Geotectonic framework of the Blueschist Unit on Anglesey–Lleyn, UK, and its role in the development of a Neoproterozoic accretionary orogen

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Abstract

A 560–550 Ma, 5 km × 25 km Blueschist Unit extends NE–SW on the island of Anglesey, Wales, UK, and continues to the southwest for more than 70 km along the northern coast of the Lleyn Peninsula. It has the shape of a shallow-dipping slab or sheet up to a few kilometres thick that was exhumed from the subduction zone and emplaced into the accretionary complex to the northwest. Today the top boundary of the slab is commonly a thrust that was originally a low-angle normal fault at its top in the subduction zone; above it is an accretionary complex and a unit of high-grade gneisses. The bottom boundary is today a thrust (that was originally a thrust), below which is a unit of low-grade or unmetamorphosed rocks belonging to an olistostrome-type accretionary complex. This thrust was originally at the bottom of the slab when it was exhumed in the subduction zone. The sandwiched assemblage was created by the tectonic insertion of the blueschist between the other units. Folding, particularly during late doming of the tectonic sandwich, rotated the top normal-fault boundary into a thrust. Later, high-angle, NE–SW-trending normal faults displaced the tectonic stratigraphy in horst and graben.

A 200 km long and 200 km wide, 680–450 Ma calc-alkaline volcano-plutonic belt extends southeastwards from the blueschist belt via northern Wales to central England, suggesting that the subduction of oceanic lithosphere was to the southeast, and this is consistent with the extrusion of the thin high-pressure slab into the accretionary complex to the northwest. This took place on the western accretionary margin of Avalonia.

Finally, we outline the key steps involved in unravelling the structure of a Pacific-type accretionary complex.

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1. Introduction

Blueschists (BS), locally with eclogites, form an important component of many accretionary, Pacific-type and collision-type orogens, and their study provides key information not only on their metamorphic history, but
also on their structure, and accordingly on their subduction tectonics and polarity (e.g. Miyashiro, 1973, 1994; Ernst, 1975, 1977). Blueschist–eclogite units were typically exhumed by a process of wedge extrusion as thin (ca. 1 km width) slabs that were emplaced as shallow-dipping structures over or into adjacent accretionary wedges, the prime modern analogue of which is the Sanbagawa high-pressure metamorphic unit in Japan (Maruyama, 1990; Maruyama et al., 1996; Masago et al., 2005). Well-investigated, post-Cretaceous examples around the circum-Pacific demonstrate that wedge extrusion was the result of a shallow subduction angle caused by an approaching buoyant mid-oceanic ridge at the leading edge of the circum-Pacific continental margin, and was coincident with widespread, landward, calc-alkaline arc magmatism (Maruyama et al., 1996; Maruyama, 1997).

Blake (1888) first discovered glaucophane in schists on the island of Anglesey, Wales (Fig. 1). Greenly (1919) made the classic description of the BS unit (Fig. 2), Gibbons and Mann (1983) first reported the presence of lawsonite, Horák and Gibbons (1986) classified the blueschist amphiboles, Gibbons and Gyopari (1986) described an anticlockwise PT trajectory, and Gibbons (1981) described glaucophane on the adjacent Lleyn Peninsula. Dallmeyer and Gibbons (1987) reported an \(^{40}\text{Ar}/^{39}\text{Ar}\) mineral age on phengite of 560–550 Ma for the blueschists which they interpreted as the metamorphic crystallization age. In spite of these metamorphic studies of the blueschists, and of structural-tectonic investigations of these and associated rocks in Anglesey (Wood, 1974; Barber and Max, 1979; Shackleton, 1975), the structural framework of the Anglesey–Lleyn blueschists is unknown, particularly with regard to that of modern analogues.

Our recent investigations of the accretionary orogen of Anglesey–Lleyn have led to the definition of new mineral isograds and metamorphic zones in the Blueschist Unit (Kawai et al., 2006), and in particular to a study of the top and bottom boundaries of the high-pressure unit, in order to work out its structural evolution following the deep-seated blueschist facies metamorphism. The aim of this paper is to describe the structure of the Anglesey–Lleyn Blueschist Unit, and to produce...
a new tectonic model that explains its subduction and exhumation history. These results have major implications for the tectonic environment of the Anglesey–Lleyn accretionary orogen on the active continental margin of Avalonia in the Neoproterozoic and early Palaeozoic.

2. The Anglesey–Lleyn Blueschist Unit

The main geological units on Anglesey and Lleyn are shown in Figs. 1 and 2. The Blueschist Unit on Anglesey is bordered on both sides by the accretionary complex of the Gwna Group. The olistostromal New Harbour Group and the passive margin sediments of the South Stack Group occur to the northwest, and the Coedana granite is situated in the Central Anglesey gneisses. The Central Anglesey Schist Unit that occurs on the eastern side of the Coedana granite is mainly composed of mica schists and minor metabasite lenses.

