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The Geology of Anglesey, North Wales: project scoping study

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The Geology of Anglesey, North Wales: project scoping study

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) to describe the geology and history of geological research on Anglesey, North Wales. The geology of this island, which ranges from Neoproterozoic to Pleistocene in age, is highly complex and has been the focus of scientific research since the 19th Century. However, a number of key scientific questions remain unanswered. A multidisciplinary Anglesey project is proposed to investigate the geological evolution of this island and will examine: **(1)** the tectonic drivers and processes responsible for the assembly of Anglesey from the late Neoproterozoic through the Lower Palaeozoic (Cambro-Ordovician); **(2)** the sedimentology and stratigraphy of the Ordovician and Silurian sequences on Anglesey and their relationships to the Lower Palaeozoic succession of mainland Wales; **(3)** Devonian and Carboniferous basin evolution on Anglesey and its relationships to the Upper Palaeozoic succession of mainland north-west Wales; and **(4)** the subsequent, glacial history of Anglesey with particular reference to the control of bedrock geology on temporal and spatial changes in subglacial processes and landform development beneath Irish Sea ice stream during the Late Devensian.

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1 Introduction

This report provides a summary of the geology and history of geological research on the island of Anglesey, North Wales. The geology of this island, which ranges from Neoproterozoic to Pleistocene in age, is highly complex and has been the focus of scientific research since the mid-19th Century. However, a number of key scientific questions regarding the geological evolution of this island remain unanswered.

A multidisciplinary Anglesey project is proposed which aims to provide a new baseline geological dataset to replace the current early 20th Century survey, and to rebuild BGS' knowledge of the metamorphosed and complexly deformed rocks as part of an ongoing investigation into the 'geological foundations' of Wales. Key to this will be investigation into: **(1)** the tectonic drivers and processes responsible for the assembly of Anglesey from the late Neoproterozoic through the Lower Palaeozoic (Cambro-Ordovician); **(2)** the sedimentology, structure and stratigraphy of the Ordovician and Silurian sequences on Anglesey and their relationships to the Lower Palaeozoic succession of mainland Wales; **(3)** Devonian and Carboniferous basin evolution on Anglesey and its relationships to the Upper Palaeozoic succession of mainland northwest Wales; and **(4)** the subsequent, glacial history of Anglesey with particular reference to the temporal and spatial control of bedrock geology on subglacial processes and landform development beneath Irish Sea ice stream.

2 Geology of Anglesey and History of Research

The history of geological research on Anglesey commenced during the 19th Century (notably by Blake and Matley) and preceded the publication of the two volume memoir *The geology of Anglesey* by Greenly (1919). Although the field of earth sciences has 'evolved' over the intervening years, this highly detailed memoir still remains one of the main sources of relatively unbiased field based (site specific) geological information for anyone studying the geology of Anglesey. The memoir was accompanied by the publication of a one inch to the mile geological map of the island in 1920; republished, effectively unchanged at the 1:50 000 scale, by the British Geological Survey in 1972.

In this report, for ease of description, the history of geological research on Anglesey has been divided into five main sections: **(i)** the pre-Ordovician or Monian geology; **(ii)** Ordovician-Silurian; **(iii)** Siluro-Devonian rocks of the Old Red Sandstone Facies; **(iv)** Carboniferous; and **(v)** Quaternary to recent.

2.1 PRE-ORDOVICIAN OR MONIAN GEOLOGY

The pre-Ordovician rocks, collectively referred to as *Monian* by Blake (1888), or *Mona Complex* by Greenly (1919), occur beneath the Arenig overstep sequence on Anglesey (see following section). Greenly (1919, 1920) subdivided the Mona Complex into three main units: **(i)** the granitic rocks and gneisses of central Anglesey; **(ii)** the fine-grained "Penmynydd" schists (which form the host for the Monian or Anglesey blueschists) exposed on the eastern side of the island; and **(iii)** a sequence of deformed metasedimentary rocks with subordinate meta-igneous rocks and a regional-scale mélange, collectively termed the "*Bedded Succession*" (Table 1).

Table 1. Lithostratigraphy and facies correlation for the "*Bedded Succession*" proposed by Greenly (1919). Southern facies – the Monian metasedimentary rocks exposed on Holy Island and the southwestern part of mainland Anglesey; Northern facies – Monian sedimentary rocks exposed in northern Anglesey; Western facies – the Gwna mélange exposed on Anglesey; Eastern facies – the Gwna mélange exposed on the Llyn Peninsula.

	Group	Southern facies	Northern facies	Western facies	Eastern facies
	Penmynydd zone of metamorphism	Correlated in part with the Fydlyn and Gwna Groups			

	Plutonic intrusions				
Bedded Succession	Holyhead Quartzite				
	South Stack Series	i. Stack Moor Beds			
		ii. Llwyn Beds	i. Coeden Beds		
	New Harbour Group	New Harbour Beds	Amlwch Beds		
		i. Celyn Beds	i. Bodelwyn Beds		
		ii. Soldiers Point Beds	ii. Lynas Beds		
	Skerries Group	Church Bay Tuff	Skerries Grits		Tyfry Beds
			Church Bay Tuff		
	Gwna Group			Gwna Beds (sedimentary)	Gwna Beds (volcanic)
	Fydlyn Group				
	The Gneisses				

The first major revision of Greenly's work was carried out by Shackleton (1954, 1969, 1975), who introduced the term "*Monian Supergroup*" for the metasedimentary sequence exposed on Anglesey and the Llyn Peninsula. Shackleton (1975) recognised broad facies changes within this supergroup and implied that they: **(i)** record a progressive shallowing of the basin; and **(ii)** are consistent with the deepening of the basin towards the southeast, with a source of detritus to the northwest. Shackleton (1954) interpreted the typically narrow transitions between rocks of differing metamorphic grade at various localities on Anglesey and the Llyn Peninsula as being due to rapid prograde metamorphism. This "*prograde metamorphic transition*" model was applied to the gneiss and granitic rocks of central Anglesey, which were interpreted by Shackleton (1954, 1969) as having been derived from the lower grade Monian metasedimentary rocks. This model was contested by Baker (1969) who recognised that a number of the key localities, referred to by Shackleton (1969) in support of this model, actually represented mylonitic shear zones which juxtapose rocks of different metamorphic grade. This fundamental observation removed the need to establish relative age relationship(s) between the three main units of the Mona Complex.

The advent of plate tectonic theory in the 1960's to early 1970's saw a renewed interest in the geology of the Mona Complex. The potential significance of the Monian blueschists, mélange, serpentinites, gabbros and associated volcanic island-arc related rocks was recognised by several workers, most notably Thorpe (1972, 1975, 1979), Wood (1974) and Maltman (1977, 1978, 1979). As a result, the Mona Complex became viewed as recording the presence of a late Precambrian subduction system involving plate convergence towards the south-east, beneath southern Britain (Thorpe, 1972, 1975; Wood, 1974). In this model, the volumetrically restricted mafic and ultramafic rocks contained within the metasedimentary rocks of the New Harbour Group, and exposed on Holy Island, were interpreted as part of a tectonically emplaced ophiolitic assemblage (Thorpe, 1972, 1975, 1979; Wood, 1974; Maltman, 1977, 1978, 1979).

In a controversial publication, Barber and Max (1979) challenged the previously held views of Monian geology by suggesting a radical reinterpretation of the Monian Supergroup (Shackleton, 1969, 1975; after Greenly, 1919) and arguing for a Cambrian, rather than Precambrian, age for at least part of the Mona Complex. Barber and Max (1979) erected a tectonostratigraphy for the Monian Supergroup, identifying a number of major tectonic breaks (thrusts) separating the main units within this metasedimentary sequence (Table 2). They considered the predominantly pelitic and semi-pelitic rocks of the New Harbour Group to have been deformed within a subduction zone, prior to their tectonic emplacement upon the undeformed South Stack Group. This interpretation was contested by several workers, who emphasised the similarity between the polyphase deformation history recorded by the pelitic units within the South Stack Group and that of the New Harbour Group (Wood, 1979; Powell, 1979; Maltman, 1979; Gibbons, 1979; Kohnstamm, 1979). The apparent differences in the style and intensity of deformation recorded by the South Stack and New Harbour groups was considered to have been governed by gross lithological contrasts between these two units (Wood, 1979; Powell, 1979; Maltman, 1979; Gibbons, 1979; Kohnstamm, 1979; Cosgrove, 1980; Phillips, 1989, 1991b).

Table 2. Tectonostratigraphy for the Monian Supergroup proposed by Barber and Max (1979).

