Caledonian Structures in Britain

South of the Midland Valley

Edited by
J. E. Treagus
Department of Geology,
The University, Manchester

GCR editor: W. A. Wimbledon

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Chapter 2

Southern Uplands

INTRODUCTION – A STRUCTURAL PERSPECTIVE

J. E. Treagus

The stratigraphical framework

For almost a hundred years, after the first researches of Lapworth (1874, 1889) and the work of the Geological Survey of Scotland (Peach and Horne, 1899), there was a curious lack of interest in the structure of the Southern Uplands. Today, the area is celebrated internationally for its structures, which are perhaps the most quoted examples of folds, cleavage, and faults developed in an ancient accretionary prism. In the early Palaeozoic, that prism lay just to the north of the presumed Iapetus suture.

The gross stratigraphical framework of the rocks is largely that established by Peach and Horne (1899), and is shown in Figure 2.1. The rocks are dominantly greywacke, with a smaller proportion of mudstone and shale, and a minor, but significant, amount of basic igneous rock associated with black shale. Although only sparsely fossiliferous, the rocks have been shown to range in age from the Arenig Series in the north to the Wenlock in the south. They generally exhibit a steep dip to the north-west or south-east.

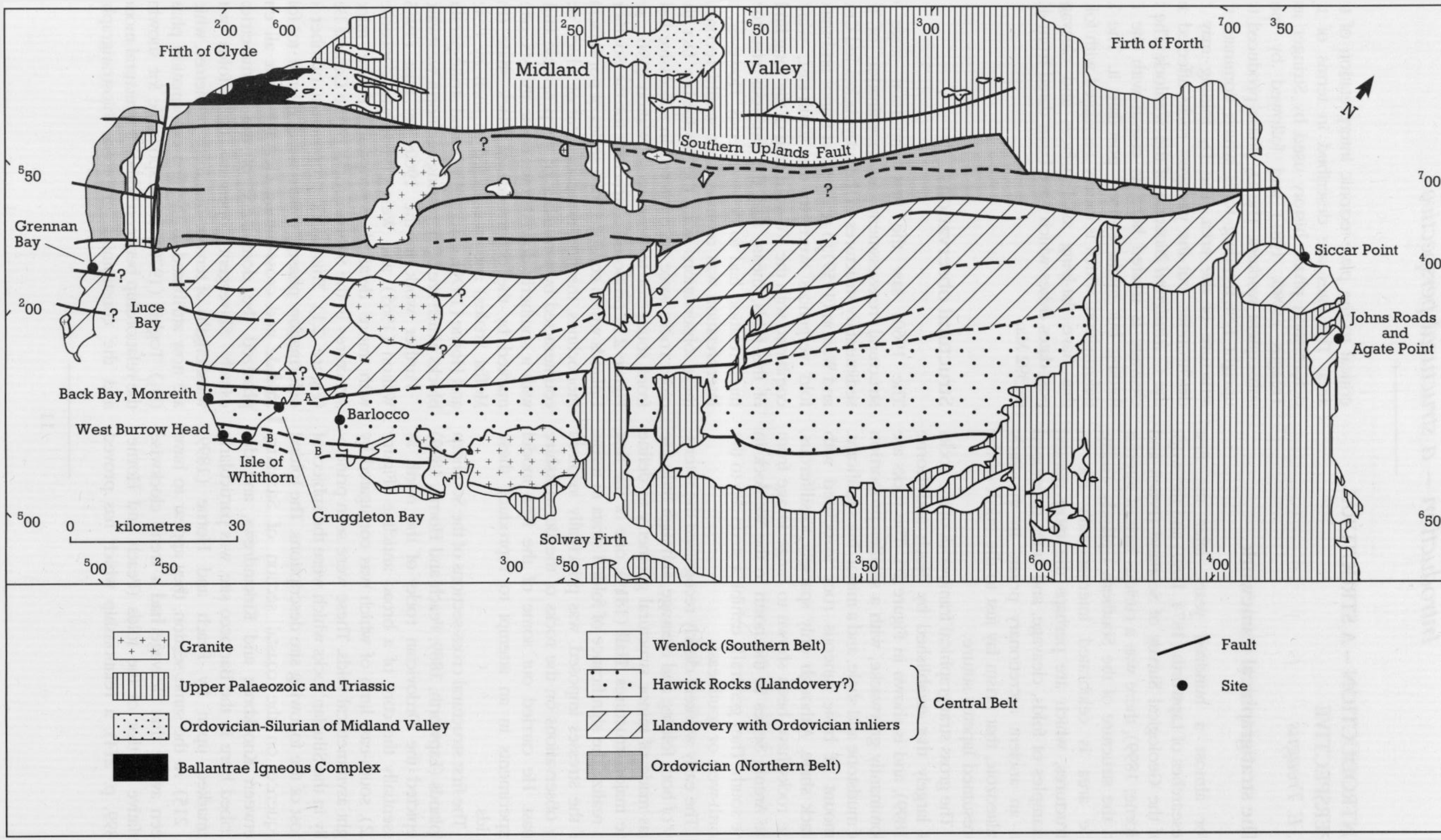
The early workers clearly recognized the intensity of both folding and cleavage, although little use was made of minor structural geometry to define the major structures. Hall (1815), one of the first to realize the significance of folded strata in terms of the stresses imposed, was principally inspired by observations on the rocks of the Berwickshire coast. He carried out some of the first model experiments in an attempt to reproduce these folds.

The first structural cross-sections of the Southern Uplands (Lapworth, 1889; Peach and Horne, 1899) depicted the Ordovician rocks of the north as essentially the core of a broad anticline (Figure 2.2), south-east limb of which was corrugated by tight asymmetrical folds. These were seen principally in the Silurian rocks which were the subject of most of the following site descriptions. The folded sequence on the coastal section of Stewartry between Knockbrex and Kirkandrews, and described here in the Barlocco site, was particularly remarked upon by Peach and Horne (1899, p. 215). At the same section, they appear to have been aware that cleavage had a trend clockwise relative to that of the folds (Peach and Horne, 1899, p. 214), a relationship which has proved critical to the plate-tectonic interpretation of the area. The sites are described in terms of the deformation phase history used by Stringer and Treagus (1980, 1981) and followed by most subsequent workers. The D_1 phase produced the upright ENE-trending folds which dominate the structure of the area. The D_1 folding may be diachronous, but the youngest rocks affected are the *C. lundgreni* biozone of the Wenlock. The S_1 cleavage is treated here as coeval with the D_1 folding but might entirely post-date it. The D_2 deformation, which is locally associated with folds that have flat-lying axial-surfaces and cleavage, post-dates dykes which have been dated from 403 to 392 Ma.

Structural observations

The 1960s saw the first important stage of structural reassessment. An examination of the sedimentary structures in the greywackes led Craig and Walton (1959) to realize that minor and major fold vergences were to the south-east, which, combined with the NW-younging of the long limbs of the folds, meant that the previous structural interpretation had to be erroneous. However, an interpretation was required that would reconcile these observations with the irrefutable fact that older rocks were encountered in successive belts from south-east to north-west. Walton (1961; see Figure 2.2) proposed a structure for the Southern Uplands which consisted of a series of north-facing monoclines, the northward descent of which was counteracted by a number of steep reverse faults with a southerly downthrow. These thrusts, often marked by the occurrence of black shale (the Moffat Shales) and interpreted as such by Peach and Horne (1899), essentially bound strike-parallel blocks which are of increasing age north-westward.

Further work in the 1960s by Rust (1965), Walton (1965), and Weir (1968) was concerned with more detailed description of the minor structures in the Silurian rocks of the Central Belt (Figure 2.1). This work proposed a number of deformation phases which were related to fold attitude and cross-cutting cleavages, but all emphasized the dominance of the asymmetrical, usually SE-vergent, open to tight folds with wavelengths of tens or hundreds of metres, which are now attributed to the first deformation phase (D_1). Toghill (1970) was responsible for showing the relationship between Walton's structural model and the constraining graptolite biostratigraphy.



Firth of Clyde
Midland
Valley
Firth of Forth
N
Southern Uplands Fault
Grennan Bay
Luce Bay
Back Bay, Monreith
West Burrow Head
Isle of Whithorn
Barlocco
Cruggleton Bay
Solway Firth
Siccar Point
Johns Roads and Agate Point
0 kilometres 30
Granite
Upper Palaeozoic and Triassic
Ordovician-Silurian of Midland Valley
Ballantrae Igneous Complex
Wenlock (Southern Belt)
Hawick Rocks (Llandovery?)
Llandovery with Ordovician inliers
Ordovician (Northern Belt)
Central Belt
Fault
Site

The only description of detailed structure in the Ordovician of the Northern Belt is that of Kelling (1961). Although some of the more elaborate structural histories have now been simplified (Weir, 1979; Stringer and Treagus, 1980, 1981), this work recognized two important structural features: firstly, the presence of steeply plunging and curvilinear hinges and, secondly, the presence of a superimposed local deformation, producing cleavage and axial surfaces with flat to moderate dips to the south-east.

Stringer and Treagus (1980, 1981) interpreted the deformation history of the Southern Uplands in terms, essentially, of a single deformation phase (D_1) with local modification by D_2. From observations principally in the Hawick Rocks, in the Wigtown Bay area, they described D_1 folds as generally tight and upright with first-order folds having amplitudes of about 300–500 m and spacing of 0.25–3.0 km. The folds of this scale are asymmetrical with vergence to the south-east, but intermediate folds, seen on a scale of one hundred metres or less, locally verge to the north-west in narrow belts on the short limbs of the major folds (see Figure 2.6A). Plunge is typically gentle to moderate (0–45°), both north-east and south-west. A belt of rapid plunge variation (50–90°), giving rise to local downward-facing, was identified near the southern margin of the Hawick Rocks.

