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The tectonic implications of some small scale structures in the Mona Complex of Holy Isle, North Wales

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Abstract—The rocks of the Rhoscolyn area of Anglesey, North Wales have been subjected to more than one phase of deformation. The result is a complex and often confusing array of minor structures. Using these minor structures, an attempt is made to recognise the major deformation phases that have affected the rocks and to reconstruct the tectonic history of the area. In order to do this it is necessary to consider the deformation of minor structures such as pinch-and-swell; the origin of certain lineations; the problems associated with the buckling of a material that contains two mechanically active planar fabrics, e.g. cleavage and bedding, and the use of pre-existing quartz veins to determine the mechanism of folding.

INTRODUCTION

IN 1894 Pumpelly in Pumpelly *et al.* (1894) commented on 'the general parallelism which exists between the minute and general structure'. This point was taken up by van Hise (1895) who quotes Pumpelly 'the degree and direction of the pitch of the fold are indicated by those of the axes of the minor plications on its side'. Since then the relationships between minor structures and major structures have been examined in detail (see summaries by Leith 1923, Willis 1934 and Wilson 1961) and the study of minor structures has become a powerful tool used by the structural geologist to determine the geometry and orientation of major structures.

However, several problems may still arise when attempting to use minor structures to determine the geometry of a major structure and the deformation history in an area of polyphase deformation, for in such circumstances earlier groups of minor structures are commonly overprinted by later structures which may in turn be affected by an even later deformation.

The superposition of minor structures can occur either by the sequential development of structures with progressive deformation during a single phase of deformation or as the result of two or more separate tectonic events.

Major phases of deformation are generally associated with a 'group' of minor structures some of which may be deformed by minor structures which develop slightly later but which are related to the same deformation phase. If such 'groups' of structures can be recognised in the field, the major phases of tectonism that have affected an area can be discussed without recourse to the listing of countless minor deformation episodes that characterise and confuse many structural descriptions of areas of multiple deformation.

Each group of structures can be considered separately and a detailed picture of the major deformation phases deduced. The relative importance of each major phase can also be determined using criteria such as extent and intensity of the deformation.

The island of Anglesey which forms the north west corner of the principality of Wales is underlain by a succession of metamorphic rocks which Greenly (1919, 1930) referred to as the Mona Complex. He divided the complex into three main units, the Gneisses, the Bedded Succession and the Coedana Granite. The relative age of these units and their structural relationships are still controversial and these problems are reviewed and critically discussed by Barber & Max (1979).

The Bedded Succession has been divided into six units by Greenly and the stratigraphical sequence that he proposed is shown in Table 1. He concluded that the Bedded Succession was upside down and that it represented the overturned limb of a large recumbent fold. A short clear account of how Greenly arrived at these conclusions can be read in the Geological Survey Regional Guide to North Wales (George 1961). Shackleton (1954), from his observations of graded bedding and other criteria which can be used to establish the 'way up' of sediments and metasediments, recognised that the Bedded Succession was in fact the 'right way up'. This threw considerable doubt on the existence of the large recumbent nappe structure that Greenly had proposed to explain the 'inversion'. The stratigraphical sequence established by Shackleton in 1969 and as amended in 1975, which is generally accepted today, is also given in Table 1.

The lower units of the Bedded Succession are well exposed in the cliffs around Holy Isle. The impressive exposures of minor structures in these cliffs have been described by Greenly (1919) and Wilson (1961) and a study of them has led to a greater understanding of deformed lineations (Ramsay 1967, Watkinson 1972) and crenulation cleavage (Cosgrove 1976). These minor structures, however, have generally been studied in isolation, in an attempt to understand their mechanism of formation, and not in the context of determining the major structures. In this paper an attempt is made to return to the original use of minor structures, using them to determine the structure and deformation history of the area around Rhoscolyn (Fig. 1).

TABLE 1

a. SUCCESSION ACCORDING TO GREENLY	b. SUCCESSION ACCORDING TO SHACKLETON 1975
Holyhead Quartzite	Fydlyn Felsitic Formation
South Stack Series	Gwna Group
New Harbour Group	Skerries Group
Skerries Group	New Harbour Group
Gwna Group	Rhoscolyn Formation
Fydlyn Group	Holyhead Quartzite Formation
	South Stack Formation

Only structures that form in the lowest three units of the Bedded Succession, i.e. the South Stack Formation, the Holyhead Quartzite Formation and the Rhoscolyn Formation are considered and the relationship between the Bedded Succession and the other units of the Mona Complex is not discussed.

The South Stack Formation is a mixed sequence of schistose grits, greywackes and sandstones with interbedded shales. Individual lithological units are commonly about one metre thick.

The Holyhead Quartzite Formation is a pure, white, recrystallised sandstone made up of massive sandstone beds with some pelitic intercalations.

The Rhoscolyn Formation is a sequence of schistose greywackes. They are essentially similar to the South Stack beds but contain fewer thick pelitic horizons. In places they are separated from the overlying New Harbour Group by a thin horizon of volcanic rocks, Fig. 1(c).

The geographical location of the area studied and a geological sketch map are shown in Fig. 1. A simplified geological cross section through the south western corner of Holy Isle is shown in Fig. 2. Once the correct stratigraphical succession of these metasediments is recognised, it can be seen that the 'antiform' shown in Figs. 1(c) and 2 can be referred to as an 'asymmetrical anticline' (the Rhoscolyn anticline) of which the steeper limb faces to the south east. This fold, which is the dominant structure in the area, plunges 22° towards the north east on a grid bearing of 067° and has an axial plane which dips 74° towards the north west.

It will be shown in the following sections that by studying the minor structures it is possible to demonstrate that the tectonic history of the Rhoscolyn area involved at least three separate deformation phases termed here D_1, D_2 and D_3 each having its associated folds F_1, F_2 and F_3, cleavage S_1, S_2 and S_3 and lineation L_1, L_2 and L_3. The bedding is termed S_0.

GENERAL DISCUSSION OF THE MAJOR AND MINOR STRUCTURES

Although the rocks of Rhoscolyn have been subjected to more than one phase of deformation the bedded character of these metasediments is still very apparent, especially when the rocks are viewed from a distance of 10–15 m. The rapid alternation of what were originally sandstones and shales can still be clearly seen and in the 'sandstones' (now quartzites) sedimentary structures, e.g. current bedding and slump structures, are still preserved. However, in the pelitic horizons all trace of bedding has been lost and the planar fabrics in these horizons are transposition fabrics. Evidence can be found for two, three or even more transpositions.

In order to determine the tectonic history of an area it is therefore useful to consider first the structures in the more

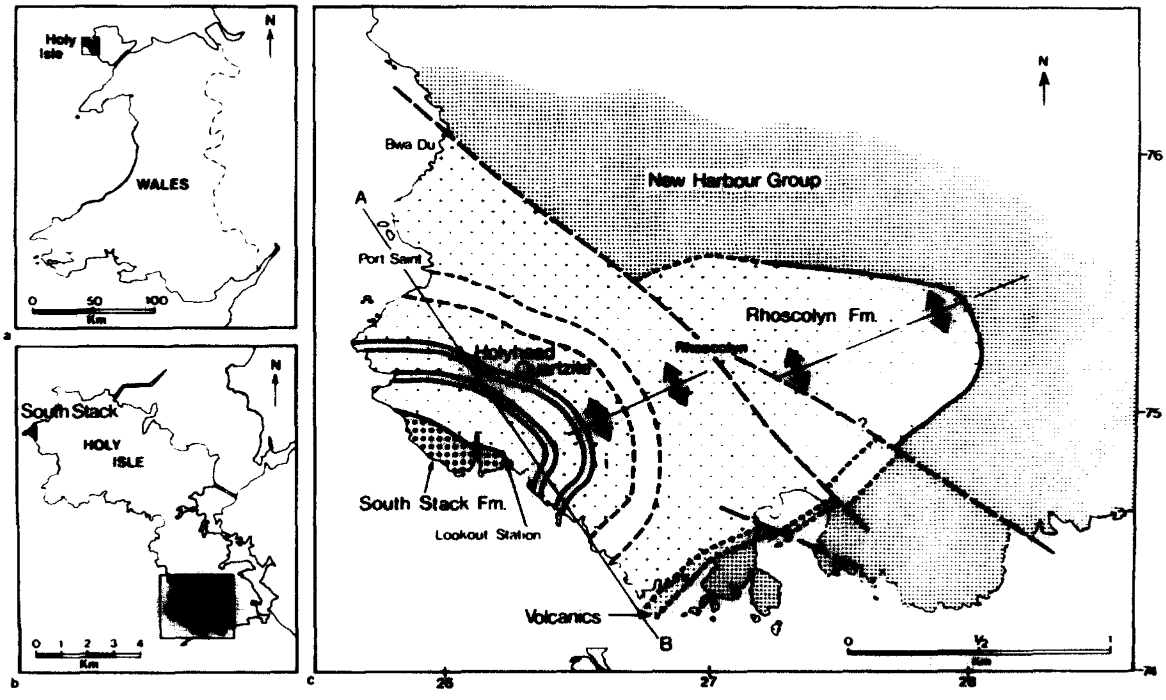

Fig. 1. Geographical location of the area studied and a geological sketch map of the Rhoscolyn area.

