STRUCTURAL ANALYSIS AND TECTONIC SIGNIFICANCE OF THE CARMEL HEAD THRUST BELT, ANGLESEY, NORTH WALES

Thesis submitted for the degree of
Doctor of Philosophy
at the University of Leicester

by

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July 2008
Abstract

The Carmel Head Thrust Belt (CHTB) is a major tectonic feature that records a complex history of polyphase deformation in N Anglesey, NW Wales, British Isles. This thesis tests the hypothesis that the CHTB developed by S-directed contraction that was subsequent to SE-directed ductile contraction (D1-D2) which is recorded elsewhere in western Anglesey, and on Holy Island. Also, this study tests whether the CHTB was formed as part of a Palaeozoic accretionary wedge complex. Detailed structural analysis and synthesis of data collected along three coastal transects in NE, N and NW Anglesey form the basis for the study. Major lithological units were examined in thin-section for petrographic textures, microstructures and deformation processes.

The macro- and the micro-structural data indicate that lithological units in N Anglesey underwent S-directed brittle contractional deformation (D3), associated with anchizonal metamorphism. Structures associated with brittle shortening cross-cut SE-directed folds and shear zones (D1-D2) recorded in the greenschist-grade New Harbour and South Stack groups schists and phyllites. D1-D2 occurred after early Cambrian time, synchronous with the Caledonian orogeny. The D3 event occurred during the early Devonian Acadian orogeny and involved southward propagation of the CHTB with a dextral component. Since Ordovician time and prior to Acadian thrusting, transtensional basins were developed which were then locally inverted within a S-vergent thrust wedge. D3 CHTB structures are cut by E-W and N-S extensional faults. The E-W normal faults are related to a Permo-Triassic extensional event and considered D4, whereas the N-S normal faults are considered D5 and formed subsequent to emplacement of a regional Tertiary dyke swarm that affected Anglesey and NW Wales.

The Gwna Group and Ordovician rocks were not affected by pre-D3 tectonism and regional metamorphism. The Gwna Group is affiliated with Ordovician rather than Mo- nian rocks. The Gwna mélange is the youngest unit of the Gwna Group, underlain by the Fydlyn beds and the Skerries Formation. The Gwna mélange contains crude stratigraphy, was originally olistostromal and became tectonosomal during CHTB development.

The CHTB in N Anglesey documents a major S-directed collisional event, whereas western, central and SE Anglesey record two separate and opposite dipping lower Palaeozoic subduction zones. The NW-dipping subduction zone is beneath NW Wales, and is in the same polarity as the SE-directed D1-D2 deformation. Central Anglesey represents a micro-continent, and the SE-dipping subduction zone was beneath southeastern-most Anglesey and NW Wales. The results of this study shed new light on the Palaeozoic amalgamation history of the British Isles.
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Acknowledgments

This project is funded by a scholarship granted from the Science Dept, Education College, King Abdul-Aziz University, Madinah, Saudi Arabia. Several colleges (including a faculty of Science) were established in 2004. These colleges are now part of Taibah University in Madinah. The Faculty of Science, Taibah University has been the body of funding for this project since 2004.

I would like to thank Dr. Dickson Cunningham for his valuable supervision, strong support and guidance during 2006-2008, who developed the project by his important recommendations and ideas. I also appreciate his help in the field, and his help in developing my scientific writing. I am also grateful to Dr. Steve Temperley for his supervision and support between 2004 and 2006, who deserves the credit for creating this project and choosing the study area. He also gave plenty of time during office, lab and fieldwork, and put his effort that lead to understanding the project’s problems. Also, I am thankful to the Dept. of Geology staff and students at the University of Leicester.

I am in debt to my family including my wife, my daughter Lojain, my son Abdulrahman and my youngest daughters Ayshah and Arwa for their patience, support and home environment. Many thanks to my family in Saudi Arabia especially my mother and sister for their family support and hoping Godspeed. Finally, I would like to say thanks to Dr. Muneer Khashoqji from the Faculty of Science, Taibah University in Madinah for his kind support and taking care as in a father and son relationship.
Chapter 1

Introduction

This thesis concerns the structural analysis and tectonic significance of the Carmel Head Thrust (CHTB), Anglesey, N Wales (Fig. 1.1). This study relies mainly on detailed fieldwork along coastal transects of northern Anglesey, as well as microscopic examination of key lithologies and their inherent structures. In this chapter, discussion of location, objectives, research methodology and geological background provide a framework of this thesis. This is followed by a review of thrust wedges and their tectonic setting, which provides a topical background for testing the thesis hypothesis that the Carmel Head Thrust Belt (CHTB) is part of a late Palaeozoic contractional wedge. The CHTB occupies northern Anglesey, and records S-directed brittle contractional deformation, subsequent to an earlier event of SE-directed ductile deformation. As a result, rock units showing signs of ductile deformation overprinted by the late CHTB brittle deformation in northern Anglesey and older rocks are tectonically interleaved with younger units that are deformed mainly by CHTB deformation. In this thesis, the poly-deformation history of the CHTB in the context of Palaeozoic subduction and collisional events is addressed.

1.1 The CHTB location and tectonic significance

Anglesey is located in the north-westernmost part of Wales (Fig. 1.2), in the British Isles (Fig. 1.1). Anglesey lies within a part of the British Isles that was affected by the Caledonian Orogen, also known as the Appalachian and Scandian Orogen in northern America and western Europe, respectively. This orogenic belt extends for some 7500 km from south-eastern USA through the British Isles to Scandinavia, Greenland and
Figure 1.1: Anglesey’s location (boxed) within the framework of main basement (Pre-Silurian) lithotectonic belts of the British Isles (after Treagus, 1992).
Svalbard, parallel to the Atlantic ocean (Fig. 1.3; Treagus, 1992; Van’Staal et al., 1998). The orogen was formed by the collision and amalgamation of the Laurentia, Avalonia and Baltica palaeo-continents. The Caledonian Orogen involved the docking of Laurentia against Avalonia and Baltica, and the closure of a palaeo-ocean known as the Iapetus Ocean (e.g. Woodcock & Strachan, 2000). The orogen in the British Isles is divisible into areas directly involved in the main Caledonian deformation and areas affected only by late Caledonian deformation (Fig. 1.1). The Caledonian rocks in Scotland with the late Caledonian rocks north of the Iapetus Suture are believed to be part of Laurentia, whereas the late Caledonian rocks south of the Iapetus Suture are regarded as Avalonian, in which the Iapetus Suture marks the boundary between the two domains (e.g. Carney et al., 2000).
Figure 1.3: Regional map showing the location of the British Isles within the Appalachian - Caledonian belt (after Treagus, 1992). The figure also shows the Laurentia and Baltica palaeo-continents. Map patterns correspond to different Appalachian-Caledonian domains. Key: B.I., the British Isles.

Treagus (1992) included Anglesey as part of the Precambrian rocks of the southern British Isles (Fig. 1.1). However, the geology and structures in northern Anglesey differ from the geology and structures seen in western, central and southern Anglesey (Fig. 1.4). The northern part of Anglesey contains lithological sequences faulted by the S-directed Carmel Head Thrust Belt that cuts northern Anglesey and trends east-west. The thrust belt was discovered, mapped and described by Greenly in his historical 1919 geological map of Anglesey and accompanying memoir. The geological history of N Anglesey, including rock types and deformation recorded there, has been historically correlated with the geological history of Lake District and Isle of Man (Fig. 1.1). The contractional deformation in the Lake District and Isle of Man is normally classified as late Caledonian (Jackson et al., 1995; Woodcock et al., 1999). Therefore, it is a working hypothesis that the contractional deformation in northern Anglesey is also related to late Caledonian terrane assembly.
Figure 1.4: Generalised geology map of Anglesey (diagram from Duff & Smith, 1992).
West Anglesey, including Holy Island (Fig. 1.5), contains SE vergent anticlines and synclines, with SE-directed thrust faults in between (e.g. Phillips, 1991b). On Holy Island, deformation involved more than one phase of folding and associated greenschist metamorphism, which is similar to the Caledonian deformation (Treagus, 1992). Therefore, it is likely that west Anglesey rocks likely record Caledonian deformation (Coward & Siddans, 1979). The central and southern Anglesey regions are underlain by Precambrian basement, which is comprised of granitic gneisses and blueschists, interleaved with Phanerozoic rock and cut by NE-SW strike-slip faults that run across the island (Gibbons et al., 1994; Kawai et al., 2006). Anglesey is bound to the south and separated from North Wales by two major strike slip faults; the Menai Strait and Berw faults which are believed to extend across the Irish Sea into southeastern Ireland (Fig. 1.2; Gibbons, 1987).
The northern (late Caledonian) part of Anglesey contains a discrete and separate domain of imbricate brittle thrust faults known as the Carmel Head Thrust Belt (Fig. 1.5). Previous work and data to be presented in this thesis indicate that the deformed belt along the northern coastline of Anglesey is younger and different in deformation style than deformed areas of western, central and southern Anglesey. Therefore, the CHTB is particularly interesting because it records a different deformational history that sheds light on the late Caledonian assembly of N Wales. In order to better understand the structural evolution and regional tectonics of the CHTB, three coastal transects were chosen to conduct a detailed structural analysis and produce a tectonic synthesis (Fig. 1.5). The first coastal transect is along the east coast from Point Lynas (4785 9340) in the north to Dulas Bay (4730 8850) in the south. The second transect is along the north coast from Porth Wen (4090 9475) in the north to Cemaes Bay (3745 9375) in the south. The third transect is on the west coast from east Carmel Head (3055 9300) in the north to Porth Defaid (2915 8625) in the south. Geological maps, cross-sections and block diagrams, detailed outcrop sketches, structural data plots, photographs of key features and thin-section photo-micrographs are provided in subsequent chapters, and form the basis for the structural analysis and tectonic synthesis.

Anglesey has convenient access for the most part, and has attracted scientists and geologists for two centuries. The geological evolution of Anglesey has been a long standing research focus in the Geology Department at the University of Leicester. Dr. S. Temperley and Prof. B. Windley have previously supervised postgraduate and undergraduate research projects there. Ongoing interests includes this project, and a separate PhD project supervised by Dr. J. Zalasiewicz on Parys Mountain, within the Carmel Head Thrust Belt, in northern Anglesey. B. Windley with Japanese collaborators have recently been involved with structural and metamorphic projects in south and southwest Anglesey (e.g. Kawai et al., 2006).
1.2 Aims and objectives

This study specifically aims to:

- Test the hypothesis that the Carmel Head Thrust Belt (CHTB) records a history of contractional deformation that is different and distinct from contractional deformation recorded elsewhere in Anglesey and NW Wales.

- Evaluate the proposition that the CHTB is part of an early Palaeozoic accretionary wedge related to the closure of the Iapetus Ocean.

The main aims include specific objectives:

- To document the internal structural architecture of the CHTB, its poly-deformational history, and the lithotectonic units that comprise it.

- To document the kinematic evolution of the thrust stack and compare and contrast it with the SE-directed contractional deformation recorded in western and central Anglesey.

- To understand the inter-relationship between the structural and metamorphic history, with emphasis on the deformation mechanisms and mechanical role of fluids during thrusting.

- To determine the tectonic setting of the CHTB in relation to the subduction history and closure of the Iapetus Ocean and collision of Laurentia and E. Avalonia.

1.3 Methodology

- Selective lithological and structural mapping and completion of detailed coastal transects.

- Systematic oriented sampling.

- Petrologic, kinematic and rheologic analysis of fault zones during field and optical microscope work.

- Analysis and interpretation of Landsat TM and airborne magnetic data.
1.4 Previous work

Anglesey was mapped for the first time by Henslow (1822), who recognised four major rock units on Anglesey including the Mona Complex, Palaeozoic rocks, Old Red Sandstone and Carboniferous rocks. The Mona Complex was thought to be Archaean (e.g. Callaway & Bonney, 1884), because it was reported to contain sillimanite gneisses (Greenly, 1896b). Blake (1888) recognised the blueschists in SE Anglesey, called it the Monian System and regarded it as Precambrian. Matley (1900) mapped the Carmel Head Fault, and suggested that it is the boundary fault between the Monian and non Monian rocks. Greenly worked on Anglesey for more than half a century, and documented most of the regional geology and lithostratigraphy of Anglesey (Greenly, 1896, 1897, 1899, 1902, 1900, 1908, 1913, 1921, 1922, 1923, 1930, 1937, 1940, 1942, 1946, 1948, 1949, 1950; Greenly et al., 1926, 1928). His most significant contribution is his geological map of Anglesey and accompanying memoirs (Greenly, 1919). Bates (1963, 1966, 1968, 1972, 1974) worked extensively on the stratigraphy and structures of the Ordovician cover sequence. Allen (1965) investigated the Old Red Sandstone facies rocks in eastern Anglesey, and proposed a new subdivision of four Devonian formations. Nichols (1962, 1966, 1968) documented the petrology and structures of the limestones of the Carboniferous rocks in central Anglesey. Thorpe (1972, 1974, 1978, 1979) focused on mafic rocks on Anglesey and their tectonic emplacements. He also interpreted their geological environmental formation based on geochemical analysis. Maltman (1975, 1977, 1978, 1979) published on the serpentinite rocks and their tectonic emplacement within the Mona Complex. From 1980 to 1990, Gibbons (1981); Gibbons & Mann (1986); Gibbons et al. (1985); Gibbons & Gyopari (1986); Horak & Gibbons (1986) contributed literatures on the blueschists of SE Anglesey, and on the tectonic setting of the Mona Complex and Anglesey (Gibbons, 1985, 1989, 1990, 1990a, b; Dallmeyer & Gibbons, 1987). The ductile deformation in Holy Isle attracted researchers during the late eighties, through the nineties and the beginning of the new millennium (Lisle, 1988; Phillips, 1991b; Roper, 1992; Treagus et al., 2003; Hassani et al., 2004). In the last two years, the blueschists in SE Anglesey have been studied and interpreted as part of a subduction-accretion complex (Kawai et al., 2006, 2007). Other previous work concerning the geological history of Anglesey is included in subsequent chapters in relevant sections.
1.5 Geological setting of Anglesey

Anglesey is an island that is situated immediately NW of mainland Wales. The surface geology of Anglesey is dominated by what has been called the Mona Complex and Coedana Granite (Blake, 1888; Greenly, 1919; Gibbons et al., 1994). The Mona Complex covers an area of about 500 $km^2$ on land, and over 1000 $km^2$ of submarine outcrop (Gibbons, 1983). Geologically, Anglesey may conveniently be divided into northern, central, and southeastern regions (Fig. 1.6; Thorpe, 1993). The northern region of Thorpe (1993) includes western Anglesey and Holy Island (Fig. 1.6). Data to be presented in this thesis indicate that Thorpe’s northern region is divisible into northern and western regions, which divides Anglesey into four regions: northern, western, central and southeastern. The Mona Complex in northern and western Anglesey is composed mainly of the Monian Supergroup (Shackleton, 1975), comprising, from base to top, the South Stack Group, New Harbour Group, and Gwna Group. Greenly (1919) assumed that Monian stratigraphic succession had been tectonically overturned. Shackleton (1954, 1956, 1969, 1975) however, revised this interpretation by showing that the sequence was the right way up, with the South Stack Group underlying the New Harbour Group. Above these two main groups, Greenly (1919) recognised the Skerries and Fydlyn units, and Gwna mélange. It is usual nowadays to refer to these collectively as the Gwna Group (e.g. Gibbons et al., 1994). Central Anglesey is comprised of Coedana granite, orthogniesses, hornfels, mylonite shear zone and pillow lavas that is believed to be part of Gwna Group (Gibbons, 1983). Chemical analysis of the pillow lavas suggest that they have mid-ocean ridge basalts (MORB) geochemistry (Thorpe, 1993). Southeastern Anglesey is bound from central Anglesey by the Berw Fault Zone, and contains mainly blueschists. The Berw Fault Zone and the Menai Strait Fault that separates Anglesey from NW Wales, are believed to be major terrane boundary (Gibbons, 1987; Woodcock & Gibbons, 1988).

In northern Anglesey, parts of the Gwna Group, New Harbour Group and dated Ordovician rocks are found in the hanging-wall of the Carmel Head Thrust (Greenly, 1919; Matley, 1928; Gibbons et al., 1994). Due to less deformation and metamorphism in the Skerries unit, the Fydlyn rocks and the Gwna mélange in northern Anglesey, Gibbons & Ball (1991), and Barber & Max (1979) have put these three units into a single group. Gibbons & Ball (1991) call it the Gwna Group, while Barber & Max (1979) referred to
it as the Cemlyn Unit (Fig. 1.7). Barber and Max interpreted the contact between the New Harbour Group and their Cemlyn Unit as a tectonic discontinuity. The Monian Supergroup has been presumed to rest unconformably on a basement of gneisses and the Coedana granites (Greenly, 1919), although this has not been proven (Barber et al., 1981). The latter represents a tectonic slice of a late Precambrian granite intrusion, approx. 600 Ma old (Hudson & Stowell, 1997). The northern zone of Anglesey comprises a single tectonic domain, the Carmel Head Thrust Belt.

In central Anglesey, the Mona Complex is separated from a mudstone/siltstone succession believed to have been deposited unconformably on an Arenig-age erosion surface by the Carmel Head Thrust Belt to the north (Bates, 1974), and to the southeast by a steep mylonite belt. The central region of Anglesey extends from the mylonite belt in the NW, to the Berw Fault Zone. The central region is a complex domain of steep, NE-SW trending subvertical faults and mylonite zones representing boundaries between often very disparate lithologies. Slip and shear directional indicators imply significant, multiphase strike-slip motions, no doubt responsible for the juxtaposition of the variable rock units.
Figure 1.7: Stratigraphical sequences in the Mona complex proposed by Greenly and modified by Shackleton, and a structural sequence proposed by Barber and Max (diagram from Duff & Smith, 1992).
The latter include high grade orthogneisses, the Coedana Granite, Gwna Group units, Ordovician mudstones, Devonian sandstones and carboniferous strata.

The SE region is bound by the Berw Fault Zone to the north, and Menai Straits Fault to the south, and possibly extends into mainland Wales to the SE (Fig. 1.4; Barber & Max, 1979; Gibbons et al., 1994). It includes a significant amount of rocks affected by high-pressure - low-temperature (HP-LT) metamorphism, including mafic blueschists that have yielded 40Ar/39Ar cooling ages of 550-560 Ma (Dallmeyer & Gibbons, 1987). These ages have been interpreted as dating post-metamorphic cooling, probably induced by oblique uplift on sinistral transtensional movements along the Menai Strait fault system.

There exists a distribution of lithological units, mainly as NE-SW trending slivers, bound by NE-SW trending strike-slip faults and shear zones. These imply a long complex history of motions in a composite transcurrent zone (e.g. Gibbons, 1990c). Individual faults in some cases bring into contact rocks exhumed from significant depth such as blueschists, gneissises, with rocks that have never been metamorphosed such as Gwna Group units, upper Palaeozoic sedimentary rocks (Nutt & Smith, 1981). Overall, the tectonic setting represented by Lower Palaeozoic and older rocks implies a long term active margin (Duff & Smith, 1992; and references therein).

Metamorphic rocks from amphibolite and blueschists to eclogite occur in subduction zones, in which they resemble the rocks that are emplaced between the overriding and underthrust plates. Also, the eclogite is evidence for a subducted slab (Cloos, 1984). The blueschists and eclogite are HP-LT rocks that are typically exhumed in accretionary prisms (e.g. Goncalves et al., 2000). The South Stack Group consists mainly of thinly bedded micaceous sandstones, whereas the New Harbour Group is mainly thinly bedded pelites (Greenly, 1919). Several units throughout the succession are found of mafic greenschists, and within the NHG are mainly in the form of deformed pillow lavas and fragments thereof (Maltman, 1975). Towards the middle of the succession, a discontinuous horizon of serpentinite and gabbro bodies is found almost certainly representing remnants of ophiolite affinity (Maltman, 1975, 1978; Phillips, 1991a; Thorpe, 1993). Geochemical analysis of the basaltic rocks within the New Harbour Group suggests that have characteristics of suprasubduction zone (Thorpe, 1993). The NHG resembles distal turbidites, which is inferred from primary sedimentary structures such as water-escape structures and Bouma sequences (Phillips, 1991a). Wood (1974) suggested that the New Harbour
Group sediments were deposited as turbidites on oceanic crust and may be related to broadly coeval blueschists of the SE Zone.

In western Anglesey, the South Stack and New Harbour Groups have been affected by two main syn-metamorphic ductile deformational events (e.g. Maltman, 1975, 1978). The first deformational event is fold dominated and is associated with a steeply dipping axial planar cleavage. The second deformation resulted in the development of shallow, heterogeneously developed cleavage with reworking of first phase fabric elements ranging from weak to intense (Treagus et al., 2003). D1-D2 deformation is a progressive regional greenschist facies, and a progressive SE-directed shear event which occurred prior to the deposition of the Ordovician succession (Phillips, 1991b). D1 formed the major anticlines on Rhoscolyn, and the latter was modified, overturned and sheared by D2 (e.g. Treagus et al., 2003). Hassani et al. (2004) argued that folds in Rhoscolyn and South Stack were formed by D2 (Fig. 1.4). Phillips (1991b) mapped most of the ductile SE-directed thrusts along the coastline from Rhoscolyn and northward. A maximum age has been provided by dating of detritus zircons (Collins & Buchan, 2004). These show that the South Stack Formation was deposited no earlier than c. 500 Ma, suggesting a late Cambrian depositional age for the South Stack Group.