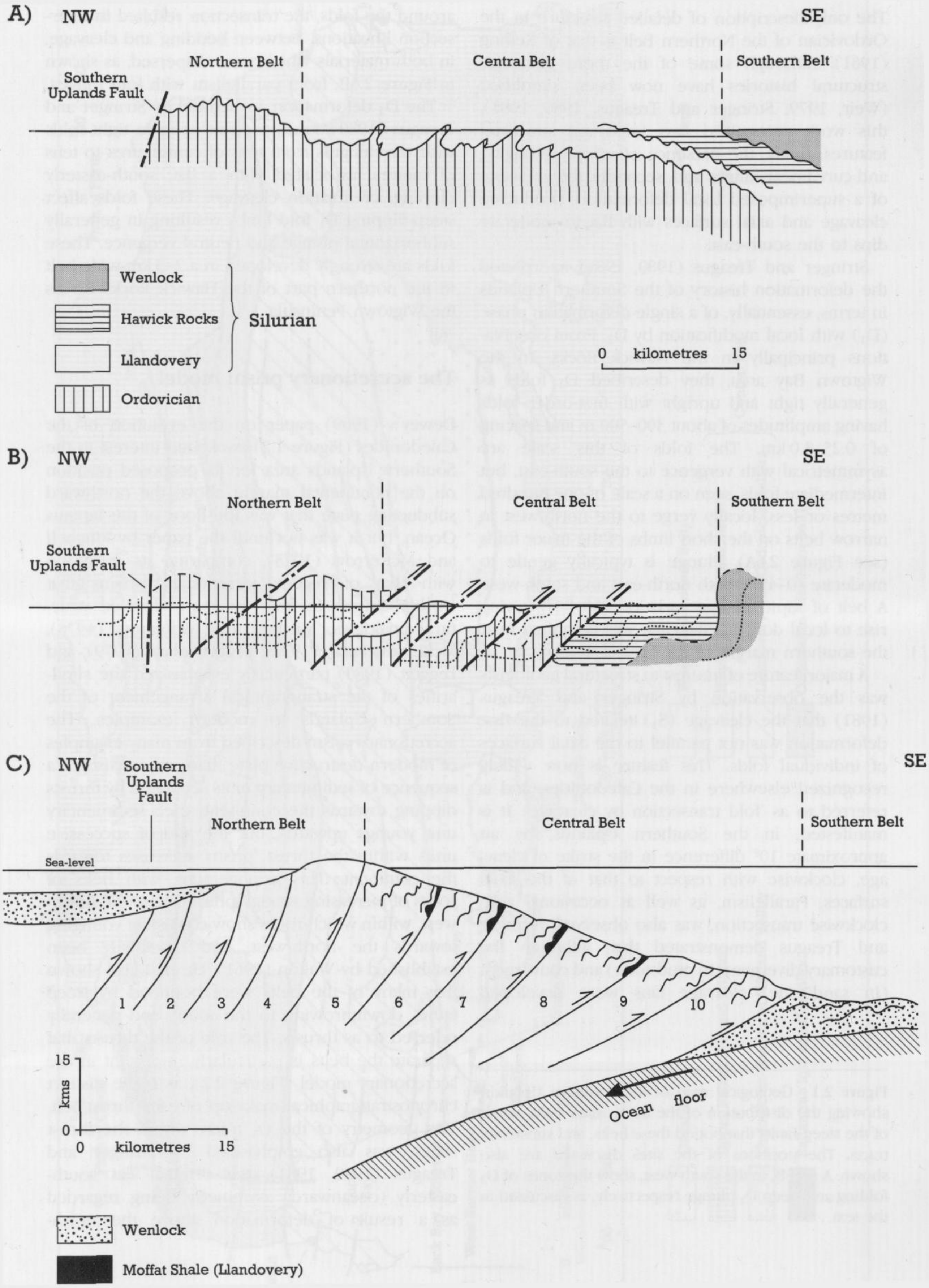
A major feature of interest to structural geologists was the observation by Stringer and Treagus (1981) that the cleavage (S_1) related to the first deformation was not parallel to the axial surfaces of individual folds. This feature is now widely recognized elsewhere in the Caledonides, and is referred to as 'fold transection by cleavage'. It is manifested, in the Southern Uplands, by an approximate 10° difference in the strike of cleavage, clockwise with respect to that of the axial surfaces. Parallelism, as well as occasional anticlockwise transection, was also observed. Stringer and Treagus demonstrated that, although the customary divergent (in mudstone) and convergent (in sandstone) cleavage fans were developed around the folds, the transection resulted in intersection lineations, between bedding and cleavage, in both materials which were dispersed, as shown in Figure 2.6B, from parallelism with fold hinges.

The D_2 deformation, as defined by Stringer and Treagus (1980), is exposed as open to tight folds with wavelengths from tens of centimetres to tens of metres, associated with a flat, south-easterly dipping, crenulation cleavage. These folds affect steep-dipping D_1 fold limbs resulting in generally subhorizontal plunge and neutral vergence. These folds are strongly developed in a 2–3 km-wide belt in the northern part of the Hawick Rocks across the Wigtown Peninsula.

Figure 2.1 Geological map of the Southern Uplands, showing the distribution of the three main belts, some of the steep faults that bound these belts, and subsidiary tracts. The positions of the sites discussed are also shown. A and B, in the south-west, show the zones of D_2 folding and steep D_1 plunge respectively, as discussed in the text.

The accretionary prism model

Dewey's (1969) paper on the evolution of the Caledonides (Figure 1.2) awakened interest in the Southern Uplands area for its proposed position on the continental margin above the northward subducting plate that was the floor of the Iapetus Ocean, but it was not until the paper by Mitchell and McKerrow (1975), comparing its evolution with that of recent accretionary prisms that workers began to look for more detailed structural analogies. Mitchell and McKerrow (1975), McKerrow *et al.* (1977), Leggett *et al.* (1979), and Leggett (1980) particularly emphasized the similarities of the stratigraphical arrangement of the Southern Uplands to modern examples. The accretionary prism described from many examples of modern destructive plate margins, consists of a sequence of sedimentary units separated by thrusts dipping towards the continent; each sedimentary unit youngs upwards, but the age of successive units within the thrust 'prism' increases towards the continent. This arrangement, with belts of rocks of increasing stratigraphical age to the north-west, within which rocks show consistent younging towards the north-west, had essentially been established by Walton (1961). He had also shown that many of the belts were bounded by steep faults, downthrowing to the south, and generally referred to as thrusts. The role of the thrusts that separate the belts is particularly important in the accretionary model (Figure 2.2), as is the distinct chronostratigraphical make-up of each thrust-belt. The geometry of the D_1 folds, within the thrust slices, was also emphasized by Stringer and Treagus (1980, 1981), the original flat south-easterly (oceanward) asymmetry being regarded as a result of deformation above the north-


A)
NW
SE
Northern Belt
Central Belt
Southern Belt
Southern Uplands Fault
Wenlock
Hawick Rocks
Llandovery
Silurian
Ordovician
0 kilometres 15
B)
NW
SE
Northern Belt
Central Belt
Southern Belt
Southern Uplands Fault
C)
NW
SE
Southern Uplands Fault
Northern Belt
Central Belt
Southern Belt
Sea-level
1
2
3
4
5
6
7
8
9
10
Ocean floor
15
kms
0
0 kilometres 15
Wenlock
Moffat Shale (Llandovery)

westerly subducting ocean-floor with subsequent rotation, to a steep attitude, within the thrust-bound packets. The plunge variations of the folds was also attributed to proximity to the thrust zones.

Detailed structural observations on the thrusts themselves have been sparse, partly owing to their poor exposure. Until recently (for example, Rust, 1965; Toghill, 1970; Fyfe and Weir, 1976; Cook and Weir, 1979), work has concentrated on thrust geometry and stratigraphical separation, and observations on shear-sense or timing, with respect to D_1, have been rare. Webb (1983) considered that thrusts in the Ettrick imbricate structure resulted from south-easterly-directed extension of rotated short limbs of the D_1 folds, but that they pre-dated the S_1 cleavage.

Stringer and Treagus (1981) and Treagus and Treagus (1981) have attempted to relate the non-axial plane cleavage in the Southern Uplands to this plate tectonic setting. They pointed out that a non-orthogonal relationship between the initial folds in the sedimentary pile and the subsequent stresses, caused by oblique ocean closure, would result in the observed transection of folds by cleavage. Other workers (for instance, Sanderson *et al.*, 1980) have interpreted the phenomena in terms of transpression, essentially a combination of pure shear perpendicular to the sedimentary strike and simple shear (sinistral) parallel to that strike, as a consequence of oblique convergence of the margins of the Iapetus. Such a model predicts horizontal stretching near the ocean suture and down-dip stretching away from the suture. Such strain variations are recorded in the Irish Caledonides, but in the Scottish Southern Uplands, Stringer and Treagus (1981) record only very weak down-dip extension in the flattening strain associated with cleavage. Thus the obliquity between cleavage and the axial planes of folds is particularly important evidence for the model of the Southern Uplands as a part of an ancient accretionary prism. More precise strain measurement will help in the clarification of the model.

Figure 2.2 Cross-sections of the Southern Uplands. (A) After Lapworth (1889); (B) after Walton (1961); (C) reconstructed profile of the accretionary prism, in Wenlock times. The tracts 1–10 are of decreasing age south-eastward, within each tract rocks young to the north-west. The style of the D_1 folding is shown schematically in the Llandovery and Hawick Rocks of the Central Belt (after Leggett *et al.*, 1979).

Several workers have identified isoclinal folds which appear to be pre-D_1 folding, particularly in the Hawick Rocks. Rust (1965) was the first to appreciate the presence of such large-scale isoclinal folds and their presence has been confirmed in several of the present site investigations. Such folds, as well as disrupted units and other slump structures, are identified by Knipe and Needham (1986) as an essential part of the early evolution of accretionary complexes.

Recent work

There has been a spate of work in the Southern Uplands since 1986, much of it stratigraphical and sedimentological, which has resulted in variations on and repudiation of the accretionary prism model. Some papers (see below) provide important new structural data, which undoubtedly will be used in future site selection. Barnes *et al.* (1987), for example, report new work in the Rhinns of Galloway (McCurry) and on the Wigtown Peninsula (Barnes), in previously undescribed rocks of the Central Belt. Unusual aspects of this work are the description of a substantial belt of north-verging D_1 folds in SE-younging rocks, with northward downthrow on steep faults on the Rhinns. Thrusting, both north and south down-throwing, is syn-D_1, as are the steeply plunging folds, except where rotated locally by post-D_2 deformation. Kemp and White (1985) and Kemp (1987) have detailed, for the first time, some Southern Belt rocks of Wenlock age. Apart from new palaeontological and sedimentological data, which reveal the highly imbricated nature of the northern part of this belt, he discusses the nature of the 'sheared zones' which characterize the rocks: the bedding is imbricated and disrupted, and they are affected by SE-verging folds, faulting, and boudinage. The origin of these zones appears to be partly soft-sediment deformation, but essentially they formed during D_1, partly post-dating S_1. Common, sinistral, steep-plunging folds post-date D_1.

The attack on the interpretation of the Southern Uplands as a forearc accretionary prism especially by Hutton and Murphy (1987), Morris (1987), and Stone *et al.* (1987) is mentioned above. The detailed scrutiny of greywacke provenance and palaeocurrents has shown that there was a significant Ordovician input of sediment from the south, much of it derived from a missing volcanic arc, that is an arc destroyed through subduction or strike-slip faulting (see below). These and other, essentially sedimentological, arguments are certainly going to produce a reassessment of the structural evolution of the Southern Uplands in future years.

