 000 scale Sheet SH 64 and 65 (Snowdon) (1989) and the 1:50 000 scale Sheet 119 (Snowdon) (1997). The description given below is based largely on Howells *et al.* (1987) and is presented in stratigraphical order.

Description

Yr Arddu forms an elongate synclinal outlier situated along the site of a deep-seated fracture on the south-eastern margin of the Snowdon eruptive centre (Howells *et al.*, 1991). The site includes sandstones and siltstones of the Cwm Eigiau Formation (interlayered with rare, thin, acid tuffs), which are overlain by the Yr Arddu Tuffs, one of the oldest units within the Lower Rhyolitic Tuff Formation. The Yr Arddu Tuffs form a pile more than 180 m thick, intruded by later rhyolite domes, a distinctive breccia dyke, and sills of dolerite.

Exposure on Yr Arddu is excellent and all of the main lithologies can be studied in a traverse from immediately south of Gareg Bengam at 6182 4520 to the vicinity of Llynnau Cerrig-y-myllt at 6330 4722 (Figure 6.42).

The lower beds comprise interlayered siltstones and mudstones coarsening up into blue-grey, well-bedded sandstones and siltstones. The sandstones are flaggy to massive and locally conglomeratic with common cross-bedding and channelized pebbly sandstones. The presence of plagioclase crystals and lithic-tuff fragments indicates that the coarser sandstones are probably volcaniclastic. The siltstones are grey and homogeneous and may include thin layers of laminated sandstone up to 2 cm thick. Thin (up 3 m thick), pale weathering beds representing fine-grained reworked air-fall and/or primary non-welded rhyolitic ash-flow tuff with reworked tops are commonly developed. The primary ash-flow deposits comprise delicate cuspate and bubble shards and a few feldspar crystals. Also present are tuffaceous sedimentary rocks, thin coarse-grained lithic tuffs and debris-flow deposits with acid tuff clasts in a silt matrix (e.g. at 6181 4512). The tuffaceous sedimentary rocks, 1–20 cm thick, commonly display trough cross-bedding and abundant minor syndepositional faults.

Shelly faunas, dominated by disarticulated brachiopods and fragmentary trilobites, occur typically in the coarser sandstone layers and have been collected mainly from the south-eastern and north-eastern margins of Yr Arddu, (for example at 6224 4519 and 6360 4701). Originally interpreted as indicative of a Soudleyan age, the presence of *Kloucekia apiculata*, *Flexicalymene planimarginata* and *Broeggerolithus nicholsoni* (see plate 9 in Howells and Smith (1997) and plate 4 in Howells *et al.* (1991) for examples) indicate a Longvillian age. Detailed collecting has established the Longvillian–Soudleyan boundary on the eastern side of Yr Arddu.

Upslope, outcrops from Gareg Bengam to the summit of Yr Arddu are dominated by massive white-weathering, welded and non-welded rhy-

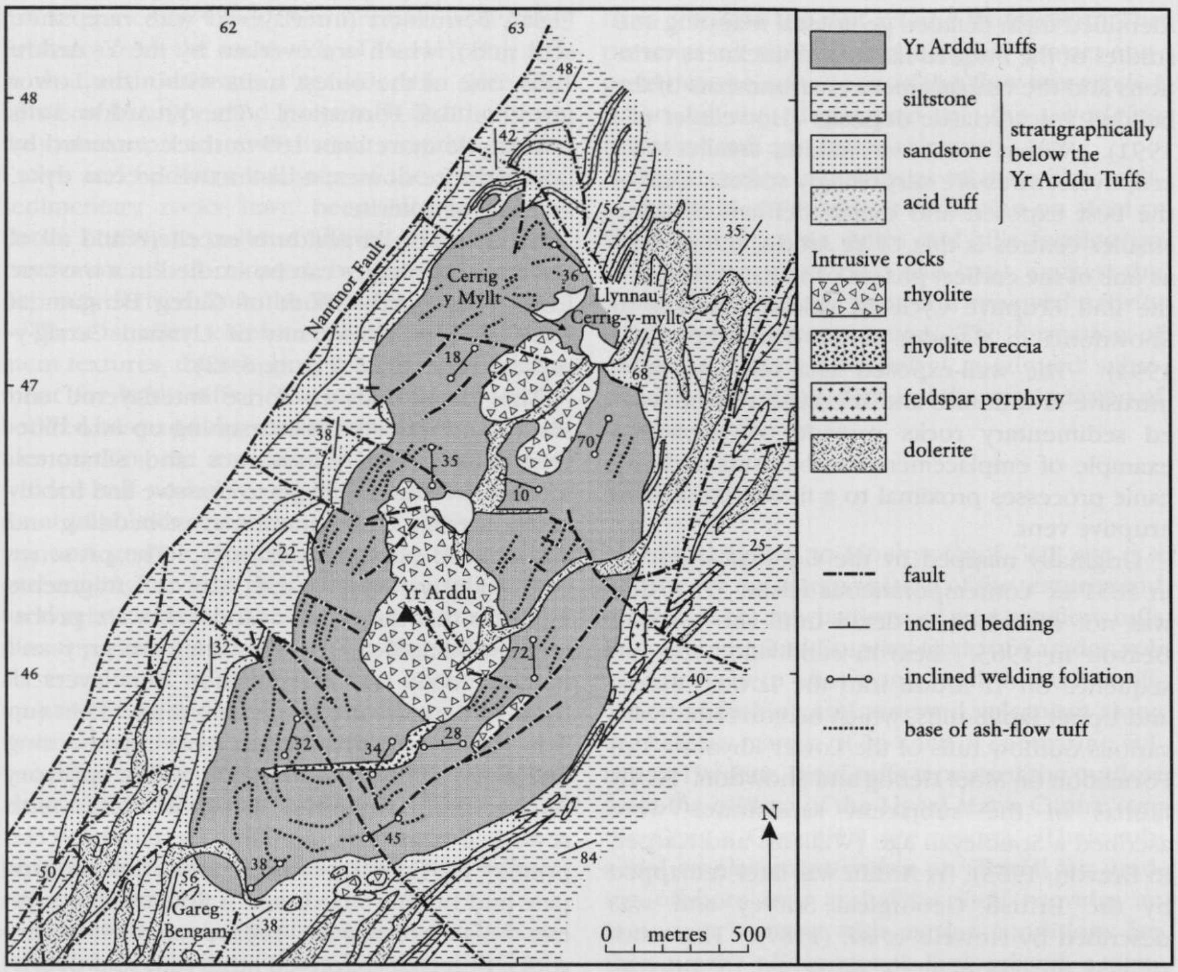


Figure 6.42 Map showing the Yr Arddu Tuffs, subjacent sedimentary rocks and associated intrusions (after Howells *et al.*, 1987).

olitic pumice-lapilli tuffs interlayered with pyroclastic breccia deposits. They form a series of distinctive scarp features and intervening depressions, reflecting the primary stratification in the tuffs, and define a broad synclinal structure. Resting discordantly on the underlying sandstones, the tuffs are variably cleaved and eutaxitic fabrics, defined by chloritic segregations and fiamme, subdivide the sequence above Gareg Bengam into a series of welded and non-welded ash-flows. They are devitrified, locally crystal rich, and siliceous nodules, up to 40 cm in diameter, are often concentrated near the bases and tops of flows. Petrographical descriptions of these tuffs are given in Howells *et al.* (1987). Reworking of the tops of the tuff beds is common near the base of the sequence as indicated by the presence of cross-lamination and shelly debris, including disarticulated brachiopods and crinoid fragments (e.g. at 6219 4524). The tuffs grade into block-and-ash tuffs and pyroclastic breccia deposits, dominated by pumice fragments up to 35 cm in diameter and blocks of acid tuff and rhyolite up to 1.5 m. Minor clast compositions include siltstone, sandstone, basalt and dolerite. A weak eutaxitic foliation is present and is commonly moulded around the blocks.

Midway up the slope to the summit and near the axis of the synform, a dyke-like apophysis of rhyolitic breccia cross-cuts the tuffs. This apophysis, up to 10 m wide, comprises blocks of flow-banded and flow-folded rhyolite up to 2 m in diameter set in a matrix of lapilli-tuff.

Immediately south of the main summit crags, the largest of the two rhyolite domes on Yr Arddu cuts through the tuffs. The contact zone is marked by the spectacular development of

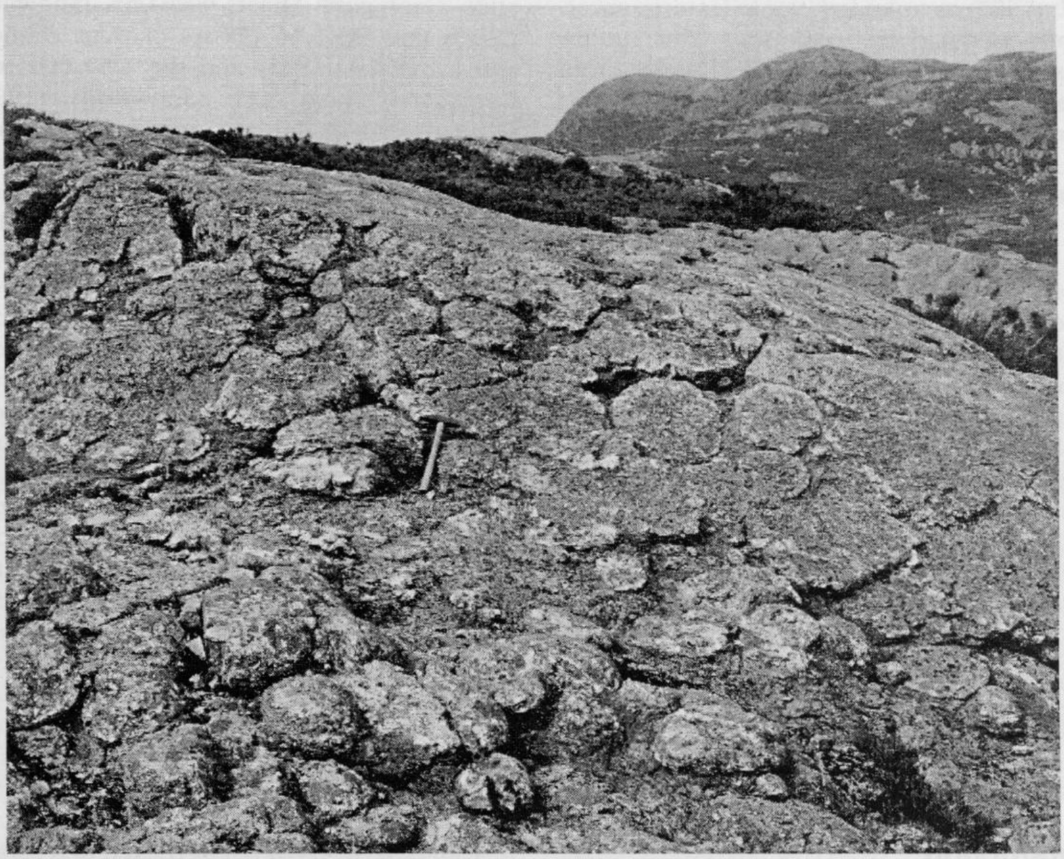


Figure 6.43 Siliceous nodules at the top of an acid ash-flow tuff, Lower Rhyolitic Tuff Formation, Yr Arddu. (Photo: BGS no. A14435.)

siliceous nodules locally up to the size of footballs (Figure 6.43). Typically the rhyolites are sparsely porphyritic, and flow-banded. The second and smaller dome is centred about Cerig y Myllt where it is cut by a dolerite sill.

Interpretation

By Caradoc times Snowdonia had undergone regional subsidence and was the site of a major NE-trending incipient rift or graben structure that became the focus for the 2nd Eruptive Cycle of magmatism in North Wales. The bedforms and faunal assemblages of the background sediment within the graben reflect the development of a moderate- to high-energy subtidal shallow-marine environment and indicate local uplift and temporary emergence prior to the onset of volcanic activity.

Within this incipient graben structure, and close to the eastern margin of the future Lower Rhyolitic Tuff Formation caldera, the Yr Arddu Tuffs represent a significant local accumulation of primary welded ash-flow deposits with lesser volumes of block- and ash-flow tuff and pyroclastic breccia deposits (Howells *et al.*, 1987). In contrast to the more internally uniform outflow facies of the Lower Rhyolitic Tuff Formation their heterogeneity suggests proximity to an eruptive source, and a linear NE-trending fissure is thought to underlie the site. The general absence of grading, the concentration of blocks near the bases of individual flows, the limited evidence for reworking and erosion, and the lack of interbedded sediments all suggest that volcanic activity from this vent was largely uninterrupted and dominated by suppressed eruptive columns. Geochemical correlations with the rhyolite domes suggest that they were probably emplaced into the fissure during the waning stages of activity.

The inward-dipping (centroclinal) configuration and the locally large discordance at the base of the tuff pile have been interpreted by Howells *et al.* (1987) as volcanotectonic features subsequently modified by tectonism. The outflow facies from this fissure-controlled centre crops out as a series of welded ash-flow tuffs on Moel y Dyniewyd immediately to the NW of Yr Arddu.

Conclusions

The Yr Arddu GCR site provides a magnificent section through a minor fissure-controlled eruptive centre formed in a shallow-marine environment. Significant volumes of tuff and breccia accumulated close to their source, within an elongate depression and were later intruded by rhyolite domes representing resurgent activity along an underlying fissure. This fissure line represents an important early axis of magmatic activity parallel to the trend of the main graben structure and later fissures within the developing Lower Rhyolitic Tuff Formation caldera.

SNOWDON MASSIF (SH 622 562–615 524)

M. Smith

Introduction

During Caradoc times, volcanic activity in Snowdonia migrated spatially within a large graben-like structure, termed the Snowdon Trough (Campbell *et al.*, 1988; Kokelaar, 1988) which was marked by the formation of a series of large caldera centres within a predominantly marine environment. Deep-seated NW-trending fractures influenced both the formation of this trough and the tectonic evolution of individual caldera structures during distinct phases of collapse and resurgence. Of these caldera structures, the Snowdon Centre is the largest and most clearly defined (Howells *et al.*, 1991) and has been the subject of detailed investigation by numerous workers over the last two decades of the 20th century. The GCR site lies within this centre and preserves a thick volcanic succession, recording developments within the northern, deepest part of the caldera, which developed during the 2nd Eruptive Cycle of Howells *et al.* (1991).

The geology of Snowdon was originally described in detail by Williams (1927) and was remapped by the Geological Survey between 1970 and 1983. It is included in the 1:25 000 scale Geological Sheets SH64/65 (Snowdon) (1989) and SH65/66 (Passes of Nant Ffrancon and Llanberis) (1985) and the 1:50 000 scale Geological Sheet 119 (Snowdon) (1997). General field guides are provided by Roberts (1979) and Howells *et al.* (1981) and detailed descriptions for the various parts of the succession, including geochemical analyses, are given by Howells *et al.* (1986, 1991) and Kokelaar (1992).

The succession within the GCR site is contained in three major rock basins or cwms separated by narrow serrated ridges, and comprises three formations belonging to the Snowdon Volcanic Group (Figure 6.44). The lower unit, best exposed in Cwm Llan, Cwm Tregalan, around Llyn Llydaw and Lliwedd, comprises a thick accumulation of acid ash-flow deposits known as the Lower Rhyolitic Tuff Formation (LRTF). This is succeeded by basaltic activity represented by the Bedded Pyroclastic Formation (BPF) which crops out extensively within the north-facing Cwm Glas and Cwm Uchaf, west of Glaslyn, the summit area of Snowdon and the north-eastern flanks of Lliwedd. The youngest strata, the Upper Rhyolitic Tuff Formation (URTF), mark a return to acidic volcanism, possibly related to resurgent caldera activity, and are preserved only around the northern cwms, particularly on Clogwyn y Person and Snowdon summit itself. Numerous rhyolitic sills and domes dominate the northern half of the site and show complex intrusive and extrusive relationships with the above strata.

Volcanogenic quartz–sulphide mineralization is important throughout the Snowdon Massif and has been related to hydrothermal alteration by mineralizing fluids during the waning stages of caldera activity (Reedman *et al.*, 1985). At a regional scale, the rocks are buckled into a series of open NE-trending synclinal and anticlinal fold structures representing the imprint of the Caledonian Orogeny in the area.

Description

The site area exposes strata of the Cwm Eigiau Formation, the three formations of the Snowdon Volcanic Group, and related high-level intrusions (Figure 6.44).

Fine-grained siltstones and mudstones of the Cwm Eigiau Formation are exposed in a number of small quarries in Cwm Llan (6134 5250) and represent the oldest strata in the GCR site area.

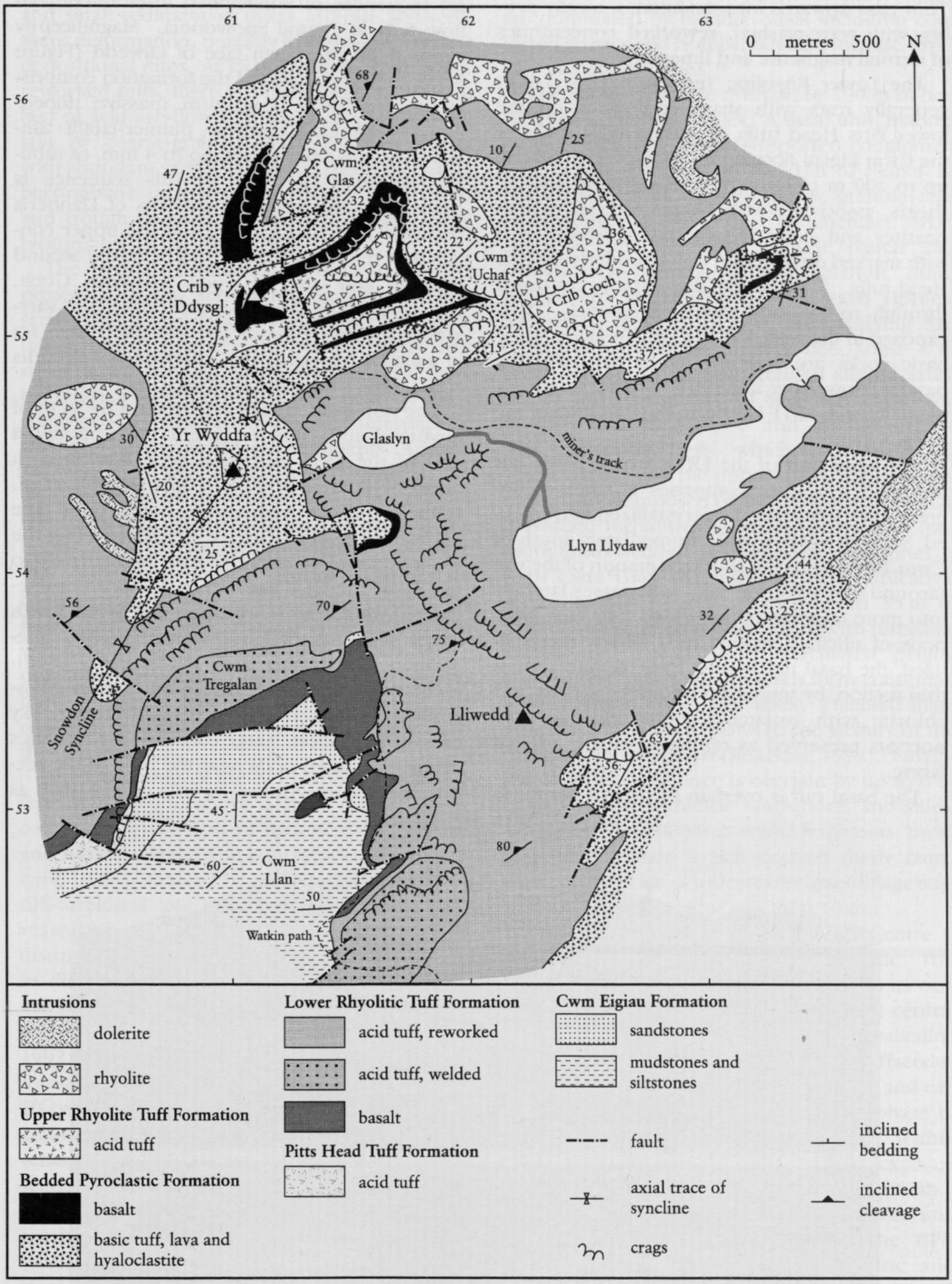


Figure 6.44 Map of the Snowdon massif, modified after BGS 1:25 000 sheets 64/65 (1989) and 65/66 (1985).

They pass upwards into sandstones, locally pebbly, with wave-washed, reworked concentrates of detrital magnetite and ilmenite.

The Lower Rhyolitic Tuff Formation (LRTF) generally rests with sharp conformity on the lower Pitts Head tuffs or sedimentary rocks of the Cwm Eigiau Formation. However, in places, up to 100 m of intrusive and extrusive basaltic sheets, associated with pillow breccias, hyaloclastites and basic tuffaceous sandstones rest with marked discordance on the underlying Pitts Head tuffs. Southwards, they rapidly cut down through to the underlying sandstones. Well exposed in the west wall of Cwm Tregalan, these basic rocks are referred to as the sub-LRTF basalts (Howells *et al.*, 1991) and are comparable to the sub-LRTF basalts in the east limb of the Idwal Syncline.

The basal unit of the LRTF, which crops out around Cwm Llan, comprises a white-weathered, intensely jointed, recrystallized and foliated, welded ash-flow tuff. Immediately south of Cwm Tregalan, at the southern margin of the site (around 618 528), the basal unit passes laterally into more impersistently welded tuffs with large pods of silicified welded tuff. Finely recrystallized, the basal tuff is seen to be dominated, in thin section, by aggregates of quartz, sericite and chlorite with isolated altered feldspar phenocrysts preserved as remnants of the original fabric.

The basal tuff is overlain by one of the thickest sequences of non-welded intracaldera ash-flow tuffs in central Snowdonia. Magnificently exposed on the north face of Lliwedd (Figure 6.45), the greater part of the formation comprises up to *c.* 500 m of uniform, massive, unbedded, non-welded rhyolitic pumice-lapilli ash-flow tuff with small clasts, up to 4 mm, of tubular pumice. The base of this sequence is exposed farther north in the Pass of Llanberis (Howells and Smith, 1997) and the upper contact with the overlying BPF can be traced around Glaslyn and the SE side of Crib Goch. Petrographically, the tuffs are dominated by varying admixtures of shards and feldspar crystals set in a matrix of sericite and chlorite (see Howells *et al.*, 1986 for further details).

The non-welded tuffs are overlain by 38 m of reworked tuffs that represent the uppermost part of the LRTF and have been described in detail by Fritz *et al.* (1990) and Howells *et al.* (1986). These beds crop out around the Snowdon Massif, but are best exposed along the western shore of Llyn Gwynant immediately to the SE of the GCR site. They comprise coarse-grained tuffaceous sandstones, interlayered with lesser amounts of laminated tuffaceous fine-grained sandstones and mudstones. Sedimentary structures include dune trough cross-stratification, wave ripples, and hummocky cross-stratification. Large concretionary nodules occur as isolated pods near the base of the section and are interpreted by Fritz *et al.* (1990) as

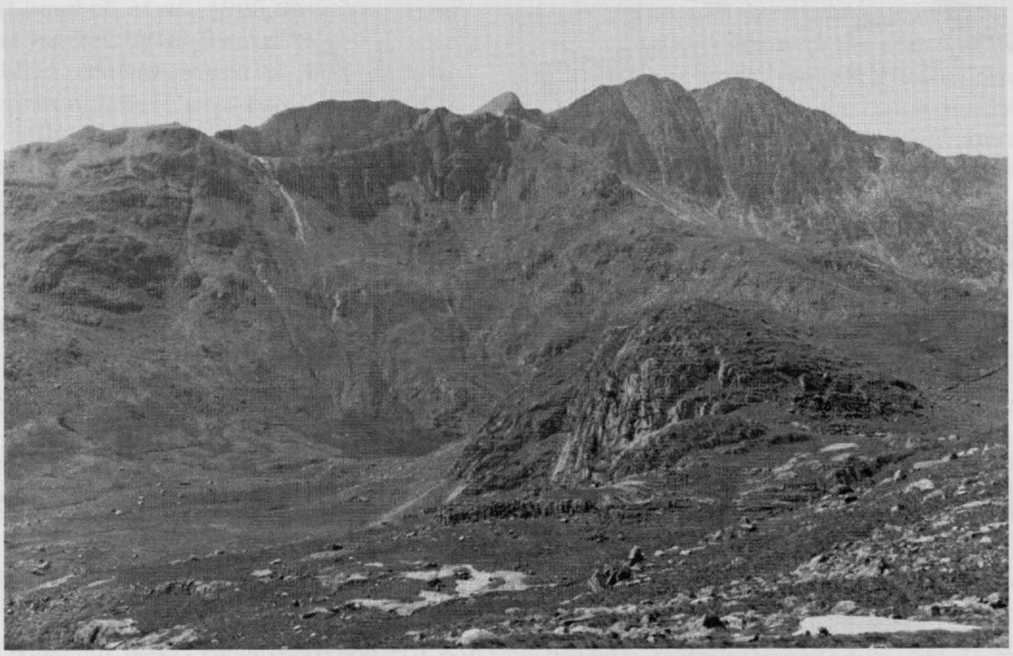


Figure 6.45 Lliwedd from Miner's Track showing the contact between the Lower Rhyolitic Tuff Formation and the Bedded Pyroclastic Formation near the centre of the ridge. (Photo: BGS no. A14391.)

early diagenetic features. Contorted bedding and small sedimentary dykes indicate soft-sediment deformation, possibly in response to rapid depositional rates. At 15 m above the base of the reworked tuffs, there is a prominent 12 m-thick bed of acid ash-flow tuff, which in turn is overlain by coarse-grained tuffaceous sandstones with abundant sedimentary structures, including herringbone cross-beds, horizontal lamination and trough cross-stratification; it is extensively bioturbated in the uppermost 3 m.