massive, competent units which only responded to the major tectonic events and, secondly, to consider the more complex array of structures that is formed in the less competent, pelitic horizons which developed structures in response to the slightest tectonic 'hiccup'.

Figure 2 is a profile sketch of the Rhoscolyn anticline and shows some of the minor structures associated with it. These include minor folds, kink bands, pressure solution cleavage, crenulation cleavage, pinch-and-swell structures, intersection lineations and cusp structures. The figure represents a summary of the field observations from which the tectonic history of the area is to be determined.

Before discussing these structures in detail and considering their implications for the tectonics of the area the reader may find it of interest to consider the logic used in arranging the structures chronologically and in subdividing them into three groups associated with three separate deformation phases.

There is no unique method of analysing the information presented by the minor structures of Fig. 2 or of synthesising the tectonic history of the area from this data: each geologist will have his own method. The arguments set out briefly below are those used by the author.

The Holyhead Quartzite which is folded around the Rhoscolyn anticline contains two cleavages. One cleavage is statistically parallel to the axial plane of the anticline and the other is folded around the anticline. Both cleavages are deformed by kink bands. From these observations it can be concluded that at least three phases of deformation D_1, D_2 and D_3 affected the area. The first cleavage S_1 associated with the earliest deformation D_1 is folded around the Rhoscolyn anticline. The second cleavage S_2 associated with the second deformation D_2 is axial plane to the Rhoscolyn anticline and the third deformation D_3 deforms both these cleavages.

Having established that at least three phases of deformation affected the area it is useful to attempt to group the various minor structures with the appropriate deformation. One simple method that can be used to help subdivide the minor structures into D_1, D_2 and D_3 structures is that of determining whether or not the minor structures have been deformed. Deformed minor structures will be associated with one of the earlier deformations D_1 and D_2, D_3 structures will be undeformed.

The easiest group to identify are the minor structures (folds and kink bands) associated with the third deformation (these structures are undeformed). D_3 structures are only sporadically developed and it is clear that the D_3 deformation was much less intense than the D_1 and D_2 deformations both of which produced more pervasive deformations. Because the D_3 deformation is only sporadically developed many D_2 structures are also undeformed. However, the principal compression direction during the D_3 deformation was sub-vertical whereas the principal compression direction during the D_2 deformation was horizontal. Consequently the orientation of axial planes of F_2 and F_3 folds are generally sufficiently different to enable F_3 folds and undeformed F_2 folds to be easily distinguished in the field. There are numerous minor folds associated with the Rhoscolyn anticline and their geometry 'S', 'M' or 'Z', depends upon their position on the anticline, labelled X–X in Fig. 2. Some of these small-scale D_2 folds in layers XX, fold pre-existing pinch-and-swell structures, lineations and a cleavage. These pinch-and-swell structures, lineations and the cleavage must therefore be associated with the D_1 deformation.

The above is a brief outline of the method used to identify the separate deformation episodes affecting the area and to associate each minor structure with the appropriate episode.

Once all the minor structures have been assigned to one of the major deformation phases the groups of structures related to each deformation phase can be considered in turn in order to obtain a more detailed understanding of the different phases.

STRUCTURES ASSOCIATED WITH THE FIRST DEFORMATION PHASE D_1

Cleavage

One of the most pervasive minor structures on Holy Isle is the early cleavage, S_1, which is folded around the D_2 Rhoscolyn anticline (see Fig. 2). This cleavage is refracted as it passes through the boundaries between the different types of sediments (Fig. 2.1 and also Wilson 1961, fig. 23) and the morphology and mode of formation of this cleavage depends on the lithology of the rock in which it developed.

In the massive Holyhead Quartzite the S_1 fabric is a closely spaced pressure solution cleavage, whereas in pelitic horizons of the South Stack Formation and the Rhoscolyn Formation it is developed as a crenulation cleavage. The change in orientation of the S_1 cleavage around the Rhoscolyn anticline is shown in Fig. 2. In order to determine the original orientation of the S_1 cleavage which will be statistically parallel to the original orientation of the F_1 fold axial planes the anticline must be 'unfolded'. To do this it is necessary to know by what 'mechanism' of folding the Rhoscolyn anticline formed. Although this is not known with certainty, as is indicated below, it is possible to argue on the basis of field observations and experimental evidence that the gently dipping limb of the anticline has probably undergone very little rotation during the D_2 folding whereas the sub-vertical limb has probably undergone considerable rotation.

Experimental and theoretical work on kink bands (Cobbold *et al.* 1971) show that they often develop in materials with a high mechanical anisotropy and that layer rotation is confined primarily to the kink band with very little rotation of the external foliation Fig. 3(a). Field observations of highly anisotropic sedimentary piles, e.g. turbidites show that folds which develop on both large and small scales often have the geometry of kink bands. The rocks folded by the Rhoscolyn anticline include (a) the South Stack Formation, (b) the Holyhead Quartzite and (c) the Rhoscolyn Formation. Units (a) and (c) are made up of considerable thicknesses of well bedded