The variations in the accretionary prism model, for instance the role of imbricate thrusting and the timing of collision (Hutton and Murphy, 1987; Stone *et al.*, 1987), may eventually be resolved by the detailed examination of the structures such as the geometry of the D_1 folds, the timing of the transecting S_1 cleavage, the strain variation, particularly towards and within the thrust zones, the significance of the plunge variation, and especially the relationship between thrusting and faulting and other deformation events. Of particular interest will be a comparison of the structural history and style of the Northern Belt with that of the Silurian rocks. Hutton and Murphy (1987) report cleaved Middle Ordovician (*gracilis* biozone) shales as clasts in the Silurian, and Morris (1987) describes an earlier deformation history in the Ordovician of the Longford Down Inlier in Ireland.

As yet, the most significant structural contribution to the new models has come from Anderson and Oliver (1986), in a reinterpretation of the displacement on the Irish Orlock Bridge Fault. The apparent equivalent of this fault in Scotland, the Kingledores Fault, separates the Ordovician of the Northern Belt of the Southern Uplands from the essentially Silurian rocks of the Central Belt (Figure 2.1). It features in the accretionary prism interpretations (for example, Leggett *et al.*, 1979) as one of the major thrust boundaries. From evidence, principally in the Irish outcrops, Anderson and Oliver (1986) demonstrate that, whatever its early history, the fault suffered significant sinistral strike-slip movements in the Late Silurian and they argue that these movements were of the order of 400 km. Hutton and Murphy (1987) claim that this fault was responsible for the removal of the missing volcanic arc, mentioned above, and Hutton (1987) argues that it is one of the several major, strike-slip terrane boundaries which have featured in the evolution of the British Caledonides.

Another of these terrane boundaries would be the Southern Uplands Fault, the northern boundary of the rocks treated in this volume. Traditionally, it is seen as a steep fracture (with major splays into the Glen App, Stinchar Valley, and Lammermuir Faults). It is assumed to have a downthrow to the north-west, based on the contrast of Lower Palaeozoic facies on its two sides and on the truncation of the Lower Devonian on its northern side. In the accretionary prism models, the fault is usually shown as a successor to one of the powerful, steep, NW-downthrowing thrusts, but Bluck (1986) also suggests that it is the site of NW-thrusting which has caused the juxtaposition of the trench sediments of the Southern Uplands against the proximal forearc deposits of the Girvan area to the north. Again, from consideration of sources of Lower Palaeozoic sediments north and south of the fault, Hutton (1987) argues for substantial strike-slip motion in the Late Silurian. Exposures of the fault zone are highly brecciated, fractured and veined, but there are no reports of any local criteria which can be used to prove the Caledonian displacement sense.

Faults

Minor faults of post-D_1 age, which are probably Caledonian in age, abound in the Southern Uplands. Many workers report brecciation and other symptoms of brittle deformation coincident with the major strike-parallel thrust faults, as well as those at high angles to the strike. The N–S wrench faults, with sinistral displacement, are particularly widely reported. Dextral wrench faults with a more north-east trend are also reported (Weir, 1979). Other post-cleavage faults and fractures, showing a wide range in orientation, can be seen in most of the sites described; many clearly have a displacement, but the absence of markers makes a unique calculation of displacement sense, or amount, difficult. Low-angle faults, with both north-west and south-east dips, with both thrust and normal displacement, and throws apparently in the order of a few centimetres, can be deciphered in most shore sections. No overall stress vector pattern has been proposed.

Timing of deformation

The precise timing of the various stages of the Caledonian deformation in the Southern Uplands is not always clear. In particular, there are dates for neither the development of the D_1 folding, which might be expected to be diachronous across the fold belt, nor for the cleavage development. However, D_1 folds and S_1 cleavage affect rocks of at least the *C. lundgreni* biozone of the Wenlock Series. Dykes which post-date S_1 and largely pre-date D_2 folds (Stringer and Treagus, 1980) have been dated (Rock *et al.*, 1986) between

418 and 395 Ma. These dykes are mostly cut by the Devonian granites which have dates ranging from 408 to 392 Ma. The writer's observations on contact porphyroblasts suggest that the Cairnsmore of Fleet Granite (392 ± 2 Ma) pre-dates, or is closely associated with, D_2: this relationship is very similar to the relationship seen between the granites and folds (D_2) in the Lake District. Lower Devonian lavas (Upper Gedinnian) unconformably overlie folded Silurian at St Abb's Head as well as in the Cheviots, where the lavas are cut by the Cheviot Granite dated at 391 Ma. Although these lavas are often quoted (Powell and Phillips, 1985) as Upper Gedinnian in age, McKerrow (1988) points out that both the faunal evidence and the latest radiometric dates (389–383 Ma; Thirlwall, 1988) would allow a Late Emsian age (perhaps about 397–390 Ma) for the main deformation event. Such a date would correlate well with that deduced for the Lake District and Wales (Soper *et al.*, 1987; Soper, 1988; McKerrow, 1988) and with part of the Acadian Orogeny of Canada.

The selected sites are shown in Figure 2.1. In spite of the detailed sections of the Northern Belt by Kelling (1961), it was not possible to select any site in these rocks which would illustrate their typical D_1 style. It is hoped that future work will especially clarify the relationships of the cleavage and thrusts to the folds. All the sites selected thus far are located in the Central Belt greywackes and mudstones of Llandovery (presumed) and Wenlock age, and all exhibit the dominant NE–SW strike and steep dip that characterizes most of the Southern Uplands.

All the sites (except for Burrow Head) also show the characteristic NW-younging on the long limbs of the SE-verging D_1 folds, as well as transection of the folds by the S_1 cleavage. One site (Back Bay, Monreith) illustrates the style of the deformation, and two (Burrow Head and Grennan Bay) illustrate the nature of the faulted junctions. No suitable site was found to illustrate the later faulting, including the Southern Uplands Fault and parallel fractures.

SICCAR POINT (NT 81187100–81307095)

J. E. Treagus

Highlights

Siccar Point is one of the world-renowned localities where Hutton (1795) first recognized the significance of unconformities in the geological record. In the context of this volume, it exemplifies the style of folding in the Silurian, which led Hall (1815) to make his important deductions concerning the relationship of stress to the formation of folds, through experiments.

Introduction

This coastal site exposes the angular unconformity between: 1. beds of Llandovery greywacke and shale; 2. beds of Upper Old Red Sandstone (ORS) breccia and sandstone (Figure 2.3). The tight folding and cleavage of the end-Caledonian deformation, seen in the Silurian, contrast strikingly with the gentle dips of the ORS. The breccias contain fragments of cleaved Llandovery rocks. The site was one of the localities at which the significance of unconformities in the geological record was first appreciated (Hutton, 1795; Playfair, 1805). Moreover, the folds in the Silurian of this coast, so well seen in the site, are those which inspired Sir James Hall (1815) to undertake his early experiments in model rock deformation.

Description

The Silurian strata, exposed over about a 100 m^2, are folded in a tight synform, whose limbs dip steeply south, with an interlimb angle of 25°. The fold plunges 35/240°, with its south-east limb overturned and an axial-surface attitude of 080/66°S. Cleavage in siltstones and shales, interbedded with the greywackes, has an attitude 105/74°N and thus transects the axial surface. Way-up structures (bottom structures, graded bedding, and ripple cross-lamination) show the fold to be an upward-facing syncline.

The Old Red Sandstone beds dip gently north; the unconformity surface, although broadly parallel to this dip, exhibits local irregularities due to differential erosion (often along strike) of the underlying greywackes and shales (Figure 2.3). These irregularities cause certain greywacke beds to protrude several metres above the principal planar unconformity surface. Indeed, the whole synclinal fold, described above, is one such major irregularity protruding above the unconformity surface.

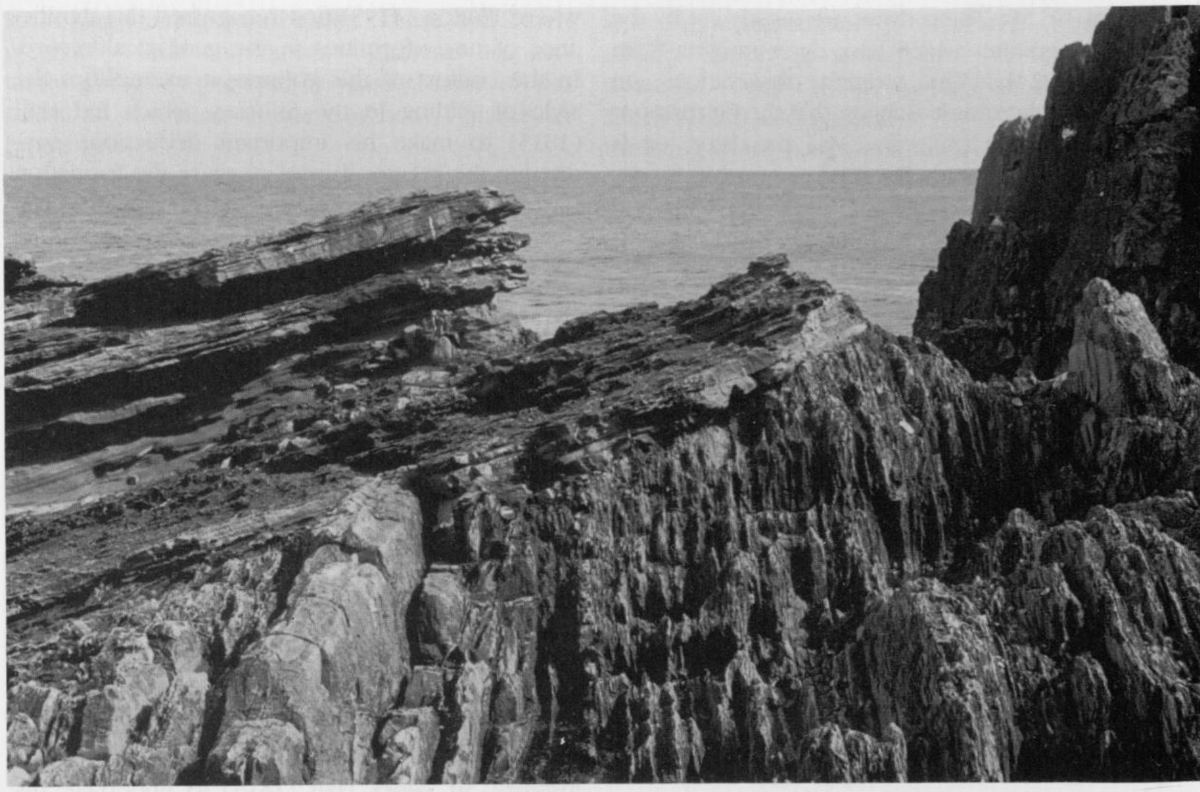


Figure 2.3 Siccar Point. Subvertical Silurian greywackes and cleaved shales on the south limb of a tight Caledonian syncline are unconformably overlain by Upper ORS breccias and sandstones. View looking east with lens cap (centre) for scale. (Photo: J. Roberts.)