The Blueschist Unit extends NNE to SSW from the eastern side of Anglesey Island to the southwestern end of the Lleyn Peninsula, a total distance of about 70 km (Fig. 2). On Anglesey the unit is bounded on its western and eastern sides by late steep, NE–SW-striking Berw and Menai Strait (Fig. 3A) faults, respectively. We will demonstrate that the original attitude of the Blueschist Unit in relation to its bordering rocks was sub-horizontal. At a small outcrop the top boundary of the Blueschist Unit is overlain by unmetamorphosed Gwna Group rocks and Holland Arms gneisses (Fig. 3B). The bottom boundary crops out at the western end of the Lleyn Peninsula where schists are underlain by unmetamorphosed or low-grade rocks belonging to an accretionary complex. The three key areas,
3. The Blueschist Unit on Anglesey, and its top boundary

On Anglesey the metamorphic grade of the Blueschist Unit has been sub-divided into three mineral zones: I, II and III that are separated by crossite and barroisite isogrades (Fig. 3, after Kawai et al., 2006). The appearance of crossite defines the beginning of Zone II. Zone I has a chlorite–epidote mineral assemblage. But, the basaltic lavas of the Gwna Group to the east have only chlorite, which we ascribe to thermal hydration metamorphism on the ocean floor; i.e. they were not metamorphosed by the regional metamorphism that affected Zones I–III. These chloritic basaltic lavas correspond to similar unmetamorphosed Gwna Group basaltic lavas in SW Lleyn.

In Fig. 3D, the spatial distribution of the mineral zones, passing from east to west, indicates a structurally...
downwards, westward increase of P and T from Zones I to II towards a central structural horizon (Zone III), and then a corresponding decrease farther westwards from III to I (Kawai et al., 2006).

The Blueschist Unit (5 km × 25 km) in Zone III contains lenses of well-preserved glaucophane-bearing metabasic rocks up to 5 km long, as shown on the geological map of Anglesey (British Geological Survey, 1980), the wall-rocks of which mostly consist of chloritic and micaceous schists without glaucophane. Many metabasic lenses consist of hornblende schist, some of which in less retrogressed areas contain glaucophane. Mineral lineations defined by well-developed Na-amphibole on foliation surfaces and crenulation fold axes trend NNE-SSW (Fig. 3A). Zone II (3 km × 11 km) on the eastern side of Zone III also contain lenses up to 1.5 km long of glaucophane-bearing metabasic rocks.

The top boundary of the Blueschist Unit is exposed on its eastern and western margins (Fig. 3). On the eastern margin tuffs of the 614–572 Ma Arfon Group (Tucker and Pharaoh, 1991; Compston et al., 2002) rest above a thrust on unmetamorphosed accretionary rocks of the eastern Gwna Group (Greenly, 1919) (Fig. 3C), which in turn rest on an extensional fault above the Blueschist Unit.

On the western margin in a 200 m × 1000 m area foliated, micaceous Holland Arms gneisses, which have a Rb–Sr whole-rock isochron age of 595 ± 12 Ma (Beckinsale and Thorpe, 1979), and NS-trending sub-horizontal isoclinal fold axes (Fig. 3B), are separated from the Blueschist Unit by a high-angle extensional fault that is marked as thrust on Fig. 3B in its rotated position. Although the original relationship between the Holland Arms gneiss and the Blueschist Unit is unexposed, the attitude of shallow-dipping rocks in the klippe suggests that surrounding, weakly metamorphosed accretionary rocks of the Gwna Group rest on schists of the Blueschist Unit with a sub-horizontal tectonic contact, which means in turn that the high-grade gneisses also overlie the Gwna Group with a tectonic contact. Further lithological characteristics and structural relationships on this top boundary are well observed on the southwest Lleyn Peninsula to be described below.

4. The Peninsulas of Porth Dinllaen and Penrhyn Nefyn

Gwna Group accretionary rocks and blueschist–phengite schists (Schist Unit) crop out on the Porth Dinllaen Peninsula and Penrhyn Nefyn Peninsula on the northern coast of the Lleyn Peninsula (Fig. 4A and B).

High-angle secondary faults trending NW and NE separate the two groups of rocks.

The Gwna Group, best exposed on Porth Dinllaen Peninsula, mostly consists of a 1 km-thick pile of pillow lavas, massive basaltic flows and minor pillow breccias, the pillows being largely undeformed. The lavas commonly contain inter-pillow lenses of red chert or limestone. Hydrothermal mineralization is recorded in sulphide-rich massive basals and quartz veins. The facing directions of the pillows are shown in Fig. 4B. On the western side of Penrhyn Nefyn (Fig. 4A) pillow lavas are associated with volcanic breccias. We correlate these undeformed volcanic rocks with comparable undeformed pillow lavas and associated rocks of the Gwna Group in southwest Lleyn (Figs. 7A and 8A) and on Llanddwyn Island (Fig. 3).