### 1.5.1 Thrusting in the Northern Region

Thrusting in northern Anglesey was discovered by Greenly (1919). He showed a thrust fault trending curvilinearly from Carmel Head in the extreme NW of Anglesey to Porth Corwgl in the extreme NE. This fault is referred to it as Carmel Head Thrust in text. However, while Greenly illustrated examples of thrusts in profile view along the north coastal belt of Anglesey, he did not systematically map the thrust faults. Shackleton (1954, 1956, 1969, 1975) overlooked the thrusting and assumed stratigraphical continuity between the New Harbour and Gwna Groups. However, contacts between the New Harbour Group and other lithological units in the CHTB appear to be entirely tectonic, mainly in the form of thrusts (see also Bates, 1974; Barber et al., 1981). Gibbons et al. (1994) revised the map of Anglesey by including more thrusts branching off the main Carmel Head Thrust, which they suggested should be named the Carmel Head Thrust system (Fig. 1.5).
1.6 Current work

Due to discoveries of many thrusts distributed throughout the Northern Region, north and south of the Carmel Head thrust, the zone of thrusting herein is referred to as the Carmel Head Thrust Belt (CHTB). Three major coastal transects are presented on the east, north and west coasts of northern Anglesey. The transects cover the extent of the CHTB belt towards the south of Anglesey. Detailed transects and block diagrams are provided to summarise lithological and structural relationships. Major lithological units within the CHTB were analysed in the field and by thin-section work, which includes textural and petrographic descriptions for the rock units, and their fabrics.

The presence of a thrust belt that incorporates diverse lithological units that have different litho-tectonic environments of formation such as mélangé, Ordovician sedimentary rocks, greenschist-grade metamorphic rocks and the basement gneisses requires a comprehensive evolutionary model. Therefore, at the end of this thesis, an interpretive model for northern Anglesey is provided, which involves accretionary complex formation followed by subduction-accretion and/or collision.

1.7 Thrust wedges tectonic setting

This section aims to review accretionary wedges, keeping in mind the following variables: their tectonic setting; internal structure; morphology and evolution. The purpose of this revision is to provide a basis for testing the hypothesis that the Carmel Head Thrust Belt of northern Anglesey represents a portion of an early Palaeozoic accretionary wedge (related to the closure of Iapetus Ocean). Thus, this section helps to define those remnants of an accretionary system represented in northern Anglesey.

1.7.1 Definition of an accretionary wedge

Accretionary wedges typify many convergent margins, where material is scraped off the upper parts of the downgoing plate, and underplated or otherwise accreted onto the upper plate, the latter representing the hanging-wall of the subduction system. Accretionary prisms or wedges are important crustal growth sites, where oceanic and other deep-water sediments and rocks are uplifted, deformed, and transformed to continental crust (Werff,
The accretionary wedge has been compared to that of a wedge of snow against a moving snowplow. This is known as "Critical Wedge Theory", in which wedges are internally on the verge of failure throughout, and geometry is defined by the material strength and the strength of the basal detachment (Gutcher et al., 1998). There are two types of accretionary wedges: broad and wide wedges such as the Alaskan and Makran wedges; or steep and narrow such as in Chile and Japan (Gutcher et al., 1998). Accretionary wedges occur as an evidence of continental growth of rocks and sediments of the distal and tapered area of an overriding plate, which converges with a subducted plate (Busby, 2004). This material and continental detritus, and the uppermost layers of the basaltic oceanic crust scrape off along imbricate thrust faults, and this material in turn fills in trenches at the toe of the accretionary wedge, (e.g. Barr et al., 1999). Also, the downgoing continent deforms as duplexes of underplating material form (e.g. Kukowski et al., 2002).

### 1.7.2 Convergent margins types

There are two types of convergent margins: subduction and collision, one type involving subduction of oceanic crust beneath either an oceanic or continental upper plate, the other involving continent-continent collision after intervening oceanic crust has been subducted. Subduction is initiated by rapid sinking of old, cold oceanic lithosphere over many tens of millions of years, and the age of the lithosphere that reaches the trench and is subducted becomes progressively younger (Busby, 2004). Material on that conveying belt will be accreted in front of the overriding plate, and an oceanic arc and forearc will develop (Fig. 1.8). After developing an arc and forearc, part of the sediments of the forearc and oceanic crust will be incorporated into the accretionary wedge by offscraping and underplating. The other part of the sediments will find its way to the forearc deposit, which partly comprise olistostrome deposits (Fig. 1.8).
Figure 1.8: 3D diagram for a subduction zone (diagram from Press *et al.*, 2003).
The wedges in this tectonic setting can be continental crust underplating the fore-arc rocks of oceanic crust, such as the accretionary wedge along the Eastern Sunda-Western Banda Arc (Werff, 1995). The other way an accretionary wedge can be formed by underplating oceanic crust under continental crust, in which it develops a continental arc in land. The Andean accretionary wedge is an example of this kind of setting.

### 1.7.3 Subduction and subduction zones: nature and consequences

Convergent margins involving subduction zones are divided into oceanic or subcontinental, depending on whether the overriding plate is oceanic or continental. These subduction zones are marked by trenches, which are a linear depression in the ocean floor where the subducted plate bends and starts its descent into the mantle (Moores & Twiss, 1995). Consequently, volcanic arcs will develop on top of the overriding plate, which will be a source of volcanism as well as magmatism.

In the subduction zone, the overriding and the subducted plates are controlled by two opposing boundary forces (Price & Audley-Charles, 1987). The plunging part of the subducted plate is called the downgoing slab. The slab varies in extend from 0° – 90° and may dip for more than 600 km in the mantle (Doglioni et al., 1999). The subducted plate forms an outer swell that exhibits normal faults at the top, which are caused probably by its bending into the mantle (Werff, 1995). When the subducted plate has gone down to its maximum dip, and the subduction is still active, it will resist by rupturing and detachment (Price & Audley-Charles, 1987).

### 1.7.4 The trench and forearc regions: basic description

The main features of subduction-related convergent margins are the trench, accretionary wedge, forearc basin, and the arc (Fig. 1.8). The trench is the feature that marks the outer limit of the subduction zone in plan view. Studies of the structure and morphotectonics of the accretionary wedge along the Eastern Sunda-Western Banda Arc by Werff (1995), showed that the trench is a V-shaped basin. The trench also has inner and outer slopes, with the subducted plate beneath the inner slope. The forearc region is the area of the overriding plate that has the forearc basin, which is adjacent to the arc and partly overlies the accretionary wedge. The latter (also known as the accretionary prism) is a
thick wedge of predominantly sedimentary rocks, derived (along with a limited amount of mafic oceanic crustal slivers) from the downgoing slab, although sedimentary material derived from the arc and forearc regions of the overriding plate can also contribute to the wedge. The volcanic arc is the region of active volcanic and plutonic activity marked by a chain of volcanoes (Moores & Twiss, 1995). Much of the eroded volcanic arc detritus find its way into forearc basins.

The accretionary wedge is the main locus of crustal deformation above the shallower parts of subduction zones. The outer limit of deformation is represented by the foot of the inner trench slope, such that this physiographic boundary marks the deformation front (Moores & Twiss, 1995). In accretionary wedges, material of both the footwall and hangingwall plates are juxtaposed and shortened. The transfer from the footwall to the hangingwall plate is usually termed accretion, whereas the possibly temporary transfer from the hangingwall to the footwall plate is defined as erosion (Doglioni et al., 1999). Accretionary wedges are also domains of enhanced fluid activity, mainly due to the expulsion of overpressured fluids contained in unlithified and partly lithified sediments, together with hydrated mafic oceanic crust which has also been accreted (e.g. Wallace, 2005).

1.7.5 Subduction-accretion, and the concept of dynamic equilibrium

Forearc accretionary wedges represent dynamic systems in which material is frontally and/or basally accreted (Glodnya et al., 2005). The shallow parts of subduction-accretion systems, including classic frontal accretionary wedges, are regarded as material cycling systems with conveyor-belt like subduction, accretion, exhumation and at least partial redeposition of the material in the trench (Glodnya et al., 2005). Structural elements developed within accretionary complexes can be linked to specific deformation increments. They reflect the specific deformation history and are related to the modes of accretion, convergence rates, petrology and other factors (Glodnya et al., 2005). These elements such as imbricate faults and duplexes are developed in different parts of accretionary wedges.

The process of subduction-accretion starts at shallow levels where imbricate-thrusts are generated by progressive incorporation of trench fill at the toes of accretionary wedges.
(e.g. Kusky & Bradley, 1999). Toward the base of accretionary wedges, underplating occurs by thrust duplexing as a result of increasing pressure and temperature (Fig. 1.9). This is known as the underplating mechanism, which explains thickening of wedges by accretion rather than pure shortening, and causes passive uplift of margins and localisation of deformation at the base of the trench slope (e.g. Platt et al., 1985; Kukowski et al., 2002).

Subduction-accretion is a continental growth mechanism (e.g. Barr et al., 1999). The process has been cited as having generated large volumes of continental crust, dominantly through secondary growth, characterised by rocks of oceanic and continental margin affinity. While shallow-level accretion accounts for classic wedge development, evidence of much deeper level accretion, beneath and far landward of the fore-arc accretionary complex, has also been documented (e.g. Barr et al., 1999). During deep level accretion, sediments may be subducted to depths of at least 30 km before being underplated, together with slivers of oceanic crust, to the base of the overlying wedge (e.g. Moore et al., 1991). Fragments of seamounts, plateaus and even continental crust may be underplated as opposed to recycled into the mantle, hence contributing to crustal growth (e.g. Barr et al., 1999: and references therein).
Tectonically, subduction-accretion represents one of several mechanisms which interact in order to maintain a state of dynamic equilibrium in the subduction system (Barr et al., 1999). Its long term operation will result in a progressive oceanward outgrowth of continental crust, characterised by sequences of deformed and metamorphosed oceanic-continental margin rock associations (Barr et al., 1999).

1.7.6 Internal structure of accretionary wedges

Accretionary wedges have several distinct component parts, including the trench, toe, basal décollement, internal thrust-dominated domains, upper extensional zone and a backstop. Offscraping occurs by the development of frontal imbricate thrusts at the toe of an accretionary wedge. This represents the stage of accretion that has low slope and an extended length (Fig. 1.10). In the lower part of an accretionary wedge, there is underplating, which steepens the slope. The underplating of accretionary material results in the development of a basal and internal fold-thrust belt. Ujiie (2002) has recognised S2 cleavages and related them to underplating in their model. Therefore, thrust-folds might be considered D2 in one tectonic setting if they form by underplating. In the upper part of the accretionary wedge, normal faulting is generated where the upper oceanward dipping slope is high. This might reflect acquisition of dynamic equilibrium. Eventually, deeper rocks that developed in lower parts of accretionary wedge will be exhumed either by erosion or by the development of major listric normal faults (Fig. 1.11).

The décollement fault is a zone of profound structural changes in orientation, and a discontinuity in plate velocity, which represents the boundary between the upper plate and the lower plate (Moore, 1989). Tectonic mélanges often characterise the décollement zone (Raymond & Terranova, 1984). This zone is frequently a high pressure conduit for fluid expulsion, which has a major impact on structural development in the accretionary wedge.

The backstops may dip toward the arc or toward the trench depending on the specific convergent margin system (Werff, 1995: and references therein). An accretionary wedge with trench-ward backstop is called a two-sided accretionary wedge (Moores & Twiss, 1995: and references therein). If at the largest scale the system is transpressional, the backstop may be represented by a major strike-slip fault zone (e.g. Ramos & Kay, 1992).
1.7.7 Mélange development and distribution

A mélange (from the French for mixture) is usually considered to be a tectonic unit that develops in semi-brittle settings, most typically represented by accretionary wedges. Other mixed or chaotic deposits of entirely sedimentary origin are known as olistostromes, characterised by disordered arrangement of blocks of one or more lithologies embedded in a matrix of another. Both can occur in accretionary settings, but they have different tectonic settings. Olistostromes form by sedimentary processes such as slumping and gravity sliding (Rast & Horton, 1989), although subsequent deformation may convert such deposits to tectonic mélanges.

Mélanges typically consist of lensoid fragments of diverse rock types in an anastomosing foliated matrix rich in phyllosilicate material (Fig. 1.12). Fragments may range in volume from several $mm^3$ to several $km^3$. They comprise a wide range of lithotypes, such as volcanics, chert, gabbro, or limestone, and other marine sediments from shallow and deep sources. Depending on factors such as rock strength, fluids pressure and temperature, mélanges can exhibit brittle and/or ductile behavior. For example, the mélange of
Figure 1.11: The development of an accretionary wedge. A- Is the level of imbrication, and the slope is low. B- The slope is steeper by underplating, and listric faults are developing at the top due to gravitational collapse. C- The listric normal faults compensates for the growing of the wedge. Note the accretion stages occurs similar to duplexes, in which the younger faulting or accretion near the toe. D- The listric faults are exhuming high pressure rocks at depth, and late thrust faults extend the toe, which is a respond to the normal faulting, (diagram from Platt et al., 1985).
McHugh Complex, Alaska exhibit both styles (Kusky & Bradley, 1999). Mélanges of the Northern Apennines exhibit disrupted folds in fine-grained matrix (Bettelli & Vannucchi, 2003). Mélanges of Gwna group, northern Anglesey, NW Wales, show brittle behavior (Fig. 1.12).

Mélanges may develop in 4 deformation stages (Cowan, 1985). Stage 1 is defined by initial disruption of layers involving layer-parallel extension and boudinage. Stage 2 results in broken formations as a result of the activation of thrusts and back-thrusts. By stage 3, increasing dismemberment, from stage 1 and stage 2 processes, has resulted in juxtaposition of blocks of diverse lithology. By stage 4, lenticular inclusions are bounded by an anastomosing network of subparallel slip- and shear-surfaces. Another somewhat similar classification scheme has been devised by Raymond & Terranova (1984) also involves a 4-stage development, with stages named α, β, σ and γ (Fig. 1.13).

Mélanges are a common constituent of many accretionary complexes, and in other tectonic settings such as foreland basins and strike-slip fault zones (Needham, 1995). In accretionary wedges, there are décollement related mélanges, which develop beneath the décollement zone (Ujiie, 2002). Other mélanges are developed at the toe, in the trench.
Other mélange is products of shear zone (fault zone), and by out of sequence thrusts (Needham, 1995). All these examples of mélange occur at or near the toe, which represent a shallow tectonic environment. However, mélange can develop deeper in the subduction zone (Bebout & Barton, 2002).

### 1.7.8 Fluids and fluid processes in accretionary wedges

Dewatering of trapped fluids in accretionary wedges occurs due to burial and tectonic overpressure, as well as mineral dehydration and hydrocarbon generation (e.g. Saffer & Screaton, 2003; and references therein). Dewatering can occur in two different ways: by diffusing discretely across the entire wedge through the rock matrix, and diffusion along fractures, faults and conduits (Mann & Kukowski, 1999). Figure 1.14 shows the generation and origins of fluids and their possible pathways. Fluids that are related to compaction are mainly rich in H$_2$O relative to CO$_2$, such that H$_2$O controls the chemical properties of fluids when pressure and temperature increase (Manning, 2004). The increase of pressure and temperature leads to increase of H$_2$O ionization, which make it attractable to solutes such as silica and alkali. Fluids that are related to dehydration at greater depths are characterised by distinct chemical and isotopic signatures (Saffer & Screaton, 2003; and references therein)
Figure 1.14: A cross section showing possible origins of chaotic deposits along with dewatering of sediments that could disrupt rocks (diagram from Cowan, 1985).

Other fluids are characterised by deep crustal compositions which are indicative of long-distance migration along conduits (Brown et al., 2001). Channeled fluid-escape occurs mainly along the décollement zone and along imbricate faults, which link with and are synthetic to the décollement zone (Chamot-Rooke et al., 1992). Veins are the signatures of fluid-escape pathways, and buried fluid-rich material results in an increase of pore-fluid pressure, which will induce fractures that will be filled by precipitates from solution to form veins. Cyclic release of fluid may take place by repeated opening and closing of the fracture like a valve (Sibson, 1990; Nicolas, 1984). Two generations of veins may develop that have a cross-cutting relationship: pre-failure extension veins, and discharge veins lying within fault zones (Sibson, 1990). Fault valve behavior is a preferred mechanism for fluids associated with high angle reverse faults, in which stacking of the thrust faults occur at the toe of an accretionary wedge, eventually forming a high angle reverse fault at the rear of the wedge. Also, vertical veins or fluids occur when the regional stresses are extensional due to the creep of the toe of an accretionary wedge, in order to maintain balance (Carter et al., 1990). The latest fluid-escape occurs at the upper levels of the accretionary wedge.
1.7.9 The mechanics of a Coulomb wedge, brief review

The mechanism of accretionary wedges has been compared to critical Coulomb wedge theory (e.g. Moores & Twiss, 1995). The theory assumes that the basal décollement is a plane that slopes upwards towards the foreland at an angle. The equation of equilibrium requires that the driving forces that push the thrust wedge toward the foreland must be balanced by the resisting forces that tend to prevent motion. The driving forces are constant, but increase when the area over which they act increases. Meaning that if the wedge is thick, then it will overcome the resistant forces. The resistance to thrusting comes from the décollement. The pore fluid pressure on the décollement is important in that it decreases the resolved normal stress and frictional resistance, which decreases the driving forces. If the slope of the décollement is high, then the friction is high, but the strength of the rocks counteracts the effect of friction.

The model assumes that the wedge at critical stress for fracture defined by the Coulomb fracture criterion and the deformation occurs continuously on the fault plane. However, the deformation in accretionary wedges is accommodated by discontinuous slip events over finite areas of faults within and at the base of the sheet (Moores & Twiss, 1995). Only by averaging these events over a long period of time, on the order of perhaps tens of thousands to hundreds of thousands of years, a pattern of pervasive deformation and slip of the entire thrust wedge would be seen on the décollement that is assumed in the model.

1.7.10 Conclusion

The presence of an accretionary wedge is typical of some convergent margins, where material is scraped off a subducting lower plate. They are sites of deposition and erosion, where oceanic and other deep-water sediments and rocks are uplifted, deformed, and transformed to continental crust. Accretionary wedges are characterised by several tectonic components, including the trench, toe, basal décollement, main thrust wedges, backstop and upper extensional zone. Mélange is a tectonic unit, which develops in semi-brittle settings such as accretionary wedges. The development of both olistostromal and tectonic mélanges often accompany and add to accretionary wedge development, while active sedimentation usually contributes to the volume of the system. Tectonic mélange
development results from fault-related dismemberment and shearing along the basal detachment, aided by incorporation of olistostromal material into the zones of deformation. The mechanism of accretionary wedge development may be largely explained by Coulomb Critical Wedge Theory, which is reviewed briefly in this thesis. Fluid escape is facilitated by channeling along conduits, principally the décollement zone and other thrust zones, and by hydraulic fracturing. Forearc accretionary wedges are dynamic systems accommodating subduction, accretion, exhumation and redeposition of the material in the trench. Subduction-accretion represents one of several mechanisms which interact in order to maintain a state of dynamic equilibrium at active margins.

1.8 Subsequent chapters

Chapter two describes the main lithological units observed in the field in the CHTB. Chapter three presents field structural data for each of the three transects, a description and interpretation of macro- and micro-structures and deformation processes. Chapter four describes the Gwna Group rock types and structures, and discusses implication of tectono-stratigraphy. Chapter five involves an analysis of the CHTB structural features and tectonic setting. The last chapter presents the conclusions and implications of the research.
Chapter 2

Major lithological units within the CHTB and their associated structures

2.1 Introduction

This chapter describes major lithological units within the CHTB, as well as their characteristic structures. The lithological units are described in chronological order from oldest to youngest. However, as they are mainly fault-bound assemblies; their original stratigraphic order is not always clear. The rock units contrast in composition, age and environment of formation. Low and high-grade metamorphic rocks are structurally mixed by brittle faulting and mélange development. In many cases, cleavage and other tectonic structures formed during CHTB development overprint primary sedimentary features and earlier formed fabrics.

The rocks of northern Anglesey are part of what is known as the Mona Complex. The Mona Complex is divided mainly into basement rocks and a bedded succession (Greenly, 1919). The basement rocks are represented by the Coedana granite and paragneisses. The bedded succession is known as the Monian Supergroup, which is comprised of three groups: South Stack Group (SSG), New Harbour Group (NHG) and Gwna Group (e.g. Shackleton, 1975; Gibbons & Ball, 1991). The boundary between each group is defined by a major fault.
The Monian Supergroup is separated from Ordovician cover by the Carmel Head thrust contact (Fig. 2.1; Bates, 1972, 1974). The Ordovician rocks unconformably overlie polydeformed and metmorphosed rocks of the Monian Supergroup and Coedana terrane in central Anglesey (e.g. Neuman & Bates, 1978). The Siluro-Devonian red conglomerates and sandstone-siltstones (the Old Red Sandstone ORS) overlaps all older units. In the following sections, the stratigraphy documented in this study is described, starting with the oldest units and ending with the youngest units: granite gneisses, Nebo Unit, South Stack Group, New Harbour Group, Ordovician rocks, Gwna Group, Silurian mudstones and volcanics (Parys Mountain) and the ORS facies rocks.
2.2 Granitic gneisses

This unit is composed of abundant banded granitic lenses in fine-grained foliated gneissose material. The gneisses have a light pink weathered surface and dark buff fresh surface. The gneisses are characterised by exfoliated outcrops and hummocky geomorphology. They are cut by a series of spaced N-S quartz veins (2900 9278), to the west of the northern fault contact (Fig. 2.2). In thin-section the rock contains mainly plagioclase, minor quartz and biotite (Fig. 2.3), and it has an overall composition of a biotite granite. Also, all minerals are brittle fractured on the microscale and fractures overprint the gneissic texture.

