Precambrian Rocks of England and Wales

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Chapter 7

Anglesey and the Lleyn Peninsula (Llŷn)

Introduction

J.M. Horák and W. Gibbons

The sites covered in this chapter lie within, or to the north-west of, the Menai Strait Fault System (Figure 7.1) and represent the most lithologically varied suites of Precambrian rocks in southern Britain. Exposures cover the island of Anglesey (Ynys Môn) and extend to the south-west along the north-western side of the Lleyn Peninsula (Llŷn), on the mainland, as far as Bardsey Island (Ynys Enlli). Greenly (1919) referred to these rocks as the Mona Complex, a term now superseded by the concept of several Monian fault-bounded blocks or 'terranes', each with a distinct tectono-metamorphic history (Bassett *et al.*, 1986). These have been collectively termed the Monian Composite Terrane, as discussed further in Chapter 1. The more complex histories of these terranes, which include polydeformed blueschists, distinguishes them from the 'British Avalonian Terranes' located to the south-east of the Menai Strait Fault System, thus making the latter a major terrane boundary (Gibbons, 1987).

Three rock masses of this region can be further classified as individual terranes in their own right. Such nomenclature forms the basis of the GCR network systems (Figure 1.5), and is compared with the equivalent lithostratigraphical names of the units as follows:

- Coedana Complex – Coedana Terrane of Chapter 1
- Eastern Schist Belt – Aethwy Terrane
- Monian Supergroup – 'Monian Supergroup Terrane'

The following sections provide introductory details of each of these terranes and where available include evidence for their age. In recent years, palaeontological and stratigraphical evidence has been presented to suggest that all or part of the Monian Supergroup may have an early Cambrian age (Barber and Max, 1979; Muir *et al.*, 1979; Peat, 1984b; Tietzsch-Tyler and Phillips, 1989; Bennett *et al.*, 1989; Gibbons *et al.*, 1994). In view of the considerable uncertainty still surrounding the precise age of this sedimentary sequence, the GCR sites relating to the Moinian Supergroup have been retained within this chapter to maintain continuity and context with the regional geology.

Greenly (1919, 1920) published the first detailed work on the Monian rocks of Anglesey, producing a memoir and the linework and colour on the accompanying, still current, BGS map. He divided the Monian rocks into granite and hornfels, gneisses, low-grade predominantly metasedimentary rocks, and a belt of schist outcropping in central and eastern Anglesey. Originally interpreting the granite (Coedana Granite) to post-date the metasedimentary rocks, he later reconsidered this and interpreted the gneisses, granite and hornfels as forming their ancient basement. This model stood unopposed until Shackleton (1954, 1956) introduced a key revision of Monian stratigraphy by recognizing the use of way-up criteria within the metasediments. Shackleton (1954, 1956, 1969) also attempted to revise Greenly's interpretation of the metamorphic history of the Monian rocks. He presented a model whereby the granite was interpreted as the anatectic product of metamorphism of the low-grade sediments, with the schists and gneisses representing intermediary stages. Studies of the Monian rocks on Llŷn reinterpreted the schist belts as ductile fault zones (Gibbons, 1983) and this led the way both to an abandonment of Shackleton's '*prograde metamorphic transition*' and the development of a terrane model for the Monian rocks. Bassett *et al.* (1986) defined three terranes; the Coedana Complex, the Monian Supergroup and the Eastern Schist Belt, separated from each other by brittle faults, or by ductile shear zones such as the Central Anglesey Shear Zone of Figure 7.1. Each terrane has by definition had a separate history and unproven relationships to the other terranes.

Coedana Complex

The Coedana Complex, described in the Tyddyn Gyrfer, Maen-gwyn Farm and Gwalchmai site reports, has three components: low-grade hornfels, high-grade metamorphic rocks (the Central Anglesey Gneisses), and the Coedana Granite, which crops out over an area of 30 km^2 and volumetrically forms the most important component. The mapping and petrological work of Greenly (1919), supplemented by the work of Horák (1993), shows both porphyritic and non-porphyritic varieties with a variation in mineralogy from biotite- and minor garnet-bearing, to highly leucocratic, muscovite and garnet-bearing granite and aplite. Garnet compositions have

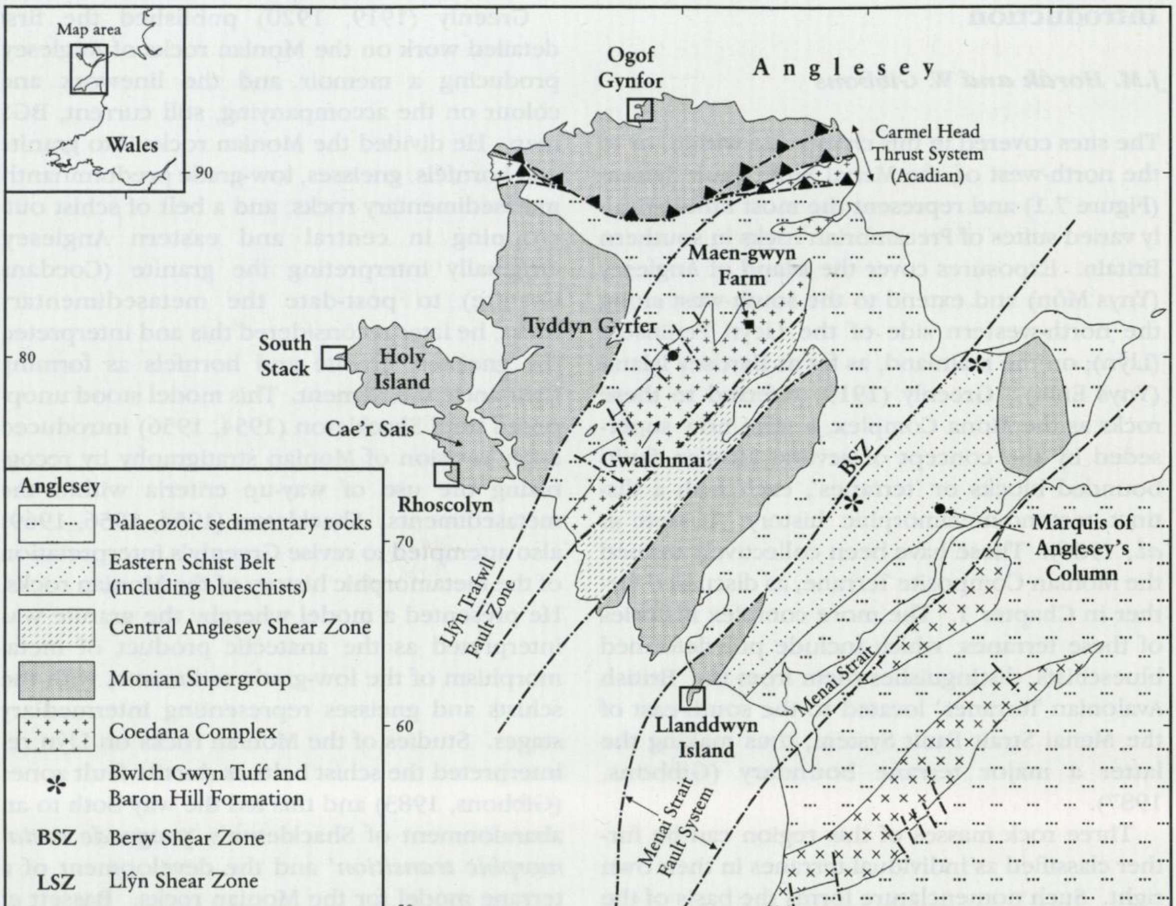

Figure 7.1 Geological map showing simplified geology and location of GCR sites (bold lettering) in the Anglesey–Llŷn region.

been confirmed as spessartine-rich from the leucocratic facies (Horák, 1993). All facies are pervasively affected by ductile deformation, such that the intrusion can be classified more accurately as a protomylonitic, or locally mylonitic, metagranite (Horák, 1993). Both the mineralogy and the whole-rock geochemistry confirm the calc-alkaline, subduction zone affinity of the intrusion. A U-Pb zircon age date of 614 ± 4 Ma (Tucker and Pharaoh, 1991) supports *c.* 600 Ma ages obtained by previous workers (e.g. Fitch *et al.*, 1964, 1969; Moorbath and Shackleton, 1966; Beckinsale and Thorpe, 1979), and the upper intercept of 1443 Ma for the discordia is consistent with the ϵNd model ages of 1300–1430 Ma (Davies *et al.*, 1985), indicating derivation of the granite from an older crustal source.

In comparison with the Coedana Granite, since the initial work of Greenly (1919), little work has been undertaken on the gneisses; specifically, their relationship with the granite and hornfels remains unproven as contacts between these units are either faulted or unexposed. Like the granite, the gneisses have suffered considerable retrogression and are overprinted by much brittle deformation. This is most likely Palaeozoic in age, as the most highly deformed outcrops of gneiss lie as slivers within the Carmel Head Thrust System (Gibbons *et al.*, 1994), a structure attributed to movements during the Acadian Orogeny. Paragneisses, ranging from pelite to semi-pelite, but also including minor outcrops of calc-silicates, are associated with amphibolite. The local presence of sillimanite and migmatitic textures provides evidence for upper amphibolite facies conditions of metamorphism, as seen at the Tyddyn Gyrfer GCR site. The gneisses are especially important to our understanding of the Avalonian of southern Britain as they are the only examples of high-grade metamorphic rocks. They also allow correlations to be made with the Rosslare Complex of south-east Ireland, providing some indication of the original extent of these late Precambrian terranes.

Eastern schist belt

A narrow (< 5 km), NE–SW oriented, and fault-bounded belt of blueschists and associated rocks, defining the Aethwy Terrane (Chapter 1), crops out in south-east Anglesey. Greenly (1919) referred to this metamorphic belt as the Aethwy unit of the *'Penmynydd Zone of Metamorphism'*, a term that has fallen into disuse as it includes several, apparently unrelated schistose units. The metamorphic rocks of south-east Anglesey, though small and poorly exposed, are famous worldwide for preserving some of the oldest, and yet still mineralogically fresh, blueschists on Earth (Marquis of Anglesey's Column and Penrhyn Nefyn sites). The rocks are dominantly metasedimentary phengitic mica schist and metabasaltic glaucophane schist, although lawsonite schist and spessartine-rich metasediments have also been recorded (Gibbons and Mann, 1983; Gibbons and Horák, 1990). Blueschist metamorphism was accompanied by intense deformation, producing a mostly flat-lying foliation, isoclinal folds and a north–south trending mineral lineation.

The geochemistry of the basic rocks within the Anglesey blueschist reveals a strong MORB (mid-ocean-ridge basalt) signature (Thorpe, 1972c; Phillips, 1989) and suggests that these rocks represent a slice of Precambrian oceanic crust. ^{40}Ar–^{39}Ar cooling ages derived from amphiboles in the blueschist indicate a latest Precambrian age (560–550 Ma; Dallmeyer and Gibbons, 1987). Such ages are interpreted as having been produced during rapid uplift of the blueschists through their mineral blocking temperatures (*c.* 500°C) during oblique movements on the Menai Strait Fault System (Figure 1.4). Slightly older ages (580–590 Ma; Dallmeyer and Gibbons, 1987) have been obtained from a metagabbroic protolith to one of the blueschist metabasites, and are interpreted as recording an earlier sub-seafloor-metamorphism (Gibbons and Gyopari, 1986).

The north-western margin of the Anglesey blueschist belt is characterized by a steep, schistose, high strain zone referred to as the Berw Shear Zone. High-level brittle movements along this lineament have juxtaposed Carboniferous sedimentary rocks against Precambrian blueschists (Greenly, 1919). Most of the south-eastern margin of the blueschist belt is covered by an unconformable Carboniferous sequence, but north of the Menai Bridge the schists are in tectonic contact with the Gwna Group mélange (Gyopari, 1984). All contacts between the Anglesey blueschists and other rocks therefore are either unconformable or tectonic. The blueschists are interpreted as having originally belonged within a Precambrian accretionary prism (Figure 1.4), one small slice of which has been preserved within the Menai Strait Fault System. The latter structure is interpreted as just one of a family of such terrane boundaries, running sub-parallel to the former Avalonian subduction-related faults, that dispersed slivers of the subduction system as plate convergence became progressively more oblique through latest Precambrian times (Gibbons and Horák, 1996). One consequence of this was the tectonic incorporation of 'Arfon-type' volcanic-arc lithologies, such as the Bwlch Gwyn Tuff, within the Berw Shear Zone (Figure 7.1), as discussed further in the introduction to Chapter 6. It follows from this model (Figure 1.4) that all the Precambrian rocks of southern Britain, along with those of Nova Scotia and Newfoundland, Canada, could belong to the same Avalonian subduction system.

Monian Supergroup

The Monian Supergroup, originally described by Greenly (1919) as the 'Bedded Succession', is a thick (up to 7.5 km) tripartite sequence of low-grade metamorphic rocks dominated by metasediments. The base of the supergroup is not seen, and the highest unit is overlain unconformably by Arenig strata. The three units that together comprise the supergroup are as follows.

- Gwna Group, spectacular mélange with no coherent internal stratigraphy (Ogof Gynfor, Penrhyn Nefyn and Braich y Pwll and Parwyd sites).
- New Harbour Group, mostly semi-pelites but locally containing basalt, gabbro and serpentinite (Cae'r Sais site).
- South Stack Group, which mostly consists of psammitic meta-turbidites; it is the oldest component of the Monian Supergroup (South Stack and Rhoscolyn sites).

Shackleton (1954, 1969) used sedimentary structures preserved within the South Stack Group to prove this meta-turbiditic sequence to be right-way up, thus revising Greenly's (1919) initial interpretation. A later controversy was provoked by Barber and Max (1979), who argued for a tectonic contact between a supposedly older New Harbour Group and underlying South Stack Group. This was similarly disproved by various authors, notably Cosgrove (1980). The Gwna Group incorporates various other lithostratigraphical units, previously named as the Skerries and Fydlyn groups (Greenly, 1919; Shackleton, 1969), but these names have become disused as all of these rocks are essentially part of the same chaotic mélange (Gibbons and Ball, 1991). An alternative view of Phillips (1989, 1991), however, was that the Skerries unit is part of the New Harbour Group.

The age of the Monian Supergroup is poorly constrained, and has been variously referred to as Precambrian and Cambrian (Gibbons *et al.*, 1994). A minimum age is provided by the overlying late Arenig (Fennian) sediments, and a maximum age is provided by clasts of granite within the Gwna Group (Horák *et al.*, 1996) that resemble, and are correlated with, the Coedana Granite (614 Ma). Less definitive is the presence of (?Precambrian) stromatolites in Gwna mélange limestone clasts, the possible presence of ?Cambrian microfossils in cherts associated with pillow-lava clasts in the mélange, and supposedly Cambrian *Skolithos* burrows in the South Stack Group (Barber and Max, 1979;Muir *et al.*, 1979; Peat, 1984b). Lithostratigraphical correlations with the Cullenstown Formation, exposed in south-east Ireland, suggest that the Monian Supergroup could be Cambrian rather than Precambrian (Bennett *et al.*, 1989; Tietzsch-Tyler and Phillips, 1989; Gibbons *et al.*, 1994).

The presence of calc-alkaline igneous detritus in some parts of the New Harbour Group, combined with the geochemistry of the basalt contained within this group, suggests a subduction-related tectonic setting (Thorpe *et al.*, 1984; Phillips, 1989; Gibbons *et al.*, 1994). Its sedimentary rocks contain detritus indicative of their derivation by the progressive unroofing of an andesitic volcanic arc, although Phillips (1991a) notes that the arc was probably extinct by this time. The South Stack Group, on the other hand, contains detritus indicative of a quartzose to mixed recycled orogenic provenance (Phillips, 1991a). It may represent part of a submarine fan complex within a forearc or backarc basin, or may have been deposited within a later (Cambrian) basin that received detritus from a Precambrian arc being degraded during strike-slip dispersal of an extinct Avalonian subduction system (Phillips, 1991a). The Gwna Group mélange contains oceanic pillow basalt associated with deep-water cherts and limestone, and may represent the higher levels of a subduction-related accretionary prism, or some collision-related olistostrome.

The Monian Supergroup commonly exhibits polyphase deformation, especially on Holy Island in western Anglesey, and along the west and south-west coast of Llŷn. The exposures around Rhoscolyn and South Stack on Holy Island are spectacular, revealing several generations of folds and related cleavages: these are the best exposures of polydeformed rocks in southern Britain. The ages of these deformations are, however, poorly known. It is unclear how many of the fold generations owe their origin to late Caledonian ('Acadian', i.e. ?late Silurian to early Devonian) compression, and whether some of the early phases relate either to Precambrian or Cambrian–Tremadoc deformation events, or both.