<table>
<tr><th>Tectonic unit</th><th>Group</th><th>Formation</th><th>Age</th></tr>
<tr><td rowspan="7">Cemlyn Unit</td><td>Llanvirn shales</td><td></td><td rowspan="2">Ordovician</td></tr>
<tr><td>Arenig grits</td><td></td></tr>
<tr><td colspan="3">Unconformity</td></tr>
<tr><td>Gwna Mélange (2)</td><td></td><td rowspan="4">Cambrian</td></tr>
<tr><td>Greywacke Group (Skerries Group)</td><td></td></tr>
<tr><td>Gwna Mélange (1)</td><td></td></tr>
<tr><td>Church Bay Tuff</td><td></td></tr>
<tr><td colspan="4">Thrust/unconformity</td></tr>
<tr><td>New Harbour Unit</td><td>New Harbour Group</td><td></td><td>?</td></tr>
<tr><td colspan="4">Thrust</td></tr>
<tr><td rowspan="3">South Stack Unit</td><td rowspan="3">Holy Island Group</td><td>Rhoscolyn Formation</td><td rowspan="3">?</td></tr>
<tr><td>Holyhead Quartzite Formation</td></tr>
<tr><td>South Stack Formation</td></tr>
</table>

The increasing recognition of ductile fault rocks on Anglesey and the Llyn Peninsula, commonly occurring in subvertical shear zones that separate radically different rock units, led directly to the application of the suspect terrane concept to the Mona Complex (Gibbons, 1983, 1987, 1989). Gibbons (1987, 1989) recognised the presence of sinistral, transcurrent kinematic indicators in one of the most prominent of these shear zones, the Berw Shear Zone, in south-eastern Anglesey. Gibbons (1989) concluded that the Mona Complex could be subdivided into at least four suspect terranes, the boundaries of which are all tectonic. The four terranes are: **(i)** the Sarn Complex of the Llyn Peninsula; **(ii)** the blueschist belt exposed in southeastern Anglesey; **(iii)** the Coedana Complex of central Anglesey; and **(iv)** a thick sequence of low-grade metasedimentary rocks and mélange, the Monian Supergroup (Shackleton, 1975), which crops out extensively across Anglesey and the Llyn Peninsula. The granitic and gneissose rocks of the Sarn Complex are interpreted as representing the north-western edge of the Avalonian basement exposed elsewhere in south and west Wales, and central England (Gibbons, 1989). Gibbons (1987, 1989) concluded that the Monian blueschists, and their host schistose metasedimentary rocks, represent a sliver of exotic material caught up within early transcurrent movements along the Menai Strait Fault System. The Coedana Complex, which includes the c. 614 Ma muscovite-garnet Coedana Granite (614 ± 4 Ma, U-Pb zircon; Tucker and Pharaoh, 1991) and a suite of meta-mafic, granitic and pelitic gneisses, may have formed an older basement to the Monian Supergroup. Metamorphism of the amphibolite facies gneisses within the Coedana Complex has recently been dated at 666 ± 7 Ma (U-Pb zircon; Strachan *et al*., 2007). The suspect terrane model emphasises the importance of brittle and ductile fault rocks within the Mona Complex and places special significance on the marked contrasts in geology across these major tectonic boundaries. The problem then became one of examining these boundaries in detail to obtain new data to evaluate the tectono-metamorphic histories of the proposed suspect terranes to test whether geological connections can be established across these boundaries. Recently, Strachan *et al*. (2007) have shown that metamorphism of the Coedana Complex gneisses is similar in age (c. 666 Ma) to that of Malverns Complex of southern Britain, arguing that both crustal blocks share a similar tectonothermal history. They suggests that the Coedana and Malverns complexes represent part of the same basement complex that was later interleaved with subduction zone components during the latest Neoproterozoic to earliest Cambrian in response to transcurrent fault movements along the north-west margin of Avalonia (c.f. Gibbons and Horák, 1996). Strachan *et al*. (2007) argue that, if this interpretation is correct, then there is no need to view Anglesey as being a ‘suspect terrane’ relative to the rest of Avalonia.

2.1.1 Monian Supergroup

Rocks belonging to the Monian Supergroup (Shackleton, 1975), the “*Bedded Succession*” of Greenly (1919) (Table 1), crop out extensively on Anglesey and the Llyn Peninsula. Shackleton (1969, 1975) subdivided this metasedimentary sequence into four main groups overlain by an acid volcanic formation (Table 3).

Table 3. Lithostratigraphy of the Monian Supergroup proposed by Shackleton (1954, 1969, 1975).

	Group	Formation	Estimated thickness
Monian Supergroup		Fydlyn Formation	50 m
	Gwna Group		3000 m
	Skerries Group	Skerries Grits Formation	500 m
		Church Bay Tuffs Formation	
	New Harbour Group		2000 m
	South Stack Group	Rhoscolyn Formation	1400 m
		Holyhead Quartzite Formation	
		South Stack Formation	

Shackleton, with the aid of way up evidence (e.g. graded bedding, cross-lamination), was able to demonstrate that the South Stack Group was in fact the oldest exposed unit and, therefore, inverted Greenly’s original succession (Table 1). Subsequently, Barber and Max (1979) argued for the presence of major thrusts separating the South Stack and New Harbour groups, and between the New Harbour Group and the remainder of the Supergroup (Table 2). However, a formal definition of the constituent groups within the Monian Supergroup had yet to be published (see Greenly 1919; Shackleton, 1969, 1975; Barber and Max, 1979, Gibbons, 1983). This was partially addressed by Phillips (1989, 1991a), who made the first attempt to formalise the lithostratigraphy of the Monian Supergroup, subsequently refined by Howells (2007) (Table 4) (also see Gibbons and Ball, 1991; McIlroy and Horák, 2006). The Monian Supergroup was generally considered to be late Precambrian to early Cambrian in age (Greenly, 1919; Crimes and Dohnau, 1969; Shackleton, 1975, Barber and Max, 1979; Muir *et al*., 1979) with the unconformable Arenig overstep sequence (Beckly, 1987) providing the only real age constraint.

Tietzsch-Tyler and Phillips (1989) correlated the metasedimentary rocks of the Holy Island Group with the lithologically and sedimentologically similar Cahore Group of south-east Ireland, suggesting a completely Cambrian age for the Monian Supergroup; an interpretation which has been confirmed by the detrital zircon study of Collins and Buchan (2004).

The simplest interpretation of Monian Supergroup lithostratigraphy is in terms of three principal groups: the Holy Island, New Harbour and Gwna groups (Table 4). Neither the stratigraphic base or top of this Supergroup is exposed. The **Holy Island Group** (c. 1000 m) is the lowest unit and is further divided into the South Stack, Holyhead and Rhoscolyn formations (Phillips, 1989, 1991a; Howells, 2007). The group comprises a sequence of metamorphosed (greenschist facies) and polydeformed, turbiditic (T_{abcde}, T_{abc} and T_{bcde}) metasandstones, metasiltstones, and metamudstones (pelites), interpreted as having been deposited by a prograding (towards the west/north-west), sand-rich submarine fan system (Phillips, 1989, 1991a). The locally thick orthoquartzites (e.g. the Holyhead Quartzite) within this sequence are interpreted as major channel-fill deposits within a mid- to inner-fan setting, which transported mature quartz-rich detritus from a relatively shallow marine environment, deeper into the basin. Bimodal palaeocurrent current evidence from the Holy Island Group record both lateral and axial transport within a north-east to south-west trending basin (Wood, 1974; Phillips, 1989, 1991a), with a primary source of detritus from the south-east. Detrital zircons populations within the metasandstones of the South Stack and Holyhead formations have yielded a depositional age of 501 ± 10 Ma (Collins and Buchan, 2004) for the Holy Island Group. Strachan *et al.* (2007) noted that the age range of detrital zircons within the South Stack and Holyhead formations is comparable to that obtained from the Coedana Complex; the latter may, therefore, have formed part of the source terrane for these quartzofeldspathic metasedimentary rocks. Correlation of the Holy Island Group with the Cullenstown Formation (Crimes and Dohnau, 1969; Bennett *et al.*, 1989; Bruck and Vanguestaine, 2004) and an enlarged Cahore Group (Tietzsch-Tyler and Phillips, 1989) suggests that this turbidite fan system extended to the south-west, linking the Monian Supergroup to the Late Precambrian/Lower Palaeozoic geology of south-east Ireland (Phillips, 1991a).

Table 4. Revised lithostratigraphy for the Monian Supergroup based upon Phillips (1989; 1991a) and incorporating the amendments of Howells (2007).

Group	Formation	Thickness	Type section	Boundaries
Gwna Group		3000 m	Llanbadrig [SH 375 946]	Top – not exposed Base – gradational (Gibbons and Ball, 1991)
New Harbour Group	**Skerries Formation**	200-300 m	The Skerries [SH 260 940]	Top – gradational into the Gwna mélange (Greenly, 1919) [SH 3000 915; SH 315 907] Base – gradational
	Lynas and Bodelwyn formations	Northwestern Anglesey 1000-2000 m		Top – gradational into the Gwna mélange (Gibbons and Ball, 1991) Base – not exposed, possibly tectonic
		Southwestern Anglesey 2000-3000 m	Port-y-Post [SH 2436 7600] to Bwa Du [SH 2600 7625]	Top – faulted contact with Skerries Formation [SH 2890 8580] Base – tectonised sedimentary contact with the Holy Island Group [SH 2700 7464; SH 2420 8035; SH 2362 8370]
Holy Island Group	**Rhoscolyn Formation**	300 m	Rhoscolyn between [SH 2647 7495] and Porth-y-Corwgi [SH 2700 7470]	Top – tectonised sedimentary contact with the New Harbour Group Base – conformable upon the Holyhead Formation [SH 2647 7495]
	Holyhead Formation	500 m	Bwa Du [SH 2600 7640] to Porth Saint [SH 2595 7590]	Top – corresponds to the top of the Holyhead Quartzite [SH 2647 7495] Base – conformable upon the South Stack Formation [SH 2048 8230; SH 2580 7544]
	South Stack Formation	400 m	Penrhyn Mawr [SH 2110 8062]	Top – conformable with the overlying Holyhead Formation Base – not exposed

The **New Harbour Group** comprises a thick sequence (estimated thickness c. 2000-3000 m) of polydeformed and metamorphosed (greenschist to sub-greenschist facies) chlorite-mica-schists and phyllites, which preserve very little evidence of the original lithologies or depositional environment. However, in northern Anglesey, near Amlwch, the sequence is less deformed and metamorphosed (sub-greenschist facies). In this area, the lower mudstone-rich sequence of the Bodelwyn Formation grades upwards into the fine- to coarse-grained volcaniclastic metasandstones of the Lynas Formation; the latter containing coarsening and thickening upward cycles (Kohnstamm, 1982) suggesting that the New Harbour Group was also deposited in a turbidite fan system (Shackleton, 1969, 1975; Kohnstamm, 1982; Phillips 1989, 1991a). However, in contrast to the Holy Island Group, sandstone deposition was apparently dominated by massive, structureless, grain-flows or fluxo-turbidites (Kohnstamm, 1982; Phillips, 1991a).