Interpretation

The principal interest of this site is that it displays, in a unique three-dimensional manner, Silurian rocks, folded and cleaved during the Caledonian Orogeny, eroded probably during mid-Devonian times and subsequently overlain by the terrestrial Upper Old Red Sandstone. However, it also exemplifies the style of D_1 deformation seen locally. There is no modern description of the structure of this coast, except where the folds show the complex curving hinges (Dearman *et al.*, 1962), described at John's Road also in the Central Belt. It is, therefore, of interest that this site shows very similar features to those described to the south-west, showing the persistence of such features, especially the same clockwise transection of folds by cleavage.

This site is the only locality in the Southern Uplands where the three-dimensional nature of the unconformity can be clearly seen. The contrast between the vertical greywacke and the horizontal red sandstones led to an understanding, not only of the fundamental earth movements that rocks undergo (Hutton, 1795), but also to an appreciation of the scale of erosion involved and thus to the immensity of geological time. The style of the folding along this coast, exemplified by this site, also led Sir James Hall (1815) to perform his early experiments and to make important deductions concerning the relationship between stress and folding, specifically that horizontal crustal shortening could be responsible for folding.

The unconformity at Siccar Point, though renowned for Hutton's appreciation of the significance of the phenomenon, does not in fact constrain the 'end-Caledonian' climax in the Southern Uplands very tightly. Elsewhere, in the south-western Southern Uplands, Wenlock rocks are unconformably overlain by Upper ORS sediments and intruded by post- or syn-deformation granites dated about 400 Ma. Nearer the present site, at St Abb's Head, folded Llandovery rocks are unconformably overlain by Lower Devonian lavas, and in the Cheviots probable Wenlock rocks are overlain by lavas of the same age. The possible age of the Caledonian deformation events is discussed in the Introduction to this chapter.

Conclusions

This site has been included as a unique and historic locality in the Southern Uplands to demonstrate the unconformity between the Silurian greywackes, strongly deformed in the Caledonian Orogeny, and the flat-lying undeformed Upper Devonian red sandstones. It also illustrates the D_1 deformation style of the north-eastern exposures of the Central Belt; the truncation of D_1 folds, at the locality, by the flat-lying Upper Old Red Sandstone breccias and sandstones is the clearest example in the Southern Uplands, of the timing of the Late Caledonian deformation. It allows a comparison with the similar style of deformation seen in exposures to the south-west at Barlocco, Cruggleton Bay, and West Burrow Head; that is, the asymmetry of the fold, the attitude of its limbs, axial-surface, fold hinge, and the clockwise transection of the cleavage.

JOHN'S ROAD AND AGATE POINT (NT 95286411–95476410)

J. E. Treagus

Highlights

The plunge variations at John's Road are extraordinary, by the standards of any slate-belt folding, and are certainly the best exposed and most dramatic yet described in the 'non-metamorphic' Caledonides. The plunge variations occur in a zone some 300 m wide, but the regional context is not known.

Introduction

This site is located in the Llandovery rocks of the Central Belt (Figure 2.1) in the poorly described Berwickshire coastal section. Originally reported in the Geological Survey Sheet Memoir (Geikie, 1863), they have subsequently attracted the detailed description by Dearman *et al.* (1962). The regional setting of this coast section appears to be broadly similar to that of the Hawick Rocks in the Scottish south-west coastal sections (see below).

Unfossiliferous Silurian greywacke siltstone and cleaved shale generally dip steeply to the north-west and young in the same direction, but in detail are affected by folds, of a variety of scales, with gentle plunge and south-east vergence.

Dearman *et al.* (1962) described a zone on this coast, some 250 m wide across strike, in which the regional fold pattern alters to one in which fold plunge changes not only to vertical and steeply downward-facing (as in the Isle of Whithorn), but also to gently plunging, downward-facing attitudes. Agate Point and John's Road are the two principal localities which Dearman *et al.* (1962) described within this zone.

Description

In the 4 km coastal exposures, between Eyemouth and Burnmouth, the rocks show the typical structural features of this belt of the Southern Uplands, with steep or north-west-dipping and north-west-younging sequences, interrupted by folds with wavelengths of between 5 m and 20 m. These folds are open to tight, south-east-verging, with gentle plunges to the south-west or north-east, and are upward-facing on subvertical axial surfaces. In the Eyemouth area, immediately north-west of the site, fold plunges of 20–40°SW are characteristic, with variations up to 50°SW and 20°NE. About 100 m north of John's Road, plunge values to the south-west begin to increase; no obvious planes of movement are associated with this change. The plunge variations continue in a zone of some 300 m with a return to more usual plunges to the south of Agate Point. The zone may, in fact, extend beyond this point, but no data are available in the rather inaccessible cliff section to Burnmouth. Two localities have been selected in this zone, described in detail by Dearman *et al.* (1962), because they provide the best exposures of the full plunge variation.

Agate Point (NT 95416411)

This area, some 25 m by 50 m, illustrates the typical plunge behaviour of the folds; the folds (Figure 2.4) can be followed on to the islands to the north-east of the site. The map is based on Figure 3 in Dearman *et al.* (1962). Four greywacke units were mapped around the axial surfaces of four folds (1–4 on map). The folds are tight, with limb dips about the vertical, striking NNE or NE. Sedimentary structures provide clear evidence of the direction of younging, as indicated.

Plunge varies within the site, from 20° upward facing, to 28° downward facing. Fold 1 shows the most marked and rapid variation from 70°NE (downward-facing), through the vertical to 50°SW (upward-facing) over some 15 m. To the north-

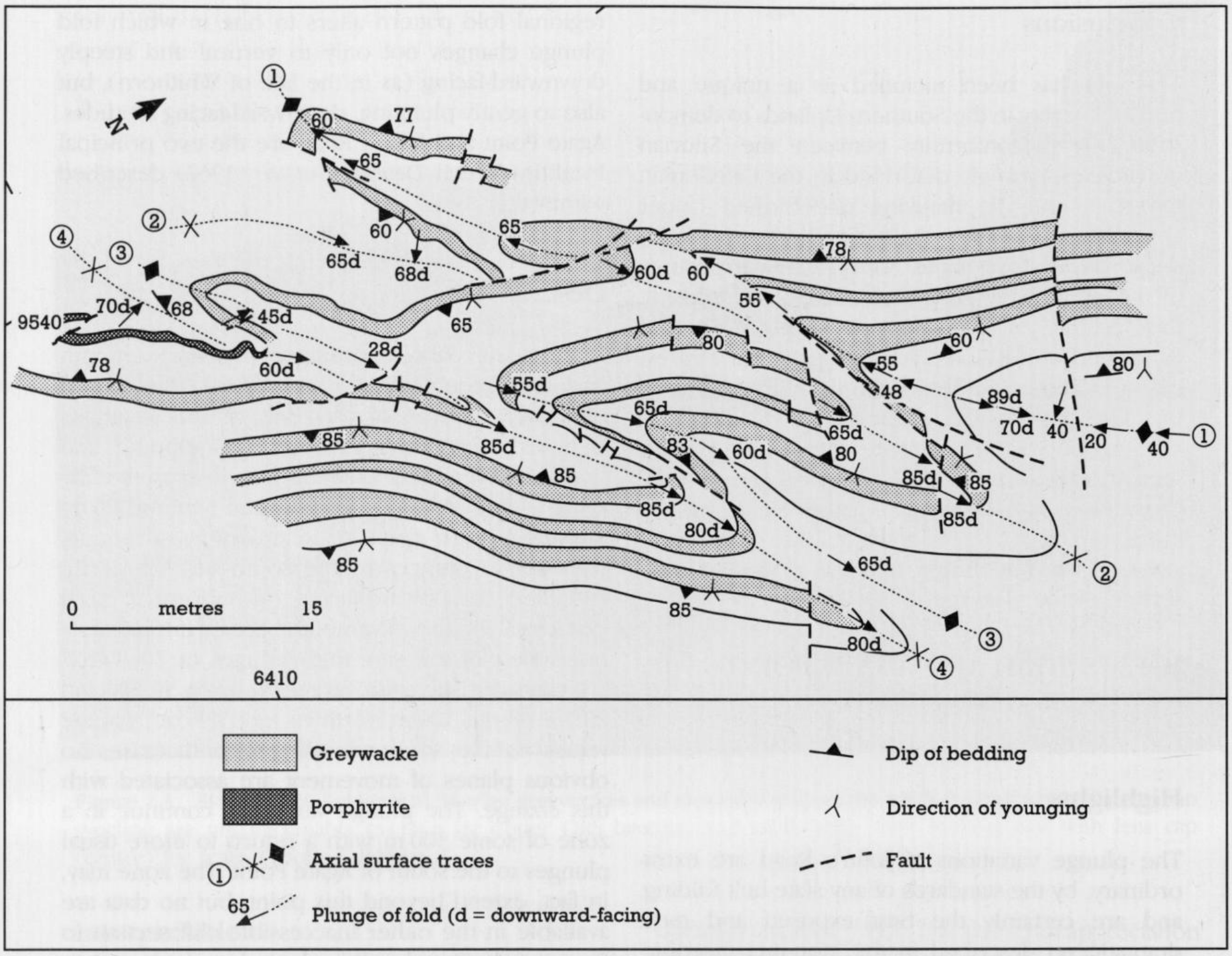


Figure 2.4 Geological map of Agate Point (after Dearman *et al.*, 1962).

east, this fold can be traced to beds where hinges plunge as low as 20°SW. Folds 2, 3 and 4 all show similar variations, from vertical to 45°NE (downward-facing). Discontinuities occur on the fold limbs (see map) and may well have been essential, as zones of high shear strain, to the mechanism whereby the steep plunges were achieved.

John's Road (NT 95366414)

This locality is one rib of rock, some 40 m by 10 m, in a broader zone of plunge variation. The exposure illustrates, particularly well, plunge variation in three dimensions. The exposure is well documented in Dearman *et al.* (1962, Figure 5; see Figure 2.5, this volume). The greywacke–shale sequence here is folded into a prominently displayed anticline–syncline pair, which plunges steeply south-west. Successive fold hinges, of this fold pair, can be followed to the north-east where they rapidly pass through the vertical and assume low plunges (30° and less) towards the north-east. These folds can be shown, from the younging evidence, to be downward-facing and provide a most dramatic illustration of the plunge variation. Again, discontinuities can be observed on fold limbs and these, together with beds of disrupted material, may provide evidence of the origin of the plunge variation.

