STRUCTURAL AND PETROGRAPHIC
STUDY OF THE MONIAN ROCKS OF
THE RHOSYCOLYN DISTRICT, HOLY ISLAND,
ANGLESEY, NORTH WALES, UNITED KINGDOM

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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STRUCTURAL AND PETROGRAPHIC STUDY OF THE MONIAN ROCKS OF THE RHOSCOLYN DISTRICT, HOLY ISLAND, ANGLESEY, NORTH WALES, UNITED KINGDOM

1 Introduction

This study concerns the detailed structure and petrography of a part of the metasedimentary Bedded Series of the Monian rocks which outcrop in exposure along the coast and, with less frequency, inland in the vicinity of the village of Rhoscolyn on Holy Island, Anglesey, North Wales.

The purpose of this study is two-fold. First, in an area where the rocks have recorded several phases of deformation, it is often difficult to interpret the structure. Through detailed mapping and stereographic analysis of the orientation of the small-scale structures present, the large-scale structure of the area is elucidated.

Second, the wide variety of lithologies present have responded differently to the stresses they were subjected to during deformation. The relationship between the styles of deformation, as reflected by the geometry of folding, fracturing, and faulting, and the lithologies in which this deformation is realized is examined.
II Nature and Location of the Field Area

Holy Island is an island, approximately thirty-five square kilometers, located immediately off the west coast of Anglesey, a much larger island, which in turn lies off the mainland of North Wales.

The field area encompasses a large portion of the southwest corner of the island. Along the coast, the northwest boundary of the area is located immediately southwest of the Caravan Parks at Porthyrarian and extends inland approximately east northeast to the Rhoscolyn Primary School. The eastern boundary extends roughly south of the school to the church at Rhoscolyn, where it jogs southeast for approximately two-hundred meters before continuing southwest to the coast at Porth yr Hwngan. The southwest and western perimeters of the area are bounded along the coast by the Irish Sea.

With the exception of the rounded bosses that rise abruptly in the northern portion of the area, the inland topography is of low relief and is dotted by numerous small farms and cottages. Much of this terrain is pasture land or is in crops and, therefore, affords very poor exposure. In contrast, the rough and craggy coastline with its spectacular sea cliffs and small bays and inlets provides excellent outcrop exposure.
III Methods Employed

The geologic map and structural data presented here were initially prepared for a field exercise while attending the Sixth Annual Session of the British Isles Summer Field Course.

Six days were spent in reconnaissance and mapping of the area. The mapping was done on a scale of 1:10,000, using the 25 inch Ordnance Survey Sheet: Anglesey XV13.

Approximately 300 measurements were taken of the attitudes of the planar and linear elements throughout the area. Using the procedure described by Ramsey (1967), a geometric analysis of the structural data was done.

Twenty samples were collected and thin sectioned to aid in the petrographic description of the units.
IV Previous Investigations

With a history of research dating as far back as 1610 (Speed), Anglesey must rank among the truly classic areas of geological investigation.

Of the earlier works, perhaps the most notable is a memoir by Henslow (1822), who provides an excellent description and discussion of the rocks and structures present, as well as appending a fine map of the island. He notes the difference between bedding and foliation (something which later workers-Blake (1888) and others-often confused), and ascribes the latter to "crystalline force assisted by moisture and pressure". In his discussion of the Mona Complex, Henslow refers to these beds as "the oldest stratified rocks".

Being a bit more specific, Sedgwick (1838) included these rocks in his Lower Cambrian, but, according to Greenly (1919), later retracted this view and did not specify an age.

The first map and the official memoir of the Geological Survey of Great Britain on the geology of Anglesey were published in 1853 and 1866 respectively, with the surveying done by Ramsey, Schwyn, Smyth and De la Beche (Ramsey 1866). With some reservation, a Cambrian age was given for the "chlorite schists". For a period of approximately fifteen years (1877-1891), the age question pervades the literature.

The internal stratigraphy of the Mona Complex was first described by Callaway (1881) who was then able to refute earlier claims of a Cambrian age (Hicks 1879) based on correlation to the mainland Cambrian strata.

Blake (1888), in a comprehensive study of the microscopic petrography and structure of the Monian rocks, was unable to find any break within the
group and come to regard it as a single Precambrian System which he termed the Monian.

Greenly (1919) provides perhaps the most comprehensive study of the Mona Complex to date. With an extraordinary eye for detail, Greenly's observations are flawless. Although more recent work by Shackleton (1954, 1969) has necessitated an inversion of Greenly's stratigraphy, his work remains the definitive account of the geology of Anglesey.

On Holy Island, the most recent work is that of Wood (1960), Trefz (1973), and Maltman (1973). Working in the present area of study, Wood (1960) examined the geology of the Bedded Series in the Rhoscolyn district, placing a major emphasis on the structures of the Rhoscolyn Anticline. Trefz conducted a study of the mechanisms and resultant geometry of folding in the New Harbour Bells north of the present field area, while Maltman examined the nature of the suite of ultramafic emplacements in the present area of study and on Anglesey.
V Stratigraphy

Greenly (1919) subdivided the Mona Complex into nine units. They are listed from youngest to oldest:

7. The Penmynydd Zone of Metamorphism...Mica schists, hornblende schist, and glaucophane schist

6. The Plutonic Intrusions..........Granite, diorite, gabbro, and serpentine

Bedded Succession

7. Holyhead Quartzite.............Quartzite

6. South Stack Series.............Grit, mica schist

5. New Harbour Group..............Grit, mica schist, jasper, and spilitic lava

4. Skerries Group..................Conglomerate, Grit, and tuff

3. Cwna Group......................Grit, phyllite, quartzite, limestone, jasper, graphitic phyllite, spilitic lava, albitediabase, and the metange