Rather than representing a separate group, the poorly-bedded volcaniclastic metasandstones (composed of predominantly andesitic detritus) of the Skerries Formation (Kohnstamm, 1980, 1982; Phillips, 1989) represent a more proximal, mid- to inner-fan facies within the New Harbour Group turbidite system (Greenly, 1919; Phillips, 1989, 1991a ; Howells, 2007). Mineralogical and geochemical studies have shown that the dissected volcanic arc provenance of the New Harbour Group contrasts markedly with the quartzose continental provenance of the underlying Holy Island Group (Phillips, 1989; 1991a). The geochemical characteristics of the New Harbour Group metasedimentary rocks are similar to those of sandstones deposited in a continental island-arc setting. The sand-dominated nature of the Holy Island and New Harbour group turbidite fan systems, coupled with their complex provenance and depositional setting, led Phillips (1989, 1991a) to suggest that these metasandstone-dominated sequences were deposited in a tectonically active, possibly strike-slip basin.

Deformation of the Holy Island Group and, to a lesser extent, New Harbour Group has been the focus of several detailed studies (Cosgrove, 1980; Lisle, 1988; Phillips, 1991b; Roper, 1992; Hudson and Stowell, 1997; Stowell *et al.*, 1999; Starkey, 2002; Treagus, *et al.*, 2003; Hassani *et al.*, 2004). These studies have largely focused upon the small-scale structures associated with the development of the Rhoscolyn Anticline (Holy Island). Both polyphase, comprising a NW-directed D1 event followed by SE-directed D2 (Cosgrove, 1980; Treagus, *et al.*, 2003; Hassani *et al.*, 2004), and single, progressive SE-directed deformation (Phillips, 1991b) models have been erected to explain the often complex deformation structures developed within the South Stack and New Harbour groups. In both models the Rhoscolyn Anticline is considered to be of D2 age. Deformation in the structurally/stratigraphically lower parts of the Monian Supergroup is considered to be pre-Arenig in age, based upon the presence of the Arenig overstep sequence on Anglesey. Hassani *et al.* (2004), however, concluded that the D2 event recorded by the Monian Supergroup correlates with the SE-verging Caledonian deformation affecting the Monian units and Ordovician cover sequence exposed elsewhere on Anglesey. The presence of deformed Monian-derived fragments (schist, jasper, metabasalt and volcanic rock) within the coarse-grained sandstones at the base of this overstep sequence (Bates, 1972; Phillips 1989), however, suggests that the Monian Supergroup was deformed prior to the deposition of this sedimentary sequence; hence, providing indirect evidence for a pre-Arenig age for the deformation of the Monian Supergroup. Consequently, the actual age of this deformation is not constrained and its relationship(s) to the deformation events effecting the Lower Palaeozoic cover sequence on Anglesey and similar aged sequences in mainland Wales, remains poorly understood.

The New Harbour Group contains within it at least two horizons of arc-related metabasalts (Thorpe *et al.*, 1984; Phillips, 1989) and a horizon of serpentinised ultramafic rocks and metagabbros (Maltman, 1977; Phillips, 1989). The geochemical signature of these basaltic volcanic rocks and postulated ophiolitic affinity of the ultramafic and gabbroic rocks have been used in support of a subduction related setting for the Monian Supergroup (Thorpe, 1972, 1975, 1979; Wood, 1974; Thorpe *et al.*, 1984). The interpretation of the ultramafic and gabbroic rocks as part of a '*Monian ophiolite*' was, however, contested by Maltman (1977, 1978, 1979) and later by Phillips (1989) (see below).

The New Harbour Group is in turn overlain by the **Gwna Group** (Table 4). The Gwna Group is dominated by a regional-scale mélange which contains allochthonous clasts, from a few millimetres to several kilometres across, of a wide range of igneous (e.g. MORB basalt, granite) and sedimentary rocks (e.g. orthoquartzite, stromatolitic limestone, oolitic limestone, mudstone, volcaniclastic sandstone) set in a sand- to mud-grade matrix. Muir *et al.* (1979) identified the stromatolitic limestone olistoliths as being of the Vendian-Cambrian form *Georginia*, as well as Lower Cambrian age microfossils within the deepwater sediments intercalated with the basalt lavas of Llanddwyn Island, placing a maximum age constraint of Lower Cambrian on the formation of the mélange. The Gwna mélange has also recently been reported to contain olistoliths of hemi-pelagic mudstone containing ice-rafted debris (dropstones) (Kawai *et al.*, 2008). Unpublished work on the Gwna Group has suggested that the mélange also contains olistoliths of much younger Ordovician (Caradoc or younger) strata. However, previously published work has shown that the Gwna Group is unconformably overlain by the basal conglomeratic units of the Ordovician (Arenig) overstep sequence on Anglesey (e.g. Bates, 1972; Ruston *et al.*, 1999). Consequently, the presence of Ordovician-aged olistoliths within the Gwna mélange has yet to be substantiated. A clast of muscovite-garnet granite extracted from the mélange has yielded Rb-Sr muscovite ages of 621 ± 6 Ma and 619 ± 6 Ma (Horák *et al.*, 1996); i.e. comparable to the age of the Coedana Granite and Sarn Igneous Complex. Adjacent to the contact with the Gwna Group, the New Harbour Group is highly disrupted, with this disruption being interpreted by Gibbons and Ball (1991) as having occurred when the rocks were still only partially lithified. Although a crude, ghost-like internal stratigraphy can be locally recognised within the Gwna mélange (based upon the variation in the dominant clast lithology), no formal/mappable division of the group has yet been established (see Greenly, 1999; Barber and Max, 1979; Gibbons, 1980, 1983; Howells, 2007).

Greenly (1919) considered the mélange to be a tectonic breccia, but Shackleton (1969, 1975) thought that its distribution, the largely unstratified nature of the matrix, and its relatively sharp contacts were consistent with an olistostrome or slide breccia. The emplacement of the Gwna Group was clearly initiated by a series of catastrophic events, possibly in response to tectonically induced instability during the closure of the Monian sedimentary basin. The estimated thickness of the group (c. 3000 m) means that its generation is likely to have occurred in response to a series of failures, rather than one single 'high-magnitude' event. It has been proposed that there were two major collapse events in the emplacement of the mélange and that 'flow' was directed to the east (Howells, 2007), although this is difficult to substantiate. The wide range in composition of the olistoliths indicates sediment characteristics of an active plate margin and rocks of a possible 'exotic' oceanic origin. The presence of some Coedana Complex-like granitic clasts within the mélange suggest that this complex was exposed at the time of the disruption and, consequently, that the Gwna Group was deposited after 614 Ma.

Despite the fact that the sedimentology of the Monian Supergroup is relatively poorly understood, a number of plate tectonic models, commonly involving late Precambrian subduction, have drawn heavily upon interpretations of the Monian metasedimentary rocks and their included meta-igneous rocks (see Thorpe *et al.*, 1984; Wood, 1974; Gibbons and Horák, 1996; Kawai *et al.*, 2006; Kawai *et al.*, 2007). The arc-related metabasalts (Thorpe *et al.*, 1984; Phillips, 1989) and serpentinised ultramafic rocks and metagabbros (Maltman, 1977, 1978, 1979; Phillips, 1989) within the New Harbour Group, in particular, have been used in support of a subduction related setting for the Monian Supergroup (Thorpe, 1972, 1975, 1979; Wood, 1974; Thorpe *et al.*, 1984). The validity of the interpretation of the ultramafic and gabbroic rocks as part of a *'Monian ophiolite assemblage'* was contested by Maltman (1977, 1978, 1979), who interpreted these volumetrically restricted rocks as a deformed intrusive body. However, all of the contacts between the metabasaltic volcanic and ultramafic rocks and the host metasedimentary rocks are either highly tectonised, faulted, or hopelessly obscure. The primitive tholeiitic to locally boninitic geochemical signature of the basaltic volcanic rocks, typical of intra-oceanic plate subduction (Thorpe *et al.*, 1984; Phillips, 1989), contrasts markedly with the calc-alkaline, continental volcanic arc provenance of the host New Harbour Group sedimentary rocks (Phillips, 1989; 1991a). Consequently, Phillips (1989), suggested that these highly altered and disrupted meta-igneous bodies may represent olistoliths within the New Harbour Group. If correct, this would suggest that the meta-igneous rocks contained within the New Harbour Group represent the dismembered remains of an older (?Neoproterozoic/Avalonian) ophiolitic/oceanic island-arc complex. In the 'subduction model' the turbiditic metasandstones of the Holy Island and New Harbour groups, coupled with the presence of the regional-scale mélange (Gwna Group) were considered to represent part of an accretionary prism (Thorpe, 1972, 1975, 1979; Wood, 1974; Thorpe *et al.*, 1984; Kawai *et al.*, 2006). Phillips (1989, 1991a), however, found no unequivocal evidence to support the deposition of the Holy Island and New Harbour groups within a trench system associated with south-easterly directed plate subduction, favouring their deposition within an active continental margin setting, possibly within a strike-slip controlled basin. Consequently, the depositional setting of the Monian Supergroup within the broader context of the Lower Palaeozoic of the Caledonian orogen remains unequivocal.