The Bedded Pyroclastic Formation (BPF) is preserved across Snowdonia, mainly within a series of synclinal inliers, and records the shallow-marine accumulation of basaltic pillow and sheet lavas, breccias, hyaloclastites and basic tuffs from a series of vents. These deposits show complex internal relationships and interdigitate with well-bedded tuffaceous sediments. Around Snowdon, the BPF is preserved high up in the glaciated cwms of Cwm Glas and Cwm Uchaf, in the steep cliffs above Glaslyn, and around the upper flanks of Snowdon summit (Figure 6.46). The complex geological history contained in these sections was described in detail by Kokelaar (1992) and Kokelaar *et al.* (1994) and was summarized by Howells *et al.* (1991). Here, only a brief account of the main lithologies and their geological features is presented and the reader is referred to the above accounts for further information.

The basal units of the BPF, exposed in the NE face of Snowdon above Glaslyn (Figure 6.46), comprise up to 95 m of basaltic tuffs, breccias and hyaloclastites. The contact with the underlying LRTF is marked by 5–6 m of thinly bedded tuff-turbidites and cobble conglomerates with vesicular scoria and glassy shard fragments. Two distinct agglomerate vents or necks, up to 280 m in diameter, have been distinguished by their markedly discordant relationships to the LRTF and the lower tuffs and turbidites (Kokelaar, 1992). The vents consist of subangular to rounded basic lapilli and blocks of basalt, up to 20 cm across, set in a rather indeterminate fine-grained basaltic matrix. The basal beds and the vents are then, in part, cut out by the overlying sequence, which consists of turbidites, conglomerates and breccia deposits. In Cwm Glas this break is marked by a 6 m-thick sequence of flow-banded rhyolite lava and the emplacement of large rhyolite intrusions within the LRTF. The overlying sedimentary strata have a total thickness of 75 m and comprise reworked turbidites, lithic-vitric breccias, and conglomerates. Beds are dominated by basaltic clasts including contorted spatter and bombs, but also include rhyolites and shelly debris.

The above strata are overlain by 190 m of heterolithic sedimentary rock. A basal unit, marked by cross-stratified matrix-supported conglomerates, is succeeded by up to 50 m of coarse- to fine-grained turbiditic sandstones, granule conglomerates and siltstones. Sedimentary structures are abundant and include planar and trough cross-bedding, cross-lamination, hummocky cross-stratification and wave ripples. Separating these beds from the overlying turbidites is a distinctive marker bed, some 4 m thick, of fine- to medium-grained altered sandstones and acid tuffaceous beds with carbonate nodules and brachiopod and crinoid debris. The uppermost beds, which form the crags above Glaslyn and the upper south face of Crib y Ddysgl, are composed of 140 m of massive thickly bedded turbiditic sandstones passing up into more thinly bedded, finer-grained sandstones.

In Cwm Glas, the overlying beds indicate a return to basaltic activity with up to 85 m of basaltic tuffs and lavas interleaved with turbiditic sandstones. The lavas are vesiculated, plagioclase-phyric, pillowed and often form columnar-jointed sheets up to 4 m thick. Detailed mapping has traced these flows to the vicinity of the earlier vents in Glaslyn (Kokelaar, 1992). Finally, the complete sequence is overlain by up to 6 m of pebbly and turbiditic sandstones, and silicic siltstones. Rich in basalt scoria fragments, these beds also contain a rich derived shelly fauna with brachiopods of a *Dinorthis* assemblage suggesting water depths of less than 10 m.

The final activity of the Snowdon Centre is represented by the Upper Rhyolitic Tuff Formation (URTF) which is restricted in its outcrop to a series of small outliers within central Snowdonia. The formation includes peralkaline acidic ash-flow tuffs, bedded tuffs and tuffaceous sedimentary rocks and rare basaltic beds and can be related compositionally to the last phase of rhyolite intrusion (Howells *et al.*, 1991). Within the GCR site, the formation is superbly exposed on Clogwyn y Person (Figure 6.47) and Crib y Ddysgl, where up to 100 m are preserved and rest with gentle unconformity on the BPF. Pebbly sandstones, with both rhyolitic and basaltic clasts, locally mark the base, but laterally these beds are overstepped by the main ash-flow tuff. The main tuff, up to 35 m thick, has a

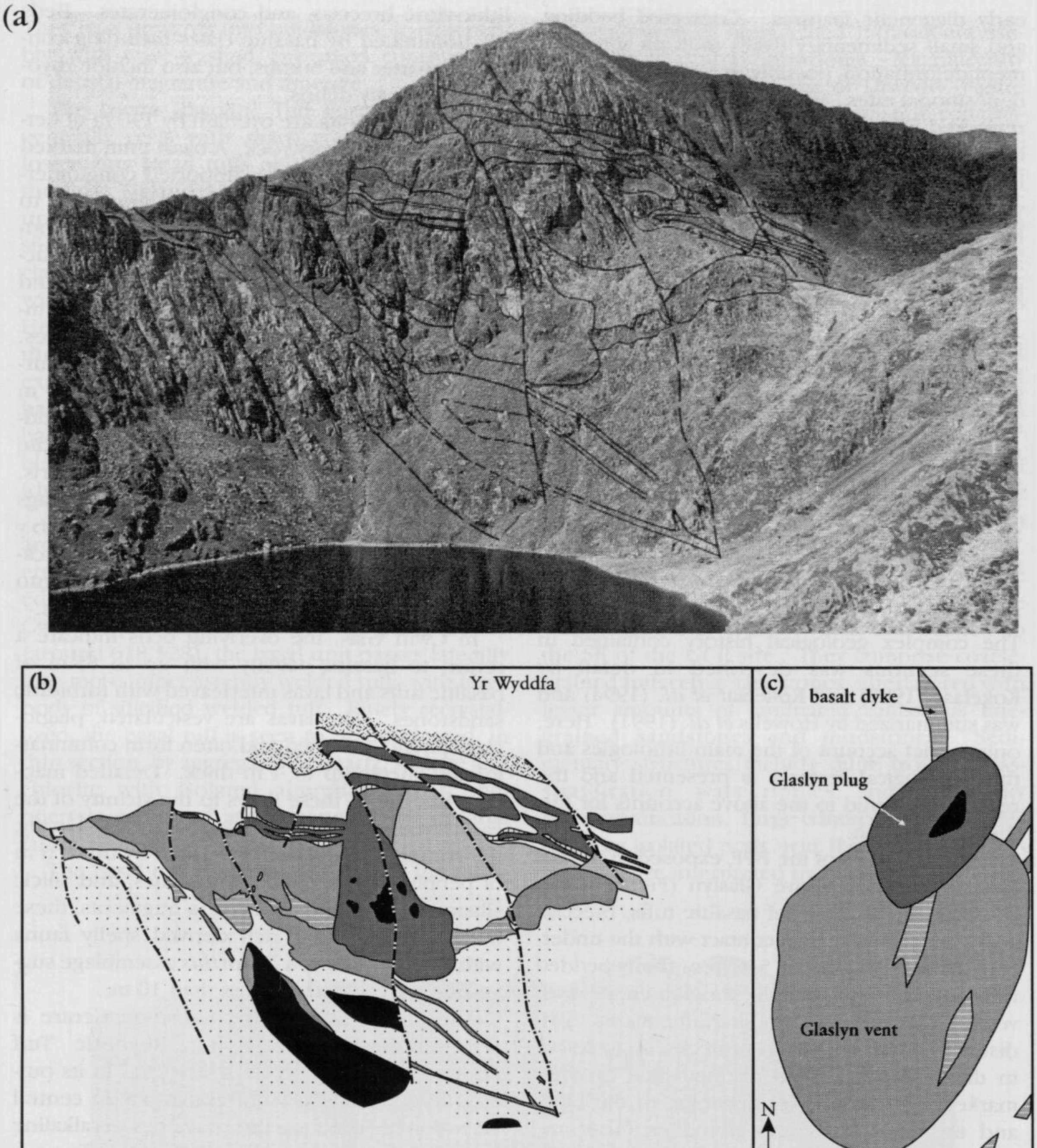


Figure 6.46 Details of the Bedded Pyroclastic Formation cropping out on the NE face of Yr Wyddfa, Snowdon above Llyn Glaslyn. (a) Photograph of NE face with geological boundaries added. (b) Key to the geological units exposed in a. (c) Sketch map of the Glaslyn Vent Complex. Reproduced from Howells *et al.* (1991).

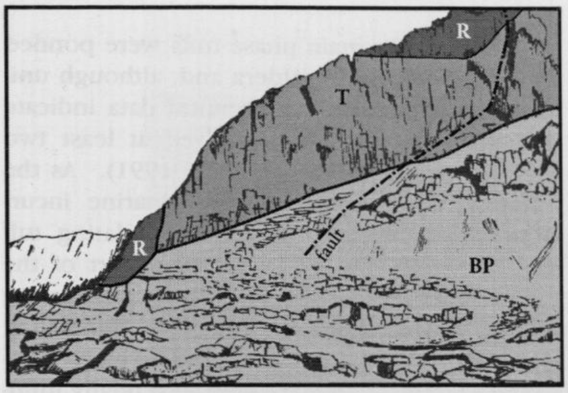
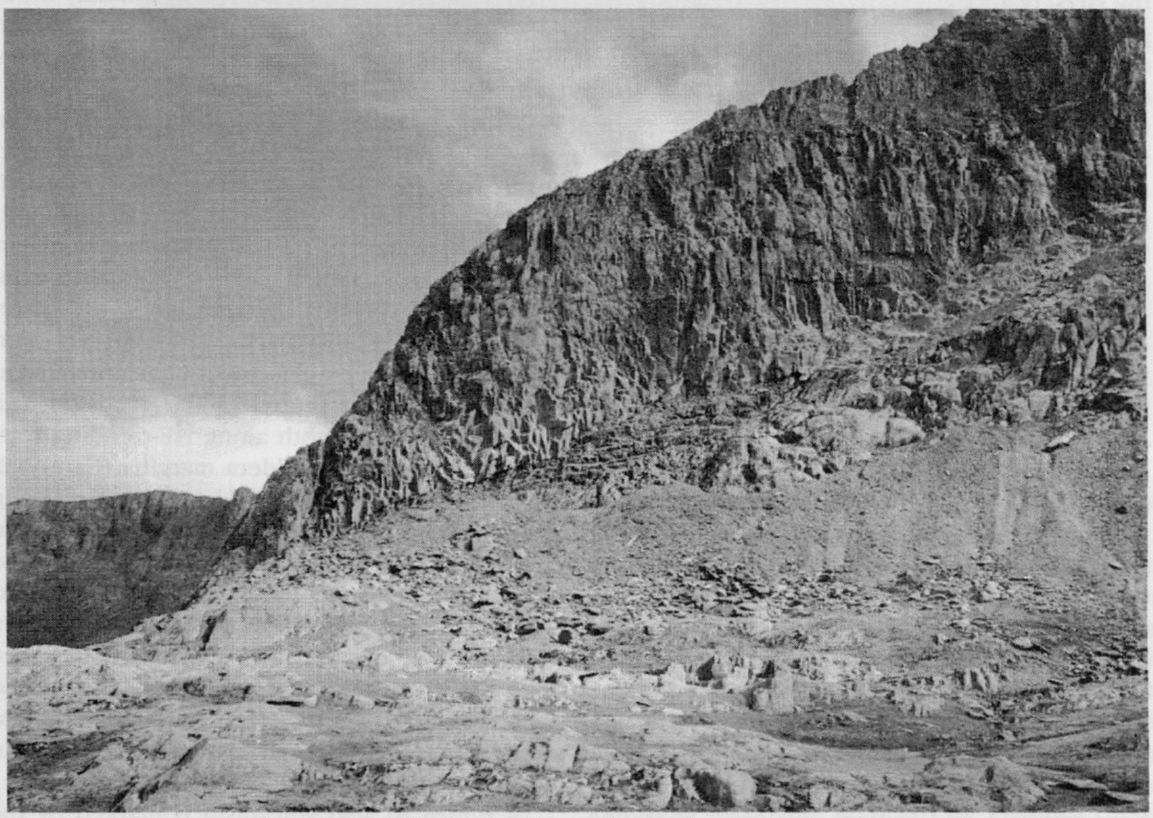


Figure 6.47 The ridge of Clogwyn y Person (SH 615 554) viewed from Cwm Glas. The ridge comprises well-jointed, acidic ash-flow tuff (T) at the base of the Upper Rhyolitic Tuff Formation. Below lie bedded basaltic sediments, basalt and hyaloclastite of the Bedded Pyroclastic Formation (BP), and above an intrusive rhyolite (R). Reproduced from Howells *et al.* (1991).



distinctive, bleached weathered surface with lithic clasts and carbonate nodules, and grades up into fine-grained silicified tuff near the top of the section. Petrographically, the URTF is heterogeneous (Howells *et al.*, 1991) and comprises quartz, feldspar, sericite and chlorite with dispersed shards and a few lithic clasts of acid tuff, perlitic glass and chloritized basaltic fragments. On Crib y Ddysgl, the welded tuff is overlain by up to 40 m of fine-grained, bedded tuffs, tuffaceous siltstones and thin intercalations of basaltic tuff. The siltstones are silicified, with planar and low-angle cross-lamination. Snowdon summit is composed of a small outlier, some 25 m thick, of flaggy, acid tuffs and tuffaceous siltstones which are assigned to the URTF.

Both intrusive and extrusive rhyolite bodies are intimately associated with the LRTF and were emplaced prior to, during and after the deposition of the ash-flow tuffs. They are clearly exposed on the northern flanks of Snowdon, typically forming the serrated ridges south of the Llanberis Pass, such as Crib Goch. The intrusions cut the LRTF and are generally overlain by the basic tuffs and lavas of the BPF. On Clogwyn y Person, a rhyolite dyke that intrudes the BPF can be traced up into a dome overlying the main ash-flow tuff of the URTF, indicating late-stage activity. Typically pale-weathering, the rhyolites are strongly jointed, flow-banded and sparsely porphyritic; perlitic fracturing and autobrecciation are common.

Interpretation

The lower strata of the Cwm Eigiau Formation form part of the substrate onto which the 2nd phase of volcanic activity linked to the Snowdon Centre, here represented by the Pitts Head tuffs, was emplaced. Regional studies have inferred the presence of a NE-dipping palaeoslope with prograding alluvial fans in the south passing northwards into delta-front deposits (Reedman *et al.*, 1987; Howells *et al.*, 1991). In Cwm Llan, the presence of bands of heavy mineral concentrates indicates wave activity and the progradation of a wave-influenced beach. Into this environment, volcanic activity, within the evolving Snowdon caldera, commenced with the localized eruption of basaltic lavas and tuffs from a series of small vents which were probably controlled by deep-seated NE-trending fractures. The marked unconformity at the base of these basalts indicates uplift and erosion, and Howells *et al.* (1991) suggested that this, in part, reflects the upward propagation of pre-existing basement faults, probably triggered by the emplacement of magma into the cover sequence and the formation of a periclinal anticline within the sediments underlying the LRTF. This structure, termed the Beddgelert Pericline, is unique in the Caradoc strata of Snowdonia and heralds the main phase of ash-flow eruption; it later became the focus for volcanic activity, faulting and mineralization.

The LRTF represents a major period of ash-flow eruption and caldera collapse. From the evidence of facies and thickness variations, basal contacts and the distribution of associated rhyolite intrusions, Howells *et al.* (1986) inferred the presence of a caldera structure some 15 km in diameter. The section of tuffs within the Snowdon GCR site represents the infill to this caldera. Early eruptions, represented by the basal welded unit, are interpreted as reflecting a distinct eruptive event, possibly located on vents aligned along the NE-trending crest of the Beddgelert Pericline. In Cwm Tregalan, this unit rests conformably on reworked and subaqueously erupted basalts, indicating emplacement in a marine environment. This contrasts with the predominantly subaerial emplacement further south.

The overlying main phase tuffs were ponded within the Snowdon caldera and, although uniform in appearance, geochemical data indicate that their accumulation involved at least two eruptive phases (Howells *et al.*, 1991). As the caldera progressively subsided, marine incursions began to rework the accumulating tuff pile. Sections through the upper part of the LRTF represent a progressively shallowing marine environment with rapidly fluctuating water depths and local topographical highs within the caldera. Sedimentation in a tidally influenced beach environment is indicated by the herringbone cross-beds, re-activation surfaces and bioturbation (Fritz *et al.*, 1990).

Although the subsidence is greatest in the northern part of the LRTF caldera, as indicated by the thick pile of intracaldera tuffs, on the evidence of the extrusion of rhyolite domes, and the subsequent complex interplay between basaltic magmatism and water depth, it is considered that the general subsidence was interrupted by resurgent uplift. This uplift has been attributed to the emplacement of acid magma at depth and is represented by the intrusion of a series of rhyolites both along NE-trending fractures and along the caldera margins (Campbell *et al.*, 1987; Howells *et al.*, 1991). Following resurgence and reworking, basic magmatism represented by the BPF occurred across Snowdonia. The detailed work of Kokelaar (1992) in the Snowdon Massif recognized a complex history with repeated uplift, emergence and subaerial erosion of a series of basalt island volcanoes. A total uplift of more than 336 m and subsidence of more than 500 m has been calculated by Kokelaar (1992.).

A return to acid volcanism is marked by the URTF, which is intimately associated with high-level rhyolite intrusion and final activity within the Snowdon caldera.

Conclusions

The Snowdon Massif GCR site provides important sections detailing the main phases of extrusive and intrusive volcanic activity related to the Snowdon Centre, a major caldera that developed in a predominantly marine setting. The spectacular ice-sculpted cwms and hanging valleys of Snowdon offer an unrivalled opportunity to study the complex three-dimensional geological relationships within part of this caldera

Figure 6.48 The Idwal Syncline viewed along the axis, across Llyn Ogwen towards Cwm Idwal and the Devil's Kitchen. (Photo: BGS no. L2390)

structure. Numerous studies have revealed the complex inter-relationships, through time, between alternating acid and basic magmatism, changing styles of volcanic activity and the background sedimentation. These relationships, most clearly expressed within the later stages of basaltic activity, represented by the Bedded Pyroclastic Formation, provide valuable insights into the ancient environments of Snowdonia during Caradoc times.

CWM IDWAL (SH 646 606–640 583)

M. Smith

Introduction

Cwm Idwal is a National Nature Reserve of outstanding geological, geomorphological and botanical interest that is easily accessible from the A5 trunk road near Llyn Ogwen. The geology is varied and complex and includes features of volcanological, sedimentological, and structural importance that are clearly displayed in the eastern and southern cliffs above Llyn Idwal and in the lower ground NW of Ogwen Cottage (Figure 6.48).

The GCR site encompasses a heterogeneous sequence of rock types ranging from rhyolitic ash-flow tuffs, basic tuffs and lavas, to intrusive rhyolites, all interlayered with volcaniclastic marine sedimentary rocks (Figure 6.49). It includes representatives of the two main eruptive cycles related to major caldera activity within central Snowdonia during Caradoc times. Outflow tuffs from both the 1st Eruptive Cycle, related to the Llwyd Mawr Centre, and the 2nd Eruptive Cycle, related to the Snowdon Centre are present. Of particular interest are the sections through the Lower Rhyolitic Tuff Formation (LRTF), of the 2nd Eruptive Cycle, which record the deposition of caldera-sourced pyroclastic breccias and welded tuffs, passing up into reworked tuffs and turbidites. The shelly faunas contained within the sedimentary rocks indicate an age range of Soudleyan to Longvillian (mid-Caradoc).

The primary survey of the area was completed in 1852 (Ramsay, 1881) and later the area was partly described by Williams (1930). Detailed remapping by the Geological Survey at the

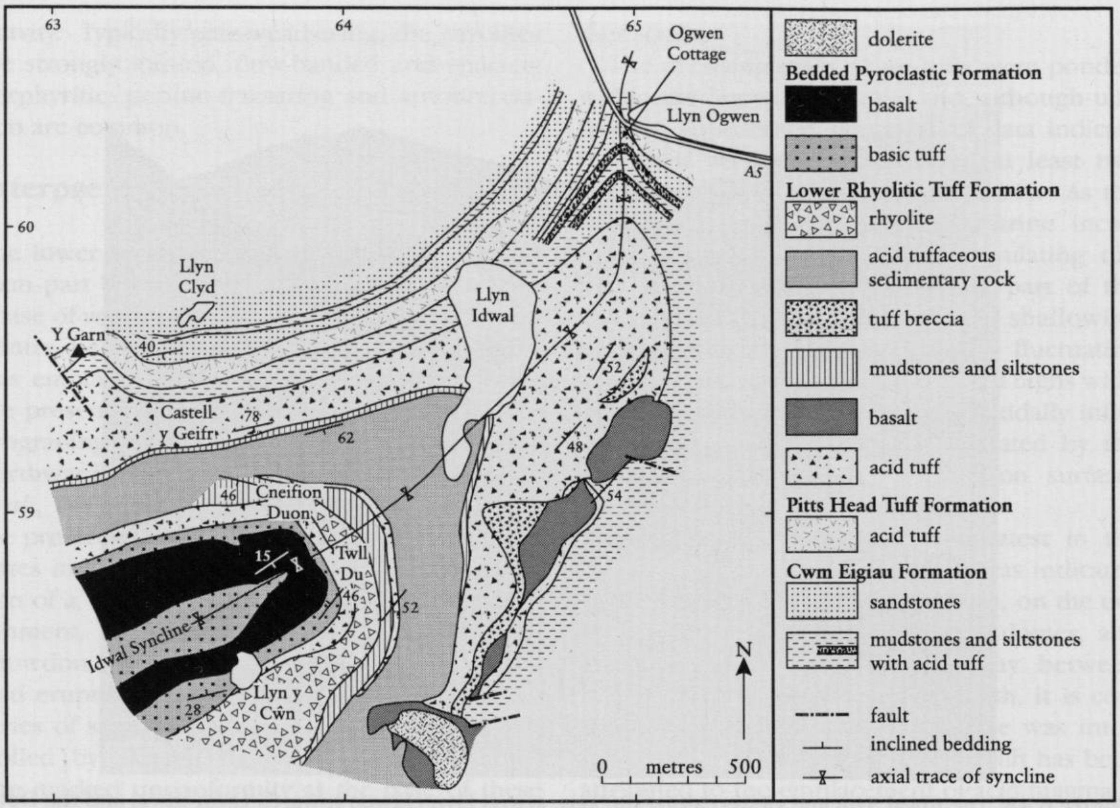


Figure 6.49 Map of the Cwm Idwal GCR site, after BGS 1:25 000 Sheet 65/66 (1985).

1:10 560 scale was completed in 1977 and incorporated into the 1:25 000 scale geological Sheet SH65/66 (Passes of Nant Ffrancon and Llanberis) (1985). General descriptions of Cwm Idwal were given by Roberts (1979) and Howells *et al.* (1981), with detailed descriptions of parts of the succession in Reedman *et al.* (1987), Fritz *et al.* (1990), Howells *et al.* (1991) and Kokelaar *et al.* (1994). Geochemical data were presented by Howells *et al.* (1991).

In ascending order the succession includes the Cwm Eigiau Formation, the Pitts Head Tuff Formation, the Lower Rhyolitic Tuff Formation (LRTF) and the Bedded Pyroclastic Formation (BPF). The strata are deformed in a classic open symmetrical synclinal fold termed the Idwal Syncline (Fitches, 1992). This NE-trending structure, and the complementary Tryfan Anticline to the east, are major fold structures formed during Caledonian orogenesis.

Description

In the site area, strata occurring immediately below the Snowdon Volcanic Group (the Cwm Eigiau Formation), and three formations belonging to the Snowdon Volcanic Group are magnificently exposed.