The Schist Unit has two main outcrops, eastern and western, and contains several types of schistose rocks. In the eastern unit on Penrhyn Nefyn (Fig. 4A) the most common lithology is a meta-volcanic basic schist that consists of epidote, chlorite, actinolite, and albite (Gibbons, 2000) and contains relict massive basaltic flows, deformed flattened pillows up to 5 cm across, and blueschists in which crossite replaces actinolite as in the main blueschists of Anglesey (Gibbons, 1981; Kawai et al., 2006). Adjacent phengite schists (Fig. 4A) contain quartz and albite (Gibbons, 2000); we confirm the presence of phengite. These glaucophane–phengite schists belong to the northern end of the Blueschist Unit of the Lleyn Peninsula shown in Fig. 2. Adjacent tonalitic schists contain low strain zones with a well-preserved tonalitic texture; Gibbons (2000) correlated these rocks with tonalite belonging to the nearby Sarn Complex.

The western Schist Unit on the western side of Porth Dinllaen peninsula (Fig. 4B) contains much chloritic schist, which we interpret as a mafic volcaniclastic sediment. The schist contains many lenses up to 2 m long that demonstrate crude stratigraphic zones through the schists, each some tens of metres thick. Passing from east to west a zone with red chert lenses is followed successively by zones rich in sandstone lenses and then in limestone lenses. We consider that the lenses are derived from broken up beds of chert, sandstone and limestone. In the top of this chloritic mélange there is a 50-m block of homogeneous metabasalt, above which is a bedded succession of turbidites and sandstones. We interpret the western Schist Unit as accretionary rocks overlain by clastic sediments. Although the present contact of the pillow lavas with the western Schist Unit is a steep fault, we presume that the original relationship was a sub-horizontal fault, as seen on the SW Lleyn Peninsula, and therefore that this is a top boundary of the Schist Unit.
Fig. 4. (A) Geological map and cross-section of Penrhyn Nefyn Peninsula to the east of the Porth Dinllaen Peninsula. (B) Geological map and cross-section of the Porth Dinllaen Peninsula.
5. SW Lleyn Peninsula; bottom and top boundaries of the Schist Unit

Our geological map of the southwestern end of the peninsula (Figs. 2 and 5) shows two blocks of the Schist Unit (that do not contain glaucophane here), the structural relationships of which with surrounding rocks are described below.

5.1. Bottom boundary

A klippe of Zone I schist crops out on a 550 m-high hill that rises steeply from the sea at the western end of the area shown in Fig. 5. It consists of steeply dipping slaty mudstone that contains relicts of metabasic greenschist (predominately basaltic tuff), sandstone, mudstone, and rare chert and limestone.

The Schist Unit is separated from an underlying unmetamorphosed olistostrome-type accretionary complex by a sub-horizontal, phyllonite-bearing thrust (Fig. 6A). The steeply dipping schists are truncated by the sub-horizontal thrust. This is the bottom boundary of the Anglesey–Lleyn Blueschist Unit, as discussed in detail later. Fig. 6B and C shows thrusts near the boundary between the Schist Unit and the underlying rocks.

Below the thrust the steeply dipping, unmetamorphosed olistostrome-type mélange (accretionary complex) consists of metabasites that contain olistoliths of basalt, limestone, quartzite and sandstone.
complex) has a matrix of mafic mudstone that contains many, mostly 5–30 cm-size, lenses of quartzite (maximum is 17 m × 25 m; Fig. 6D), red chert, dolomitic limestone, and basaltic greenstone (Fig. 6D). The olistostromal mudstone mélangé passes stratigraphically downwards to ca. 35 m-thick sandstone that makes up the controversial Gwyddel Beds. Many authors (e.g. Shackleton, 1975; Roberts, 1979) described these as bedded acidic tuffs. However, from our observations in the field and in thin section we conclude they are bedded sandstones, in agreement with Gibbons and McCarroll (1993). The bedded sandstones are underlain conformably by a well-preserved, but small, section displaying ocean plate stratigraphy. A 1 m-thick bed of hemi-pelagic mudstone passes downwards to 7 m of bedded red chert (marked on Fig. 5) that is underlain by a 1 m-thick basalt (not marked on Fig. 5).

All the main units described above are transected by secondary high-angle extensional faults (Figs. 5 and 6A) that have the effect of uplifting and exposing the bottom boundary of the Schist Unit in a horst (Fig. 5).

5.2. Top boundary

The top boundary of the Schist Unit is exposed in the bay of Parwyd Llech-y-menyn (Fig. 5); Fig. 7 shows the geological map and Fig. 8 some relevant photographs. Gwna Group rocks are here thrust over mafic chloritic schists without glaucophane belonging to Zone I of the Schist Unit (Figs. 5 and 7A).