2. Fydlyn Group.....................Felsitic lavas and tuffs

1. The Gneisses......................Basic and acid gneiss

Shackleton (1954, 1969) was the first to notice the presence of sedimentary structures in the highly contorted South Stack Series and Rhoscolyn Beds. Using the concept of facing, Shackleton (1957) was able to determine
that Greenly's Bedded Succession was, in fact, upside down. Noting the
greater thickness of Holyhead Quartzite on the northern portion of Holy
Island, Shackleton (1969) proposed a gradual facies change southward, with
the Holyhead Quartzite thinning and interfingering with beds of pelite and
semipelite in the Rhoscolyn district. He recognized the lowermost massive
quartzite in the Rhoscolyn Anticline as the Holyhead Quartzite, but con-
sidered the overlying pelites, psammites, and semipelites as a separate
unit, which he termed the Rhoscolyn Beds. These beds are equivalent to the
upper South Stack Series of Greenly.

The revised Bedded Succession, in accordance with Shackleton (1969),

is as follows:

Fydlyn felsitic group
Gwna Group
Skerries Group
New Harbour Group
Rhoscolyn Beds
Holyhead Quartzite
South Stack Beds

Although the base or top of the succession is nowhere exposed, it is be-
lieved to have a thickness of the order of 7000 meters (Shackleton 1969).
Within the field area of this study, the four lower members of this success-
ion are present, as well as ultramafic intrusions of serpentine and carbon-
atized gabbro.

The stratigraphic distribution in the area mapped is displayed in
Plate 1.
The South Stack Series

The South Stack Series, being the lowest member of the succession, is located in the core of the Rhoscolyn Anticline, and is, therefore, exposed along the coast from approximately the most easterly of the two fault inlets below the coast guard station, to the small inlet at Porth Gwalch.

The unit is composed of highly contorted beds of schistose greywackes, pelites, semipelites and thin quartzites that plunge gently to the northeast. The more massive greywackes, which range in thickness from two to fifteen feet, grade upward into the thinner units of semipelite, pelite and quartzite, which are, in turn, overlain by more massive greywacke. The greywacke units appear to maintain their thickness laterally, although it is often difficult to determine thicknesses due to the high degree of deformation that all of the units have recorded.

Minor folding on nearly all scales is well exhibited by all of the units of the South Stack.

Thin section examination of the schistose greywackes reveal that they are quartz, chlorite, and muscovite schist. Despite the schistosity, the rocks have retained much of their original clastic texture. Recrystallization has been confined largely to the matrix where the mud fraction has been replaced by fine-grained fibrous chlorite and muscovite, which show a crude alignment in two directions.

The quartz fraction predominates. Most of the larger (1mm-1/5mm in diameter) subangular quartz grains exhibit their original grain boundary texture, although occasional pressure-solved boundaries are seen. In these clasts, the embayed grains are separated by fine partitions of matrix material of chlorite and muscovite. Nearly all quartz grains exhibit wavy
or undulose extinction. Recrystallization of the quartz fraction appears to be confined to fine grains, where subgrain formation and polygonization is common. It is in this size fraction, only, that the recrystallized quartz grains appear somewhat flattened in the schistosity.

A small amount of detrital alkali and plagioclase feldspar is present. The plagioclase feldspar show albite twinning and have anorthite contents within the andesine range. The alkali feldspar is present as small, sub-rounded porphyroblasts, containing fine inclusions of sericite and muscovite. Although no definite overgrowths boundaries are visible, textural evidence suggests the porphyroblasts may have grown from pre-existing detrital alkali feldspars.

Ilmenite, tourmaline, magnetite, sphene and rutile are present in small amounts as accessory minerals.

Holyhead Quartzite

Of the three lower units of the Rhoscolyn Anticline, the Holyhead Quartzite provides the best exposure inland. The base of the unit is exposed on the southeast limb of the Rhoscolyn Anticline near the bottom of the cliffs south of the coast guard station, and on the northeast limb, midway up on the northern cliffs of Porth Gwalch. It marks an upward transition from a coarse greywacke unit at the top of the South Stack Beds to a very pure, massive quartzite which is the Holyhead Quartzite.

The Holyhead Quartzite of the field area is approximately 40 meters thick and, except for three schistose pelitic beds which occur near the middle of the unit, is a remarkably homogeneous, pure, schistose quartzite.
The thickest of the pelitic units is approximately 3 meters in breadth. This unit can be traced inland for a short distance from the sea cliffs where it is well exposed. As it starts to bend north and northwestward toward the coast guard station (Plate 1), it no longer outcrops, but a depression in the topography probably delineates the units' location. Three thinner pelitic horizons occur at the same level in the quartzite near Rhoscolyn Head and, although these are more difficult to trace inland, they appear to correlate to the thicker beds on the southeast limb.

The top of the Holyhead Quartzite provides perhaps the most easily recognized contact in the area where, on the southeast limb of the anticline, an abrupt quartzite dip slope stands in contrast to physiographically lower lying units of semipelite, pelite and quartzite of the Rhoscolyn Beds. On the northwest limb of the anticline, the transition upward is less abrupt. The contact was picked where the overlying beds were judged to be more argillaceous.