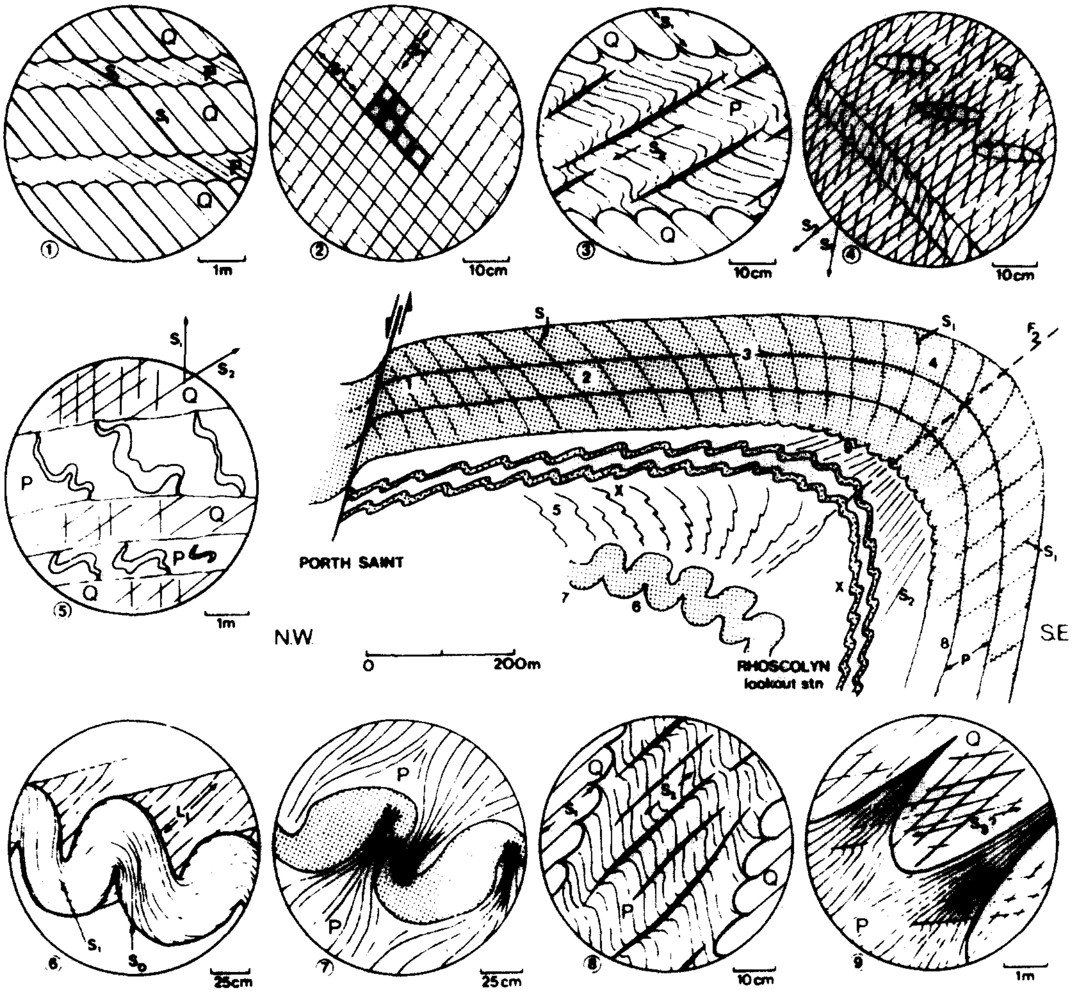

Fig. 2. A cross section through the southern part of Holy Isle [section A–B Fig. 1(c)]. Minor structures observed at localities 1–9 are shown in the insets 1–9 respectively (Q = Quartzite; P = Pelite).

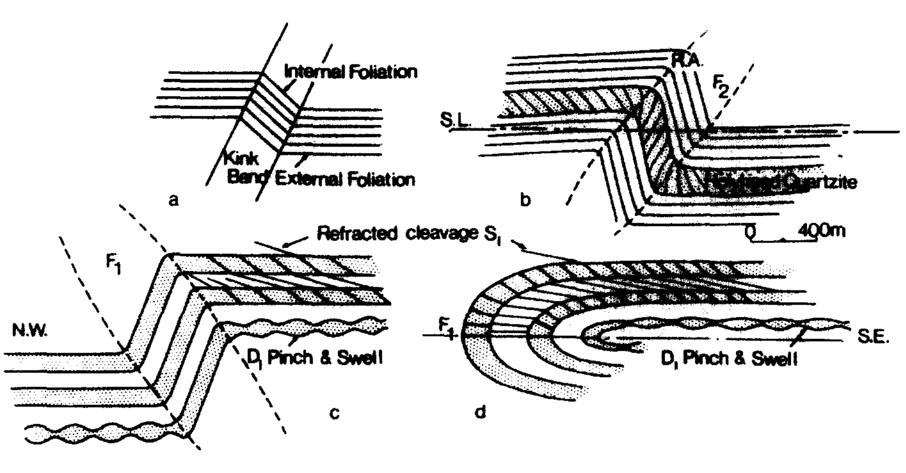

Fig. 3. (a) A sketch of a kink band defining terms used in the text. (b) The Rhoscolyn anticline shown as part of a large kink structure (d) A recumbent fold (a D_1 structure) whose geometry is compatible with the field observations of the D_1 cleavage and pinch-and-swell structures. At present there is insufficient field data available to enable the scale of the F_1 structure to be determined or to determine whether or not the structure is a recumbent fold as indicated in (d) or a kink structure with the kink band boundary dipping to the south east (c).

metasediments which sandwich the more competent, less anisotropic unit (b). This sedimentary pile has a high mechanical anisotropy. Consequently it is suggested that the Rhoscolyn anticline may be a large 'kink' structure (Fig. 3b).

If it is assumed that the Rhoscolyn anticline is a 'kink' structure then one can argue that the subhorizontal limb (i.e. the external foliation) rotated very little during the D_2 deformation and that the S_1 cleavage in the Holyhead Quartzite and in the pelitic horizons of this limb is approximately in its original position. Although the S_1 cleavage in the pelitic horizons within the Holyhead quartzite and between the quartzite layers of both the Rhoscolyn Formation and the South Stack Formation has been mainly transposed into an S_2 crenulation cleavage, it can still be demonstrated in the gently dipping limb of the Rhoscolyn anticline that the original orientation of the cleavage was either subhorizontal or very gently dipping to the south east. The quartzite layers in the Rhoscolyn beds underlying the main quartzite are folded by D_2 folds. However, it can still be clearly seen that the S_1 cleavage in these quartzite layers originally dipped gently to the south east (Fig. 2.6).

Folds

Despite the fact that the S_1 cleavage is so well developed, F_1 folds are remarkably elusive. No unequivocal examples of F_1 folds are known to the author. A few indistinct traces of early folds can be seen in the Holyhead Quartzite, e.g. at G.R. SH267748, however these may be sedimentary slump folds; certainly, horizons of well developed slump folds (F_0) occur in the quartzite units of the South Stack Formation in the core of the Rhoscolyn anticline.

Pinch-and-swell structures

Many of the thin quartzite beds in the Rhoscolyn Formation developed pinch-and-swell structures during the D_1 deformation. These structures (Fig. 2.7) probably formed during the late stages of the development of the F_1 folds when the limbs of these folds were at a high angle to the maximum principal compression direction. The influence of these pinch-and-swell structures on the refolding of the quartzite beds during the second deformation D_2 is discussed in the section on D_2 structures.

Quartz veins

A set of quartz veins developed parallel or sub-parallel to the early cleavage S_1 in the pelitic horizons. These veins which were deformed during the D_2 deformations are extremely useful strain markers and often enable the D_1 and D_2 deformations to be easily separated.

Having briefly discussed some of the structures associated with the first deformation their tectonic implications can now be considered. It will be recalled that there is a lack of convincing F_1 folds, that the orientation of the bedding after the D_1 deformation was subhorizontal, that the development of pinch-and-swell structures indicated that the principal compression associated with the D_1 deformation was at some time at a high angle to the bedding and that the S_1 cleavage originally dipped gently to the south east in the quartzites and was subhorizontal in the pelitic horizons. These facts point to the possible existence of a recumbent F_1 structure (Fig. 3d). The scale of this structure is difficult to determine. As mentioned earlier Greenly (1919) concluded that the rocks of the Rhoscolyn anticline were upside down and in order to account for this inversion he suggested that they were part of the overturned limb of a recumbent fold (nappe). Shackleton (1954) has demonstrated that the beds are in fact 'right way up'. Having shown Greenly's assumption regarding the 'way up' to be erroneous, Shackleton justifiably questions the existence of the large recumbent nappes. However, the existence of the well developed D_1 minor structures summarised above poses the questions, "are these structures related to a larger structure?" and if so "what is the geometry of the large D_1 structure?" It can be seen from Fig. 3(d) that the refraction and orientation of the S_1 cleavage and the development of D_1 pinch-and-swell structures are compatible with rocks of the Rhoscolyn anticline being part of the upper limb of a recumbent fold which closes to the north west.

The exact geometry of the large F_1 folds is difficult to determine from observations taken from only one limb. Several possibilities exist including a large recumbent nappe of the type postulated by Greenly, a series of small recumbent folds, or a series of reverse kink-like structures (Fig. 3c) with axial planes dipping to the south east.

STRUCTURES ASSOCIATED WITH THE SECOND DEFORMATION D_2

Folds

The area is dominated by structures formed during the D_2 deformation. F_2 folds are developed on several scales ranging from the Rhoscolyn anticline with a wavelength of 2 km which were formed by the buckling or kinking of the Holyhead quartzite, to minor folds with wavelengths between 5 mm and 5 cm formed by the buckling of the early cleavage, S_1.

The quartzite layers in the South Stack Formation in the core of the Rhoscolyn anticline, see XX in Fig. 2, developed buckles during the D_2 deformation with wavelengths ranging between 0.5 and 5 m. Many of these quartzite layers had, as already mentioned, developed pinch-and-swell structures during the D_1 deformation. These structures are commonly found to govern the wavelength of the F_2 folds (Figs. 4 and 2.7).