2.1.2 The Coedana Complex

The poorly exposed Coedana Complex of central Anglesey comprises a polydeformed and metamorphosed sequence of amphibolite facies sillimanite and garnet-bearing pelitic gneisses and meta-mafic rocks, intruded by the Coedana Granite (Greenly, 1919; Horák, 1993). The gneisses are coarse-grained, foliated rocks with pale and dark coloured layers which Greenly (1919) referred to as 'acidic' and 'basic' respectively. They consist mainly of (locally) migmatitic metasedimentary and metabasic gneisses with a locally developed, more schistose facies containing meta-limestone, graphitic schist and orthoquartzite. Mineralogical assemblages indicate that the rocks were metamorphosed under middle to upper amphibolite facies conditions (Horák, 2000). These peak metamorphic conditions are recorded by the mineral assemblages: sillimanite ± garnet ± biotite ± oligoclase ± quartz ± ilmenite within the pelitic migmatitic gneisses; and hornblende ± oligoclase ± biotite ± garnet ± clinopyroxene ± ilmenite ± quartz ± apatite ± titanite in the metamafites. The age of this metamorphic event has been dated at 666 ± 7 Ma (U-Pb zircon) by Strachan *et al*. (2007). Shackleton (1954, 1969) concluded that these gneisses were formed as a result of prograde metamorphism of the lower grade Monian Supergroup metasedimentary rocks; a model contested by Baker (1969) who recognised that the margins of the Coedana Complex are tectonic. Limited whole-rock geochemical data obtained by Phillips (1989) indicates that the metabasic gneisses within the Coedana Complex can be clearly discriminated from the New Harbour Group metabasalts, and that they show characteristics of basaltic rocks emplaced/erupted in a continental, possibly subduction-related setting.

The Coedana Granite is undeformed and, therefore, post-dates the formation of these polydeformed metamorphic rocks. Published U-Pb zircon ages indicate that crystallisation of the granite took place at 614 ± 4 Ma (Tucker and Pharaoh, 1991); a slightly younger, but less reliable, Rb-Sr whole-rock isochron age of 603 ± 34 Ma was obtained for Coedana Granite by Beckinsale and Thorpe (1979). Greenly (1919) recognised four facies within the intrusion: **(1)** the pink coloured, 'normal' granite which contains chloritic aggregates; **(2)** an orthoclase porphyritic granite; **(3)** a finer grained muscovite granite which forms a marginal facies to the main granite body; and **(4)** a suite of fine-grained granitic veins. Although Greenly (1919) concluded that the granite intruded into and locally merged with the gneisses, clear relationships to support this interpretation are not exposed. A fine-grained hornblende-facies hornfels and quartzite in contact with, and as xenoliths within, the granite indicate that the host gneisses were in fact relatively cool at the time of intrusion. The presence of xenoliths of this hornfels within the granite further suggests that it may have actively intruded into and deformed/disrupted its own thermal aureole.

The north-western boundary of the Coedana Complex is apparently formed by the Llyn Traffwll Fault, which juxtaposes the high-grade gneisses against the much lower grade (greenschist facies) metasedimentary rocks of the New Harbour Group. However, these high-grade metamorphic rocks may extend farther to the north-west, forming the basement to a Monian Supergroup cover sequence (Phillips, 1989). The Llyn Traffwll Fault has accommodated a prolonged history of movement, with sedimentological evidence indicating that it formed a positive topographic feature which locally controlled the deposition of the Arenig overstep sequence (Bates, 1972). Earlier brittle movement along the fault resulted in the development of a wide zone of cataclasite (Gibbons, 1983, 1989; Phillips, 1989). Gibbons (1989) and Howells (2007) conclude that cataclasis along the Llyn Traffwll Fault post-dated the deposition of this Ordovician cover sequence. However, Phillips (1989) found that these brittle fault rocks were solely derived from the quartzose gneisses and metamafites of the Coedana Complex, indicating that they are more likely to relate to a pre-Arenig phase of movement which probably occurred entirely within the Coedana Complex.

The south-eastern boundary of the Coedana Complex is marked by a wide ductile shear zone (Gibbons, 1983, 1989; Mann, 1986). This shear zone also deforms the south-eastern margin of the Coedana Granite and resulted in the tectonic interleaving of highly deformed elements of both the Coedana Complex and Gwna Group. Although this boundary is believed to represent a major 'terrane' boundary within the Monian Complex (Gibbons, 1983, 1989), the structural evolution, kinematics and original geometry of this complex shear zone are poorly understood. Strachan *et al*. (2007) have demonstrated that the age of metamorphism within the Coedana Complex is similar to that of the Malvern Complex farther to the south-east, concluding that the Precambrian gneisses of Anglesey probably evolved in close proximity to the Avalonian basement of southern Britain during the mid- to late Neoproterozoic. As a result, these workers argue that the Coedana Complex of central Anglesey is not a 'suspect terrane', but rather it represents the north-west extension of the Avalonian continental basement.

The gneissose and granitic rocks of the Coedana Complex have been correlated with a suite of similar lithologies present within the Precambrian Rosslare Complex (Max and Dhonau, 1971; Max and Long, 1985; Bennett *et al*., 1989; Murphy, 1990) of southeast Ireland (Gibbons, 1983). The Rosslare Complex occurs to the south-east of the Cullenstown Formation (correlated with the Holy Island Group by Tietzsch-Tyler and Phillips, 1989), with the latter having been interpreted as part of a deformed cover sequence to this basement complex (Bennett *et al*., 1989; Murphy, 1990). The age of emplacement of the Coedana Granite of central Anglesey is comparable to the c. 614 Ma U-Pb age obtained for the Padarn Tuff Formation of the Arfon Group of the Welsh mainland (Tucker and Pharaoh, 1991); although a slightly younger U-Pb age of 604 Ma has recently been obtained for an ignimbrite from this volcanic group (Compston *et al*., 2002). The similarities in ages between the Arfon volcanic rocks and Coedana Granite and led Tucker and Pharaoh (1991) to suggest a genetic relationship between this intrusion and the Arfon Group, minimising the importance of any transcurrent offset across the Menai Straits Fault Zone.

2.1.3 The Penmynydd Zone or Blueschist terrane

The *Penmynydd Zone* (Greenly, 1919) or *Blueschist terrane* (Gibbons, 1983; 1989; Howells, 2007) of southeastern Anglesey comprises a variably exposed belt of polydeformed metasedimentary rocks that contain lenses of metabasic igneous rocks. The fine-grained, micaceous schistose metapelites which dominate this belt contain disrupted lenses of quartzite, foliated metalimestone, metagabbro, metabasalt and graphitic schist (Greenly, 1919). The main focus of study within this belt, however, has been the variably preserved high-pressure – low-temperature blueschist facies metamorphic assemblages within metabasalts and associated metasedimentary rocks; most importantly the presence of blue amphibole (crossite) and lawsonite near to the eastern margin of the terrane (Gibbons 1981; Gibbons and Mann, 1983; Gibbons *et al*., 1985; Gyopari and Gibbons 1986; Horák and Gibbons, 1986; Kawai *et al*., 2006; Kawai *et al*., 2007; Treagus, 2007; Kawai, 2007). Although metamorphosed, these metabasaltic volcanic rocks retain the geochemical characteristics of MORB basalts (Thorpe, 1972, 1975, 1979; Thorpe *et al*., 1984; Phillips, 1989). The metamorphic grade and MORB geochemistry of these metavolcanic rocks have formed the major tenets supporting the existence of a Neoproterozoic subduction system in north Wales (Thorpe, 1972, 1975, 1979; Wood, 1974; Thorpe *et al*., 1984; Kawai *et al*., 2006; Kawai *et al*., 2007a and b). Analyses of $^{40}Ar/^{39}Ar$ and phengite mica data have yielded uplift ages of approximately 560-550 Ma for the blueschist facies metamorphic event, and 580-590 Ma for an earlier greenschist facies event, possibly associated with sea floor metamorphism (Gibbons *et al*., 1985; Gyopari and Gibbons 1986; Dallmeyer and Gibbons, 1987). Recent work by Kawai *et al*. (2006) on the mineral assemblages contained within the metabasaltic lavas has divided the Blueschist terrane and adjacent Gwna Group into three, gently easterly dipping zones separated by two isograds: **zone 1** - sub-greenschist facies (crossite isograd); **zone 2** - blueschist facies (barroisite isograd); and **zone 3** – epidote amphibolite facies. Kawai *et al.* (2006) suggest that these zones are folded by a major south-easterly dipping antiform which closes towards the north-west, with folding and metamorphism occurring in response to south-easterly directed plate subduction beneath Avalonia at around 560-550 Ma. The existence of this large-scale antiform was disputed by Treagus (2007), who also argued that relating the structure of the Anglesey blueschist belt to the geometry of a subduction-accretion complex was "*premature*" (for reply see Kawai *et al.*, 2007). The recently published detrital zircon study of Collins and Buchan (2004) has demonstrated that the Monian Supergroup, which includes the Gwna Group, was deposited during Cambrian to possibly early Ordovician and is, therefore, considerably younger than the tectonothermal event responsible for blueschist facies metamorphism. Consequently, the difference in age between blueschist facies metamorphism and deposition of the Gwna Group represent a major flaw in the 'subduction model' proposed by Kawai *et al.* (2006).