The top boundary surface of the Schist Unit is a ca. 50 m-thick thrust duplex that dips 45° northwest (Fig. 8B). Several parallel or divergent northerly dipping thrusts within the Gwna Group are in the hanging wall of the thrust duplex (Fig. 7A). Fig. 8C and D shows minor south-vergent thrusts within the major thrust duplex.

The Gwna Group largely consists of pillow basalts, at least 20 m thick (Figs. 7B and 8A) that are overlain
Fig. 7. (A) Geological map of the central graben on the coast in southwest Lleyn extending eastwards from the bay of Porth Felen to the bay of Pared Llech-y-menyn, as shown on Fig. 5. Position of photos of Fig. 8 indicated. The map shows many thrusts that have imbricated the Gwna Group accretionary complex in the hanging wall of the main thrust at Pared Llech-y-menyn. (B) Geological columnar section of primary ocean plate stratigraphy that has been imbricated in the Gwna Group.

by 2 m of brown pelagic limestone succeeded by 5 m of red-bedded chert; this represents ocean plate stratigraphy (Fig. 7B). The Gwna Group is located in a graben that has subsided differentially with respect to its neighbouring horst blocks, thereby preserving the top boundary. The western margin of the Gwna Group is occupied by a secondary, high-angle NS-striking normal fault that dips 70° east, marking the western side of the graben, whereas the eastern margin is occupied by a major thrust that dips 45° west. On the eastern side of Parwyd bay (Fig. 5) a 30 m-wide strip of retrogressed garnetiferous gneiss (the Parwyd gneiss) is overlain unconformably by Ordovician sediments (Matley, 1928; Roberts, 1979; British Geological Survey, 1994; Gibbons, 2000). The eastern boundary of the Parwyd gneiss is marked by a sub-vertical fault that has a small amount of thrust movement that has brought up the gneisses (section of Fig. 5). We suggest that an original thrust, probably subsidiary to the major thrust on the western side of the bay, was reactivated by the normal fault at the eastern end of the graben, but insufficiently to remove all the thrust offset.

We agree with Gibbons (1983) who considered that the Schist Unit is comparable to the Blueschist Unit on Anglesey and showed that it extends along the Lleyn Peninsula to the schists on Penrhyn Nefyn. The upper
Fig. 8. Four photos of key features at localities on the coast in southwest Lleyn marked in Fig. 7. (A) Undeformed pillow basalt in the Gwna Group. (B) Top boundary of the Schist Unit which is a thrust that dips 45° northwestward at the bay of Pared Llech-y-menyn. Looking to the NE. There are several parallel or divergent faults in the hanging wall (Fig. 7A). (C and D) Southeast-verging minor thrust duplexes a few metres above the major thrust in (B).

schists in Fig. 5 contain clasts of limestone, basaltic lava, quartzite, red shale and chert. The schists increase in metamorphic grade eastwards from mafic chloritic schists at Pared Llech-y-menyn to phyllites, and ultimately to micaceous and basic, actinolitic schists at Trwyn Bychestyn headland—see Fig. 5 (Matley, 1928; Shackleton, 1956; Gibbons, 2000). This increase in grade is downwards from the top towards the centre of the Schist Unit.

Combining the overall geometry of this top boundary with that of the bottom boundary on Anglesey and Lleyn (Fig. 9A), we conclude that, when the Blueschist-bearing Schist Unit moved from depth towards the surface, it was juxtaposed at a crustal level with the overlying Gwna Group along an extensional fault and with the underlying olistostrome-type accretionary complex along a thrust (Fig. 9B).

6. The magmatic arc

Fig. 1 shows key geological outcrops and boreholes with their isotopic ages in Wales, the Welsh borderland and English Midlands. We emphasize the many calc-alkaline igneous rocks that belong to this 200 km-wide magmatic arc that occurs as inliers within Phanerozoic cover sedimentary rocks. Reliably dated rocks in this arc formed in four main stages (Gibbons and Horák, 1996).