Field observations (Fig. 5a) and experimental work on the folding of a layer containing pinch-and-swell structures (Fig. 5b & c) (Penge 1976) indicate that buckles form such that one limb incorporates the 'pinch' portion and the other limb the 'swell' portion of the pinch-and-swell structure. The buckles are asymmetric even

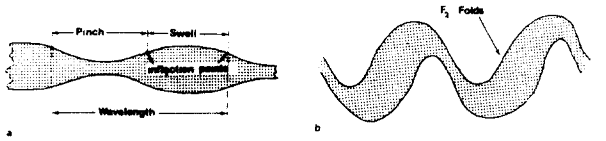

Fig. 4. (a) A sketch of a pinch-and-swell structure defining terms used in the text. (b) A buckled pinch-and-swell structure. Note how one limb of a fold contains the 'swell' part and the other limb the 'pinch' part of the pinch-and-swell structure.

when the maximum principal compression is applied parallel to the layer containing the pinch-and-swell structures and the wavelength of the buckles is governed entirely by the 'wavelength' of the pinch-and-swell structure.

Prior to the onset of the second deformation, the quartzite layers of the South Stack Formation and the Rhoscolyn Formation contained two mechanically active fabrics, i.e. the bedding S_0 and the cleavage S_1. Both these fabrics buckled during the second deformation but not synchronously (Fig. 6a–c). Initially the bedding buckled and the quartzite layers developed folds with a low wavelength thickness ratio ($\simeq 7$) (Fig. 6b), the wave length sometimes being controlled by pre-existing pinch-and-swell structures. As these folds amplified, the efficiency of buckling as a mechanism of layer shortening decreased and the folds eventually 'locked up'. At this point in the deformation the early cleavage began to fold wherever it was suitably oriented with respect to the maximum principal compression. Suitable orientations of the cleavage occurred on alternate limbs and the type of folds that formed were 'internal buckles', i.e. buckles whose amplitude dies out in the fold profile. The formation of internal buckles is discussed by Biot (1964) and Cobbold *et al.* (1971). A line drawing of the photograph shown in Fig. 5(d) is shown in Fig. 6(d). In the limbs in which the cleavage does not buckle, the cleavage is at a high angle (often 90°) to the principal compression direction associated with the second deformation. In these limbs the intensity of the early cleavage is increased by the process of pressure solution, see Figs. 5(d) and 6(d).

Fig. 6. (a) (b) (c) The buckling of two mechanically active foliations, the bedding S_0 and the early cleavage S_1, during the second deformation. The two foliations do not buckle synchronously, S_0 buckles first. If the unfolded layer (a) contains pinch-and-swell structures then even if the maximum compression acts along the layer the folds that develop will be asymmetric (see text). (d) A line diagram of Fig. 5(d) showing the folding of the two fabrics S_0 and S_1.

Cleavages

The intensity of the cleavage associated with the second deformation is variable. Like the early cleavage S_1, the type of cleavage developed during the second deformation depends upon the lithology of the rock in which it develops.

In the Holyhead Quartzite and the quartzite members of the Rhoscolyn Formation and the South Stack Formation both the S_1 and S_2 cleavages are generally pressure solution cleavages. (Locally, however, where the S_1 pressure solution cleavage is very well developed the S_2 cleavage may develop as a crenulation cleavage.) The development of the second pressure solution cleavage does not usually destroy the first pressure solution cleavage. However, on the overturned limb of the Rhoscolyn anticline the S_1 and S_2 pressure solution cleavages are parallel. Consequently the formation of the S_2 cleavage simply intensifies the S_1 cleavage and only one cleavage is apparent. Where S_1 and S_2 are not parallel, e.g. around the hinge and on the gently dipping limb of the Rhoscolyn anticline (Fig. 2) both cleavages can be clearly seen. They slice the Holyhead quartzite into lozenge-shaped rods and constitute a pencil cleavage (Fig. 2.2).

The cleavage that develops in the pelitic horizons during the second deformation is a crenulation cleavage. The development of this type of cleavage is restricted to rocks that possess a good mechanically active fabric or layering.

The buckling of a rock made up predominantly of mica and quartz, where the micas are aligned to form a planar fabric, and where the quartz and mica are uniformly distributed (e.g. a bedding plane fabric or a slaty cleavage), has been discussed in Cosgrove (1976), where it is shown that by a combination of microfolding and an associated mineral redistribution the mica/quartz fabric can be 'transposed' into alternate quartz rich and mica-rich layers. The width of these layers is approximately one quarter of the wavelength of the microfolds that developed in the mica/quartz fabric. By the process of 'metamorphic differentiation' an originally uniform distribution of quartz and mica is differentiated into quartz-rich and mica-rich layers (sometimes known as tectonic striping). The resultant fabric generally has a high mechanical anisotropy (not only is it a multilayer made up of alternate quartz-rich and mica-rich layers, but each layer possesses a strong planar mineral fabric parallel to the layering) and is very susceptible to deformation and retransposition during subsequent tectonic events. The buckling and transposition of such a transposition fabric is also discussed in Cosgrove (1976), where it is shown that the fabric is transposed into another transposition fabric also made up of alternate quartz-rich and mica-rich layers. The width of these layers is greater than those of the first transposition because the wavelength of the microfolds