In both localities, the shale beds are affected by a weakly developed cleavage, which is NE–SW-trending and broadly parallel to the axial surfaces of the folds. No mineral fabric, or other exceptional

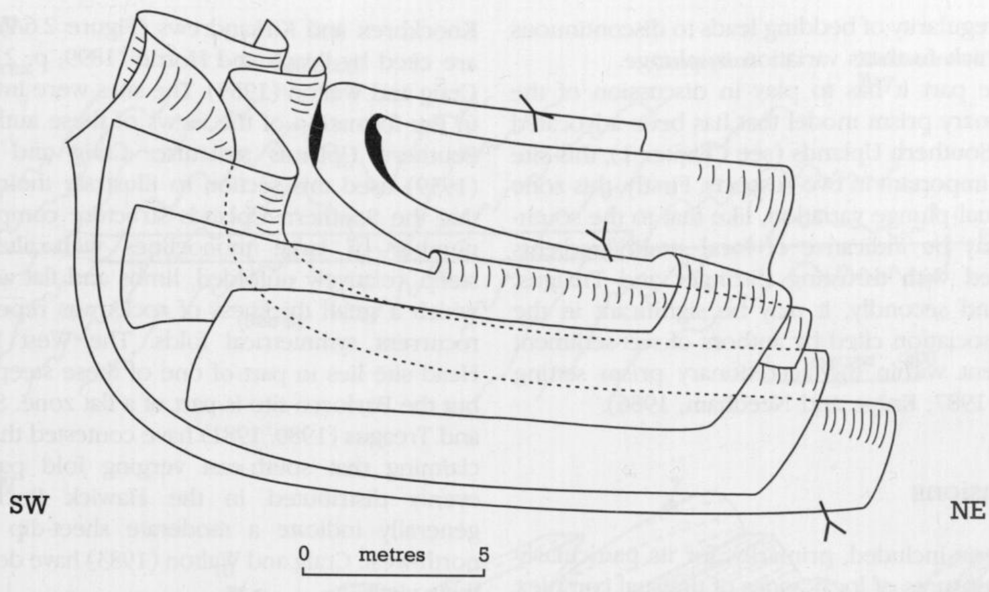


Figure 2.5 Diagrammatic representation of the folds at John's Road (after Dearman *et al.*, 1962).

textural features of finite strain, have been observed in the field, which might be used to explain the exceptional fold plunge variation.

Interpretation

The interest of this site lies not only in the unusual range of plunge variation, but in the short distance over which it occurs. Within the Southern Uplands, the features exhibited in the site are unique; comparable examples have not been described. Somewhat similar features have been reported by Stringer and Treagus (1980, 1981) and the Isle of Whithorn site described in this volume; in these instances, however, the plunge variation is neither as extreme, nor is it seen to occur over such short distances.

Dearman *et al.* (1962) attribute the plunge variation to refolding, claiming that 'it can be demonstrated that folds, with a NE–SW axial trend, have been refolded about NW–SE axes and that the two show a common axial plane' (p. 275). In discussion of the paper by Dearman *et al.* (1962), Westoll (p. 283) comments, that such a phenomenon might be a consequence of 'a single continuous movement picture' resulting from the directions of expulsion of intergranular water. Other speakers comment on the lack of superimposed minor structures and the possible contribution of wet-sediment deformation (pp. 284–5). Stringer and Treagus (1980 pp. 328–9), in their discussion of plunge variations seen in a somewhat similar zone in the south-west Southern Uplands, appeal to heterogeneous strain both within the zone and of the zone itself relative to the rocks outside, and to the physical rotation of packets of folds bounded by shear planes.

There has been widespread interest in reports of strongly curvilinear and 'sheath' or 'eyed' folds in recent years. These reports (Roberts and Sanderson, 1974; Cobbold and Quinquis, 1980) have been based on observations in the field of modelled folds where strong extensional strains are observed. However, there is no evidence of such strong extensional strains, or indeed, of any unusual strain pattern in the rocks where these phenomena are reported from the Southern Uplands.

The rocks of this site do exhibit two features which may be important in future research. Some sequences are noticeably disturbed and individual beds cannot be traced far along strike. This may be due to bedding-plane movements during folding and, certainly, there are also discordant zones along which there is similar disturbance. However, it is possible that the fold plunge variation might be partly attributed to the existence of soft-sediment folding (cf. Webb and Cooper, 1988, describing similar situations in the Lake District), which pre-dated the tectonic folding and with which the local chaotic bedding might be associated. Irregularity of bedding leads to discontinuous beds which furthers variation in plunge.

In the part it has to play in discussion of the accretionary prism model that has been advocated for the Southern Uplands (see Chapter 1), this site may be important in two respects. Firstly, this zone of unusual plunge variation, like that to the south-west, may be indicative of local strain gradients associated with thrusting (Stringer and Treagus, 1980) and secondly, it may be significant in the clear association cited by authors of wet-sediment movement within the accretionary prism setting (Kemp, 1987; Knipe and Needham, 1986).

Conclusions

This site is included, primarily, for its particularly clear exposures of local zones of unusual complex folding. These contortions were perhaps produced by the intense compressive stress that was generated during the Caledonian mountain-building episode (orogeny). In general, fold structures elsewhere have a fairly regular form, but at this locality the hinges of the folds are strongly curved, sometimes by as much as 165°. This is exceptional not only in the Southern Uplands but in the Caledonian Orogenic Belt as a whole. These zones are important in understanding the evolution of the large-scale structure of the Southern Uplands, as indicating the presence either of local strain gradients associated with thrusting or horizons which suffered wet-sediment deformation, the latter associated with the accretionary prism which, prior to the orogeny, existed on the northern side of the Iapetus Ocean.

BARLOCCO (NX 58054880–58904820)

J. E. Treagus

Highlights

The coastal section, which is easily accessible and continuously exposed, illustrates all the typical features of the Caledonian D_1 folding and cleavage in the Hawick Rocks, and the geometry of D_1 folds in the Central Belt of the Southern Uplands.

Introduction

This site is part of the shore exposures between Knockbrex and Kirkandrews (Figure 2.6A), which are cited by Peach and Horne (1899, p. 215) and Craig and Walton (1959). The sites were important in the formation of the views of these authors on Southern Uplands structure. Craig and Walton (1959) used this section to illustrate their theory that the Southern Uplands structure comprised a number of large monoclines with alternating steep, relatively unfolded, limbs and flat zones in which a small thickness of rocks was repeated in recurrent symmetrical folds. The West Burrow Head site lies in part of one of these steep limbs, but the Barlocco site is part of a flat zone. Stringer and Treagus (1980, 1981) have contested this view, claiming that south-east verging fold pairs are evenly distributed in the Hawick Rocks and generally indicate a moderate sheet-dip to the north-west. Craig and Walton (1983) have defended their view.

The typical features of the D_1 deformation in the Hawick Rocks, seen in this site, are very similar to those in other adjacent Llandovery and the Wenlock formations. These features have also been described in papers by Stringer and Treagus (1980, 1981), where this section is mentioned in particular. Most of the characteristics of Southern Upland folding, described by Walton (1983), can be observed in this section. The typical features are: the wavelength, asymmetry, and plunge variations of the folds and the transection of these folds by the S_1 cleavage.

Description

The principal feature illustrated in this site is one common to much of the Southern Uplands, that of steeply dipping greywackes, younging to the north-west, but periodically interrupted by small-scale fold pairs. In this section, alternating greywackes (0.3 m to 3 m thick) dip steeply to the north-west or south-east. Sedimentary structures – grading, loading, and cross-stratification – are usually found to demonstrate the dominant north-west younging. About twenty major fold pairs are exposed, with an average wavelength of 42 m. Minor folds with wavelengths down to 5 m also occur, but shorter wavelengths are rare.

The folds are mostly tight to moderately tight (interlimb angle 20–70°) with axial surfaces which are subvertical. Hinge style varies according to lithology, thickness, and position in a fold stack; some in massive greywackes are concentric, but more typically alternating greywacke, siltstone, and

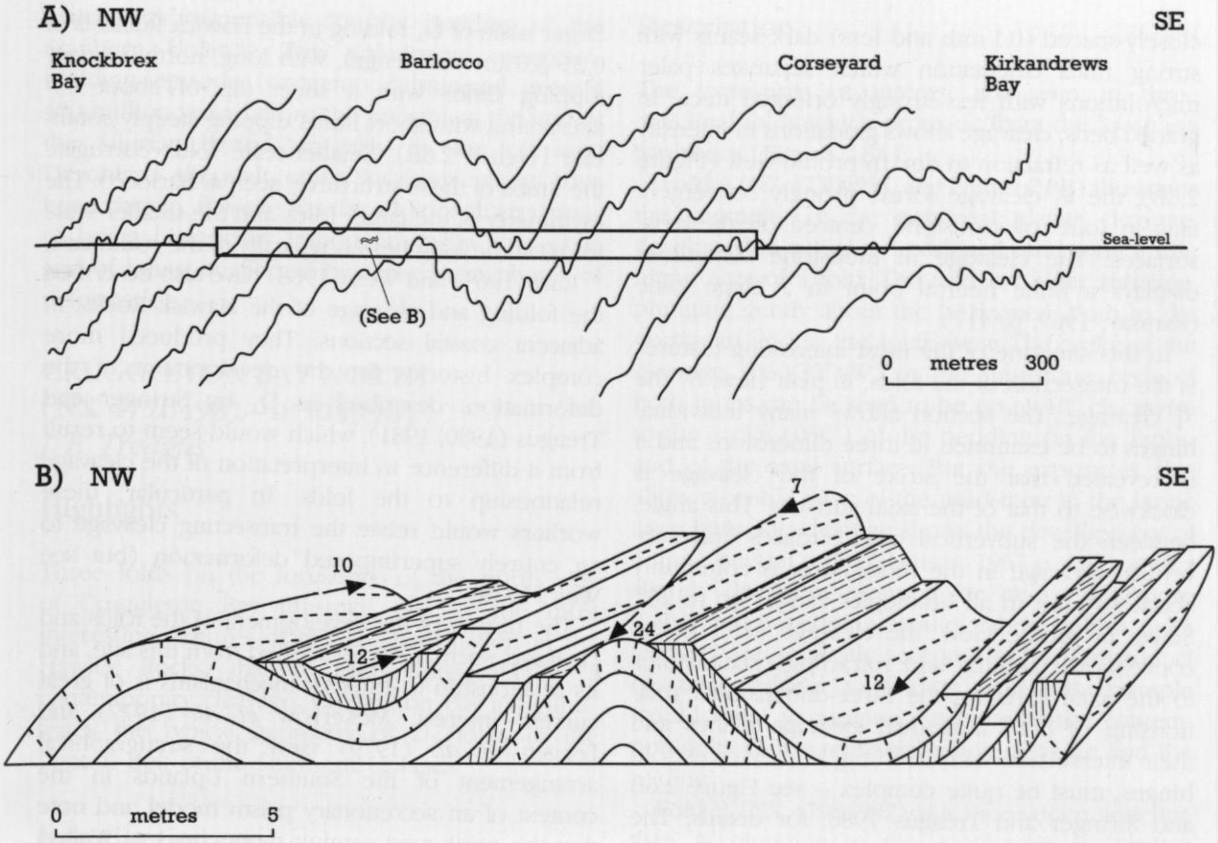


Figure 2.6 (A) Diagrammatic fold profile of the Knockbrex Bay–Kirkandrews Bay coast section, with box indicating the location of the Barlocco site. Approximate position of the folds illustrated in (B) is also shown. (B) Typical fold and cleavage geometry at the Barlocco site, based on field observations at NX 5835 4865. Cleavage is shown: open spaced in sandstones and narrow spaced in mudstone. Plunge of fold hinges and cleavage–bedding intersections are also shown (after Stringer and Treagus, 1980, figure 2).

mudstone multilayers show a style intermediate between chevron and 'similar' (that is, Class 1C, Ramsay, 1967).