In thin section, the Holyhead Quartzite reveals itself as a very pure quartzite, containing very little feldspar. White mica and, more commonly fine fibrous chlorite define a weak, anastomosing first schistosity ($S_1$). The first schistosity is best defined by the flattened, elongate, recrystallized quartz grains. Present as well are larger, more rounded quartz grains, that have retained more of their original clastic character. A strain-slip second schistosity ($S_2$) is well expressed in thin section by the rotation of quartz grains elongate in $S_1$ into a plane at a high angle to the initial schistosity ($S_1$). A third and similar set of strain-slip planes lies at nearly right angles to the first schistosity. A further discussion and description of these angular relationships is given in the sections that follow.
Accessory minerals present include zircon, apatite, tourmaline, and ilmanite.

The Rhoscolyn Beds

The Rhoscolyn Beds are a series of interbedded schistose semipelites, pelites and quartzites which are similar in character to the South Stack Series. The difference in the two units is expressed best by the presence of two rather thick quartzite units in the middle of the Rhoscolyn Beds. Although these units appear very white and pure in weathered exposure, in thin section, they show appreciable amounts of chlorite and muscovite. Feldspar is rare, although more common than in the Holyhead Quartzite. Magnificent large-scale sedimentary bottom structures, resembling flute casts on a grand scale, are present at the base of the upper quartzite at Bwa Gwyn. Their orientation indicates current transport from the northeast.

The presence of two quartzite units on the northwest limb of the Rhoscolyn Anticline is in contrast to the single unit exposed on the southeast limb. Lack of exposure inland does not allow for direct correlation across the Anticline, and it is, therefore, difficult to determine the relationship between these three units.

In plan view (Plate 1), the lowermost quartzite, exposed at Porth Saint on the northwest limb, appears to correlate with the single quartzite unit on the southeast limb. The younger quartzite at Bwa Gwyn is then left uncorrelated to a similar unit on the southeast limb. Although a similar quartzite unit may be present to the southeast of the arbitrarily defined southeast boundary of the area, it seems equally plausible that a change in facies to a more argillaceous sediment has occurred and, as a result, the
unit is no longer recognizable on the southeast limb. The presence of progressively thicker sequences of quartzite at approximately the same stratigraphic levels to the northwest of the mapping area is in agreement with this interpretation. Because the last appearance of this quartzite occurs immediately southeast of the projected anticlinal trace, one could argue that this unit has been attenuated during folding. This seems unlikely, however, since the lower-lying quartzite unit shows no such effects and maintains its thickness across the Anticline.

The greywacke units are equivalent in character to those of the South Stack Series. These units, which often show graded bedding, range in thickness from 2-3.5 meters, and pass gradationally upward into schistose pelite which, in turn, is overlain by more greywacke, or, in a few cases, massive quartzite. (Plate 2)

Plate 2: Well exposed contact between semipelite, which grades upward into pelite (pervaded by quartz veins), and massive schistose greywacke at the base of the Rhoscolyn Beds on the steeply inclined, south-east limb of the Rhoscolyn Anticline. Conjugate sets of F3 kink bands may be seen in the lower right hand corner of the photograph.
As in the South Stack Series, first and second minor folds are well
developed.

New Harbour Group

Of the number of lithologies of the New Harbour Group, only the semi-
pelitic mica schists are present in the field area. Being extremely hard
and durable, these rocks afford better exposure inland than the underlying
units of the Rhoscolyn Anticline with which they are in fault contact.

The semipelites of the New Harbour Group consist of alternating fine
laminae of light green micaceous-rich material and pale green quartzite
material. (Plate 3) The quartzite layers vary in thickness from less than
1 cm. up to 5 cm. in width but are typically 2-3 mm in width. The micaceous
layers are usually thinner, averaging, perhaps, 1 mm. in width.

Plate 3: Characteristic laminated appearance of the New Harbour semipelites
of the field area. Folds are F2 structures.
Under the microscope, it is possible to see that the quartz and mica-rich layering is an original sedimentary structure that has been further enhanced by metamorphic segregation. The quartz-rich layers contain abundant small flakes of chlorite, whose basal planes are aligned parallel to the banding. These are the source of this layer's dull grey-green color. The quartz, itself, has been totally recrystallized. Quartz quartz-grain boundaries are most often dentate or implicated with subgrain formation frequently occurring at the margins of the grain. Grain polygonization, deformation banding, and undulose extinction are prevalent throughout this fraction. In sections cut perpendicular to the layering, quartz grains are elongate and flattened parallel to the banding, with grain axial ratios on the order of 3:1. Also elongate, parallel to the banding, are lens-like pods of quartz which are distinct because of their coarse-grained character. The grains in these pods are only slightly elongate in comparison to those of the surrounding quartz matrix, or to the pods in which they are contained, and exhibit recrystallization features similar to those of the matrix quartz.

Feldspar, both plagioclase and alkali, are present in these layers as well, and constitute about 5-10% of the rock as a whole. Plagioclase is present as angular crystals, showing overgrowths, while the alkali feldspar is rounded prophyroblastic albite, containing randomly-oriented inclusions of a blady-white mica, possibly muscovite.

The mica-rich layers are composed, nearly exclusively, of muscovite and are in abrupt contact with the quartz layering. These layers show notable pinch and well (Plate 4) when followed laterally but are, everywhere, seen to persist horizontally.

The muscovite in these layers is dominantly oriented with basal planes, parallel to the banding, but, in places, shows shear. Muscovite in these
Plate 4: Pinch and swell of muscovite-rich layer of the New Harbour semi-pelite. X25

areas have been rotated out of their initial flat-lying position to an attitude at low angles to the banding. Where these layers pass into folds, they become crenulated, with the muscovite being oriented in a series of small tight microfolds.