The western margin of the Blueschist terrane, where it is faulted against the Gwna Group, is formed by a subvertical zone composed of very fine-grained, mylonitic to phyllitic rocks, referred to as the Berw Shear Zone (Gibbons, 1983, 1987, 1989) or Berw Fault (Howells, 2007). Kinematic indicators developed within these ductile fault rocks record a sinistral transcurrent sense of movement, with the Berw Fault forming the most westerly strand of the Menai Strait Fault System (Gibbons, 1990). The eastern margin of the terrane is not exposed, but is likely to be formed by one of the major fault strands running down the Menai Straits. On the Llyn Peninsula an extension of one of the faults within the Menai Straits Fault System juxtaposes the Gwna Group against the Sarn Complex (see below). This fault is marked by mylonitic zones composed of steeply inclined, fine-grained recrystallised schist and phyllite.

2.1.4 The Sarn Complex

The Sarn Complex forms a narrow outcrop on the Llyn Peninsula where it separated from the Gwna Group, to the north-west, by a Llyn Shear Zone; the latter forming part of the Menai Strait Fault System (Gibbons, 1987; Howells, 2007). The Sarn Complex is unconformably overlain by lower Ordovician (Arenig) sedimentary rocks. The complex is mainly composed of variably foliated and xenolithic, calc-alkaline dioritic to granitic rocks (including the pale adamellitic Sarn Granite) which have been interpreted as representing part of the north-western edge of the Avalonian terrane (Gibbons, 1989; Howells, 2007). The petrology and geochemistry of the igneous rocks have been used to suggest that they were emplacement in a subduction-related arc setting (Horák, 1993; Horák *et al.*, 1996). A gabbro from within the complex has yielded an U-Pb zircon age of 615 ± 2 Ma (Horák *et al.*, 1996), comparable to that of the Coedana Granite of central Anglesey and the c. 614 Ma age obtained for the Padarn Tuff Formation of the Arfon Group of the Welsh mainland (Tucker and Pharaoh, 1991); although a slightly younger U-Pb age of 604 Ma (SHRIMP) has recently been obtained for an ignimbrite from this volcanic group (Compston *et al.*, 2002). Horák *et al.* (1996) concluded that the Neoproterozoic Sarn Igneous Complex formed during the same regional Arvonian arc-related magmatic event as the Arfon Group. These authors argued that the petrological differences between the Sarn and Coedana granitic rocks negates any direct correlation between the two plutonic suites, even thought they have similar ages.

2.2 ORDOVICIAN-SILURIAN SEDIMENTARY AND IGNEOUS ROCKS

In North Wales the Ordovician rocks crop out in a broad tract surrounding the Cambrian rocks of the Harlech Dome, and extend westwards across most of the Llyn Peninsula and onto Anglesey. Only the lower parts of the Ordovician succession are preserved on Anglesey, where they form an unconformable overstep sequence that places a minimum age constraint on the deposition and deformation of the underlying Monian Supergroup (see section 2.1). The Anglesey sequence lies in a is rather different structural situation to that exposed elsewhere in North Wales as it consists of the remnants of sandstones and mudstones deposited on a palaeo-high formed by the Irish Sea horst complex (Bevins *et al.*, 1992). It is thought to have been deposited during periods of marine high-stand, namely the Fennian Stage of the Arenig, the Llanvirn and the Costonian Substage of the early Caradoc (Rushton *et al.*, 1999). The sedimentary facies and faunas present within the sequence on Anglesey are different to contemporaneous rocks of the Welsh Basin, which Rushton *et al*. (1999) suggested provides support to the theory that Anglesey represents an independent terrane.

The Ordovician sequence on Anglesey is mainly exposed in a Y-shaped tract occupying the central and northern parts of the island, where it unconformably overlies the Precambrian rocks of the Coedana Complex and Cambrian Monian Supergroup. The northern boundary of the tract is formed by the Carmel Head Thrust; a low-angle, south-easterly directed brittle thrust fault which affects both the Monian Supergroup and younger Lower Palaeozoic cover sequence (Greenly, 1919; Bates, 1974; Barber and Max, 1979). Elongate slivers of Ordovician rocks also occur in central and northeastern Anglesey, with two small outliers occurring on the north coast at Gynfor. The inshore, transgressive facies of the late Arenig (Fennian, Beckly 1987) age sequence comprises the Carmel and overlying Treiorwerth formations. These locally conglomeratic, variably cross-bedded sandstones and interbedded siltstones, and the faunas they contain, were first reported by Greenly (1919) and subsequently described in detail by Bates (1972) and Neuman and Bates (1978). However, a coherent, mappable stratigraphy within the Ordovician succession on Anglesey remains to be established. The shallow-water brachiopod faunas present within the Carmel and Treiorwerth formations form part of the 'Celtic Province' and were interpreted by Neuman and Bates (1978) as having developed around a group of small islands developed on the Irish Sea Horst, at a time when Anglesey and the Welsh Basin were separated by a wide expanse of ocean. However, Beckley (1987) and Cope *et al.* (1992) disagree with this interpretation, arguing that Anglesey formed an integral part of the Welsh Basin.

Beckly (1987) concluded that after a relatively passive initial marine transgression, the Anglesey area foundered dramatically in response to fault-controlled subsidence. This accompanied the deposition of a thick sequence (up to 650 m) of conglomerates which dominate the Treiorwerth Formation. These debris flows thicken towards, and were apparently banked up against, the scarps formed during syn-sedimentary faulting (Beckley, 1987; Rushton *et al*., 1999). The conglomerates contain pebbles and cobbles of foliated chlorite-quartz-schist and jasper derived from the Monian Supergroup indicating that the latter metasedimentary sequence was deformed prior to the deposition of the Arenig overstep sequence (Bates, 1972; Phillips, 1989).

The Nantannog Formation of late Arenig (Fennian) to mid-Llanvirn (Abereiddian) age, comprises a sequence of sandy mudstones, sandstones and pebbly, coarse-grained sandstones which contain deeper water faunas, including graptolites. It rests directly upon the Carmel Formation and is interpreted as representing the lateral, deeper water equivalent to the Treiorwerth Formation. A thick (20 m), westerly-derived (Bates, 1972) slide-conglomerate within the Nantannog Formation (at its type locality) contains large (up to 0.6 m), subangular blocks of chlorite-quartz-schist, quartzite, granite, jasper and gneiss derived from the Monian Supergroup and Coedana Complex. This provides evidence for the Monian Supergroup and Coedana Complex having been juxtaposed/accreted next to each other, prior to late Arenig times, and furthermore indicates that these polydeformed and metamorphosed rocks were periodically exposed during the deposition of this overstep sequence. Fault-bound outliers of Ordovician sedimentary rocks occur within the Monian Supergroup on the north coast of Anglesey at Gynfor (Bates, 1972, Barber and Max, 1979; Ruston *et al.*, 1999). These outliers were described in detail by Greenly (1919) who assumed they were all Caradoc in age (*gracilis* Zone). Subsequently, however, Bates (1968) demonstrated the presence of Arenig (Porth Wen Group) as well as Caradoc rocks (Llanbadrig Group) within the outliers. The conglomerates of the Porth Wen Group (Torllwyn and Porth Cynfor Conglomeratic formations), which forms the lowest exposed unit within the outliers, rest unconformably upon the Gwna Group (Greenly, 1919) demonstrating that the latter is pre-Arenig in age. Both sequences possess a steeply dipping cleavage, indicating that they were deformed together after the mid-Ordovician (Barber and Max, 1979).

The Lower Palaeozoic volcanic rocks in northeast Anglesey form a small (c. 6 km x 1 km), elongate belt centred on Parys Mountain. The Parys Mountain Volcanics are composed of a bimodal association of basalt and rhyolite consisting up to 200 m of probable welded ash-flow and debris flow deposits, basic tuffs/lavas, rhyolite lavas and high level intrusions (Pointon and Ixer, 1980; Pointon, 1980; Southwood, 1984; Leat *et al.*, 1986). Geochemical studies (Leat et al., 1986) have shown that the rhyolites are highly evolved, high-K type subalkaline rocks. The associated basalts show geochemical characteristics of lavas erupted in a transitional environment between volcanic arc and within-plate settings. Leat *et al.* (1986) concluded that this basalt-rhyolite association developed within an extensional environment. Volcanism was associated with polymetallic sulphide mineralisation, with the high-level rhyolitic magmas possibly providing the heat to drive this hydrothermal system. These volcanic rocks overlie mudstones of Arenig to Llanvirn age (Pointon and Ixer, 1980), and are in turn, locally overlain by a Llandovery age mudstone sequence (Bates, 1972). These relationships have been used to suggest an Upper Ordovician age for the volcanic rocks, and support the conclusion that they were erupted in a submarine environment (Wheatley, 1971; Pointon and Ixer, 1980; Pointon, 1980). However, unpublished zircon dates indicate a Silurian age (ca. 430 Ma).

Preserved in opencast workings above the Parys Mountain volcanic rocks is a sequence of Silurian graptolitic mudstones. Greenly (1919) lists the faunas recovered from these rocks and assigns them to a range of early to mid Llandovery graptolite Biozones. However, the results of unpublished research by Leicester University have raised serious questions about the veracity of this earlier account. The recent discovery by the Leicester team of forms of *Monograptus lobiferous* with morphologies more closely resembling Scottish (Southern Uplands) examples of this taxon rather than those found in the Welsh Basin (Zalasiewicz, pers. comm.), has enormous implications for the structural evolution of this northern portion of the island.