The ratio of the width (measured horizontally) of the north-west-younging limbs to the south-east-younging limbs of these folds is, on average, 4:1, a reflection of the asymmetry of these south-east verging fold pairs (Figure 2.6A). It is estimated that, if it could be assumed that faulting was unimportant in the section, the sheet dip is about 45° to the north-west.

It is clear, however, that the fold section is interrupted by a great number of fractures, some subvertical strike-parallel or dip-parallel, others dipping at low angles. Occasionally, it is possible to demonstrate apparent displacements of a few centimetres to a metre, but the absence of marker horizons makes matching across possible faults difficult and calculation of the precise movement sense problematical. One steep dip fault is particularly obvious in the section, from the displacement of the folds on the upper foreshore relative to those on the lower foreshore.

Another feature of the site is the variation in plunge of the D_1 hinges, and the consequent variation in fold profile and the impersistence of individual hinges. Many hinges are sub-horizontal, but others plunge up to 30°, both to the north-east and south-west, and occasionally, across the foreshore, individual hinges can be seen to display this range within strike lengths of 10 m or more.

This site can also be used to examine the essential features of the S_1 cleavage in the Hawick Rocks. In sandstones, the cleavage is formed by parallel or anastomosing partings of 0.01–0.05 m. A weak, preferred, dimensional orientation of the quartz or feldspar is sometimes apparent, and dark seams, mica and opaque mineral concentrations, are the result of pressure solution. Even in the cleaved mudstones, the cleavage is domainal, with closely-spaced (0.1 mm and less) dark seams with strong mica orientation which separates paler microlithons with less-strongly oriented mica. In graded beds, cleavage shows gradations in intensity as well as refraction in dip. In profile view (Figure 2.6B), the S_1 cleavage forms strongly convergent fans in folds of sandstone, centred on the axial surfaces. The cleavage in mudstone sometimes displays a finite neutral point in a hinge zone (Ramsay, 1967, p. 417).

In this site, one of the most interesting features is the transection of the folds, in plan view, by the S_1 cleavage. The section allows many individual hinges to be examined in three dimensions and it is revealed that the strike of the cleavage is clockwise to that of the axial surfaces. This angle, between the subvertical axial surfaces and subvertical cleavage in the mudstones, is commonly about 10°, but in all lithologies ranges up to 25°. Since, in profile view, the cleavage exhibits the conventional fanning and refracting relationships to the axial surfaces, the three-dimensional relationship of both individual cleavage planes and their intersection with bedding, as they cross fold hinges, must be quite complex – see Figure 2.6B and Stringer and Treagus 1980, for details. The principal difference from conventional cleavage and bedding relationships is that their intersection can be seen curving clockwise across fold hinges to become steeper on the limbs. Great care has to be taken in using the relationship between cleavage and bedding (in plan view) in the conventional way to interpret fold geometry.

Interpretation

The coastal section at Barlocco has been drawn upon by several workers in their interpretation of the Southern Uplands. In Peach and Horne (1899, p. 215) it is one of the few coastal sections remarked upon and then for the intensity of the folding exhibited. Craig and Walton (1959, 1983) and Walton (1961) used this coast as a model for their influential theory that the structure of the Southern Uplands comprises large-scale monoclines descending towards the north-west, made up of alternating steep belts of relatively unfolded rocks and flat belts (as at Barlocco) of strongly folded rocks.

Stringer and Treagus (1980, 1981) also refer extensively to this coastal section, but were unable to substantiate the monocline model (Stringer and Treagus, 1983). Instead, they maintain that the larger scale of D_1 folding in the Hawick Rocks is of 0.25–3.0 km wavelength, with long, north-westerly dipping limbs with a sheet dip of about 45° alternating with short limbs dipping steeply south-east (Figure 2.6B). Smaller-scale folds corrugate the limbs of these structures, seen at Barlocco. The asymmetry of the larger folds and the smaller-scale folds on the long limb is typically to the south-east.

Rust (1965) and Weir (1968) have also described the folding and cleavage of the Hawick Rocks, in adjacent coastal sections. They produced more complex histories for the development of the deformation, described as D_1 by Stringer and Treagus (1980, 1981), which would seem to result from a difference in interpretation of the cleavage relationship to the folds. In particular, these workers would relate the transecting cleavage to an entirely superimposed deformation (but see Weir, 1979).

The history of the development of the folds and cleavage, such as that described from this site, and its relationship to external mechanisms is of great current interest. McKerrow *et al.* (1977) and Leggett *et al.* (1979) view the stratigraphical arrangement of the Southern Uplands in the context of an accretionary prism model and note that the north-west-verging monoclines of Walton (1961) are opposite to those seen in modern accretionary prisms. Stringer and Treagus (1981) suggested that the style of folding observed by them (steep south-east vergence) was consistent with the ocean-verging, initially recumbent attitude expected in accretionary complexes, subsequently rotated into their present attitude in association with imbricate thrusting. Knipe and Needham (1986), working in an adjacent coast section, have identified disrupted rocks, thrusts and thrust-related folds which they show are similar to those described from modern accretionary prisms. Such features may well be present in the Barlocco site.

Conclusions

The Barlocco site has been selected as superbly exemplifying the principal features of the main Caledonian deformation (D_1) in the Southern Uplands. Rocks deposited in the seas of the early Silurian Period are here deformed by folds and cleavage planes (which in plan view are seen to cut across the folds). These features were produced by the intense compression of this area resulting from the convergence and final collision of the 'North American' and 'European' continents, which was responsible for the building of the Southern Uplands. This Caledonian mountain-building episode (orogeny) culminated around 400 million years before the present, at the end of the Silurian Period or early in the following Devonian. Although other locations might have been chosen, this site has the additional attractions of being historically important, easily accessible, and of being unaffected by subsequent phases of deformation.

CRUGGLETON BAY NORTH (NX 47704981–48504998)

J. E. Treagus

Highlights

Three folds on the foreshore of the north side of Cruggleton Bay illustrate one of the most interesting features of the D_1 deformation in the Hawick Rocks, that of folds transected by a contemporary cleavage. Cruggleton Bay also illustrates the typical geometry of D_1 folds in the Central Belt of the Southern Uplands.

Introduction

The rocks of the Cruggleton Bay area are the typical greywackes, siltstones, and mudstones of the Hawick Rocks. Their structure was first described by Rust (1965), although this coastal section must have provided inspiration for Lapworth's (1889, Figure 3) influential cross-section of the south-west Southern Uplands. In his discussion of the deformation of the Whithorn area generally, Rust (1965) clearly regarded folds, such as those seen at Cruggleton Bay, as D_1 (his F_1), but the cleavage that crosses them in a clockwise sense he considered to be later (his F_3). Stringer and Treagus (1980, 1981) interpreted the cleavage as essentially contemporary with the folds, although having a non-axial plane (transecting) relationship to them.

The site is not as continuously exposed as adjacent parts of the coast, but it offers the best opportunity to observe the full three-dimensional relationships between D_1 folds and the clockwise transecting cleavage (Figure 2.7).

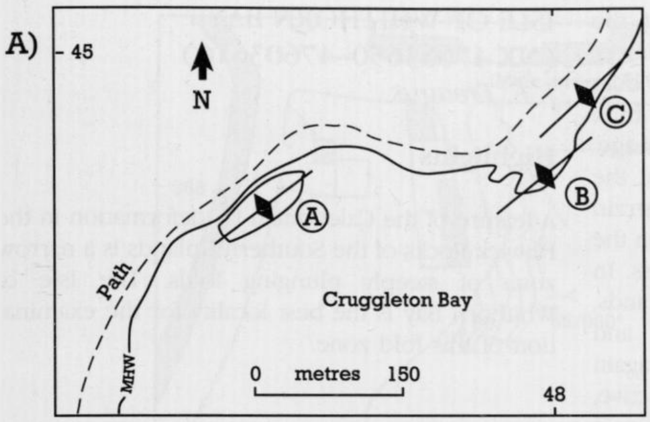
Description

The exposures of interest are seen in three anticlinal folds which protrude from the low-lying foreshore (Figure 2.8A).

Fold A (NX 47704981; see Figure 2.8B) illustrates the geometry of the non-axial planar cleavage, developed in a slightly reddened mudstone in the hinge area of a fold. The fold is a tight anticline, plunging gently about the horizontal, both to the north-east and to the south-west. The strike of the cleavage (060/70°NW) in the mudstone beds of both limbs can be seen to be up to 10° clockwise to the strike (050°) of the bedding on the limbs, and of the axial surface. But the exposures also allow a profile view of the mudstone in the hinge area; here, the cleavage shows the development of a finite neutral point (Ramsay, 1967 p. 417), with a slightly divergent cleavage fan above it (Figure 2.8B), and a bedding-parallel fabric below. Such features are generally accepted to be the product of strain related to folding, and this example would seem to provide evidence of the contemporaneity of the non-axial plane cleavage and the folding.

Fold B (NX 47984982) is a more open anticline than A, plunging to the south-west. It displays alternating sandstone and mudstone beds with, in profile, classic convergent cleavage fans in the sandstones and near axial-planar cleavage in the mudstones. Because of the plunge and the flat nature of the outcrop, it is possible to walk across successive fold hinges of bedding, along the one axial surface, and it is quite clear that cleavage in both sandstones and mudstones consistently transects the axial surfaces and fold hinges in a clockwise sense. This is one of the most convincing and photogenic (Figure 2.7) exposures that demonstrates this phenomenon.

Fold C (NX 48004992) is also an anticline demonstrably transected by the cleavage, but its principal attraction is the geometry of its hinge area, which is exposed for some twenty metres along its length. The hinge exhibits two gentle plunge culminations, as well as variation in strike of its axial surface. These features are characteristic of many of the small-scale folds of the Southern Uplands.