Greenly (1919) called this unit the Gader gneisses, which are exposed along the northwestern coast. The unit is equivalent to the Coedana granite (e.g. Greenly, 1919). The unit is bounded by a fault contact to the north (2930 9275), which separates the gneisses from black mudstone (Fig. 2.2), and by a fault to the south (2910 9222) that separates the unit from quartzite beds associated with Ordovician black mudstone. The southern fault contact was not recognised by Greenly who considered the quartzite beds to be part of the gneisses. Figure 2.4 indicates that the gneisses are thrusted over the quartzite beds. This fault is part of a major thrust fault system which occurs at Porth Hwch (2930 9210; Fig. 2.5). The unit was incorporated and reworked by the CHTB. Its granitic composition suggests that it may be a thrusted sliver of continental crust.
Figure 2.2: (a) View of the northern fault contact of the gneisses (2930 9275). (b) N-S quartz veins west of the northern contact (2900 9278). See Fig. 2.5 for locations.
Figure 2.3: (a) Gneissosity in the granite. The texture can be seen at (2890 9250). (b) The granite is deformed by brittle deformation imposed on the gneissosity; sample was to the north of southern contact (2900 9225). See Fig. 2.5 for location.
Figure 2.4: (a) The thrust fault contact to the south, north of Porth Hwch (2910 9223). (b) The quartzite unit below the gneisses and above the black mudstones at Porth Hwch (2930 9210).
Figure 2.5: Geological map of the northwestern part of Anglesey, from east Carmel Head (2960 9305) to Porth Nant (3935 9140).
2.3 Nebo Unit

This unit typically has two outcrop appearances. It commonly consists of green massive and blocky layered rocks that are mainly interbedded quartzite and chlorite schist. This appearances occurs between Gwichiaid Slide (4790 9125) and south of Porth Holygen (4810 9050). In addition, it also appears as reddish banded pelites and psammites, interpreted as interbedded meta-arkosic sandstone and siltstone, south of Porth Holygen (4810 9050) to Gareg Fawr (4770 8965; Fig. 2.6). Greenly (1919) thought that the reddening was due to original depositional overlap by the Old Red Sandstone unit that has since been removed by erosion. Carter (1988) and Greenly (1919) described the unit as para-gneisses because of banding formed by calc-silicate, quartzite pelitic schist and amphibolite bands. Bates & Davies (1981) thought that the unit is decomposed acid gneiss, because Greenly (1919) reported a host of metamorphic minerals including minerals composition as quartz, feldspar and biotite, sillimanite, garnet and idocrase.

Thin-sections of this unit show that it is arkosic meta-sandstone, and is folded and schistose, in which schistosity is defined by muscovite. In thin-section, the green part of the unit consists of massive quartzite with chlorite-rich fine-grained material defining schistosity rather than gneissosity (Fig. 2.7). High-grade metamorphic minerals were not observed. It is possible that high-grade mineral assemblage was replaced by chlorite and white mica, during subsequent deformation to the ductile deformation. The best descriptive name for this unit, in the author’s opinion, is pseudo-paragneiss.

The unit is exposed in northeast Anglesey (Fig. 2.8), and is separated from black Caradoc mudstones by a normal fault to the north, and by a thrust fault to the south. The unit is complexly deformed with variable bedding orientations (Fig. 3.13). It is exposed as flat and inclined beds, and exhibits refolded folds. Moreover, there is more than one geometry of tight isoclinal as well as recumbent folds. The unit is exposed also as boudinage mélangé blocks, and is cut by imbricate thrust faults. It also features normal faults dipping to the north and south that modified the pre-existing fold and thrust geometries.
Figure 2.6: (a) Interbedding of pelite and psammite beds in the massive rocks of the Nebo unit. Photo from Gwichiaid Slide (4790 9125). (b) Banding formed by bedding in the reddish rock of the Nebo unit. Location at (4793 8985).
Figure 2.7: (a) The composition of the Nebo unit: interbedding of quartz and feldspar. Location of sample (8970 4782). (b) Schistosity is defined by white mica, photo from the previous thin-section. (c) Typical microfold of bedding. Sample location (4810 9050). (d) The green part of the Nebo unit consists of interbedded quartz and mica that are broken as boudins. Sample from Porth Holygen (4050 9080).
Figure 2.8: Geological map of northeastern Anglesey.
Figure 2.9: Different structural features typically observed in the Nebo units: (a) refolded fold (4805 9110), (b) recumbent folds of bedding (4785 8975), (c) isoclinal fold of bedding (4790 8990), (d) broken beds (4808 9035; mélange) and (e) inclined interbedded pelite and psammite (4810 9050).
2.4 South Stack Group (SSG)

The SSG is known as the Coeden beds in the northern part of Anglesey, and is composed of deformed and metamorphosed, thinly bedded quartzites and turbiditic psammites with interbedded pelites (Greenly, 1919). The Coeden beds are not exposed on the northern coastline of Anglesey, but crop out in the middle of the CHTB (Fig. 2.1). The SSG is the lowest unit of the Monian Supergroup. The group is overlain to the north by the New Harbour Group (NHG), also known as the Amlwch beds, and bound to the south by the Carmel Head thrust fault that separates the beds from Ordovician rocks structurally below. The South Stack Group is correlated to the Cahore Group in southeast Ireland, which is middle to upper Cambrian in age, has similar stratigraphy and deformation histories to the SSG, and is unconformably covered by Arenig deposits that contains clasts of the NHG (Tietzsch-Tyler & Phillips, 1989). Also, Collins & Buchan (2004) proved a late Cambrian (501 ± 10 Ma) age for the SSG by detrital zircon dating. Table 2.1 shows the lithostratigraphy of the South Stack, New Harbour and Gwna groups.

2.5 New Harbour Group (NHG)

The rocks of the New Harbour Group in northern Anglesey were called the Amlwch beds by Greenly (1919). The beds are characterised by a pale green colour on the weathering surface. The rocks consist predominantly of meta-pelite although with a relatively high proportion of thinly bedded (cm-scale) psammite layers. They are mainly fine-grained chlorite schist. In thin-section, the main mineral phase is fine-grained chlorite, biotite and quartz of greenschist metamorphic grade. The quartz minerals form crenulation folds of what seems to be relict bedding (Fig. 2.10). The crenulation folds could be interpreted as preserved intrafolial F1 folds, which are found in Holy Island (Maltman, 1975, 1978, 1979; Phillips, 1991a,b). The rocks are characterised by M, S, Z and W crenulation folds. Thin-section analysis indicates that the NHG contains at least three fabrics, cross-cut by CHTB cleavage. Therefore, thrust-related deformation associated with the development of the CHTB resulted in brittle and semi-brittle reworking of the greenschist facies fabrics of the New Harbour Group at macro and microscale.
<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Thickness</th>
<th>Type section</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gwna Group</strong></td>
<td>Gwna mélange</td>
<td>3000 m</td>
<td>Llanbadrig (375 946)</td>
<td>Top not exposed</td>
</tr>
<tr>
<td></td>
<td>Fydlyn</td>
<td>about 100 m</td>
<td>Ynys Fydlyn (2910 9180)</td>
<td>Top-conformable with the Caradoc mudstone</td>
</tr>
<tr>
<td></td>
<td>Skerries</td>
<td>200 - 300 m</td>
<td>The Skerries (260 940)</td>
<td>Top-thrusted with the Gwna mélange, Porth Hwch</td>
</tr>
<tr>
<td><strong>New Harbour Group</strong></td>
<td>Lynas</td>
<td>1-2 km</td>
<td>Northwestern Anglesey (2436 7600)</td>
<td>Top-thrusted with the Gwna mélange</td>
</tr>
<tr>
<td></td>
<td>Bodelwyn</td>
<td>2-3 km</td>
<td>Southwestern Anglesey (2600 7625)</td>
<td>Top-thrusted with the Skerries Formation</td>
</tr>
<tr>
<td><strong>South Stack Group</strong></td>
<td>Rhoscolyn</td>
<td>300 m</td>
<td>Rhoscolyn (2647 7495)</td>
<td>Top-thrusted</td>
</tr>
<tr>
<td></td>
<td>Bodelwyn</td>
<td>500 m</td>
<td>Bwa Du (2600 7640)</td>
<td>Base-conformable</td>
</tr>
<tr>
<td></td>
<td>Holyhead</td>
<td>500 m</td>
<td>Bwa Du (2600 7625)</td>
<td>Base-thrusted</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>400 m</td>
<td>Penrhyn (2110 8062)</td>
<td>Base-not exposed</td>
</tr>
</tbody>
</table>

Table 2.1: The Monian Supergroup lithostratigraphy, modified after Phillips (1991a, b). See also Barber & Max (1979); Gibbons & Ball (1991); Howells (2007)
Figure 2.10: Typical photo-micrograph showing (a) multiple cleavages within the NHG and (b) schistosity cut by CHTB cleavage. Samples taken from north of Porth Corwgl (4715 9265).
At Porth Corwgl (4715 9260), in the northeast of Anglesey (Fig. 2.8), the Carmel Head thrust contact separates the NHG to the north from Ordovician black sandstone and mudstone to the south. In NW Anglesey, the NHG is faulted against the black mudstones west and east of Carmel Head (2960 9305; Fig. 2.5). Therefore, there appears to be a regional fault contact between the NHG and the black mudstone, i.e. the Carmel Head Thrust fault. However, the Carmel Head fault contact is not continuous at the surface, and is separated by intervening normal faults. The New Harbour group is the most dominant rock unit exposed in the CHTB, forming most of the exposed rocks in the hanging-wall of the Carmel Head thrust.

At Porth Defaid (2915 8625), northwestern Anglesey, the NHG is overthrusted by a volcaniclastic unit called the Skerries Formation (Fig. 2.5). To the south of the thrust, the rocks of the NHG contain internally thrusted gneissic blocks (Fig. 2.11). Further to the south of the gneiss block, the NHG is characterised by NE plunging z-shaped folds, which are typical asymmetric folds of the dominant fabric found commonly in the NHG (Fig. 2.11).

Figure 2.11: The NHG at Porth Defaid (2915 8625). (a) A gneiss block within the NHG (2915 8625). (b) Z-shaped folds in NHG schists, the classic style of NHG (2900 8610).
2.5.1 NHG previously mapped as Skerries and Gwna Mélange

Some areas that contain the NHG were previously mapped as the Skerries unit or Gwna mélange based on exposure appearance alone (Greenly, 1919). Foliated rocks in the Skerries unit, Gwna mélange and NHG form similar appearing exposures with green weathered surfaces. In the northern study area, the Gwna mélange was mapped adjacent to the Skerries rocks, separated by the Porth Cynfor strike-slip fault (Figs. 2.13,2.1). Also, a sliver of rocks bound by the Fydlyn beds and the Nant Formation at Trwyn Crewyn (2920 9145) was mapped by Greenly (1919) as the Gwna mélange (Fig. 2.5). However, in thin-section, the rocks are chloritic schists and they contain asymmetric tight folds of bedding (intrafolial F1 folds) cut by more than one set of cleavage (Fig. 2.12). These are typical features of the NHG and therefore, these exposures previously mapped as Skerries and mélange units are interpreted here to belong to the NHG. In conclusion, the Trwyn Crewyn (2920 9145) sliver and the rocks that are in the hanging-wall of the Carmel Head thrust fault apart from the Gwna mélange belong to the NHG.

2.6 Ordovician cover

The Ordovician cover has the second most dominant unit after the NHG in the study area. It consists mainly of three sequences: Arenig conglomerates in northernmost Anglesey, interbedded Arenig black sandstone-siltstone and Caradoc mudstones. In northernmost Anglesey, the Ordovician rocks consist of Arenig conglomerates faulted against the NHG and the mélange of the Gwna Group (Fig. 2.13). In NE Anglesey, south of the Carmel Head thrust fault, the Ordovician rocks consist of interbedded Arenig sandstone-siltstone, and Caradoc mudstone (Fig. 2.5). In NW Anglesey, there is only Caradoc mudstone. The bedded rocks are cross-cut by slaty-phyllitic cleavage, which are cut by thrust faults. The Ordovician sandstones and mudstones are mainly exposed as a belt that trends east-west and is bound by the Carmel Head Thrust contact to the north.

2.6.1 Arenig conglomerates

In northernmost Anglesey the Ordovician conglomerates have previously been divided into three formations, and typically they consist of matrix and particle-supported con-
Figure 2.12: (a) A thin-section from Porth Cynfor (3935 9485) and shows folding similar to the NHG. (b) From Porth Wen (4090 9475) and shows reworked NHG. (c) From the same unit, near the lower contact (4010 9450), and also shows folding of NHG. (d) A thin-section of the ridge north of Porth Nant at Trwyn Crewyn (2920 9145), and it shows recrystallisation and folding cut by CHTB deformation.
Figure 2.13: Geological map of Cemaes Bay (3745 9375) - Porth Wen (4090 9475) area in the northernmost part of Anglesey. This maps shows the relationship of Gwna Group, Arenig conglomerates and the NHG.
glomerates. The size of the fragments varies from pebbles and cobbles to boulder-sized blocks of limestone, jasper and quartzite that lie in a sandy and muddy matrix. The unit coarsens towards the north, suggesting a northern provenance (Duff & Smith, 1992). The conglomerates also exhibit two different weathering surface colours: yellowish brown and dark purple. The conglomerates are thrust over the Gwna mélange along a basal unit of quartzite that was classified by Bates (1972) as Gwna quartzite (Figs. 2.13, 2.14).

The yellowish brown conglomerate is exposed near Ogof Gynfor (3785 9475; Fig. 2.13). This unit is known as the Ogof Gynfor Formation (OGF), which is about 60 metres thick and is Arenig in age (Al-Shammary, 1985; Bates, 1972). The OGF is an oligomict and has both angular and rounded clasts varying from cobble to boulder size, which are matrix-supported. They have very poor stratigraphic continuity, are ungraded and have no internal sedimentary structural features. For these reasons, they are regarded as being most compatible with deep-water debris flow deposits of marine environment rather than shallow water deposits worked by traction currents (Fig. 2.14; Al-Shammary, 1985; Temperley, 2005).

The dark purple conglomerates consist of the Torllwyn and Porth Cynfor formations, which are about 55 and 140 metres thick respectively (Al-Shammary, 1985). The Porth Cynfor Formation (PCF) is the basal unit of the Torllwyn Formation (TF). The PCF consists of white quartzite and red jasper pebbles and cobbles in a conglomerate that has a purple matrix of sand or mud. The PCF rests on a white homogeneous quartzite unit, and shows normal grading indicating way-up (Fig. 2.15). In thin-section, the PCF conglomerate shows poor sorting and subangular to sub-rounded grains (Fig. 2.15a). Ripple marks on the bottom of the quartzite beds at Porth Llanlleiana (3875 9505) also indicate way-up (Fig. 2.15b). In thin-section, the quartzite consists of poorly sorted coarse sand, and rounded clasts supported by a siliceous and calcite matrix (Fig. 2.15). The quartzite beds are faulted against Gwna mélange (Fig. 2.16b).

The TF is composed of interbedded conglomerates and sandstone, and laminated siltstone and mudstone (Fig. 2.15). Bates (1972) found brachiopods that suggest an early Ordovician, Arenig age. The contact between the basal unit beds and the TF conglomerate is gradational in the Llanlleiana area (3820 9500) between Ogof Gynfor and Porth Llanlleiana (3875 9505; Fig. 2.13), and is abrupt elsewhere. Eroded strike slip and normal fault zones divide the succession into 2 peninsulas, geographically (Fig. 2.13). Therefore,
Figure 2.14: Ogof Gynfor conglomerate and quartzite. (a) The location where Bates (1972) showed an unconformity between conglomerate and mélange. For more details, see Barber & Max (1979). (b) A close photo of the conglomerate of Ogof Gynfor. (c) the quartzite marker beds.
Figure 2.15: (a) The PCF conglomerate showing normal grading (3960 9475). Arrow indicates younging direction. (b) The PCF in thin-section shows poorly sorted and sub-angular grains and a well defined cleavage. Sample from (3880 9515). (c) The basal conglomerate of the TF, seen at (3830 9480). (d) Well-developed cleavage within the conglomerate (3877 9515). (e) Ripple marks on the lower surface of the quartzite bed (3877 9510). (f) the quartzite in thin-section.
the PCF/TF succession is present in the Llanlleiana area (3820 9500), north of Porth Llanlleiana (3875 9505) and between Porth Cynfor (3830 9485) and Porth Wen (4090 9475), faulted against tectonised Gwna mélange (Fig. 2.13). The PCF/TF succession was interpreted to be deposited by a mass flow mechanism possibly on a very steep slope in a submarine fan setting (Al-Shammary, 1985).

**Basal quartzite beds**

Bates (1972) thought that the truncation surface shown in (Fig. 2.14) separates the conglomerate and Gwna quartzite because typically rest on a very homogeneous bedded quartzite. The other two units of conglomerate are also associated with basal quartzite unit north of Ogof Gynfor, at Porth Llanlleiana (3875 9505) and Porth Cynfor (3830 9485; Fig. 2.13). The quartzite beds are overlain by the conglomerates at Ogof Gynfor and Porth Llanlleiana, and their contacts with the quartzite beds are depositional contacts. The quartzite beds are thrust over the Gwna mélange in Llanlleiana area (3820 9500) and at Porth Llanlleiana (3875 9505; Fig. 2.16). The bedded quartzite beds at the core of the Ogof Gynfor conglomerate seem to be folded and brecciated (Fig. 2.14). This implies that the quartzite beds are associated with the conglomerates. Therefore, this study places the quartzite beds as part of the conglomerates, and distinguishes them from quartzite blocks within the mélange. The latter are tectonised and mixed with other blocks. Therefore, the lower contact of the Arenig conglomerates with the Gwna mélange is a thrust contact in N Anglesey.

**2.6.2 Black Sandstone-siltstone Mudstones (BSM) unit**

The BSM unit combines two mapped sequences: interbedded Arenig black sandstone and siltstone, and slaty blue-black Caradoc mudstone (Fig. 2.8). The unit is overthrusted by the Amlwch beds (NHG) at Porth Corwgl, on the eastern coast. They occupy most of the northeastern coast with the Nebo unit inlier, from Porth Corwgl to Dulas Bay (Fig. 2.8). From Porth Corwgl (4710 9265) to Tyllau Duon (4725 9230; Fig. 2.8), they consist of two units interbedded sandstone-siltstone and mudstone rocks. The sandstone-siltstone is called here as Porth Gorwgl Formation, which is mapped as Arenig rocks by Greenly
Figure 2.16: a- The quartzite/conglomerate depositional contact, east of Porth Llanlleiana. b- The quartzite/Gwna mélange thrust contact, Porth Llanlleiana (3875 9505). Perspective looking E.
(1919). From Tyllau Duon to Ogof Fawr (4755 9210; Fig. 2.8), the rocks have been described as comprising conglomerates with a variety of Precambrian pebbles and boulders, and breccia interbedded with mudstones (Bates & Davies, 1981). Examination of this unit for this project shows that it is a conglomeratic unit consisting of conglomerate and very coarse sand fragments in a black matrix. This unit is interpreted here as equivalent to the Porth Corwgl Formation because Greenly (1919) mapped it as Arenig rocks. The conglomeratic unit at Ogof Fawr (Fig. 2.8) is faulted against fine-grained light-green mudstones with a phyllitic fabric that passes southwards to blue-black pyritous mudstone. The phyllitic and the blue-black rocks are called here the Gwichiaid Formation, and it is Caradoc in age. The phyllite rocks were affected by low-angle thrust faults. The blue-black mudstones of Gwichiaid Formation are faulted at the Gwichiaid Slide (4790 9125; Fig. 2.8) by a normal fault zone against the Nebo unit. The Gwichiaid Formation blue-black mudstones are associated with a basal unit of coarse pebbly sandstones and thin boulder beds with a mud matrix (Bates & Davies, 1981), which are Caradoc in age (Greenly, 1919). In thin-section, the rocks at the Gwichiaid Slide (4790 9125) are fine-grained sandstone inter-bedded with hemipelagite mud, with a well defined cleavage (Fig. 2.17).
Further to the south along the eastern coastline, thin alternations of sandstones and mudstones dip and young to the north (Fig. 2.18), and are separated from the Nebo inlier by a thrust fault at Gareg Fawr (4770 8965). This is known as the Dulas Formation (DF), which contains a number of primary structures such as normal grading, bioturbation and slump structures, and is Arenig in age (Bates & Davies, 1981). The DF in thin-section shows well sorted and sub-angular to sub-rounded sandstone and siltstone (Fig. 2.18b). The thin alternations of the sand and mud beds suggest deposition by turbidites. The other Arenig conglomeratic sandstone-siltone rocks in central Anglesea, however, were interpreted as being of shallow water environment (Neuman & Bates, 1978; Neuman, 1984).

The black mudstone unit is interleaved with and faulted against mélange, gneisses, NHG, Fydlyn and Skerries units in the Carmel Head area, northwest Anglesea (Fig. 2.5). The black mudstone unit is underlain by yellowish brown sugary sandstone; together they comprise the Nant Formation (NF) of northwest Anglesea (e.g. Carter, 1988). The NF is characterised by slaty cleavage and low-dipping thrust faults cutting the cleavage, north of the Coedana granite. There are two black mudstone slivers thrustled under the NHG west and east of Carmel Head (2960 9305; Fig. 2.5). The Nant Formation is repeated inland, to the east of Ynys-y-Fydlyn (2910 9180; Fig. 2.5). Neuman & Bates (1978); Neuman (1984) interpreted the sedimentary environment of the black mudstones in central Anglesea, as being of shallow water environment.