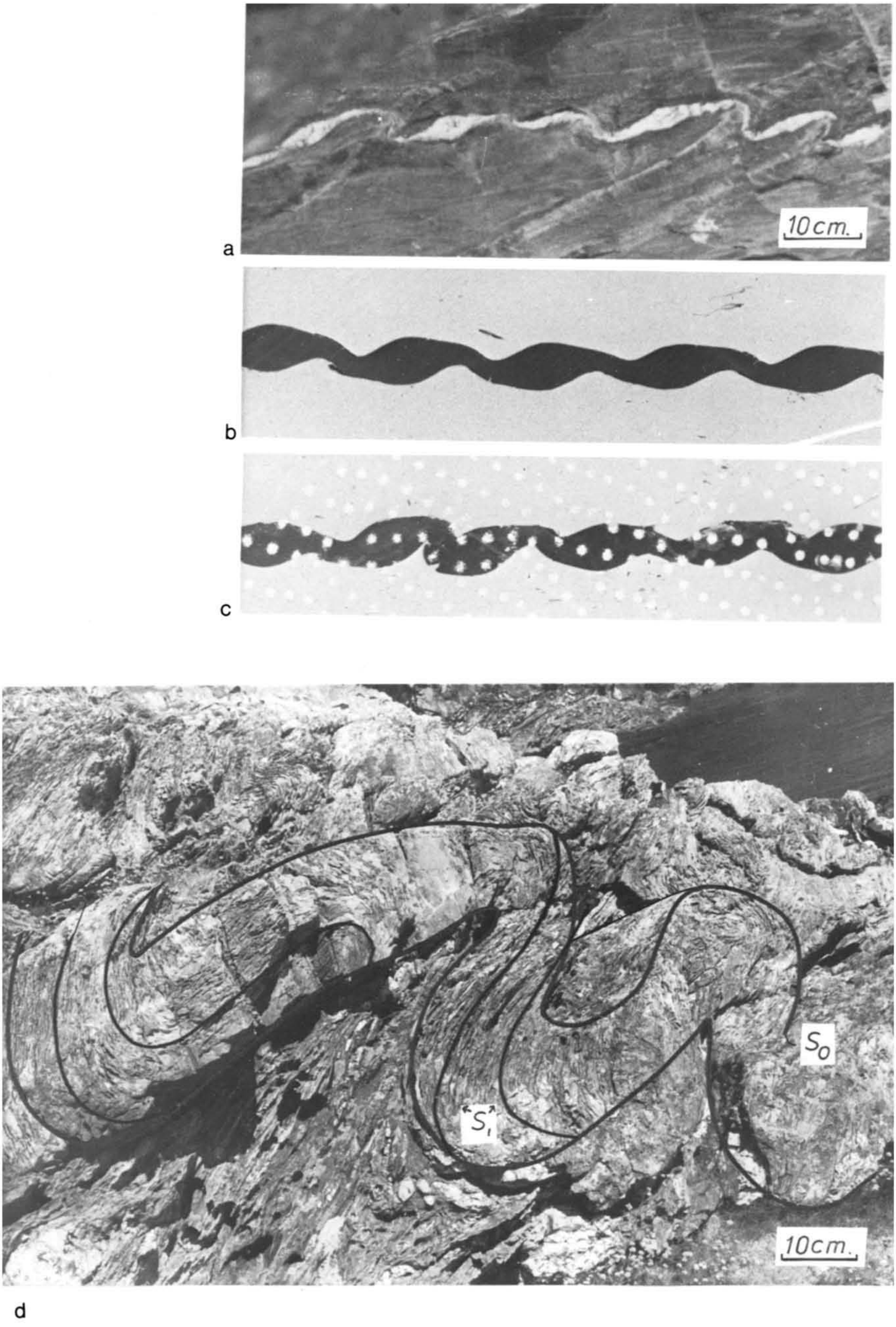

Fig. 5. (a) Folded quartz vein containing pinch-and-swell structures. Note how the wavelength of the folds is governed by the wavelength of the pinch-and-swell structures. West of Castaneras, North Spain. (b) and (c) Folded pinch-and-swell structures developed experimentally in plasticine layers set in a less competent plasticine matrix. The principal compression was at 20° to the layer in experiment (b) and 30° to the layer in experiment (c) (after Penge 1976). (d) Folds in a quartzite layer in the South Stack Formation at Rhoscolyn, formed during the second deformation D_2. Both the bedding S_0 and the early cleavage S_1 are buckled. A line diagram of this figure is shown in Fig. 6(d).

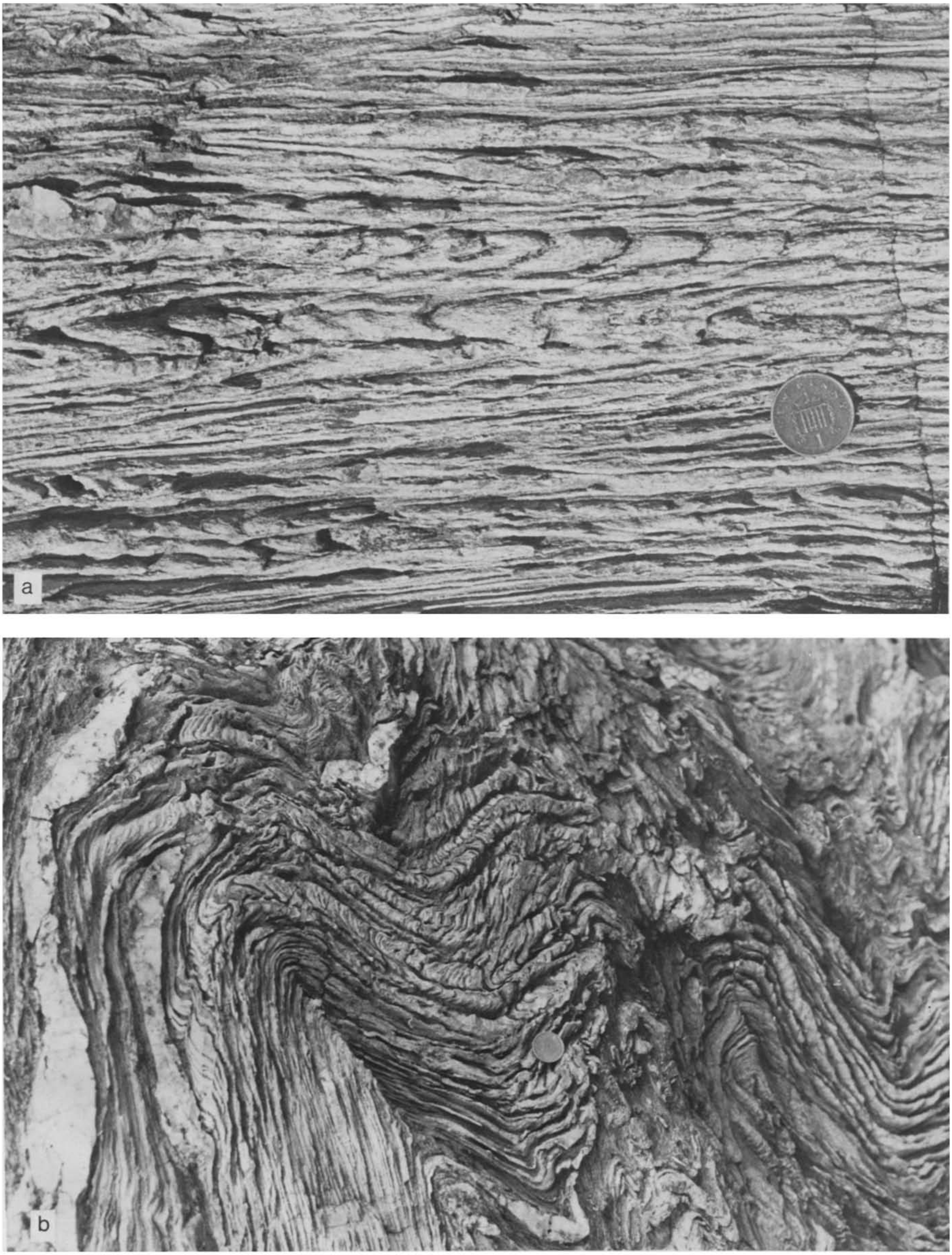

Fig. 7. (a) An undeflected crenulation cleavage. (b) A gently folded crenulation cleavage, D_2. Both examples from the New Harbour Group. Diameter of the coin is 2 cm.