It should be noted that two of the following GCR sites (Penrhyn Nefyn and Braich y Pwll to Parwyd) contain the boundary between the Monian and Cymru terranes (Chapter 1), and as a result they expose lithologies more appropriate to the latter. These constitute the Parwyd Gneiss and the Sarn Complex, which are for convenience described here but whose origins, age and geochemistry are discussed in the introduction to Chapter 6, along with the other rocks of the Cymru Terrane.

TYDDYN GYRFER (SH 383 808)
POTENTIAL GCR SITE

J.M. Horák

Introduction

The Tyddyn Gyrfer site (Figure 7.2) provides a small but informative exposure of interleaved paragneisses and amphibolites, representative of the upper amphibolite facies gneisses of the Coedana Complex. This site is important because exposures of high-grade metamorphic rocks are uncommon within the Neoproterozoic of southern Britain, and those with a metasedimentary protolith are even rarer. In addition to this, it was from here that Horák (1993) sampled the gneisses for Sm-Nd whole-rock analyses. These data, along with petrological information, support a correlation between the Coedana Complex and the Rosslare Complex of south-east Ireland.

The main occurrence of Coedana Complex gneisses lies to the north-west of the main Coedana Granite outcrop and consists of both metasedimentary rocks and metabasites. Two

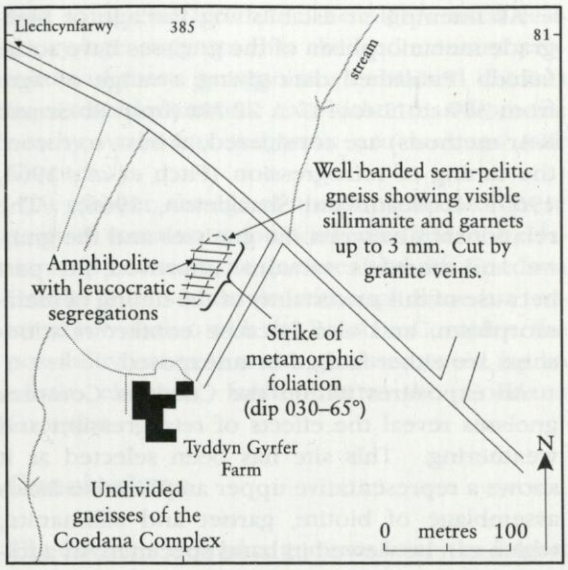

Figure 7.2 Locality map of the Tyddyn Gyrfer site.

further highly cataclased exposures of gneisses, the Nebo and Gader inliers, crop out in the north-eastern and north-western corners of the island respectively and form slices within the Carmel Head Thrust System (Figure 7.1). Migmatized pelites and semi-pelites dominate the metasediments, but minor occurrences of calc-silicate gneisses are present in the Nebo Inlier.

The relationship between the gneisses, hornfels and granite has elicited much debate. Blake (1888) first differentiated the paragneissic and orthogneissic components. Subsequently, Greenly (1919) interpreted the gneisses as the old gneissic basement to the Monian Supergroup. One of the most significant findings of his detailed mineralogical and textural study was the identification of sillimanite as part of a garnet-biotite gneiss assemblage. A controversial re-interpretation of the gneisses was made by Shackleton (1954, 1956), who proposed that rather than being an old basement, they could be interpreted as part of a metamorphic transition from the low-grade Monian Supergroup metasediments, via Penmynydd schists, with the Coedana Granite as the final product of ultra (high-grade) metamorphism. Subsequent works refuted Shackleton's model and re-established that of Greenly. Gibbons (in Bassett *et al.*, 1986) grouped the gneisses, hornfels and granite together as the Coedana Complex.

All attempts at establishing the age of high-grade metamorphism of the gneisses have so far failed. Published data giving a range of ages from 389 ± 11 to 447 ± 22 Ma (from Rb-Sr and K-Ar methods) are considered, at best, to record the timing of retrogression (Fitch *et al.*, 1964, 1969; Moorbath and Shackleton, 1966). The relationship between the gneisses and the granite and hornfels remains unproven, in part because of this uncertainty of the timing of metamorphism, and also because contact relationships are either faulted or unexposed.

All exposures within the Coedana Complex gneisses reveal the effects of retrogression and weathering. This site has been selected as it shows a representative upper amphibolite facies assemblage of biotite, garnet and sillimanite, which can be viewed in hand specimen, in addition to providing exposures that show the juxtaposition of amphibolite and paragneisses.

Description

The site (Figure 7.3) lies in the central area of the gneiss outcrop and forms a low rocky exposure. The dominant lithology is pale-weathering biotite-garnet-sillimanite gneiss showing banding on a 2–3 mm scale. More mafic parts contain biotite, with visible retrogression to chlorite, and subhedral almandine-rich garnets, typically up to 3 mm in diameter. The leucocratic portions have a simple assemblage of quartz and feldspar. Locally, biotite and garnet are associated with silky aggregates of sillimanite fibres a few millimetres in length. In thin section good prismatic sillimanite is observed, commonly showing biotite replacement textures similar to those described from Scotland by Chinner (1961). The gneiss is cut by leucogranite veins ranging from thin, impersistent veins less than 10 mm in width, lying sub-parallel to the metamorphic banding, to larger pods of granite typically 0.1–0.15 m in width. The foliation strikes approximately east–west and varies from moderately inclined to sub-vertical due to the presence of open folds.

The west side of the exposure reveals the presence of pale green-weathering amphibolite layers interleaved with the paragneiss. The amphibolite is fine-grained with a well-developed foliation and leucocratic segregations a few millimetres thick, which persist over distances of 30–40 cm. Unfoliated pods of feldspar and hornblende are locally present. In thin section the amphibolite shows retrogression to an assemblage of albitized and sericitized plagioclase, and hornblendic amphibole replaced by actinolite and chlorite.

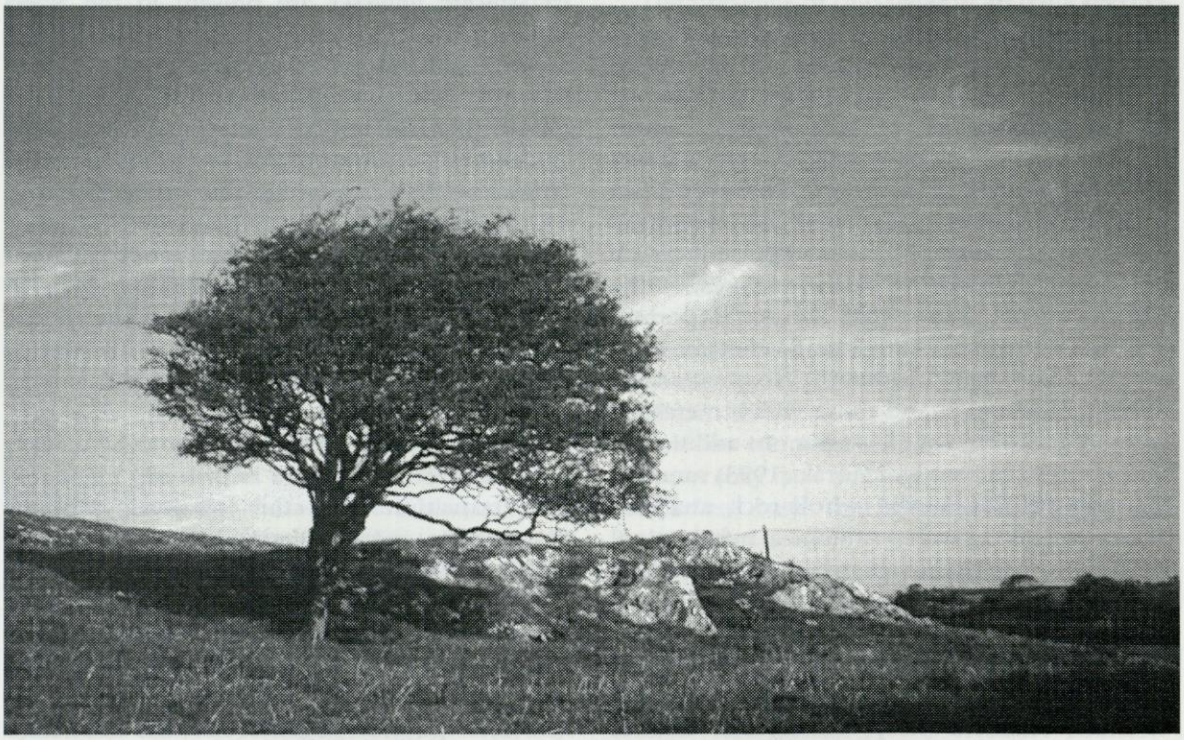

Figure 7.3 Coedana Complex gneiss exposures at Tyddyn Gyrfer farm, looking east. (Photo: J.M. Horák.)

Interpretation

The petrological studies of Greenly (1919) and Horák (1993) indicate that the mineralogical assemblage within the paragneisses is diagnostic of upper amphibolite facies conditions within the sillimanite stability field. Unfortunately, the state of retrogression in the biotite and feldspar precludes more detailed thermobarometric calculations to determine the precise temperature and pressure conditions of metamorphism. On the basis of amphibolite mineralogy, however, an approximation to these conditions would be temperatures above the granite-wet solidus, within the sillimanite stability field, and pressures between 2.7 and 5 Kb. As the metamorphic layering does not contain distinct melanosomes and neosomes, the possibility exists that these may represent injection migmatites (Winkler, 1979); in this instance, however, the melt is considered to be derived from melting of Coedana Complex paragneisses as opposed to a Coedana Granite source. Exposures at Mynydd Mwyn-Mawr, 2.5 km to the north-east of this site, although lacking diagnostic metamorphic minerals, show clear migmatite textures in pelites and semi-pelites. The amphibolites are interpreted as thin sills or dykes intrusive into the paragneiss protolith. Where preserved, the original amphibolite mineral assemblage of amphibole (typically magnesio-hornblende) and plagioclase is consistent with upper amphibolite conditions of metamorphism although the state of retrogression precludes more specific determination of pressure and temperature conditions.

Paragneiss samples from this locality were analysed for Sm-Nd isotopes by Horák (1993). Attempts to determine a metamorphic age from whole-rock-garnet Sm-Nd pairs failed to produce reliable results due to insufficient rare earth element fractionation by the garnet. Whole-rock Sm-Nd data showed, however, that the paragneisses have crustal residency ages of 1800 Ma, considerably older than most other Neoproterozoic rocks in southern Britain, but consistent with the ages yielded by the Rosslare Complex in south-east Ireland. These crustal residency ages, combined with whole-rock geochemical and isotopic data from the amphibolites, support previous correlations made between these two crystalline complexes (Gibbons, 1990), and serve to show the south-westward extension of the Coedana Complex into south-east Ireland. The high crustal residency age suggests that the sedimentary protoliths of these paragneisses contained detritus from an older cratonic area rather than from the nearby Avalonian magmatic arc terranes (see Chapter 1).

At present, the age of metamorphism of these gneisses remains unconstrained as does the relationship between the gneisses and the Coedana Granite and its hornfels. Although there is a tentative correlation with the Rosslare Complex, the possibility exists that the gneisses could be an exotic element, faulted into the Coedana Complex.

Conclusions

The Coedana Complex gneisses form the largest outcrop of paragneisses (gneisses with a sedimentary protolith) in southern Britain, and this site in particular provides representative exposures of rocks metamorphosed at upper amphibolite facies within the Complex. Isotopic data obtained from this site have supported the correlation with the Rosslare Complex of south-east Ireland, providing evidence for the extension of the Coedana Complex across the southern Irish Sea.

MAEN-GWYN FARM (SH 425 825)
POTENTIAL GCR SITE

J.M. Horák

Introduction

This site records the original intrusive relationship between two components of the Coedana Complex, namely the Coedana Granite and its low-grade hornfels. Country rock relationships are rare among the Precambrian intrusions of southern Britain, and in all other instances where they are preserved they are generally associated with volcanic successions. The sedimentary nature of these hornfels serves to detail part of the pre-intrusion history of the complex.

The hornfels were studied in detail by Greenly (1919) who regarded them as equivalent to the Church Bay Tuffs, now interpreted by Gibbons and Ball (1991) as part of the Gwna Group, and by Phillips (1991a) as part of the New Harbour Group, Monian Supergroup. Subsequent, but unpublished, views of Greenly revoked this (1919) interpretation and instead considered the hornfels as a sedimentary sequence, with a volcanic component, into which the Coedana Granite was intruded. Greenly provided a detailed petrological study of the hornfels, dividing them into cryptocrystalline and crystalline varieties, which were further, subdivided by Horák (1993) into four sub-types. Only three can still be observed in outcrop, the predominant sub-type being the fine-grained quartzo-feldspathic hornfels and the next most common, a slightly coarser muscovite-bearing variety.

The hornfels occur both as a marginal country rock to the granite, on its north-eastern and south-western sides, and as xenolithic masses within the intrusion. In many instances, particularly where the hornfels rim the granite, they have responded in a brittle fashion to deformation and this has resulted in movement along the original intrusive contact. This site has been chosen as it consists of a small mass of hornfels that is both submerged in and cross-cut by granite, so demonstrating unequivocally the original relationship between the two units. The greenschist-facies metamorphic grade and deformation state of the hornfels provide useful information on the emplacement environment of the granite.

The intrusive age of the Coedana Granite has been dated at 614 ± 4 Ma (U-Pb zircon method) (Tucker and Pharaoh, 1991), which is consistent with the metamorphic ages derived from the hornfels (e.g. Moorbath and Shackleton, 1966; Fitch *et al.*, 1969). Further details of the ages are given in the introduction to Chapter 7.

Description

The site (Figure 7.4) encompasses typical muscovite hornfels. The hornfels are fine-grained and generally steel-grey in colour, but locally they show centimetre-scale variations in the mica and quartz content that defines an original (S_0) sedimentary layering. The low-grade nature of the hornfels also preserves a second fabric (S_1) which, being virtually parallel to S_0, forms a composite fabric in the rock.

To the north-west of the farmhouse, a small rocky knoll exposes both the fine-grained and muscovite-bearing varieties of hornfels enclosed within the granite. The hornfels have pale colours and are more bleached than the exposures in the farmyard. Banding on a centimetre scale represents the S_0 layering. Parallel to that structure is a more closely spaced (millimetre scale) fabric designated as S_1. This composite fabric dips steeply to the south-west. In the middle of the north-western side of the site, two small granite veins up to 6 cm wide cut the hornfels at a low angle to the composite fabric and are traceable for a distance of a few metres. A few metres towards the south-western end of the outcrop, two larger granite veins cut the hornfels at a high angle to the fabric and the south-western end of the exposure is entirely within coarse-grained granite. The granite cutting and enclosing the hornfels is non-porphyritic and biotite-bearing, with pink K-feldspar; it has a weakly developed ductile foliation striking 290°. It is noteworthy that this site is just 500 m to the south-east of Greenly's type locality for the Coedana Granite, near to Coedana Chapel. There, weakly porphyritic granite shows a well-developed, NE–SW trending, ductile foliation.

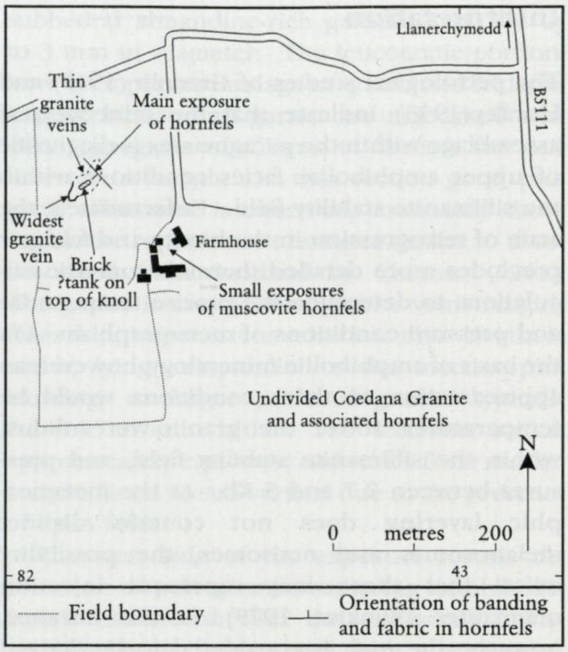

Figure 7.4 Locality map of the Maen-gwyn Farm site.

Interpretation

The hornfels represents quartzo-feldspathic sedimentary rocks whose composite fabric records a pre-intrusion history involving two episodes, S_0 representing the formation of the original sedimentary layering, and S_1 a tectonic foliation associated with a folding deformation observed locally. Both of these structures are interpreted as having developed prior to the intrusion of the

Figure 7.5 Exposures at Maen-gwyn Farm showing muscovite hornfels of Coedana Complex cut by thin granite veins (running horizontally from tape on hammer handle). The hammer is oriented parallel to the composite fabric in the hornfels. (Photo: J.M. Horák.)