2.7 Gwna Group

The Gwna Group encompasses diverse lithologies. It is comprised of three units: the Skerries Formation, Fydlyn beds, and Gwna mélange unit (Table 2.1). These three units of the Gwna Group are in the upper part of the Monian Supergroup (Table 2.1; Shackleton, 1975; Barber & Max, 1979; Gibbons & Ball, 1991). The lower unit of the Gwna Group (Skerries Fm.) was previously thought to be part of the NHG, and has a gradational contact with the New Harbour Group (Phillips, 1991a,b; Howells, 2007). The Gwna mélange unit of the Gwna Group was thought to have a gradational sedimentary contact with the New Harbour Group, which is the second group of the Monian Supergroup (Gibbons & Ball, 1991). Also, the Gwna Group was thought to have a similar age.
Figure 2.18: (a) Bedded sandstone and siltstone of the Dulas Formation near Ogof Fawr. (b) The DF in thin-section is bedded and affected by fracturing perpendicular to bedding.
to the New Harbour (NHG) and South Stack Groups (e.g. Muir et al., 1979; Gibbons, 1983). However, data provided in this study and presented later suggest that the contacts between the NHG and the three units of the Gwna Group are thrust contacts. In addition, the contacts that separate the three units from one another are thrusts. Also, the three units of the Gwna Group are significantly less deformed and metamorphosed than the lower two units of the Monian Supergroup (see also Barber & Max, 1979; Gibbons, 1983; Gibbons & Ball, 1991). These observations suggest that deformation and metamorphism of the Gwna Group is linked to a later deformation that is younger than the (D1-D2) deformation event that affected the South Stack and New Harbour groups. Also, the style, geometry and condition of deformation and the degree of metamorphism that occurred in the Gwna Group is similar to the deformation and metamorphism associated with the Ordovician rocks. These observations are further documented and discussed in chapter IV, which is devoted to the geology of the Gwna Group.

2.8 Silurian mudstones

Silurian mudstones are exposed at the core of the overturned syncline of Parys Mountain (Figs. 2.1, 2.19), and are Llandovernian in age (e.g. Bates, 1966; Westhead, 1993). There are unsilicified and silicified mudstones (Bates & Davies, 1981). The unsilicified mudstones are soft and contain abundant bioturbation features. The silicified mudstones are flinty with pyrite crystals and cut by quartz veins. Parys Mountain comprises a bi-modal sequence of acid lavas and tuffs, and basic lavas with associated volcaniclastic sediments (Westhead, 1993). The Parys Mountain crops out as a “hairpin-shaped” exposure of volcanic rocks that are associated with brecciated and conglomeratic rocks (Fig. 2.19; Bates & Davies, 1981). The rocks host copper massive sulfide deposits associated with the volcanic rocks, which were dated as Lower Silurian (Barrett et al., 2001). This is the only locality within the CHTB that has these Silurian mudstones and volcanics (Fig. 2.19). The conglomeratic and brecciated rocks that are associated with the volcanic rocks may represent a high energy depositional system, e.g. debris flow (Westhead, 1993).
2.9 Old Red Sandstone (ORS) facies rocks

The ORS is a general facies when referring to the Siluro-Devonian red bed sequence in the UK. The Siluro-Devonian red bed sequence is dominated by red pebbly sandstones with green reduction spots (Bates & Davies, 1981), which crop out at low tide at Trwyn Cwmrwd (492 902; Fig. 2.8). The rocks gently dip toward the east, and were correlated with the Old Red Sandstone by Greenly (1919). This unit unconformably overlies the Nebo unit near Trwyn Cwmrwd (4915 9010; Fig. 2.13). The coastline is full of boulders of those rocks derived probably from till, which were probably eroded from above the Nebo unit and Ordovician rocks. The boulders are composed of pebbles of quartz within a red matrix of sandstone. This is known as the Bodafon conglomerate, which is the basal unit of the Devonian rocks (e.g. Carter, 1988). The Devonian rocks crop out mainly south of Dulas Bay, from Traeth yr-Ora to Lligwy Bay (Fig. 2.20). Carter (1988) and Treagus (1992) showed that the Devonian sandstone and conglomerate succession is cleaved, folded and thrust faulted. The Devonian rocks comprise four formations south of Dulas Bay (Allen, 1965; Bates & Davies, 1981):
• Taeth Lligwy Formation (TLF) 25m of alternation of fine-grained red sandstones and sandy siltstones without carbonates.

• Porth Mor Formation (PMF) 350m of purple cross-bedded sandstones, red siltstones and limestones and dolomites. The lower part of the PMF contains polymict conglomerate comprising clasts of quartzite, schist, gneiss and vein quartz of the Mona Complex, and mudstone, slates and sandstone from the Ordovician rocks.

• Traeth Bach Formation (TBF) 130m of mainly red siltstone with intercalations of limestones and dolomites.

• Bodafon Formation (BF) 3-45m. mainly sandstones and siltstones, which are exposed in the core of a syncline.
Figure 2.20: Geological map from Dulas Bay to Lligwy Bay on northeastern coast of Anglesey, showing the Siluro-Devonian red beds sequence, diagram from Bates & Davies (1981). This map is to the south of the E transect area.
Chapter 3

Structural geology of the CHTB, North Anglesey: results of 3 coastal transects, deformation processes and micro-structures

Three cross-strike coastal transects were studied in northern Anglesey to document the structural features and geometry of lithological units of the CHTB. Completion of these transects involved observations and measurements of primary and secondary structures, measurements and sketches of key exposures and detailed mapping. The measured data for each transect are summarised in cross-sections, block diagrams, and on lower hemisphere stereographic projection plots. The transects are subdivided into domains based upon stratigraphic assemblages and changes in structural style; each domain is bounded by a major fault. Each transect is divided into shorter sections, for examples A-B-C etc, to follow the coastline curvature. Therefore, the transects cut across structural trends along true and apparent dip directions. The transects contain contractional structures associated with the CHTB as well as older and younger structures unrelated to the development of the CHTB. In addition, analysis of microstructures and cross-cutting features that record separate deformation events within the CHTB is included.
3.1 Transect 1

Transect 1 is 4 kms long and follows the east coast of northern Anglesey, from Point Lynas (4785 9340) to Dulas Bay (4730 8850; Fig. 3.1). The transect is divided into four domains (Fig. 3.2). Domain I is dominated by the Amlwch Beds, or the New Harbour Group (NHG). Domain II comprises the black Arenig sandstones-siltstones of Porth Corwgl Formation and Caradoc mudstones of Gwichiaid Formation. Domain III is distinguished by the Nebo unit. Domain IV contains interbedded sandstones and siltstones of the Dulas Formation and Caradoc mudstones. A fifth domain is included in the summary block diagram containing the Old Red Sandstone (ORS) unit, and described from Treagus (1992).

Transect 1 is the type section of the deformation associated with the development of the Carmel Head Thrust Belt because it contains the Carmel Head Thrust contact, and other thrust contacts that displaced older over younger rocks. This older over younger structural relationship does not always occur in the N and W transects. Also, the largest exposure of the New Harbour Group occurs in this NE domain, where it is possible to see clearly that the NHG possesses D1-D2 structures, and is cross-cut and overprinted by the CHTB related cleavage. This indicates that the CHTB thrusts and cleavage as related to a subsequent (D3) deformation. Moreover, younger structures that cross-cut D3 thrusts and cleavage are therefore assigned to D4 and D5 deformation events. The block diagram in fig. 3.3 also shows stereographic projection plots of the structural data taken from the transect area. Description and synthesis of stereoplot data follows in section 3.1.6.

3.1.1 Domain I

Domain I contains outcrops of the NHG from Point Lynas to Porth Corwgl (Fig. 3.2). The NHG is distinguished by its pale green colour due to mainly chlorite-rich rocks that formed by regional greenschist metamorphism. The NHG is typically affected by crenulation folds of both bedding (S0) and S1 cleavage (Fig. 3.4). They are asymmetrical, tight and SE-vergent folds with mainly low-angle plunges. The folds observed within domain I are dominantly part of one generation of folds of bedding and S1 cleavage, and there are no evidence of F1 folds of bedding. Therefore, these folds are considered to be part of the D2 event and are F2. Any existing F1 folds were overprinted by S1 cleavage and
subsequent shearing due to thrusting. The S1/S0 (F2) minor folds are interpreted to form a 1st-order F2 folds. There are 6 interpreted anitforms from Point Lynas to Porth Corwgl, and they vary in wavelength from 100-400 m (Fig. 3.2). This is based on changes in the style of minor folds, from Z-, through M- to S-shaped folds, and changes in the cleavage dip (Figs. 3.4, 3.5).

Thrust faults within the domain reworked and overprinted the F2 folds, and show top-to-the-south kinematics. Cleavage surfaces are associated with the S-directed brittle thrusting, and are typically steeper than the S2 cleavage. The associated cleavage related to the Carmel Head Thrust Belt is then S3 developed during D3 event. The Carmel Head thrust contact occurs at Porth Corwgl and bounds the domain to the south. The fault is inferred because the New Harbour Group is exposed north of Porth Corwgl, and the Arenig black sandstone-siltstone of Porth Corwgl Formation is exposed to the south of Porth Corwgl. In addition, on the hanging-wall of the fault, New Harbour Group F2 minor folds are reoriented, tight and plunge to the east and west. Greenly (1919) calculated the amount of the fault displacement to be at least 20 km. The Porth Corwgl Formation in the footwall are extensively cleaved by S3, which is a bedding-parallel cleavage.

Figure 3.4 and 3.5 show low-angle thrusts dipping towards the north, which exploits the S2 cleavage. The thrusts are parallel to S0/S1 surfaces. There are also S-directed apparent normal faults associated with the development of the CHTB in domain I. For example, the fault shown in Fig. 3.5-C appears to change its motion from normal to thrust sense. This fault is probably a folded thrust. The southerly dipping extensional faults could be interpreted as Reidel shears developed in response to extension occurring within the hanging-wall of the northerly dipping thrust. The thrusts surfaces seem to be planer with very thin fault zones. The thrusts have reworked the earlier structures, flattened F2 minor folds and brecciated S0/S1 surfaces.

The thrusts are cut by normal faults. This suggests that the normal fault is younger, and related to an extensional history that followed the development of CHTB. These extensional faults typically strike parallel or sub-parallel to the CHTB system, they cross-cut the thrust faults and exploit secondary surfaces such as cleavage planes and fractures. Fig. 3.6 shows minor folds overprinted by cleavage and thrust faults.
Figure 3.1: Geological map of eastern transect from Point Lynas to Dulas Bay. Map on left shows major rock units and important faults. Map on right is of same area and shows locations of exposures studied, transect segments and key outcrop locations (st. 78, etc) discussed in text or shown as figures.
Figure 3.2: Transect one from Point Lynas to Dulas Bay.
Figure 3.3: A block diagram of transect 1 and lower hemisphere stereo graphic projection for different data sets. Domain V incorporated data of Treagus (1992).
Figure 3.4: Minor folds of bedding and S1 cleavage of NHG, cut by thrusts and normal faults.
Figure 3.5: NHG F2 minor folds are cut by S3 cleavage, thrusts and normal faults.
3.1.2 Domain II

Domain II is comprised of black interbedded sandstone and siltstone and mudstone from Porth Corwgl to the Gwichiaid Slide (4790 9125; Fig. 3.1). High cliffs of this unit made it difficult to access the entire section, but profiles were produced for most of the localities visited. The domain is characterised by cleavage cut by top-to-the-south shear (C) surfaces and thrust faults. The cleavage within the Ordovician mudstones is S3 in age because S1 and S2 occur within the New Harbour Group and were formed prior to the deposition of the Ordovician overstep sequence on Anglesey. The S3 cleavage in
this domain is parallel to the bedding. The bedding is isoclinally folded, but fold hinges are very difficult to identify except in a few localities. The thrusting varies from very low-angle to high-angle. Boudins of sheared bed of sandstone are both symmetrical and asymmetrical, which are sheared by cleavage, S-C and C’ fabrics (Fig. 3.7). S-C fabrics, thrust faults, low-angle south-directed normal faults and C’ surfaces all indicate that significant simple shear strain was accommodated throughout the domain.

At Ogof Fawr, the Arenig interbedded sandstone-siltstone of Porth Corwgl Formation is faulted against the Caradoc mudstone of Gwichiaid Formation (Figs. 3.1-3.2). South of Ogof Fawr and north of Ogof Fach (Fig. 3.2), a major thrust fault zone deforms the blue-black pyritous mudstone. This fault zone is made evident by low-angle thrust faults (Fig. 3.8), and an increase of metamorphic grade from slate to green phyllite, in which the Ordovician rocks resemble the NHG. This fault zone is cut by a large normal fault that is eroded into a v-shaped gully at Ogof Fach (Fig. 3.8E,F). The normal fault trends northwesterly and dips steeply to the NE. This is typical of the normal faults throughout the transect that ignore and cross-cut older mid to low-angle thrust faults. The major thrust fault disappears south of Ogof Fach because of the effect of normal faults. Another similar thrust crops out north of Porth Gwichiaid (Fig. 3.9). Figure 3.9 shows the northern corner of Porth Gwichiaid where both the thrust fault and the cleavage have a very low-angle dip. At Porth Gwichiaid, south of the thrust fault, the S3 cleavage in the mudstone is a slaty cleavage, and is cut by thrust faults that are cut by normal faults (Fig. 3.9). A few back-thrusts cut the cleavage of the black mudstones at Porth Gwichiaid (Figs. 3.9-D and 3.10-A). The southern corner of Porth Gwichiaid shows the cross-cutting relationship between the thrust and normal faults (Fig. 3.10). The black mudstone is bounded by a major normal fault to the south at Gwichiaid Slide (4790 9125; Fig. 3.11). The Gwichiaid normal fault is about 15 m thick fault zone that dips gently to the north, and cross-cut by steeper normal faults within the fault zone. It is very difficult to give an estimate of the amount of displacement, but it has to be in kilometers because older rocks of the Nebo unit were lithified and deformed in a deeper environment that is different below the Caradoc rocks that were developed in a shallow marine environment. The Gwichiaid normal fault bounds the domain, and separates the black mudstone unit from the Nebo unit.
3.1.3 Domain III

The third domain is dominated by the Nebo unit, to the south of the Caradoc mudstone. The unit is exposed along most of the coast. Therefore, it was possible to produce many field sketches of key lithological and structural features and cross-cutting relationships. The unit is the most deformed unit along this transect. The Nebo unit was partially mapped as paragneiss due to interlayering of chlorite-rich and quartzite beds. The unit is affected by multiple fold generations, which are cross-cut by brittle thrusts and S3 cleavage. The thrust faults are cross-cut by dextral strike-slip faults, and normal faults cross-cut the thrust and strike-slip faults. The unit is also deformed by low-angle normal faults, which are kinematically linked to the thrust faults (Fig. 3.12a). The dextral fault in Fig. 3.12b strikes WNW and dips to the south. The amount of displacement is probably 1-5 meters.

South of Porth Helygen, a hanging-wall antiform cut by the underlying S-directed thrust fault is a typical example of concentric folds within this part of the CHTB (Fig. 3.13). This style of fold is kinematically linked to the adjacent thrust faults, and is considered to be a D3 structure (F3).

The field sketches of the unit reveal the effects of multiple folds, thrust and normal faults (Figs. 3.14-3.15). The multiple F1-F2 folds of S0 - S0/S1 are associated with low-grade metamorphism. The F1-F2 folds are open folds north of Porth Helygen (Fig. 3.2), and are isoclinal and recumbent folds south of Porth Helygen. Therefore, they are
Low-angle thrust surface in the phyllite rocks, north of Ogof Fach.

Map view of quartz lineation on thrust surface

On the footwall of Ogof Fach normal fault, older fabrics indicate major thrust fault overprinted by normal motion

Figure 3.8: Outcrop sketches and photos of key structural features within the black mudstone unit between Ogof Fawr and Ogof Fach.
Figure 3.9: The northern part of Porth Gwichiaid: sketches of exposures.
Figure 3.10: Porth Gwichiaid field sketches and cross-sections continued, showing cross-cutting relationship between S3 fabrics, thrust and normal faults.
Figure 3.11: The southernmost profiles of the BM unit including its faulted contact with the Nebo unit at Gwichiaid Slide (4790 9125). This fault is the boundary between domains II and III.
Figure 3.12: (a) Top-to-the-south normal fault, and (b) dextral fault, Porth Helygen.
Figure 3.13: A hanging-wall antiform in the Nebo unit

different from the concentric geometry of F3 folds, which is associated with thrusting. However, the multiple folds are cross-cut by the S-directed thrusts. Therefore, the F1-F2 folds appear to be equivalent to the NHG F1-F2 folds, which are part of D1-D2 structures.

E-W striking normal faults are listric faults and consist mainly of two conjugate sets (Fig. 3.16). The mount of displacement range of the E-W normal faults is 5-10 meters. The E-W normal faults are cut by N-S high-angle normal faults with a sinistral component, parallel to the coastline (Fig. 3.17). The N-S normal faults have larger amount of displacement, which ranges from 20-100 meters. These appear to be the latest faults that cut the structures of northeastern Anglesey. The southern boundary of this domain is a major thrust fault that thrusts this unit over the rocks of the Dulas Fm, which is a black Arenig interbedded sandstone and siltstone unit.

3.1.4 Domain IV

This domain follows the coast from Ogof Fawr to Dulas Bay (Fig. 3.1). The domain is dominated by two units, mixed Arenig sandstones and siltstones of the Dulas Formation and the black Caradoc mudstone. Each unit has a different style of folding, and they are separated by a thrust fault (Fig. 3.2). Therefore, domain IV is divisible into two sub-domains, in which the mixed sandstones and siltstones unit occupies the northern sub-domain and the mudstone represents the southern sub-domain. Also, the bedding in the northern sub-domain varies from low to high-angle dip, and it is affected by S-directed
Figure 3.14: Field sketches of the Nebo unit south of the Gwichiaid Slide (4790 9125). Blank areas in the sketches are massive blocks lacking bedding or cleavage.
Figure 3.15: Individual field sketches from the Nebo unit, continued.
Figure 3.16: Nebo unit, detailed field sketches south of Porth Helygen.
Figure 3.17: Key field sketches from the Nebo unit, north of Gareg Fawr fault.
low-angle thrust and normal faults. The southern sub-domain contains an open anticline marked by a basic sill and associated with axial planar slaty cleavage.

The domain is bounded to the north by the Gareg Fawr Thrust Fault (GFTF) (Fig. 3.18). In the footwall of the GFTF, the Arenig unit contains a asymmetrical S-vergent anticline (Fig. 3.18). The fold verges to the south directly beneath the GFTF and appears to be associated with the thrusting, and is therefore an F3 fold (Fig. 3.18). A quartz vein is associated with a S-directed normal fault in the footwall of the GFTF. The quartz vein dip suggests that fluid flow was perpendicular to the cleavage and at about 30° to the GFTF. The quartz vein exploited weak C’ surfaces. Further to the south, the bedded rocks are thrusted and normal faulted. Figure 3.19 summarises the cross-cutting relationships between the thrust and normal faults. The S-directed thrust faults are cut by S-directed normal faults. The S-directed normal faults and the open fold are cut by E-W normal faults that dip to the north and south.

### 3.1.5 Domain V

This domain is directly south of the studied transect and is dominated by the Silurian Old Red Sandstone (ORS) unit. Structural data from Treagus (1992) are incorporated here to link with data collected for this project. The ORS rocks were folded, cleaved and faulted by a major S-directed thrust fault. The fault within the ORS unit is the southernmost thrust fault known along the east coast. Therefore, it is considered the sole fault for the CHTB in northeastern Anglesey. Hence, it indicates that the thrusting associated with the development of the CHTB is post-Silurian (Westhead, 1993).

### 3.1.6 Data synthesis

From north to south, the transect is divided into five domains (Fig. 3.3). The domains are bounded by faults; most of them are thrust faults that displaced older units on top of older units. The normal fault between domain II and III is the only domainal boundary that displaced younger on top of younger units. The ORS rocks of domain V unconformably overlap the black mudstone of domain IV. However, the ORS rocks are internally affected by a S-directed fault, and are folded into a synform (Fig. 3.3). Domain I and II contain deeper more metamorphosed rocks, now juxtaposed by thrust...
Figure 3.18: Gareg Fawr thrust fault separates the Nebo unit from the Dulas Formation. The figure shows other features such as the F3 fold, and normal faults.
Figure 3.19: Key features of domain IV along NE coast. Top-to-the-south normal faults, cut by late normal faults. Also, the open fold of the Caradoc mudstone is cut by normal faulting.
faults against a unit of less metamorphosed interbedded sandstone and siltstone. Therefore, the fault-bounded domains can be interpreted as a series of foreland-vergent faults that thrusted older rocks over younger rocks. The foreland is in the southern part and the hinterland is in the northern part.

Domain I contains F2 minor folds. The F2 minor folds are interpreted to be part of a series of major asymmetrical antiforms and synforms (Fig. 3.2). The wavelength between the antiforms varies from 100-400 m. Domain II exhibits bedding-parallel S3 cleavage, and can be interpreted as a series of isoclinal folds of bedding. Domain III contains refolded beds that are equivalent to F1-F2 folds, which are open folds in the northern part, and are isoclinal and recumbent in the southern part of the domain. Domain IV comprises a hanging-wall antiform in the northern part faulted against an open fold in the southern part (Fig. 3.2). The Arenig interbedded sandstone-siltstone is thrusted over the Caradoc black mudstone in domain II and IV. Therefore, the Arenig sandstone-siltstone/Cardoc mudstone contact in domain II is also a thrust fault that overprinted their unconformable relationship. Domain V is a major open synform of bedding cut by a S-directed thrust fault near the hinge area (Treagus, 1992; Carter, 1988).