Opaque minerals are concentrated in the muscovite layers, while quartz and chlorite are rare to absent.

Detrital, fine granular epidote is abundant throughout the specimens studied. Many grains show some sign of recrystallization, although in most cases the detrital nature is retained. Epidote abundance appears to be in no way affected by the layering.
VI General Structure

In map view (Plate 1), the structure of the Rhoscolyn District appears simple, being dominated by a single large-scale feature, the Rhoscolyn Anticline. In the field, the structure appears considerably more complex due to the extensive development of parasitic folds and the superimposition of planar and linear elements that are the relics of three distinct periods of deformation.

The Rhoscolyn Anticline is a large asymmetric fold that verges to the southeast and plunges 15-30 degrees northeastward. It is a first generation fold \( (F_1) \); a fact that may be inferred from the refolded nature of the axial planar schistosity and, in a few instances, of minor folds, by younger structures. Beds on the shallower northwest limb record dips of 20-30 degrees, while those on the steeper, southeast limb rarely have dips less than 50 degrees. Overturned bedding is observed in a few localities on this limb.

Minor \( F_1 \) folds are well-developed on both limbs of the Anticline. These may generally be characterized as relatively large, open, upright, cylindrical structures whose orientation closely mimics that of the major structure. The amplitudes of these folds vary greatly. Small folds, with amplitudes ranging from 0.75-3.5 meters, can be seen in the multi-layered South Stack Series and Rhoscolyn Beds, while in the massive Holyhead Quartzite, the minor anticline that comprises a large portion of Rhoscolyn Head has an amplitude on the order of 20-30 meters. Layer thickness is rarely maintained across first folds; rather, thickening in the hinge
region and slight to moderate attenuation of the limbs is most commonly observed. A nearly vertical axial planar schistosity, defined by the alignment of the basal planes of muscovite flakes, is present in all three of the lower units of the Rhoscolyn Anticline, but is absent in the New Harbour Group.

In contrast to the large, broad, open first folds, second generation folds are invariably small, very tight, asymmetric, overturned structures. They develop exclusive of first folds, only in the thin, more ductile, pelitic and semipelitic horizons where they fold the first schistosity. In the less ductile quartzite and quartz-rich greywackes of the area, the second episode of deformation has tightened and often reoriented first folds, resulting in a convergent fanning of the first schistosity across these structures.

Within the pelitic horizons, the segregation of quartz veins parallel to the first schistosity (Plate 5) is ubiquitous and greatly facilitates the

Plate 5: Segregation of quartz veins precisely parallel to the first schistosity in a pelitic rich unit.
recognition of the second deformational episode. These veins, measuring approximately 1.25 cm. to 10 cm. in width, are often folded into attitudes of the same orientation as minor $F_2$ folds within the same units. The second schistosity is commonly axial planar to these folded veins. These folds provided the most frequent, and often the only means for measuring the attitude of the second fold axis. The angular relationships of the planar elements discussed above are well illustrated in Plate 6.

Plate 6: Fault block between two small faults in the South Stack Series opposite Maen-y-Fran showing the relationship between bedding, first schistosity, folded veins and axial planar second schistosity.
The small, tight, overturned, second fold in the pelitic and semipelitic units are often accompanied by penetrative axial planar second schistosity ($S_2$). Although $S_2$ commonly develops in these units in the absence of $F_2$ folds, it is not sufficiently well-developed in less pelitic units to be seen without the aid of a microscope.

A third episode of deformation is marked by the formation of small kink bands that are present in all the units of the area. Only a few of these small monoclinal folds could be reliably measured, and then exhibited a wide diversity of orientations. On a few occasions, conjugate sets of kink bands were observed. (Plate 2)

Based on field evidence, it is difficult to determine whether these folds do, in fact, represent a separate third stage of deformation.

Wood (1960) recognized 4 types of shear folds (kink bands) and equates their formation to the second episode of deformation, although it is not clear how the diversity of their orientation is resolved. Although kink banding undoubtably related to the second period of folding is present in some of the pelitic and semipelitic units, the author has found evidence which suggests a separate set of shear folds kinks the second schistosity, and, therefore, postdates it's formation.

The preceding discussion has dealt only with the structures of the three lowest units in the area. The style of deformations of the New Harbour Group is markedly different and is, therefore, discussed separately.

Faulting

Although fault recognition has been facilitated by wave action on fault planes along the coast, the subdued topography inland provides little
information that is of use in the extrapolation of faults away from the coast, which is therefore speculative.

The single exception is the North Stack Fault which brings the downthrown New Harbour Group in fault contact with the Rhoscolyn Beds. The North Stack Fault and the Namarch Fault to the northeast of the area traverse the length of the island, dividing it into three structural blocks. (Shackleton, 1969). Greenly (1919) states that the throw of the North Stack Fault is visibly 500 feet, as evidenced by the height of the sea cliffs to the north of the area.

Moving southwestward from the North Stack Fault, a pair of normal faults, trending northwest-southeast, spaced approximately 3 meters apart, are responsible for the White Arch at Bwa Gwyn. The strike of these faults when traced inland, corresponds to the strike of the fault face which forms the northeastern cliffs of Porth Saint. The throw along this fault is difficult to determine. If the physiographically lower-lying, thick quartzite unit on the southwest side of the fault correlates to the higher quartzite horizon on the northeast side, the fault is normal and downthrown to the southwest with a displacement of approximately 3 meters.