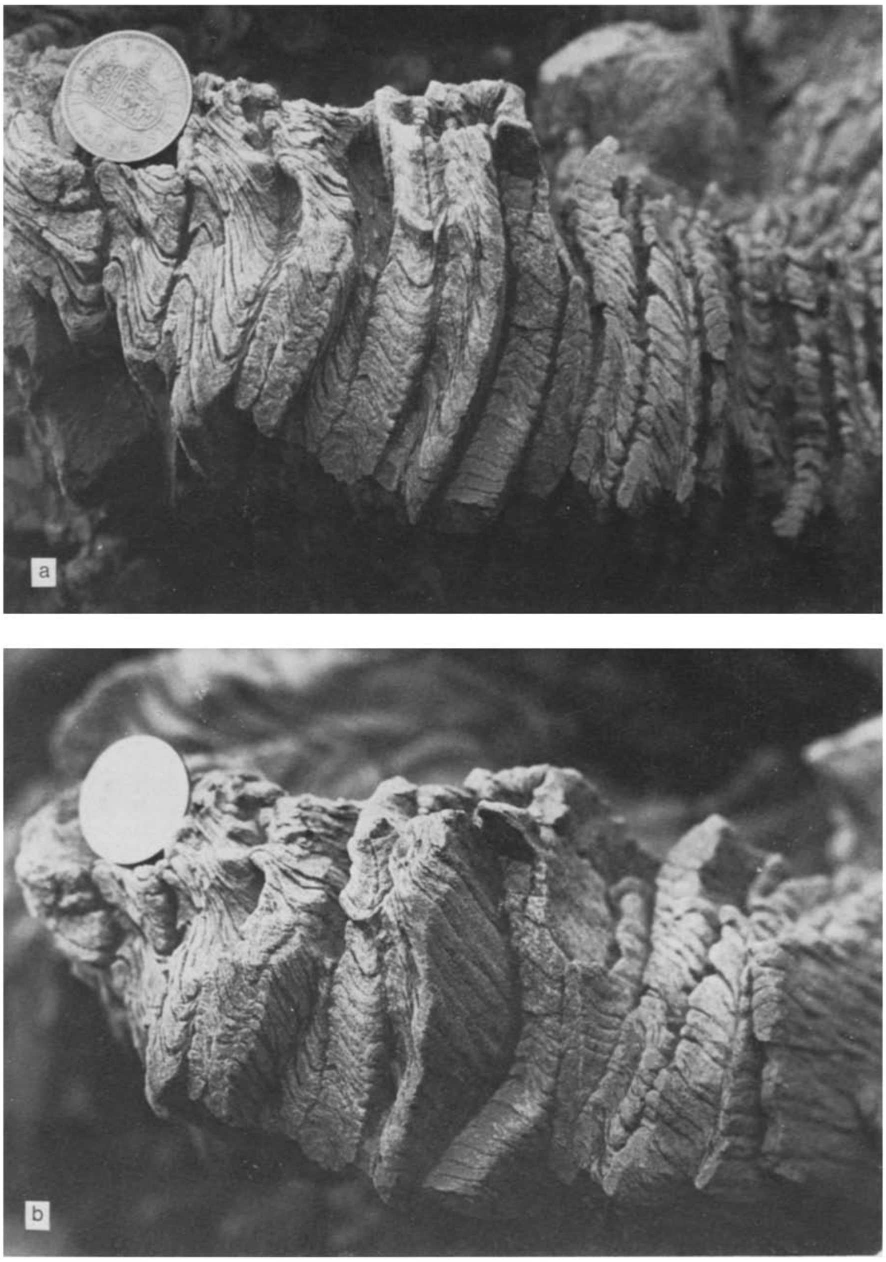

Fig. 8. Folds in the Rhoscolyn Formation photographed normal to the fold profile (a) and oblique to the profile (b). An S_2 crenulation cleavage has been formed by the buckling of an S_1 crenulation cleavage. Note on (b) the lineation caused by the intersection of the S_1 crenulation cleavage and the S_2 crenulation cleavage. Figure 9 is a labelled line diagram of Fig. 8(b). The diameter of the coin is 2.3 cm.

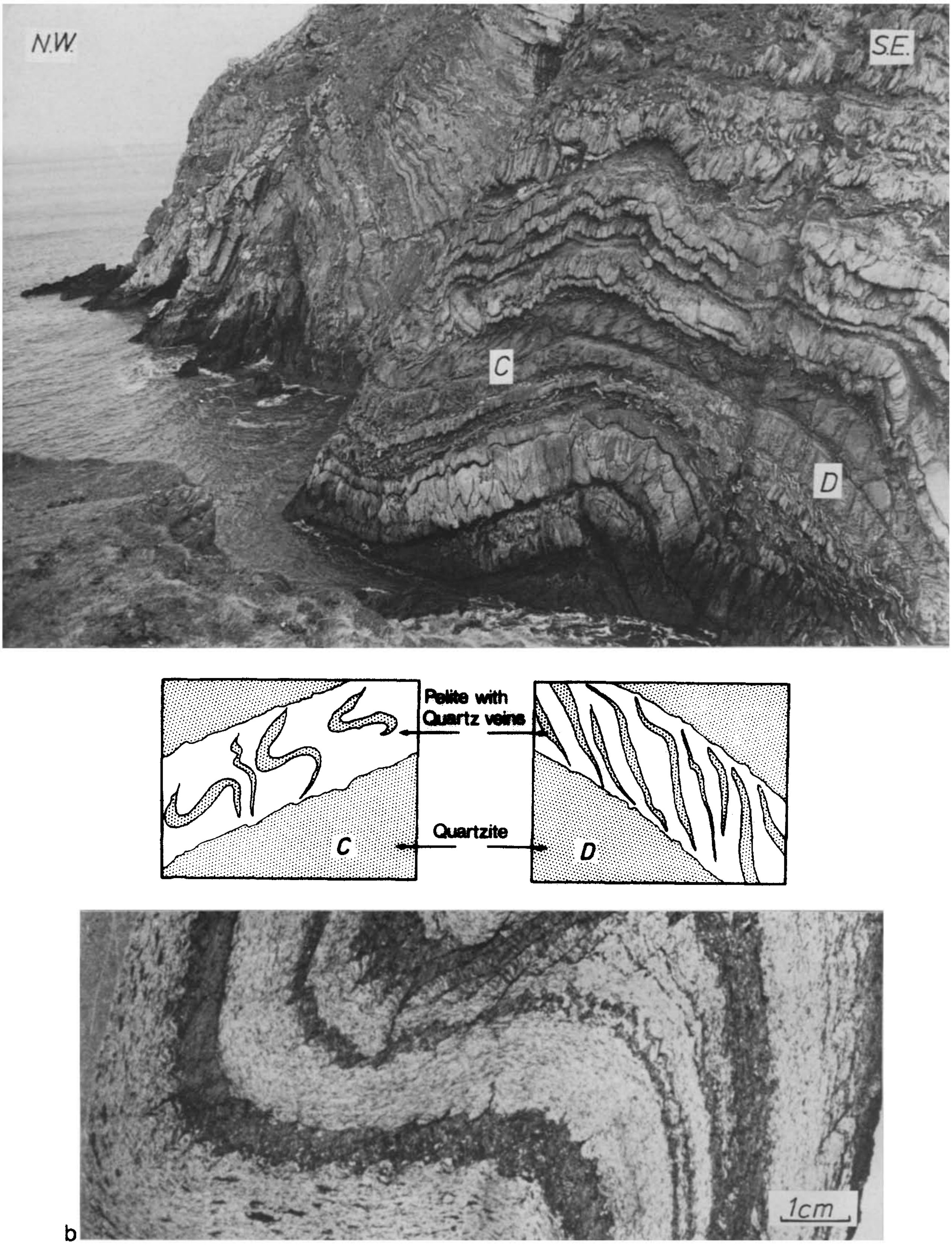

Fig. 11. (a) F_2 folds in the South Stack Formation at South Stack. During the development of these folds quartz veins in the pelitic layers were folded in the north west dipping limbs (C) and underwent a body rotation in the south east dipping limbs (D). See also Fig. 12. (b) This is a photomicrograph of a folded transposition fabric. Cusp structures are developed at the interface between the quartz-rich (light) and mica-rich (dark) layers. A line diagram of this photomicrograph is shown in Fig. 13(c).

associated with the second transposition is larger.

Microfolding, metamorphic differentiation and the formation of crenulation cleavage are three successive stages in the transposition of a mineral fabric or layering. Transposition of a tectonic fabric may have occurred many times in areas with a tectonic history that involved several phases of deformation. Each transposition will produce a layering that is wider than the layering of the previous transposition. An example of a transposition fabric from the New Harbour Beds which overlie the South Stack Series (see Table 1) is shown in Fig. 7(a). The remnants of fold hinges can still be seen in some of the quartz-rich layers. At some localities this fabric is not folded, e.g. Fig. 7(a), at others it is gently folded, e.g. Fig. 7(b), and at others it is completely transposed into a new fabric.

The S_2 cleavage in the pelitic horizons within and below the Holyhead Quartzite is a crenulation cleavage formed by the microfolding of the S_1 cleavage, which is commonly itself a crenulation cleavage (Fig. 8). It can be seen that both the fabric being folded to form the S_2 cleavage in Fig. 8 and the fabric that was folded to form the transposition fabric shown in Fig. 7(a) are made up of quartz-rich and mica-rich layers, i.e. are themselves transposition fabrics. It is interesting to speculate what 'fabric' was folded to produce these fabrics. They could have been formed either by the microfolding of a sedimentary fabric in the shales or by the microfolding of a pre-S_1 tectonic fabric. A third tectonic event, discussed briefly later, causes microfolding of the S_2 crenulation cleavage in places and the local development of a third transposition fabric.

Various stages in the formation of the S_2 crenulation cleavage can be found, e.g. Figs. 7 and 8, and these throw considerable light on the origins of some of the lineations which occur throughout the area.

Lineations

Lineations of various ages and of various origins are developed in the rocks of the area. Figure 9 is a labelled line diagram of the photograph shown in Fig. 8(b) and shows the relationship between the S_1 crenulation cleavage, the S_2 crenulation cleavage and the lineation L_2 on the S_2 cleavage plane. The lineation L_2 on the S_2 cleavage planes is an intersection lineation caused by the intersection of the S_1 crenulation cleavage (a transposition fabric of alternating mica-rich and quartz-rich layers) with the S_2 crenulation cleavage, i.e. a cleavage/cleavage intersection lineation. This lineation appears as numerous long strips of quartz separated by thin strips of mica and often looks deceptively like the quartz crystal fibre slickensides that are often found on fold limbs.

Many of the lineations found in these rocks are deformed, e.g. L_1 lineations are often deformed by the deformation D_2. The L_1 intersection lineations can be conveniently divided into two types, those formed on the bedding, S_1 on S_0 and probably S_0 on S_1. The S_1 on S_0 lineations are found folded around the F_2 folds in the quartzite layers of the Rhoscolyn Formation and the South Stack Formation (Fig. 10).