S0 Bedding, F2 minor folds, S3 cleavage, thrust faults and normal faults are plotted on equal area stereonets for the whole transect (Fig. 3.3). S1 and S2 occurs only in the NHG and the Nebo unit, but only F2 minor folds are plotted because S1 and S2 are intensively folded whereas F2 is consistent in orientation. F2 folds are tight and upright folds, and the majority have low-angle plunge to the ENE, although some plunge WSW. Poles to S0 show bedding strikes mainly to the WSW-ENE and dips to the NNW. Poles to S3 mainly plot in the south and the cleavage typically dips steeper than S0. The NNW major dip of S0 and S3 suggests that D3 is top-to-the-south. Thrust faults strike WSW-ENE, and typically dip at a lower angle than S3. The poles to normal faults suggest two conjugate sets dipping steeply towards the north and south, and striking mainly E-W.

3.2 Transect 2

Transect 2 follows the northernmost Anglesey coast from Cemaes Bay (3745 9375) to Porth Wen (4090 9475; Fig. 3.20). The transect is divisible into 3 domains bounded
by younger normal and strike slip faults (Fig. 3.21). This part of northern Anglesey is characterised by Gwna mélange units overthrust by Ordovician conglomerates and interleaved with Caradoc mudstone. The conglomerates/mélange succession is inter-thrusted with the NHG. The mélange and the conglomerates developed by olistostromal, mélange and debris flow processes (Shackleton, 1975; Schuster, 1979; Temperley, 2005). The rocks contain S3 cleavage cut by thrust faults and C shears. Crude relict bedding extends along the S3 cleavage, and is cut by imbricate thrust faults. The thrusts are also cut by normal faults. The mélange and the conglomerates developed by olistostromal, mélange and debris flow processes (Shackleton, 1975; Schuster, 1979; Temperley, 2005). The rocks contain S3 cleavage cut by thrust faults and C shears. Crude relict bedding extends along the S3 cleavage, and is cut by imbricate thrust faults. The thrusts are also cut by normal faults. The Arenig conglomerates are thrust over Gwna mélange, which suggests that they are older (Fig. 3.20). The rock units strike mainly ESE, which is slightly different from the main E-W trend of the CHTB. The conglomerates/mélange succession is separated from the NHG along strike by dextral faults, and across strike by thrust faults (Fig. 3.23). The fault is covered by coarse-grained beach deposits. However, the sense of movement was established because the New Harbour Group rocks cleavage is deflected to the north into the fault strike. Based on cross-cutting relationships, the strike-slip faulting appears to be younger than the thrusting but probably older than the normal faulting. Fig. 3.22 shows a summary of transect 2 in a block diagram, and stereographic projection of different data set, such as bedding (S0), cleavage (S3), thrusts and normal faults. Description and synthesis of stereoplot data follows in section 3.2.2.

3.2.1 Domains of transect 2

Domain I

The first domain is on the eastern side of Porth Wen (4090 9475); Fig. 3.20). The NHG in this domain is thrust faulted against Caradoc mudstone that is thrust faulted against Gwna mélange unit. The contact between the NHG and the mudstone succession contains reworked parts of the NHG within the mélange. The NHG north of the fault zone shows isoclinal folds of bedding overprinted by S-C fabrics and thrust faults (Fig. 3.24).

Domain II

The next domain is to the west of Porth Wen, and it extends from Porth Cynfor north-eastwards (Fig. 3.23). This domain has conglomerates of the Porth Cynfor Formation
Figure 3.20: Geological map of N coast of Anglesey from Cemaes Bay (3745 9375) to Porth Wen (4090 9475). Top map shows locations of all outcrops studied and location of photos and field sketches.
Figure 3.21: Transect two from Cemaes Bay (3745 9375) to Porth Wen (4090 9475).
Figure 3.22: A block diagram and lower hemisphere stereographic projections of the data of transect 2. Key: CB, Cemaes Bay; PB, Porth Badrig; BP, Badrig Point; OG, Ogof Gynfor; PL, Porth Llanlleiana; PC, Porth Cynfor; PW, Porth Wen.
Figure 3.23: (a) general view of domain II from Porth Cynfor northwards. (b) Porth Cynfor dextral fault separates the NHG and overlying rocks from the Gwna mélange unit. (c) The NHG on the hanging-wall of the dextral fault and (d) Gwna mélange to the west on the footwall.
(PCF) and Torllwyn Formation (TF), and Gwna mélange faulted over the NHG. Also, the NHG is separated from the Gwna mélange by a dextral fault at Porth Cynfor. The PCF and TF conglomerates are repeated by thrusting in this domain.

**Domain III**

The third domain of transect 2 is from Cemaes Bay (3745 9375) to Porth Llanlleiana (3875 9505; Fig. 3.20). This domain exhibits Gwna mélange faulted against the NHG (Figs. 3.25-3.27) in Cemaes Bay (3745 9375; Fig. 3.20). The Gwna mélange along Cemaes Bay (3745 9375) consists of interbedded quartzite and limestone beds. The beds are broken and elongated but they can be aligned to form a ghoast stratigraphy. The quartzite/limestone beds are faulted against the New Harbour Group. The north, the quartzite/limestone interbedding is overthrust by a tectonised broken bedded conglomeratic unit (Fig. 4.5a). To the north of this conglomeratic unit, a stromatolitic limestone is present for another 50 metres. At Porth Badrig, the mélange is formed by faulted blocks of quartzite and Caradoc mudstone, bedded limestone and blocks of jaspyre basalt. This olistostromal mélange is faulted against the carbonate rocks. From Llanbadrig Point to Ogof Gynfor, the mélange is characterised by stratified limestone and dolomite (Fig. 4.5d).
There are two thrust faults north of Cemaes Bay within carbonate blocks (Fig. 3.28). Several brittle faults also affect the olistostromal component of the mélange (Fig. 3.28). Figure 3.29 shows the Badrig Point fault (Fig. 3.20), which is a 3 metre wide brittle fault zone that contains S-C fabrics, and shows rotation of the hanging-wall rocks. This fault separates a bedded carbonate block from a bedded quartzite block within the olistostromal component of the Gwna mélange. To the ENE of the Badrig Point fault, the olistostromal part of the Gwna mélange rocks is overthrust by bedded limestone and dolomite. The carbonate rocks are also deformed by thrust faults. At Ogof Gynfor, ENE of the Badrig Point area, a hanging-wall anticline contains conglomerates of the Ogof Gynfor Fm and a basal quartzite in the inliers of the fold. The fold is evident by the repetition of the conglomerates north and south of the quartzite beds, and change in dip directions of the quartzite beds. The conglomerates are interpreted to be overthrust Gwna mélange rocks, adjacent to the hanging-wall anticline. The fold and the fault are cut by normal faults. To the ENE of Ogof Gynfor fault (Fig. 3.20), a brittle fault repeats the succession of Gwna mélange (Fig. 3.30). The above-mentioned imbricate faults dip about 50 degrees toward the NNE and trends ESE. The blocks of the olistostromal mélange are affected by boudinage, which caused further reduction in block size (Fig. 3.31).

The conglomerates/Gwna mélange succession and NHG were deformed by E-W normal faults (Fig. 3.28), which are cut by N-S normal faults. This multiple extensional history is evident also in Porth Llanlleiana (3875 9505; Fig. 3.21), in which the mélange unit in the west of the Porth is opposit to the conglomerate in the east (Fig. 3.38a). Fig. 3.38b shows the northernmost part of the third domain where conglomerate with a basal quartzite unit is faulted against mélange. This relationship is overprinted by the normal faulting that separates the two units at Porth Llanlleiana (3875 9505). The normal faults are eroded, and are part of Porth Llanlleiana (3875 9505).

3.2.2 Data synthesis

The Caradoc mudstone within the Gwna mélange is overthrust by the NHG in domain I (Fig. 3.21). The Gwna mélange is overthrust by the conglomerates in domain II (Fig. 3.20). The NHG is overthrust by Gwna mélange, which is overthrust by conglomerates in domain III (Fig. 3.20). There are imbricate thrust faults distributed throughout
Figure 3.25: Detailed structural cross-sections for Cemaes Bay (3745 9375).
Figure 3.26: Detailed structural cross-sections for Cemaes Bay (3745 9375), continued.
Figure 3.27: The northernmost part of Cemaes Bay (3745 9375): detailed structural cross-section.
Figure 3.28: (a) and (b) are two thrust faults deforming the carbonate rocks north of Cemaes Bay. (c) A thrust contact between the mélange matrix and carbonate rocks, east of Badrig Point. (d) S-C fabrics affecting the bedded carbonate block east of Badrig Point.
Figure 3.29: Detailed cross-section for Badrig Point.
Figure 3.30: Detailed cross-section for a brittle thrust zone that cuts the Gwna mélange north of Ogof Gynfor.

Figure 3.31: Disruption of blocks within Gwna mélange by pervasive boudinage of competent quartzite layer.
Figure 3.32: The Ordovician succession to the east of Llanlleiana Porth in (a) is against Gwna mélange to the west of the Porth in (b).
domain II and III (Fig. 3.22). The three domains are separated by younger faults. If the three domains are combined by ignoring and removing the deformation of the normal and dextral faults, the rocks would be Ordovician conglomerates and mudstones and Gwna mélange succession inter-thrust with the NHG, and sheared by the imbricate thrusts. NHG/Caradoc mudstone thrust in domain I may represents then a bounding thrust to a system of imbricate thrust faults. The Gwna mélange/NHG thrust in domain III may represent a leading and floor thrust. The whole transect can interpreted as a truncated duplex system (see also, Carter, 1988). The Porth Cynfor dextral fault is oblique to the S-vergent duplex and strikes NE. Interpretation of remotely sensed data (see the inset of transect 2) suggests that the Porth Cynfor fault extends and links with Cemaes Bay thrust contact to the south. Therefore, it appears to be related to the thrust system, in which it represents a tear fault.

Conversely, the transect can be interpreted as containing imbricate faults without inter-thrusting, in which the NHG is overthrust by the Gwna mélange that are overthrust by the conglomerates. The thrust faults were exhumed at different levels, and this led to changes from the NHG through the mudstones, conglomerate and Gwna mélange rocks to the NHG. The younger Ordovician rocks and the Gwna mélange were deformed during thrust fault development.

The Gwna mélange is a complex unit, which contains blocks of granite, NHG and younger conglomerates and mudstones indicating that it was formed prior to and during the brittle contractional deformation that pervasively affected it. Therefore, weathering and erosion of the NHG, and deposition and erosion of conglomerates and mudstones, preceded brittle contractional CHTB development.

Structures in transect 2 are consistent with top-to-the-south thrusting as indicated by stereoplots of S0, S3 and thrust faults for the whole transect (Fig. 3.22). The thrust fault planes and S0 are similar in orientation to S3, but they are slightly rotated toward the east (Fig. 3.22). The normal faults show a disseminated pattern, but they are poles of the E-W and N-S extensional faults. Both faults have two conjugate sets. Field work suggests that the N-S normal faults are the youngest faults in the transect (Fig. 3.22).
3.3 Transect 3

Transect 3 runs from east Carmel Head (2960 9305) to Porth Defaid (2915 8625) in northwest Anglesey (Fig. 3.33). This transect is the longest transect in the study area, and extends for 10 km. Part of the transect covers the NW corner of Anglesey. Therefore, the transect has E-W and N-S sections. The transect can be subdivided into three domains that reflect different structural styles (Fig. 3.34). Structural data of this transect are summarised in a block diagram, which includes stereographic projection of different data set (Fig. 3.35). Description and synthesis of stereoplot data follows in section 3.3.4.

3.3.1 Domain I

This domain occurs at the NW corner of Anglesey from east Carmel Head (2960 9305) to Porth Nant (3935 9140; Fig. 3.33). It consists of two component parts, E-W and N-S. The E-W section occurs from Carmel Head eastwards. The N-S section is from Carme southwards to Porth Nant (3935 9140). Domain I is dominated by large and mappable slivers of diverse rock units that dip north and are bound by thrust faults (Fig. 3.33). The E-W part of this domain is composed of NHG rocks faulted against Caradoc mudstones that are faulted against the Gwna mélange, which is faulted against a NHG sliver near Carmel Head (Fig. 3.34). The N-S part of the domain consists of the granitic gneiss overlain and underlain by black mudstone, and the Gwna Group overlain by black mudstone. There are also faults within the Gwna Group and the Caradoc mudstone.

At Carmel Head, the NHG sliver is underthrust by underthrusted by the Caradoc mudstone west of Carmel Head (Fig. 3.36), and overthrusted by a Gwna mélange sliver (Fig. 3.37). The two bounding faults of the NHG represent separate strands of the Carmel Head thrust fault, which merge into one fault inland toward the ESE (Fig. 3.33). The two faults have a very low-angle NNE dip and ESE strike. They are cut by steep normal faults that appear to follow older S3 cleavage surfaces. The lower thrust contact of the NHG occurs west of Carmel Head, and contains fabrics that indicate a dextral component of displacement (Fig. 3.36). The fabrics strike ENE-WSW, dip the north and occur in a 2 meters thick fault zone of brecciated New Harbour Group rocks. In the hanging-wall of this fault, the NHG contains an isoclinal antiform with associated minor folds that
Figure 3.33: Geological map of western transect from east Carmel Head (2960 9305) to Porth Defaid (2915 8625). Map on left shows major rock units, major faults and folds. Map on right is of same area and shows locations of outcrops studied, transect segments and key outcrop locations shown as figures.
Figure 3.34: Transect 3 from east Carmel Head (2960 9305) to Porth Defaid (2915 8625), shows geological units and structural features.
Figure 3.35: Transect 3 block diagram with lower hemisphere equal area stereonets of transect structural data.
trend parallel to the thrust fault. The minor folds are tight F2 folds and plunge steeply, and suggest that the large-scale isoclinal fold is parallel to the Carmel Head Thrust, and plunges steeply to the WNW. The Gw나 мélange sliver occupies the Carmel Head area, and is composed of carbonate and quartzite blocks surrounded by brecciated rocks that were originally from the NHG. The мélange sliver is internally faulted, and contains S-C fabrics in the brecciated NHG rocks (Fig. 3.37). The S-C fabrics are similar to the S-C fabrics found in the east that cut the slaty cleavage associated with the Ordovician rocks, which suggests that is linked to D3 thrusts. The Gw나 мélange is affected by a S-directed normal fault east of Carmel Head (Fig. 3.38a).

The Caradoc mudstones occupy the E-W part of the domain from the Carmel Head thrust fault to the Gader gneiss (Fig. 3.33). The contact between the gneisses and mudstone is a thrust contact. The contact is marked by about 1/2 meter thick fault zone that seems to be composed of fine-grained material that are originally mudstone. The fault zone is a steep fault zone, and dips towards the north. The mudstone was deformed also by low-angle thrust faults, north of the fault contact (Fig. 3.38). These faults have the style of thrust wedges with splays of imbricate faults branching off the basal faults, and they dip at a lower angle than the major fault zones. The thrust faults are bedding-parallel, and affected by a very open anticline. If the imbricate thrusts are continuous, they would cross-cut the major fault zone. The low-angle thrust faults are also cut by extensional faults. Figure 3.39-b shows a normal fault that cuts thrust faults at a high angle north of the Gader gneiss. The normal faults seem to be parallel to S3 cleavage, which is similar to the normal faults that cut the Carmel Head Thrust, further to the north. The Caradoc mudstones contain many quartz veins within S3 cleavage, north of the Gader gneisses and south of Carmel Head.

The N-S part of the domain starts with the Gader granitic gneiss, south of the Caradoc mudstone (Fig. 3.33). The gneisses are cut by spaced quartz veins, west of the northern fault contact (Fig. 2.2b). The gneissose foliation is folded, cut by thrust faults and S3 cleavage. At Porth Hwch (2930 9210; Fig. 3.33), a series of brittle thrust faults has resulted in emplacement of the Gader gneiss over the Caradoc mudstone and the three formations of the Gw나 Group. This thrust package dips gently toward the north and trends E-W. One of the main faults is the Porth Hwch (2930 9210) thrust that contains a thrust wedge geometry, in which steeper thrust faults root into the main low-angle thrust
Figure 3.36: (a) A thrust fault covered by boulders of NHG separates the NHG from the black mudstones. (b) Fabrics show dextral top-to-the-SE. (c1,2) Riedel fabrics (parallel inclined fractures) indicate a dextral component and overall dextral thrusting along this contact.
Figure 3.37: (a) A thrust fault between the mélange (above the rucksack) and NHG, Carmel Head. (b) The limestone blocks within the mélange. (c) The S-C fabrics in the footwall of a fault zone shown in (d). A camera case shown for scale. (d) The pencil is on the surface of a fault, and the compass is on a fault zone.
Top to the south normal fault affects the melange on the northernmost part of the NW area.

Figure 3.38: S-directed thrusts and normal faults of the northwestern transect. See figure 3.33 for locations.
fault. This fault separates the Fydlyn from the Skerries units (Fig. 3.40). The Hwch fault is cut by steep to vertical normal faults that affect the Fydlyn and mudstone rocks, and form a small synform bound by the faults. From Porth Hwch (2930 9210) to Ynys-y-Fydlyn (2910 9180), progressively southwards, the Gwna mélange unit is overthrust by the Skerries unit that is overthrust by the Fydlyn unit which is in turn overthrust by the Gwna mélange unit north of Ynys-y-Fydlyn (2910 9180; Fig. 3.41). Fabrics in the Gwna mélange unit, shown in figure 3.41 suggest top-to-the-south kinematics on a steep fault that trends E-W.

The Porth Hwch (2930 9210) fault cuts a large quartz vein that is almost vertical (Fig. 3.40). The presence of quartz veins along the W transect suggests an environment rich in fluid. The cross-cutting relationship suggests that the fluids exploited surfaces such as cleavage, which then cut by the thrusting. The vein is oblique to the thrust fault, in which it is oblique to the main stress ($\sigma_1$) of the thrust fault. This suggests that the vein may have formed by hydraulic fracturing induced by an increase of in pore-fluid pressure, during thrust loading.

The southern sliver of the Fydlyn unit is repeated by a major thrust fault, the Fydlyn thrust fault (Fig. 3.42). The fault dips towards the north and trends E-W, and crops out within a natural arch. The fault rotated the bedding. The thrust fault is cut by 2 sets of normal faults, which are eroded and expressed within the headland of Ynys y-Fydlyn (2910 9180). The normal faults consist of two sets of conjugate high-angle normal faults that strike SE and dip NE, and strike NE and dip NW. These faults are most likely related to post-CHTB development because they cut the thrust faults.

The Fydlyn unit is faulted against a sliver of NHG, south of Ynys y-Fydlyn (Fig. 3.33). The sliver contains well-developed S0/S1 cleavage that is cut by low-angle thrust faults. To the south, the contact between this unit and the sandstone of the Nant Formation (NF) is a north-dipping cataclastic fault zone containing broken quartz pebbles in a fine-grained matrix. Previous work such as that of Carter (1988) looked at these elongated quartz pebbles and cobbles and thought that they represent part of the Gwna mélange (Fig. 3.43). He, therefore, put a major unconformity between the cataclasite and the sandstone because the Nant Formation dips toward the south, and the NHG sliver dips toward the north. This thesis demonstrates that these elongated quartz fragments are part of a cataclasite fault zone that represents the boundary between domain I and II. This
fault zone marks a major change in dip from north-dipping imbricate slivers to steeply south dipping bedded rocks of the Nant Formation (NF) and the Skerries unit further south (Figs. 3.33-3.34).

3.3.2 Domain II

The domain starts from Porth Nant (3935 9140) in the north to Porth Defaid (2915 8625) in the south (Fig. 3.33). The first unit is the bedded Nant Formation. The Nant Formation is thrusted over the Skerries, south of Porth Nant. The fault is associated with a zone of quartz veining which cut the Skerries beds over a width of about 100 metres. This domain is more homogeneous than domain I because it is occupied mainly by the Skerries unit. The Skerries unit is affected by a series of open synforms and antiforms, south of Porth Nant to Porth Defaid (2915 8625). The gentle folds of the Skerries unit were inferred by changes in dip direction throughout the unit. However, only one hinge can be actually seen north of Porth Trefadog (Fig. 3.33).

The Skerries formation consists of two units at Church Bay (Fig. 3.33) that are separated by an overthrust. A detailed cross-section was produced for Church Bay, to show the structures within the Skerries units. Exposures in the back of the bay contain an overall open synform fold cut by normal faults. The open synform is bounded by the Church Bay overthrust to the south. The normal faults define small half-grabens.

The two Skerries units were affected by a systematic set of north-dipping fractures that are distributed throughout the unit from north to south (Fig. 3.44). The Skerries rocks were affected by steep normal fault zones that dip towards the north and the south (Figs. 3.45-3.46 and 3.47). The normal faults also cross-cut the Church Bay overthrust at high angles and strike E-W.