The fault gullies of the southeast-facing cliffs, below the coast guard station, form a second pair of subparallel faults. Trending northwest-southeast, the northmost of the two faults is responsible for the blowhole inlet along strike to the northwest. Vertical displacement is thought to be about 3 meters with the southeast side being downthrown.

A series of northeast-southwest trending faults lie exposed in fault chasms between Maen-y-Fran and Rhoscolyn Head. It was not possible to determine the amount of displacement along these faults.
A small thrust in the northwest corner of the field area brings New Harbour semipelites in fault contact with serpentinite. Although the amount of displacement could not be determined accurately, movement was probably minimal, possibly 1.5–2 meters.
VII Metamorphism

A low temperature, low pressure thermal event has left the rocks of the area in the lower greenschist facies of metamorphism. Thin section examination of textural evidence suggests this event postdated the first episode of deformation but predated or occurred simultaneously with the second.
VIII The Structural Components

The structural components are comprised of planar and linear features of three generations. Their attitudes are shown on the structural map. (Plate 7)

Bedding (S₀)

As noted earlier, due to the complex nature of parasitic folding, bedding is often difficult to distinguish. When plotted on an equal area net, the poles to bedding fall along a great circle, striking N40W with a dip of 64 degrees SE, indicating the fold axis of the major structure trends N50E with a plunge of 26 degrees NE. (Fig. 1) The poles to the bedding-first schistosity surfaces in the New Harbour Group, although showing less dispersion, define the same great circle, indicating that these beds have also been flexed across the Rhoscolyn Anticline. (Fig. 4)

First Schistosity (S₁)

The first schistosity is readily distinguished in all of the units of the area by nature of it's near vertical orientation. In the New Harbour Group, it lies parallel to bedding and is, therefore, not treated as a separate element. In projection, the poles to S₁ indicate that this plane strikes N63E, dipping 56 degrees NW. (Fig. 1) The pole cluster is centered along the great circle to the poles to bedding, reaffirming statistically that the first schistosity is axial planar to first folds.
Second Schistosity ($S_2$)

The semipelitic and pelitic beds are the only units in which the second schistosity develops with any regularity. When observed in the field, the dip of $S_2$ is consistently seen to be shallower than $S_1$, and when second minor folds are present, $S_2$ is commonly axial planar. When the poles to $S_2$ are plotted, they form a broad cluster which defines an average $S_2$ plane that strikes E08S, dipping 30 degrees N. (Fig. 2)

Axial Planes to $F_2$ Folds

Within the New Harbour Group, $S_2$ has not developed megascopically. In order that the attitude of $F_2$ folds could be measured, approximate axial planar surfaces were constructed and measured whenever possible. The poles to these surfaces, when plotted, show that $F_2$ folds with a southwesterly vergence possess nearly the same orientation as the second folds of the underlying units. (Fig. 4) $F_2$ planar surfaces of two folds which strike at nearly 90 degrees to the majority of $F_2$ folds measured, were observed immediately SE of Porthygaran, and $F_2$ folds that verge to the NW were observed on a few occasions as well. The significance of these structures is discussed in a later section.

Axial Planes to $F_3$ Folds

Measurement of the attitude of third folds was achieved in the same way as the measurement of second folds in the New Harbour Group. The wide scatter of these measurements shown in Fig. 3, is indicative of the variety of attitudes that these folds exhibit, although the difficulty in attaining accurate measurement, as alluded to earlier, is undoubtedly reflected.
First Fold Axes

As would be expected, measurements of the fold axes of minor first folds cluster around the fold axis derived from the great circle to the poles to bedding. (Fig. 1) The average trend of these measurements is N48E with a plunge of 29 degrees NE. The line formed by the intersection of $S_1$ and $S_0$ also parallel the fold axis. Both of these measurements lie in the plane of $S_1$ which again confirms it's axial planar orientation to first structures.

Second Fold Axes

Measurements of the second fold axes and the intersection of $S_1$ and $S_2$ fall in a loose cluster along the great circle defined by the poles to $S_2$, indicating the axial planar orientation to second folds. The mean trend of these linear elements is N47E with a plunge of 30 degrees NE. (Fig. 2) Within a small margin of error, first and second folds are coaxial.

In the New Harbour Group, axial planes to second folds show greater scatter, indicating the greater variety of fold orientations in this unit. (Fig. 4) Two cross folds near Porthygaran trend N05W and N14E with plunges of 21 degrees and 10 degrees, respectively.

Third Fold Axes

Although kink bands are ubiquitous to the area, they are very rarely exposed in three dimensions, as is indicated by the scarcity of this measurement. (Fig. 3) The three measurements obtained range in trend from N30E to E01N with plunges varying from 24 degrees to 25 degrees NE.
Mineral Elongation Lineation in the New Harbour Group

This lineation is well developed on the exposed bedding schistosity surfaces of the New Harbour Group. In the pelitic horizons, it often consists of aligned dark minerals, while in the psammitic laminae, it is expressed by elongate quartz fibers. It varies in trend from S42E and E10S with the majority of measurements falling around E30S. (Fig. 4) The lineation is most often observed to plunge southeastward at angles from 2-10 degrees, but northwestward plunges of the same magnitude are by no means rare. The trend of the lineation is approximately normal to the majority of the second fold axes. When $F_2$ folds are encountered, the lineation is folded over them. (Plate 3) Ramsey (1967) has used data from folded

Plate 8: Mineral elongation lineation in the New Harbour semipelite folded over an $F_2$ fold.