Bates (1974) recognised two main deformation events effecting the Lower Palaeozoic rocks of Anglesey: an earlier phase, possibly during late Silurian times, that led to tight folding and the variable development of a slaty cleavage, culminating in reverse faulting; and a later, second phase, which post-dated intrusion of a suite of basic dykes, and is characterised by reverse faulting followed by normal faulting and mineralisation.

2.3 OLD RED SANDSTONE SUCCESSION (?LATE SILURIAN – EARLY DEVONIAN)

In comparison to the wealth of information available on the geology of the Mona Complex there has been very little written on the Old Red Sandstone sedimentary succession exposed on Anglesey. These red beds were first described in detail by Greenly (1919) who although recognizing the gross lithological similarities with the Lower Old Red Sandstone facies of south Wales and the Welsh Borders, viewed the succession on Anglesey as having been deposited in a separate northern basin. Allen (1965) carried out the first detailed sedimentological study of the red beds on Anglesey, dividing the succession into four formations; namely the Bodafon (oldest), Treath Bach, Porth-y-Mor and Treath Lligwy (youngest) formations (summarised by Davies, 2005).

The Bodafon Formation (3-45 m thick) rests unconformably upon gneisses of the Mona Complex and comprises a sequence of conglomerates and pebbly sandstones intercalated with minor red siltstone lenses. The conglomerates contain extraformational (exotic) clasts derived from the local Mona Complex basement. The Treath Bach Formation (≥ 130 m thick) is dominated by red calcrete-rich siltstones with minor extraformational conglomerates and thin pebbly sandstones. Pebbles within the conglomerates are mainly derived from the local Monian and Ordovician rocks. The Porth-y-Mor Formation (c. 347 m thick) is the thickest unit within the Devonian succession on Anglesey. It comprises a series of fining-upward cycles with each cycle comprising a tabular to trough cross-bedded basal conglomerate, overlain by cross-laminated to planar laminated, coarse- to fine-grained sandstone which passes upwards into muddy siltstone, with occasional beds of impure limestone (calcrete). Palaeocurrent indicators within the Porth-y-Mor Formation indicate that it was mainly deposited by currents flowing from the north-east. The Treath Lligwy Formation rests conformably upon the Porth-y-Mor Formation and is characterised by fine-grained sandstones (bioturbated) and siltstones.

Allen (1965) interpreted the Bodafon Formation as a alluvial fan sequence deposited along the margin of the Old Red Sandstone basin, which was flanked to the south-west by an upland area composed of Mona Complex and Ordovician rocks. These older rocks provided the main source of detritus for the alluvial gravels. Away from the basin margin, the Bodafon Formation interdigitates with the ephemeral playa lakes (non saline) and channelized fluvial deposits of the Treath Bach and Port-y-Mor formations, respectively. Allen (1965) interpreted the overlying Treath Lligwy Formation as having been deposited in perennial lakes with the reduction in calcrete and abundant bioturbation being equated with a high water table and less prolonged periods of subaerial exposure of the lake sediments.

Early palaeogeographical models suggested that the Old Red Sandstone succession on Anglesey was deposited in a narrow basin, which opening towards the north-east, was connected to the Midland Valley of Scotland (Greenly, 1919; Wills, 1952). This basin was thought to be structurally isolated from the sequences in south Wales and the Welsh Borders. Allen (1965), suggested that the Anglesey succession was deposited at the margin of a broad depositional tract connected to the main basin to the south and fed by rivers flowing from the northwest (also see Allen, 1974; Allen and Crowley, 1983; Bluck *et al.*, 1992; Davies, 2007).

The red-bed succession is strongly deformed with E-W trending fold axes and a penetrative northward dipping cleavage. Much of coastal sequence occupies the steeply-inclined to overturned south-facing limb of the Lligwy Bay Syncline, and dips steeply to the north. However, aside from Greenly's (1919) description and inclusion in a number of regional syntheses (see Treagus, 1992), there are no detailed accounts of the Old Red Sandstone structure, or of its contact relationships, and this currently precludes the structural comparison necessary to understand the palinspastic tectonic setting and timing of its deformation.

A major uncertainty regarding the Old Red Sandstone succession on Anglesey is it age. A mid-Devonian age has been suggested (Hurst *et al.*, 1978), but the presence of the folding and cleavage makes this unlikely (Allen and Williams, 1979; Hurst *et al.*, 1979). Allen (1965) attributed the pervasive deformation displayed by the Anglesey sequence to the widely recognised mid Devonian (late Caledonian-Acadian) tectonic event and correlated the Porth-y-Mor Formation to the Dittonian (Lochkovian) and Brecconian deposits of Pembrokeshire and the Welsh Borders (Allen, 1974b, 1977). However, due to the absence of fossil, or other direct dating evidence, the age of the sequence remains unproven and must be a key topic for future research.

2.4 CARBONIFEROUS SUCCESSION

The late Asbian to Brigantian (Dinantian) carbonate sequence on Anglesey comprises a sequence of bioclastic limestones and subsidiary terrigenous sandstones that were deposited along the margin of a broad shelf lagoon that covered most of North Wales, and lay to the north of the residual Caledonian upland (George 1958; Bates and Davies, 1981; Walkden and Davies, 1983; Davies, 1984; 1991; Davies *et al.*, 2004). The sequence is divided into five limestone formations resting upon a basal sandstone (Table 5; Davies, 1983). The bedded cherts, which cap the Anglesey succession, have previously also been viewed as Dinantian in age, but recent work on the North Wales Mainland (Davies *et al.*, 2004) now favours their inclusion in the Namurian Series (Silesian). The limestone succession represents the only significant thickness of strata preserved which accumulated at the landward margin of the shelf lagoon. The sequence is strongly cyclic, with over 20 transgressive-regressive shallowing-upward cycles having been recognised within this complex succession (see Table 5; Davies, 1983; Walkden and Davies, 1983). The tops of the individual cycles show evidence of penecontemporaneous subaerial exposure and weathering (Davies, 1991). The limestones immediately below these palaeokarstic surfaces display structures and fabric typical of calcretes (Davies, 1991). The cyclicity and the associated formation of the palaeokarst features has formed the main focus of research within the Carboniferous on Anglesey (Greenly, 1900, 1901; Bates and Davies, 1981; Walkden and Davies, 1983; Davies, 1983; 1984; 1991).

The palaeokarstic emergent surfaces are locally marked by the presence of spectacular (5 m deep, 3 m wide) sandstone-filled 'pipes' (Greenly, 1900, 1901; Baughen and Walsh, 1980). Walkden and Davies (1983) noted that these so-called 'pipes' are unlike normal late Dinantian palaeokarst features in North and South Wales as they are much deeper and filled by detrital sandstones, rather than by palaeosol. The sandstones were derived from the Precambrian and older Lower Palaeozoic rocks on Anglesey during periods of marine inundation and record deposition within a nearshore environment. However, during marine regressive phases this siliciclastic detritus was carried across the shelf via large (20 m deep, 200 m wide), anastomosing channels cut into the newly lithified carbonates (Bates and Davies, 1981; Davies, 1983; 1994; Walkden and Davies, 1983). Davies (1983, 1994) described the sequences which infill these palaeovalleys: fluvial conglomerate pass up into to estuarine mudstones containing flood-generated sheet sandstones, with wave reworked tops. These are capped by calcareous barrier-spit sandstones. The sandstone pipes appear to have developed on the terraced margins to these channel complexes, and Walkden and Davies (1983) concluded that this karstification was largely due to overbank solution rather than any climatic effects. It was further suggested that Dinantian cyclicity on Anglesey was probably driven by eustatic sea level change, now widely acknowledged to have a glacigenic origin (Davies *et al.*, 2004).

The Pennsylvanian (Upper Carboniferous) rocks of Anglesey have received little attention subsequent to Greenly's (1919) account, which has been relied upon in all subsequent descriptions (e.g. Calver and Smith, 1974). Greenly distinguished a sandstone-dominated 'Millstone Grit' from an overlying 'Coal Measures' succession and a yet younger 'Red Measures' sequence. He also provided details of workings and boreholes, which proved at least 14 coal seams, and of the fossil collections obtained from these rocks. The presence of the listeri Marine Band from a level in the middle of the 'Millstone Grit' confirms that much of this unit is Westphalian (Langsettian Stage) in age and non-marine mussel discoveries make it doubtful whether any of the overlying coal-bearing deltaic sequence extends into the younger Duckmantian Stage. The Anglesey 'Red Measures' are equivalent to the Plas Brereton Formation of the adjacent mainland (Howells *et al.*, 1985) and similarly record alluvial red-beds and brockram-style breccia deposition typical of the now widely recognised Warwickshire Group (Davies *et al.*, 2004 and references therein).

Table 5. The lithostratigraphy of the Dinantian succession on Anglesey (Davies, 1983; Walkden and Davies, 1983).