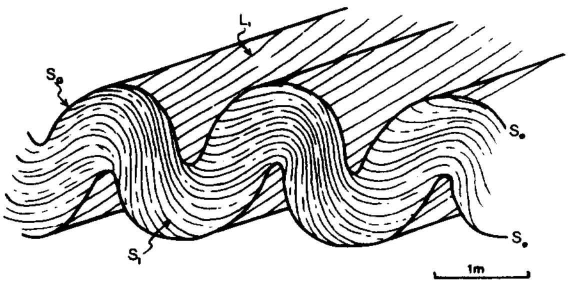

Fig. 10. An intersection lineation L_1 caused by the intersection of an S_1 pressure solution cleavage with the bedding S_0, deformed by F_2 buckles in the South Stack Formation.

The L_1 lineation on the S_1 crenulation cleavage planes was formed in a similar way to the lineation on the S_2 crenulation cleavage planes shown in Figs. 8(b) and 9. An appropriate figure to illustrate the formation of the L_1 lineation would be the same as Fig. 9 except that S_2 and L_2 of Fig. 9 would be S_1 and L_1 and the folded cleavage S_1 of

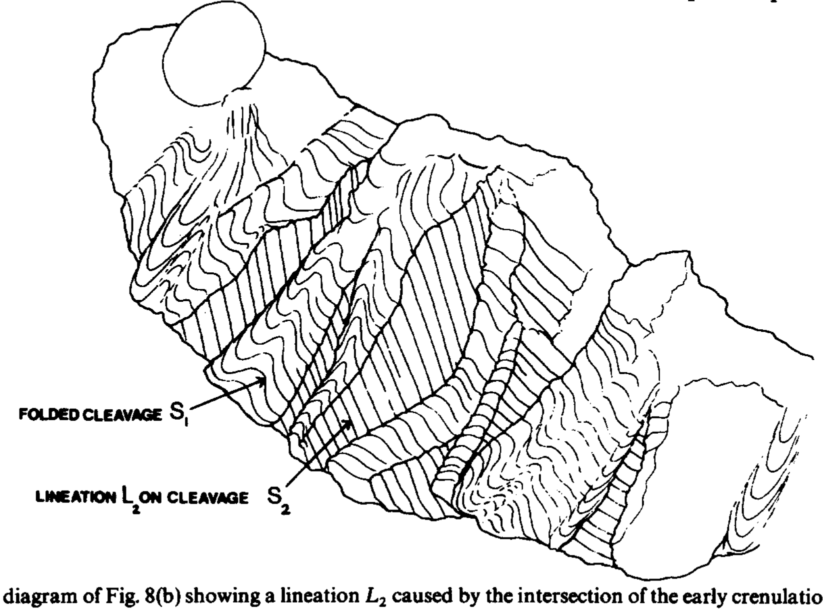

Fig. 9. A line diagram of Fig. 8(b) showing a lineation L_2 caused by the intersection of the early crenulation cleavage S_1 on the later crenulation cleavage S_2.

Fig. 9 would be either a sedimentary fabric, S_0, or a pre-S_1 tectonic fabric. It has not been possible from field observations to decide conclusively between these two possibilities. The S_0 (?) on S_1 lineation is often found folded around the F_2 folds formed by the buckling of the S_1 crenulation cleavage in the pelitic horizons.

Figure 10 shows an L_1 lineation deformed around F_2 folds in a quartzite layer from the South Stack Formation. The lineation is caused by the intersection of an S_1 pressure solution cleavage with bedding and is parallel to the F_1 fold axes. The angle between this lineation and the F_2 fold axes is therefore the angle between the F_1 and F_2 fold axes (approximately 15–20°). It must be remembered however that unless the F_2 folds in the quartzite layers are formed by flexural flow folding and have not been affected by post buckle flattening this angle would have changed during the F_2 folding (see Ramsay 1967, pp. 463–464).

Deformation of the quartz veins

The effect of the second deformation D_2 on the quartz veins developed in the pelitic horizons during the early deformation D_1 can be used to demonstrate that the formation of the F_2 multilayer folds in the South Stack Formation and the Rhoscolyn Formation was by the process of flexural slip. It will be recalled that these veins are parallel or sub-parallel to the early cleavage. The veins were deformed during the formation of the F_2 folds and the effect of this deformation on the veins is found to depend upon which limb of an F_2 fold the veins occur. Veins on the north west dipping limbs are folded but those on the south east dipping limbs are generally not. This difference of behaviour on the two limbs is particularly well seen in the F_2 folds in the South Stack Formation at South Stack (Figs. 1 and 11a). The development of these folds is shown schematically in Fig. 12. If it is assumed that the folding occurs by flexural slip and that the quartz veins deform in response to the shear couple set up in the pelitic horizons between the quartzite beds as the relatively competent quartzite beds slide past each other during folding, then the opposite sense of shear on the two limbs would cause veins in the north west dipping limbs to buckle and veins in the south east dipping limbs to undergo a body rotation. This is exactly what is observed to occur in the field.

Cusp structures

Cusp structures may develop at the interface between two materials when the maximum compression is parallel or at a low angle to the interface (Biot 1965, Dieterich & Onat 1969). The cusp 'points' close into the more competent material.

In the Rhoscolyn area cusp structures are developed on at least two scales. Relatively large cusps with a wavelength of approximately 1 m occur in places at the junction between pelitic bands and the Holyhead Quartzite (Fig. 2.9). Smaller cusps with wavelengths of approximately 2 mm occur at the junction between the quartz-rich and mica-rich layers of the transposition fabrics formed in the pelitic horizons. All cusps point into the quartz-rich layers (Figs. 2.9, 11b and 13).

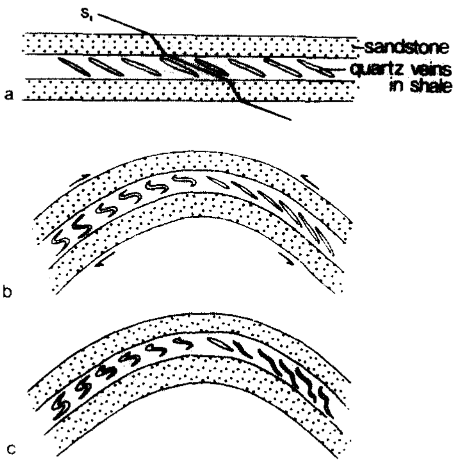

Fig. 12. Various stages in the formation of the folds shown in Fig. 11(a). (a) Horizontal beds after the deformation D_1. The quartz veins are restricted mainly to the pelitic horizons and are sub-parallel to the cleavage S_1. (b) Beds folded into F_2 folds. The shear couples generated in the pelitic horizons as the quartzite layers slide past each other during the formation of the F_2 folds causes the quartz veins to buckle in the northwest dipping limb (lefthand side) and to undergo a body rotation in the southeast/dipping limb. (c) The only visible effect of the D_3 deformation on these F_2 folds is the low amplitude buckling of the quartz veins in the southeast dipping limbs [see also Fig. 11(a) limb D].

Experimental work by Cobbold (1969) indicates that for Newtonian viscous materials the rate of amplification of cusp instabilities is very slow and that a characteristic wavelength will not readily appear. However, Figs. 11(b) and 13 show cusp structures with a very regular wavelength at a quartz-rich, mica-rich layer interface. Thus there is an apparent discrepancy between the experimental work and the field observations. It is suggested that the well developed cusp wavelength is not in fact related to the properties of the interface but to the periodic disturbance of the interface caused by the 'internal' buckling of the mica-rich layer. These buckles determine the wavelength of the cusps and control their initiation. Various stages in the formation of the small scale cusp structures can be observed in the field. It is found that if a transposition fabric buckles during a subsequent deformation two orders of folds may develop (Fig. 13). The first order (larger) folds are formed by the buckling of the quartz/mica multilayer and the second order (smaller) folds are formed by the buckling of the mica fabric in the mica-rich layers (Cosgrove 1976, especially fig. 14). The wavelengths are approximately 4 cm and 2 mm respectively.