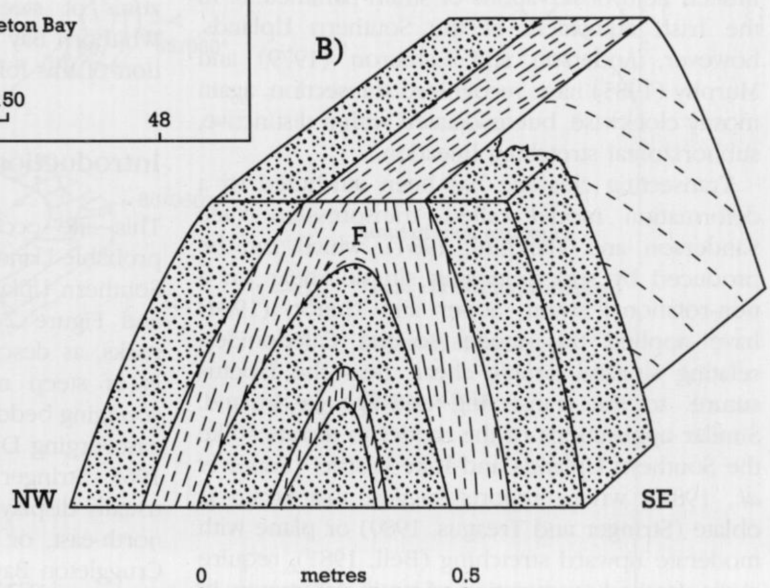


Figure 2.8 Cruggleton Bay. (A) Location map showing position of Folds A, B, and C. (B) Schematic diagram of Fold A, drawn from field sketches, showing relationship of cleavage (dashed) to the folded greywackes (dotted). F = finite neutral point.

Interpretation

Rust (1965) in his description of the deformation history of the Whithorn area proposed that there had been four important phases (F_1–F_4). Stringer and Treagus (1980, 1981) only recognized two phases D_1 (incorporating Rust's F_1 and F_3) and D_2 (Rust's F_2 and F_4). As stated above, these divergent views rest largely on the variation in interpretation of the age of the dominant cleavage in the area, S_1 of Stringer and Treagus, S_3 of Rust. Rust (1965) observed that this cleavage transected folds of his F_1 and F_2 generations, but was axial-planar to locally developed, steeply plunging folds (see Isle of Whithorn) which he therefore regarded as of third generation (his F_3). Stringer and Treagus (1980, 1981), on the other hand, from evidence in this site and other localities, maintain that the dominant cleavage, although transecting, was essentially contemporaneous with the formation of the D_1 folds. These folds locally assume steep plunges, and there they show the axial-planar relationship of the cleavage in vertical profile view.

The arguments for the contemporary age of cleavage and folding lie in the observation that the cleavage geometry is a product of the strain variations related to the fold geometry. The most commonly observed relationship of this type is the fanning and refraction of cleavage, symmetrical to the axial surfaces of folds in profile view (see Figure 2.6B, Barlocco site). At Cruggleton Bay, the most persuasive relationship is that the clockwise transecting cleavage is clearly seen to have the usual detailed geometry (see Figure 2.8B) around finite neutral points, seen in thickened mudstone hinges between adjacent greywacke beds. Such a relationship is taken to indicate that the cleavage pattern is a direct response to strains that developed in the tightening hinge (Ramsay, 1967, p. 417).

The origin of transecting cleavage, which has now been widely recognized in the Lake District and Wales (Soper *et al.*, 1987), has excited great interest, in the context of the closing of the Iapetus Ocean. Stringer and Treagus (1980, 1981) and Treagus and Treagus (1981), from observations in

Figure 2.7 Cruggleton Bay North. D_1 folds in Silurian siltstones and mudstones, plunging to the south-west, transected by non-axial plane cleavage. (Photo: P. Stringer.)

the Southern Uplands, have suggested that the phenomenon could result from the development of fold axial surfaces in an orientation other than the conventional one perpendicular to the bulk shortening and thus not parallel to the cleavage. The model was developed by assuming that the strain did not depart significantly from plane strain with moderate subvertical stretching, based on the limited field observations of strain parameters. In the Irish equivalent of the Southern Uplands, however, Anderson and Cameron (1979) and Murphy (1985) have recognized transection, again mostly clockwise, but associated with a distinctive, subhorizontal stretching lineation.

Transecting cleavage has been attributed to a deformation módel called 'transpression' (see Sanderson and Marchini, 1984), which can be produced by superimposing simple shear on a non-rotational strain. Soper and Hutton (1984) have applied this model to the Caledonides, relating sinistral simple shear, near the Iapetus suture, to the transecting cleavage in Ireland. Similar applications of the model to terranes like the Southern Uplands and Lake District (Soper *et al.*, 1987), where reports suggest that strain is oblate (Stringer and Treagus, 1980) or plane with moderate upward stretching (Bell, 1981), require more detailed examination of strain parameters in rocks such as those at Cruggleton and Barlocco.

Conclusions

The site has been selected for inclusion in the Geological Conservation Review for its illustration of the relationship of cleavage to folding. The three-dimensional forms of a number of large folds can be seen with great clarity at this locality. The cleavage (fine, very closely spaced, parallel fractures) is orientated slightly obliquely to the trend (hinges) of the fold (it is therefore described as being non-axial planar), and yet they are contemporary. The phenomenon is important in the understanding of the movements that ended the Caledonian Orogeny in Britain, around 400 million years before the present. The non-parallelism of fold axial surfaces and cleavage suggests that when the Iapetus Ocean closed at that time, its margins were oblique to the direction of closure.

ISLE OF WHITHORN BAY (NX 47663650–47603616)

J. E. Treagus

Highlights

A feature of the Caledonian D_1 deformation in the Hawick Rocks of the Southern Uplands is a narrow zone of steeply plunging folds. The Isle of Whithorn Bay is the best locality for the examination of this fold zone.

Introduction

This site occurs within the Hawick Rocks, of probable Llandovery age, in the Central Belt of the Southern Uplands – see 'Introduction', Chapter 1, and Figure 2.9. The regional attitude of these rocks, as described by Craig and Walton (1959), is of steep north-west-dipping and north-west-younging bedded sediments, interrupted by south-east-verging D_1 folds on a variety of scales (Rust, 1965; Stringer and Treagus, 1981). These folds usually display a range in plunge up to 30° to the north-east, or the south-west (see Barlocco and Cruggleton Bay: Figure 2.10).

At Whithorn Bay the plunge variations are on a larger scale and only become apparent from careful examination of successive outcrops. These folds, which are part of a 1500 m wide belt (Figure 2.1) across the Whithorn Peninsula, may be related to one or more strike-parallel thrusts. This site also reveals from examination of way-up criteria, the presence of an isoclinal fold which pre-dates D_1. Such folds have been described from several localities in the Hawick Rocks; they have been interpreted as the products of soft-sediment deformation, developed early in the history of the accretionary prism.

Stringer and Treagus (1980) described this zone, near the south-west margin of the Central Belt (labelled B on Figure 2.1), which exhibits the steeply plunging and locally downward-facing D_1 folds, seen at this site. Rust (1965) interpreted the steep-plunging folds of the Whithorn area as a response to a third episode of shortening, which affected already vertically dipping rocks. Stringer and Treagus (1980) interpreted these folds as an exceptional development of the ubiquitous D_1 folds, with the associated S_1 cleavage.

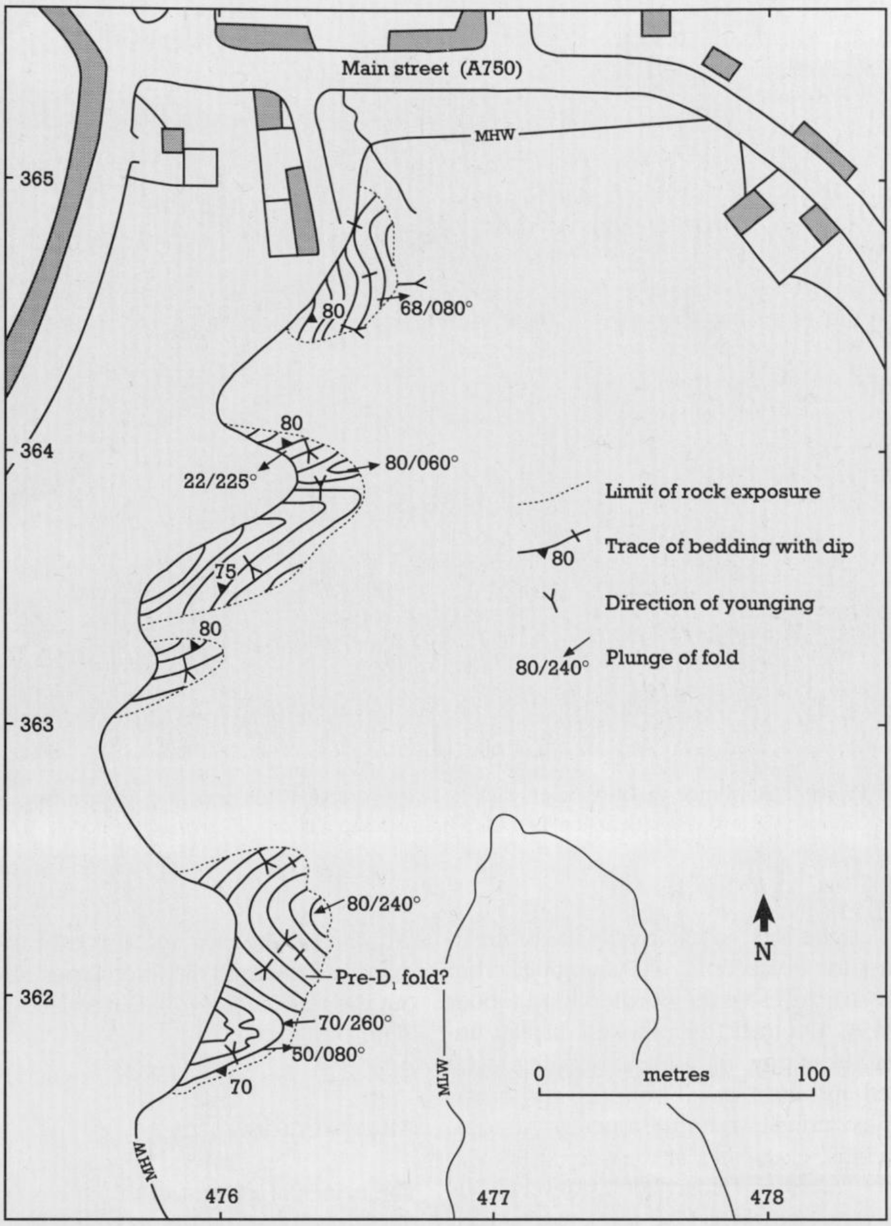


Figure 2.9 Sketch of the Isle of Whithorn Bay site.