The lower strata of the Cwm Eigiau Formation, which crop out in the western part of the site (Figure 6.49) and form the crags west of Llyn Idwal, can be traced both south-westwards to Y Garn and northwards into the Braich tu du GCR site. They overlie the Capel Curig Volcanic Formation conformably and comprise steeply dipping very fine-grained structureless sandstones interlayered with siltstones and thin mudstones. Beds containing disarticulated brachiopod shells are common and are well exposed around 6487 6041, NW of Ogwen Cottage. By comparison with the Berwyn district, these faunal associations have been assigned to the *Dinorthis–Macrocoelia* community (Pickerill and Brenchley, 1979) and provide important information on the palaeoenvironment prior to the main volcanic events. A prominent knoll at the north-western end of Llyn Idwal (6430 5981) shows excellent exposures of cross-bedded sandstones overlain by contorted, wavy siltstones and fine-grained sandstones. The overlying welded tuff also contains a raft of contorted sandstone. Similar features, with lobate and

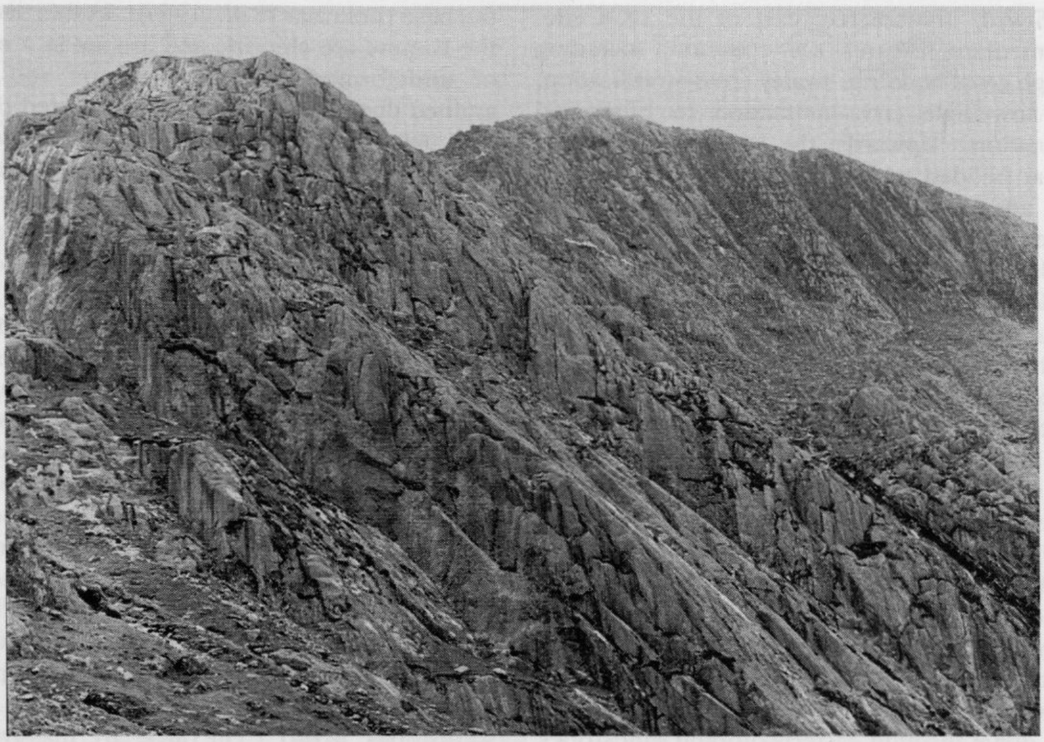


Figure 6.50 The Idwal Slabs, on the eastern limb of the Idwal Syncline, composed of acidic ash-flow tuffs of the Lower Rhyolitic Tuff Formation. (Photo: BGS no. L2636.)

flame structures, are also preserved in quarry sections west and NW of Ogwen Cottage, (for example at 6492 6082), and together these features indicate syn-emplacement deformation of semi-lithified sediments immediately beneath the Pitts Head tuffs.

The overlying acidic ash-flow tuff is the most northerly representative of the Pitts Head Tuff Formation in Snowdonia and is the distal outflow facies from a major caldera centre located some 25 km SW at Llywd Mawr (see the Craig y Garn GCR site report). The tuff varies from 30–50 m in thickness and is well exposed in numerous sections and cuttings immediately south and north of the A5 road, (for example at 649 606), and in the lower western crags rising up across the ridge of Castell y Geifr to Y Garn. The base is generally concordant on the underlying sandstones.

Three main sub-units are recognized in the Pitts Head Tuff at this locality: a basal non-welded zone 1–2 m thick and rich in feldspar crystals with a vitroclastic texture; this grades up into 25–45 m of white, siliceous, welded tuff with a prominent eutaxitic foliation; and an upper fine-grained tuff. Distinctive ragged, flattened and streaky fiamme, up to 5 cm in length, are present throughout the central part of the tuff. Some 5 m above the base, cooling and contraction joints are well developed and fiamme increase markedly in size. The welding foliation is accentuated by siliceous segregations locally reaching 30 cm in length, although these are less well developed compared with the southern outcrops around Moel Hebog. Zones of siliceous nodules 1–3 cm in diameter occur irregularly through the tuff and rheomorphic flow textures, indicated by the variable orientation of the fiamme with respect to the margins of the flow, are common. Locally, (for example at 6476 6024), strong linear fabrics may be observed, and are interpreted as having formed by extreme extension in the flowing and compacting tuff (Howells *et al.*, 1991). The upper sub-unit comprises cleaved vitric dust-rich tuff, which is variably welded and locally reworked.

The Pitts Head tuffs, in turn, are sharply overlain by up to 200 m of sandstones representing a continuation of the Cwm Eigiau Formation with fining-upward sequences and rare thin mudstones. These strata form the striated and ice-sculpted ridges, crags, and waterfalls immediately east of Llyn Ogwen and have been described in detail by Orton (1988) in Cwm

Bochlwyd, immediately east of the GCR site. Sedimentary features are common, including trough cross-bedding, swaley cross-stratification, and low-angle cross-lamination to horizontal lamination. Upwards, the sandstones become planar bedded with thin layers of tuff-turbidite and are characterized by careous-weathering lenses of winnowed, disarticulated brachiopod shells, coquina-filled scours and rare, low to moderately dipping cross-beds with shells dispersed along the foresets.

The acidic ash-flow tuffs, intrusive rhyolites, breccias and interbedded sedimentary rocks which comprise the overlying Lower Rhyolitic Tuff Formation (LRTF) dominate the well-known cliff sections and prominent Idwal Slabs around the eastern and southern parts of the site (Figure 6.50).

The LRTF is a heterogeneous unit up to 110 m thick, which rests with marked disconformity on the underlying sedimentary rocks. This discordance increases to the south to an unconformity (Howells *et al.*, 1986). In the west, the LRTF cuts down through easterly-dipping sandstones, locally cutting out thin tuffaceous units, and comprises welded primary ash-flow tuffs with no intercalated sediments. In contrast, on the eastern limb of the Idwal Syncline the basal relationships are complicated by intrusive basalts, lavas and the development of a pyroclastic breccia facies at the base of the LRTF.

The basal sections of the LRTF are best seen at the foot of a wall immediately SW of two streams that drain into Llyn Idwal at 6470 5894. Here, the basal beds include vesicular, massive basaltic pillow lavas, heterolithic basaltic debris-flow deposits and thin turbiditic tuffs. The debris-flow deposits contain subrounded basalt blocks up to 1 m in diameter, in a fine-grained matrix of basic tuff with dispersed feldspar crystals. The overlying pyroclastic breccia, up to 12 m thick, comprises a coarse lithic breccia occurring as layers or lenses which thin and pass laterally into the host matrix-supported ash-flow tuff. Individual blocks, 0.1–0.7 m in length, range in composition from basalt, acid tuff and rhyolite to rare sandstone and siltstone. A crude stratification can be discerned by variations in grain and clast size, and lithology.

The main part of the LRTF is a thick sequence of stratified welded lapilli ash-flow tuffs with beds up to 1.5 m thick and a prominent eutaxitic foliation. Thin breccia layers similar to the basal breccia have been recorded up to 42 m above the base (Kokelaar *et al.*, 1994). In thin section, the fiamme are chloritic and are set in a matrix of undeformed devitrified shards and fine-grained dust. Several units are indicated on the 1:25 000 scale map and are separated by laterally impersistent layers of siltstone. The highest beds are composed of well-bedded and upwardly graded reworked tuffs. A dark porcellaneous laminated fine-grained tuff marks the top of the sequence.

The overlying sedimentary rocks, up to 100 m in thickness, have been described in detail by Fritz *et al.* (1990). The lowest bed is a 2 m-thick laminated pyritic mudstone, passing up into tuffaceous siltstones with hummocky and swaley cross-stratification and abundant large carbonate concretions. Above, are up to 75 m of brown-weathering, greenish coarse-grained volcaniclastic sandstones with interbeds of pale tuffaceous siltstone and rare impersistent ash-flow tuffs. Individual bed thicknesses range between 10–50 cm and show a progressive upward decrease in the volcaniclastic component. The sandstones, up to 7 cm thick, are massive and planar bedded with flat, locally scoured bases and reworked hummocky tops. Sedimentary features include cross-lamination, ripples, grading, washouts, intraformational unconformities, and slump folds with contorted bedding indicating deformation of semi-lithified sediment (for example at 6402 5904).

The upper parts of the backwall of Cwm Idwal are dominated by a thick columnar-jointed rhyolitic lava flow, which can be traced across the core of the synclinal structure. The rhyolite lava is dark blue-grey, flinty and finely banded with locally developed perlitic fracturing. The upper surface, exposed along the footpath between Cneifion Duon and Y Garn, is brecciated, and in places, hollows and depressions are infilled with coarse volcanic detritus. The zones of brecciation contain classic jig-saw breccia fabrics and can be traced laterally into flow-banded rhyolite indicating in-situ autobrecciation. The rhyolite lava is in places separated from the overlying BPF by up to 35 m of planar and cross-laminated rhyolitic tuffaceous sandstone representing the top of the LRTF.

The Bedded Pyroclastic Formation (BPF) crops out to the SW of Twll Du (or Devil's Kitchen) and around Llyn y Cwn, immediately south of the GCR site. Up to 24 m of flaggy-bedded, greenish basic tuffaceous sedimentary rocks and coarse-grained tuffaceous sediments

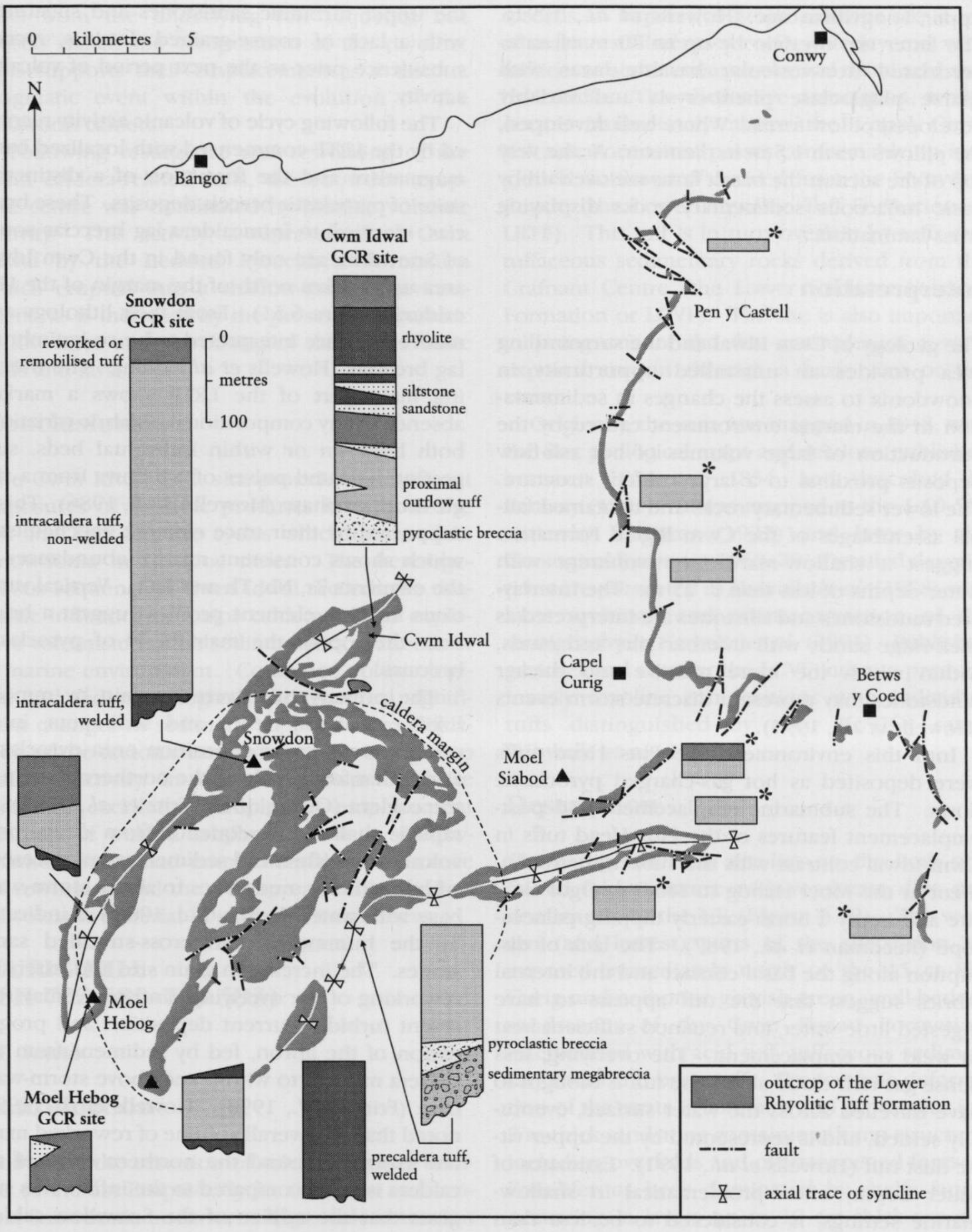


Figure 6.51 Outcrop and measured sections of the Lower Rhyolitic Tuff Formation. Asterisks indicate distal outflow tuff sections. After Howells *et al.* (1991).

including block- and lapilli-rich beds are exposed. Sedimentary structures, including cross-lamination and wave-rippled surfaces, are common. Elsewhere, these beds grade into volcaniclastic sedimentary rocks with a sparse shelly fauna, interpreted as indicating a probable upper Longvillian age (Howells *et al.*, 1991). The latter are overlain by up to 70 m of autobrecciated non-vesicular basaltic lavas with sparse plagioclase phenocrysts and variably developed pillow forms. Where well developed, the pillows reach 1.5 m in diameter. At the very top of the section the basalt lavas are overlain by basic tuffaceous sedimentary rocks displaying cross-lamination.

Interpretation

The geology of Cwm Idwal and the surrounding area provides an unrivalled opportunity in Snowdonia to assess the changes in sedimentation in the marine environment caused by the introduction of large volumes of hot ash-flow deposits proximal to a large caldera structure. The lower sedimentary rocks and contained faunal assemblages of the Cwm Eigiau Formation suggest a shallow-marine environment with water depths of less than *c.* 25 m. The interlayered sandstones and siltstones are interpreted as shelf-ridge sands with interbar silts and muds, within which the more massive and thicker sandstones may represent discrete storm events (Howells *et al.*, 1991).

Into this environment the Pitts Head tuffs were deposited as hot gas-charged pyroclastic flows. The submarine emplacement and post-emplacement features of the Pitts Head tuffs in Cwm Idwal contrast with the subaerial environment at the Moel Hebog to Moel yr Ogof GCR site and imply a north-easterly dipping palaeoslope (Reedman *et al.*, 1987). The lack of disruption along the basal contact and the internal fabrics suggest that the tuff appears to have ingested little water, and retained sufficient heat to weld on emplacement. The overlying, less dense gas-rich cloud above the tuff is thought to have travelled across the water surface, eventually settled, and is represented by the upper vitric dust tuff (Howells *et al.*, 1991). Estimates of water depth, often problematical in shallow-marine settings, is considered to be less than 20 m, and therefore it would seem unlikely that the tuffs would have been completely submerged.

The overlying sandstones, with their abundant sedimentary features and transported faunal debris, represent the continuation of marine conditions with high-energy regimes on a mid- to outer storm-dominated shelf (Orton, 1988). With time, deeper water conditions prevailed; the upper turbiditic sandstones and siltstones, with a lack of coarse-grained detritus, record subsidence prior to the next period of volcanic activity.

The following cycle of volcanic activity recorded by the LRTF commenced with localized basic magmatism and the formation of a distinctive suite of pyroclastic breccia deposits. These breccias, identical to intracaldera lag breccias south of Snowdon, are only found in the Cwm Idwal area up to 4 km north of the margin of the LRT caldera (Figure 6.51). From their lithology and nature, they are interpreted to be co-ignimbritic lag breccias (Howells *et al.*, 1986). The overlying main part of the LRTF shows a marked absence of any compositional or fabric variations both between or within individual beds, suggesting repeated pulses of ash-flows from a single eruptive phase (Howells *et al.*, 1986). This is supported by their trace element geochemistry, which shows consistent relative abundances of the elements Zr, Nb, Th and TiO_2. Vertical variations in trace element profiles suggest a break near the top of the main body of pyroclastic breccias.

The primary tuffs were overlain by remobilized pyroclastic debris and sediments, interpreted to represent deposition on a pyroclastic apron that formed along the northern margin of the caldera (Orton, 1988; Fritz *et al.*, 1990). A rapidly shallowing sequence from deep, non-volcanically influenced sedimentation represented by the black mudstones to above storm-wave base with water depths of *c.* 100 m is indicated by the hummocky and cross-stratified sandstones. The increase in grain size and extensive reworking of the overlying sandstones may represent turbidity-current deposition and progradation of the apron, fed by sediment from the caldera margin, to within and above storm-wave base (Fritz *et al.*, 1990). Howells *et al.* (1991) noted that the overall volume of reworked material exposed around the northern edge of the caldera is small compared to the infill. This suggests that the edifice of the Snowdon caldera had a limited subaerial expression and ponding of eruptive products occurred within a shallow-marine depression.

A thick rhyolite flow was intruded into the upper part of the LRTF; the presence of an autobrecciated carapace indicates that this was probably locally extrusive onto the sea floor. The overlying tuffs and their rhyolitic clasts, which mark the top of the LRTF, are geochemically distinct from the underlying tuff sequence but closely match the composition of the rhyolite. This supports their emplacement as a distinct magmatic event within the evolution of the Snowdon caldera.

Following resurgence and reworking of the main caldera-related tuffs, the Snowdon eruptive centre was dominated by basaltic volcanic activity. This activity is represented at Cwm Idwal by the Bedded Pyroclastic Formation which erupted into a shallow-marine environment, as is indicated by the presence of basaltic pillow lavas and reworking of the upper basic tuffs and lavas.

Conclusions

The Cwm Idwal GCR site provides magnificent exposures of volcanic products from both the 1st and 2nd eruptive cycles which occurred in Snowdonia in Caradoc times. The heterogeneous sequence at Cwm Idwal records the dramatic influence of major caldera-related explosive volcanism on the sedimentation patterns in a marine environment. Combined volcanological and sedimentological studies reveal significant changes in sediment supply and modification of the tectonic environment in response to volcanic activity. In addition the Cwm Idwal site provides excellent examples of emplacement features of welded ash-flow tuffs in a shallow-marine setting and emphasizes the importance of reworking and the widespread redistribution of volcanic material in such an environment.

CURIG HILL
(SH 722 580–736 593)

M. Smith

Introduction

Following the cessation of volcanic activity related to the 1st Eruptive Cycle, northern and central Snowdonia underwent large-scale extension in later Caradoc times to form an elongate NW-trending trough or graben structure. The sediments and lesser volumes of acidic and basic tuffs that infilled this trough provide valuable information on the environment of deposition and volcanic activity prior to the initiation of the 2nd Eruptive Cycle of acid ash-flow tuff volcanism in North Wales.

The GCR site in the vicinity of Curig Hill records an impressive heterogeneous sequence of marine sedimentary rocks, interlayered with tuffaceous sedimentary rocks and distal acid and basic tuffs. This distinctive association, which occurs immediately above the Capel Curig Volcanic Formation, passes conformably up into a distal outflow tuff derived from the Snowdon Centre (the Lower Rhyolitic Tuff Formation or LRTF). This tuff is in turn overlain by tuffs and tuffaceous sedimentary rocks derived from the Crafnant Centre (the Lower Crafnant Volcanic Formation or LCVF). The site is also important in being one of the few examples of a well-exposed section through a basic vent or tuff cone.

Originally, the area was mapped in 1848, with the first geological maps and sections published between 1851 and 1854, and described by Ramsay (1881). It was mapped at the 1:10 560 scale by Williams (1922) and later by the Geological Survey in 1968–70. Detailed descriptions are presented in Howells *et al.* (1978) with later revisions and re-interpretation of the stratigraphy in Howells *et al.* (1991). Published geochemical data for the LCVF indicate predominantly rhyolitic compositions with individual tuffs distinguished by their Zr/TiO_2 ratios (Howells *et al.*, 1991).

Description

The Curig Hill GCR site lies on the limb of a paired fold structure with moderate dips predominantly to the NE (Figure 6.52). The western (and lowest) parts of the succession are exposed immediately north of the A5 at Plas Curig and comprise greyish-green, well-bedded sandstones of the Cwm Eigiau Formation, interbedded with acid tuff, tuffaceous sedimentary rocks and basic tuffs. Pre-tectonic deformation of the strata is common and prominent in a 2 m-thick sandstone containing slump structures including overfolds and oversteepened foresets. Fossiliferous beds dominated by shelly faunas occurring in layers up to 10 cm thick are also common locally; north of Curig Hill these include the brachiopod *Plaesiomys multifida*, indicating a Soudleyan age. Elsewhere along strike, the presence of Longvillian faunas near the top of the section suggests that the Soudleyan–Longvillian boundary probably lies within the sequence.

The interbedded acid tuffs are fine grained and composed of devitrified, recrystallized fragmentary shards and dust, with or without a mudstone matrix. Locally, with increasing additions of sedimentary debris, the tuffs grade into tuffaceous sandstones and siltstones. Generally up to 5 m thick, the tuffaceous sandstones commonly show cross-bedding in the tops of units and washouts. In places they are disturbed by soft-sediment deformation, for example north of the Capel Curig Youth Hostel (at 7258 5811).

Basic tuffs form two distinctive layers within the succession. The lower crops out as a wedge-shaped intrusive mass some 200 m wide, forming the mass of Curig Hill immediately to the north of the Bryn Tyrch Hotel (724 581) (Figures 6.52 and 6.53). Well-cleaved, poorly sorted and rarely graded, the basic tuffs contain abundant volcanic blocks and lapilli, with bedding defined by grain-size variations and clast or block concentrations. Petrographically the tuffs are composed mainly of aggregates of chlorite, carbonate and iron oxide.

Grain-size analysis reveals that towards the summit of the hill there is a gradual increase in the size of the blocks and lapilli. This is associated with the development of a slumped, agglomerate zone characterized by blocks of tuff up to 1 m in diameter and penecontemporaneous minor faults. In addition, there are important variations in the dip patterns around the hill. In the west concentric inward (centroclinal) dips decrease from 80° to 50° towards the zone of slumped agglomerate. In contrast, above a planar discordance, which trends N–S within the eastern part of the tuff pile, dips of between 25° to 30° are more constantly to the east. The tuffs here are finer grained and include lenses of fine-grained reworked tuff and tuffaceous sedimentary rocks and pass conformably up into younger sandstones typical of the Cwm Eigiau Formation.