It can be established from the field observations summarised in Fig. 13 that the buckles in the mica-rich layer (2nd order buckles) pre-date the buckling of the quartz/mica multilayer (first order folds). During the formation of the first order folds the cusp structures that fall on the inner arc X of a buckling quartz-rich layer are amplified and those that fall on the outer arc Y are suppressed (see Figs. 11b and 13).

The larger scale cusps (Fig. 2.9) at the junction of the

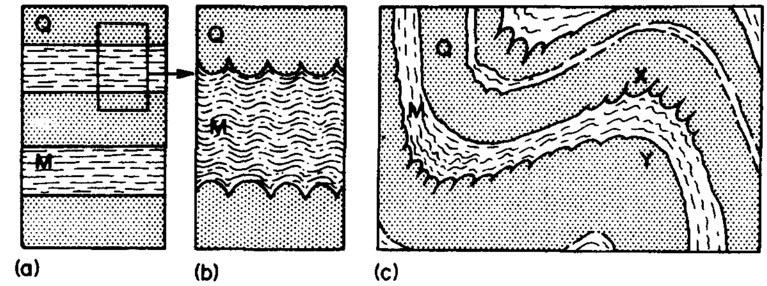

Fig. 13. Three stages in the buckling of a transposition fabric made up of alternating quartz-rich (Q) and mica-rich (M) layers approximately 6 mm wide. (b) shows buckles developed in mica-rich layer and the formation of cusps at the layer interface. The wavelength of the cusps is governed by the wavelength of the folds in the mica-rich layer. (c) At this stage in the buckling of the transposition fabric the quartz-rich layers have buckled. The cusps at the layer interface are amplified in the inner arcs of the folds in the quartz-rich layers (X) and suppressed at the outer arcs of the folds. See Fig. 11(b) for scale.

pelitic horizons and Holyhead quartzite are probably early D_2 structures which were amplified during the formation of the Rhoscolyn anticline in a similar manner to the cusps shown in Figs. 11(b) and 13, if they fell on the inner arc of the Rhoscolyn anticline. Whether these cusps are sedimentary structures (load casts?), D_1 structures or early D_2 structures which, like the cusps of Fig. 11(b) and 13, were amplified by subsequent D_2 events, is difficult to say.

STRUCTURES ASSOCIATED WITH THE DEFORMATION PHASE D_3

Evidence for a minor deformation phase D_3 is provided by kink bands and minor folds which deflect both the S_1 and S_2 cleavages (e.g. Figs. 2.4 and 2.9). The kink bands commonly occur in conjugate sets and locally one of the conjugate bands may develop as an array of en echelon bands (see Fig. 2.4). F_3 folds can be found folding the S_2 cleavage in some pelitic horizons (Fig. 2.9). They are approximately coaxial with the F_1 and F_2 folds but have sub-horizontal axial planes. The maximum principal compression during the D_3 deformation was vertical.

It will be recalled that the quartz veins, associated with the deformation D_1, developed in the pelitic horizons and were parallel or sub-parallel to the S_1 cleavage which originally dipped very gently to the south east. As a consequence of the D_2 folding some of these quartz veins were folded [Figs. 11(a), limb C and 12] and others [i.e. those in the south-east dipping limbs of the F_2 folds, Figs. 11(a), limb D and 12] underwent a body rotation which resulted in their dip being increased. The vertical, principal compression associated with D_3 tended to buckle these steeply dipping veins. However, as the D_3 deformation was relatively weak the F_3 folds in the veins are generally only poorly developed e.g. Figs. 11(a), limb D and 12(c).

DISCUSSION

Greenly (1919) concluded that the Bedded Succession represented an approximately continuous sedimentary sequence. Barber & Max (1979) however have suggested that major tectonic breaks may exist within the Bedded Succession, particularly between the New Harbour Group and the underlying beds (Table 1). They point out that the beds below the New Harbour Group appear to be relatively undeformed compared with the New Harbour Group and suggest that the New Harbour Group (already foliated, lineated and folded) was thrust over the undeformed South Stack Formation, Holyhead Quartzite and Rhoscolyn Formation. These undeformed beds were then folded by a latter deformation, probably associated with the Caledonian orogeny.

The study, presented in this paper, of the rocks underlying the New Harbour Group indicates that these rocks and the New Harbour Group have been subjected to comparable tectonic histories. For example, Maltman (1977) who discussed the deformation history of the New Harbour Group to the north of Rhoscolyn, recognised three deformation events. D_1 which produced a foliation dipping moderately to the north west, D_2 which folded the bedding/foliation into conjugate folds with north east to south west/trending axes, one set facing south east and the other north west, and a minor deformation D_3 which formed kink bands. He also records the local development of small F_2 folds with axes trending north west to south east. Khonstamm (personal communication) working on the New Harbour Group around Amlwch, also recognises three deformation events. D_1 which produced a moderately dipping foliation S_1, D_2 which produced folds with axial planes dipping to the north and north east and D_3 which produced folds with horizontal axial planes. He has also found evidence for a cataclastic event between D_2 and D_3. Gibbons (personal communication) found evidence of three deformation phases in the Gwna and Penmynydd rocks on the Lleyn Peninsula. D_1 produced a strong flat-lying fabric, D_2 produced large upright or south east-facing folds and D_3 was associated with thrusting. It is suggested that although the three deformation histories described above are not identical they are sufficiently like the deformation history of the rocks below the New Harbour Group described in this paper to indicate that the rocks below the New Harbour Group have been exposed to the same tectonic events as the New Harbour Group.

The difference in the amount of deformation of the New Harbour Group and the underlying beds is due primarily to differences in lithology. The New Harbour Group is made up predominantly of pelitic rocks whereas the underlying beds contain numerous psammitic beds some of considerable thickness (e.g. the Holyhead Quartzite). Inevitably the psammitic rocks are not as deformed as the pelitic rocks. If, however, structures in the pelitic horizons of the underlying rocks are compared with structures in the New Harbour Group they are generally found to be indistinguishable in terms of fold style, intensity of deformation and number of deformation events.

It is argued on the basis of the above discussion that the difference in the amount of deformation between the New Harbour Group and the underlying beds cannot be used to justify the insertion of a thrust between the two.

CONCLUSION

Although the South Stack Formation, the Holyhead Quartzite and the Rhoscolyn Formation have been subjected to several phases of deformation the bedded character of these metasediments is still very apparent. The rapid alternation of what were originally sandstones and shales can still be clearly seen and in the 'sandstones' sedimentary structures, e.g. current bedding and slump structures, are still preserved. However, in the pelitic horizons all trace of bedding has been lost and the planar fabrics in these horizons are transposition fabrics. Evidence can be found for two, three or even more transpositions.

It is suggested on the basis of the study of minor structures that the rocks of the Rhoscolyn area have been subjected to at least two major deformation phases followed by a less intense deformation. The folds associated with these three phases of deformation are approximately coaxial. The axial planes of the F_1 folds originally had a shallow dip to the south east, those of the F_2 folds dip to the north west and the axial planes of the F_3 folds are subhorizontal. Cleavages developed in association with all three deformation episodes and the type of cleavage developed depended primarily on the rock type. Crenulation cleavage is generally restricted to the more pelitic horizons and pressure solution cleavage to the more psammitic horizons.

A variety of intersection lineations, e.g. cleavage/cleavage and cleavage/bedding, were formed and many of these were deformed by subsequent deformation. These lineations, together with the quartz veins formed during the first deformation, can be used as strain markers to record later deformations and to indicate the mechanism of formation of later folds, e.g. an examination of deformed quartz veins reveals that some of the F_2 folds were formed by the process of flexural slip folding. Minor structures formed during one deformation, e.g. pinch-and-swell structure and cleavage, often play an important rôle in controlling subsequent deformation.

The New Harbour Group, which are predominantly pelitic rocks, appear to be more deformed than the underlying beds (the South Stack Formation, the Holyhead Quartzite and the Rhoscolyn Formation). This is primarily due to differences in lithologies. The underlying beds contain many psammitic horizons, some of considerable thickness. If the deformation in the New Harbour Series is compared with the deformation in the pelitic horizons of the underlying units they are found to be comparable. It is concluded that the New Harbour Group and the underlying beds have probably experienced the same deformation history.

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