Age	Formation	Thickness	Minor Cycles
Brigantian	Red Wharf Cherty Limestone Formation	c. 55 m	Castell-Mawr beds
			Castell-Mawr sandstone (sheet sandstone)
			St. David's beds
			St. David's sandstone (sheet sandstone)
			Upper Dwlban beds
			Dwlban sandstone (channel sandstone)
			Lower Dwlban beds
			Thelwal sandstone (channel sandstone)
	Treath Bychan Limestone Formation	c. 96 m	Pen-y-Coed beds
			Betws sandstone (channel sandstone)
			Upper Dinas beds
			Benllech sandstone (channel sandstone)
			Lower Dinas beds
			Upper Morcyn beds
			Treath Bychan sandstone (sheet sandstone)
			Lower Morcyn beds
			Porth-y-Rhos beds
			Aber sandstone (channel sandstone)
			Porth-yr-Aber beds
			Eglwys Siglen beds
			Clan'r-Afon sandstone (channel sandstone)
Asbian	Moelfre Limestone Formation	c. 32 m	Upper Harbour beds
			Lower Harbour beds
			Upper Lookout beds
			Lower Lookout beds
			Dafarn sandstone (channel sandstone)
			Upper Helaeth beds
			Middle Helaeth beds
			Lower Helaeth beds
			Helaeth sandstone (channel sandstone)
	Flagstaff Limestone Formation	c. 38 m	Royal Charter beds
			Pedolau sandstone (channel sandstone)
			Pedolau beds
			Upper Moryn beds
			Lower Moryn beds
			Porth Forllwyd beds
			Forllwyd sandstone (channel sandstone)
			Lligwy beds
	Careg Onen Limestone Formation	c. 45 m	
	Basal Sandstone	up to 50 m	

2.5 QUATERNARY TO RECENT

In comparison to the relative wealth of published information on the bedrock geology there is very little published work on the Quaternary geology of Anglesey (Greenly, 1919; Embleton, 1964; Helm, 1971; Helm and Roberts, 1984; Harris, 1991; Hart, 1995; Campbell *et al*., 1995; Thomas and Chiverrell, 2003; Thomas and Chiverrell, 2007). The island's geographical position, coupled with the range of landforms and deposits left after ice retreated at the end of the last ice age, means that the superficial geology of Anglesey is key to understanding the evolution of a major ice sheet which occupied the Irish Sea during the late Devensian.

It has long been recognised that ice flowed south through the southern Irish Sea basin during the Late Devensian glaciation (Tiddeman, 1872; Jehu, 1909; Mitchell, 1960; 1972; Synge, 1964; Bowen, 1973a, b), merging with the Irish Ice Cap to the west and the smaller Welsh Ice Cap to the east to form the Irish Sea Ice Stream (Merritt and Auton 2000; Evans and O'Cofaigh, 2003; Hiemstra *et al*., 2006; Roberts *et al*., 2007). Since Tiddeman (1872), most workers have agreed that the advance and retreat of the Irish Sea ice was terrestrial. However, Eyles and McCabe (1989) argued that during the Late Devensian ice expanded down the Irish Sea basin when the floor was isostatically depressed, followed by a marine re-flooding event during deglaciation. These authors believed that this resulted in a rise in relative sea-levels up to 100 m OD, interpreting most of the outcropping glacigenic sequences below this height as glaciomarine in origin. Subsequent work around the Irish Sea basin (Harris, 1991; McCarroll, 1991, 1995, 2001, 2005; Scourse, 1991a, b; Austin and McCarroll, 1992; McCarroll and Harris, 1992; Harris *et al*., 1997; Thomas *et al*., 1989; 2004; Merritt and Auton, 2000; Hambrey *et al*., 2001; O'Cofaigh and Evans, 2001; Scourse and Furze, 2001; Evans and O'Cofaigh, 2003; Glasser *et al*., 2004; Etienne *et al*., 2006; Thomas and Chiverrell, 2007; Roberts *et al*., 2007) has rejected this model and the consensus view is that the deposits associated with the Irish Sea Ice Stream, including those on Anglesey, are principally terrestrial in origin.

Anglesey occurs at the eastern margin of the Irish Sea Ice Stream, where ice moving south-west met, coalesced with and ultimately decoupled from ice emanating from the Welsh Ice Sheet centred on Snowdonia (McCarroll, 2005; Thomas and Chiverrell, 2007). Thomas and Chiverrell (2007), utilising their own field mapping, BGS maps and memoirs, and the work of Embleton (1964) and Thomas *et al*., (1998) provided the first description of the geomorphology, stratigraphy, sedimentology and glacitectonic structures developed on Anglesey and the adjacent areas of mainland Wales and the Llyn peninsula. Thomas and Chiverrell (2007) divided Anglesey into three sediment-landform assemblages. Northern Anglesey is covered by landforms and sediments which these workers interpreted as representing an extensive subglacial depositional assemblage (assemblage zone 1). These deposits consist of a locally derived diamicton which is moulded into an extensive drumlin field (Greenly, 1919), which provides evidence for ice streaming towards the south-west. The geomorphological map published by Thomas and Chiverrell (2007) (see fig 2 of Thomas and Chiverrell, 2007) shows a potential relationship between the size and distribution of the drumlins and the underlying bedrock; a feature not recognised by these authors. Also on this published map is a clear, arcuate ridge of bedrock marking the line of the Carmel Head Thrust. Importantly, drumlins are absent over this feature suggesting that this bedrock structure may have exerted some influence on deformation and landform development within the glacier bed.

To the south-east, covering a tract across central Anglesey, is a zone comprising north-east to south-west trending ice-moulded bedrock ridges, which mimic the regional strike of the underlying Precambrian, Lower Palaeozoic and Carboniferous bedrock. This tract corresponds to the subglacial erosional assemblage (assemblage zone 2) of Thomas and Chiverrell (2007). The remainder of the island which borders the Menai Straits was assigned by Thomas and Chiverrell (2007) to their undifferentiated subglacial erosional and depositional assemblage (assemblage zone 3). This comprises a mix of elongate bedrock ridges, sporadic solitary drumlinoid landforms and deeply entrenched bedrock channels; the latter include the Menai Straits and the Bangor to Y Felinheli trench of Embleton (1964). On Anglesey, assemblage zone 3 also includes the proglacial outwash deposits which occur around Lleiniog (Helm and Roberts, 1984; Hart, 1985) and subglacial esker sediments near Llangefni (Thomas and Chiverrell, 2003). The sediment-landform assemblage zones recognised by Thomas and Chiverrell (2007) clearly reflect the underlying bedrock geology suggesting that it may have influenced processes occurring within the ice sheet or glacier bed, therefore, exerting a control on ice sheet dynamics along at least part of the eastern margin of the Irish Sea Ice Stream.

3 Key scientific questions

A number of key scientific questions remain concerning the geological evolution of Anglesey. These can be are briefly outlined in the following sections.

3.1 NEOPROTEROZOIC TO LOWER PALAEOZOIC TECTONIC EVOLUTION

The original detailed survey of Greenly (1919) coupled with information contained within a number of subsequent PhD theses (e.g. Kohnstamm, 1983; Phillips, 1989; Horák, 1993) should allow the production of a revised map of the geology of the Mona Complex with very little new mapping. The focus of additional fieldwork, therefore, should critically examine the relationships between the main lithostratigraphic and tectonic units present within the Mona Complex. The application of the suspect terrane concept to the Mona Complex represented a major advance in our approach to understanding the geology of Anglesey. It emphasised the importance of major ductile and brittle faults within the Mona Complex and placed special significance on the marked contrasts in geology across these tectonic boundaries. So the problem has become one of examining these boundaries in detail, and to unravel the tectono-metamorphic histories recorded by the proposed suspect terranes to test whether geological connections can be established across these boundaries. Although some connections have been established, for example linking the Coedana and Sarn complexes to the Avalonian basement geology of southern Britain, a number of key questions remain regarding the Neoproterozoic to Cambrian evolution of Anglesey:

- Although the detrital zircon study of Collins and Buchan (2004) has provided a maximum age constrained for the Holy Island Group, a major outstanding problem is the age of the remainder of the Monian Supergroup. The age of this sequence should therefore be established, as a key to providing the context by which to interpret the depositional and tectonothermal evolution of the Monian Supergroup;
- The provenance, depositional environment and tectonic setting of parts of the Monian Supergroup remain poorly understood. Even so, the turbiditic metasandstones of the Holy Island and New Harbour groups, coupled with the presence of the regional-scale mélange (Gwna Group), have been regarded as forming part of an accretionary prism developed during late Precambrian subduction. Alternatively, this metasedimentary sequence has been interpreted as having been deposited within a tectonically active strike-slip basin formed during the break-up of the northwestern margin of Avalonia during the Late Precambrian to Lower Palaeozoic. An integrated sedimentological and petrographic, geochemical and isotopic provenance study will be used to shed light on the depositional/tectonic setting of Monian Supergroup and provide valuable information on the source terrane(s) that contributed detritus into this tectonically active basin;
- The correlation of the Holy Island Group with the Cullenstown Formation and/or enlarged Cahore Group has been made, linking the Monian Supergroup to the Late Precambrian/Lower Palaeozoic geology of south-east Ireland. However, the relationship(s) between the Monian Supergroup and the Cambro-Ordovician sequence exposed on mainland Wales, or elsewhere within Avalonia (for example Newfoundland), remain unknown. Consequently, the proposed project should include a collaborative study focusing on placing the Monian Supergroup into the broader context of the Lower Palaeozoic basin evolution. This will allow a greater understanding of the

palaeogeography and tectonic drivers acting along the northern margin of Avalonia from the late Precambrian to early Ordovician within the Caledonian orogenic belt;