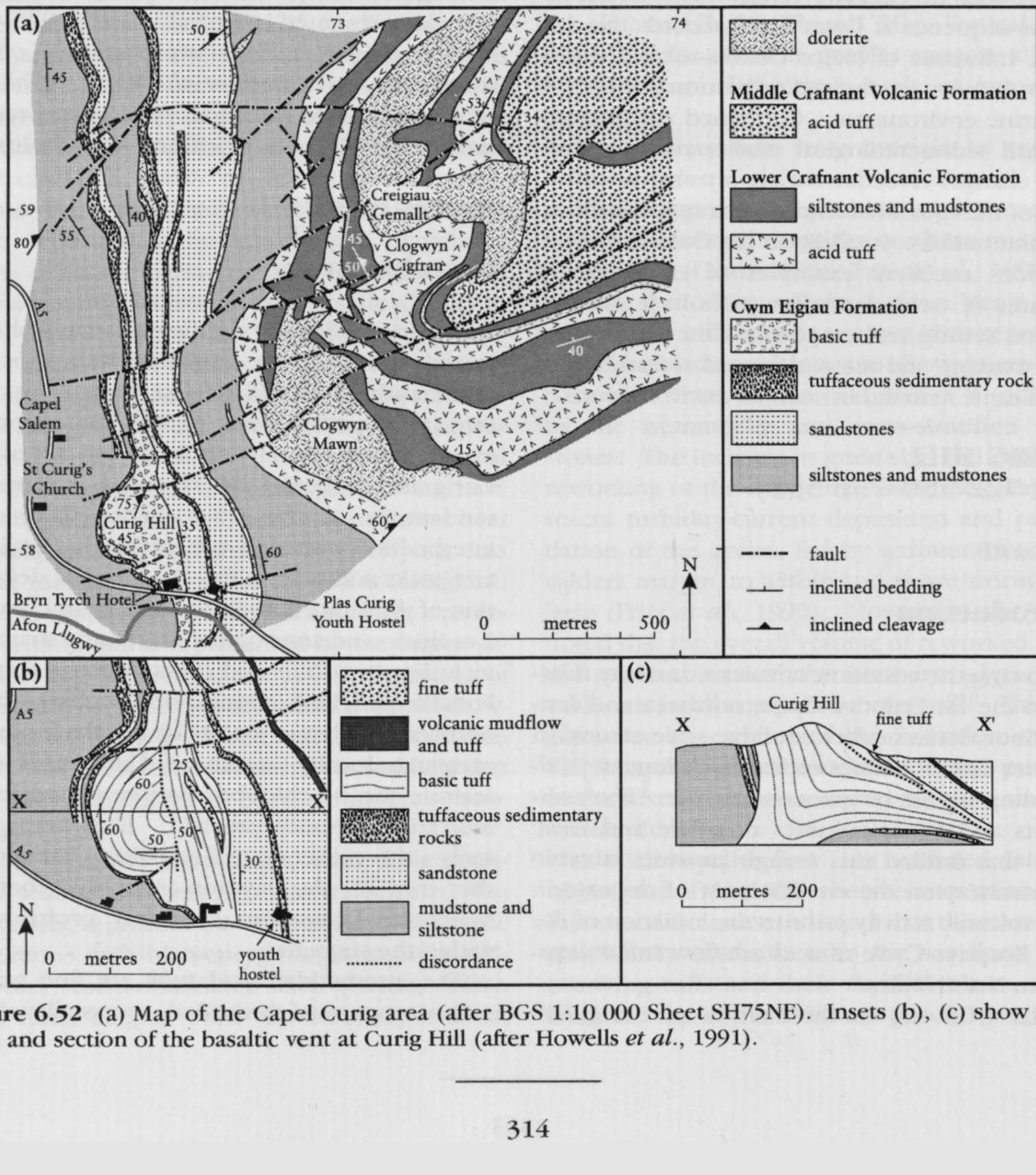


Figure 6.52 (a) Map of the Capel Curig area (after BGS 1:10 000 Sheet SH75NE). Insets (b), (c) show sketch map and section of the basaltic vent at Curig Hill (after Howells *et al.*, 1991).

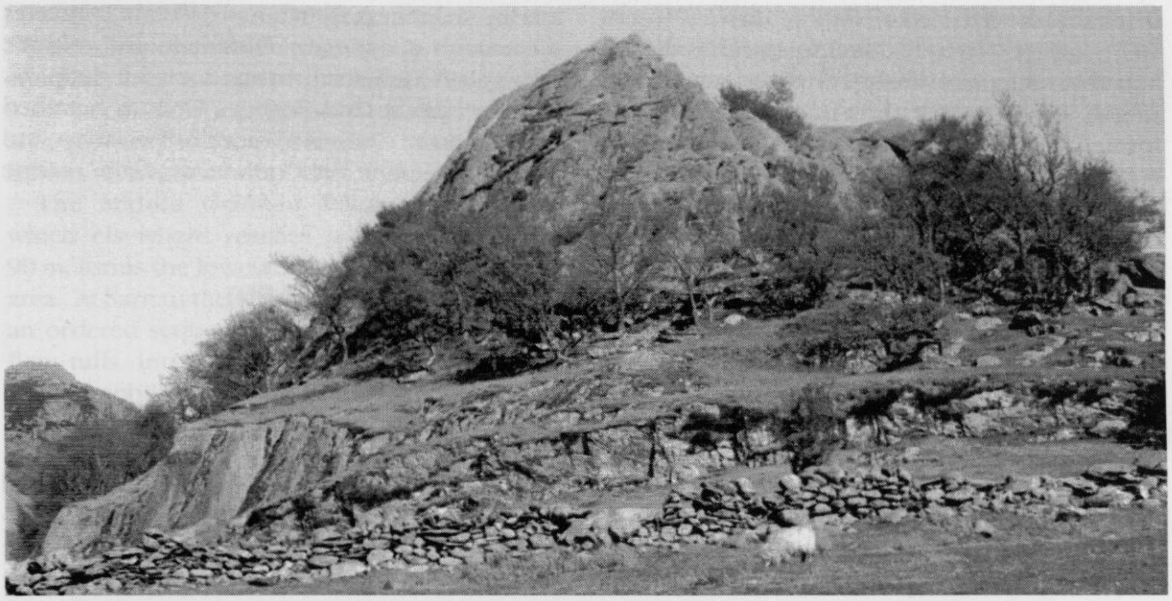


Figure 6.53 Base of bedded basalt agglomerate, Curig Hill 'vent' with acid tuff forming the lower feature near the wall. (Photo: BGS no. L1868.)

The upper basic tuff layer lies near the top of the sandstone succession at 7275 5790. It is composed of two distinct horizons: a lower laharic mudflow, less than 2 m thick, includes angular clasts of sedimentary rock and acid tuff showing a crude alignment parallel to the regional bedding; and an upper basic tuff, 2–3 m thick, which marks the contact between sandstones and overlying mudstones and siltstones. Well-exposed around 7275 5793, the tuff contains clasts of chloritized and altered basalt and basic pumice or scoria in a fine-grained matrix.

The higher parts of the GCR site, from Clogwyn Mawr across to Creigiau Gemallt, are dominated by a succession of NE-dipping acidic ash-flow tuffs separated by siltstones and mudstones and intruded by a dolerite sill.

The overlying volcanic rocks are poorly cleaved, often flinty, vitric, non-welded acid tuffs with variable proportions of crystals and lithic clasts. The lower tuff (No. 1 of the LCVF of Howells *et al.* (1973, 1978)) is equivalent to part of the most easterly outflow tuff of the LRTF (Howells *et al.*, 1991). Up to 56 m thick at 7270 5760, the tuff displays a distinctive upwards-fining sequence from a basal zone rich in crystals and lithic clasts, through a sparsely porphyritic middle part with small pumice clasts, to a fine-grained crystal-depleted top. The basal zone includes clasts of siltstone, brachiopod and trilobite fragments, and rare ooliths. The middle zone, between 7 and 21 m above the base, is regularly bedded with thin (up to 3 cm) well-cleaved silty layers and passes up into massive columnar-jointed tuff with clasts of pumice and rhyolite. Above are interbedded siltstones and mudstones.

The middle tuff (No. 2 of the LCVF) is well exposed on Clogwyn Cigfran at 7295 5873, where it is underlain by a rusty brown-weathering feldspar-phyric dolerite sill. The tuff is uniform and massive with visible pumice clasts, feldspar crystals and rare siliceous nodules. The upper tuff (No. 3 of the LCVF), up to 40 m thick, is a more heterogeneous unit, distinguished by the absence of xenocrysts and a wide range in shard sizes. Forming the eastern slopes of Clogwyn Cigfran (e.g. at 7321 5879), it includes clast-rich vitric tuff interlayered with tuffaceous siltstones. Lithic clasts include andesite, hyaloclastite, basic and acid tuff, pumice and siltstone. Bedding is demonstrated at 21 m above the base by a thin agglomeratic bed with rounded clasts.

Interpretation

The strata in the Curig Hill GCR site area lie within the middle part of the interval between the two major Caradoc eruptive cycles in Snowdonia and have been interpreted as marking a marine transgression, with the progressive development of deeper water environments from shallow marine to offshore down a south-facing palaeoslope. Sedimentological studies in adjacent areas have interpreted the sandstones in the lower part of the succession as having formed within fluctuating inner and outer shelf regimes subject to periodic storm events (Orton, 1988). Within this environment the acid tuffs and tuffaceous sedimentary rocks represent distal ash fall-out, subsequently reworked in the marine environment and disrupted by soft-sediment deformation. The coarser-grade tuffs probably represent secondary emplacement by transport as high-density debris flows and slurries of pyroclastic debris.

The centroclinal dips, lateral wedging and grain-size variation in the lower basic tuffs of Curig Hill were interpreted by Howells *et al.* (1978, 1991) to represent the upper levels of an intrusive funnel-shaped volcanic vent which probably fed a tuff cone on the ancient surface. The cone superstructure was reworked and the sediments were redeposited as the fine-grained bedded volcaniclastic sediments at the top of the section. The limited contamination of the adjacent sediment with basaltic debris suggests that such eruptions were minor and that debris dispersal was limited.

The lowest tuff of the overlying Lower Crafnant Volcanic Formation is the sole distal representative of a rhyolitic ash-flow tuff (Lower Rhyolitic Tuff Formation) derived from the Snowdon Centre. The fine-grained top of vitric dust probably represents the elutriation of devitrified and recrystallized volcanic dust and ash material from the head of the pyroclastic flow. The overlying tuffs and tuffaceous sedimentary rocks are the products of rhyolitic ash-flow eruptions with limited ingestion of substrate sediment and were emplaced in a deep-water marine environment. Later remobilization of these tuffs was periodic and localized.

Conclusions

The Curig Hill GCR site preserves an important section recording the reworking of volcanic deposits and sedimentation between the two major eruptive cycles in Snowdonia. A complex heterogeneous sequence of marine sedimentary and volcaniclastic deposits indicates the progressive subsidence and development of a major trough. The products of initial basaltic eruptions, in shallow shelf settings, were progressively reworked and buried by finer-grained marine sediments from a more distant source as the trough deepened. Distant minor volcanic activity released small volume ash-fall deposits. The start of the 2nd Eruptive Cycle is heralded by the Lower Crafnant Volcanic Formation and its emplacement into quiescent deep marine conditions.

SARNAU (SH 779 587–776 600)

M. Smith

Introduction

The Sarnau GCR site provides key exposures of the eruptive products from the most north-easterly and youngest of the three major eruptive centres that were active during the 2nd Eruptive Cycle in Caradoc times in Snowdonia. In contrast to the two other centres at Snowdon and Llwyd Mawr, the Crafnant Centre is completely buried by younger strata and its eruptive history and palaeoenvironment can only be inferred from its outflow products. The exposed strata at the Sarnau site include the Middle and Upper Crafnant volcanic formations which represent acid ash-flow tuffs derived from this centre, and their emplacement into dark marine mudstones and siltstones suggests a deep water submarine eruption.

Originally mapped by the Geological Survey in 1848, the area was included in a regional study by Davies (1936) but was not studied in detail until the resurvey on the 1:10 560 scale by the Geological Survey in 1968–70. The site area is covered by the geological sheets SH75 (Capel Curig and Betws-y-Coed), 1:25 000 scale (1976), and 109 (Bangor), 1:50 000 scale (1985). The strata, of Longvillian age, are described in Howells *et al.* (1978, 1991) and comprise ash-flow tuffs and reworked tuffs of rhyolitic to rhyodacitic composition. They are probably contemporaneous with the Bedded Pyroclastic and Upper Rhyolitic Tuff formations in central northern Snowdonia and form part of the Snowdon Volcanic Group.

Description

The Sarnau site (Figure 6.54) lies in the wooded uplands NNW of Betws-y-Coed, between Llyn Sarnau and Mynydd Bwlch-yr-haiarn. Moderately dipping to the north and east, the strata lie on the SE limb of an anticline, one of a series of NE-trending open fold structures in the area. A complex array of steeply dipping brittle faults form prominent topographical features in the area and are the focus of lead and zinc mineralization (Howells *et al.*, 1978).

The Middle Crafnant Volcanic Formation, which elsewhere reaches a total thickness of 90 m, forms the lowest stratigraphical unit in the area. At Sarnau the formation is characterized by an ordered sequence of thin, primary acid ash-flow tuffs, interlayered with flaggy, evenly bedded, remobilized tuffs, tuffaceous to volcaniclastic sedimentary rocks, and black pyritic mudstones and siltstones. These form a series of well-developed scarp and dip features (e.g. at 7730 5880). The interlayered sedimentary rocks comprise mainly dark-grey structureless mudstones and siltstones with infrequent ribs of turbiditic sandstone. The mudstones and siltstones contain varying proportions of iron oxide, sericite and chlorite, with scattered fragments of feldspar crystals, locally up to 0.5 mm in length. The thin sandstones are normally graded with scoured and loaded bases often marked by concentrations of pyrite. Flame structures, indicating subsequent deformation of the sequence while semi-lithified, include lobes of sandstone completely surrounded by flames of the underlying mudstone.

The various units range from primary tuffs through tuffaceous to volcaniclastic sedimentary rocks and display a wide range of grain size from ash to breccia. The thin flaggy turbiditic tuffs with recrystallized cuspate shards set in a fine-grained vitroclastic and micaceous matrix show fine cross-lamination and grading and may contain fragmentary fossiliferous debris including crinoid columns and graptolites (Howells *et al.*, 1978). The coarser tuff-breccias are well exposed in the forest track (at 7705 5910) where they form massive beds up to 1.3 m thick with blocks of angular to subrounded, indurated siltstone, mudstone (Figure 6.55) and tuffaceous and volcaniclastic sedimentary rocks, and are invariably associated with thin fine-grained siliceous air-fall tuffs. Some of the blocks show a faint internal planar lamination that parallels the irregular periphery of the block indicating that the blocks were probably unlithified at the

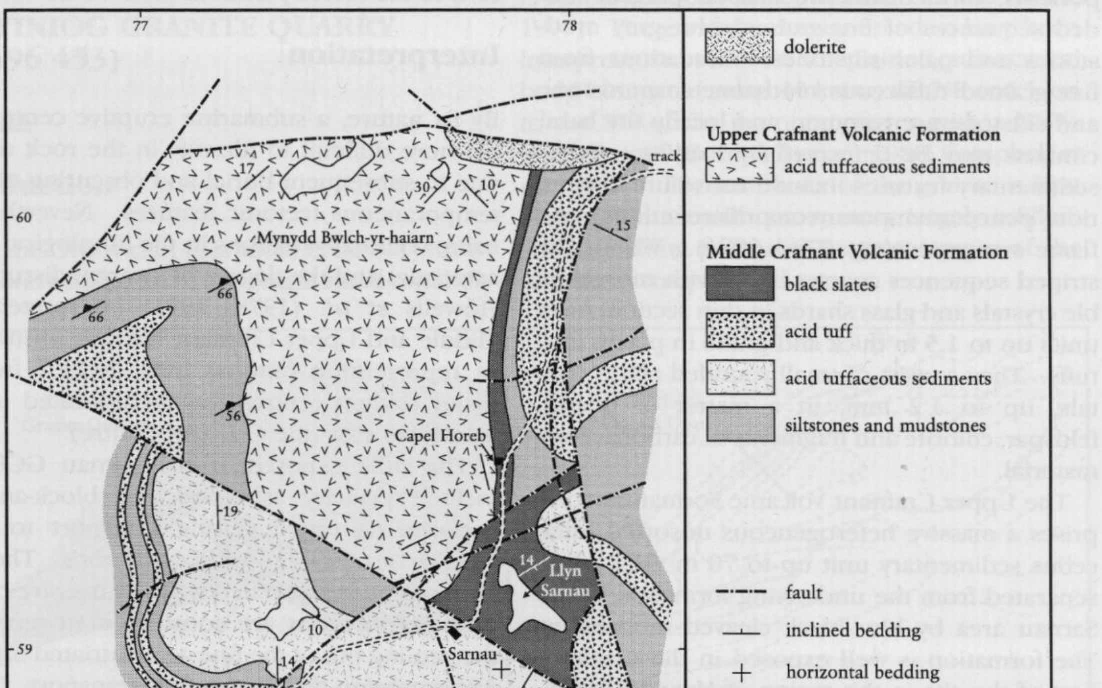


Figure 6.54 Map of the Sarnau GCR site area, after BGS 1:10 560 sheets SH75SE (1977) and SH76NE (1979).

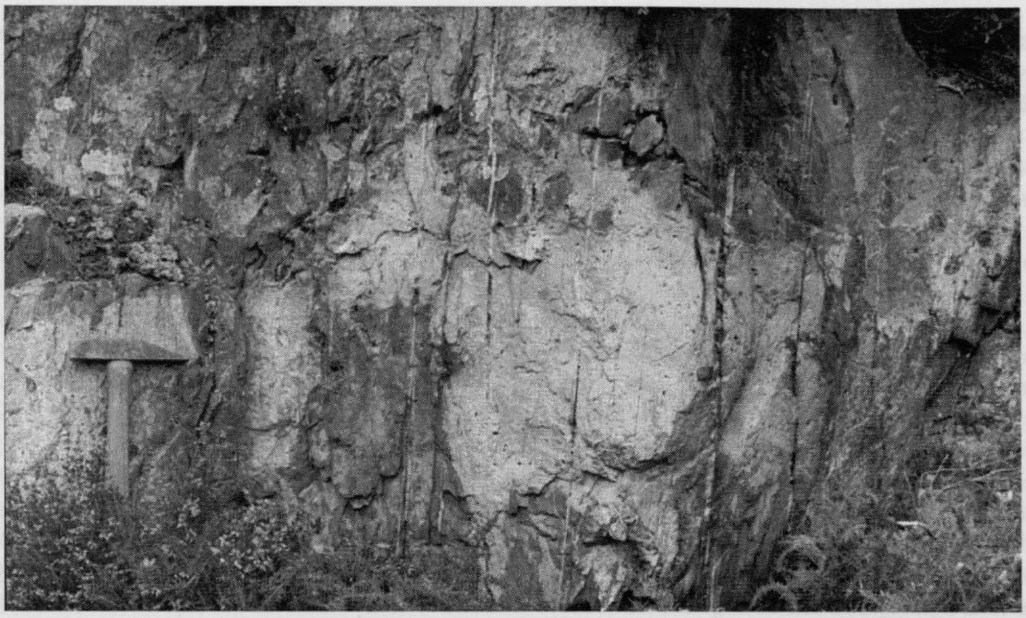


Figure 6.55 Acid ash-flow tuff with blocks and clasts of mudstone, Middle Crafnant Volcanic Formation, Sarnau (SH 7721 5891). (Photo: BGS no. L2905.)

time they were incorporated into the breccia.

The reworked tuffs, comprising varying admixtures of pyroclastic and sedimentary components, form distinctive striped parallel-bedded sequences of fine-grained blue-grey mudstones and paler siltstones. Gradations from fine-grained tuffaceous mudstone to mudstone and siltstone are common and locally the basal contacts may be deformed by loading. Other sedimentary features include convolute lamination, penecontemporaneous microfaulting, and flame structures (e.g. 7745 5884). Within the striped sequences coarser beds, with recognizable crystals and glass shards in thin section, form units up to 1.5 m thick and grade in places into tuffs. They consist of small rounded albite crystals, up to 1.2 mm, in a matrix of quartz, feldspar, chlorite and fragments of carbonaceous material.

The Upper Crafnant Volcanic Formation comprises a massive heterogeneous unsorted tuffaceous sedimentary unit up to 70 m thick. It is separated from the underlying formation in the Sarnau area by blue-black cleaved mudstones. The formation is well exposed in the northern part of the site in the region of Mynydd Bwlch-yr-haiarn but is poorly bedded and only forms subdued scarp features. The tuffaceous rocks are generally structureless, strongly cleaved due to the high proportion of mudstone, and consist of cuspate shards with fragmentary feldspar crystals and pumice admixed with fine aggregates of chlorite, sericite and carbonaceous material. The proportions of constituents are highly variable. A typical exposure is in a small quarry adjacent to the forestry track at 7729 6019.

Interpretation

By its nature, a submarine eruptive centre will be more difficult to identify in the rock record due to subsequent burial and obscuring of contemporaneous tectonic features. Nevertheless, using regional variations in the lithological characteristics and the degree of internal disruption, Howells *et al*. (1978, 1991) interpreted the Middle and Upper Crafnant volcanic formations as representing outflow tuffs derived from a major caldera centre tentatively located to the north and east (the Crafnant Centre).

The tuffs exposed at the Sarnau GCR site include primary ash-flows and block-and-ash deposits disrupted during transport to form slurries of unstable pyroclastic debris. The thin siliceous beds associated with the massive coarse tuffs and breccias are considered to represent the settling out of the fine ash elutriated into the water column during ash-flow transport. These were also subject to reworking and were resedimented as tuff-turbidites represented by the striped beds. The frequent restriction of convolute lamination to these thin beds may be the result of emplacement of tuff on partly lithified water-saturated tuffaceous sediment which deformed thixotropically, possibly in response to seismic shocks (Howells *et al.*, 1978).

Within the Upper Crafnant volcaniclastic deposits, the general lack of sorting and internal bedding suggests that they were deposited from high-density turbid flows of pyroclastic debris that incorporated sedimentary material from a semi-lithified substrate during transport. As Howells *et al.* (1991) noted, however, such a process might not be expected to produce such a well-mixed sequence, and an alternative model of an underwater explosive eruption through unlithified mud could also be considered.

Conclusions

The GCR site at Sarnau represents a typical series of primary and reworked acid ash-flow tuffs emplaced within a deep water marine environment. It provides a well-exposed section through tuffs erupted from the Crafnant Centre, the most north-easterly of the three main Ordovician caldera centres which developed during the 2nd Eruptive Cycle in Snowdonia in Caradoc times.

FFESTINIOG GRANITE QUARRY (SH 696 453)

M. Smith

Introduction

Within the Ordovician (Caradoc) cycle of volcanism in Snowdonia there are only a small number of subvolcanic intrusions that are not spatially related to the main eruptive centres. Among the largest are the granite plutons of Tan y Grisiau and Mynydd Mawr, which lie several kilometres outside the main zone of Caradoc caldera structures, intrusions and related extrusions as defined by Howells *et al.* (1991). They were emplaced mainly into Lower Ordovician (Tremadoc) or Cambrian (Merioneth) sandstones and siltstones. Sections in the Ffestiniog Granite Quarry provide a rare example of the contact relationships and autometasomatic effects that occurred in the granite roof during volatile streaming and crystallization. The area was originally described by Jennings and Williams (1891) and later revised by Bromley (1963), whose maps and descriptions are incorporated into the recent resurvey (Howells and Smith, 1997).

The Tan y Grisiau Granite has an outcrop area of *c.* 4 km^2 and is intruded into sandstones and siltstones of the Dol-cyn-afon Formation (Figure 6.56). The outcrop pattern is that of a truncated ellipsoid but the extent of the hornfels and aureole and associated geophysical anomalies show a much larger body at depth (Howells and Smith, 1997). The gravity and magnetic data have been interpreted to reflect a steep-sided, sub-vertical body, elongated some 10 km to the NE and 5 km to the SW of the main exposures with a NNW-dipping roof (Cornwell *et al.*, 1980; Campbell *et al.*, 1985). The roof zone of the granite is best exposed in a small quarry, now largely infilled, situated along the north-eastern margin of the granite outcrop.

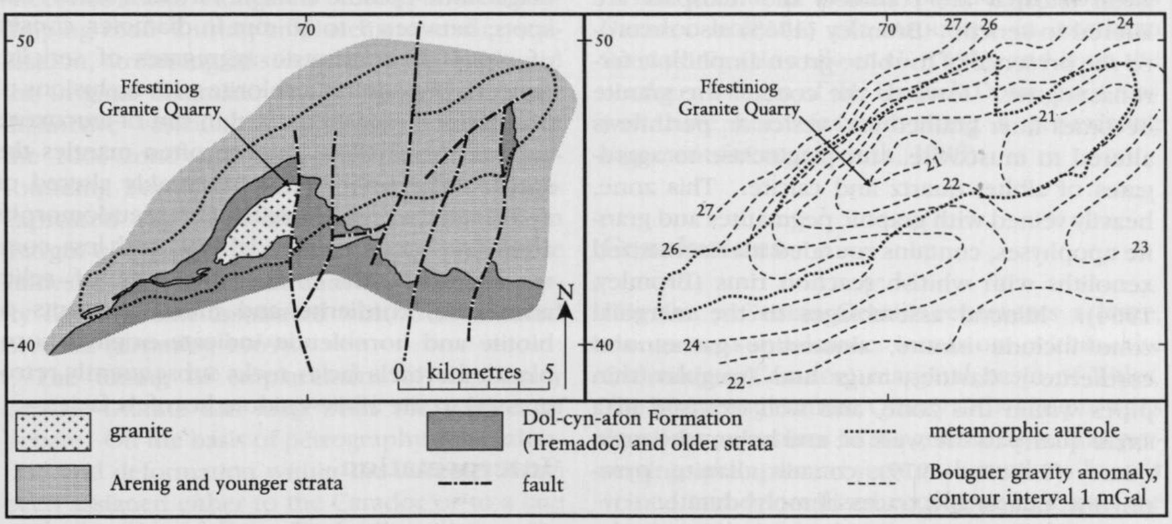


Figure 6.56 Map of the Ffestiniog area showing the surface outcrop and limit of metamorphic aureole of the Tan y Grisiau Granite and the associated Bouguer gravity anomaly.