6.1. 680–670 Ma

Early arc magmatism. The Malvern Complex mainly comprises calc-alkaline granodiorite, diorite, tonalite and granite (Thorpe et al., 1984), and has a U/Pb zircon age of 677 ± 2 Ma and a U–Pb monazite age of 670 ± 10 Ma (Tucker and Pharaoh, 1991).
Fig. 9. Simplified cross-sections across Anglesey–Lleyn showing the present-day structure and tectonic evolution of the Blueschist–Schist Unit. (A) The present-day structure that has been divided by secondary high-angle faults into an anticline in Anglesey and a horst and graben in Lleyn. (B) Simplified cross-section of the original structure of the Blueschist–Schist Unit. Removal of the high-angle secondary faults has reconstructed the original tectonic stratigraphy that has been folded after exhumation. The three oblong blocks refer to the areas where we observe the present-day structures marked directly above in (A). (C) Cartoon showing the exhumation of the BS unit as it was transported from SE to NW in the upper subduction zone (see also in Fig. 10C). The Blueschist Unit is being tectonically juxtaposed and sandwiched between unmetamorphosed or low-grade accretionary complexes; it has a thrust at its bottom and an extensional fault at its top that enable it to be exhumed during wedge extrusion. After exhumation, the folding into an anticline and syncline changed the orientation of the faults; the extensional fault at the bottom boundary became a thrust which we observe today in (A). (D) Geological columnar section showing the original tectonic stratigraphy between the four units (olistostrome-type accretionary complex, Schist Unit, Gwna Group, and Holland Arms gneiss).
Fig. 10. Simplified cross-sections along a NW–SE profile from Anglesey through Wales to Central England marked in Fig. 1, to illustrate the geodynamic evolution of the active western margin of Avalonia from about 680–450 Ma. See text for more details. (A) First, minor magmatism in the Malverns at 677 Ma. (B) Main arc activity at 620–600 Ma at Sarn, Arfon, Glinton, Orton and Chaldecote. The crustal melt Coedana leuco-granite formed as a result of ridge subduction. (C) A ductile wedge of an accretionary complex, a few kilometres thick, was subducted, recrystallized under blueschist facies conditions, and then exhumed to a mid-upper crustal level, possibly assisted by a shallowing subduction angle. Metamorphic zones and isograds indicate that the wedge has an antiformal isoclinal structure. (D) The South Stack and New Harbour Groups were underthrust into the base of the accretionary wedge during final stages of subduction in the Cambrian. This underthrusting led to doming of the already accreted complex, as result of which the Coedana granite and gneisses became isolated from the western margin of Avalonia from which they were derived. Arc magmatism continued in the Tremadoc to Caradoc in NW Wales.
6.2. 620–600 Ma

Rocks that formed in this main period of arc magmatism are: (a) the Sarn Igneous Complex in the Lleyn Peninsula that consists of calc-alkaline monzogranite, gabbro, granodiorite, diorite, and tonalite and has a $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 615 ± 2 Ma (Gibbons and Horák, 1996; Horák et al., 1996); (b) the 4 km-thick volcanioclastic Arfon Group in NW Wales that contains clasts of Monian (Anglesey) metasedimentary rocks and is overlain by fossiliferous Cambrian slates (Shackleton, 1975; Horák et al., 1996). A rhyolitic ash-flow tuff has a U–Pb zircon age of 616 ± 2 Ma (Tucker and Pharaoh, 1991), and an ignimbrite has a SHRIMP zircon age of 605 ± 1.6 Ma (Compston et al., 2002); (c) felsic tuffs in the Glinton and Orton boreholes have U–Pb zircon ages of 616 ± 6 and 612 ± 21 Ma, respectively (Noble et al., 1993); (d) the Coedana granite on Anglesey (Greenly, 1919) is a leuco-granite that contains muscovite, biotite and garnet, retains locally a pre-granite foliation, lacks a chilled margin, has granitic veins rich in garnet, and close to its contact with mica-tourmaline hornfels the granite in places contains tourmaline. Greenly (1919) concluded that “the affinities of the Coedana granite to some metamorphic granites are close”. In contrast, Gibbons and Horák (1996) suggested that the Coedana granite was a product of arc magmatism. We suggest that it is a crustal melt granite, the high temperature for which was provided by ridge subduction (Fig. 10B). The granite has a U–Pb zircon age of 613 ± 4 Ma (Tucker and Pharaoh, 1991); (e) the Chaldecote volcanic rocks with bimodal basalt-rhyolite lavas erupted in a back-arc basin in central Wales, but calc-alkaline arc-type lavas erupted again in the Llanvirn to Caradoc on the southeastern side of the Welsh basin (Woodcock and Strachan, 2000). Although subsequent late Caledonian deformation inverted fractures inherited from the basement, created slate belts, and shortened the width of the early Palaeozoic arc belt, it did not destroy the primary volcanic structures in the arc rocks, and it did not affect sufficiently the distribution of the magmatic rocks to prevent recognition of the arc (Kokelaar, 1988).