Coedana Granite, because veins of the latter cut across the composite fabric. The weak, post-magmatic, ductile fabric seen in the granite veins is equated to the extensive brittle deformation seen in the hornfels; other than post-dating S_1, the age of this deformation is not known.

The mineral assemblage of the hornfels: chlorite–muscovite–biotite, is indicative of low-grade metamorphism in the greenschist facies. Isotopic data derived from metamorphic muscovite from the hornfels yielded dates of 596 ± 15 Ma by the Rb-Sr method (Moorbath and Shackleton, 1966) and 598 ± 10 Ma by K-Ar analysis (Fitch *et al.*, 1969). Such values are consistent with this metamorphism (and cooling) occurring after the intrusion of the Coedana Granite at 614 ± 4 Ma (Tucker and Pharaoh, 1991). These data also demonstrate that the foliation and folding observed in the hornfels are Precambrian in age.

Conclusions

The rocks exposed at this site have an important bearing on the evolution of the Coedana Complex, and in particular the history of heating and deformation experienced by the country rocks into which the Coedana Granite was intruded. On display here are representatives of both the muscovite-rich and fine-grained varieties of the hornfelsed country rocks along the margin of the granite. Their low-grade, greenschist facies metamorphism contrasts with the upper amphibolite grades attained in the gneisses seen at the Tyddyn Gyrfer site. These exposures demonstrate that at least one phase of ductile deformation (S_1) affected the hornfels, before the intrusion of veins emanating from the Coedana Granite.

GWALCHMAI (SH 379 766–381 773)

POTENTIAL GCR SITE

J.M. Horák

Introduction

This site lies on the western margin of the granite outcrop and has been proposed for the GCR because it illustrates particularly well the textural range of the Coedana Granite, here consisting of porphyritic, non-porphyritic and aplitic facies. The central part of the site (Figure 7.6) falls within the actively working Gwalchmai Quarry, suggesting the possibility of continuing good exposure.

The Coedana Granite constitutes one of the three units of the Coedana Complex (Bassett *et al.*, 1986). Its outcrop trends NE–SW, although exposure is poor in its north-eastern and south-western extremities. To the south-east the granite is bounded by low-grade hornfels and rocks of the Central Anglesey Shear Zone, which may in part have a granite protolith (Horák, 1993). On the north-western side it is flanked by the Central Anglesey Gneisses and a minor outcrop of hornfels. In all instances the contact with the gneisses is faulted or unexposed.

Greenly (1919) provided the first detailed study of the granite, identifying facies variations and the presence of two fabrics, referred to as the *old foliation* and *mylonitization*. Although he initially considered the granite to intrude the metasedimentary rocks of the Monian Supergroup, he later reconsidered this and incorporated the Coedana Granite with the gneisses into the *ancient floor* (Greenly, 1919). Shackleton (1954, 1956) introduced a new model, re-interpreting the granite as the ultimate product of anatexis of the Monian Supergroup whereby the schists and gneisses represented intermediary stages of metamorphism. On the basis of later studies on the Monian rocks of Llŷn, Baker (1969) and Gibbons (1983) demonstrated that Shackleton's 'prograde metamorphic transition' model was not valid. Gibbons' (1990) terrane tectonic analysis of Monian geology once again grouped the Coedana Granite and its hornfels with the Central Anglesey Gneisses to form the Coedana Complex (Bassett *et al.*, 1986).

The Coedana Granite has been subject to more isotopic age dating than any other Monian unit. The earliest attempts to date the Coedana Granite produced a Rb-Sr whole-rock age of 581 ± 14 Ma and K-Ar and Rb-Sr muscovite age of 576 ± 13 Ma respectively (Fitch *et al.*, 1964, 1969; Moorbath and Shackleton, 1966). The low initial $^{87}Sr/^{86}Sr$ ratio of 0.7017 ± 0.0015 obtained by Moorbath and Shackleton (1966) was taken as indicating a mantle derivation for the granite, although this contradicted Shackleton's prograde metamorphic theory for its origin. More recently, Beckinsale and Thorpe (1979) published a whole-rock Rb-Sr age of 604 ± 4 Ma, using samples from Gwalchmai Quarry, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7086 ± 9, which was interpreted as representing contamination of a mantle-derived melt, either by crustal material or by melting of a crustal protolith. A suggestion was also made that the granite could have been derived from melting of Monian paragneisses, such as those described from Holland Arms, southern Anglesey, by Beckinsale and Thorpe (1979).

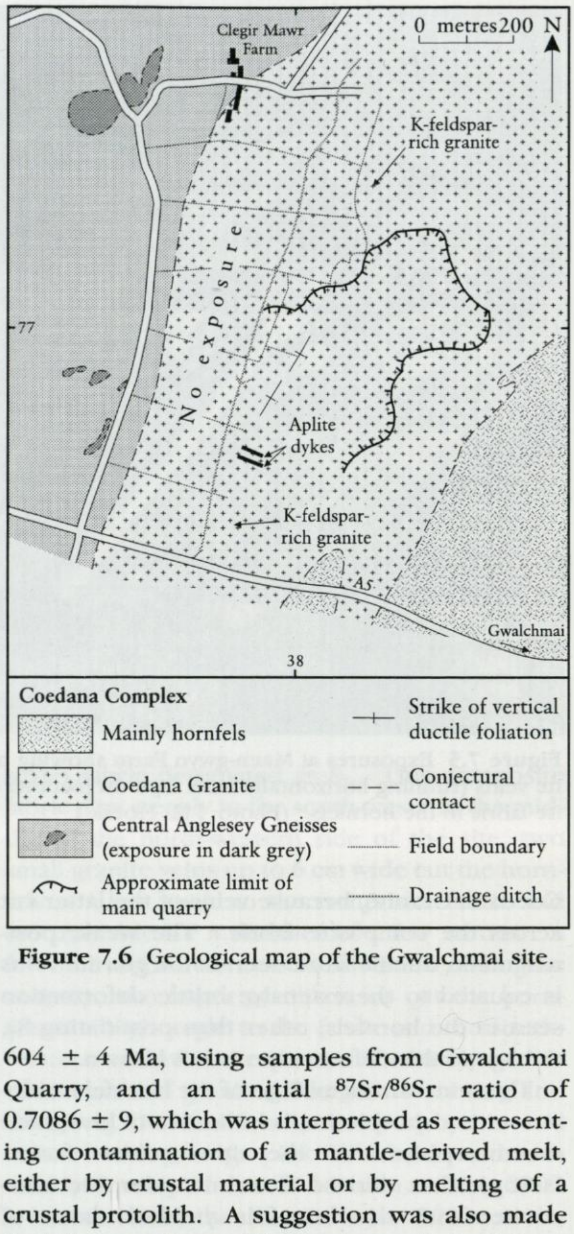

Figure 7.6 Geological map of the Gwalchmai site.

The publication of a U-Pb zircon age of 614 ± 4 Ma (Tucker and Pharaoh, 1991) has constrained precisely the age of crystallization of the Coedana Granite. Furthermore, the upper intercept of the U-Pb discordia provided an age of 1443 ± 34 Ma, consistent with the 1350–1430 Ma NdT(DM) model age of Davies *et al.* (1985).

In contrast to the amount of isotopic work carried out on the granite, only a single whole-rock geochemical analysis has been published (Thorpe, 1982), although representative data were presented by Horák (1993). These geochemical analyses must be interpreted with caution in view of the pervasive ductile deformation present within the Coedana Granite, which is largely a protomylonite or a mylonite. It was found that the granite had an evolved composition (all samples with > 70 wt % SiO_2 and many > 74 wt % SiO_2), and an arc-related signature. The geochemical and isotopic data indicate that the Coedana Granite has an intrinsically 'Avalonian' signature, suggesting that it represents an outboard, fault-bounded sliver of the Avalonian subduction system.

Description

The site demonstrates a number of facies of granite. *Porphyritic granite* is medium-grained, less commonly coarse-grained, with a greenish pink colour. Typical exposures of this facies are seen on the ridge east of Clegir Mawr (SH 388 772), where the large alkali-feldspar phenocrysts appear pale pink. Many exposures show evidence that the granite has experienced ductile deformation, the result being most clearly displayed by deformed quartz crystal aggregates, which exhibit a crudely developed rodding fabric. Cut blocks (Figure 7.7) and thin sections show the extent of brittle deformation represented by fracturing of feldspars, chlorite-filled fractures and local brecciation textures.

Thin sections show that the primary morphology of quartz crystals has been modified or destroyed, biotite crystals are altered to chlorite and realigned to form impersistent foliae, and feldspars show limited recrystallization (although brittle deformation is the dominant process). Garnet pseudomorphs from this locality, although possibly xenocrysts from the gneisses, are more likely to be igneous in origin as they do not preserve evidence of inclusions and have euhedral form (Horák, 1993). The contact relationships between the porphyritic and non-porphyritic facies are not well defined, which is in part due to deformation and weathering that has obscured original textures.

Non-porphyritic granite is the most abundant facies within the Coedana Granite. Its mineralogy varies from that of a relatively mafic, biotite-rich rock, which more closely resembles the porphyritic facies, to a more leucocratic variety. The facies weathers white to pale green, with broken surfaces showing mica, dominantly biotite, defining a foliation of variable intensity. More extensively deformed samples are commonly deeply altered and cut by chlorite veins, thus preserving little evidence of primary igneous texture.

Aplite is the least abundant facies within the Coedana Granite and occurs as narrow veins of fine-grained granite up to 1.5 m wide, cutting the other granite varieties, for example in the

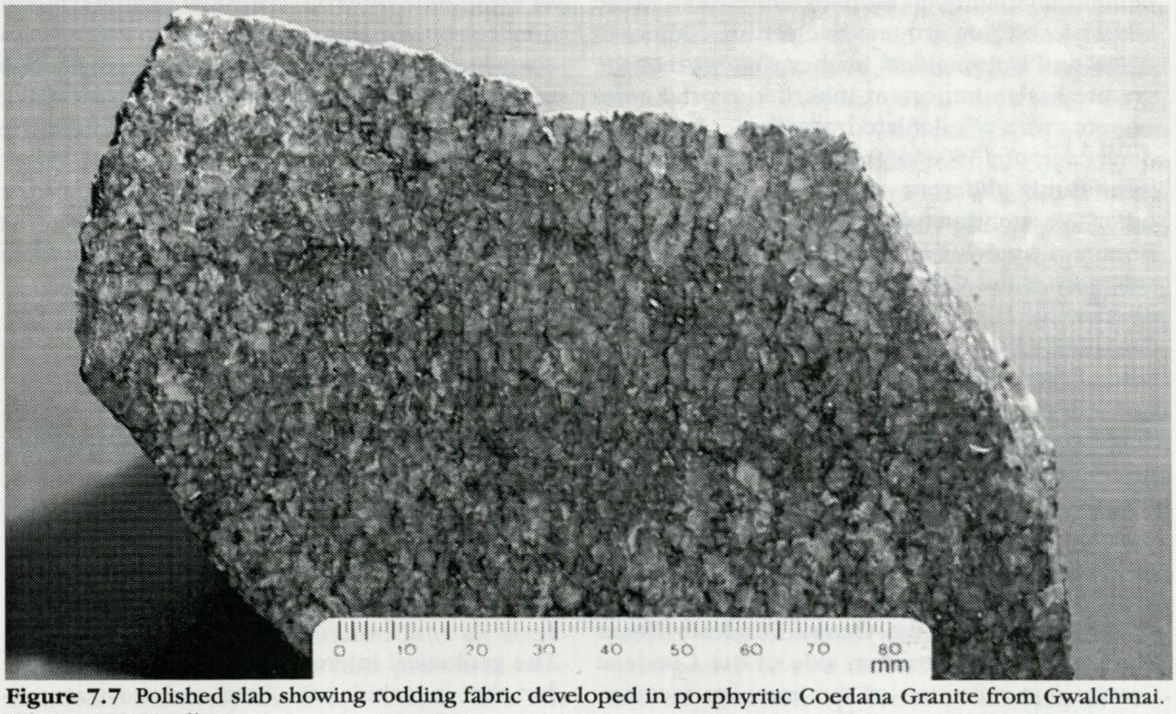

Figure 7.7 Polished slab showing rodding fabric developed in porphyritic Coedana Granite from Gwalchmai. (Photo: J.M. Horák.)

locality just north of the A5 (SH 378 766). The aplite is pale pink to cream in colour, has a fine-grained saccharoidal texture, and contains small muscovite laths. Deformation of this facies is not obvious in hand specimen, but thin sections show that quartz is extensively recrystallized. Accessory minerals are scarce, but pseudomorphs, after possible garnet, have been recorded. This is substantiated by a thin section of aplite from an exposure south-east of Coedana Chapel (several kilometres north-east of this site and the type locality for the Coedana Granite), which shows abundant euhedral to subhedral garnet. This exposure was mapped by Greenly (1919), but unfortunately no longer exists, so the composition of the garnet in the aplite remains unanalysed.

Interpretation

The Coedana Granite represents the most extensive outcrop of plutonic igneous rock within the Monian Composite Terrane and this site is highly representative in that it demonstrates the occurrence of three out of the four granite facies that have been recognized. The site also allows observation of deformation textures, both at outcrop scale and within large blocks with weathered surfaces within the quarry.

Geochemical data indicate that the granite has an evolved composition and can be classified as being dominantly a monzogranite that arose within a volcanic arc tectonic setting. Mineralogical and isotopic data further suggest that the granite has an important inherited crustal component, with a calculated average crustal residency age of 1350–1430 Ma. This value is not significantly different to that determined for other Precambrian plutonic rocks of southern Britain. It precludes the granite being derived solely from the Central Anglesey Gneisses, one of the other components of the Coedana Complex, but does not rule out these gneisses being contaminants, or having a minor role as one of several protoliths supplying the melts that formed the granite. The geochemical signature, and the precise resolution of its magmatic age, have together enabled Gibbons and Horák (1996) to categorize the granite as belonging to Avalonian Event 2, which is the main arc-magmatic phase (Figure 1.4).

The presence of the Central Anglesey Shear Zone on the south-eastern side of the Coedana Granite is a reflection of the complex tectonothermal history that the Coedana Complex has experienced, compared to the history of contemporary plutons elsewhere in southern Britain. Horák (1993) interpreted the Coedana Complex and granite as a sliver of the main Avalonian arc that has been dissected from its original position by transcurrent faults. Kinematic indicators in the shear zone that provide evidence for sinistral movement, show that the Coedana Granite could have originated some unknown distance to the north-east of its present location.

Conclusions

The Gwalchmai site contains good exposures of the Coedana Granite, which in terms of its chemistry is a typical calc-alkaline volcanic arc granite generated in the late Precambrian Avalonian subduction system (Figure 1.4). The main lithologies demonstrated at the site are the porphyritic, non-porphyritic and aplite facies of the granite. These original textures were largely overprinted and obscured by a later deformation that has resulted in the development of an impersistent rodding fabric and foliation, accompanied by extensive recrystallization of the granite. The stress regime causing this may in large part have been transmitted from movements occurring along a major ductile fault zone, the Central Anglesey Shear Zone, on the south-eastern side of the granite outcrop. Thus the granite has had a more complex history than its contemporaries elsewhere in southern Britain. Interpretations of the shear zone suggest that after intrusion, the granite was transported from its position in the main Avalonian arc and moved over some unknown distance to the south-west along the Avalonian subduction complex. This tectonic setting is comparable to that observed today in the San Francisco Bay area, where transcurrent movement along the San Andreas Fault is currently transporting the Salinian Block (a sliver of arc granite) northwards.

MARQUIS OF ANGLESEY'S COLUMN (SH 535 715)

W. Gibbons

Introduction

The geological interest of this site resides in the fact that it includes the best, and most accessible, exposures of blueschist in Great Britain. Blueschist is an unusual metamorphic rock produced by the subduction of oceanic crust and is, therefore, known worldwide from sites of ancient and modern plate convergence such as California, Japan, New Caledonia and Corsica. Preservation of blueschist is rare, and this is especially the case for pre-Mesozoic examples. The Anglesey blueschists are Precambrian in age and as such are one of the oldest, and quite probably *the* oldest, assemblage of blueschists in the world. The presence of blue glaucophanic amphibole, typical of blueschist, in Anglesey was first recognized by Blake (1888) who described rocks exposed at this locality. Later descriptions, and additional petrological, geochemical, and isotopic data were published by: Adye (1906), Greenly (1919), Holgate (1951), Gibbons and Mann (1983), Horák and Gibbons (1986), Gibbons and Gyopari (1986), and Dallmeyer and Gibbons (1987).