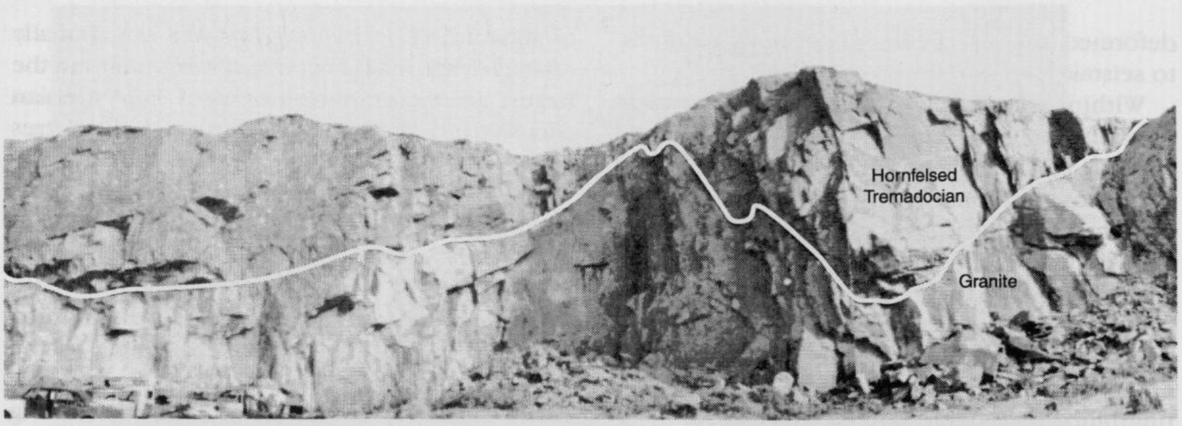


Figure 6.57 The roof zone of the Tan y Grisiau granite intrusion, Ffestiniog Granite Quarry. (Photo: reproduced from Roberts, 1979.)

Description

The Ffestiniog Granite Quarry GCR site exposes the upper contact of the Tan y Grisiau Granite, here dipping 40° to the NW. The contact is clearly discordant (Figure 6.57) and separates Tremadoc siltstones and mudstones in the upper part of the quarry face from a distinctive roof facies of the granite.

In the lower quarry face (now largely obscured) the granite is a grey-green, homogeneous, fine-grained equigranular mosaic of plagioclase (albite–oligoclase), perthite and quartz with dark clots (0.5–1.0 cm in diameter) of chlorite after biotite. Common accessories include magnetite, zircon and allanite with traces of titanite, monazite, fluorite and epidote. In thin section, granophyric intergrowths of quartz and alkali feldspar are common and feldspars are altered to sericite. Bromley (1963) also recorded the presence of the blue-green amphibole ferrohastingsite. Towards the contact the granite becomes finer grained and vesicular, perthite is altered to muscovite, and plagioclase to aggregates of albite, quartz and calcite. This zone, heavily veined with graphic pegmatites and granite apophyses, contains rounded metasomatized xenoliths with whitish reaction rims (Bromley, 1964). Mineral assemblages in the marginal zone include biotite, almandine garnet and cordierite. Cavities, vugs and irregular thin pipes within this zone, and well exposed in a small quarry to the west of, and below, the main quarry (Roberts, 1979), contain allanite, pyrophyllite, quartz and traces of molybdenite.

The overlying country rocks belong to the Upper Sandstone Member of the Dol-cyn-afon Formation and comprise well-bedded medium- to fine-grained sandstones and siltstones. Immediately adjacent to the granite these strata are a very fine-grained, flinty, yellow-grey, unfoliated hornfels with irregular planar light and dark banding. In thin section a granoblastic texture of quartz with decussate muscovite is dotted with irregular dark blebs of chlorite and magnetite. Rare euhedral laths of sericite and chlorite may represent pseudomorphs after andalusite. Thin veins of albitic feldspar, often following early joints, and associated with enhanced levels of sericitic alteration in the adjacent wall rocks, are interpreted as former pathways for escaping volatiles.

At 10–15 m from the contact, the above rocks pass gradationally up into coarser grained, foliated, spotted hornfelses comprising the assemblage albite-epidote-chlorite-sericite-quartz. The spots, between 1 to 10 mm in diameter, consist of radial or concentric aggregates of sericite, quartz and penninitic chlorite with inclusions of fine-grained magnetite. A thin rim of leucoxene and microcrystalline chlorite often mantles the spots. Where the spots are weakly altered or deformed they are identifiable as pseudomorphs after porphyroblastic andalusite and less commonly cordierite. The presence of relict andalusite, cordierite and minor amounts of biotite and hornblende indicate original hornblende hornfels facies rocks subsequently retrogressed to the albite-epidote hornfels facies.

Interpretation

Compositionally, the Tan y Grisiau Granite has a rhyolitic to rhyodacitic trace element signature and Howells *et al.* (1991) noted a close comparison with the main phases of rhyolite dome emplacement in the Lower Rhyolitic Tuff Formation caldera. The granite appears to have been emplaced by stoping and contains a prominent marginal zone choked in places with partially digested xenoliths associated with pegmatite and tourmalinized breccias, and cut by veins of micrographic aplite and granophyre. Deformation within much of the granite is weak to non-existent and the lack of a penetrative foliation or mineral lineation supports a passive emplacement model. Locally, however, discrete narrow (1–2 m wide) zones of intense strain have been recorded (Smith, 1988). These zones, often associated with sheared dolerite dykes, are characterized by an intense foliation, a marked reduction in grain size and mylonitic fabrics; they indicate that the granite was deformed during the Caledonian Orogeny. Deformation is more clearly expressed in the overlying aureole rocks which are characterized by the development of thermal spots in sedimentary rocks up to 1 km stratigraphically above the granite roof. The spots, composed mainly of radial aggregates of sericite, quartz and chlorite, make excellent strain markers and have been studied by a number of workers (Bromley, 1963; Coward and Siddans, 1979; Smith, 1988; see review by Scott, 1992).

The extensive hornfels aureole and associated geophysical anomalies clearly show that the outcrop in the Tan y Grisiau area represents only a small part (less than 10%) of a large granite body (Figure 6.56). Subsurface, the granite has a sheet-like form, elongated NE–SW, with a NW-dipping roof. During emplacement and crystallization, streaming of silica-rich volatiles altered the original magmatic assemblage, producing a distinctive vesicular mineralized facies within the roof zone and retrogression of the surrounding hornfels. This autometasomatism is expressed elsewhere along the north-western margin of the granite with enhanced radiogenic values in areas of allanite mineralization and cavity development associated with tourmalinized breccias (Bromley, 1969).

The timing of emplacement of the Tan y Grisiau Granite has long been the subject of debate. On the basis of petrography, mineralization and deformation within the aureole, it has been assigned either to the Caradoc or to a late stage in the Caledonian Orogeny (see Bromley, 1969 for review). To the SW of the main outcrop, granophyric apophyses and sheets intrude Arenig strata, and transgress the mid-Caradoc unconformity (Smith *et al.*, 1995) and the disrupted strata within the Rhyd mélange (Bromley, 1969; Smith, 1988; Howells and Smith, 1997). The extent of the hornfels (thermal spotting) aureole (Bromley, 1963, 1969) further indicates that rocks up to Costonian–Harnagian in age (the Moelwyn Volcanic Formation) are affected whereas younger rocks are not. Thus, the granite is stratigraphically constrained to the Caradoc. This, together with its geochemical correlations with the Lower Rhyolitic Tuff Formation, suggests that it is a subvolcanic intrusion associated with the 2nd Eruptive Cycle of caldera volcanism in North Wales (see the Snowdon Massif GCR site report).

Magnetic studies by Piper *et al.* (1995) indicate that the tilt-adjusted remnance directions are pre-Silurian and that magnetization occurred after deformation in late Ordovician times. K-Ar isotopic determinations by Thomas *et al.* (1966) suggest an age of *c.* 408 Ma, and recent Rb-Sr determinations by Evans (1990) provide an age of 384 ± 10 Ma. In common with many other younger Caledonian granites in North Wales these are considered to be reset ages affected by low-grade metamorphism and deuteric alteration during the Acadian Event (Evans, 1991). The emplacement age is probably concordant with the Mynydd Mawr Granite (438 ± 4 Ma) and the Bwlch y Cwyion hornfels (454 ± 20 Ma) which are the only two North Wales granites currently known to have escaped isotopic resetting (Evans, 1991).

The granite is broadly parallel to the main Caradoc volcanic rift structure in northern Snowdonia (Howells *et al.*, 1991), and is on the northern margin of the Harlech Dome, so it may well have been focused along a pre-existing basement fracture (Smith, 1988).

Conclusions

The Tan y Grisiau Granite represents a large, elongate, subvolcanic intrusion within the Ordovician (Caradoc) marginal basin of Wales. The Ffestiniog Granite Quarry GCR site provides excellent exposures of the granite as well as preserving an important section through its heavily veined and mineralized roof zone and into the overlying hornfelsed sedimentary rocks.

PANDY (SJ 195 362, 199 360 AND 197 356)

P.J. Brenchley

Introduction

The Pandy GCR site consists of three outcrop areas in the Ceiriog Valley near Pandy, Denbighshire, where three tuffs, belonging to the Cwm Clwyd, Swch Gorge and Pandy tuff formations, are well exposed. Two of these tuffs are products of explosive silicic volcanism, and comprise pumiceous ash-fall, ash-flow, and pyroclastic surge deposits, while the third is mainly composed of volcaniclastic sandstones, deposited at the coastal fringe of subaerial ash-flow tuffs. The tuffs clearly show a range of depositional processes. The three tuffs relate to activity at volcanic centres widely separated across North Wales, contemporaneous with the major caldera volcanism of Snowdonia (Howells *et al.*, 1991; Bevins *et al.*, 1992) (see, for example, the Snowdon Massif GCR site). The centres were apparently short-lived and produced discrete subaerial pyroclastic deposits within a predominantly marine succession, implying contemporaneous emergence in some way linked to the volcanism.

Research on the volcanic rocks in the Berwyn has occurred in two main phases. The first involved the mapping and preliminary description of the volcanic rocks. Ramsay (1866), in the Geological Survey Memoir, reported the continuity of 'ash bands' along the northern flank of the Berwyn, while subsequently the outcrops and petrography of the igneous rocks were described in several papers in the early part of the 20th century, most notably by Cope and Lomas (1904) and Cope (1910, 1915). Cope (1910) included the first attempt to reconstruct volcanic events from the sequence of deposits. Groom and Lake (1908) presented a detailed account of the Glyn Ceiriog area that included perceptive descriptions of the pyroclastic deposits, recognizing that the flinty felsitic parts of the Pandy Tuff had a vitroclastic texture and were not intrusive as others had thought previously. They also noted the 'bogen'-like texture of what is now recognized as a welded tuff. Resurvey by the Geological Survey of part of the eastern Berwyn area (Wedd *et al.*, 1927, 1929) showed errors in the previous maps of the Swch Gorge and Pandy tuffs and established their true continuity along the northern flanks of the Berwyn. Subsequently, in the second phase of investigation, detailed studies of the pyroclastic beds focused on the depositional processes and environments (Brenchley, 1964, 1969, 1972).

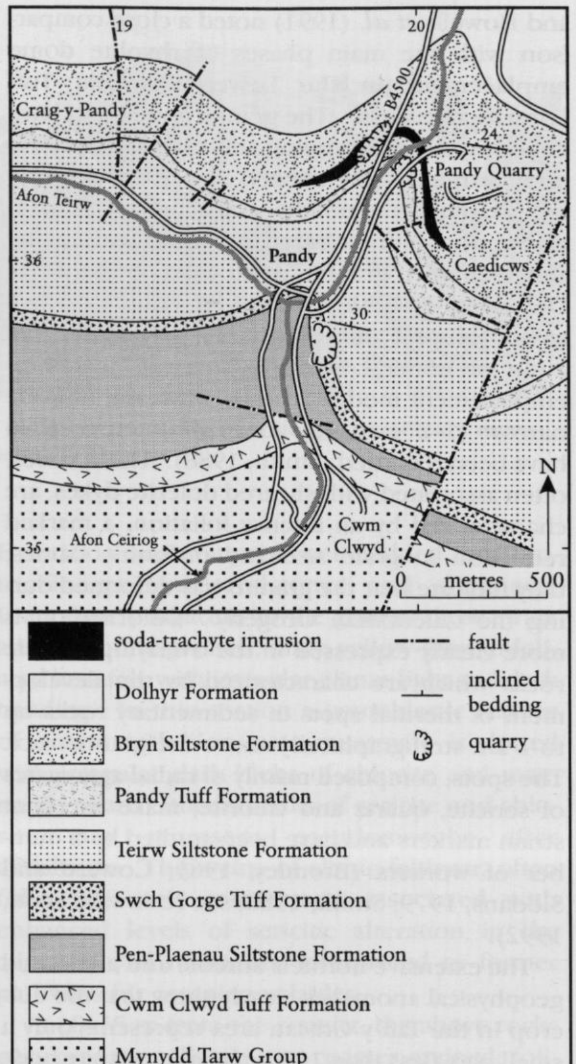


Figure 6.58 Map of the Pandy area.

The Pandy GCR site is critical to understanding the Caradoc volcanic history of the Berwyn area of North Wales. It is particularly important because the pyroclastic deposits exhibit magnificently many of the characteristic features of the explosive silicic volcanism that was widespread across North Wales. The significant localities are within a small area, the tuffs are well exposed and are relatively unaffected by deformation or metamorphism, so that they retain remarkably clear details of primary vitroclastic textures. Additionally the contacts between the Pandy Tuff and the marine sedimentary rocks above and below, and the internal relationships between the constituent welded and unwelded ash-flow tuffs, contribute to an understanding of the nature and origin of transiently emergent volcanic islands. The site therefore contributes to a broader view of silicic volcanism in the context of the Ordovician marginal basin of Wales (Kokelaar *et al.*, 1984b).

Description

Strata of Caradoc age, including the three main tuff formations, crop out along the north flank of the Berwyn and are intersected by the Ceiriog Valley near Pandy, where the succession is well exposed on the valley sides (Figure 6.58). The Caradoc sedimentary strata that separate the tuff formations are predominantly silty mudstones with interbedded sandstones, interpreted as having formed in shallow subtidal environments in water depths of less than 25 m (Brenchley and Pickerill, 1980). The tuffs are probably all of Soudleyan age, though the Pandy Tuff could be Lower Longvillian (Brenchley, 1978).

The Cwm Clwyd Tuff is a sequence of bedded tuffs that are well exposed in crags on the eastern slopes of the Ceiriog Valley (Figure 6.58). It comprises alternations of thick-bedded lithic-crystal-pumice and thin-bedded pumiceous tuffs with partings typically 1–2 cm apart. The thick-bedded tuffs are tabular and may be massive, normally graded or, more rarely, inversely graded. Normal grading is most common in the coarser lithic lapilli-tuffs which show a reduction in grain size and increase in the amount of pumice towards their tops. The juvenile component of these tuffs is mainly pumice shreds and up to 12% quartz and 40% albite crystals, together with a variable content of accidental lithic clasts of pink rhyolite up to lapilli grade. The thin-bedded vitric tuffs are tabular, parallel-laminated or cross-laminated with dips of up to 10°. The vitric fraction in the tuffs is generally fine-grained tubular pumice, but bicuspate or tricuspate glass shards predominate in some beds. Accretionary lapilli occur in beds a few centimetres thick, interbedded within the sequence at several levels. The lapilli, which are flattened in the plane of the bedding, typically have a rim of fine vitric ash enclosing a pumice core. At the top of the sequence there is a massive unit of vitric-crystal tuff, 4 m thick, with irregular-shaped pumice lapilli weathered to form cavities. One laterally impersistent breccia containing blocks of tuff similar to the enclosing sequence is interpreted as a lahar deposit infilling a small channel and this, together with a few small channels containing a concentration of lithic clasts, is the only record of erosion and reworking of the tuffs.

The Swch Gorge Tuff, well exposed in quarries and crags on the eastern slopes of the Ceiriog Valley (Figure 6.58), comprises 40 m of volcaniclastic sandstones. The succession consists of thick-bedded, generally tabular sandstones up to 1 m thick that commonly appear massive although some show large-scale cross-stratification. There are thin shale partings between some beds, while large flakes of mudstone, some showing imbrication, are present in some of the sandstones. Desiccation cracks are known from a loose block. The sandstones are medium grained and are composed predominantly of feldspar and grains of volcanic rock with laths of feldspar, suggesting that they are from a lava source and not derived from the ash-flow tuffs that form the thicker Swch Gorge Tuff sequence farther west (Brenchley, 1969). Rare graptolites have been recorded from within the Swch Gorge Tuff at Pandy (Groom and Lake, 1908) and a varied trilobite–brachiopod fauna occurs in the thinner-bedded sandstones at the top of the sequence (Brenchley, 1978).

The Pandy Tuff is exposed in crags on both the eastern and western slopes of the Ceiriog Valley and in quarries at Caedicws, Craig-y-Pandy and near Pandy (Figure 6.58), where a particularly flinty facies of the tuff was exploited for the production of china. The sequence through the Pandy Tuff is best exposed in the Pandy Quarry where it consists of 6 m of massive lithic-crystal-vitric tuff overlain by 21 m of massive vitric-pumice lapilli-tuffs that have unflattened pumice in the basal metre, show flattened pumice fiamme and a eutaxitic texture through the succeeding 8 m, and pass transitionally into a further 12 m of unwelded tuffs (Brenchley, 1964). In the top few metres of the tuff there is a marked increase in the abundance of uncompacted pumice clasts. The overlying sedimentary rocks lie in erosional hollows in the tuffs and contain a shallow-marine brachiopod–bryozoan–bivalve fauna (Harper and Brenchley, 1993). The quarries at Caedicws and Craig-y-Pandy show a similar sequence, but detail is partly obscured by large silicic nodules. Columnar-jointing of the welded ash-flow tuff is

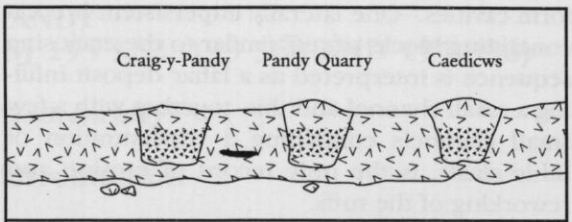


Figure 6.59 Relationship between welded and unwelded ash-flow tuffs in the Pandy area.

particularly well preserved at Caedicws.

In the crags laterally adjacent to the quarries and throughout most of the outcrop of the Pandy Tuff, welded tuffs are absent and the sequence consists of massive lithic-crystal-vitric tuffs, characteristically with coarse accidental lithic clasts at the base (coarse-tail grading) that range up to a few centimetres in diameter and protrude from the rock face. No internal divisions have been recognized within this development of the tuff, except in crags below the eastern end of Craig-y-Pandy where there is one horizon 6 m above the base where the clasts are concentrated to form a bed that thins laterally from 3 m to 4 cm over a distance of 12 m. The base of the Pandy Tuff is sharp but commonly irregular where the tuff has loaded into the underlying marine sediments, which locally contain detached blocks of the tuff several metres long. The marine mudstones extend upwards as tongues into the tuff, and sandstone beds are deformed into ball-and-pillow structures.

Interpretation

The site exhibits diverse pyroclastic deposits, formed by ash-fall and ash-flow processes representing accumulations related to separate volcanic centres in a generally marine, marginal basin setting. The Cwm Clwyd Tuff, with its predominance of fine pumice and beds of accretionary lapilli, records plinian or phreatoplinian eruptions that deposited more than 40 m of ash subaerially to a distance of at least 7 km from the volcanic centre. Beds have low-angle cross-stratification, in some instances occurring in stacked sets, implying deposition from currents. The low dip in most of the laminae and the variable direction of foreset dips suggest that the associated bedforms were low-amplitude, long-wavelength, sinuous dunes constructed by pyroclastic surges. The massive, thick-bedded lithic-crystal-pumice tuffs and the graded lithic-crystal-pumice lapilli-tuffs were interpreted as ash-fall tuffs by Brenchley (1972) because of their tabular nature and the vertical separation of the lithic clasts from the pumice in the graded beds. However, neither of these criteria is diagnostic and many of the beds could equally well have been deposited from pyroclastic surges. The range of bed types, including massive, inversely graded, graded and parallel-laminated or cross-laminated tuffs, could all be associated with downcurrent changes in the flow characteristics and depositional mechanisms of pyroclastic currents (Chough and Sohn, 1990). There is, however, a close relationship between ash-fall deposits and pyroclastic density currents, because ash columns may collapse (Cas and Wright, 1987) and evolve into different or varying concentrations and it is likely that the Cwm Clwyd Tuff records both ash-fall and pyroclastic surge deposits.

In contrast to the Cwm Clwyd Tuff, the Swch Gorge Tuff, in the Ceiriog Valley, is mainly reworked rather than primary. A high proportion of lithic grains of lava appear to have been derived from a source outside the immediate area, or from a local source that was entirely destroyed by erosion. Additionally there are a few thin interbedded marine mudstones. Laterally, towards the east, the volcaniclastic sandstones are interbedded with ash-flow tuffs and within 15 km the succession thickens and is wholly composed of ash-flow tuffs. The lateral association with welded ash-flow tuffs and the shallow subtidal sediments above and below (Brenchley and Pickerill, 1980) place the volcaniclastic sediments in a shallow-marine context. This is supported by the brachiopod–trilobite fauna at the top of the tuff that belonged to a *Dinorthis* community living in estimated water depths of less than 10 m (Pickerill and Brenchley, 1979). The presence of flat mudstone clasts within the sandstones and the record of desiccation cracks suggest an intertidal setting. Some of the thick-bedded sandstones are cross-stratified, suggesting that dune bedforms were present, but other beds are either massive or planar laminated and some are separated by a mud parting. The welded ash-flow tuffs of the Swch Gorge Tuff probably formed islands of low relief (Brenchley, 1969) and the volcaniclastic sandstones in the Ceiriog Valley appear to represent an intertidal coastal fringe with dunes and sand flats intermittently covered by mud layers.

The Pandy Tuff represents a third type of pyroclastic accumulation, which is almost wholly composed of ash-flow tuffs. Throughout most of the length of its outcrop the tuff is a massive unwelded ash-flow tuff with a distinctive content of accidental lithic lapilli. The presence locally of a lenticular laharic deposit within the tuff suggests that it was formed from more than one flow. The deformation of the underlying substrate shows that the tuff was deposited on unconsolidated marine sediments. The absence of any signs of marine reworking suggests that if the pyroclastic flow deposited its contents in a marine environment, accretion above sea level was very rapid. Alternatively the sea floor may have been uplifted tectonically.

The welded ash-flow tuffs, confined to three separate short lengths of outcrop, form a single cooling unit and have a concentration of pumice at their top reflecting segregation during transport and eventual deposition from the waning current. Their lateral margins are not exposed, but it appears that the welded ash-flow tuffs abut against the unwelded ash-flow tuffs (Figure 6.59). They are interpreted as ash-flow deposits that infilled canyons incised into the non-welded ash.

Conclusions

The Pandy GCR site incorporates three contrasting manifestations of silicic volcanism in a shallow-marine setting towards the edge of the Ordovician marginal basin of Wales. Each volcanic formation is both underlain and overlain by shallow-marine sedimentary rocks, but two of the three tuffs were deposited subaerially, the third on the coastal fringe of a volcanic island. The Cwm Clwyd Tuff was formed from the products of explosive steam- and gas-charged (plinian/phreatoplinian) eruptions. Deposition was probably from pyroclastic flows and by ash-fall, but the relative frequency of the two depositional processes is uncertain. The Swch Gorge Tuff is formed of volcaniclastic sandstones deposited in an intertidal environment with shallow-marine dunes and sand flats, on the coastal fringe of a volcanic island. The Pandy Tuff is composed of ash-flow tuffs that appear to have accumulated fast enough in a marine environment to form a volcanic island or were deposited on a tectonically uplifted surface. The initial sheets of unwelded tuff were dissected by canyons that became the conduits for subsequent ash-flows which formed welded tuffs.