lineations in the New Harbour semipelites, to the north of the present area, to explain a method of computing the direction of movement during folding. He derived a movement direction to the northwest.
* pole to bedding (S₀)

• pole to first schistosity S₁

○ trend and plunge of first fold axis (F₁)

▼ trend and plunge of intersection of S₁ and S₀ (L₁)
Fig. 2

- Pole to second schistosity (S2)
- Trend and plunge of second fold axis (F2)
- Trend and plunge of intersection of S1 and S2 (L2)
Fig. 3

- pole to axial planes of F3 folds
- trend and plunge of third fold axis
New Harbour Data

- pole to layering (So)
- pole to axial planes of F2 folds
- trend and plunge of mineral elongation (Lo)
- trend and plunge of second fold axis
- pole to axial planes of F3 folds
IX Deformational History

The well-preserved, extensive, parasitic folds of the Rhoscolyn Anticline, which have developed with varying intensities and styles within each of the respective lithologies, provides an excellent opportunity for the comparison of the controls on the development of minor structures within individual lithologies, on both a microscopic and macroscopic scale.

Before such a comparison can be made, it is first necessary to distinguish between the minor structures in each lithology that are the result of the different deformational episodes. The fact that these three episodes are discretely recognizable is not necessarily reflective of the ease with which the structures themselves may be differentiated. For example, because first and second folds are essentially coaxial, the second folds can only be readily distinguished from the first where they are seen to fold the axial planar first schistosity. As will be demonstrated later, second folds form dominately by shear. Individual macroscopic second folds are thus nearly always restricted to mica-rich layers. Difficulties arise in differentiating between first and second folds in the mica-poor psammitic layers, where shearing has affected the attitude of first folds but has not visibly folded the first schistosity.

In this section, the structures of each deformational episode are examined with regard to the lithologic units in which they occur.

The First Deformation \( (F_1) \)

First generation folds show a variety of styles but may be generally characterized as broad open folds of large wavelengths that overfold to the
southeast and possess a near vertical axial planar schistosity. Fold geometries vary with the amount of inherent anisotropy (bedding surfaces) a unit possesses and the ductility and thickness of the individual beds.

In the thick, massive quartzite units of the area, the first deformation has resulted in the formation of large flexural flow folds, with geometries that most closely resemble similar folds. The previously mentioned minor anticline at Rhoscolyn Head exhibits this geometry. When measured perpendicular to bedding, the hinge region of this fold is about twice the thickness of the limbs.

Parallel or concentric folds are present in a few of the thinner layers of quartzite and semipelite in the South Stack Series opposite Maen-y-Fran. Although these folds have been tightened during the second phase of deformation, they are essentially first folds. Layer thickness is maintained perpendicular to bedding, and folding, therefore, has occurred dominantly by flexural slip.

In the thicker, more ductile units of semipelite, in both the South Stack Series and Rhoscolyn Beds, flexural flow folding is again the dominant mechanism of deformation. These units show even greater thickening in the hinge regions with a correspondingly greater attenuation of the limbs and are generally more tightly folded than the massive quartzite units. Folds of this nature in the Rhoscolyn Beds may be seen on a small inlet along the coast, about 400 meters southwest of the coast guard station. Anticlinal hinges are completely pinched out while the limbs rapidly thicken downward toward thick synclinal hinges.

In comparison to the other lithologies of the Rhoscolyn Anticline, the pelitic units represent perhaps the most passive response to the first episode of folding. Individual first minor folds are not observed, rather
the configuration of the upper and lower contacts of these units conform to the outline of the confining beds. The disharmonic minor folds, so commonly observed in the South Stack Series, are due to the high ductility differences between the low to moderately ductile psammitic and semipelitic units which responded more rigidly during folding, and the highly ductile pelitic units which behaved passively. (Plate 9)

Plate 9: Disharmonic folds in the South Stack Series exposed in the most westerly of the two large fault chasms below the coast guard station.

When comparing the fold styles of the first deformation, it is interesting to note that, for a single lithology, with units varying only in thickness, two distinct folding mechanisms exist. Flexural flow is the dominant mechanism for folding in the thick units of these lithologies. An explanation of these observed relationships is offered by Donath and Parker (1964), who state that the strain within a flexed layer is localized
along its upper surface and is equal to the ratio of thickness of the layer to the radius of curvature of its lower surface. If the radius of curvature remains relatively constant, increasing thickness is accompanied by an increase in strain. This increase in strain may result in fracturing, or, as is the case in the thick quartzite and semipelite units, flowage. Material migrates from areas of greatest stress in the limbs to areas of least stress in the hinge region.

The first schistosity is very regularly developed in all the rocks of the Rhoscolyn Anticline, and is primarily responsible for their schistose appearance. The degree to which \( S_1 \) develops appears to be a function of the amount of oriented platy minerals present.

Although there is little muscovite in the quartzite units, those grains that are present form a strong anastamosing network of subparallel surfaces which are enhanced by flattened, strained detrital quartz grains. (Plate 10) When recrystallization has taken place between basal muscovite planes, small, recrystallized quartz show good growth orientation.
With an increased muscovite content, the semipelites show a strong, well-aligned, planar fabric. Detrital quartz is again flattened in the schistosity which has been further enhanced by abundant, well-oriented, small, rectangular recrystallized quartz grains. (Plate 11)

Plate 11: Semipelite of the Rhoscolyn Beds showing large flattened quartz which has retained much of its original elastic character. Smaller recrystallized rectangular quartz lies in the first schistosity which is best defined by the alignment of muscovite flakes.