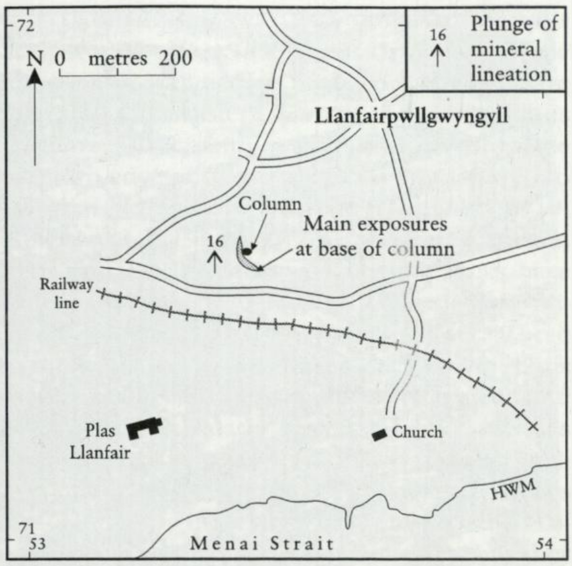

Figure 7.8 Location of the Marquis of Anglesey's Column site. Note that the area to the north of the railway line is mainly underlain by metabasaltic blueschist with a foliation (not shown) that is flat-lying, varying about the horizontal.

Description

The Anglesey blueschist is exposed as a series of crags in woods beneath the Marquis of Anglesey's Column (Figure 7.8). The rocks comprise fine-grained, intensely foliated and lineated, dark blue-grey schists in which the foliation is folded by intrafolial folds. The mineralogy of these rocks comprises: amphibole, epidote, albite, chlorite and quartz. The amphiboles are of especial interest because many crystals are polymineralic (Figure 7.9), with a blue glaucophanic rim and a green core of actinolite and/or barroisite (Adye, 1906; Greenly, 1919; Gibbons and Gyopari, 1986). Dallmeyer and Gibbons (1987), who produced ^{40}Ar-^{39}Ar uplift ages of 560–550 Ma, have confirmed the late Precambrian age of these rocks.

Interpretation

The initial interest of this site focused on the fact that the rocks had an unusual mineralogy and were unique within Great Britain. Dewey (1969) and Wood (1969) were the first to emphasize the tectonic significance of this site in terms of its preservation of evidence for former plate subduction. They interpreted the rocks as having been produced by the rapid tectonic burial of oceanic crust and incorporation into an accretionary prism within which high pressures were attained at relatively low temperatures. It is this unusual combination, of high pressures and low temperatures, that allows the blueschist mineral assemblage to crystallize. Several plate tectonic models followed, although the highly faulted and complex nature of Anglesey geology imposed little constraint on such interpretations. There was thus no agreement on whether the oceanic slab dipped south-east (Dewey, 1969; Rast *et al.*, 1976; Virdi, 1978; Barber and Max, 1979; Coward and Siddans, 1979; Anderton *et al.*, 1979; Gibbons, 1980) or north-west (Baker, 1969; Shackleton, 1975). Thorpe (1974) and Barber *et al.* (1981) suggested a double subduction system, with the Benioff (subduction) zones dipping in either opposing directions, or both towards the south-east. Gibbons (1983, 1987, 1990), observing the narrow, fault-bounded outcrop of the Anglesey blueschists, suggested that it is a small slice of a former subduction system that has been strike-slip faulted into its present position within the Menai Strait Fault System. The concept of 'exotic' or 'suspect' terranes was thus introduced to the interpretation of Anglesey geology, based primarily on the existence of the Anglesey blueschists. This view was refined by Gibbons and Horák (1996) into a model whereby the blueschists were preserved as a slice of accretionary prism – termed the 'Aethwy Terrane' in Chapter 1 –

Figure 7.9 Microphotograph of the Anglesey blueschist at the Marquis of Anglesey's Column site. The blueschist consists of glaucophanic, blue amphibole (pale grey areas) and epidote (white laths). The crystal at the centre has an actinolitic core (pale grey) surrounded by barroisite (darker grey), with the outer pale-toned rim of the crystal being blue glaucophane. (Photo: W. Gibbons.)

caught up in a transition from orthogonal subduction to transcurrent faulting (Figure 1.4). The only other locality in Wales where glaucophanic blue amphibole is found is at the GCR site on Penrhyn Nefyn foreshore; these exposures appear to represent a continuation of the same blueschist belt.

Conclusions

The exposures of metamorphic rocks beneath the Marquis of Anglesey's Column are of international interest. They preserve fresh blue amphibole-bearing assemblages typical of rocks subducted at oceanic trenches along modern destructive plate margins, where cold rocks are buried quickly and so subjected to high pressures whilst remaining 'refrigerated' at relatively low temperatures. Such blueschists are only relatively rarely exposed around the world and are a sure indication of former subduction having taken place. Old blueschists (>300 Ma) are even rarer, and the Anglesey examples have been shown to be Precambrian, which makes them amongst the oldest such rocks known in the world. They are of added mineralogical interest because they contain polymineralic amphiboles; individual crystals have been preserved in the act of recrystallizing from a green to blue amphibole as pressures increased. Their preservation as a narrow strip – named the Aethwy Terrane – within a steep fault zone has been interpreted as not only indicating former plate subduction but also is suggestive of a significant component of transcurrent fault movement having acted upon the basement rocks of Anglesey. Application of the maxim '*the present is the key to the past*' allows comparisons to be made between the processes that produced and preserved the Anglesey blueschists with those operating at currently active plate margins such as along western North America.

SOUTH STACK (SH 203 823)

W. *Gibbons*

Introduction

The cliffs around South Stack lighthouse (Figure

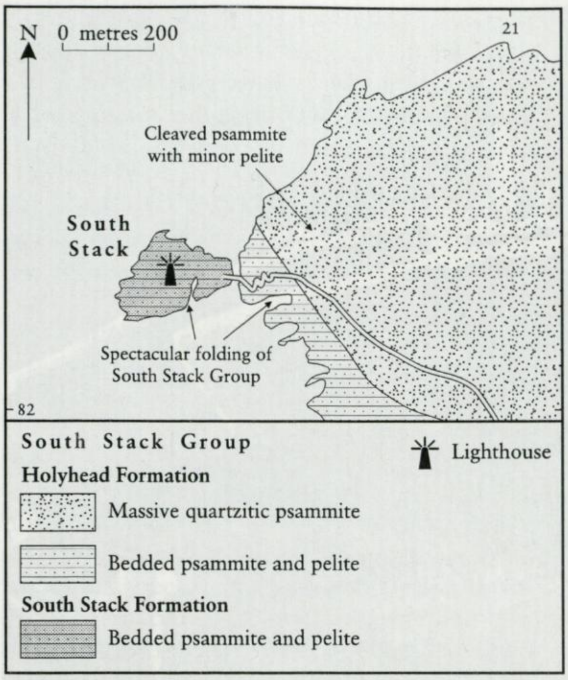

Figure 7.10 Locality map of the South Stack site. After Greenly (1919) and Phillips (1991b).

7.10) display some of the most magnificent exposures of folded metasedimentary rocks in Britain. In the original Memoir of the Geological Survey, Edward Greenly (1919) described these exposures as an 'amazing revelation', and the site has since become justifiably popular as a readily accessible location to view spectacular fold structures. Apart from its purely aesthetic appeal, South Stack is the type locality of the South Stack Group. In this basal unit of the Monian Supergroup, arguments over its age have centred in part on the supposed presence of *Skolithos* worm burrows at this locality (Greenly, 1919; Barber and Max, 1979). The site has also been a key component of stratigraphical, structural and sedimentological studies published by Greenly (1919), Shackleton (1954, 1969) and Phillips (1991a,b).

Description

The site exposes a sequence of well-bedded but deformed and metamorphosed clastic sedimentary rocks (quartzite, sandstone, siltstone and mudstone) belonging to the lower part of the South Stack Group. The western part of the site, the lighthouse-capped sea stack of South Stack itself, is the type locality for the group (Figure 7.11). Phillips (1991a) has proposed that this lowest part of the South Stack Group should be referred to as the South Stack Formation. Above this unit, the eastern part of the site contains more massive, white quartzite, which forms the western edge of the outcrop of a unit referred to as the Holyhead Quartzite (Greenly, 1919; Shackleton, 1954, 1969) or Holyhead Formation (Phillips, 1991a). The sedimentary rocks have been deformed into a series of upright to SE-verging folds with gentle plunging axes. These structures are best preserved on the cliffs beneath the lighthouse and on the mainland opposite; particularly impressive fold cascades in these cliffs may be viewed from the path leading down to the lighthouse. These exposures are commonly used as a field teaching laboratory. They are impressive in themselves, but they also demonstrate: how parasitic folds develop on the limbs of larger structures, how axial planar cleavage develops in association with folds, and how such cleavage refracts through alternating competent and incompetent layers. Furthermore, the exposures offer a graphic illustration of how planar structures, such as bedding and cleavage, may be distinguished from linear structures, such as fold axes and mullions.

In addition to the more obvious structural importance, the sedimentology of the South Stack Group exposures at this site is of considerable interest. Examples of graded bedding in turbiditic greywackes are visible in the cliffside along the path to the lighthouse. At the clifftop north of the lighthouse, Greenly (1919) and Barber and Max (1979) have recorded vertical *Skolithos* worm burrows. Other sedimentary structures include sole structures, cross-lamination and climbing ripple cross-lamination, convolute lamination and water escape structures. The site is a good example of how such sedimentary structures can be well preserved in turbidite sequences despite the effects of folding, cleavage–formation, and a pervasive low-grade (lower greenschist) metamorphic overprint.

Interpretation

South Stack has played a key role in the interpretation of Anglesey geology. It was here that Shackleton (1954) first illustrated the critical importance of using way-up structures to interpret stratigraphical sequences, and in doing so proved that Greenly's (1919) original interpretation of these rocks as being overturned was in

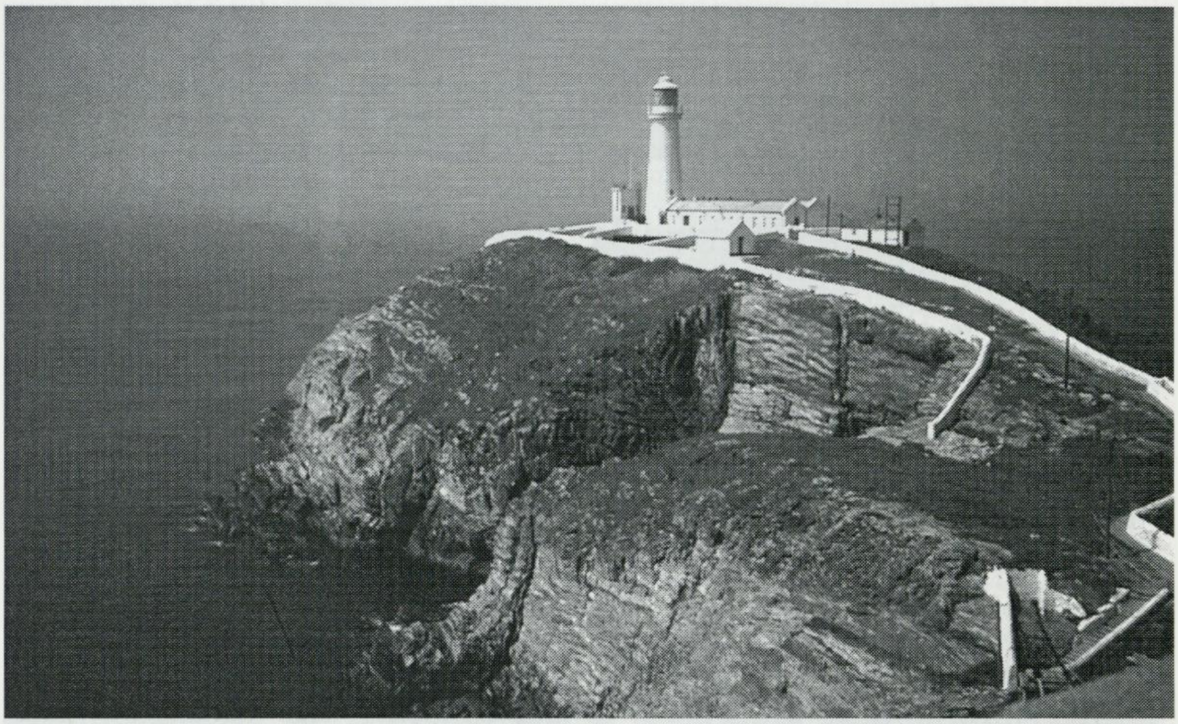

Figure 7.11 South Stack lighthouse built on folded psammites belonging to the South Stack Group. (Photo: W. Gibbons.)

fact incorrect. Despite the excellent exposure, however, the exact age of the South Stack Group remains uncertain. Traditionally the rocks have been considered to be Precambrian, although the claim that *Skolithos* is present in the sedimentary strata has been used to support interpretation of these as Cambrian in age (Barber and Max, 1979). More recent support for such an interpetation has come from comparisons with lithologically similar Palaeozoic rocks in south-east Ireland (Crimes and Dhonau, 1967; Tietzsch-Tyler and Phillips, 1989; Phillips, 1991a; Gibbons *et al.*, 1994).

The sedimentation of the South Stack Group has been broadly compared with that typical of trench, or trench-slope, settings in modern subduction systems (Wood, 1969). Many sedimentary structures described within strata at this site have been attributed to the classical Bouma turbidite sequences. In the depositional model of Phillips (1991a), the Holyhead Formation, with both channel and interchannel turbidite fan associations represented, was interpreted to have formed in the middle to inner part of a submarine fan complex. The high proportion of arenaceous material within the South Stack Formation was viewed as recording a well-developed outer-fan system of laterally coalesced and vertically stacked fan lobes (Phillips, 1991a). Sedimentary petrographical data indicate that the South Stack sediments had a continental provenance, although this source area remains as yet unidentified.

Conclusions

The exposures of folded metasedimentary rocks in the cliffs around South Stack provide one of the most graphic and memorable geological localities in Great Britain. This is certainly the most easily accessible and safe place to view such rocks in Anglesey. It is the type locality for the South Stack Group, which contains trace fossils supposed to be *Skolithos* worm burrows. The site reveals excellent examples both of sedimentary structures produced by turbidite deposition in a submarine fan environment, as well as tectonic structures produced by regional compression of a sequence of marine clastic sediments. It is an excellent place to study folding and cleavage formation, and to gain an impression of how the Earth's crust can be deformed during tectonism. From a historical perspective, it was here that Robert Shackleton effected a major revision of Edward Greenly's original interpretation of Anglesey geology, and the locality has remained a focus of interest over later discussions concerning the Precambrian *versus* Cambrian age of the South Stack Group.

RHOSCOLYN (SH 260 763–272 751)

W. Gibbons

Introduction

The exposures of deformed metasedimentary rocks on the Rhoscolyn coast have become among the most intensively studied sites of structural geological interest in Great Britain. Following initial descriptions by Greenly (1919), they were re-interpreted by Shackleton (1954, 1969, 1975), became a subject of some controversy after a paper published by Barber and Max (1979), and a consequent focus of detailed structural studies by Cosgrove (1980), Lisle (1988), and Phillips (1991b). The site (Figure 7.12) has been chosen because it is quite simply world class in its exposure of multiple deformed metasedimentary rocks. There is nowhere better in Great Britain to observe and demonstrate three-dimensional fold geometry, cleavage-bedding relationships, and the superposition of several deformation phases on low-grade metasediments. Furthermore, although metamorphosed and highly deformed, these rocks preserve a recognizable lithostratigraphy and include excellent examples of sedimentary structures, making the site of interest to stratigraphers and sedimentologists as well as structural geologists. The site is the type locality for the Rhoscolyn Formation, the highest of three units that comprise the South Stack Group in western Anglesey (Phillips, 1991a). The combination of a varied and traceable lithostratigraphy combined with a complex structural history makes the site an excellent field laboratory for teaching geological mapping techniques.