6.3. 575–550 Ma

Late arc magmatic rocks include: (a) a tuff in the volcanioclastic Arfon Group in NW Wales (Shackleton, 1975) that has a SHRIMP U–Pb zircon age of 572 ± 1.2 Ma (Compston et al., 2002); (b) in the Welsh borderland a rhyolitic lava in the Uriconian Group consisting of basalts, basaltic andesites, dacites and rhyolites (Thorpe et al., 1984) has a U–Pb zircon age of 566 ± 2 Ma, and the Ercall granophyre that intrudes felsic lavas has a U–Pb zircon age of 560 ± 1 Ma (Tucker and Pharaoh, 1991). Bentonite and tuff in the Longmyndian Supergroup (Pauley, 1990) have SHRIMP zircon ages of 567 ± 2.9 and 556 ± 3.5 Ma, respectively (Compston et al., 2002); (c) in the Malvern Hills a rhyolitic tuff occurring within a calc-alkaline tholeiitic basalt–andesite–rhyolite association in the Warren House volcanic group (Thorpe et al., 1984) has a U–Pb zircon age of 566 ± 2 Ma (Tucker and Pharaoh, 1991); (d) in the English Midlands the Charnian Supergroup contains felsic tuffs, andesites and dacites, agglomerates and granodioritic intrusions (Pharaoh et al., 1987). Compston et al. (2002) obtained SHRIMP zircon ages on tuffs of 566 ± 3 and 559 ± 2.0 Ma.

6.4. Tremadoc–Caradoc (ca. 488–448 Ma)

Arc volcanoes, associated with at least six major rhyolitic calderas, resurgent and collapsed calderas, two andesitic strato-volcanoes, Strombolean cones, and intra-arc graben, developed on already accreted crust at a destructive plate margin in Wales (Gibbons, 1998). They gave rise to voluminous basic, intermediate and particularly felsic rocks with an overall calc-alkaline chemistry in the late Tremadoc in NW Wales and in the late Tremadoc or early Arenig in SW Wales (Kokelaar, 1988). In the Arenig to Caradoc bimodal basalt-rhyolite lavas erupted in a back-arc basin in central Wales, but calc-alkaline arc-type lavas erupted again in the Llanvirn to Caradoc on the southeastern side of the Welsh basin (Woodcock and Strachan, 2000). Although subsequent late Caledonian deformation inverted fractures inherited from the basement, created slate belts, and shortened the width of the early Palaeozoic arc belt, it did not destroy the primary volcanic structures in the arc rocks, and it did not affect sufficiently the distribution of the magmatic rocks to prevent recognition of the arc (Kokelaar, 1988).

7. Discussion

In the first plate tectonic synthesis of the geotectonic development of the British Isles, Dewey (1971) considered, reasonably, that the Caledonian and Hercynian collisional orogenies were the most important events responsible for formation of the continental crust. In the following decades later plate tectonic models similarly regarded collisional orogeny as predominant, because the role of accretionary orogens was little appreciated internationally at that time. This imbalance was accentuated by the subsequent emphasis placed on terrane analysis (e.g. Gibbons, 1987, 1989), which overplayed the role of primary volcanic structures in the arc rocks, and it did not affect sufficiently the distribution of the magmatic rocks to prevent recognition of the arc (Kokelaar, 1988).
plex, and the significance of Anglesey–Lleyn for the palaeogeographic reconstruction of the Avalonian active continental margin.

The protoliths, not only of the Anglesey–Lleyn Blueschist Unit, but also the overlying and underlying units, are all accretionary in origin, having formed by subduction of an oceanic plate.

### 7.1. Ocean plate stratigraphy (OPS) in accretionary complexes

Ocean plate stratigraphy (MORB basalt–chert–hemipelagic mudstone–clastic turbidite–sandstone–conglomerate) records the travel history of an oceanic plate from a ridge to a trench (Isozaki et al., 1990; Matsuda and Isozaki, 1991), and in an accretionary orogen it may be preserved in zeolite to granulite and blueschist facies rocks (e.g. Kimura et al., 1996; Okamaoto et al., 2000).

OPS has played a major role in working out the palaeohistory of many accretionary complexes in the western and southwestern Pacific (e.g. Kimura et al., 1992; Wakita and Metcalfe, 2005), and of the early accretionary stage of collisional orogens of the Caledonides of Ireland (Ryan and Dewey, 2004), and the Himalaya of Tibet (Ziabrev et al., 2004). Although OPS may be present at the top of an ophiolite, in most accretionary orogens only the OPS is preserved, because the ultramafic rocks, gabbros and sheeted dykes are typically subducted in Pacific-type plate margins, leaving only the peeled-off OPS to be accreted (Isozaki et al., 1990; Kimura and Ludden, 1995). We wish to acknowledge the fact that the only author who previously identified and correctly interpreted ocean plate stratigraphy in Anglesey–Lleyn was Roberts (1979, p. 6), although he did not call it as such. We have recognized numerous examples of OPS in Anglesey and Lleyn. In Japan and California the predominant pelagic chert deposit of OPS in a trench is up 100–200 m thick, representing 100–200 m.y. duration of travel time from a mid-oceanic ridge to a trench (Isozaki and Blake, 1994; Isozaki, 1996). In contrast, in Anglesey–Lleyn the best-preserved OPS has up to about 5–10 m of bedded chert (intact and not reduced by deformation), suggesting a very short travel time in the oceanic domain and buoyant subduction of a mid-oceanic ridge immediately before the blueschist formation. Metabasalts in the Gwna Group of Anglesey–Lleyn have MORB-type geochemistry (Thorpe, 1993).