The fine grain nature of the pelitic units, as well as the abundance of blady muscovites and biotite has allowed for nearly total recrystallization of the quartz fraction to small rectangular grains, oriented parallel to the basal planes of the micas, giving these rocks a very strong, totally pervasive, first schistosity. (Plate 12)

In the New Harbour Group, the first schistosity has developed precisely parallel to the compositional banding. The mineralogy does not suggest the attainment of a metamorphic grade high enough to allow for the total
Plate 12: Strong alignment of quartz, muscovite and biotite in $S_1$. This relationship is best seen at the base of the photograph where biotite is concentrated in two parallel bands. Crenulation and folding of $S_1$ is reflective of the relatively ductile manner in which the pelitic units responded to the second episode of deformation. X25, Nichols crossed

segregation observed, and this banding must, therefore, be considered to be primarily sedimentary in origin.

The schistosity is defined by the parallel alignment of the basal planes of dominantly chlorite in the psammitic layers and muscovite and chlorite in the pelitic laminae. Flattened quartz grains in the psammitic layer define a crude foliation, which parallels the schistosity. No folds to which an $F_1$ age could be given were found in the New Harbour Group, and this is, therefore, not an axial planar structure. As noted earlier, the plot of the poles to this structure, although they show a broad cluster, fall along a great circle, whose axis roughly coincides with the first fold axis of the underlying unit, suggesting that, while no minor $F_1$ structures
are present, the New Harbour Group has been gently folded across the Rhoscolyn Anticline.

The difference in the orientation of $S_1$ must, therefore, be explained on a mechanical basis. It is apparent by the lack of $F_1$ minor folds that the beds of the New Harbour Group have yielded by purely flexural slip during the first folding episode. The New Harbour Group is the youngest unit of the stratigraphic succession of the area and was, therefore, subjected to lower confining pressures and stress during deformation. The extreme amount of mechanical anisotropy afforded by the alternating fine pelitic and psammitic laminae provided abundant slip planes. As this unit was flexed over the underlying beds, the first schistosity was imparted as a result of the shear that was taking place along these planes. The mineral elongation lineation described earlier is, in part, a result of this flexural slip. Wood (1960) and Maltman (1973) have arrived at similar interpretations for the different behavior of this unit.

The Second Deformation ($F_2$)

The small tight $F_2$ folds present in the pelitic and semipelitic lithologies and tightening of essentially first folds in the semipelitic and psammitic units has been accomplished largely by slip along bedding and first schistosity surfaces.

Evidence for shear is abundant in the field. Perhaps the most convincing observations are the sigmoidal shape of the segregated quartz veins in the thinner pelitic beds and the way in which $S_1$ is seen to be drawn into parallelism with bedding along lithologic contacts in some of the semi-pelitic and pelitic units. (Plate 13)
Plate 13: Sigmoidal quartz veins segregated parallel to S₁ in a thin pelitic unit in the Rhoscolyn Beds which have been drawn into parallelism with a lithologic contact.

The segregation of quartz veins parallel to S₁ in the pelitic lithologies is an interesting event which warrants more detailed examination.

In the field, the veins completely pervade pelitic horizons, giving these units an unmistakable appearance, which was most useful in distinguishing bedding in outcrop exposure and in determining throw along inferred fault planes.

The segregation along S₁ surfaces and the subsequent deformation of these veins into folds possessing an F₂ orientation implies that they were secreted after S₁ was imparted and before, or during, the second episode of
deformation. This relative age is in agreement with the age of the low
temperature regional metamorphism of the area, as evidenced by the attitude
of rotated albite porphyroblasts in the semipelites of the New Harbour Group.

Thin section examination reveals the quartz veins are composite, con-
sisting of optically continuous bands of highly strained fibrous quartz.

(Plate 14) Deformation lamellae and banding are common to all the quartz

Plate 14: Optically continuous bands of fiberous quartz in a quartz vein
from a pelitic unit of the South Stack Series. The thinner red
streak that transects these bands is a crack in the slide. X25
with Rot I plate inserted.

grains, as is subgrain formation and polygonization. (Plate 15) The com-
posite banding, which roughly parallels the vein margins, is quite persis-
tent laterally, although band thickness is often extremely variable. The
quartz within the bands are elongate normal to the vein margins. The inter-
face of the bands is sometimes marked by a thin median suture of pelitic
material. In the absence of this suture, the quartz band boundaries are highly implicated, with the intercalations often being dentate in form.

Plate 15: Deformation lamellae, subgrain formation and grain polygonization in the quartz vein shown in Plate 14. X40, nicols crossed

The evidence presented indicates that the dilation of $S_1$ planes occurred in increments, accompanied by influxes of quartz. The growth of quartz into subparallel bands possessing a strong preferred orientation may be due to crystallization along planar $S_1$ surfaces. Individual fibers within a band represent crystal growth during dilation, while the pelitic interfaces between bands represent the end of a period of dilation and precipitation. As many as ten such episodes may be inferred from the two quartz veins examined in thin section. Assuming symmetric growth with dilation, growth in this manner necessarily implies that the oldest quartz to crystallize occurs in the middle of the vein, while the youngest quartz is present at the margins.
Although the pelitic units are undoubtably the most mica-rich beds of the area, they must have been, initially, more quartz-rich than their present composition would indicate.