The importance of the site is that it exhibits particularly well some important aspects of Ordovician (Caradoc) silicic volcanism in a small, accessible and well-exposed area. The site is particularly relevant to an understanding of the genesis of transiently emergent volcanic accumulations in general, and contributes more particularly to an overall understanding of silicic volcanic processes in the Ordovician marginal basin of Wales.

TRWYN-Y-GORLECH TO YR EIFL QUARRIES (SH 348 455–363 461)

T.P. Young and W. Gibbons

Introduction

The Trwyn-y-Gorlech to Yr Eifl quarries GCR site (Figure 6.60) encompasses a superbly exposed transect across the Garnfor Multiple Intrusion, one of the most interesting of a number of major Ordovician intermediate and acidic intrusions that crop out along the north limb of the Llŷn Syncline. An outer microgranodiorite is exposed on the coast at Trwyn-y-Gorlech in the west and in the Yr Eifl quarries to the east. The Yr Eifl quarries also expose the 'Blue Rock', a dark porphyritic hypersthene-bearing microgranodiorite. The centre of the GCR site, the mountainside of Garnfor, exposes an inner, microtonalitic intrusion that is also exposed in the smaller Garnfor Quarry.

Tremlett (1962) interpreted the field relationships of the Garnfor Intrusion as indicative of a 'Caledonian' age (end Silurian to Early Devonian). In a subsequent article (Tremlett, 1972), he described the geochemistry of these rocks, but his interpretation relied heavily on the distribution of elements now generally believed to be mobile during alteration and low-grade metamorphism (see Merriman *et al.*, 1986). Croudace (1982) revised the geochemical interpretation of these intrusions using 'immobile' elements and mineral chemistry, and demonstrated a genetic link between the granitoid intrusions and the Moelypenmaen lavas (see the Moelypenmaen GCR site report), thus establish-

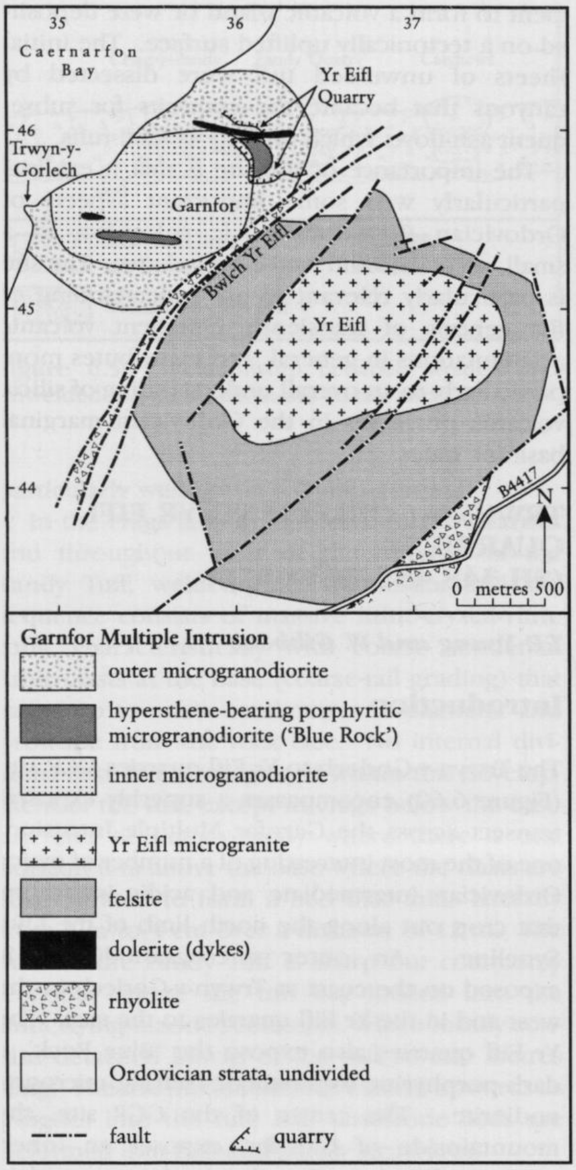


Figure 6.60 Map of the Garnfor Multiple Intrusion, north Llŷn (adapted from Tremlett, 1962).

ing the Ordovician age of the intrusions. Leat and Thorpe (1986) reworked the data of Croudace (1982) and argued that the intrusions form part of a peralkaline evolutionary series, together with the Moelypenmaen lavas.

Description

The Garnfor rocks comprise an outer intrusion of white or pink microgranodiorite and an inner intrusion of microtonalite of grey vitreous appearance, with a finer groundmass than the outer intrusion (both intrusions were described as 'granodiorite porphyry' by Tremlett, 1962). The inner intrusion becomes more mafic, with more enclaves towards its centre and shows a chilled margin at its contact with the outer intrusion. Both inner and outer intrusions are cut by smaller bodies of 'blue rock', a microgranodiorite similar to the outer intrusion but with a bluish-grey groundmass. These field relationships established the relative succession of the intrusions, which were subsequently cut by several dolerite dykes orientated NW–SE.

In petrographical detail, the outer intrusion is porphyritic with cumulophyric clots and individual phenocrysts of plagioclase showing chemical zonation from An_{58} to An_{28}, and commonly rimmed by orthoclase. The groundmass includes plagioclase with interstitial quartz, hornblende, biotite and magnetite. The inner intrusion shows similar core-to-rim plagioclase zonation (An_{48-20}), with a mafic mineral assemblage comprising magnetite and ilmenite, rare biotite, and scattered pyroxene crystals which become more abundant inwards.

Interpretation

Croudace (1982) and Leat and Thorpe (1986) referred the intrusions and volcanic rocks of Llŷn to the 'Lleyn volcanic complex'. Young *et al.* (in press) have suggested the presence of two distinct volcanic centres on Llŷn, one around Llanbedrog and the other farther north in the Nefyn district. The Llanbedrog centre, which produced the Llanbedrog Volcanic Group (Woolstonian), is largely restricted to the area south of the Efailnewydd Fault, whereas the products of the more northerly centre, which is slightly older (?Soudleyan–Longvillian), crop out along the northern limb of the Llŷn Syncline. Both volcanic sequences show an evolution from early trachybasaltic volcanism, through trachydacites, culminating in the eruption of rhyolitic tuffs. It would appear likely therefore that the evolution of the igneous rocks reported by Croudace (1982) and by Leat and Thorpe (1986) did not occur as a single event, but happened on two occasions. The distribution of the large granitoid intrusions, such as the Garnfor Multiple Intrusion, along the northern coast of Llŷn suggests a closer spatial relationship with the more northerly centre than with the younger Llanbedrog eruptive rocks.

Investigation of the geochemistry of the Garnfor intrusions by Croudace (1982) demonstrated that the rare-earth elements show a negative correlation with SiO_2, and it was argued that this was likely to have been produced through the fractionation of apatite. The analyses of the Garnfor intrusions plot in the field of trachydacite on the TAS (total alkalis vs silica) diagram and in the field of trachyandesite on the Zr/TiO_2 vs Nb/Y diagram (Winchester and Floyd, 1977). Tremlett (1962) argued that the range of compositions in the intrusions suggest that magma mixing or contamination was involved, with more basic material progressively contaminating the acid magma. Croudace (1982) demonstrated that the range of compositions was more likely to have been generated through fractional crystallization. Hence, the sequence of lithologies described by Tremlett (1962) derives from the progressive tapping of a magma chamber and the 'xenoliths' are in fact co-magmatic enclaves.

Conclusions

The well-exposed Garnfor Multiple Intrusion provides evidence for processes operating in an alkaline magma chamber. The geographical location of the intrusion suggests that it is likely to have been associated with a major centre of alkaline volcanism in northern Llŷn that is of probable Soudleyan–Longvillian age. As such it represents one of the best exposures in North Wales of an arc-related subvolcanic intrusion complex involving multiple intrusive events. It is especially interesting in revealing an acid-to-basic sequence of intrusive events, suggesting the progressive evacuation of a fractionating and possibly layered magma chamber at depth.

PENRHYN BODEILAS (SH 318 422)

T.P. Young and W. Gibbons

Introduction

The Penrhyn Bodeilas GCR site (Figure 6.61) preserves one of the best-exposed and most accessible of several intermediate to acid Ordovician intrusions that crop out east of Nefyn in northern Llŷn. The intrusion is particularly interesting in being rich in co-magmatic enclaves, and is considered to represent a subvolcanic intrusion.

Description

The Penrhyn Bodeilas Granodiorite Intrusion is exceptionally well exposed in coastal outcrops around the headland of the same name. The intrusion is a coarse-grained, greyish coloured granodiorite. It contains crystals of plagioclase 3–4 mm in length and of intermediate composition (An_{32}). Similarly sized clots of mafic minerals (hornblende, some clinopyroxene, chlorite and magnetite) occur together within a fine-grained (1 mm) groundmass, mostly of plagioclase together with quartz-feldspar intergrowths. Enclaves include examples of both basic and intermediate composition ('dolerite' and 'andesite' of Tremlett, 1962) (Figure 6.62). A late-stage, more evolved magmatic component is represented by thin aplitic veins, most of which are steep and strike NNE–SSW. Some of these late-stage aplites show chilled margins against the main body of the intrusion (Tremlett, 1962).

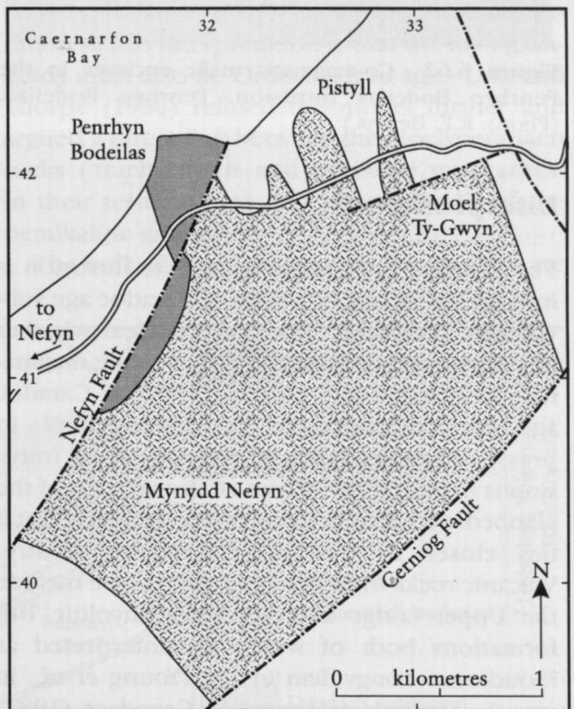


Figure 6.61 Map of the Penrhyn Bodeilas Intrusion, north Llŷn (adapted from Tremlett, 1962).

Figure 6.62 Co-magmatic mafic enclaves in the Penrhyn Bodeilas Intrusion, Penrhyn Bodeilas. (Photo: R.E. Bevins.)

Interpretation

The Penrhyn Bodeilas Granodiorite Intrusion is interpreted as one of a suite of Caradoc age subvolcanic intrusions. It remains unclear whether this intrusion was directly related to the magmatism associated with either of the two Caradoc age magmatic centres in Llŷn (Young *et al.*, in press). The geographical position of the intrusion is marginal to the area of distribution of the Llanbedrog Volcanic Group (Woolstonian), but it lies closer to the more northerly centre. Volcanic rocks from this northern centre include the Upper Lodge and Allt Fawr Rhyolitic Tuff formations both of which are interpreted as ?Soudleyan–Longvillian in age (Young *et al.*, in press). Analyses presented by Croudace (1982) plot in the trachyandesite field on the Zr/TiO_2 vs Nb/Y diagram (Winchester and Floyd, 1977).

Conclusions

The Penrhyn Bodeilas Granodiorite Intrusion is a well-exposed example of a high-level subvolcanic slightly alkaline intrusion belonging to one of the magmatic centres that developed on Llŷn in Caradoc times. It is of particular interest in containing a suite of abundant and compositionally variable co-magmatic enclaves, and a well-developed late aplitic facies preserved as a swarm of steeply inclined dykes.

MOELYPENMAEN (SH 338 386)

T.P. Young and W. Gibbons

Introduction

The excellent exposures of trachyandesitic rocks at Moelypenmaen (Figure 6.63) represent one of the best-preserved examples of intermediate igneous rocks produced during the widespread Caradoc magmatism in North Wales. Moelypenmaen is a low rocky hill on the northern limb of the Llŷn Syncline NW of Pwllheli. The majority of the rocks exposed on the hill are basaltic trachyandesites referred by Young *et al.* (in press) to the Penmaen Formation of the Llanbedrog Volcanic Group (not named after this locality, but after the hill of Penmaen on the western outskirts of Pwllheli). In addition, the southern side of the hill has small exposures of both the Foel Ddu Rhyodacite Formation and the base of the Carneddol Rhyolitic Tuff Formation, which are younger, more evolved components of the Llanbedrog Volcanic Group.

Matley and Heard (1930) described the succession at Moelypenmaen as 'oligoclase-keratophyre' and 'pyroxene-soda-trachyte' (corresponding respectively to the Penmaen and Foel Ddu formations of the current nomenclature). The rocks dip steeply to the north, and it was not until areas farther south in the Llŷn Syncline were mapped (Matley, 1938) that it was realized that the beds are overturned and actually young to the south. Tremlett (1962, 1969, 1972) described the dominant rock type at Moelypenmaen as andesite (part of his 'Main Andesitic Series').

Moelypenmaen is of greatest significance because of the geochemical studies undertaken by Tremlett (1969), Croudace (1982) and Leat and Thorpe (1986), which revealed the intermediate chemical character of these rocks. Intermediate rocks are comparatively rare among the products of the Caradoc igneous centres of central Snowdonia (see the Snowdon Massif and Cwm Idwal GCR site reports), but are volumetrically much more important in volcanic centres preserved in central and north-western Llŷn.

Description

The bulk of the succession exposed at Moelypenmaen comprises a massive unit of basaltic trachyandesites at least 200 m thick, the uppermost part of which shows amygdales orientated at a high angle to bedding. No evidence to suggest individual flow units within the body of these lavas has been recorded. The rocks have andesine and less abundant augite phenocrysts within a dark-green chloritic groundmass with flow-aligned plagioclase microlites; amygdales reach up to 1.3 mm and are mostly infilled with chlorite.

The southern part of the site includes a second basaltic trachyandesite flow, 30 m thick and separated from the main body of trachyandesites by approximately 50 m of sandstones, which are locally conglomeratic and fossiliferous. These are in turn overlain by the Foel Ddu Rhyodacite Formation (represented by small exposures of a thin, red-coloured flow-foliated lava) and the base of the crystal-rich tuffs of the Nant y Gledrydd Member of the Carneddol Rhyolitic Tuff Formation.

Mapping by Young *et al*. (in press and unpublished data) suggests that the Moelypenmaen locality is very close to the eastern limit of the distribution of the Llanbedrog Volcanic Group on the northern limb of the Llŷn Syncline. The Foel Ddu Rhyodacite Formation is reduced to only a few metres at Moelypenmaen, and the Penmaen Formation, despite being at least 200 m thick at Moelypenmaen, is absent at Pont Penprys, only 1200 m farther east. Tuffs of the Carneddol Rhyolitic Tuff Formation do continue to the east, although they are much reduced in thickness.

Interpretation

Tremlett (1962, 1969, 1972) proposed that most of the major granitoid intrusions of northern Llŷn are 'Caledonian' in age (end-Silurian to Early Devonian), largely on the basis of structural arguments. Croudace (1982) considered that the Moelypenmaen andesite lavas were generated by approximately 70% fractional crystallization of a primitive tholeiitic magma, and that the peralkaline microgranites and granophyres probably represent residual melts (less than 10%) of the same, or similar magmas. The implication of this interpretation is that the Llŷn granitoids must also be Ordovician in age. Leat and Thorpe (1986) refined the model further and argued a direct link between the Moelypenmaen rocks ('trachybasalts and probable mugearites' in their terminology) and the evolution of the peralkaline granitoids.

The bulk of the Moelypenmaen exposures are

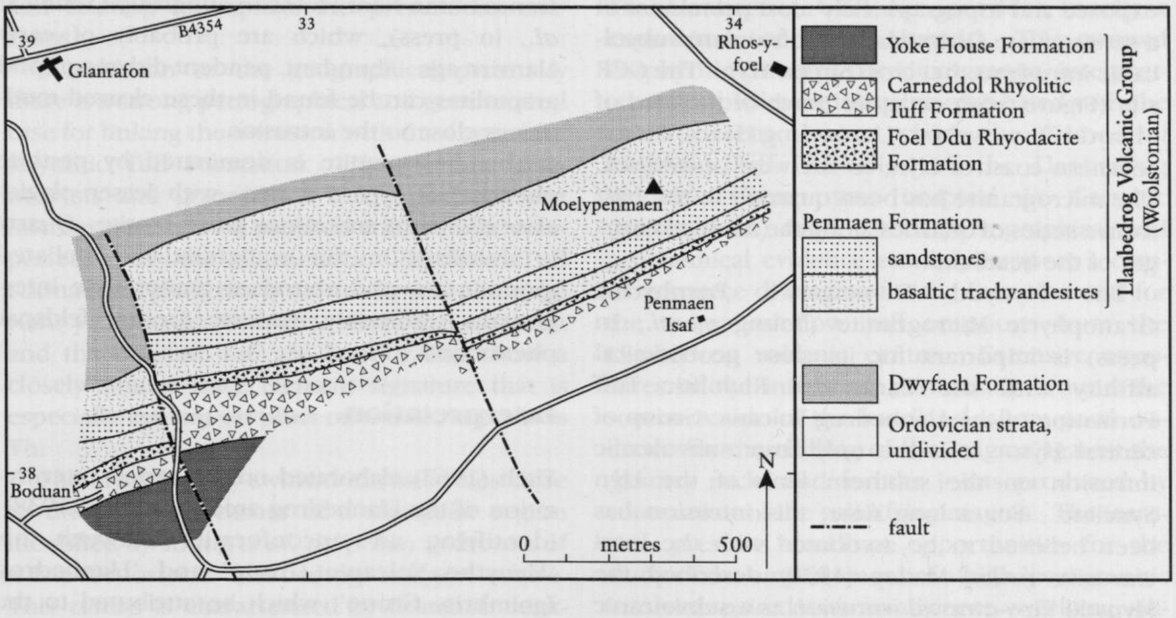


Figure 6.63 Map of the Moelypenmaen area, north Llŷn.

now recognized to represent the earlier, less evolved products of magma emanating from a major volcanic centre near Llanbedrog (Young *et al.*, in press). However this site is of additional interest in preserving more evolved representatives derived from the same centre, namely the Foel Ddu Rhyodacitic Formation and the Carneddol Rhyolitic Tuff Formation.

Conclusions

The well-exposed basaltic trachyandesites of Moelypenmaen are excellent representatives of intermediate rocks in the transitionally alkaline volcanic centres of Llŷn. Such rocks contrast with the subalkaline centres of central Snowdonia where intermediate rocks are comparatively rare. The existence of a range of overlying volcanic lithologies from andesite to rhyolite makes this site especially representative of the magmatic centre that produced the Llanbedrog Volcanic Group and associated intrusions.

LLANBEDROG (SH 337 307)

T.P. Young and W. Gibbons

Introduction

Llanbedrog Head preserves one of the best-exposed and topographically most prominent of a series of late Ordovician (Woolstonian) subvolcanic intrusions that crop out on Llŷn. The GCR site (Figure 6.64) occupies much of the area of Mynydd Tir-y-cwmwd (Llanbedrog Head), on the southern coast of Llŷn, to the west of Pwllheli. The microgranite has been quarried in the past from a series of quarries along the southern margin of the headland.

The Mynydd Tir-y-cwmwd Porphyritic Granophyric Microgranite (Young *et al.*, in press) is important for its close geochemical affinity with the Carneddol Rhyolitic Tuff Formation of the Llanbedrog Volcanic Group of central Llŷn. It is the only large subvolcanic intrusion on the southern limb of the Llŷn Syncline. For a long time, this intrusion has been believed to be associated with the local extrusive rocks; Matley (1938) described the Mynydd Tir-y-cwmwd intrusion as a subvolcanic plug of 'granite porphyry' and Fitch (1967) identified an unconformity within the local volcanic succession, which he attributed to the effects of the intrusion of the Mynydd Tir-y-cwmwd intrusion (his 'Llanbedrog Granophyre').

The intrusion is one of the few on Llŷn for which an Ordovician age has been accepted by almost all previous authors. Tremlett (1969) interpreted the Mynydd Tir-y-cwmwd Porphyritic Granophyric Microgranite as contemporary with the Caradoc volcanic succession, despite interpreting many other intrusions, such as the Garnfor Multiple Intrusion (see the Trwyn-y-Gorlech to Yr Eifl quarries GCR site report) as having a younger, end-Silurian to Early Devonian age. Croudace (1982) re-investigated the granitoid intrusions of Llŷn and interpreted them all as being of Ordovician age.

Description

The Mynydd Tir-y-cwmwd Porphyritic Granophyric Microgranite intrusion forms Llanbedrog Head, and is elliptical in plan (1500 m E–W and 900 m N–S). The intrusion has major radial and concentric joint sets which are well exposed in the quarries around the southern margin. The joint pattern suggests that the present level of erosion is close to the exhumed top of the intrusion. At one point in the SW of the intrusion a small fault downthrows part of the roof, so that baked mudrocks are exposed in contact with the microgranite. The country rocks (the 'Tal-y-fan argillites' of Fitch, 1967) are undivided mudstones of the Nant Ffrancon Subgroup (Young *et al.*, in press), which are probably of early Llanvirn age. Abundant, pendent didymograptid graptolites can be found in these cleaved mudstones close to the intrusion.

The microgranite is dominated by perthite phenocrysts (up to 4 mm) with lesser plagioclase (0.7 mm) and minor green biotite. Quartz is abundant in the equigranular, unfoliated groundmass, and abundant granophyric intergrowths commonly nucleate around feldspar phenocrysts.

Interpretation

Fitch (1967) elaborated on the earlier interpretation of the Llanbedrog area by Matley (1938), identifying an unconformity between his 'Mynytho Volcanic Group' and 'Llanbedrog Ignimbrite Group', which he attributed to the topographical effects of the intrusion of the

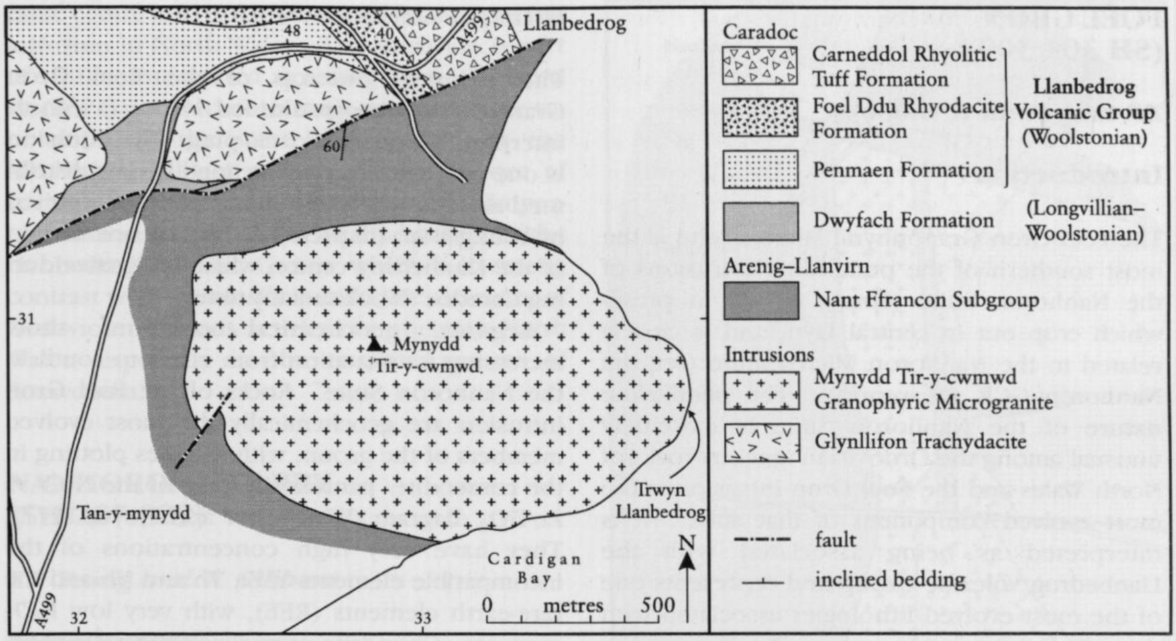


Figure 6.64 Map of the Llanbedrog area, south Llŷn.

Mynydd Tir-y-cwmwd intrusion (his 'Llanbedrog Granophyre'). The stratigraphical position of Fitch's unconformity is equivalent to the base of the Carneddol Rhyolitic Tuff Formation in the stratigraphical scheme of Young *et al.* (in press), although the remapping of the area did not prove the existence of an unconformity but instead emphasized the importance of folding and faulting to explain the present-day outcrops.