The sense of younging of OPS is one of several critical methods to estimate the polarity of subduction (Isozaki, 1996; Maruyama, 1997), and on Anglesey–Lleyn such younging consistently suggests eastward subduction before and after exhumation of the Blueschist Unit.

### 7.2. Top and bottom boundaries of a Blueschist Unit

In order to work out the tectonic framework and evolution of a Blueschist Unit, it is necessary to define its top and bottom boundaries. Both boundaries of the Blueschist–Schist Unit crop out on Lleyn Peninsula, and the top boundary on Anglesey. Although Gibbons (1987) defined the Menai Strait fault as a terrane boundary, it clearly does not separate rocks of different type and origin, and has not displaced appreciably the upper and lower parts of the Schist Unit.

Fig. 9A shows a cross-section of the present-day structure of the Blueschist–Schist Unit from Anglesey to Lleyn. After removing the secondary high-angle faults, Fig. 9B illustrates the overall original structure of the Schist Unit as a tectonic slab, after its exhumation and after weak folding. A slab exhumed during wedge extrusion in a subduction zone is floored by a thrust and roofed by a normal fault (Maruyama, 1997). Fig. 9C shows the structural relations on the top and bottom boundaries of the high-pressure unit as it was exhumed at the top of the subduction zone; it was separated from overlying and underlying rock units by an extensional fault and a thrust, respectively (see also Fig. 10C). Note that the top extensional fault is still preserved as such in eastern Anglesey (Fig. 9A), but that it has been rotated by the folding into a present-day thrust in SW Lleyn (Fig. 9A). Doming and folding of a tectonic slab is to be expected in an accretionary plate margin, because of buoyancy of the newly accreted, juvenile, hydrated crust and of subsequent compressional deformation (e.g. Maruyama et al., 2002).

### 7.3. Original nappe structure

Most blueschist and bordering units in accretionary orogens are displaced by secondary normal faults (Maruyama et al., 1996). After removing the effects of the late high-angle faulting, the original nappe structure and tectonic stratigraphy within the subducted tectonic slab can be reconstructed. In Anglesey–Lleyn the nappe pile has the following ascending units: an olistostrome-type accretionary complex, the BS-bearing unit, the Gwna Group accretionary complex, and on top the Holland Arms gneisses (Fig. 9D), which we suggest continue westwards as the Coedana gneisses of Anglesey (Fig. 10). We speculate that the Central Anglesey Schist Unit is imbricated, repeated, but retrogressed examples of the Blueschist Unit. We make this suggestion because of the remarkable similarity in lithology and internal structure of these rock groups. We think that Greenly
(1919) realized this possibility because he noticeably marked the Central Anglesey Schist Unit (Fig. 2) and the Blueschist Unit (Fig. 3) with the same symbol, as ‘Pennynydd Zone of Metamorphism’ on his geological map (this is British Geological Survey, 1980) and in his text. If this idea is correct, it would support our correlation of the Holland Arms gneisses with the Coedana gneisses, which we have made independently on structural grounds.

Note that all the units were metamorphosed under very low-grade conditions such as the zeolite or prehnite–pumpellyite facies, except for the high-grade gneisses at the structural top and the Blueschist Unit. All four units are separated by low-angle faults that were displaced by high-angle secondary faults (Fig. 5).

The nappe structure can be explained by two stages in the growth history of the Avalonian-early Caledonian margin through plate subduction. Firstly, the units that young downwards were formed or inserted successively downwards by underplating in the accretionary wedge in the subduction zone on the hanging wall of Avalonia. Secondly, the Blueschist Unit was inserted into a structurally central position or intermediate level of the above wedge. The BS unit was most likely exhumed preferentially from mantle depths to an upper crustal level as a wedge during extrusion into the shallow-level accretionary complex (Maruyama, 1990; Maruyama et al., 1996).

7.4. Exhumation tectonics of the Blueschist Unit

The metamorphic assemblages, deformation fabrics and senses of shear along the boundary planes between the Blueschist Unit and the overlying and underlying units strongly indicate that the Blueschist Unit moved from a mantle depth of ca. 35 km into an upper crustal depth of <5–6 km where the accretionary complex was present (Figs. 9C and 10C). Asymmetrical kinematic indicators on the top and bottom boundaries demonstrate that the Blueschist Unit was extruded as a solid tectonic slab to the northwest, where it had a thrust at its bottom and an extensional fault at its top (Fig. 9C). Masago et al. (2005) reported similar geometry in the Cretaceous Sanbagawa BS in SW Japan from contrasting senses of shear along the top and bottom boundaries of the high-pressure slab.