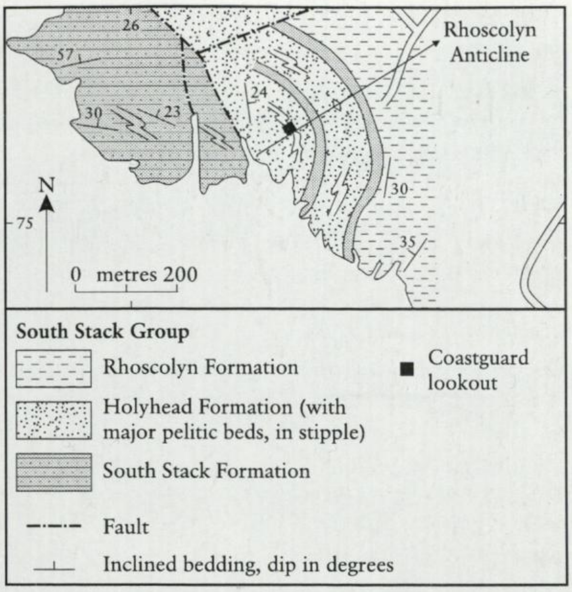

Figure 7.12 Geological map of the Rhoscolyn Anticline. Modified from Phillips (1989, fig. 4.24)

Description

The main interest of this site focuses on the presence of a prominent NE-plunging, SE-verging fold known as the Rhoscolyn Anticline (Shackleton, 1969). The core of this structure runs inland beneath the Coastguard Lookout and the NE-plunge of the structure means that it can be superbly viewed in the coastline immediately to the south-west (Figure 7.13). These cliffs reveal intensely corrugated, well-bedded, turbiditic psammites and pelites. An early bedding-parallel (S_1) fabric is detectable in these metasediments, although no convincing examples of F_1 folds are present and it remains unclear whether 'D_1' was a significant tectonic event. The most prominent minor structures are related to the major anticline, with SE-verging asymmetry and a strong NW-dipping axial planar cleavage produced primarily by pressure solution acting on the sedimentary rocks during deformation. White quartz veins are commonly present parallel to this cleavage, and are especially abundant in the pelitic beds. North-easterly plunging cleavage-bedding intersections are particularly well preserved on bedding surfaces exposed around the Coastguard Lookout. Superimposed upon this S_2 cleavage are the effects of a later (D_3) deformation phase, which has resulted in the localized folding of F_2 about gently NW-dipping axial surfaces (Figure 7.14).

To the west of the Coastguard Lookout the exposures reveal the gently dipping limb of the Rhoscolyn Anticline (Figure 7.13). The best exposures are again to be found on the coastline just above high water mark, and these show abundant folds commonly sculpted into three-dimensional forms by weathering. These exposures are especially good for demonstrating fold geometries, but also provide many readily accessible examples of the NW-dipping axial planar

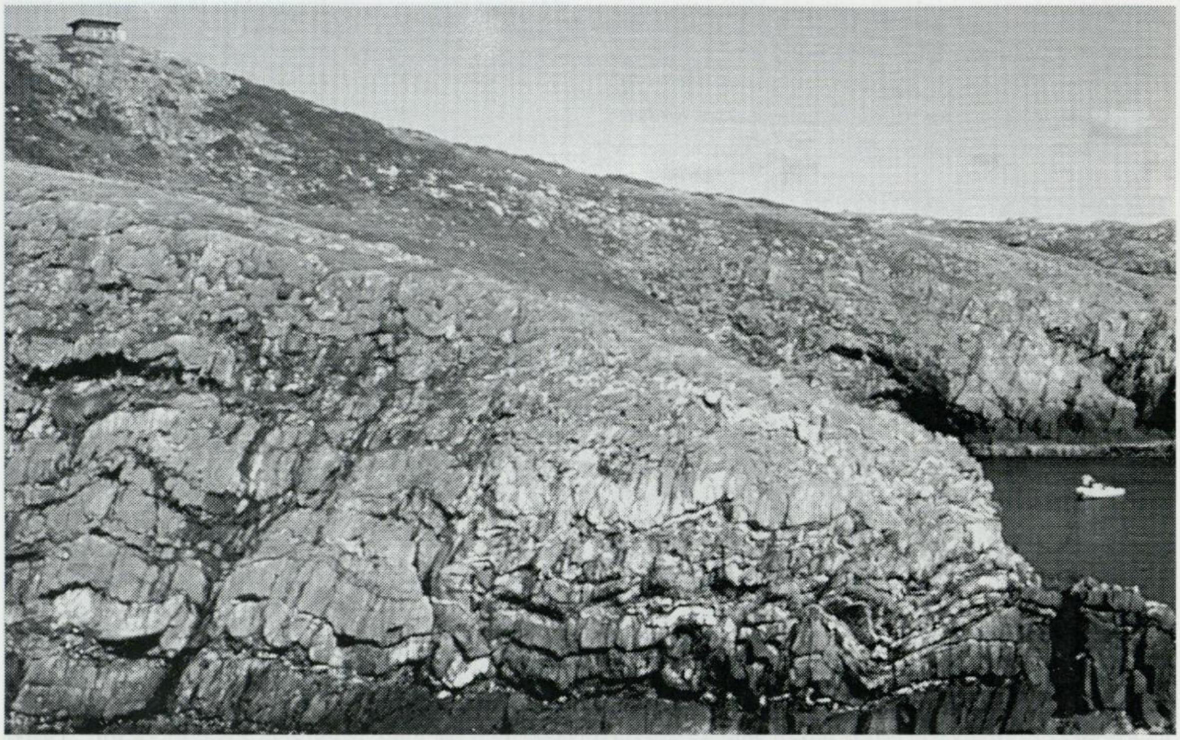

Figure 7.13 View looking east across the Rhoscolyn site. Gently dipping bedded psammites of the Rhoscolyn Formation (South Stack Group) on the north-western limb of the Rhoscolyn Anticline showing minor folds and steeply NW-dipping cleavage. The core of the anticline runs beneath the Coastguard Lookout (top left) from which the beds dip south-eastwards to the sea. (Photo: W. Gibbons.)

cleavage. This cleavage is locally folded by minor F_3 folds with flat-lying (or gently NW-dipping) axial surfaces and an associated S_3 axial planar spaced cleavage. Locally, it is also possible to observe late (D_4) conjugate kink bands with axes approximately parallel to both F_2 and F_3 fold axes.

In addition to the structural interest, this western side of the site is the best place to study the sedimentology of the Holyhead Formation, a sequence of thick quartzites and interbedded psammites (metasandstones) and pelites. There are also excellent sections in the South Stack Formation, the dominant lithology being of quartz-rich turbiditic metasandstone, in beds up to 3 m thick, interbedded with subordinate pelites. Sedimentary structures such as graded bedding and convolute lamination are locally well displayed.

To the south-east of the Coastguard Lookout the cliffs reveal the steep, south-easterly limb of the Rhoscolyn Anticline. Here the abundant and well-preserved minor structures can be compared with those on the opposite limb of the fold. The majority of the F2 folds have an 'S' geometry, and cleavage-bedding relationships show the beds to be locally overturned into a steep north-westerly dip. These exposures are particularly good for examining structures within the pelitic facies of the Rhoscolyn Formation. These pelites show spectacular cascades of F2 and F3 folds, and are full of examples of folded quartz veins. In some localities it is possible to recognize all four deformation phases, providing the opportunity to differentiate their relative ages.

Interpretation

In terms of their tectonic setting, the strata of the Rhoscolyn Formation are interpreted to have been deposited in a submarine fan environment, within a NE–SW trending basin associated with a Precambrian or Cambrian subduction system (Wood, 1969; Phillips, 1991a). According to Phillips, the formation marks a return to a mid-turbidite fan facies, more typical of that seen in the Holyhead Formation at the South Stack GCR site, on the north-west limb of the Rhoscolyn Anticline.

Figure 7.14 Minor fold in semi-pelite within the Rhoscolyn Formation at South Stack. The fold deforms an earlier cleavage (usually designated S_3) and a new pressure-solution spaced cleavage can be seen developing axial planar to the fold. (Photo: W. Gibbons.)

Shackleton (1954, 1969, 1975) used the sedimentological strucures preserved by these exposures to reinforce his interpretation of the South Stack Group as right-way-up and so disprove an earlier interpretation by Greenly (1919). Shackleton (1969) drew a sketch profile through the Rhoscolyn Anticline and demonstrated the pronounced asymmetric vergence towards the south-east. This was one of the first examples of geologists using sedimentological way-up criteria to determine the stratigraphy and fold facing directions within polydeformed terranes. Rhoscolyn has been at the centre of a controversy concerning the structural interpretation of the metasedimentary sequence in north-west Wales known as the Monian Supergroup. The more pelitic New Harbour Group overlies the South Stack Group on Holy Island. The greater deformation of the New Harbour pelites led Barber and Max (1979) to argue that they were older than, and had been thrust over, the underlying South Stack Group. Detailed work on the pelites of the Rhoscolyn Anticline, however, has shown that the pelites interbedded within the South Stack, Holyhead and Rhoscolyn formations have undergone a comparable deformation history to those in the overlying New Harbour Group (Cosgrove, 1980; Khonstamm, 1980; Phillips, 1991b; Gibbons *et al.*, 1994).

Conclusions

The coastline at Rhoscolyn is arguably the best place in Great Britain to study the effect of folding and cleavage formation on a sequence of bedded sedimentary rocks. The spectacular and photogenic exposure of the Rhosçolyn Anticline, visited regularly by numerous school and university field parties, provides a textbook example of a large asymmetric fold with associated minor folds. Several deformation phases have been recognized within these metasediments, which nevertheless commonly preserve original sedimentary structures and form part of a coherent lithostratigraphy. The site is the type locality of the Rhoscolyn Formation, deposited in a turbidite fan environment. It has yielded key evidence to support the interpretation of the South Stack Group as being older than the overlying New Harbour Group.

CAE'R SAIS (SH 268 772)

W. Gibbons

Introduction

This small site is of interest because it preserves one of the best, and certainly most accessible, exposures of metagabbro and serpentinite in Wales. The exposures at Cae'r Sais lie within an envelope of polydeformed, semi-pelitic metasediment, and together these rocks belong within the New Harbour Group. This unit represents the middle part of the Monian Supergroup, exposed as part of the pre-Arenig basement to Anglesey and south-west Llŷn (Gibbons *et al.*, 1994). Serpentinite-metagabbro complexes are unusual in Great Britain, and these rocks have been subjects of research investigations by numerous workers, from Lhuyd's (1684) note on asbestos, through Henslow's (1822) description and map, to the most recent review by Phillips (1989). Whereas the earlier workers (Bonney, 1881; Bonney and Raisin, 1889; Greenly, 1919) tended to emphasize the petrological interest of these rocks, later researchers of the 20th Century have been mostly concerned with their tectonic and geochemical significance (Dewey, 1969; Wood, 1969; Thorpe, 1972c, 1974; 1979; Thorpe *et al.*, 1984). The most detailed studies in the second half of the 20th Century have been made by Maltman (1973, 1975, 1977, 1979) and Phillips (1989). Despite all this work, the exposures remain enigmatic.

Key questions that have focused on this site concern the tectonic setting represented by these rocks, and whether they should be considered as part of an ancient ophiolite. Geochemical investigations of the serpentinites and gabbros have shown that they are tholeiitic in character and may be classified as sub-alkaline basalts. They have a similar chemistry to serpentinites and gabbros found at the mid-Atlantic oceanic-spreading ridge (Thorpe, 1972c, 1974, 1979; Phillips, 1989).

Description

The eastern side of the site (Figure 7.15) exposes typical serpentinite; it is dark green to black and locally red, with pale green, scaly and undulose foliation surfaces (Maltman, 1977). The protoliths to this metamorphic rock include both dunites and harzburgites, and pseudomorphs after both olivine and orthopyroxene up to 4 mm in size can be detected in some specimens. The present mineral assemblage of the serpentinite is dominantly serpentine (lizardite, antigorite, and bastite after orthopyroxene) and Mg-chlorite, with subordinate tremolite, chromitic spinel, magnetite, pyrite, and chalcopyrite. Locally the serpentine is partly replaced by dolomite to produce the carbonated 'ophicalcite' of Greenly (1919) and Maltman (1977).

The western part of the site comprises pale green metagabbro, which is well exposed in an old quarry face. These rocks, referred to as 'altered gabbros' by Greenly (1919) and Maltman (1977), vary from metamorphosed mela-gabbros to true metagabbros, and occur as lenticular and rounded isolated bodies within the serpentinite. Igneous textures are well preserved, despite a pervasive greenschist facies metamorphic overprint. Although clinopyroxenes are commonly partly preserved, and demonstrate original igneous poikilitic and ophitic textures, a secondary mineral assemblage is dominant. This latter overprint assemblage comprises: chlorite, actinolite, tremolite, epidote, albite, quartz, white mica, carbonate, and Fe-Ti oxides.

Interpretation

There has been considerable debate over whether the serpentinites and metagabbros exposed on Holy Island were originally intrusive into the New Harbour Group metasediments, or whether they were thrust into their present position. Another suggestion is that they represent a mélange of slices and clasts of disrupted igneous

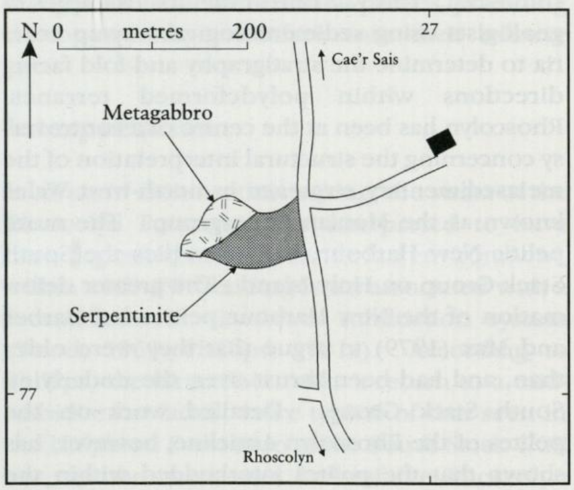

Figure 7.15 Locality map for Cae'r Sais.

rocks that slid into their present position under gravity (for full discussion see Phillips, 1989). The rocks have a generally high, but also variable, Cr content that has been interpreted as indicating a mantle origin, with some degree of fractional crystallization having taken place during their genesis. That the ultramafic and mafic protoliths had an originally oceanic origin remains in little doubt, but whether they represent part of a true ophiolite, or had some other origin such as intrusions at the outer rise of a subducting plate (Windley, 1978), remains controversial.

Conclusions

Oceanic igneous rocks are only rarely preserved in the geological record, and these examples at Cae'r Sais rank alongside a small number of broadly comparable exposures in Great Britain, such as those at the Lizard, Cornwall, and along the Highland Boundary Fault in Scotland. Both serpentinites and metagabbros are seen at Cae'r Sais, and the accessibility and lithological peculiarity of the site have made it the centre of attention for many petrological and geochemical studies. It is one of the best sites for viewing the plutonic, metamorphosed igneous rocks that lie within the New Harbour Group.

OGOF GYNFOR COAST (SH 368 938–374 946)

(GCR NAME: LLANBADRIG AREA)

W. Gibbons

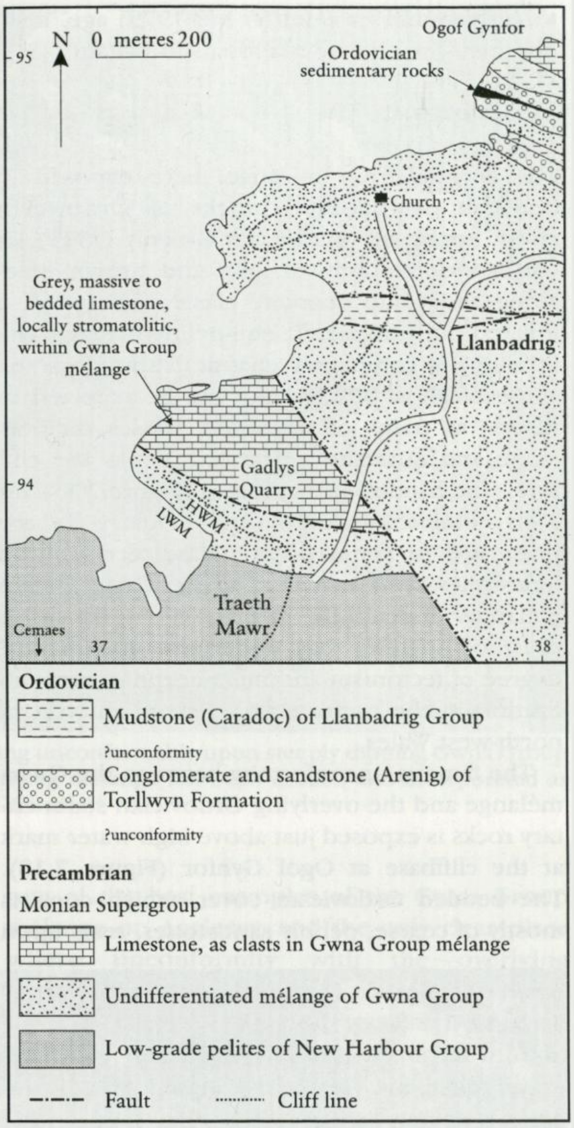

Figure 7.16 Locality map for the Ogof Gynfor Coast site.