- Although the arc-related metabasalts and serpentinised ultramafic rocks and metagabbros contained within the New Harbour Group, and MORB-derived basalt olistoliths present within the Gwna Group, have been used in support of a subduction-related setting for the Monian Supergroup, questions regarding the origin and emplacement of these meta-igneous rocks remain unresolved. The relationships of these metavolcanic and intrusive igneous rocks to the host sediments of the Monian Supergroup must to clarified, in order to establish the existence and subsequent dismemberment of any postulated Avalonian volcanic arc/subduction complex within the Welsh sector of the Caledonian orogen;
- The major faults defining the boundaries of the various Monian 'terranes' have clearly recorded a prolonged history of movement which, in some cases, likely extended from the Neoproterozoic through to at least Carboniferous times. However, the age, original geometry and kinematics of the main ductile phases of movement along the major shear zones, for example the central Anglesey shear zone that forms the eastern margin of the Coedana Complex, remain poorly constrained. Understanding the history of movement recorded by these major structures will form the basis for building a more sensible palaeogeographical reconstruction of the Pre-Carboniferous evolution of Anglesey;
- The presence of blueschist facies, MORB-related metabasalts within the Penmynydd zone or blueschist terrane of southeastern Anglesey has been one of the major lines of evidence used to support the existence of a Neoproterozoic subduction system in north Wales. Although the boundaries between the blueschist terrane and the other Monian terranes are all tectonic (for example the Berw Shear Zone), the presence of these volumetrically restricted blueschists has driven tectonic interpretations of the remainder of the Mona Complex. The relationship(s) between these high-pressure – low-temperature meta-mafic rocks and the lower grade metabasaltic, meta-gabbroic and serpentinised ultramafic rocks found elsewhere within the Mona Complex therefore need to be critically re-examined as one of the strands of the project. This will allow a more robust tectonic model for this part of the Avalonian terrane to be established.

3.2 ORDOVICIAN STRATIGRAPHY AND BASIN EVOLUTION

- Although parts of the Ordovician sequence have been divided into their constituent lithostratigraphical units (Bates, 1972), this is still a rather disjointed view of the succession on Anglesey, resulting in the relatively 'preliminary' nature of the biostratigraphical and sedimentological correlations with more thoroughly studied Ordovician sequence of the Welsh mainland. A coherent, formal lithostratigraphy for the Ordovician succession on Anglesey needs to be established.
- The nature, age and origin of the melange of the north Anglesey coast require urgent investigation. The potential gains of such a study would be: **(a)** a radical revision of the Greenly map; and **(b)** new structural models for the region.
- Allied to this, the project should confirm of the Silurian age of the Parys Mountain volcanic succession and provenance of the overlying graptolitic sequence. Such an outcome would inform a re-appraisal of the tectonic setting and emplacement of these rocks.

3.3 OLD RED SANDSTONE AND CARBONIFEROUS BASIN EVOLUTION

- Preliminary field investigations have revealed the presence of rare, but as yet indeterminate fish remains as well as green reduction spots with the potential to yield unoxidised palynomorphs. A programme of targeted collecting may, therefore, offer the opportunity for biostratigraphical dating. The use of novel isotope dating strategies (heavy mineral suites and authogenic minerals) may also provide a means of more precise relative and absolute dating.
- A detailed appraisal of the structure of the Old Red Sandstone succession, and its contact relationships, allowing comparison with the structural styles displayed by adjacent Ordovician and older bedrock units needs to be done. The apparent overstep of the Ordovician succession preserved to the north of Mynydd Bodafon suggest that the structural analysis of this region will be key to understanding the nature and evolution of northern margin of the Lower Palaeozoic Welsh Basin and its successor Upper Palaeozoic cover sequences.
- Work on the mainland Upper Carboniferous successions has revealed the effects of large-scale dissolution and founding of the former Dinantian platform associated with the marked changes in sedimentary regime recorded by Namurian chert deposition. The former extent of Westphalian deposition and the destructive effects of additional erosional regional discontinuities present within the red-bed successions of the Warwickshire Group also warrant investigation.

3.4 QUATERNARY GLACIAL HISTORY AND BED CONDITIONS BENEATH THE IRISH SEA ICE STREAM

- The glacigenic sequence and landforms present on Anglesey are key to understanding the bed conditions along the eastern part of the Irish Sea Ice Stream during the late Devensian. A detailed geological map of these sediments and the associated landforms has yet to be published. The provisional map published by Thomas and Chiverrell (2007) clearly indicates that changes in bedrock geology are reflected in the glacial geomorphology. Such changes in the landforms developed beneath the Irish Sea Ice Stream probably reflect spatial and temporal changes in ice sheet dynamics. Consequently, the sediment-landform assemblages developed on Anglesey need to be investigated in detail to provide a greater understanding of the processes active beneath, and near the margin, of this major ice sheet during the initial glaciation and subsequent deglaciation of the Irish Sea Basin. The study of this ancient glacigenic system may shed light on the processes occurring beneath modern ice sheets and glaciers during the current period of rapid climate change.

4 Proposed Anglesey Project

The proposed Anglesey project should focus on five key areas.

Area 1 - will investigate the tectonic drivers and processes responsible for the assembly of Anglesey from the late Neoproterozoic through the Lower Palaeozoic (Cambro-Ordovician) and its position within the wider Avalonian/Caledonian orogen. It will involve:

- Examination of the key relationships between the various units within the Monian Supergroup, their relationship to the overlying Ordovician cover sequence, and the nature and origin of the Gwna mélange (or mélanges).
- Detailed isotopic and detrital zircon studies are also envisaged in an attempt to establish the depositional age of the New Harbour and Gwna groups.
- Geochemical and isotopic studies are proposed to establish the eruptive/intrusive setting of the various, possibly disparate, meta-basic igneous rocks contained Mona Complex as an aid to unravelling the often conflicting evidence for the existence of an active subduction system.
- A critical re-examination of the evidence for the origin and timing of accretion of the blueschist terrane, and its relationship(s) to the Monian Supergroup so as to build a more robust geotectonic model for the Neoproterozoic to Lower Palaeozoic evolution of the Mona Complex.
- Detailed macro- and microstructural studies in collaboration with the University of Portsmouth will allow the history of movement along the major fault systems which dissect the Mona Complex to be established. Such a study is key to unravelling the relationships between the various Anglesey 'terranes' and their dispersal and eventual accretion onto the northern margin of Avalonia.
- Collaboration with scientists from Birmingham, Portsmouth and Leicester universities and the National Museum of Wales.

Area 2 - examination of the sedimentology, stratigraphy and structural relationships of the Ordovician and Silurian sequences on Anglesey and its relationships with the Lower Palaeozoic succession of mainland Wales. This area will:

- Form the main focus of field work to be carried out by BGS geologists in collaboration with academics from Leicester University.
- Establish a formal, mappable stratigraphy for the Ordovician sequence on Anglesey.
- Accompanying biostratigraphical, sedimentological and provenance studies will provide a framework on which to erect a more robust correlation with equivalent aged strata exposed on the mainland and build a detailed model of Ordovician-Silurian basin evolution within the north Welsh sector of the Iapetus ocean.

Area 3 - will examine of the evolution and tectonic setting of the Old Red Sandstone (late Silurian – Devonian) and will require:

- A detailed structural analysis and the resourcing of a programme of traditional (biostratigraphical) and innovative (isotopic) techniques to establish the age and provenance of these rocks.

Area 4 - the development of successor Carboniferous basins on Anglesey and their relationships to the Upper Palaeozoic succession of mainland north-west Wales and, therefore, require:

- Establishment of, and differentiation between the key regional tectono-sedimentary events and global drivers during basin development.
- Access to off-shore seismic data.

- Improved dating and sedimentary logging of critical contacts: regional intra-Dinantian sequence boundaries; Dinantian/Namurian contact; major intra-Westphalian erosional surfaces.
- The use of innovative analytical techniques to investigate the origins and diagenesis of early Namurian chert successions is need to explore the complex chemical changes associated with the climate-linked demise and collapse of the North Wales Dinantian platform.

Area 5 - the glacial history of Anglesey in the context of the Irish Sea ice stream, focussing upon:

- The subglacial to ice marginal processes and landform development beneath this major ice sheet.
- The control of bedrock geology on subglacial and ice-marginal processes, and the potential for the reactivation of bedrock structures during glaciation and deglaciation.
- It is intended that this work will involve collaboration with scientists from Keele University and the setting up of a co-funded (BGS/University) PhD research project.
- One spin of of this research project will be the production of a new geomorphological/superficial map of Anglesey.

5 Deliverables

Potential deliverables from the proposed project could include:

- A number of high quality of peer-reviewed publications.
- A new geological map (solid and superficial) for Anglesey.
- A number of 'holistic' publications, such as 'the Geology of Anglesey', a geological field guide.
- Popular publications, such as a mapped based tourist guide to Anglesey.
- The acquisition of up-to-date geological information/data on which to base future commercial project bids, such as decommissioning of the Wylfa Head Nuclear Power Station, future mining exploration in the area of Parys Mountain.

6 Collaboration

The proposed project will both exploit and develop the geoscience knowledge base for northwest Wales and the northern sector of the Irish Sea, develop new consortium-based collaboration with university (e.g. Leicester, Portsmouth, Keele, Durham, Aberystwyth) and museum based (e.g. National Museum of Wales) researchers, and links with other geological activities within the region (for example Anglesey Geopark, Anglesey AONB, Aberffraw Bay/Holyhead Mountain/North Anglesey Heritage Coast projects). The project will also develop cross-theme collaboration within BGS, most notably Lower Palaeozoic, Upper Palaeozoic, Quaternary Earth Systems and Landscape Evolution teams.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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