3.3.3 Domain III

This domain is composed of the NHG, which is separated from the Skerries unit by a S-directed thrust fault with a dextral component (Fig. 3.48). The fault is the boundary between domain II and III. The NHG F2 minor folds are refolded adjacent to the fault, and vary in trend from north - south to east - west (Fig. 3.49). The folding of F2 minor folds suggest major F3 folds run parallel to the fault contact. The F3 minor folds are
ESE-vergent asymmetric box-shaped folds (Fig. 3.49). The area also is affected by dextral faults that trend NNE, which are younger than the thrust because they cut it and the S3 cleavage (Fig. 3.50). This area was mapped in detail because of local complexity (Fig. 3.51). The area contains slivers of gneiss within the NHG. The gneiss are bound by ductile shear zones and refolded. At Porth Defaid (2915 8625), south of the gneiss slivers, the NHG does not appear affected by D3 brittle thrusting, but is deformed by sheath folds associated with S2 cleavage related to the F1-F2 folding. The domainal boundary is the southernmost S-directed brittle fault on the coast. Also, the NHG crops out continuously further south for 10 kms. Therefore, it is most likely that the thrust fault boundary of this domain is the sole fault of the CHTB in northwest Anglesey.

### 3.3.4 Transect 3: data synthesis

The transect is characterised by an unusual juxtaposition of older crystalline basement rocks adjacent to younger meta-sedimentary and volcaniclastic rocks, which are bound by imbricate thrust faults (Fig. 3.35). The granite gneisses are inter-thrusted with Caradoc mudstones, which is related to the Coedana granite, and is Precambrian in age. The NHG contains refolded chlorite greenschists, is late Cambrian in age and is overthrusted by the three formations of the Gwna Group; the Gwna mélange, the Fydlyn and the Skerries units in the northern, central and southern parts of transect 3 respectively. The faults that thrust young over older rocks could be pre-existing normal faults that have been reactivated. The Carmel Head thrust fault has a dextral component, which is consistent with S-directed motion along a curving and NW striking thrust fault (Fig. 2.1).

Domain I rocks have dominant dips to the north and domain II beds dip to the north and south (Fig. 3.35). S0 strikes E-W and dips to the south (Fig. 3.35). S3 typically has a ESE strike and NNE dip. Thrust faults typically have an average northwords dip, which are lower than S3 dips. F2 Minor fold plunges mainly concentrate in the SW corner of the stereoplot. Normal faults of this transect comprise E-W sets that strike NE and NW.
3.4 Summary of structural relationships

F1-F2 folds are the oldest structural features in N Anglesey. A stereoplot of S2 cleavage for the three transects indicates that S2 has a mean ENE strike and NNW dip (Fig. 3.52), which is consistent with SE-vergent F2 folds, but S2 cleavage was reoriented and reworked by S-C fabrics related to D3 structures in N Anglesey (Fig. 3.53). S3 cleavage in the lithological units of the CHTB is cut by thrust faults. A stereoplot of L3 mineral lineations found on shear and thrust surfaces for the three transects shows a mean NNW plunge, which is consistent with S-directed thrust faults (Fig. 3.52). D3 thrust faults are associated with F3 concentric folds (Fig. 3.53-a). N-directed back thrusts are only documented at Porth Gwichiaid (Figs. 3.9-d, 3.10-a), otherwise backthrusts are uncommon to absent in all transects. The S-directed thrust faults are cut by top-to-the-south D3 normal faults. The S-directed structures are cut by E-W normal faults, which are cut by N-S normal faults. The extensional structures are the most obviously expressed faults in the landscape and exert a strong control on the orientations of valleys and the drainage patterns of Anglesey.

3.5 Deformation events recorded within CHTB

The study area underwent mainly early compressional and later extensional events. The compressional events are divided into early and late events. The extensional history is also divided into early and late extensional events.

3.5.1 D1-D2

The NHG, Nebo and Gader units record a history of F1-F2 folding during SE-directed D1-D2 deformation and greenschist metamorphism (Phillips, 1991b). The SE-directed folding events occurred after the late Cambrian 501 ma and before the early Ordovician (Arenig) age (Collins & Buchan, 2004). The minimum age is evident by the presence of NHG clasts in the Arenig conglomerates (Tietzsch-Tyler & Phillips, 1989).
Figure 3.39: (a) shows black mudstones internally cut by S-directed thrust faults at east Carmel Head (2960 9305). The fault contact is covered but the mudstone records the deformation. (b) Thrust faults cut by a normal fault north of the Gader gneiss.
Figure 3.40: The Fydlyn rocks (light colour) are thrust over the Skerries rocks (dark colour) in the Hwch thrust zone.

Figure 3.41: Fabrics show top-to-the-south kinematics in the sliver of Gwna mélange faulted against the Fydlyn rocks. Perspective looking E. Pencil is parallel to C fabrics.
Unconformity within the Fydlyn unit
Fractures
S3
S0
Looking W
Ynys-y-Fydlyn
Vegetated
4 m
Thrust zone

Figure 3.42: The Fydlyn thrust zone.
Looking NE, outcrops of the cataclasite zone, north of Porth Nant. A pencil is for a scale.

Figure 3.43: (A) the sliver of NHG North of Porth Nant faulted by low-angle thrust faults. (B) the cataclasite zone at the southern boundary of the NHG sliver with the Nant Fm, north of Porth Nant.
Figure 3.44: (a) The steep brittle fracture set at Church Bay. (S. Temperley for scale.) (b) A closer look at one of the fractures showing its vertical attitude and discolouration due to fluid flow.
Figure 3.45: Detailed cross-sections of Church Bay. All perspectives are eastward looking (See Fig. 3.34 for complete section).

Church Bay

Foot path 30 m

Upper Skerries

Lower Skerries

Vegetated

Broken quartzite beds

A

B

C

D

Looking E

Looking E

Looking E
Figure 3.46: Detailed cross-sections of Church Bay continued. Perspectives are mainly eastward looking (See Fig. 3.34 for complete section).
Figure 3.47: Detailed cross-sections north of Church Bay. All perspectives are eastward looking (See Fig. 3.34 for complete section).
Figure 3.48: (a) Top-to-the-south kinematics of the sole fault at Porth Defaid (2915 8625). (b) the fault has a dextral component.
Figure 3.49: NHG minor folds plunge in different directions at Porth Defaid (2915 8625): (a) plunge to the north, (b) plunge to the west, (c) plunge toward the south and (d) is a box fold with more than one hinge.
Figure 3.50: (a) Left lateral strike slip fault. (b) Right lateral strike slip fault.
Figure 3.51: Detailed structural map for Porth Defaid (2915 8625) area. The major thrust zone between the Skerries unit and the NHG is the southernmost D3 thrust associated with the CHTB in NW Anglesey.
Figure 3.52: Lower hemisphere equal area stereoplots a)- poles to S2 cleavage, b)- mineral lineations.

Figure 3.53: (a) D3 style concentric fold in the NHG, with S1/S2 buckled, at Cemlyn Bay. (b) S-C fabrics superimposed on NHG West of Cemlyn Bay. See Fig. 1.4 for location.
3.5.2 D3

The D1-D2 structures are cut by the S3 cleavage and thrust faults, which also cut bedding and primary structures of the Ordovician-Devonian meta-sedimentary rocks. Therefore, the S3 cleavage and the thrust faults that are associated with the CHTB development are part of the D3 deformation event, which is a S-directed brittle thrust deformation. This event was previously included as part of D1-D2, in which the three deformation events together were known as D1-D2 associated brittle thrusting in northern Anglesey (e.g. Gibbons et al., 1994). This study separates and recognises the thrusting event as a younger event that took place in early Devonian time. D3 involved both pure and simple shear strain.

The D3 structures are cut by dextral strike-slip faulting, present in a few localities. The Carmel Head and Porth Defaid (2915 8625) thrust faults strike NW and have a dextral component, whereas the Porth Cynfor dextral fault strikes NE. This suggests that the dextral faults may be cross-strike tear structures that developed during propagation of the thrust belt towards the south. Also, dextral faults link thrust segments along strike. Therefore, the dextral faults are interpreted as late D3 structures. This suggests that D3 is slightly transpressional and partitioned at least locally (Woodcock et al., 1999: and references therein).

3.5.3 D4/D5

D3 structures are cut by two generations of brittle normal faults: E-W and N-S. The E-W extensional faults are part of the extensional history affecting the entire Irish Sea and N Wales region including northern Anglesey. These faults cross-cut thrusts and exploit secondary surfaces such as cleavages and fractures. These faults then are post-CHTB and interpreted to be related to a Permo-Triassic extensional event that affected the ORS palaeo-continent, after the collision and amalgamation of Laurentia, Avalonia and Baltica, and overlapping of the ORS succession (e.g. Woodcock & Strachan, 2000). The CHTB is not covered by sedimentary rocks that are younger than the Devonian ORS rocks. This suggests that the CHTB was followed by a long period of erosion and exhumation.

The E-W extensional faults are cut by N-S normal faults that are associated with sinistral displacements. The N-S faults are also subsequent to a NW striking swarm of
early Tertiary dykes that cut the entire island of Anglesey and north Wales (Fig. 3.54). The Tertiary dykes are cut by the Menai Straits fault that was reactivated by transtensional seismic activity (Bevins et al., 1996). The N-S faults are also transtensional and cross-cut all structures in N Anglesey. Therefore, the N-S faults may be related to the transtensional Menai Straits fault that cuts the Tertiary dykes. These faults are classified as D5 structures. The dyke swarm suggests continental stretching and volcanism in early Tertiary time, followed by younger transtensional faulting that continues today.

Figure 3.54: Processed aeromagnetic data, showing positive anomalies interpreted as dykes in the first derivative of the horizontal gradient of the magnetic anomaly field, measured in the direction N35°E, in North Wales, Anglesey and offshore. (Diagram from Bevins et al., 1996)

3.6 Deformation processes revealed in thin-section

The microstructural features in CHTB lithologies include flattening and shear fabrics, shear zones and micro-faults, kinematic indicators, and veins and dewatering structures related to polyphase deformation, metamorphism and fluid flow under both ductile and brittle conditions. Microstructures were studied in thin-section, in order to understand deformation processes and rheological changes during D1-D3. The thin-sections are from
the three transects in northern Anglesey, which are dominated by CHTB brittle deformation. Also, thin-sections of the NHG from Rhoscolyn, Holy Island (Fig. 2.1), were analysed to compare and contrast the NHG and the Gwna Group deformational history (Fig. 3.55).

### 3.6.1 Ductile deformation

Basement rocks such as the Gader gneiss, NHG and Nebo units are characterised by ductile deformation older than the D3 event. Thin-sections of the Gader gneisses reveal that the gneissic texture is very coarse, crystalline and is originally igneous (Fig. 2.3). Thin-sections of the NHG from northern Anglesey and Rhoscolyn, Holy Island (Fig. 2.1) show ductile deformation and greenschist grade metamorphism defined by chlorite and quartz dynamically recrystallised. The S2 cleavage in the NHG from N Anglesey is obliquely cut by S3 cleavage (Fig. 2.10, 3.55). Thin-sections of the NHG from Rhoscolyn lack S3 cleavage, and show S0 transposed by S1, which is in turn transposed by S2 that shows top-to-the-SE kinematics (Fig. 3.55). S1 and S2 are formed by recrystallised minerals such as quartz and chlorite. The quartz underwent dynamic recrystallisation as shown by grain-boundary crowns and undulose extinction. Also, the chlorite was affected by kinking. The deformation in the quartz and the chlorite suggests lower greenschist metamorphism at 250°–400°C temperature, in a semi-brittle mylonite or frictional-viscous crustal regime (Alsop & Holdsworth, 2004). The ductile deformation is also present in the Nebo unit, where micro-beds are folded (Fig. 3.56). Also, S1 cleavage is affected by kinking, and is defined by white mica suggesting low greenschist facies metamorphism (Fig. 2.7).

Thin-sections of the younger rocks such as the mudstone and Gwna mélangé show local crenulation folds of S3 (Fig. 3.56). The metamorphic conditions associated with crenulation fold development were low because the folds are essentially late-stage links that accommodated top-to-the-south movements. Undulose extinction and deformation lamellae and mechanical twinning within quartz clasts within fine-grained matrix indicate ductile deformation processes (Passchier & Trouw, 1996). However, quartz can deform in a semi-ductile manner under P-T conditions that promotes largely brittle conditions (e.g. Vernon, 2004). Mechanical twinning does not activate thermally, nor requires influence
Figure 3.55: Greenschist facies metamorphism and fabrics within the NHG, Rhoscolyn, Holy Island (Fig. 2.1). Different stages of S2 transposed on S1 and S0 surfaces: (a) shows micro-folding of S0 by S1 (the light bands), (b) S1 and folded S0 (in the middle), rotated by S2, (c) S0 is parallel to S1 (the thick dark band in the middle), and (d) complete transposition, S2 is parallel to schistosity, with further deformation by shear bands top to the right. (e) Thin-section of the NHG from N Anglesey showing relict S2 cross-cut by S3. (f) The previous thin-section showing S2 transposed by S3.
of confining pressure, however, it requires high differential stresses (Davis & Reynolds, 1996). High differential stresses might have been generated or enhanced by high fluid pressures.

### 3.6.2 Brittle deformation

Microfabrics

The development of the CHTB is associated with pervasive development of S3 cleavage. Thin-sections of the granite gneiss, NHG, Gwna mélange, conglomerates and mudstone, and the volcaniclastic units show that the S3 cleavage cross-cuts older structures such as gneissosity, schistosity and bedding (Figs. 3.56, 3.57), which is consistent with the macro-scale observations of cross-cutting relationships. The cleavage in thin-section is defined by alignment of phyllosilicates such as clay minerals. This cleavage is a slaty cleavage, which developed during very low or anchizional metamorphism (e.g. Vernon, 2004). S3 cleavage wraps around broken micro-beds and old clasts and indicates top-to-the-south kinematics (Fig. 3.57). The S3 cleavage is formed by growth of clay minerals and grain shape fabrics produced by flattening and enhanced by pressure solution (Fig. 3.58). Also, incompetent layers are flattened and competent layers are boudinaged.

The cleavage is cut by S-directed thrusts and normal faults at macro-scale. The cleavage is also cut by C fabrics in thin-section. The S3 flattening fabric and the shear surfaces indicate top-to-the-south kinematics. Laminated beds in the mélange and the meta-sedimentary rocks are cut by S-C microfabrics, which separate asymmetric boudins that indicate top-to-the-south kinematics (Fig. 3.59).

Microstructures and kinematic indicators

Other microstructures found in the metamorphosed sedimentary rocks include different types of strain shadows and micro-normal faults (Fig. 3.60). Pressure shadow microstructures are abundant in soft rocks, such as the conglomerates and the Gwna mélange. Flattened grains with strain fringes help define a grain shape fabric parallel to S3 (Fig. 3.58).
Figure 3.56: (a) Tight micro-fold of bedding of the Nebo unit, and cut by S3 cleavage. (b) Schistosity is defined by white mica and quartz. Shear bands cut the schistosity in the Nebo unit, and indicate top-to-the-south motion. (c) Crenulation folds of S3 in the mudstone, formed S3 by a micro-fault. (d) Crenulations of S3 in the mélange which suggest top-to-the-south shearing parallel to cleavage.
Figure 3.57: (a) S0 cross-cut by S3. Also, younger quartz veins occur along some the cleavage surfaces. (b) S3 is defined by phyllosilicate minerals. (c) and (d) Top-to-the-south kinematics formed by S0 and S3 cross-cutting relationship.
Figure 3.58: (a) Localised seam of pressure solution, overprinted by a fracture. (b) Enlarged grain shape fabric, showing top-to-the-south. (c) Grain shape fabrics are linked and form cleavage. (d) Strain fringes indicating top-to-the-south kinematics.
Some strain fringe fibrous mineral growth oblique to S3 cleavage suggests grain rotation and top-to-the-south kinematics (Fig. 3.58-d). Micro-normal faults are consistent in orientation with the macro-scale faults, and cross-cut D3 and older structures at relatively low-angle. The micro-normal faults affected rocks such as NHG, Nebo unit and mudstones (Fig. 3.60).

**Deformation mechanisms and role of fluids**

This section describes the main deformation mechanisms that are associated with D3 microstructures, such as cataclasis and dissolution, as well as the mechanical role of fluids. Cataclasis caused microcrack propagation and linkage in quartz and feldspars (Fig. 3.61). The cataclasis produced the brecciated texture of the Gwna mélange and the Skerries units. Also, cataclastic mechanisms occurred in discrete brittle fault zones. Dissolution driven by high differential stress led to redeposition of dissolved minerals at sites of low differential stress. This process contributed to cleavage and shear surface development.
Figure 3.60: Micro-normal faults (a) in the NHG, (b) and (c) in the mudstone, (d) in the Nebo unit.
in the younger rocks such as the mudstone, conglomerate and Gwna mélange, and to
development of the S3 cleavage which cross-cuts older cleavage in the basement rocks such
as the NHG and Nebo units (Figs. 3.57, 3.58). Also, flattening and pressure shadows
promoted development of (quartz dissolution) as strain shadows and dissolution seams,
and indicate a temperature of $200^\circ - 300^\circ$ C. Therefore, cataclasis and dissolution are
the two main deformation mechanisms that led to cleaved and faulted rocks with D3
(Passchier & Trouw, 1996).

Outcrop and thin-section observations suggest fluid flow occurred during multiple
stages, which explains the widespread quartz fragments in the Gwna mélange. Fluids
were squeezed and transferred prior to cleavage development, as evidenced by veining is
folded and deflected by cleavage (Fig. 3.62-a). Quartz veins are also cut by shear surfaces
and flattened. After cleavage development, fluids exploited cleavage as pathways (Fig.
3.57-a), and high fluid pressure fractured minerals such as quartz in the Skerries unit and
Gwna mélange (Fig. 3.62). High fluid pressure drove fluids upwards, which is evident by
quartz veins that cross-cut and kink the cleavage (Fig. 3.62-d). Trapped fluids within
quartz clasts became aligned and preferred weak surfaces for cataclasis (Fig. 3.62-c). Finally, thrusts may exploited as conduits at the last stage of fluid flow.

As a result, fluid flow induced pressure and caused brecciation of the rocks in macro-
and micro-scale. Fluid circulation resulted in regional metamorphism, which is evident
by veining before and after S3 cleavage development. The broken beds and scaly fabrics
that cross-cut and wrap around blocks and fragments in the mélange and the abundant
quartz veining suggest that the mélange tectonism and disruption was continuously fluid
assisted. High fluid pressure may have promoted the pseudo-ductile deformation, in which
the increased in fluid pressure caused ductile deformation in week minerals.

Trapped fluids were expelled after the development of the CHTB. This is evident in
Church Bay, in which rocks of the Skerries unit are altered by fluids along the steep frac-
tures that cross-cut D3 faults. This is also evidenced by dark staining cutting fractured
clasts in the micro-scale (Fig. 3.62-e). This suggests that fluid flow was parallel to the
E-W extensional faults, and occurred during and after rock dilation (Fig. 3.62-f).
Figure 3.61: (a) Brittle microcracks in quartz grain. (b) grain shattered by two sets of micro-fractures, and indicates top to the south. Tensile fractures are normal to the S-directed kinematics (c) Splitting of the grains by tensile fractures normal to cleavage. (d) After cataclasis, pieces of a grain are displaced.
Figure 3.62: (a) Quartz veins cut and deflected by S3 cleavage. (b) Brecciated grain in the Skerries unit affected by shearing. (c) quartz clast (lower left) is cut by tensile fracture that exploited trapped fluids. (d) A quartz vein cutting S3 cleavage. (e) Folded veins cut S0 of the Skerries unit. (f) Dark staining along microcracks suggesting fluid flowed through shattered grain during E-W extension.
Fault rocks

At Porth Defaid (2915 8625), a few meters thick fault zone is exposed (Fig. 3.51). In thin-section, the fault rock consists of brecciated Skerries and NHG rocks (Fig. 3.63). Thin-section of the D3 normal fault affecting the Nebo unit consists of cataclasite and pseudo-tachylite. Also, it contains synthetic en echelon micro-normal faults (Fig. 3.63). Therefore, fault rocks conditions suggests that they occurred in the upper frictional zone of the crust (Scholz, 1990; Alsop & Holdsworth, 2004).

Parts of the mélange unit are characterised by fault rock texture because the Gwna mélange although originally olistostromal, became tectonosomal. The olistostromal rocks are also known as debrites from debris flow process (Woodcock & Morris, 1999). Also, cataclasis is outstanding in the texture of the Gwna mélange. Therefore, the best descriptive name for the Gwna mélange in microscale is cataclastic debrites.

The NHG is incorporated in fault zones. At Porth Wen, the NHG was affected by brittle faulting, and shows boudinage and brecciation of quartzite beds (Fig. 3.63). The NHG at Carmel Head were deformed into mélange that consists mainly of brecciated NHG clasts.