Introduction

This locality has been described as including 'one of the finest exposures of Gwna mélange' (Barber *et al.*, 1981), and includes a well-exposed and critically important unconformable contact between this unit and overlying Arenig strata (Figure 7.16). The Gwna Group was the first mélange ever to be described in the world, indeed the term 'mélange' was coined by Greenly (1919) to describe this unit.

The relationship between the pre-Arenig basement of Anglesey and the overlying Ordovician cover was elucidated in the seminal publications of Matley (1899, 1900) and Greenly (1919). Later publications by Shackleton (1969) and Bates (1974) appeared to confirm the importance of the unconformity exposed at this site in terms of the likely huge age difference between an underlying Precambrian basement and overlying Ordovician cover. Barber and Max (1979) later challenged this generally accepted explanation, by putting forward the controversial view that the unconformity was of little significance. The south-western section of this site is of special interest because here the Gwna mélange contains abundant, very large limestone clasts. These limestones have yielded the only known examples of stromatolites in the Monian basement of North Wales. The stromatolites have been interpreted as being of late Precambrian (Wood and Nicholls, 1973) or late Precambrian to early Cambrian (Muir *et al.*, 1979) age, making them the oldest such fossils in Britain.

Description

The Gwna Group mélange, here exposed in between downfaulted blocks of Ordovician cover, has been described by Greenly (1919). It consists dominantly of grey and brown limestone and white quartzite clasts enclosed in a foliated but unbedded semi-pelitic matrix. The lithology is completely chaotic, although some sense of ghost stratigraphy can be detected in places, as trains of disrupted masses of limestone and quartzite are traced across the cliff line. The banded stromatolites (Figure 7.17) are seen on the coast west of Gadlys Quarry, and are preserved in some of the least recrystallized limestones seen anywhere in the Gwna Group mélange. Indeed, the mélange along the north coast of Anglesey has undergone the mildest degree of tectonism and metamorphic recrystallization in the entire Gwna Group outcrop of north-west Wales.

The famous unconformity between the Gwna mélange and the overlying Ordovician sedimentary rocks is exposed just above high water mark at the cliffbase at Ogof Gynfor (Figure 7.18). The bedded Ordovician cover, which consists mostly of coarse, pebbly sandstones, rests upon an irregular surface of steeply dipping quartzite-rich mélange. Prominent blocks of white quartzite project up into the overlying strata, which have draped over this irregular base. Clasts of the same white quartzite have become eroded and incorporated within the Ordovician succession. This is a classic locality for demonstrating the relationships that prove the unconformity between a sedimentary 'cover' sequence and its relatively older basement.

Interpretation

This site is key to the generally accepted view that Anglesey comprises an old basement (the 'Mona Complex' of Greenly, 1919) and a post-Cambrian cover. The exact length of time represented by the unconformity remains uncertain and somewhat controversial however. In Greenly's (1919) interpretation of the tectonic evolution of Anglesey, great emphasis was laid upon this unconformity. Greenly (1919) interpeted all of the Monian rocks, including the Gwna mélange, to have undergone intense structural deformation, including isoclinal folding and regional overturning of the succession. This view was later modified by Shackleton (1954, 1969), who recognized that Greenly's idea of wholesale regional overturning of the Monian sediments was in fact incorrect. Thus, there was

Figure 7.17 Banded stromatolitic limestone within the Gwna Group from the coastal exposures west of Gadlys Quarry. (Photo: W. Gibbons.)

Figure 7.18 Arenig conglomeratic sandstones (left) resting unconformably upon steeply dipping Gwna Group mélange (lower right). The white quartzite in the underlying mélange has been eroded and incorporated as clasts within the Arenig sediment (top left). (Photo: W. Gibbons.)

no necessity to invoke massive regional deformation, and, furthermore, this placed the Gwna Group at the top of the Monian Supergroup succession rather than at the base, thus requiring less erosion to reveal it. The subsequent discovery, albeit controversial, of supposedly Cambrian fossils in the Monian Supergroup (Muir *et al.*, 1979), added to the recognition by Bates (1968) that the overlying cover was of Arenig age (early to mid-Ordovician), rather than Caradoc (late Ordovician) as believed by Greenly; it also further reduced the necessity for a huge time gap at this unconformity (Barber *et al.*, 1981). The latter authors went further in this line of argument, and claimed that the Gwna mélange at this locality has undergone no more complex or pervasive deformation than the overlying Arenig cover strata. This final interpretation proved highly controversial because it implies that all of the deformation was Palaeozoic, probably Acadian (see discussion in Barber and Max, 1979), and this remains a matter of debate.

Conclusions

This site has been chosen because it preserves one of the best examples of the Gwna Group mélange on Anglesey, and the only clear place where unconformity with the overlying Ordovician cover sequence can be observed directly. The term 'mélange' was first defined on Anglesey, making this site of historical interest worldwide. Furthermore, the site includes the only place where macrofossils have been found in the pre-Arenig basement to north-west Wales. The exposure of an unconformity here is critical in proving the Gwna Group to be pre-Arenig, an observation fundamental to the interpretation of Welsh basement geology. However, the exact amount of time represented by the unconformity has been, and remains, the subject of great controversy.

LLANDDWYN ISLAND (SH 390 630)

W. *Gibbons*

Introduction

This site, a narrow, tidal isthmus projecting south-west from the Anglesey coastline, exposes some of the best examples of oceanic basaltic pillow lavas in Great Britain. It is the type locality (Figure 7.19) of Greenly's 'Spilitic Lavas', which form part of the Gwna Group mélange, the highest unit in the Monian Supergroup of Anglesey and Llŷn. The rocks have been designated as belonging to the Llanddwyn Spilitic Formation (Shackleton, 1975; Barber and Max, 1979).

In addition to the lavas, there are various sedimentary rocks that include sandstones, shales, superb red jaspery cherts and prominent manganiferous limestones that are commonly mixed with the dark basalts to produce spectacular lava-limestone breccias. The age of the red cherts that are associated with the Gwna basalts on Llanddwyn Island has been the subject of controversy ever since possible Cambrian microfossils were discovered in them (Muir *et al.*, 1979; Barber and Max, 1979; Barber *et al.*, 1981; Peat, 1984b; Gibbons *et al.*, 1994).

Description

Llanddwyn Island comprises a series of mostly steeply dipping to vertical lavas, limestones and other sedimentary rocks that form successive NNE–SSW-oriented outcrops running the length of the isthmus. The pillow structures in the lavas are commonly slightly deformed and cut by carbonate veins, but nevertheless are superbly preserved in many exposures, commonly showing interstitial jasper and central vacuoles. Notable, and readily accessible, exposures include those near high water mark on the beach north of the island (Figure 7.20). The pillow structures allow the way-up of the sequence to be deduced, so that the sequence can be seen to young towards the south-east. Pale pink and cream limestones, commonly mixed chaotically with brecciated basalt (Figure 7.21), are abundantly exposed down the south-western coast, at the southern tip of the isthmus, and for some distance back up the eastern coast to Porth y Clochydd. Excellent examples of lava-and-limestone breccias are seen, for example, beneath the lighthouse on the western side of Porth Twr mawr and in the exposures below high water mark to the east to Porth Twr bâch. Of particular interest are splendid exposures of bedded red jasper along the central western side of the isthmus: these are the best examples of deep-water cherts in North Wales. In the central and southern part of the site, outcrops consist of dark green, fine-grained sandstones that are distinctive enough to have been given the lithostratigraphical name 'Tyfry Beds' by Greenly (1919), later revised to Tyfry Formation by Shackleton (1975). Barber *et al.* (1981) later differentiated the Tyfry Formation from the rest of the Llanddwyn Spilitic Formation. Several undeformed porphyritic dolerite dykes cut the Gwna Group rocks at various localities along the coast, such as in Porth Twr mawr.

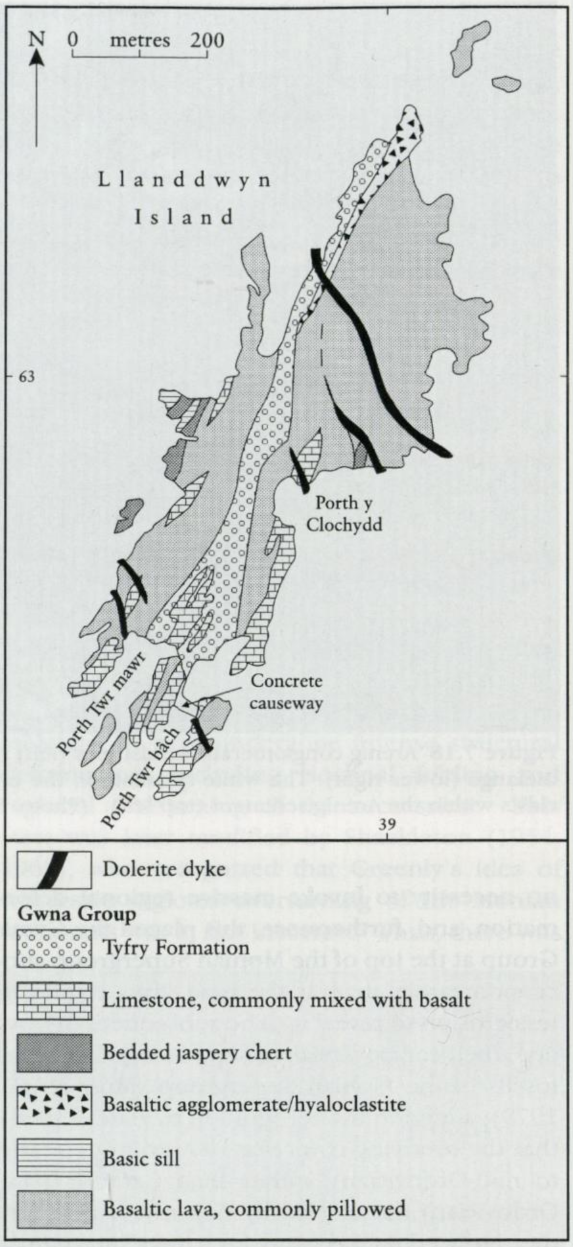

Figure 7.19 Geological map of Llanddwyn Island.

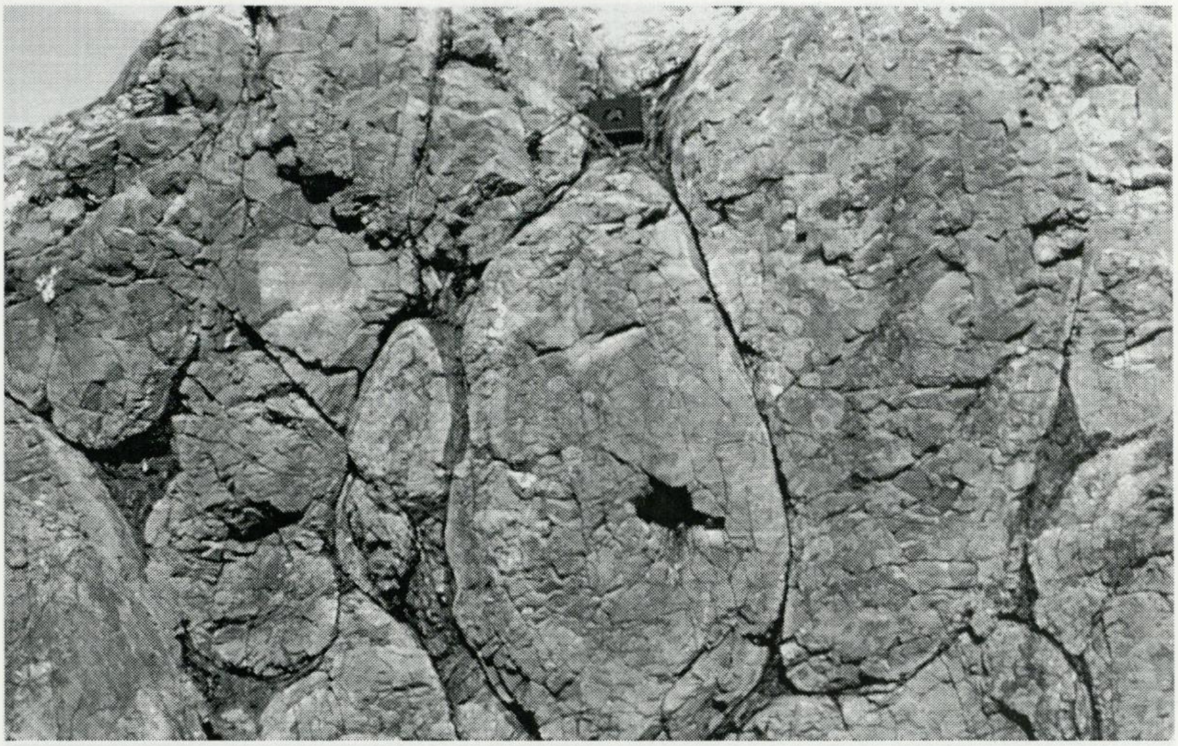

Figure 7.20 Vertical, SE-younging basaltic pillow lavas in the Gwna Group exposed immediately north of Llanddwyn Island. (Photo: W. Gibbons.)

Interpretation

This site is excellent for demonstrating the nature of basaltic pillow lavas, erupted on the sea bed as is well established by observation of modern examples. The oceanic geochemistry of the pillow lavas (Thorpe, 1972c), and the likelihood that the Llanddwyn jaspers represent deep-sea chert, have fuelled interpretation of these rocks in terms of a palaeo-subduction zone (Wood, 1969). Barber *et al.* (1981), who speculated that an unconformity exists between the Llanddwyn Spilitic Formation and the Tyfry Formation, developed this idea. According to such an interpretation, the lenticular outcrops of basaltic lava and associated breccias represent slices of ocean floor imbricated within an accretionary prism in the hanging wall of a subduction zone. The upward-facing sandstones of the Tyfry Formation might then be interpreted as deposited in basins on top of this accretionary prism. The origin of the lava-limestone breccias has not been resolved, although these exposures have a direct bearing on the conflicting 'tectonic *versus* olistostrome' interpretations of Greenly (1919) and Shackleton (1954). The report of supposedly Cambrian microfossils from Llanddwyn Island (Muir *et al.*, 1979) has proven controversial (Peat, 1984b), and the age of the Llanddwyn Spilitic Formation remains uncertain, although presumably it is either Precambrian or Cambrian.

Conclusions

The graphic exposures of steeply dipping jaspery pillow lavas at the Llanddwyn Island GCR site rank among the best of such examples preserved in Great Britain; indeed the site is the type locality for these rocks. This, combined with the spectacularly colourful mixtures of lava and limestone, makes these exposures truly exceptional. The site has also been at the centre of controversy over the age of the pre-Arenig rocks on Anglesey since it provides important (although unconfirmed) evidence for a Cambrian rather than Precambrian age for the Gwna lavas.

Figure 7.21 Deformed lava-limestone breccias exposed on southern Llanddwyn Island. (Photo: W. Gibbons.)

PENRHYN NEFYN (SH 290 408, 293 409, 296 413)

W. ***Gibbons***

Introduction

This site is a foreshore section that preserves an important contact between the two main units together compriseing the oldest rocks in mainland North Wales: the Gwna Group (Monian Supergroup) and the Sarn Complex. An intervening narrow schist belt represents the contact zone itself. Penrhyn Nefyn was selected as a GCR site because it is the only place where one can walk across a foreshore exposure northwestwards from the Sarn Complex into schists and on to the Gwna Group (Figure 7.22). Because of this, the site has figured as a key exposure in the published works of Matley (1928), Shackleton (1956), Baker (1969), Barber and Max (1979) and Gibbons (1981, 1983). Arguments over this site have epitomized the nature of the controversies that have surrounded the interpretation of the basement to northwest Wales, with disagreements focusing on the relative and absolute stratigraphical ages and on structural interpretation. The site occupies a pivotal position within the Menai Strait Fault System. It has been particularly instructive in illustrating the importance of recognizing ductile shear-zone rocks, their critical role in the interpretation of basement tectonics and their current importance to the 'terrane concept' of British Precambrian geology discussed in Chapter 1. The site is of additional interest because it is the only place on the mainland of Wales where blue amphibole-bearing schist has been discovered (Gibbons, 1981).

Description

The exposures at Penrhyn Nefyn occupy the width of the beach and are capped above high water mark by a thick mantle of sandy glaciofluvial deposits. The most westerly exposures are the least deformed and belong to Gwna Group basalts, revealing primary igneous textures such as jaspery basaltic breccias and lavas with flattened pillow structures. Locally, the lavas are cut by narrow shear zones within which the basaltic parent is transformed into low-grade mylonitic greenschist – the basic schists of Figure 7.22 (Gibbons, 1981).