In addition to the geographical proximity there is a strong petrographical and geochemical case for linking the intrusion with the Carneddol Rhyolitic Tuff Formation. The perthite phenocrysts and granophyric intergrowths of the microgranite can be matched with similar components in the Carneddol Rhyolitic Tuff Formation, particularly in its lower part (the Nant y Gledrydd Member). Both the intrusion and the rhyolitic tuff are Zr-poor and show a closely similar trace element signature that is especially evident on plots of Y vs Zr, and Nb vs Th.

The Mynydd Tir-y-cwmwd intrusion lies close to the southern corner of a triangular region identified by Young *et al.* (in press) as the site of a late Ordovician 'Llanbedrog' volcanic centre. This centre is characterized by dramatic thickness variations in the Carneddol Rhyolitic Tuff Formation, the youngest component of the Llanbedrog Volcanic Group and the one which is genetically associated with the Mynydd Tir-y-cwmwd intrusion.

Conclusions

The Llanbedrog GCR site provides excellent exposures of the Mynydd Tir-y-cwmwd Porphyritic Granophyric Microgranite, interpreted as a subvolcanic intrusion associated with the volcanic centre from which the Carneddol Rhyolitic Tuff Formation of the Llanbedrog Volcanic Group was erupted in Caradoc (Woolstonian) time. Both petrographical and geochemical evidence strongly support a common source of magma for the intrusion and for the major ash-flow tuff eruptions from the Llanbedrog volcanic centre. Extensive exposures of the intrusion, particularly around the southern side of the headland, show good evidence for the chilling of the magma against the country rocks and for the joints produced by contraction of the solidifying magma. The intrusion presents excellent opportunities for the study of the emplacement of a high-level granitic intrusion paired with an adjacent, overlying, silicic ash-flow tuff.

FOEL GRON (SH 301 309)

T.P. Young and W. Gibbons

Introduction

The Foel Gron Granophyric Microgranite is the most southern of the peralkaline intrusions of the Nanhoron Suite (Young *et al.*, in press) which crop out in central Llŷn, and is closely related to the Nanhoron Microgranite (see the Nanhoron GCR site report). The peralkaline nature of the Nanhoron Suite is extremely unusual among the Ordovician igneous rocks of North Wales and the Foel Gron intrusion is the most evolved component of that suite. It is interpreted as being associated with the Llanbedrog Volcanic Group and represents one of the most evolved lithologies associated with that alkaline igneous centre. The intrusion is elliptical in plan and is intruded into mudstones of the Nant Ffrancon Subgroup (Llanvirn).

The first field description of the Foel Gron intrusion was by Matley (1938), with subsequent descriptions and interpretations of its geochemistry by Tremlett (1972), Croudace (1982) and Young *et al.* (in press).

Description

The Nanhoron Suite comprises three strongly peralkaline intrusions, the Nanhoron Granophyric Microgranite, the Mynytho Common Riebeckite Microgranite and the Foel Gron Granophyric Microgranite (Figure 6.65). The fine-grained, pale microgranite of the Foel Gron intrusion is very slightly elliptical in plan (330 m N–S, 280 m E–W). It was initially referred to as an aplite (Matley, 1938), until Tremlett (1972) suggested that the term microgranite is more appropriate. It comprises an equigranular groundmass of anhedral quartz (0.4 mm), subhedral oligoclase (0.4 mm), subhedral alkali feldspar laths (up to 1.4 mm), altered biotite, and 1 mm clusters of quartz and alkali feldspar in granophyric intergrowths. No contacts with the country rocks are exposed, although cleaved mudstones of the upper part of the Nant Ffrancon Subgroup are exposed in close proximity to the microgranite at various points, but particularly on the NE side of the intrusion.

Interpretation

The elliptical outcrop of the Foel Gron Granophyric Microgranite led Matley (1938) to interpret it as a subvolcanic plug. The intrusion is one of several steeply inclined bodies distributed along a N–S line that has been interpreted by Young *et al.* (in press) as defining one margin of the Llanbedrog centre, which was active during Caradoc (Woolstonian) time.

Regional geochemical variations show increasing fractionation from north to south in the Nanhoron Suite. Rocks of the Foel Gron intrusion are geochemically the most evolved members of the group, with samples plotting in the comendite/ pantellerite field of the Nb/Y vs Zr/TiO_2 diagram (Winchester and Floyd, 1977). They have very high concentrations of the incompatible elements Y, Zr, Th and Nb and the rare-earth elements (REE), with very low P_2O_5 contents. Chondrite-normalized REE data show steep profiles of light REE enrichment for the Nanhoron Suite, with the Foel Gron Granophyric Microgranite showing the most dramatic values. The steepening of the profiles may be due to zircon removal, which would preferentially deplete the heavy REE. The REE profiles show marked negative Eu anomalies, suggestive of extensive plagioclase fractionation, whereas the negative Ce anomalies are extreme and may be due to fractionation of monazite.

The relationship of the Foel Gron Granophyric Microgranite (and the Nanhoron Suite as a whole) to the other acidic components of the Llanbedrog volcanic centre is uncertain but interesting. The rocks associated with the centre show an evolutionary series from trachybasalts and trachyandesites through to trachydacites and rhyodacites, all showing progressive enrichment in incompatible elements. However, the more rhyolitic compositions show a marked division into Zr-depleted rocks (the Carneddol Rhyolitic Tuff Formation and the Mynydd Tir-y-cwmwd intrusion) and Zr-enriched rocks (the Nanhoron Suite). Whatever the reason for this striking geochemical subdivision, these Zr values emphasize the geochemically extremely fractionated nature of the Foel Gron Granophyric Microgranite.

Conclusions

The Foel Gron Granophyric Microgranite is the most evolved component of the Llanbedrog volcanic centre and is the most evolved Ordovician intrusion in North Wales. This intrusion is part of a suite, interpreted as having been emplaced along a major volcanotectonic structure close to, or defining, the western boundary of the Llanbedrog caldera margin. The existence of such a peralkaline rock in the area is an important demonstration of the alkaline nature of the Llanbedrog Volcanic Group, which is in strong contrast with the mostly subalkaline character of Ordovician igneous activity elsewhere in North Wales, especially in the eruptive centres of Snowdonia.

NANHORON QUARRY (SH 287 329)

T.P. Young and W. Gibbons

Introduction

The Nanhoron Quarry GCR site preserves a rare exposure of the contact between the Nanhoron Granophyric Microgranite and its envelope of lower Ordovician sedimentary rocks. The intrusion is part of the Nanhoron Suite, a group of late Ordovician (Woolstonian) peralkaline intrusions aligned N–S along the western margin of the Llanbedrog volcanic centre. Nanhoron Quarry is a small working quarry, situated on the NW side of Nanhoron and just to the north of a major NE–SW fault (Figure 6.65). Although long-established, the quarry has expanded in recent years to satisfy an increased local demand for its product, providing new evidence concerning the contacts of the microgranite.

Description

The Nanhoron Granophyric Microgranite is exposed in Nanhoron Quarry (see Figure 6.65) and in a small quarry to the north, near Penbodlas. The host rocks are mudstones of the Nant Ffrancon Subgroup (Llanvirn). The microgranite is non-porphyritic and comprises anhedral quartz (up to 6 mm) and alkali feldspar (up to 1.0 mm), with less common subhedral oligoclase (up to 0.2 mm). A granophyric texture is variably overprinted by secondary alteration. The margin of the intrusion is fine grained, pervasively devitrified, weakly porphyritic (rare quartz, oligoclase and alkali

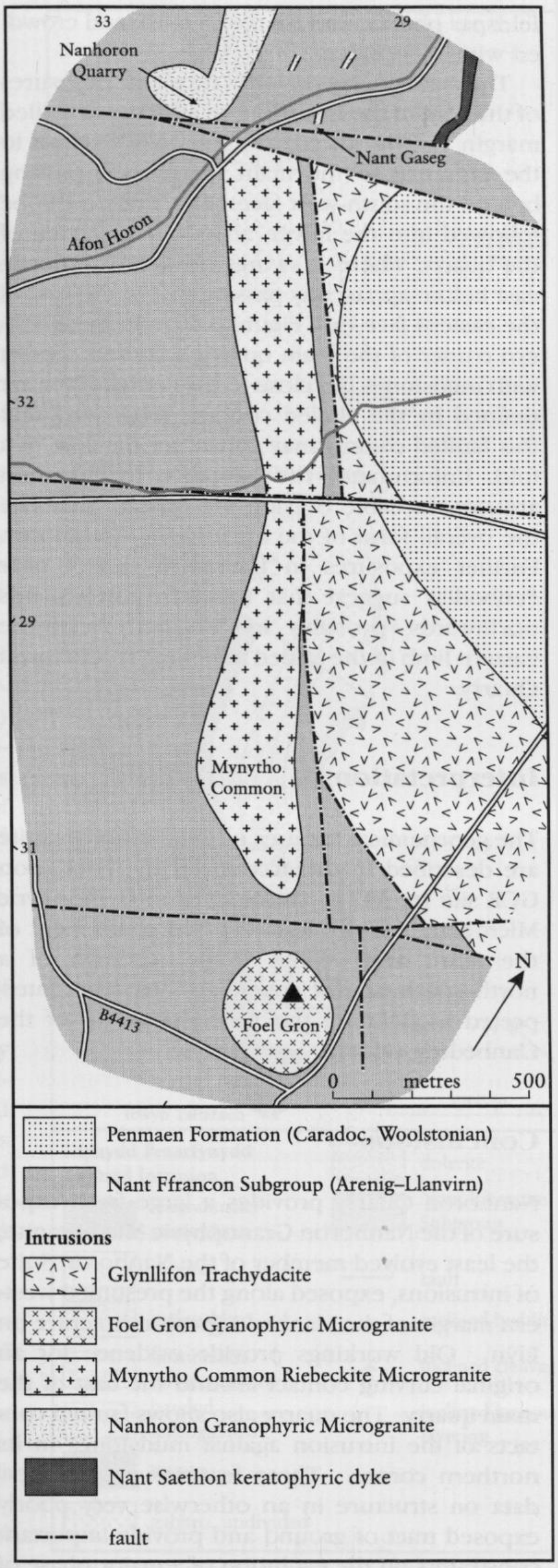


Figure 6.65 Map showing the distribution of the Nanhoron Suite of intrusions, south Llŷn.

feldspar phenocrysts up to 0.3 mm), and crowded with spherulites.

The main quarry provides excellent exposures of the core of the intrusion. In addition, a chilled margin can be traced running NW–SE close to the entrance to the main quarry and passing behind the south-west face. This margin can be followed into the lower, abandoned, section of the quarry, where it swings towards the north-east before apparently passing just to the east of the eastern face (see Figure 6.65). In the northern corner of the main quarry, a faulted contact with mudstones lies close to the centre of the arc defined by the chilled contact, suggesting that this faulted contact may constitute the core of a fold. Unfortunately the margins of the intrusion are not traceable outside the quarry, therefore the overall form of the intrusion is not known. Further exposures in the small quarry near Penbodlas suggest that the intrusion extends northwards, probably in continuity with the eastern limb of the folded structure in Nanhoron Quarry.

Interpretation

The geochemical features of the Nanhoron Suite are described in the account of the Foel Gron GCR site (p. 332). The Nanhoron Granophyric Microgranite is the least evolved component of the suite and is the most northern of a north–south line of cogenetic intrusions interpreted as defining the western margin of the Llanbedrog caldera.

Conclusions

Nanhoron Quarry provides a large fresh exposure of the Nanhoron Granophyric Microgranite, the least evolved member of the Nanhoron Suite of intrusions, exposed along the presumed western margin of the Llanbedrog volcanic centre on Llŷn. Old workings provide evidence for an original curving contact around the east of the main quarry. The quarry also shows faulted contacts of the intrusion against mudstones in its northern corner. These features present new data on structure in an otherwise very poorly exposed tract of ground and provide important constraints on the evolution of a major phase of alkaline igneous activity of Caradoc (Woolstonian) age.

MYNYDD PENARFYNYDD (SH 214 259–236 273)

T.P. Young and W. Gibbons

Introduction

The Mynydd Penarfynydd GCR site encompasses one of the best examples of a layered basic intrusion in the southern part of the British Caledonides. The site area centres on the prominent headland of Mynydd Penarfynydd, on the southern coast of Llŷn, which provides excellent coastal exposures through the intrusion (Figures 6.66 and 6.67). Much of the outcrop of the intrusion occurs within the GCR site boundary, but it continues inland to the north-east along the eastern side of Mynydd Rhiw for several kilometres, where it is only poorly exposed. The intrusion has great significance for the role it has played in influencing ideas on magma evolution during Ordovician igneous activity on Llŷn.

The Mynydd Penarfynydd Layered Intrusion was emplaced into Ordovician (Llanvirn) sedimentary rocks, close to the north-western margin of a sedimentary basin aligned along the Menai Straits Fault-zone. Most accounts have suggested that the intrusion is of Llanvirn age, pre-dating the major late Ordovician phase of igneous activity on Llŷn. Young *et al.* (in press), however, have proposed that the intrusion is associated with younger (Caradoc) Ordovician activity, being contemporary with the extrusive basaltic volcanism seen in the Nod Glas Formation.

Originally the Mynydd Penarfynydd intrusion was described as a greenstone (Sharpe, 1846; Ramsay, 1866; Tawney, 1880; Bonney, 1881; Teall, 1888). The earliest detailed description of the intrusion was provided by Harker (1888, 1889) and the area was subsequently mapped by Matley (1932). The intrusion was the subject of two major studies in the 1960s and 1970s giving rise to several publications on the geology and mineralogy by Hawkins (1965, 1970), and on the geochemistry by Cattermole (1976). More recent re-examination of the intrusion, including new geochemical data, has been undertaken during mapping of both the Aberdaron and Pwllheli 1:50 000 Geological Survey sheets (Gibbons and McCarroll, 1993; Young *et al.*, in press).

Description

The Mynydd Penarfynydd Layered Intrusion is an easterly-dipping transgressive picritic and gabbroic sill within Llanvirn sedimentary rocks (Hawkins, 1970) of the Nant Ffrancon Subgroup. At Mynydd Penarfynydd, it is intruded into the undifferentiated mudstones of the subgroup, at least 200 m above the top of the Trygarn Formation, but it lies entirely within the Trygarn Formation to the north. On Mynydd y Craig the sill is over 150 m thick, and the intrusion thins gradually over a distance of 3 km to the north, before terminating abruptly NW of Tyddyn Corn.

The intrusion best demonstrates its layered nature on Mynydd Penarfynydd, within the GCR site area. The exposed section has been fully described by Hawkins (1970) and by Gibbons and McCarroll (1993). The lower 100 m of the sill is dominated by picrite (Figure 6.67). The base of the picrites shows a complex chilled zone about 10 m thick comprising a basaltic margin up to 2 m thick (Zone A of Hawkins, 1970) and about 8 m of fine-grained hornblende gabbros (Zone B of Hawkins). The thick picrites (Zone C of Hawkins) show a variable degree of layering. The picrites are overlain by banded leucogabbros, 9 m thick (Zone D of Hawkins). Hornblende olivine-gabbros, 13 m thick, (Zone E of Hawkins) appear to lie erosively on the leucogabbros, and are rich in augitic clinopyroxene and magnetite. Above this lies a unit of banded melagabbros (Figure 6.68). Higher in the intrusion, the rocks become progressively more differentiated, through a zone of secondarily-altered feldspathic ilmenitic gabbroic and dioritic lithologies, to the granophyric rocks which form the highest part of the exposed intrusion (Zones F, G, H and I of Hawkins). One small outcrop of the roof of the intrusion occurs in a small un-named cove (at 2226 2620).

On Mynydd y Graig the gabbro typically contains brown intercumulus hornblende, commonly enclosing augitic clinopyroxene, altered plagioclase and up to 10% opaque minerals (magnetite, ilmenite, pyrite and pyrrhotite). The texture and mineralogy are similar to the hornblende-cumulate gabbros (Zone F of Hawkins) exposed on Mynydd Penarfynydd, although layering is much less well developed. On Mynydd Rhiw (outside the GCR site) the intrusion is less well exposed, but shows a similar range of lithologies, although the gabbro is commonly

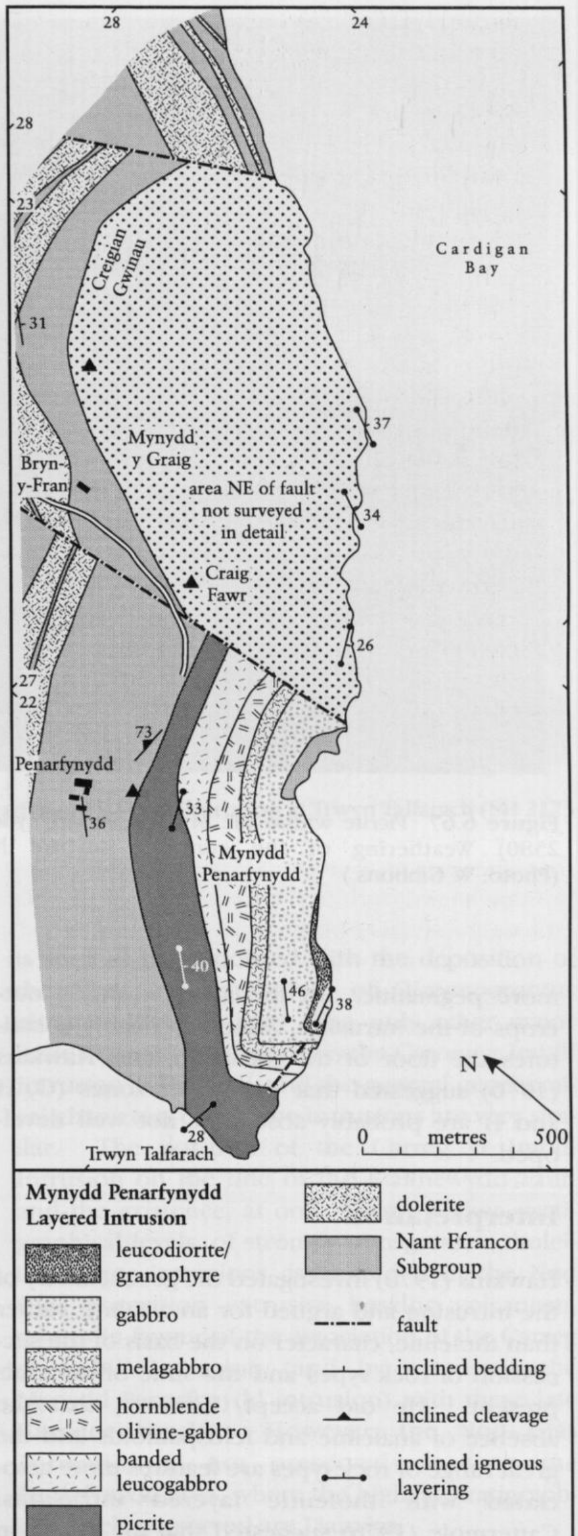


Figure 6.66 Map of the Mynydd Penarfynydd Layered Intrusion, south Llŷn.

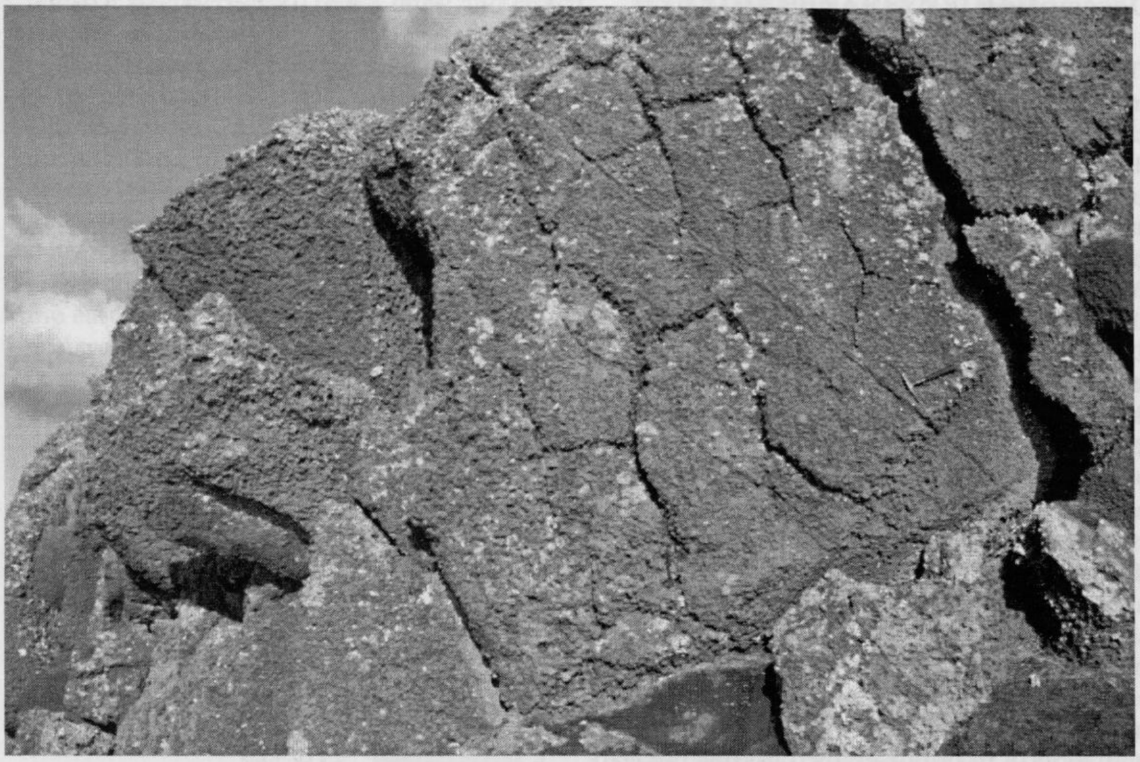


Figure 6.67 Picrite within the Mynydd Penarfynydd Layered Intrusion, north of Trwyn Talarfach (SH 2152 2580) Weathering of the cumulate texture has produced the distinctive honeycomb pattern. (Photo: W. Gibbons.)

more pegmatitic. In the most northerly outcrops of the intrusion, Zone F probably constitutes the floor of the intrusion, and Hawkins (1970) suggested that the upper zones (G, H and I) are probably absent or not well developed.

Interpretation

Hawkins (1970) investigated the geochemistry of the intrusion and argued for an alkaline, rather than tholeiitic, character on the basis of the succession of rock types and the suite of minerals present. He did accept, however, that the absence of analcime and feldspathoids and the great range of rock types are features more associated with tholeiitic layered intrusions. Cattermole (1976) suggested that the intrusion was derived through fractional crystallization of a hydrated alkali olivine basaltic magma, with the marked geochemical variations produced by the intrusion of separate influxes of magma. Young *et al.* (in press) presented new geochemical data suggesting that the Mynydd Penarfynydd Layered Intrusion is subalkaline and tholeiitic in character, rather than alkaline.

Young *et al.* (in press) described the Mynydd Penarfynydd gabbros as characterized generally by very low concentrations of incompatible elements (Zr, Nb, Y) and high total Fe, MgO, Ni, Cr and V, features that are especially marked in the picritic cumulates, reflecting olivine and/or pyroxene accumulation. Two samples of melagabbro have relatively low Ni and Cr and markedly higher concentrations of TiO_2 and V, indicative of high modal proportions of an Fe-Ti oxide. On the Zr/TiO_2 vs Nb/Y diagram Mynydd Penarfynydd samples plot in the subalkaline basalt and andesite/basalt fields. Accordingly, Young *et al.* (in press) interpreted the intrusion as a suite of tholeiitic picrites and gabbros. The geochemical characteristics of the intrusion are in marked contrast to the transitionally alkaline Upper Lodge and Llanbedrog volcanic groups (see, for example, the Foel Gron and Trwyn-y-Gorlech to Yr Eifl quarries GCR site reports).