3.6.3 Conclusion of microstructures

The microstructures confirm that older rocks contain evidence for D1-D2 top-to-the-SE structures and greenschist metamorphism. Also, they confirm that D1-D2 microstructures are cut by D3 microstructures. D3 microstructures and fabrics indicate top-to-the-south kinematics, and they formed dominantly in a brittle deformation environment. The D3 microstructures and fabrics are associated with very low metamorphic grade. S-directed thrust and normal fault rocks from northern Anglesey suggest that their formation occurred in the upper part of the crust, in the frictional zone. Moreover, microstructures show evidence for D4 deformation which is extensional deformation that cut bedding and cleavage.
Figure 3.63: (a) Fault breccia from Porth Defaid (2915 8625) fault contains a mixture of NHG and Skerries rock clasts. (b) The beds in the upper part of the thin-section of NHG are brecciated. (c) Top-to-the-south kinematics of the normal at Porth Helygen, E Anglesey. Also, showing pseudo-tachylite. (d) En echelon normal faults, affecting quartzite in the same normal fault at Porth Helygen.
Chapter 4

The Gwna Group: rock types, metamorphism and discussion of its tectono-stratigraphy

4.1 Introduction

The Gwna Group encompasses a very diverse assemblage of lithological units, mainly because it contains a mélange unit. Three units make up the Gwna Group: the Skerries Formation (lowermost unit), Fydlyn beds and Gwna mélange (uppermost unit; Barber & Max, 1979; Thorpe et al., 1984; Gibbons & Ball, 1991). Observations of these three units suggest that they have primary structures such as bedding, and secondary structures such as S3 cleavage and D3 thrust faults associated with the CHTB. They have also experienced fewer deformation events, and less metamorphism than the New Harbour and South Stack groups. In northwest Anglesey, the Gwna Group is exposed from Porth Hwch (2930 9210) to Ynys-y-Fydlyn (2910 9180; Fig. 2.5), where the Fydlyn unit is faulted against the Skerries unit which is faulted against the Gwna mélange.

4.2 Skerries rocks

The Skerries rocks consist of upper and lower units that are separated by a thrust fault (Fig. 3.40). This subdivision is significant because previous workers interpreted the
upper unit of the Skerries unit as the Gwna mélange (Phillips, 1991a,b; Howells, 2007). Therefore, it was incorrectly suggested that the contact between the Skerries Formation and the Gwna mélange is gradational instead of tectonic (Greenly, 1919).

### 4.2.1 Lower Skerries Formation

The lower Skerries unit consists of weathered yellowish-green massive volcaniclastic conglomerate, sandstone and siltstone, which was previously called the Church Bay tuffs (Greenly, 1919). This lower Skerries unit occurs mainly in the western part of northern Anglesey, from Porth Nant (3935 9140) to Porth Defaid (2915 8625; Fig. 2.1). The unit is faulted against the Nant Formation to the south of Porth Nant. A sliver of the volcaniclastic lower Skerries unit is also found within the Gwna mélange at Porth Hwch (2930 9210; Fig. 2.5). The conglomerate of the lower Skerries unit contains flattened dark green clasts, and crops out mainly north of Church Bay (3000 8975; Figs. 2.1, 4.3). The Skerries unit in thin-section shows banding and brecciation as well as volcanic fragments and fine-grained bedded sandstone and siltstone in a mud matrix (Fig. 4.1). Brittle fractures and veining are widespread, suggesting significant fluid flow during deformation (Fig. 4.1).

At Porth Trefadog (2930 8630), about 300 metres north of Porth Defaid (Fig. 2.5), the lower Skerries rocks are composed of fine-grained greenstone formed mainly by mafic hyaloclastite. The unit coarsens toward the north, where sandstone and breccia occur between Porth Trefadog and Church Bay (3000 8975). The unit also possesses primary sedimentary structures such as cross-bedding (Fig. 4.2). At Porth Trefadog, the Skerries unit appears to contain pillow lavas (Fig. 4.2). However, after close examination, the pillow shapes are merely weathered patterns on fractured beds. The rocks also show evidence of upward fluid transport, via networks of veins that were later folded (Fig. 4.2).

### 4.2.2 Upper Skerries unit

The upper unit contains predominantly quartzite beds interbedded with sandstone and siltstone. The upper unit was mapped as mélange by Greenly (1919) mainly because of the broken quartzite beds and elongated blocks in the hanging-wall of a thrust fault at Church Bay (3000 8975; Fig. 4.3), where the upper Skerries unit is faulted over the lower
Figure 4.1: (a) Banding of the Skerries meta-sandstone and meta-siltstone, with a large volcanic clast on the top. The quartz veins are folded and inclined, sample from 2945 8775. (b) Evidence of brecciation and flow, and brittle normal faulting. The light brecciated clast is fractured hyaloclastite, sample location 2953 8775.
Figure 4.2: The lower Skerries rocks show (a) broken beds that look like pillow lavas at Porth Trefadog, (b) map view of the typical fractured appearance of the Skerries rocks, location: 8690 2895, (c) tilted fractures and veins; bedding is almost flat, Porth Trefadog, and (d) cross-bedding location: 2971 8795.
Figure 4.3: (a) The broken quartzite beds at Church Bay (3000 8975). (b) The quartzite beds of the Upper Skerries below the conglomerate of Lower Skerries, north of Church Bay (3050 8945).

Skerries unit (Fig. 3.45). The two units of the Skerries sequence are affected by a series of folds from Porth Nant (3935 9140) to Porth Defaid (2915 8625; Fig. 2.5). The sequence is also affected by steep normal faults and fractures. The fracturing of the Skerries units is very intense and is formed mainly by two E-W striking conjugate sets. Fracturing led to escape of fluids that stained the fractures an ochrous colour. These fractures are part of the D4 extensional fault array.

4.3 Fydlyn rocks

The Fydlyn unit consists of coarse sandstone and conglomeratic beds which dip gently to the north. The unit is more bedded than the Skerries unit, and bedding dips gently toward the north. It also is characterised by a pale yellow and green colour. The Fydlyn
rocks are found in northwest Anglesey at Porth Hwch (2930 9210), south of the Coedana gneisses (Fig. 4.4; Fig. 2.5). They are thrust over the Skerries rocks and overlain by black Caradoc mudstone. At Ynys-y-Fydlyn (2910 9180; Fig. 4.4), the Fydlyn unit is repeated. It is also overthrust from the north by the Gwna mélange, and is faulted against NHG sliver to the south (Fig. 3.41). The Fydlyn beds are similar to the Gwyddel Formation of Llyn (Fig. 1.4), and the Gwyddel Formation is considered younger than the Gwna mélange (Matley, 1928; Shackleton, 1975). Gibbons (1983) challenged this interpretation and proposed that the Gwyddel Fm. is a large allochthonous block within the mélange. Barber & Max (1979) suggested a Caradoc age to the Fydlyn beds rather than Monian.

4.4 Gwna mélange

The mélange unit north of Cemaes Bay, near Badrig Point (3730 9455; Fig. 2.13) comprises fragments which include quartzite, limestone, dolomite, greywacke, black mudstone, and jasper set in a phyllosilicate-rich "scaly" matrix. The jasper blocks are abundant (Fig. 4.5). They were previously interpreted as altered basaltic pillow lavas because of their very dark and rounded weathered surfaces, and were then described as jaspery pillow lavas or jaspery basalt (Muir et al., 1979; Gibbons, 1983). In the vicinity of Badrig Point (3730 9455; Fig. 2.13), the classic mélange described first by Greenly (1919) is exposed. The mélange is also found at Cemaes Bay (3745 9375; Fig. 2.13), and is formed mainly of limestone and quartzite which are the main massive components of the Gwna mélange (Fig. 3.25-3.27). This part of the mélange is interpreted to be olistostromal in origin (Shackleton, 1975; Schuster, 1979; Temperley, 2005). The Gwna mélange at Carmel Head (2960 9305; Fig. 2.8) is mainly composed of breccia fragments of NHG supported by a phyllite matrix surrounding carbonate and limestone blocks. A clast of granite was found in the mélange and is probably related to the Coedana granite (Horak et al., 1996). Therefore, the tectonised blocks vary in age from Precambrian to late Ordovician (Caradoc).

Most of the mélange blocks are elongate and define a ghost stratigraphy (Fig. 4.5). The limestone blocks are stromatolitic and show evidence of soft sediment deformation (Fig. 4.5). A well-developed anastamosing fabric in the matrix wraps around the fragments and commonly is a shear fabric kinematically consistent with bounding thrusts in the
Figure 4.4: (a) The light yellowish bedded Fydlyn unit thrust over the Skerries unit at Porth Hwch (2930 9210). (b) View north of bedded Fydlyn rocks north of Ynys y-Fydlyn headland. (c) Ynys y-Fydlyn (2910 9180) headland, where Ynys-y-Fydlyn thrust zone. (d) Brecciated Fydlyn rocks at Ynys-y-Fydlyn fault zone.
Figure 4.5: (a) The broken-bedded Gwna mélange north of Cemaes Bay (3732 9390). (b) Darkly weathered jaspery basalt, Porth Badrig (3750 9430). (c) Stromatolite limestone containing soft-sediment isoclinal folds. Location of figure 3705 9405. (d) View east of ENE-dipping limestone and dolomite blocks which help define a ghost stratigraphy in the mélange, ENE Badrig Point (3730 9455).
CHTB (Fig. 4.6). The cleavage anastomoses around pebbles, cobbles and ghost bedding within a relatively homogeneous fine-grained matrix of sandstone and siltstone. The Gwna mélange and NHG are separated by a thrust fault contact, which is observed in Cemaes Bay (3745 9375) and Carmel Head (2960 9305; Figs. 2.13 and 2.5).

A sulfur-rich blue-black Caradoc mudstone sliver within the Gwna mélange is similar to the other Caradoc rocks within northern Anglesey, and is known as the Gynfor Formation. The sulfur-rich mudstone in northernmost Anglesey, is faulted over quartzite, and it is part of the Gwna mélange, at Porth Badrig (3730 9455, Fig. 4.7; Fig. 2.13). The mudstone sliver is affected by S-C fabrics that indicates S-directed kinematics, which is consistent with D3 deformation. The Caradoc mudstones, the Arenig Ogof Gynfor For-
Figure 4.7: The Caradoc mudstone is part of the mélange, with top-to-the-S fabrics. Photo from Porth Badrig (3755 9435).

mation and Porth Cynfor/Torllwyn conglomerates succession within the Gwna mélange are mappable slivers, between Porth Badrig and Porth Llanlleiana (Fig. 2.13). The Caradoc Gynfor Fm. unconformably overlies the Ogof Gynfor conglomerate, and is down faulted beneath the carbonate of the Gwna Mélange, to the north of Ogof Gynfor (Fig. 2.13). The Caradoc mudstone slivers in northern Anglesey vary in thickness from 4 - 90 metres, and may have been deposited in shallow marine setting and not by a mass flow (Al-Shammary, 1985). Therefore, the Ordovician slivers might have been caught up and juxtaposed with other blocks of the olistostromal mélange during D3 tectonism.

Some previous workers have mapped the Gwna mélange matrix as greenschist grade (Greenly, 1919), asserting that it is similar to the NHG in outcrop appearance. However, Schuster (1979) described the Gwna mélange matrix as arenaceous mudstone. It has also been described as thrust zone fault rocks (S. Temperley, person. comm. 2006). The matrix varies in colour from green to grey. The mélange matrix in Cemaes Bay (3745 9375) and at Carmel Head (2960 9305) comprises green brecciated rocks, whereas the matrix further north from Badrig Point (3730 9455) to Porth Wen (4090 9475) appears
more fine-grained and grey in colour. Therefore, to better document the variations in the lithological constituents, the mélange matrix textures and structures, textures and lithological constituent, the mélange was carefully examined in the field, and oriented samples were taken from separate mélange matrix zones.

The mélange matrix in thin-section, between Cemaes Bay and Llanlleiana area, was found to have exotic fragments of different lithics, e.g. quartzite, limestone, NHG and igneous rocks (Fig. 4.8), which is similar to the outcrop-scale olistostromal mélange. The clast in Fig. 4.8b is from a jasper-rich phyllite, which is volumetrically a small component within the New Harbour Group. Also, it is a detrital component that occurs throughout the Monian Supergroup (Greenly, 1919). At Carmel Head, the mélange consists of brecciated sandstone, quartzite and elongated NHG clasts within a silty and muddy matrix. The rocks show pale yellow colours with ghost stratigraphy, making them appear similar to fault rocks. In thin-section, the mélange shows a variety of NHG fragments (Fig. 4.8).

At Porth Cynfor (3830 9485; Fig. 2.13), a fine-grained grey mélange occurs beneath the Arenig conglomerates. This is a narrow zone of Gwna mélange that extends to the south of Porth Wen, below the purple Porth Cynfor and Torllwyn formations and above the NHG. It is composed of laminated sandstone and siltstone that is boudinaged, cleaved and fractured. It is also characterised by well-rounded pebbles and cobbles clasts of quartz within the fine matrix (Fig. 4.8); this is the arenaceous mudstone Schuster (1979). One thin-section reveals a clast of the NHG which contains an isoclinal fold (Fig. 4.8f). This means that there was an unconformity between the mélange/conglomerate succession and the previously deformed NHG. This narrow zone of Gwna mélange that is composed of dismembered and stratified siltstone-mudstones rocks may have originally been an Ordovician sequence that was incorporated into the Ordovician/NHG thrust contact (Fig. 2.13).

4.4.1 Summary of the Gwna mélange lithological variations

Based on observations from the three transects main areas, three rock types are distinguished in the Gwna mélange. In northernmost Anglesey, the Gwna mélange consists of two different lithological units. The Gwna mélange in Cemaes Bay - Ogof Gynfor area is an olistostromal mélange, and composed mainly of quartzite, limestone and dolomite. The
Figure 4.8: Photomicrographs of Gwna mélange lithological characteristics and structural fabrics (a) granitic clast surrounded by pebbly matrix, sample location 3750 9465, (b) NHG clast suggesting that NHG deposition, metamorphism and erosion preceded development of Gwna mélange, sample located at 3875 9510, (c) eroded sandstone and siltstone beds and boudins, sample from 3940 9460, (d) limestone lithic around arenaceous fine-grained matrix, sample location 3735 9463. (e) Mélange matrix bedding (inclined) cut by cleavage (flat), (f) a clast of NHG and has an isoclinal fold, south of Porth Wen (3995 9457). (g) The mélange at the Carmel Head (2960 9305) is formed mainly by clasts of NHG in fine-grained matrix.
Gwna mélange below the Arenig conglomerate succession, in the Porth Cynfor - Porth Wen area is composed of a dismembered formation of laminated sandstone and siltstone, and clasts in a fine-grained grey matrix. The Gwna mélange in the Carmel Head area consists mainly of brecciated NHG clasts in a fine-grained matrix. Therefore, mélange lithologies vary by region and along strike.

4.4.2 The texture of the Gwna mélange

Woodcock & Morris (1999) showed how a debrite can develop in five stages by listric faulting and gravity sliding. At stage one, the debrite consists of bedded rocks with a marker bed (e.g., quartzite). At stage two the beds are fractured and blocks are displaced, at stage three they are disrupted, at stage four only a ghost stratigraphy remains and at stage 5 the debrite is dominantly broken material in a low or high matrix mass flow deposit. The presence of a ghost stratigraphy in the Gwna mélange indicates that it contains intensely fractured, brecciated and disrupted internal layers which is consistent with a debrite deposit formed due to down-slope (olistostromal) movements. The Gwna mélange in the micro- and macro-scale have shown clearly that it contains evidence of deposition by olistostromal or debris flow processes. The Gwna mélange fractured and dismembered appearance at micro- and macro-scale clearly suggests that deposition by olistostromal or debris flow processes was affected by cataclasis, shearing, boudinage and pressure solution which cross-cut the original sedimentary features. Therefore, the Gwna mélange can be described as cataclastic debrites with ghost stratigraphy. Also, this suggests that the Gwna mélange underwent deformation during deposition, and during development of the Carmel Head Thrust Belt. Thus, the Gwna mélange appears more deformed than older units of the Gwna Group and the Ordovician rocks.

4.5 Perspective on metamorphism with the CHTB

The NHG and Gwna mélange reveal different petrographic textures and exhibit different styles of deformation. The NHG in northwestern Anglesey is characterised by greenschist metamorphism and recrystallisation of chlorite and quartz (Fig. 4.9), which represent the main mineral phases depending on whether the protolith was pelite or psammite. Greenschist facies metamorphism accompanied transposition of two generations of cleav-
Figure 4.9: Comparison of the NHG and Gwna mélange fabrics. (a) S2 Crenulation cleavage cutting S0/S1 in the NHG phyllites at Rhoscolyn, Holy Island. (b) S3 cleavage and local brecciation of mélange matrix and quartz, with no evidence of recrystallisation, sample location 3735 9463.

In contrast, the Gwna mélange shows no evidence of quartz or mica recrystallisation, nor greenschist metamorphism. There are no true schists in the mélange whereas the NHG rocks are typically phyllites and schists. Moreover, exotic lithics of older rocks such as NHG phyllite clasts in the mélange demonstrate that the deposition, metamorphism and erosion of the NHG clearly predate the creation of the mélange. The mélange possesses no old structures (S1 and S2) apart from bedding (S0) that is cut by CHTB-associated...
cleavage. The cleavage in the Gwna mélange consists of anastomosing fabrics and is less intensely developed than the penetrative S1-S2 fabrics of the NHG. The mélange exhibits characteristics of a tectonised olistostrome because it consists of exotic blocks that are mainly of sedimentary origin, in a fine-grained matrix cut by cleavage. Deformation occurred under anchizional or very low-grade metamorphism, and cleavage seams are filled with clay minerals, not low-grade micas. Cleavage in the Gwna mélange formed by compaction and pressure solution, cataclasis, grain-size reduction, comminution and flattening of fragments, and simple shear (Fig. 4.9b).

4.6 Discussion of the Gwna Group litho-stratigraphy

4.6.1 Observations

- Data presented in previous chapters and this chapter suggest that the Gwna Group is affected by cleavage, S-C fabrics and thrust faults that are kinematically linked to D3 structures. The same structures affected the Ordovician rocks, which preserve no history of deformation prior to D3.

- In thin-section, the Gwna Group rocks are affected by brittle deformation processes that also affected the Ordovician rocks. Micro-structures show top-to-the-S kinematics, which are consistent with macro-scale structures. The metamorphic grade in the Ordovician and Gwna Group rocks is anchizional.

- The Gwna mélange unit of the Gwna Group contains mappable slivers of the Ordovician rocks. It also contains slivers from the Skerries and the NHG rocks.

- The lower contact of the Gwna mélange is a thrust with the NHG (Fig. 3.25). The upper contact of the Gwna mélange is also a thrust contact with the Ordovician rocks (Fig. 2.16). The Gwna mélange is also overthrust by the Skerries and the Fydlyn beds (Fig. 4.4). The Fydlyn beds are unconformably overlain by the Caradoc mudstones.
• The Gwna mélange is thrust over the NHG in the northernmost part of N Anglesey, whereas the Skerries beds are thrust over the NHG in the southwestern part of N Anglesey (Fig. 3.48).

• The Gwna mélange contains detrital clasts of the NHG.

4.6.2 Conclusions

• The Gwna mélange is a tectonic unit that deformed during deposition, and subsequent contractional development of the CHTB.

• The Gwna mélange is younger than the Fydlyn beds and younger than the Skerries Formation which is the lowermost unit of the Gwna Group.

• The Gwna Group is younger than the NHG, and has an Ordovician age.

• The Gwna Group is detachable from the Monian Supergroup and is most closely affiliated with the Ordovician rocks.

• The proposed tectonic contact between the NHG and the Gwna Group by Barber & Max (1979) is confirmed in this study.
Chapter 5

Structural data synthesis and tectonic implications

In this chapter, structural data from each transect are synthesised to draw wider conclusions on the 3D architecture of N Anglesey. It also includes the tectonic setting of the Mona Complex prior to the development of the CHTB (Fig. 5.1-a). A map that reflects the new results found in this thesis and an evolutionary model for the CHTB development are included in the end of the chapter.

5.1 Synthesis of structural data

This section summarises the tectonic stratigraphy and key structural observations revealed within each transect leading to an overall interpretation of the cross-sectional structural architecture.

5.1.1 Summary of individual transect structural architecture

E transect

The E transect is mainly occupied by the NHG, the Ordovician cover and the Nebo unit inlier, which is unique to this transect. The NHG and the Nebo units represent the basement rocks, in which D1-D2 structures are cross-cut and reworked by D3 structures. Both basement rock units are thrusted over Arenig interbedded sandstones-siltstones in
the northern and the southern part of the transect. The Arenig sandstone-siltstone unit is the basal unit of the Ordovician cover. It is thrust over the Caradoc mudstones that cover about half of the CHTB area in N Anglesey (Fig. 2.1). The NHG records ductile contractional deformation, and exhibits S-vergent asymmetrical F2/F3 folds that vary in wavelength from 100 - 400 metres. The Nebo unit exhibits open and isoclinal F2 folds that have 200 - 400 metre wavelengths. The Ordovician rocks are characterised by isoclinal folds and S-C fabrics that are contemporaneous with the D3 thrusts. There are also concentric and open folds in the Ordovician rocks, associated and contemporaneous with the D3 thrust faults. The N dips of the major thrusts are consistent with an overall S-directed imbricate thrust wedge interpretation (Fig. 5.1-b). Conservative extrapolation of thrust contacts to depth suggest that they may root into a sole thrust which may break the surface as the southernmost thrust fault along the east coast identified in the ORS (Fig. 3.3). The transect is also affected by E-W normal faults that cross-cut all contractional structures. The E-W faults are cut by N-S transtensional faults.