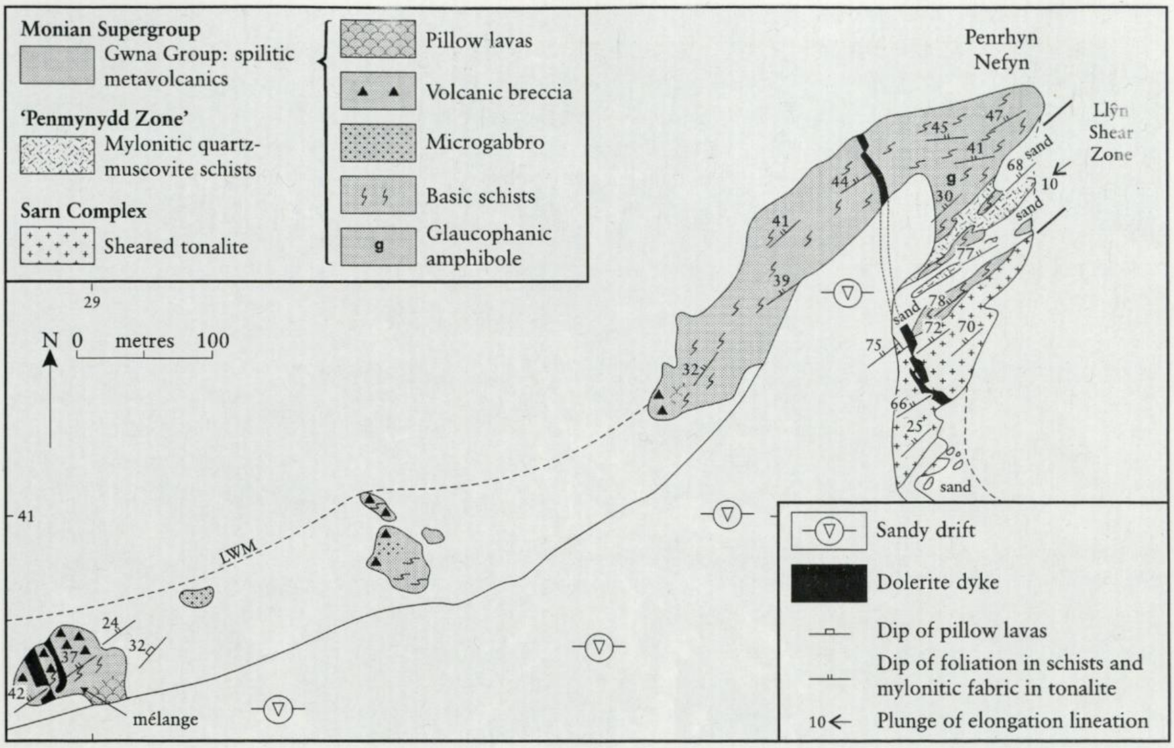

Figure 7.22 Geological map of Penrhyn Nefyn.

Such low-grade sheared equivalents of the Gwna basalts become dominant southwards, around the headland of Penrhyn Nefyn, as one moves into the schist belt referred to by previous authors as the 'Penmynydd Zone of Metamorphism' (e.g. Greenly, 1919). The majority of these greenschists are lithologically monotonous, although locally areas of massive green lavas have escaped much of the deformation. Under the microscope, these metabasic rocks reveal a greenschist facies mineral assemblage of: epidote, chlorite, actinolite, and albite.

The degree of recrystallization increases towards the south, and 60 m along the foreshore from the headland, on its east side, these basic schists are interleaved with fine-grained, semi-pelitic, mylonitic mica-schists (Figure 7.23). At this point the basic schists locally show the overprint of blue amphibole over the greenschist facies assemblage – an unusual and interesting occurrence of the greenschist–blueschist transition within a shear zone. The glaucophanic amphibole within these specimens typically co-exists with and partially replaces actinolite crystals, in much the same way as seen in the classic Anglesey blueschists exposed 20–30 km farther along strike at the Marquis of Anglesey's Column GCR site, south-east Anglesey (Gibbons, 1981; Horák and Gibbons, 1986). The slices of mica schist interleaved with the Gwna metabasites are up to 8 m wide and display intrafolial folds, a steep NW-dipping foliation, a gently SW-plunging mineral lineation, and late kinking and cataclasis. Under the microscope these are fine-grained phengite, albite, quartz schists.

The interdigitated micaceous and metabasic schists occur for some 50 m across the foreshore, beyond which, to the south, they are in abrupt tectonic contact with sheared and altered tonalite belonging to the Sarn Complex. The contact can be difficult to locate because of the intense greenschist-facies shearing that has affected all rocks, reducing them to fine-grained schists. These exposures preserve a classic transition from a coarse plutonic protolith (Figure 7.24) northward into a low-grade mylonite produced by a combination of ductile and brittle processes (Gibbons, 1980). Initially, ductile deformation processes are seen to have been completely subordinate to brittle fracturing. Closer to the mica-schist contact, however, ductile flow and recrystallization become more pervasive. Finally, there are several excellent examples of late fault brecciation, indicating contin-

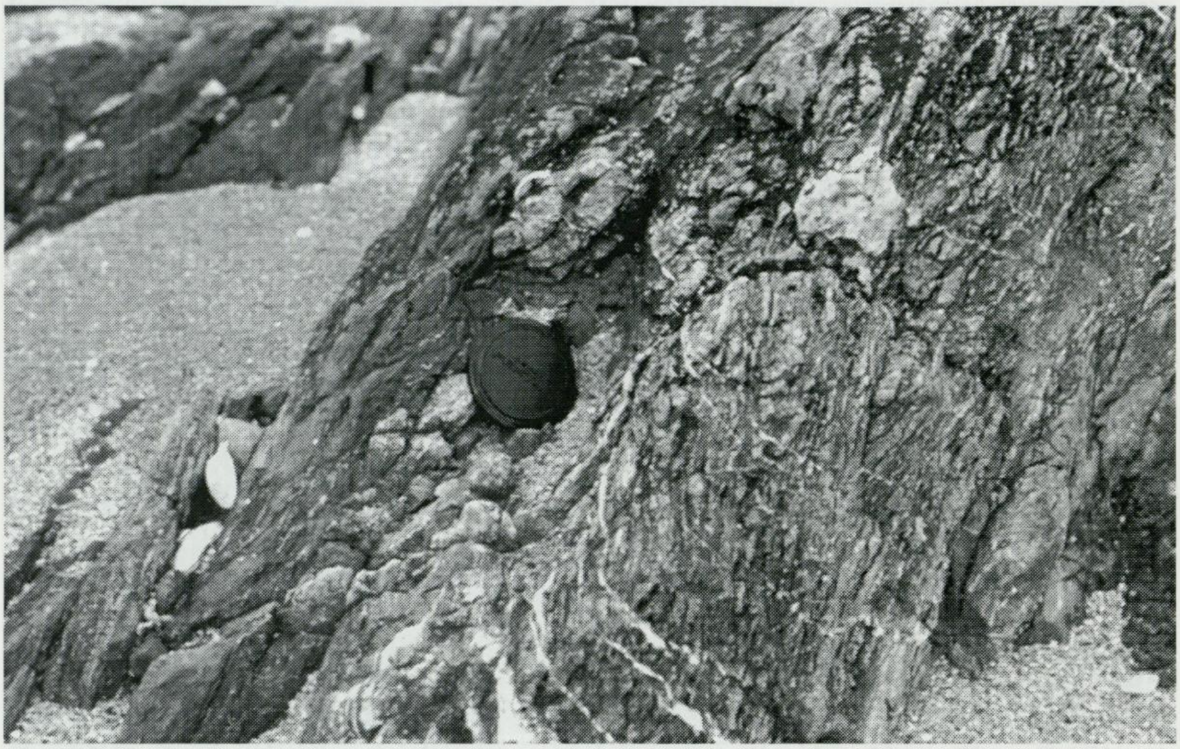

Figure 7.23 Steeply dipping, veined quartz-muscovite mylonite schist (centre) interleaved with dark metabasite derived from Gwna Group basalts (left). (Photo: W. Gibbons.)

ued reactivation of the Penrhyn Nefyn shear zone at higher crustal levels.

Interpretation

Matley (1928) was the first to map this section, and described a 'granitoid gneiss' faulted against 'Penmynydd schists', which graded from greenschists to recognizable pillow lavas towards the west. The schists were therefore considered to be the metamorphosed equivalents of the lavas, which belonged to the Gwna Group. Shackleton (1956) ambiguously referred to Matley's granitoid gneiss as both a crushed tonalite and as a gneiss. He went on to interpret this lithology as both progradational from, and locally intrusive into, the adjacent schists, and thus deduced it to be younger than the schists and Gwna Group. This conformed to his concept of a narrow prograde metamorphic transition between the lower- and higher-grade metamorphic rocks on Anglesey and Llŷn. This idea was later superseded by the recognition that many such contacts are shear zones within which there is metamorphic convergence between tectonically juxtaposed higher- and lower-grade rocks.

Baker (1969) was the first to dispute the 'prograde transition hypothesis' by pointing out that, as Shackleton (1956) had himself described, the gneiss was in fact a plutonic igneous rock and therefore irrelevant to any ideas on schist–gneiss transitions. Despite this, a later description by Barber and Max (1979) resurrected the term 'gneiss' to describe the rocks, but recognized the tectonic transition from these rocks into mylonitic schists. A major point of disagreement with all previous (and later) authors, however, was in the interpretation of the Gwna Group metabasalts and mica schists as slightly foliated laminated tuffs and spilitic lavas. This latter description of the Gwna lithologies conformed to their interpretation of the Gwna Group as being younger than, and therefore unaffected by, the schist zones of Anglesey and Llŷn. Finally, Gibbons (1980, 1981, 1983) produced a detailed map and petrographical study of the section and showed it to represent one sector of the Llŷn Shear Zone, in which a Sarn Complex tonalite was sheared against low-grade Gwna metasediments and metabasalts. Based on findings such as those at Penrhyn Nefyn,

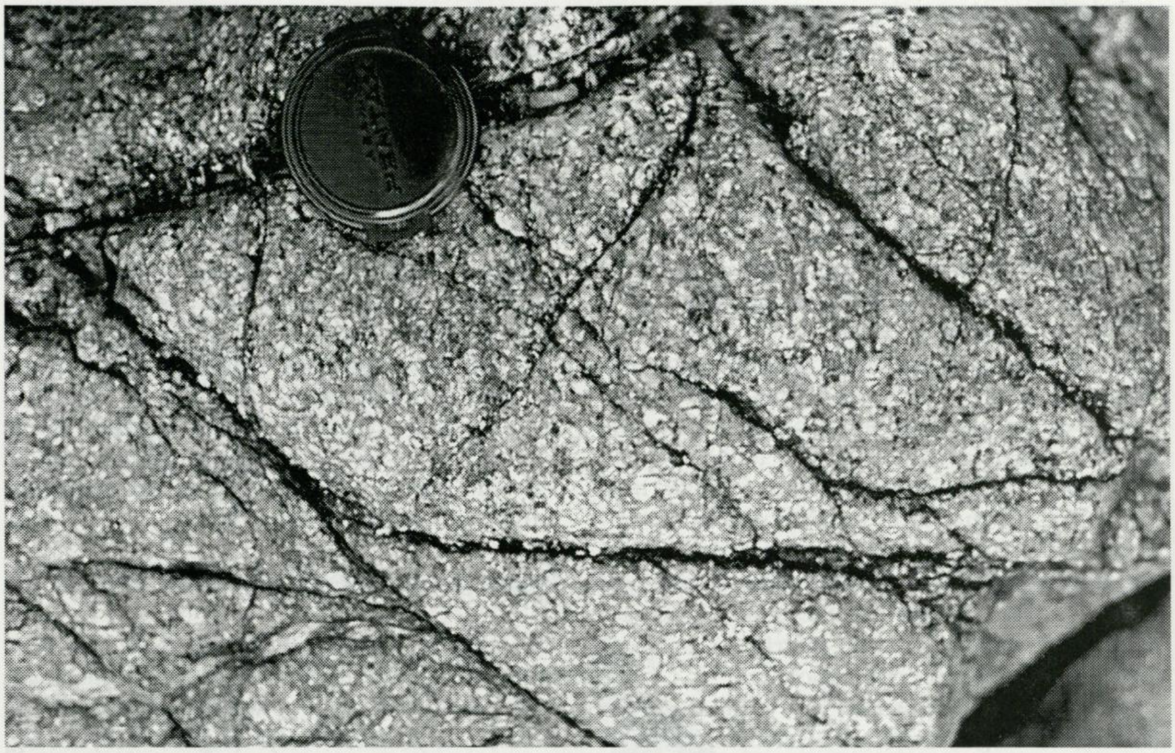

Figure 7.24 Remnants of coarse-grained plutonic igneous texture in sheared Sarn Complex tonalite on foreshore at Penrhyn Nefyn. (Photo: W. Gibbons.)

Gibbons went on (1987) to emphasize the importance of shear zones to the basement geology of southern Britain and applied the suspect terrane concept (Chapter 1). This concept recognizes the importance of strike-slip faulting within active plate margins and argues that the Sarn Complex and Gwna Group belong to two quite different subduction-related terranes – the Cymru and Monian Composite terranes respectively (Figure 1.1). These terranes were originally separated by some unknown (and possibly very great) distance and were subsequently juxtaposed during late Precambrian or early Cambrian movements along the Llŷn Shear Zone (Figure 1.4).

The remarkably conflicting accounts and interpretations of the geologically complex Penrhyn Nefyn foreshore section may be explained by a combination of: poor exposure at critical contacts, a generally very fine-grain size in hand specimens, confusion over the meaning of the term 'gneiss', a failure to recognize shear zone textures and the tendency towards metamorphic convergence and lithological similarity within such zones, and in some cases a preference to fit the interpretation of field relationships to preconceived models.

Conclusions

The Penrhyn Nefyn foreshore offers one of the very few, easily accessible exposures of metamorphic rocks on the mainland of North Wales. Fortuitously, these rocks show what is the only well-exposed example of a terrane boundary, revealed as a structural transition from the Sarn Complex to the Gwna Group: the two main components of the basement geology in this area. Given the complexities and difficulties in understanding the significance of these exposures, they have been the subject of several remarkably different interpretations. As such this site is of especial historical interest, illustrating how a combination of difficult geology, preconceived ideas, insufficient data and a limited understanding of key concepts (such as shear-zone geology) can breed a plethora of conflicting interpretations. The site is one of the few places in mainland Wales where Precambrian rocks can be easily visited, and the only place on the mainland where blue amphibole-bearing metamorphic rocks have been recorded.

BRAICH Y PWLL TO PARWYD (SH 135 258–154 244 AND 155 243)

W. Gibbons

Introduction

This 2.5 km long cliff section is situated at the south-western tip of Llŷn and provides continuous exposure of a remarkably varied sequence of rocks that include: mélange, schist, and gneiss and overlying Ordovician strata and intrusions (Figure 7.25). The exposures have been described as including some of the best examples of mélange in the world (Gibbons and McCarroll, 1993): mélanges are peculiar mixtures of rocks that form in various tectonic settings and are especially typical of destructive plate margins. In this site, sedimentary and igneous rocks, notably basaltic pillow lavas, are mixed together in a slaty matrix to produce chaotic and colourful cliff exposures.

These classic exposures are comparable to famous mélange localities elsewhere such as western California, Timor, Turkey and Iran. They form part of the outcrop of the Gwna Group, which extends from Bardsey Island to the north coast of Anglesey. They are especially instructive because they illustrate how an originally bedded sequence of sediments has become progressively disrupted, leaving only traces of the original strata in the form of a 'ghost' stratigraphy.

The stratigraphical interpretation of this Gwna mélange and its contact with adjacent schists has been the subject of considerable controversy. This interest has focused on this site because it is the only place where these relationships can be viewed in one continuous outcrop (Matley, 1928; Shackleton, 1956; Barber and Max, 1979; Gibbons, 1983; Gibbons and Ball, 1991). Furthermore, the gneisses, which lie immediately east of the schists, represent the only exposure of high-grade metamorphic rocks on the mainland of North Wales. The relationships between the younger Ordovician sedimentary cover and the older, more metamorphosed (Monian) rocks is also of special interest: on the west side of the bay known as Parwyd, the schists are thrust over the cover strata, whereas on the east side of Parwyd these strata lie unconformably upon gneisses. It is rare to see any exposed contact between the geological basement to Wales and its cover of Welsh Basin sedimentary rocks, let alone relationships that demonstrate both unconformity and thrusting within the same site.