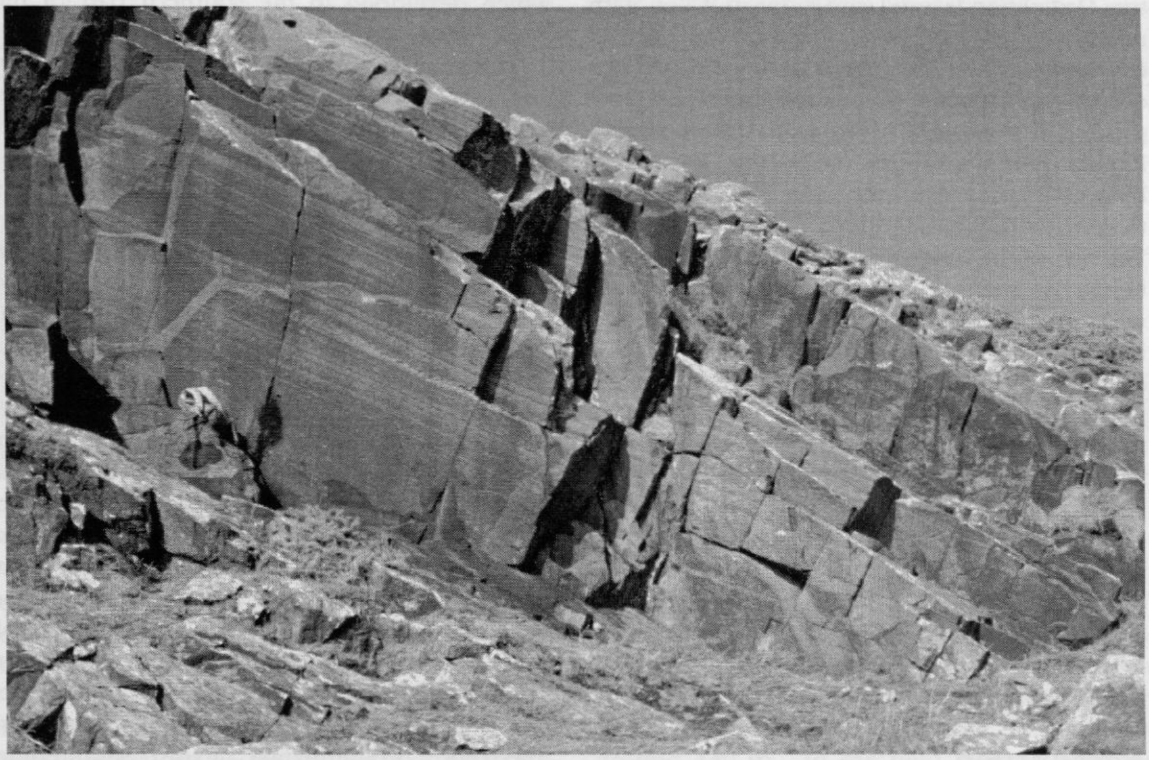


Figure 6.68 Banded melagabbros from the Mynydd Penarfynydd Layered Intrusion at Trwyn Talfarach (SH 2173 2580). (Photo: W. Gibbons.)

The Mynydd Penarfynydd intrusion has commonly been interpreted as being of Llanvirn age. However, the style of intrusion contrasts markedly with the nearby dolerite and basalt sills. Although the latter are locally transgressive, they only attain a highest stratigraphical level of intrusion close to the top of the Trygarn Formation (Lower Llanvirn) and commonly exhibit features (fine-grained apophyses, peperitic textures and pillows) suggestive of high-level intrusion into wet, unconsolidated, sediments. It is intruded, at the south-western limit of exposure, at a level 200 m above the top of the Trygarn Formation, but shows no indication of a shallow level of intrusion. The Mynydd Penarfynydd intrusion has therefore been reinterpreted as being of significantly younger, Caradoc age (Gibbons and McCarroll, 1993; Young *et al.*, in press).

The subalkaline geochemical character distinguishes the Mynydd Penarfynydd intrusion from the major mid-Caradoc volcanic centres in western Llŷn, but it is similar to the final phase of Caradoc igneous activity in western Llŷn, which is seen to be associated with the deposition of the Nod Glas Formation, of *Dicranograptus clingani* Biozone age. The only other major basic intrusion in the area is the Carreg yr Imbill Intrusion at Pwllheli, and the general geochemical characters of the two intrusions are very similar. The position of the Carreg yr Imbill Intrusion on the line of the Efailnewydd Fault and the existence, at only slightly higher stratigraphical levels, of strongly transgressive tholeiitic minor intrusions associated with the Nod Glas Formation extrusive basaltic volcanism, argues in favour of the association of the Carreg yr Imbill Intrusion (and by extension the Mynydd Penarfynydd intrusion) with these late Caradoc basalts. However, the Nod Glas Formation is not preserved close to the Penarfynydd area, where the highest stratigraphical levels preserved are Llanvirn.

Conclusions

The Mynydd Penarfynydd Layered Intrusion is a classic example of a layered basic sill, one of only two Ordovician layered intrusions in Wales, with relatively easy access to the base of the sill exposed in sea cliffs. The superbly defined layering, and the range of rock types present, from picrites through gabbros to more differentiated, intermediate lithologies, makes this site one of the best exposures of intrusive igneous rock in the southern Caledonides of the British Isles. The age of the intrusion is not known with certainty, but it is now considered to be associated with the late Caradoc basaltic volcanism seen in the Nod Glas Formation on Llŷn. This period is of great significance for it marks a major change in the style and chemistry of volcanism after cessation of activity at the major volcanic centres at Llanbedrog and Snowdon.

SKOMER ISLAND (SM 722 088–731 091, 727 086, 728 084, 738 092, AND 747 091)

R.E. Bevins

Introduction

Skomer Island, off the coast of Pembrokeshire, is composed almost entirely of volcanic and related rocks of Llandovery age (Figure 6.69). The volcanic rocks are chiefly basic in composition, with rarer intermediate and silicic rocks. They are mainly of extrusive origin, or relate to the intrusion of magma at a high level; a small proportion are pyroclastic. Rarer sedimentary rocks within the sequence reflect periods of volcanic quiescence. These sedimentary beds provide important palaeogeographical evidence for the setting in which the volcanism took place. The Skomer Island GCR site is of national importance in that it provides excellent exposures of the youngest major volcanic episode in the southern part of the British Caledonides.

The volcanic rocks are also exposed farther west on Grassholm, on the shoals known as the Hats and Barrels, and on the Smalls (Figure 6.69). To the east they are exposed on Middleholm (Midland Island) (Figure 6.70), on the Deer Park Peninsula, where crucial evidence for the age of the Skomer Volcanic Group is seen at Renney Slip (see the Deer Park GCR site report), and extending as far as St. Ishmael's. In all there is an E–W extent of some 43 km of the Skomer volcanic rocks. Clearly, this sequence represents the remnants of a major volcanic field which developed in the southern part of the Welsh Basin during early Silurian times.

The earliest, brief, accounts of the volcanic and related rocks of Skomer Island were presented by Howard and Small (1896a, 1896b, 1897), while the first major report was that by Thomas (1911). Further reference to the sequence appeared in the Geological Survey memoir to the district around Milford Haven (Cantrill *et al.*, 1916). In all of these accounts, the age of the Skomer volcanic rocks was thought to be Ordovician (Arenig). It was the detailed stratigraphical investigation of Ziegler *et al.* (1969) that established the true age of the sequence as Silurian (Llandovery); they re-examined the Skomer volcanic rocks and their associated sedimentary rocks, concluding that in fact they grade laterally and pass vertically into rocks of early Silurian age. Poorly preserved ostracodes from Middleholm (Midland Island) also argue against an Arenig age for the Skomer volcanic rocks, as does a consideration of structural relationships at Musselwick, on the Marloes Peninsula, where the Skomer volcanic rocks are apparently downthrown against sedimentary rocks of Llandeilo age (Ziegler *et al.*, 1969).

Thomas (1911) provided preliminary geochemical data for the Skomer volcanic rocks; these data were elaborated on by Ziegler *et al.* (1969) who provided, in particular, analyses of a unit termed the 'Skomer Ignimbrite'. Hughes (1977) and Fitton *et al.* (1982) presented additional geochemical data, while the most recent geochemical investigations are those of Thorpe *et al.* (1989). These last authors presented new major and trace element analyses for basic and acidic volcanic rocks from the area, concluding that in the main they are related by crystal fractionation. In addition, they reported that the silicic rocks could be divided into two unrelated groups, a high-Zr peralkaline group and a low-Zr group.

Description

Ziegler *et al.* (1969) adopted the term Skomer Volcanic Group for the thick volcanic succession exposed on Skomer Island and in the adjacent region, although no formal stratigraphical subdivision of the Skomer volcanic rocks has been established. In the absence of such, the sequence is described on the basis of field exposures, from the exposed base to the exposed top. Descriptions are predominantly of the

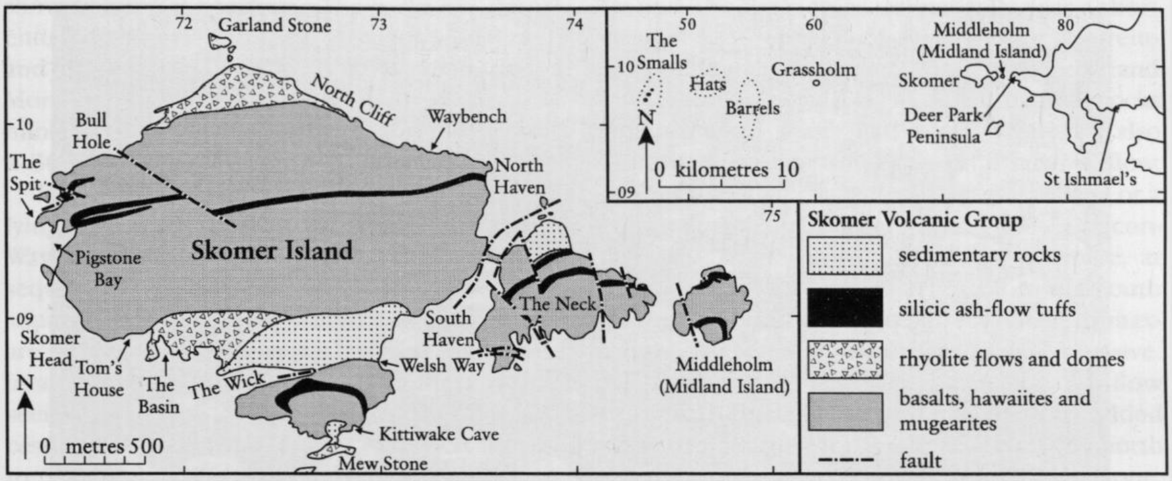


Figure 6.69 Map of Skomer Island (after Ziegler *et al.*, 1969).

coastal outcrops, in particular those along the eastern and southern cliffs, exposure inland being relatively scant and of inferior quality.

On Skomer Island, the effusive and tuffaceous rocks form up to 760 m of the exposed section, with interbedded sedimentary rocks representing an additional 140 m. The various units dip consistently to the SSE at around 20° to 30°. The oldest rocks exposed, therefore, are the silicic ash-flow tuffs of the Garland Stone and adjacent areas on the north coast, while the youngest are the rhyolites of the Mew Stone in the south.

The Garland Stone rocks were called 'soda-rhyolites' and 'soda-trachytes' by Thomas (1911). There is probably more than one unit in this section, with a composite thickness of around 130 m. In the field they are typically dark-grey in colour, locally show banding and are spherulitic in parts. They contain plagioclase feldspar (albite) crystals, along with minor Fe-Ti oxides, set in a fine-grained quartzo-feldspathic matrix. In places, shards, and pumiceous and

Figure 6.70 Oblique aerial view of Skomer Island from the NW, with Middleholm (Midland Island) and the Deer Park Penisula behind. Both islands are made up chiefly of basalts, hawaiites and mugearites of the Skomer Volcanic Group. (Photo: S. Howells.)

Figure 6.71 Spherulites (up to 10 cm across) in The Basin Rhyolite, Skomer Volcanic Group, The Basin, Skomer Island. (Photo: R.E. Bevins.)

lithic lapilli are present, set in a matrix which shows a well-developed eutaxitic texture.

To the south, as far as Tom's House on the west coast and South Haven on the east coast, a thick sequence (up to 385 m in total) of grey to greenish-grey hawaiite to mugearite lava flows is intruded by thin doleritic sheets. Both flows and sheets are particularly well exposed along the west coast of the island, for example in the vicinity of Skomer Head. The lavas form thin units, typically 5 m in thickness, separated by thin red scoriaceous layers. Very rarely, the flows show pillowed forms, for example on the north coast to the SE of the Garland Stone. In thin section, the lavas show variable degrees of alteration, some showing only very minor development of sericite in plagioclase coupled with groundmass recrystallization. They are sparsely porphyritic, with plagioclase, olivine, clinopyroxene and Fe-Ti microphenocrysts, set in a fine-grained groundmass chiefly composed of plagioclase and commonly showing a flow texture. Some flows show glomeroporphyritic clusters of olivine and plagioclase.

Within the above section thin layers of silicic rock occur, for example at Bull Hole, to the north of The Spit, and at Pigstone Bay. The layer at Pigstone Bay is up to 7.5 m thick at its maximum development; the rocks are fragmental, and contain randomly orientated pumice lapilli, whole and broken crystals and pseudomorphs after glass shards. Minor amounts of accessory minerals are present, including monazite and zircon. Fragmental, silicic rocks are also exposed on the eastern side of the island, in the vicinity of Waybench, which contain coarse lithic fragments, some of which are vesicular, associated with broken feldspar crystals.

To the east of Tom's House, extending as far as The Wick, a spectacular silicic sequence known as The Basin Rhyolite is excellently exposed. These rhyolitic rocks, which reach a maximum thickness of 77 m but thin dramatically over a distance of only 400 m, show magnificent flow-banding and flow-folding, but are perhaps best renowned for the extreme development of nodules, described originally by Rutley (1885b). The nodules, which show spherulitic forms, are best developed in the vicinity of The Basin, where they reach up to 25 cm in diameter and commonly occur in layers (Figure 6.71). The rhyolites show alternating light and dark bands on the millimetre scale, with small spherulites developed preferentially in the darker bands. In addition to the predominant spherulitic texture, the rhyolites sporadically show a snowflake texture. The rocks are almost entirely aphyric, with only very rare lithic lapilli and even rarer plagioclase microphenocrysts. Monazite and xenotime are present in very minor amounts, typically occurring as crystals 2–30 microns across.

To the east of The Basin, occupying the low-lying ground of The Wick eastwards to Welsh Way, is an intraformational sedimentary sequence described by Bridges (1976). To the south, and overlying these sedimentary rocks, are a further 74 m of hawaiite and mugearite lavas; a spectacular section through these lavas is seen to the south of The Wick. Within this succession of lavas is a distinctive red silicic tuff, up to 6 m thick, known as the Skomer Ignimbrite. This unit can be traced across the peninsula, cropping out on the east coast at Kittiwake Cove. It can then be traced across the Neck, onto Middleholm and as far as the Deer Park Peninsula, providing an important stratigraphical marker (Ziegler *et al.*, 1969). Microscopically, it shows elongate pumice fragments, lithic clasts and fiamme (up to 5 cm in length) in a recrystallized matrix with a well-developed eutaxitic texture.

The top of the section on Skomer Island is represented by the flow-banded silicic rocks of the Mew Stone. These rhyolites are up to 55 m thick, display excellent flow-folds on the northern face and show a crude columnar-jointing in the upper part of the exposed section. They are sparsely porphyritic and show well-developed perlitic textures, particularly at the base.

Interpretation

The Skomer volcanic sequence is dominated by relatively thin, uniform lava flows showing considerable lateral extent and reddened tops and bases. Ziegler *et al.* (1969) considered these to be subaerial flows, which were non-explosive in character, and did not result in the generation of any significant topography. Locally, however, lavas were either erupted under or emplaced into water, as evidenced by the rare occurrences of pillowed flows. Such flows are found near the top and at the base of the sequence and so there is no simple story of the gradual emergence or submergence of a volcanic island.

The silicic rocks show a variety of forms related to contrasting modes of eruption and emplacement. The rhyolitic lava exposed around The Basin thins dramatically over a short distance, and is thought to represent the remnants of a steep-sided extrusive flow-banded and flow-folded obsidian dome. The rhyolitic rocks exposed in the south, at the Mew Stone, are also thought to represent a thick, extrusive flow, although whether it represents a single flow or a compound set of flows is not certain. In contrast, the silicic tuffs exposed, for example, at Pigstone Bay and on the headland to the south of The Wick are relatively thin (up to 7.5 m maximum thickness) but are laterally extensive. These tuffs are recognized as being ash-flow tuffs, and show both welded and non-welded varieties. The silicic rocks exposed in the north of the island, in the vicinity of the Garland Stone, appear composite and possibly comprise both rhyolitic lava flows and ash-flow tuffs. All of the silicic rocks were apparently emplaced in a subaerial environment, although Ziegler *et al.* (1969) considered that The Basin Rhyolite formed a volcanic island which was subject to erosion in a coastal environment.

Thorpe *et al.* (1989) presented the most recent geochemical data for basic, intermediate and silicic volcanic rocks from the Skomer Volcanic Group. They concluded that the basic to intermediate lavas are hawaiites and mugearites belonging to an alkaline series. Two groups of rhyolites were discriminated, however, a low-Zr group and a high-Zr (peralkaline) group. Silicic rocks from Pigstone Bay and The Basin Rhyolite belong to the low-Zr group, while silicic rocks from the Garland Stone and the Skomer Ignimbrite belong to the high-Zr group. Thorpe *et al.* (1989) considered that rocks of the high-Zr group were derived from the hawaiites and mugearites as a result of low-pressure fractional crystallization, and relate to a basalt–hawaiite–mugearite–comendite series such as is seen in within-plate oceanic and continental settings. The low-Zr group, however, they considered to be unrelated to the other volcanic rocks exposed in the area, although recent unpublished work contradicts that view, linking their generation to the high-Zr group by crystal fractionation involving minor mineral phases, in particular monazite and xenotime (R.E. Bevins and G.J. Lees, unpublished data). The consensus is that the parental magmas were derived from a within-plate ocean-island mantle source which had been modified by earlier subduction-related events.

Conclusions

The Skomer Island site is of national importance in that it provides excellent exposures of the youngest major volcanic episode in the southern part of the British Caledonides. The volcanic rocks show geochemical features which suggest that their source rocks were influenced by earlier Caledonian subduction events.

A range of volcanic rocks, ranging from basic through intermediate to acidic compositions, are excellently exposed on Skomer Island, especially in the rugged cliffed coastline. The basic to intermediate rocks originated chiefly as subaerial flows, although rare pillowed flows show the local occurrence of subaqueous flows. The silicic rocks appear to be entirely of subaerial origin, and were generated in part as extrusive flows resulting in steep-sided domes, and in part from explosive eruptions, leading to the generation of ash-flow tuffs. The age of these various volcanic rocks is provided by their relationship to fossil-bearing sedimentary rocks on the mainland, which indicates a Llandovery age.

Geochemically, two distinct groups of silicic rocks have been determined, a low-Zr group and a high-Zr group. The latter are thought to be related to the basic to intermediate lavas through crystal fractionation, while the low-Zr group rocks have been considered to be unrelated to any of the other volcanic rocks exposed, although recent work suggests a link to the high-Zr group through crystal fractionation. The volcanic rocks are alkaline in character, and were apparently derived from a within-plate mantle source.

DEER PARK (SM 756 091–760 088)

R.E. Bevins

Introduction

Lavas, pyroclastic rocks and high-level intrusive rocks of the Skomer Volcanic Group, of Llandovery age, crop out intermittently over 40 km of a near-strike section in south Pembrokeshire. Offshore, the volcanic rocks form The Smalls in the west, the reef known as the Hats and Barrels, and Grassholm, as well as much of Skomer Island, and Middleholm (Midland Island); onshore, they crop out across the Marloes Peninsula as far east as St. Ishmael's (Figure 6.69), although exposures are scattered and poor. The thickest and best exposed development of the volcanic rocks is seen on Skomer Island (see the Skomer Island GCR site report), while exposures in the rugged coastline of the Deer Park Peninsula, at the Deer Park GCR site, provide critical evidence for the age of the group, which represents the most important episode of Silurian volcanism in the southern Caledonides of the British Isles. Broad details of the Skomer Volcanic Group are described in the Skomer Island GCR site description.

Volcanic and related rocks are well exposed all around the coast of the headland known as Deer Park, from Martin's Haven to Renney Slip (Figure 6.72). Access, however, is for the most part difficult; the easiest access is in the vicinity of Wooltack Point and at Renney Slip.

Description

Basic to intermediate lavas are the most common volcanic rocks at Deer Park, as indeed they are on Skomer Island. Some 45 m of thin (*c.* 5 m-thick), generally massive flows crop out on the headland, in places showing reddened tops and bases. These flows have been correlated with those exposed on Skomer Island in the vicinity of North Haven and South Haven (Ziegler *et al.*, 1969), and are chiefly hawaiites and mugearites (Thorpe *et al.*, 1989). Locally, as at Jeffry's Haven, the lavas are pillowed. Petrographically, they are identical to the lavas exposed on Skomer Island, being fine grained, greenish-grey in outcrop and commonly vesicular. Under the microscope they are seen to be sparsely porphyritic, containing plagioclase, clinopyroxene, Fe-Ti oxide and rare olivine microphenocrysts in a fine-grained matrix dominated by plagioclase microlites, some showing flow alignment.

Silicic rocks are rare in the Deer Park section. However, a 5.5 m-thick ash-flow tuff exposed at Jeffry's Haven, has been correlated with the 'Skomer Ignimbrite' which crops out at the southern end of the Skomer Island section (see the Skomer Island GCR site report) and on Middleholm (Midland Island). This ash-flow tuff forms an important stratigraphical marker within the Skomer Volcanic Group. Ziegler *et al.* (1969) presented major element chemical analyses of the ash-flow tuff from this locality, but no trace element analyses are available; hence it is not possible to ascribe this unit to either of the two silicic groups identified by Thorpe *et al.* (1989).

The key section for establishing the age of the Skomer Volcanic Group occurs to the south of Anvil Bay, although much of the sequence in this area is made up of sedimentary rocks. Here a 7 m-thick basalt flow, which is vesicular both at its base and top, is exposed at Limpet Rocks and extends eastwards across the promontory dividing Anvil Bay from Renney Slip. The sequence is much faulted around the bay; sedimentary beds immediately overlying the basalt are best exposed in the steep dip faces forming the north side of Renney Slip. Faunas contained within this sedimentary sequence are indicative of an early Upper Llandovery (late Aeronian, C_{1-2}) age (Walmsley and Bassett, 1976; Bassett, 1982). The unconformity at the top of the Skomer Volcanic Group is exposed on the SE side of Renney Slip.

Interpretation

The basic to intermediate lavas exposed across the site area are lateral equivalents of the lavas exposed on Skomer Island, and form a part of the Skomer Volcanic Group. Predominantly they were erupted in a subaerial environment, although locally they were either erupted or emplaced subaqueously. Silicic rocks are rare across the site area, restricted to the single occurrence of an ash-flow tuff to the south of Jeffry's Haven. This unit has been correlated with similar rocks exposed towards the top of the sequence exposed on Skomer Island; however recent work has identified a number of ash-flow tuffs on Skomer Island, at various stratigraphical levels and with contrasting chemistries (R.E. Bevins and G.J. Lees, unpublished data), and hence the correlation is in need of reappraisal.

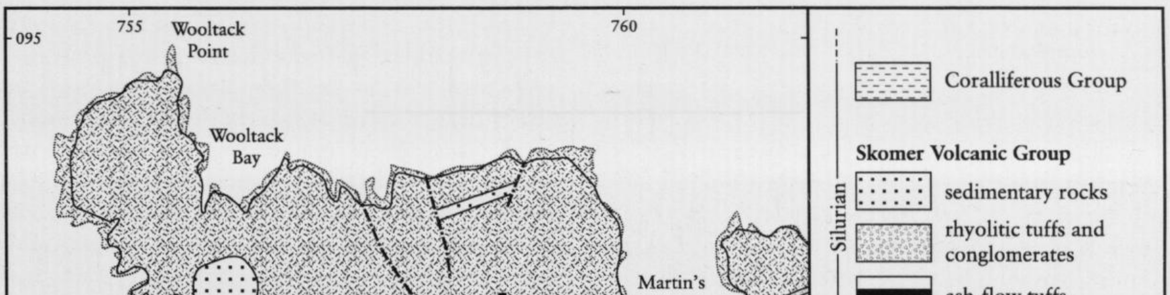


Figure 6.72 Map of the Deer Park Peninsula (after Ziegler *et al.*, 1969).

The volcanic rocks of the Skomer Volcanic Group are part of a basalt–hawaiite–mugearite–comendite series. Thorpe *et al.* (1989) presented the most recent interpretation of the geochemistry of the volcanic rocks of the group (see the Skomer Island GCR site report).

Conclusions

The Deer Park site exposes lavas and pyroclastic rocks of the Skomer Volcanic Group, along with associated sedimentary rocks. This sequence represents the most important episode of Silurian volcanism in the southern part of the British Caledonides. The Skomer Volcanic Group is best exposed on Skomer Island itself (see the Skomer Island GCR site report); however, coastal outcrops in the Deer Park area provide critical evidence for the true age of activity, based on fossils indicative of the Upper Llandovery. This volcanic sequence therefore represents the youngest volcanic episode of importance in the southern Caledonides of the British Isles.