7.5. Role of Pacific-type orogeny in relation to the origin of continental crust in the UK

A Pacific-type orogeny creates firstly, huge volumes of new juvenile crust of MORB-, OIB-types that accrete to an active margin in a subduction–accretion complex, and secondly, a coeval calc-alkaline volcano-plutonic arc, such as the ca. 200 km-wide Cretaceous belt around the Pacific. In principle therefore, the Anglesey–Lleyn Blueschist Unit should be accompanied by a coeval calc-alkaline magmatic arc to the east.

Since Dewey (1969), it has been widely accepted that southeastward subduction of oceanic lithosphere from a NE–SW-trending plate margin sited somewhere northwest of Anglesey gave rise to arc-type magmatism in a 200 km-wide belt extending from western Wales to central England starting in the late Precambrian (Thorpe, 1972, 1974; Thorpe et al., 1984; Pharaoh et al., 1987; Gibbons and Horák, 1996; Horáková et al., 1996) and continuing in the Ordovician in early Caledonian times (Fitch and Hughes, 1970; Wood, 1974; Phillips et al., 1976; Fitch et al., 1982; Kokelaar, 1988; Woodcock and Strachan, 2000). We follow this long tradition, but add embellishments of a Japanese-type subduction–accretion complex with exhumation of a high-pressure subducted slab, and of ridge subduction.

Oblique convergence led to the formation of strike-slip faults that imbricated and dismembered the subduction system with the result that the Anglesey blueschists, belonging to the accretionary prism, were caught between slivers of dismembered arc, as demonstrated by Gibbons and Horák (1996). Whilst we agree with the above subduction–arc relationships, we consider that the structural relations between the blueschists, the accretionary units and the magmatic arc can be more realistically interpreted in terms of a western Pacific analogue model, rather than by a displaced terrane model at a subduction front.

In Fig. 10, we illustrate four successive stages in the accretion and tectonic evolution of the active continental margin (Fig. 1). The earliest evidence for arc magmatism is provided by the Malvern granodiorite intrusion at 677 ± 2 Ma (Fig. 10A), but the main period was at 620–600 Ma with formation of the Glinton, Orton and Arfon Group tuffs, the Sarn Complex diorite, and the Chaldecote diorite (Fig. 10B). The crustal melt Coedana granite formed at 613 ± 2 Ma by subduction ridge metamorphism. In the period 575–550 Ma (Fig. 10C) late magmatic arc rocks include the Ercall granophyre, Uriconian rhyolite, Warren House rhyolitic tuff, and Longmyndian bentonite and tuff (Fig. 1). In Tremadoc to Caradoc times arc volcanism took place across a wide extent of Northwestern to Central Wales.

We suggest that westward wedge extrusion of the Blueschist Unit (Fig. 10C) was a result of a shallowing subduction angle caused by the previously subducted
buoyant mid-oceanic ridge (Fig. 10B) that facilitated extrusion of the deep-seated, ductile, high-pressure accretionary wedge to a shallow structural level at 575–550 Ma.

Subsequent doming uplifted the Blueschist Unit and associated rocks in central Anglesey, and gave rise to high-angle faults that cut and sliced the BS belt into lenses, and to high-angle secondary faults such as the Menai Strait fault and the Berw fault that have complicated the original structural relationships between the Blueschist Unit, the subduction–accretion complex, and the coeval arc (Fig. 10D). The doming was likely caused by underthrusting of crust to the northwest by the youngest rocks to be accreted, the platform-type sediments of the South Stack Group that have youngest detrital zircon ages of 501 ± 10 Ma (Collins and Buchan, 2004). Subduction and underthrusting of the South Stack Group at the bottom of the accretionary complex jacked up the Blueschist Unit, and likely shifted the trench position farther northwestwards. The first, Caledonian-age, arc magmatism in NW and SW Wales (Fig. 1) was in the Tremadoc, and arc activity continued through the Arenig and Llanvirn culminating in the Caradoc (Fig. 10D).

The apparent isolation of the high-grade gneisses and associated 613 Ma Coedana granite of central Anglesey has led to two main concepts concerning their tectonic origin; as a basement to the accretionary “cover” rocks (Greenly, 1919), and as a suspect terrane (Gibbons and Horáček, 1990). In contrast, we propose that these rocks belong to a klippe that originally formed part of the Avalonian continent (Fig. 10D).

In summary, the tectonic events of the BS and associated rock units in Anglesey–Lleyn took place in the following order: (1) evolution of ocean plate stratigraphy from ridge to trench, (2) formation of an accretionary complex in the footwall of the Avalonian continental margin, (3) development of the accretionary complex of the Gwna Group, (4) formation of an olistostrome-type accretionary complex, (5) subduction of accretionary material to mantle depths to form blueschist–epidote amphibolite facies metamorphism, and exhumation to an upper crustal level and (6) doming and related extensional brittle faulting.

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References