Description

The site can be subdivided into four sectors running down the coastline south-eastwards, from Braich y Pwll to Pared Llech-y-menyn, Trwyn Bychestyn, and Parwyd (Figure 7.25). The first two of these sectors expose different facies of the Gwna mélange, the third sector preserves the contact between the mélange and adjacent phyllitic schists, and the final part of the traverse includes the geologically complex cove of Parwyd, which exposes schists, gneisses and Ordovician sedimentary rocks.

Braich y Pwll to Porth Felen.

This traverse provides the best-known and most photogenic exposures of Gwna Group mélange; the spectacular clasts of white quartzite in the cliffs of Trwyn Maen Melyn (Figure 7.26) are figured in several publications (e.g. Gibbons and McCarroll, 1993). The exposures are especially striking because they include not only large, distinctive masses of white quartzite, but also clasts of basaltic pillow lava and associated manganiferous limestone, plus various sandstones, red shales, and a peculiar sequence of fine-grained siliceous bedded rocks known as the Gwyddel Beds (Matley, 1928). Furthermore, the sector has excellent structural interest because one can trace a series of upright to south-easterly verging folds across the area, these structures folding an earlier foliation with associated recumbent folds (Figure 7.27).

The cliffs around Braich y Pwll expose typical Gwna Group mélange, comprising clasts of limestone, basic lava, red shales, various sandstones and Gwyddel Beds in a grey-green slaty matrix. This mélange is overlain by one of several giant masses of bedded Gwyddel sediments, with a notable marker horizon of bedded red shales occurring at the boundary. The bedded, fine-grained sediments can be traced 500 m southwards; not only do they reveal many examples of upright (F_2) folds, but also rare examples of recumbent (F_1) structures (Gibbons, 1980). Farther south are further exposures of the underlying mélange, which continues for 400 m south-east to Trywn Maen Melyn, across superb exposures of mélange containing white quartzite

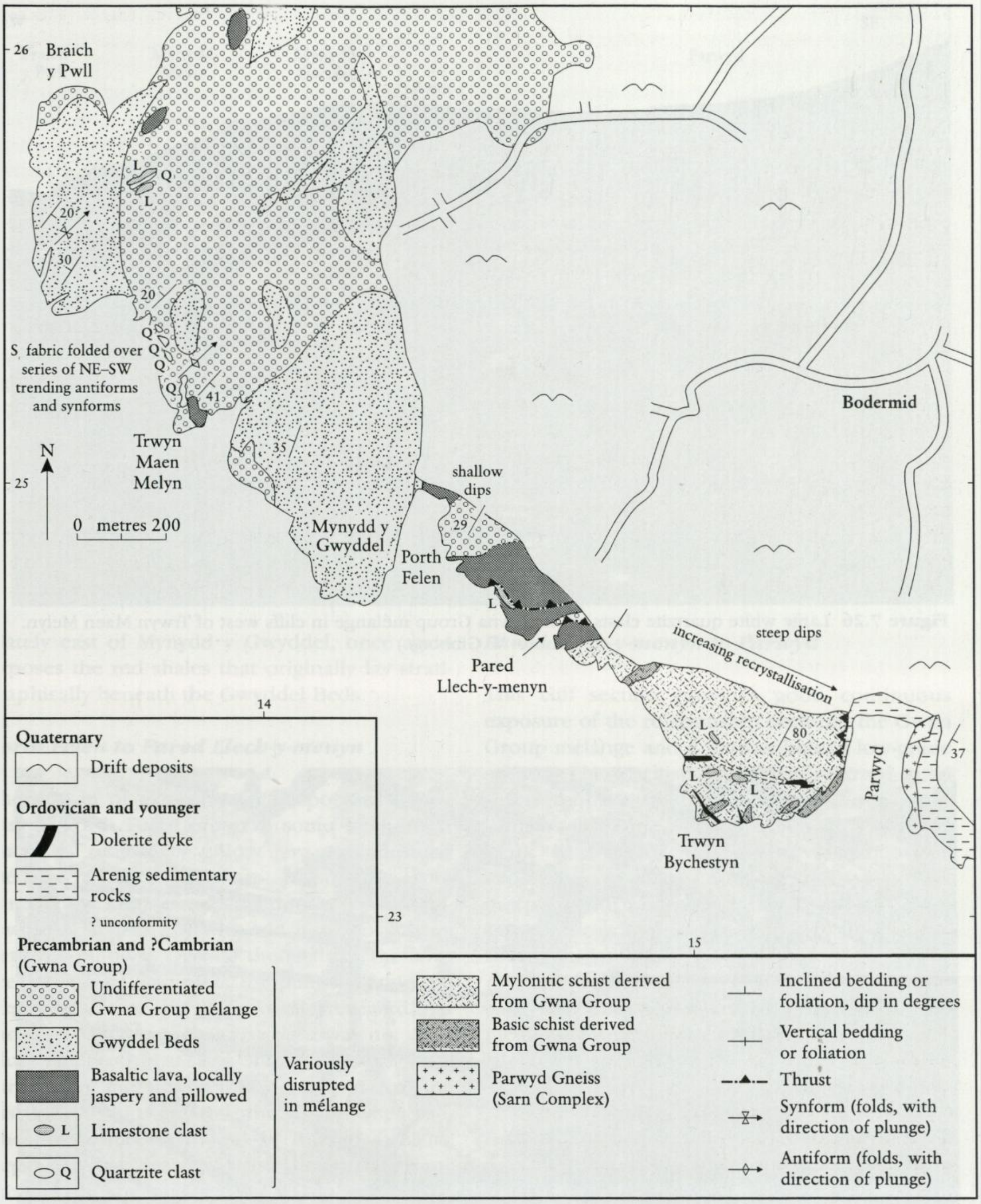

Figure 7.25 Geological map of the south-west Llŷn, Braich y Pwll to Parwyd site. For cross section, see Figure 7.28.

(the Great Quartzite of Matley, 1928) and basaltic pillow lava. Farther south-east, the site follows the coast around the prominent hill of Mynydd y Gwyddel, type locality of the Gwyddel Beds (Figure 7.28). This part of the site is notable for preserving well-developed F_2 folds with prominent steep NW-dipping S_2 foliation. Porth Felen, which indents the coastline imme-

Figure 7.26 Large white quartzite clasts within Gwna Group mélange in cliffs west of Trwyn Maen Melyn. (Photo: W. Gibbons.)

Figure 7.27 Early recumbent folds in 'Gwyddel Beds' south of Braich y Pwll. (Photo: W. Gibbons.)

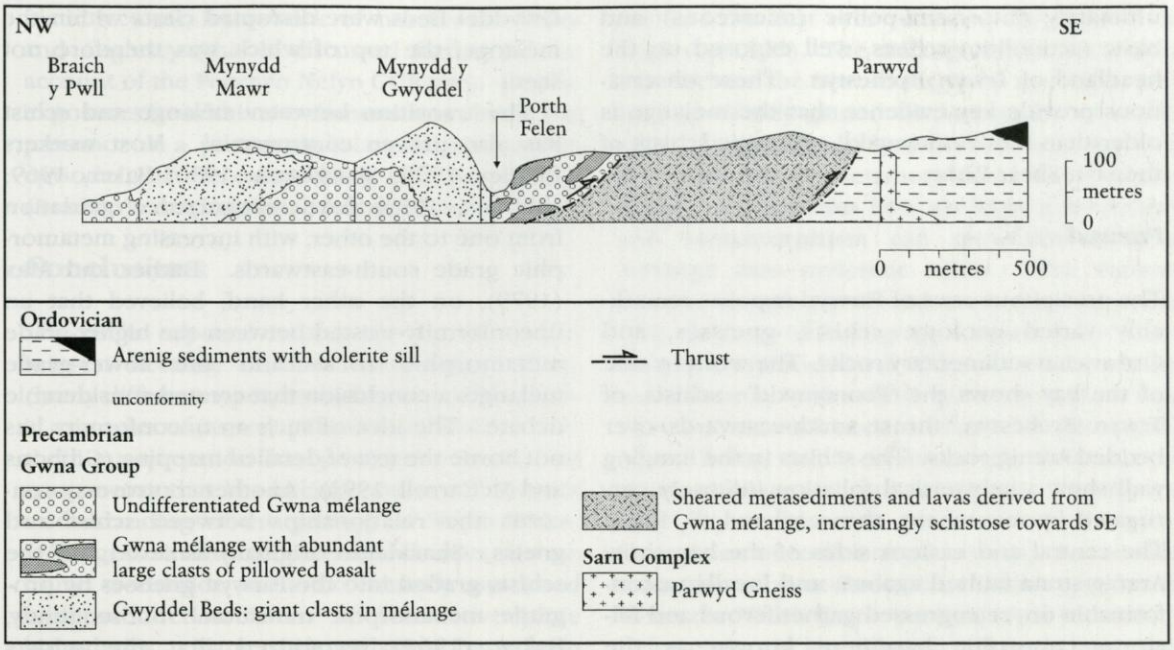

Figure 7.28 Geological cross-section (see Figure 7.25): Braich y Pwll to Parwyd (looking north-east).

diately east of Mynydd y Gwyddel, once again exposes the red shales that originally lay stratigraphically beneath the Gwyddel Beds.

Porth Felen to Pared Llech-y-menyn

The 400 m of extensive cliff exposures south-east of Porth Felen preserve some of the best examples of jaspery pillow lava-and-limestone mélange in the Gwna Group. Most of the exposures show large masses of purple basaltic pillow lavas, commonly with red jasper occurring between pillows. Despite the fact that the lavas are chaotically disrupted, the pillows within the larger masses of lava are so well preserved that they can easily be seen to be right way up. This illustrates how great slabs of rock were not overturned, but merely slid into position during the disruption that created the Gwna mélange. These exposures are also of interest because large slabs of brown, pyritic limestone occur mixed with the pillow lavas. One particularly large limestone slab is overlain by a well-exposed and accessible NW-dipping thrust, interpreted as a post-Ordovician (Acadian) compressive structure. A similar stucture forms the cliff-base at Pared Llech-y-menyn, and separates gently dipping mélange on the shallow limb of a SE-verging F_2 fold from steeply dipping mélange in the footwall to the south-east.

Pared Llech-y-menyn to Parwyd

This cliff section provides good continuous exposure of the relationship between the Gwna Group mélange and a narrow belt of low-grade schists. These schists have been referred to by several authors (see interpretation below) as the 'Penmynydd Zone of Metamorphism', after the work of Greenly (1919) on similar rocks exposed on Anglesey. Although the same metamorphic zone is seen on the Penrhyn Nefyn foreshore, here is the only place where its relationship with the mélange is well exposed. Matley (1928) described the section as grading south-eastwards from highly crumpled and disrupted metasedimentary rocks and lavas, passing rapidly into mica-schists and basic schists belonging to the Penmynydd Zone of Metamorphism. Shackleton (1956) ascribed this imperceptible transition to increasing recrystallization in which original textures are obliterated. The section immediately south-east from Pared Llech-y-menyn shows deformed, metamorphosed, upturned mélange containing clasts of red shales, basaltic lavas, limestone, white quartzite (Matley's Great Quartzite) and various other clastic sedimentary rocks immersed in a grey-green, semi-pelitic, foliated matrix. These exposures of deformed mélange grade south-east into fine-grained, highly foliated phyllites and, ultimately, into semi-pelitic (micaceous) and basic (actinolitic) schists, well exposed on the headland of Trwyn Bychestyn. These observations provide key evidence that the mélange is older than the 'Penmynydd' mylonitic schists of the Llŷn Shear Zone

Parwyd

The precipitous cove of Parwyd exposes remarkably varied geology: schists, gneisses, and Ordovician sedimentary rocks. The western side of the bay shows the 'Penmynydd' schists, of Trwyn Bychestyn, thrust south-eastwards over bedded Arenig rocks. The schists in the hanging wall show a sub-vertical foliation intensely corrugated by recumbent, thrust-related, F_3 folds. The central and eastern sides of the bay show Arenig strata faulted against, and locally unconformable on, retrogressed garnetiferous and felsic metamorphic basement known as the 'Parwyd Gneiss' (Greenly in Matley, 1928; Baker, 1969; Gibbons, 1980, 1983). This unit has been considered a component of the Sarn Complex by Gibbons (1980), Gibbons and Horák (1990, 1996) and Horák (1993). As this is regarded as part of the Cymru Terrane, rather than the Monian Composite Terrane to which the Gwna Group belongs, a summary of its lithological characteristics, geochemistry and age is given in the introduction to Chapter 6.

Interpretation

The Gwna mélange has been variously interpreted as having been produced by tectonic (endogenic) processes (Greenly, 1919) or large-scale sedimentary sliding and disruption. The latter idea was introduced to North Wales geology by Shackleton (1956) and later championed by Wood (1969). The outstanding exposures along the coast of south-west Llŷn, especially those between Trwyn Maen Melyn and Braich y Pwll, have been cited by Wood and others as being typical of the olistostromic mélange. Both Shackleton (1969) and Wood (1969) have interpreted the undisrupted masses of Gwyddel Beds in this site as representing the stratigraphical top of the Gwna mélange, thus supporting the olistostrome model whereby a chaotic unit would be sandwiched between stratigraphically coherent, bedded sequences. Gibbons and Ball (1991) and Gibbons and McCarroll (1993) disputed this conclusion, arguing instead that the Gwyddel Beds were disrupted clasts within the mélange, the top of which was therefore not seen.

The transition between mélange and schist has also proven controversial. Most workers (Matley, 1928; Shackleton, 1956; Baker, 1969; Gibbons, 1983) have recognized a gradation from one to the other, with increasing metamorphic grade south-eastwards. Barber and Max (1979), on the other hand, believed that an unconformity existed between the higher-grade metamorphic rocks and the lower-grade mélange, a conclusion that created considerable debate. The idea of such an unconformity has not borne the test of detailed mapping (Gibbons and McCarroll, 1993). Another controversy concerns the relationships between schist and gneiss. Shackleton originally believed that the schists graded into the Parwyd gneisses by prograde metamorphic transition. Subsequently, Baker (1969) recognized that the schists occurred within a zone of intense shearing deformation and introduced the term 'blastomylonite' to describe the schists. Gibbons (1983) recorded how the gneisses have been retrogressed by shearing. He further recognized that the 'Penmynydd Zone of Metamorphism' on Llŷn represents a shear zone that is a continuation of that seen farther north at the Penrhyn Nefyn GCR site. This separates two quite different rock units: the Gwna Group mélange to the north-west, and the Sarn Complex, to which the Parwyd gneisses probably belong, to the south-east. It follows from the discussion in Chapter 1, that the Penmynydd Zone is also a terrane boundary along which the Monian Composite Terrane (Gwna Group) is juxtaposed with the Cymru Terrane (Parwyd Gneiss–Sarn Complex).

To summarize why the interpretations of this site are so important it is firstly necessary to state that the exposures of Gwna mélange are truly world class and are certainly internationally famous. Any interpretation of this spectacular but enigmatic unit (and mélanges in general) is likely to focus on the exposures within this site. Secondly, one of the major revolutions in geological understanding in the second half of the 20th century was the recognition of the kinematic significance of shear zone lithologies. The Shackleton–Baker debate over the schist-gneiss relationships was a necessary precursor to the general recognition of mylonitic rocks in the basement to southern Britain and an understanding of their importance to the Precambrian plate tectonic framework of north-west Wales and Anglesey (this is discussed further in the account of the Penrhyn Nefyn GCR site). Finally, exposures from this site demonstrate clearly the presence of a pre-Arenig tectono-metamorphic episode and the overprinting of a post-Arenig (Acadian) compressional deformation.

Conclusions

The rocks exposed in this site are of special interest because of their exceptional variety (many different types, including superbly graphic examples of jaspery pillow lavas) and because their interpretation has provided a hotbed of controversy that has helped evolve our present understanding of the geology of North Wales. Mélanges are unusual, chaotic rock units that are found worldwide and are commonly associated with subduction zones at destructive plate boundaries. Many such mélanges have been described, but that within the Gwna Group remains the first ever recorded (by Greenly in Anglesey, 1919). The mélange exposures within this site are the best in Anglesey and Llŷn, and have justifiably gained the reputation of world class. The gradation between this mélange and the more highly metamorphosed rocks to the south-east illustrates how shearing deformation and metamorphism can transform such a mélange into mylonitic schist. The Parwyd Gneiss, though poorly exposed, represents the only outcrop of high-grade metamorphic basement in mainland North Wales. Furthermore the unconformity with overlying Arenig strata is one of only three such occurrences in Llŷn, its significance being that it constrains the deformation in the mélange to a pre-Arenig age. Finally, not only does this site preserve a rare sub-Ordovician unconformity, it also exposes several examples of post-Ordovician thrusts produced when the Welsh Basin was subjected to Acadian deformation in late Silurian and early Devonian times.