N transect

The N transect geology is unique within N Anglesey because it is occupied by olistostromal mélangé and debris flow conglomerates that are covered by black mudstones. These units are mainly exposed as a Mudstone/Conglomerate/Gwna mélangé (MCGM) succession, inter-thrusted with the NHG. Also, several brittle thrusts cut and repeat the MCGM succession, with no evidence of folding except in one locality. The rock units are also cut by S-C fabrics. The MCGM succession is cross-cut and repeated by S-vergent imbricate thrusts that are cut by dextral faults (Fig. 2.13). A conservative extrapolation of the imbricate fault dips suggest that they root into a floor thrust that thrusted the MGGM succession over the NHG at Cemaes Bay (3745 9375). The last thrust fault bound and transported the NHG over the MCGM succession. As a whole, the structural architecture comprises part of a S-vergent truncated duplex bound by basement rocks (Fig. 5.1-b). The imbricate thrusts are cut by a dextral fault along strike at Porth Cynfor (3830 9485) that probably represents a late-stage D3 tear fault or a lateral ramp (Fig. 2.13).
Figure 5.1: (a) Tectonic setting of SE, central and NW Anglesey including D1-D2 events. (b) Thrust wedge models for W, N and E transects representing D3 deformation event. (c) The current structures of the E and W transects including D5-D6 extensions. Note sections in B show CHTB architecture prior to subsequent N-S stretching. Thus, sections B and C are scaled exactly the same.
**W transect**

The W transect is lithologically distinctive in N Anglesey because it contains a variety of inter-thrusted rock types not found in northern and eastern Anglesey, including granitic gneisses and deformed volcanic and volcaniclastic rocks. These units crop out as thrust slivers bound by the NHG in NW Anglesey from E Carmel Head (3055 9300) to Porth Defaid (2915 8625; Fig. 3.34). Many thrust contacts have younger rocks in the hanging-wall thrusted over older rocks in the footwall. Most rock units except the Gader granitic gneiss are structurally repeated 2 - 3 times within this transect, and the Caradoc mudstone is repeated more than three times. The northern 1/3 of this transect has a high thrusting density, in which a thrust contact crops out every 200 to 400 metres. The southern 2/3rds of the transect exhibits mainly a series of open synforms and antiforms of the Skerries unit, apparently uncut by thrusts. A conservative extrapolation of the consistent northerly thrust dips suggests a S-vergent thrust wedge that may have partially inverted extensional faults (to account for the younger over older relationship), as well as incorporating various rock slivers such as granite gneiss and NHG. Bates (1974) provided sedimentological evidence for syn-sedimentary faulting during the deposition of at least the basal part of the Ordovician sequence. Also, there is an evidence of syn-sedimentary movement on the Llyn Traffwll Fault which forms the boundary between the New Harbour Group and Coedana terrane in W Anglesey (Phillips, per. comm., 2008). These faults may have accommodated movement during this syn-sedimentary phase of activity. These faults would have effected the Monian Supergroup and older rocks, as well as parts of the Ordovician sedimentary sequence (Beckly, 1987). These faults were then inverted during Carmel Head Thrust Belt development.

The thrusts may root into a sole fault, which is exposed as the southernmost thrust fault along the transect at Port Defaid (2915 8625). The Port Defaid (2915 8625) thrust fault is cut by a N-S dextral fault, which is a relationship also seen with the CHTB at Porth Cynfor (3830 9485). Also, the Porth Defaid (2915 8625) and Carmel Head thrusts contain dextral components as revealed by shear surfaces and fabrics (Figs. 3.12, 3.36). The dextral displacements represent a late stage D3 event. The transect is also affected by steep E-W normal faults that cross-cut the thrust faults.
5.1.2 Important stratigraphic and structural similarities and dissimilarities between the three transects

The NHG and the Caradoc black mudstone are the most widely exposed units in N Anglesey, and continue along strike within the CHTB region (Fig. 5.2). In contrast, the Gwna mélange unit is only exposed in the N and W transect areas. The Skerries unit, the Fydlyn beds and the Gader gneisses occur only in the W transect area. The Arenig conglomerates occur only in the N transect area. The Nebo unit, the Arenig interbedded sandstone-siltstone beds, and the ORS unit are limited to the E transect area.

The Nebo unit occurs in the middle of the E transect, and east of the Coeden beds or South Stack Group (SSG), which is overthrusted by the NHG (Fig. 2.1). The Nebo and the Coedana units are exposed as slivers parallel to each other along strike in map view (Fig. 2.1). The Nebo unit is similar to the SSG in containing multiple F1-F2 folds and associated metamorphism, and in containing similar microfolds of bedding in thin-section (Greenly, 1919). Also, the SSG and the Nebo unit are thrusted over Ordovician rocks. Therefore, the Nebo unit is a sliver that may be correlative with the Coedana beds (SSG). The southern part of the Nebo unit is similar in colour and composition to the ORS unit, suggesting that the Nebo unit has secondary Fe-oxide alteration perhaps derived from ORS Fe-bearing fluids.

The NHG and the Nebo unit (equivalent to the SSG) are interpreted as the basement rocks of the CHTB for the following reasons. The NHG and Nebo units have a greenschist metamorphic grade defined by chlorite-quartz schists and phyllites. The two units are thrusted over the Arenig conglomerates and sandstone-siltstone units, which are the basal units of the Ordovician cover. The metamorphic grade in the Ordovician and Gwna Group rocks appears lower than greenschist facies based on textural and microstructural evidence. The older F1-F2 structures in the NHG and Nebo units were reworked and overprinted by D3 structures. D3 structures cross-cut only bedding in the younger rocks, such as the Ordovician and Gwna Group units. The Gwna mélange rocks contains detrital clasts of the NHG. Also, Arenig conglomerates containing NHG clasts are believed to be unconformably deposited on the NHG in central Anglesey, which was overprinted by Carmel Head Thrust in N Anglesey (e.g. Greenly, 1919; Bates, 1963, 1968, 1972, 1974).
Figure 5.2: Major structures and lithological units within the CHTB.
The Gwna Group is comprised of three units in the W transect. From older to younger, the Gwna Group is composed of the Skerries unit, the Fydlyn beds and the Gwna mélange (Barber & Max, 1979; Thorpe et al., 1984; Gibbons & Ball, 1991). This stratigraphic order is upright because primary cross-bedding is found in the Skerries unit and indicates normal way up. The Fydlyn unit and the upper part of the Skerries unit that are exposed at Church Bay have a similar yellowish-brown appearance at exposure, and tectono-stratigraphic relationship to the lower Skerries unit (green conglomerate), in which the yellowish-brown upper Skerries and the Fydlyn units are both thrusted over the green lower Skerries rocks. On this basis, the Fydlyn and upper Skerries beds are correlated.

The Gwna mélange fractured and dismembered appearance clearly suggests deposition by olistostromal or debris flow processes that was affected by cataclasis, shearing, boudinage and pressure solution which cross-cut the original sedimentary features. The Gwna mélange underwent deformation during deposition, and during development of the Carmel Head Thrust Belt, therefore, it appears more deformed than older units of the Gwna Group and Ordovician rocks. Its lithologies vary along strike and by region because in N Anglesey, it is composed of olistostromal mélange, which is separated by the Porth Cynfor dextral fault from dismembered formation of mainly laminated sandstone and siltstone. In NW Anglesey, the mélange is composed of brecciated NHG clasts in fine-grained muddy matrix.

The NHG and the Gwna mélange are similar in that they contain slivers of exotic rocks within fine-grained material. The NHG contains paragneisses and serpentinite slivers, whereas the Gwna mélange unit contains blocks and clasts of granite, carbonate, quartzite, NHG, conglomerate, sandstone and mudstone. This suggests that both units are tectonic complexes (see also, Phillips, 1989), but their adherent clast types and metamorphic grade suggests that they formed in different tectonic settings.

5.1.3 Tectonic stratigraphy

The units in the E transect have both unconformable and normal stratigraphic relationships, which were overturned by thrusting. The N and the W transects have some sections with normal stratigraphic order after thrusting because locally younger rocks are
thrusted over older rocks. Therefore, in the 3 transect areas, the thrust history has com-
plicated the original stratigraphic succession. However, various structural and lithological
observations suggest the following original stratigraphic order (Table 5.1):

- The Gader gneisses are the oldest rock unit.

- The NHG is younger than the Gader gneisses. The NHG, Nebo unit and Gader
gneisses represent the basement of the CHTB.

- The Nebo unit is interpreted as a sliver of the SSG.

- The NHG is unconformably covered by the Arenig conglomerates and the interbed-
ded sandstones-siltstones.

- The Arenig interbedded sandstone-siltstone was unconformably covered by the Caradoc
  mudstone.

- The Gwna mélange is the upper unit of the Gwna Group, and is underlain by the
  Fydlyn beds and the Skerries rocks. Also, the upper Skerries beds at Church Bay
  are correlated with the Fydlyn beds.

- The Silurian black mudstone and the ORS are the youngest rock units incorporated
  into the CHTB. The tectonic stratigraphy with previously studied age controls are
  summarised in table 5.1.

### 5.2 Tectonic implications

This section addresses the tectonic significance of the CHTB in northern Anglesey. The
lithological and structural data imply that the CHBT in northern Anglesey has a tectonic
history that is younger than, and differs significantly from, adjacent areas of western,
central and SE Anglesey.
<table>
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<td></td>
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<td>ORS rocks</td>
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<td>vii</td>
<td>?</td>
<td>Gwna mélange</td>
<td>Gwna mélange</td>
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<tr>
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<td>Caradoc$^{(2),(4)}$</td>
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<td>black mudstone</td>
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<td>v</td>
<td>Arenig-Caradoc</td>
<td>Fydlyn beds</td>
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<td>iv</td>
<td>Arenig$^{(2),(4)}$</td>
<td>Skerries unit?</td>
<td>Conglomerates</td>
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<td>iii</td>
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<td>Nebo unit (SSG sliver)?</td>
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<td>i</td>
<td>late</td>
<td>Gader gneisses</td>
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Table 5.1: The fault-bound rocks from older to younger, and in which transect they crop out.

Key: CG; Coedana Granite. NHG; New Harbour Group. SSG; South Stack Group. ORS; Old Red Sandstone. (1; 2; 3; 4; 5 and 6 respectively after Horak et al., 1996; Greenly, 1919; Collins & Buchan, 2004; Bates, 1972; Barrett et al., 2001; Westhead, 1993)
5.2.1 Tectonic setting of western, central and SE Anglesey

The Monian complex (including N Anglesey) was thought to be part of a SE dipping subduction zone beneath the Monian rocks (e.g. Dewey, 1969). The lithological units in SE Anglesey suggest a subduction history (Wood, 1974). SE Anglesey contains slivers of blueschists that are isoclinally folded and overturned to the NW, and contains pillow lavas that are believed to be part of the Gwna Group (Kawai et al., 2006). Kawai et al. (2006) proposed a SE dipping subduction zone beneath SE Anglesey (Fig. 5.3). The model incorporated the blueschists and the pillow lavas. The pillow lavas that are associated with a SE dipping subduction zone may not necessarily be part of the Gwna Group. Also, the SE-dipping subduction zone is not in the same polarity of the SE-directed deformation in NHG, and the polarity of the S-directed deformation in Gwna Group. Therefore, Kawai’s (2006) model for a SE dipping subduction zone probably represents SE Anglesey only (Fig. 5.3).

Central Anglesey is occupied by the Coedana granite, paragneisses, hornfels and green-schist. These rock units are separated by a strike-slip faults and are Precambrian - Cambrian rocks. Therefore, central Anglesey is interpreted as a micro-continent (Fig. 5.1-a). W Anglesey is occupied by the NHG and the SSG that are separated by a SE-directed ductile shear zones, and are thrusted over the orthogneisses (Fig. 5.1-a). This study proposes a NW-dipping subduction zone beneath NW Wales, and is in the same polarity of the SE-directed D1-D2 deformation. The SSG turbidites may have been deposited on a basin that overlain the subducted slab of the micro-continent. The NHG rocks may have

Figure 5.3: Generalised cross-section of SE Anglesey, showing SE dipping subduction zone. (Diagram from Kawai et al., 2006)
been the mélange of the NW dipping and SE-directed subduction zone, in which they have been deposited at the toe of an overriding plate, and then was incorporated into an accretionary wedge, and thrusted over the SSG. The NHG includes ophiolite rocks, which suggests that the subduction zone was an arc-related subduction zone. This deformation event occurred before Ordovician time, which affiliate them with the Caledonian orogeny and relate them to the closure of the Iapetus, and may have coincided with a volcanic arc that is represented by the Leinster Massif. Eroded remnants of this volcanic arc may be present in N Anglesey as volcanic components which are weathered, eroded and deposited into the Skerries and the Fydlyn units in a small depocentre in NW Anglesey (see also, Phillips, 1989). This depocentre has been filled with the Skerries and the Fydlyn volcaniclastic rocks prior to the CHTB development. The volcaniclastic rocks have unconformably deposited over the NHG, probably during Ordovician time.

5.2.2 Tectonic evolution of the CHTB, N Anglesey

The CHTB developed by brittle thrusting associated with anchizonal metamorphism in Devonian time, suggesting it is a post-Caledonian feature that formed after the closure of the Iapetus ocean, synchronous with the Acadian orogeny. Soper & Woodcock (2003) compared and contrasted two models for the Acadian orogeny in the southern UK: a collisional and flexural basin model, and a post-collisional regional transtensional model (Fig. 5.4). The flexural basin model proposed a 'southward propagation' of Laurentia/Avalonia convergence after the closure of the Iapetus ocean, creating a flexural foreland basin that was subsequently inverted (Soper & Woodcock, 2003: and references therein). The transtensional basin development predated the contractional deformation. The transtensional deformation is suggested in N Anglesey by various depocentres that were filled with sedimentary and volcanic deposits during Silurian time, and it is suggested by the volcanics at Parys Mountain (e.g. Westhead, 1993). The extensional history occurred during intraplate rifting of a small marine basin (Barrett et al., 2001). At Parys Mountain, the extensional history was overprinted by thrusting during the development of the CHTB, which deformed the Silurian beds and volcanics into a S-vergent isoclinal synform. The thrusting and inversion were subsequent to the deposition of the post-Caledonian ORS molasse. The ORS was involved in S-directed thrusting, which indicates
an Acadian time for the development of the CHTB. The pre-CHTB extensional history is also evident in the W transect, where younger rocks are thrust over older rocks. The extensional faulting may have exhumed basement rocks such as the granite gneisses, NHG, the Skerries and the Fydlyn volcaniclastic rocks, and dropped down overlapping rocks of the Caradoc mudstone units. The normal faults probably defined horsts and grabens, which contained the original basement-cover unconformity at different structural levels. S-vergent CHTB thrusting and inversion led to overall S-directed thrust transport and fold vergence, although incomplete inversion has maintained some younger on older thrust relationships. During thrusting, rock units such as the granite gneisses, Fydlyn beds and the NHG were emplaced as tectonic slivers, and the overlapping Caradoc mudstone was offscraped and incorporated into a large scale tectonic mélange.

Figure 5.4: Lithospheric cross-sections for early Devonian time showing (a) the flexural southward progradation model and (b) the regional transtensional model. (Diagram from Soper \\& Woodcock, 2003)
The MGGM succession in N Anglesey may not have initially evolved in a tectonic setting of thrusting and inversion even though the younger MGGM succession is thrust over the NHG. The basin that was the site of the olistostromal mélange and the debris flow conglomerates may also have been a pre-CHTB transtensional depocentre on stretched continental crust of the Anglesey basement block which subsequently was collapsed and inverted as it was overridden during subduction. Or, the Gwna mélange and slivers of debris flow conglomerates may have been deposited simply as trench-fill sediments between the overriding and the subducting plates. These units were then thrust during terminal collision (Fig. 5.5). Mappable blocks of sedimentary rocks such as carbonate, quartzite, conglomerates and mudstones within the Gwna mélange suggest that the Gwna mélange was derived from marine sediments eroded from continental crust, which is consistent with the overall tectonic setting of the post-Caledonian and Acadian CHTB. As a result, the Acadian orogeny evolved in two stages after the closure of the Iapetus ocean. The first stage involved transtensional basin development that accommodated localised volcanism and sedimentation. The second stage involved thrusting and inversion during the development of the CHTB. The thrusting and inversion were overlapped by the molasse sediments of the ORS unit, which were themselves affected by CHTB shortening.
Figure 5.5: Evolutionary model for N Anglesey. (a) After the closure of the Iapetus Ocean: deposition of the Ordovician conglomerates and the black sandstone-siltstone and mudstones (adopted from Gee, 2005). (b) The first stage of the Acadian orogeny: basin development and extensional faults associated with volcanism. The small basins were filled by Devonian rocks (adopted from Soper & Woodcock, 2003). (c) Collision of the leading edge of Avalonia with Anglesey micro-continent during the second stage of the Acadian orogeny.
Chapter 6

Conclusions and suggestions for future work

6.1 Major conclusions

• The lithological units in the CHTB can be subdivided into basement and cover assemblages. The basement rocks include Cambrian chlorite-quartz schists and phyllites of the NHG and the Nebo unit (SSG). The overlapping rocks are meta-sedimentary and volcaniclastic rocks such as the Ordovician conglomerates, Gwna Group and the Devonian ORS unit. The Gwna Group is younger than the NHG, and has an Ordovician age. The Gwna Group is detachable from the Monian Supergroup and is most closely affiliated with the Ordovician rocks.

• The Gwna mélangé is younger than the Fydlyn beds and younger than the Skerries Formation, which is the lowermost unit of the Gwna Group. Thus, it is not part of the basement and Monian rocks. The Gwna mélangé is a tectonic unit that deformed during debris flow deposition, and subsequent contractional development of the CHTB. Mappable slivers of the Ordovician and Skerries rocks contained in the mélangé may have been caught up during CHTB development.
• The rock units in North Anglesey vary from east to west and are not continuous along strike except the NHG and the Caradoc mudstone. This suggests that there were separate individual depocentres that received sediment prior to CHTB development. The Gwna mélange in northernmost Anglesey may have initially developed in a trench-fill basin, and was later tectonised during D3 thrusting. The Skerries and the Fydlyn units in NW Anglesey may contain eroded remnants of a volcanic arc that developed earlier (during D1-D2?) and before CHTB development. The ORS molasse unit was deposited before or during CHTB development and was deformed during D3.

• There are five deformation events recognised in N Anglesey. D1-D2 was SE directed ductile contraction, and was associated with greenschist grade metamorphism. D3 was S directed brittle contraction associated with anchizonal metamorphism. D1-D2 structures were reworked and overprinted by D3 structures. Conservative extrapolation of north dipping D3 thrusts suggests that they may root into a sole fault, defining an overall south directed thrust wedge. In northwestern-most Anglesey, there are younger rocks overturned and thrust over older rocks suggesting that thrusting occurred in crust previously affected by normal faults that were subsequently reactivated and partially inverted. D4-D5 events produces E-W and N-S extensional faults respectively, that cross-cut all older structures and define major drainages and erosional features in N Anglesey.

• D1-D2 evolved during the Caledonian orogeny based on the SSG late Cambrian age, and the NHG erosion in early Ordovician. D3 is part of the Devonian Acadian orogeny because the Devonian ORS unit was deformed during D3. D4 was formed during Permo-Triassic regional extension because the normal faults cross-cut D3 thrusts and the youngest ORS Devonian rocks of the CHTB. D5 normal faults postdate a regional Tertiary dyke swarm and may have been active in the Quaternary.
• D1-D2 occurred during subduction of the leading edge of Avalonia beneath Laurentia and the closure of the Iapetus Ocean during the Caledonian orogeny. Laurentia/Avalonia convergence was interrupted by transtensional faulting in Anglesey during Acadian time, which suggests crustal relaxation after the Caledonian orogeny. The Devonian D3 event inverted normal faults and transtensional basins during terminal collision between Laurentia and Avalonia. During post-Caledonian collision of Laurentia and Avalonia, the ORS molasse unit was deposited and incorporated into the evolving CHTB wedge.

• Central Anglesey represents a Precambrian micro-continent that was bound by a NW dipping subduction zone in the NW and a SE dipping subduction zone in the SE. The SE dipping subduction zone beneath SE Anglesey is considered to be older than the NW dipping subduction zone beneath NW Anglesey because the blueschists are older than the greenschists. The NW dipping subduction zone is in the same thrust polarity as the SE-directed D1-D2 deformation. The NHG may have developed in an accretionary wedge setting overriding the leading edge of the central Anglesey micro-continent. The overriding plate contained a volcanic arc, which is today represented by the Leinster Massif in SE Ireland and its along-strike continuation under the Irish Sea. The NHG accretionary complex was thrust over the turbiditic rocks of the South Stack Group that were deposited on the Central Anglesey micro-continent. Thus, the NHG and SSG became part of the basement, before the development of the CHTB. NE striking lithological belts in W, central and SE Anglesey record the older D1-D2 record without a significant D3 overprint, whereas in N Anglesey, D3 deformation associated with S-directed Carmel Head thrusting is the dominant crustal feature.

• This work demonstrates that the CHTB is an important and separate regional tectonic element in NW Wales, which records an E-W striking, S-directed contractional history representing terminal Laurentia/Avalonia collision in the Devonian, following Iapetus Ocean closure.
6.2 Suggestions for future work

- Chemical analysis and geochronological study of the Nebo unit would be important to determine its protolith, degree of metamorphism, complete mineralogy and whether the Nebo unit is similar in age, composition and metamorphism to the SSG. Also, geochemical analysis and chronological study of the Skerries and Fydlyn units would be equally important to determine protolith characteristics and whether the volcanic components have an arc affinity as is assumed.

- Continued structural work along coastal sections in areas that were not investigated in this study, including southern parts of east and west Anglesey (including parts of Holy Island).

- Preliminary analysis of ETM and SPOT data in this study suggests that there are NE trending strike-slip faults that divide Holy Island into two parts and extend up to the Carmel Head thrust fault. Also, the Tertiary dyke swarm is pervasive and cuts all of Anglesey as shown by the aeromagnetic data and Greenly’s (1919) map. Thus, a field based project incorporating GIS and remote sensing data to study the Permo-Triassic faults, Tertiary dykes and subsequent extensional faults would be useful.
Bibliography