In response to strain within the unit, which was the result of slip in opposite senses on the upper and lower bedding surfaces, incremental dilation of $S_1$ occurred, accompanied by the growth of elongate quartz grains across the voids. Initially, the series of widely spaced sigmoidal dilation adequately accommodated the strain in these units, but as slip along bedding continued, the units began to buckle, and the adjacent $S_1$ surfaces, now more enriched in mica, began to slip, causing the formation of small, tight $S_2$ drag fold. With further slip along bedding and first schistosity surfaces, the quartz veins behaved rigidly and were deformed into second folds. In addition, the steep limbs of the small, tight $S_2$ drag folds became further enriched in mica by the pressure solving and migration of quartz out of these regions of greater localized stress into the hinge regions of the microfolds. (Plate 16) The resulting oriented mica-rich bands are the strain slip second cleavage ($S_2$) that is roughly axial planar to $F_2$ microfolds. The same process has occurred on the crenulated limbs of larger microfolds. Differential dissolution of quartz on the short limbs of the crenulations has led to enrichment of mica in these areas which now define $S_2$ planes. (Plates 17, 18)

In response to slip along bedding, first folds in the thinner psammitic layers have tightened and reoriented into attitudes indicative of $F_2$ structures. Fracturing in the hinge regions and fanning of the first cleavage across these folds is common. (Plate 19) Lacking well developed $S_1$ surfaces along which slip could occur, the psammitic units have responded in a more rigid fashion to the second deformation.
Plate 16: Fine grained, polygonized quartz resulting from pressure solution in the steep limb of a microfold in a pelitic layer. X25, nichols crossed
Plate 19: Disharmonic first folds which have been tightened and reoriented into structures possessing orientations common to second folds. South Stack Series, opposite Maen-y-Fran, in the core of the Rhoscolyn Anticline.

Thin section examination of the Holyhead Quartzite reveals that a strain slip second cleavage is well developed on a microscopic scale. Zones of shear are marked by the rotation of quartz, originally elongate in $S_1$, and mica, that originally defined the first schistosity, into bands measuring from .1-.4 mm. in width. (Plate 20) Similar $S_2$ shear zones are seen in the quartzites of the Rhoscolyn Beds.

$F_2$ Folding in the New Harbour Group

The second deformation in the New Harbour Group is marked by folds of differing size, style and orientation.

Folds in the psammitic layers are characteristically open, upright structures which measure approximately 5 cm. - 1 meter in wavelength and 1-30 centimeters in amplitude. With only a slight thickening in the hinge
regions, these structures may be classified as parallel or concentric folds.

Plate 20: Strain slip second cleavage in the Holyhead Quartzite. X25, nicols crossed

F2 folds are more abundant in the pelitic-rich units, where they are seen to exhibit a greater variety of styles and orientations than their counterparts in the psammitic layers. Folds in the pelitic units are most often asymmetric, with inverted short limbs and shallowly-inclined axial planes. Thickening of hinge regions has been considerable, and while not being totally similar in geometry, these structures most closely resemble similar folds.
In thin section, the limbs of folded pelitic layers are often crenulated. Mica enrichment of the short limbs of these microfolds by migration of quartz out of these areas has resulted in a non-penetrative axial planar second schistosity.

F₂ folds are commonly observed to rapidly die out or change shape in the overlying and underlying adjacent layers. This is partially reflective of the parallel fashion in which the layers have been folded, although the rapid variation of differing folding mechanisms has played an equally important role. The psammitic layers have responded to the second deformation by flexural slip, while the less competent pelitic layers show evidence of extensive flow. (Plate 3)

Although a variety of orientations of F₂ folds are present in the New Harbour Group, folds verging to the SW and less frequently, to the NW are the most abundant. While the latter orientation was recognized in the field, its significance, at that time, was not fully appreciated, and, regrettably, the precise attitude of the folds possessing this orientation was not recorded.

With a greater amount of data, Wood (1960) was able to prove that the northwesterly and southeasterly verging folds were statistically conjugate. Maltman (1973) found the orientation of the principle axes of compression was sub-horizontal, trending approximately NW-SE.

The orientation of two cross folds, observed near Porthygaran, are more difficult to explain. If one imagines the second episode of deformation in the New Harbour Group to have been largely dependent on localized conditions as the wide variety of fold styles and orientations suggests, then these fold may express a local difference in ductility, possibly brought
about by increased fluid content, which has allowed for a greater amount of
flow to occur.

Wood (1960), Maltman (1973) and Trefz (1973) offer more integrated,
complex explanations of \( F_2 \) folding in the New Harbour Group which, because
of a lack of structural data and field observations, this author can neither
verify nor dispute. It is apparent, however, that the structures present
in the New Harbour Group are more complex than the above observation might
suggest and, in this regard, the explanations offered may be somewhat
simplistic.

The Third Deformation (\( F_3 \))

The small scale, angular, step-like monoclines or kink bands which
deform bedding, first schistosity, and second schistosity surfaces, reflect
the final phase of folding of the rocks in the Rhoscolyn District.

In size, the kink bands are generally 3–5 cm. in width, and 10 cm. to
slightly over a meter in length. Individual layer thickness is maintained
across these folds. The kink bands most commonly occur as isolated single
bands, but on a few occasions, conjugate sets were observed. The geometry
of these folds appears consistent, irrespective of the lithology in which
they occur. While kink bands show a wide variation in orientation, struc-
tures with a NW vergence are the most abundant.

In the New Harbour Group, the majority of the kink bands observed
were in relative close proximity to the North Stack Fault. Noting this
relationship, Wood (1960) suggested that these small structures may have
resulted from movements along the North Stack Fault. Although a similar
correlation cannot be made for the kink bands in the underlying units, the
large number of faults that transect these units suggest such a hypothesis may be equally valid for the formation of these structures as well.
References Cited