Description

The foreshore on the western side of the bay (see Figure 2.9) contains six major D_1 hinges in the typical alternations of greywacke, siltstone, and mudstone. The rocks broadly trend NE–SW, with subvertical dips and younging to the north-west. The short limbs have a similar dip, but more north-westerly strike and young to the south-east. Thus the fold hinges are themselves subvertical and occasionally can be directly observed. In detail, some fold hinges plunge steeply north-east (some as shallow as 40°) and can be traced along their axial surfaces to plunge steeply south-west. Some hinges plunge as shallowly as 20°, giving a total range of plunge of 120° about the vertical. Unlike the John's Road site, it is not possible to demonstrate that individual hinges curve through this range. The variation in plunge is illustrated by Stringer and Treagus (1980, Figure 6c and p. 324).

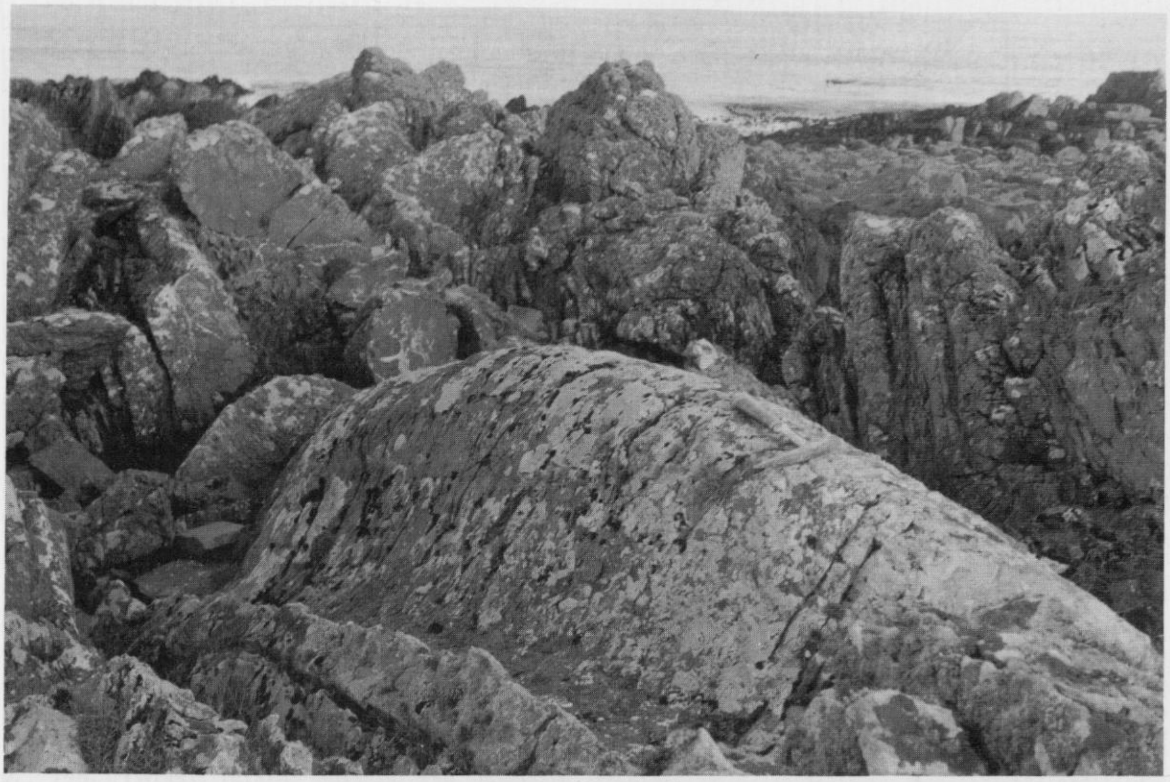


Figure 2.10 Typical fold plunge variation in Hawick Rock greywackes. This pericline, viewed from the north-west, is at Shaddock Point (NX 478 393), near the Isle of Whithorn site. (Photo: P. Stringer.)

Throughout the site, it is usually possible to demonstrate the direction of younging from sedimentary structures. At the northern end (about NX 47703645), 1 m-thick greywackes display unusually clear examples of graded bedding, with gritty, loaded and flute-casted bottoms, and cross-laminated silts and cleaved mudstones at the tops. Such indications, elsewhere at the site, show that the majority of the folds face sideways, or upwards, to the south-west. The folds that plunge to the north-east can, similarly, be shown to be downward-facing to the south-west. However, a reversal of younging of the rock sequence, at NX 47623622, which cannot be accounted for by the D_1 folds, implies the presence of a major isoclinal fold that pre-dates D_1. Similar pre-D_1 folds at Cairnhead (NX 48673838), considered to be of soft-sediment origin, have been described by Stringer and Treagus (1981, p. 141) and Rust (1965). That the folds are D_1, is clearly demonstrated from the relationship between the folds and the cleavage, the latter is everywhere developed in the finer-grained lithologies. It is approximately axial planar, showing the usual refraction through the various lithologies. The cleavage also exhibits the transecting relationship to the fold hinges, shown throughout the Hawick Rocks (Stringer and Treagus, 1980; Figure 2.11).

Interpretation

The principal interest of this site is that the steeply plunging folds, which it so clearly exhibits, are part of a zone of such structures that runs for some 20 km along the southern margin of the Central Belt (labelled B on Figure 2.1). At Whithorn the zone is 1000 m wide, whereas to the north-east, on the other side of Wigtown Bay, it appears to be represented by two narrower components (Stringer and Treagus, 1980, Figure 1). No descriptions exist of such structures in the poorly exposed inland areas, but the site at Agate Point and John's Road on the north-east coast may be part of the same, or a parallel, zone 200 km along strike.

The origin of the folds has been attributed to a post-D_1 deformation by Rust (1965). This was

Figure 2.11 Typical cleavage refraction from mud/siltstone to sandstone seen in Hawick Rocks in profile view; in plan view cleavage transects the fold hinges. Locality: Port Allen (NX 478 411), near Isle of Whithorn. (Photo: P. Stringer.)

contested by Stringer and Treagus (1980) who pointed out that:

1. these folds were part of a range of D_1 fold plunge in the area;
2. that the folds exhibit, apart from their plunge, all the usual features of D_1 folds in their wavelength, vergence and general style; and that
3. the regionally developed cleavage has the same relationships to these folds as it does to the regional D_1 folds, namely subaxial planar or slightly transecting, and refracting through the various lithologies.

Kemp (1987) described some steeply plunging folds in the Southern Belt in strongly sheared rocks, to the south-east of the zone described here. He showed that the folds have a consistent sinistral vergence and post-date early folds (and presumably cleavage). Clearly, the post-D_1 folds have a different origin, more clearly related to shearing than those discussed here.

The origin of these folds is still unexplained and will undoubtedly be the subject of further research, particularly in view of the unusual deformation characteristics that would be expected as a result of the position of these rocks in a possible accretionary prism. Stringer and Treagus (1980) suggested, firstly, that they might be related to unusual strain gradients which might be associated with the thrusting that is an essential feature of the accretionary process. Folds that curve into the extension direction are usually related to strong extensive strains (Roberts and Sanderson, 1974) often in shear zones (Cobbold and Quinquis, 1980). However, no exceptional strain parameters have been reported from these rocks, indeed the fabric suggests oblate strain. Stringer and Treagus (1980), secondly, suggested that D_1 folds may have been rotated in packets between shear planes as part of the thrust related (D_1 and later?) deformation. The boundary between the Hawick Rocks and Wenlock strata, immediately to the south-east of the zone (see West Burrow Head), may be the location of one such thrust. The site certainly contains planes or zones along which there is local disruption, intensification of cleavage and veining. These zones could mark the boundaries of anastomosing minor thrust packets, although there is apparently no great discontinuity of fold structure, or lithological type across them. The age, the sense of shear, and the relation to external stresses of the zone of steeply plunging folds is an obvious target for future work.

A second feature of interest here is the apparent presence of a pre-D_1 isoclinal fold. Such folds, unrelated to cleavage, or minor structures, have been attributed (Stringer and Treagus, 1980, 1981) to soft-sediment deformation. Again, this feature, as well as those of similar origin described by Knipe and Needham (1986) and Kemp (1987), need to be further studied. Soft-sediment structures need to be more closely related to those in accretionary prisms. Their geometry and origin in the Southern Uplands or in modern prisms cannot yet be related with confidence.

Conclusions

The site has been included in the Geological Conservation Review as the most convincing and accessible location for the study of steeply-plunging folds in the Southern Uplands. These folds, which vary considerably in their orientation (plunge), through a total range of 120° about the vertical, are highly unusual features of slate belts and must be an important, but as yet poorly understood, feature of the accretionary development of the north-western margin of the Iapetus Ocean. In the Hawick Rocks of this area they are characteristic. These folds were the product of extreme compression during the Caledonian mountain building episode at the end of the Silurian Period or early in the Devonian. They affect older folds here, thought to have formed by the slumping of unconsolidated sediments on a sloping early Silurian sea-bed, perhaps initiated by disturbances in the early stages of accretion. Thus the locality displays graphically sedimentary and tectonic deformation over a period of around 40 million years.

WEST BURROW HEAD (NX 45183411–45343411)

J. E. Treagus

Highlights

This site has total exposure across the stratigraphically and structurally important boundary between the Hawick Rocks and fossiliferous strata of the Lower Wenlock Series. The boundary here is clearly faulted, but the throw of the fault has been the subject of controversy.

Introduction

This coastal locality is important in the controversy concerning the nature of the junction between the belt of Wenlock rocks, in the south-east, and the Hawick Rocks, to their north (see Walton *in* Craig, 1983 p. 129). At Fouldbog Bay, the along-strike equivalent of this steeply dipping junction is claimed, by Craig and Walton (1959), to be marked by transitional beds from the younger Hawick Rocks south-eastwards to the Wenlock. They concluded (see also Clarkson *et al.*, 1975) that the Hawick Rocks must therefore have either a latest Wenlock or a Ludlow age. At Burrow Head, Rust (1965) claimed that transitional rocks were absent and that the junction exposed between the Hawick Rocks (assumed by him to be Upper Llandovery) and the Wenlock, was a fault which required a southward downthrow of some 3 000 m. Rust considered that the apparent transitional rocks (red mudstones associated with graptolitic Wenlock) might have been produced by fault slicing at Burrow Head, Fouldbog Bay and elsewhere.

Most recently, Kemp and White (1985) and Kemp (1986), working in the Fouldbog area and in areas further to the north-east, has claimed that the Wenlock strata south-east of the Hawick Rocks are an intensely imbricated sequence of packets successively younger in that direction; like Rust (1965), he has attributed a Late Llandovery age to the Hawick Rocks. Barnes *et al.* (1987, Figure 4) confirm Rust's (1965, Figure 4B) observation, and that of the present work, that the site lies on the short limb of a major SE-verging fold pair, with a wavelength of about 1 km. Barnes (1989) cites the graptolite evidence which firmly assigns the rocks here to the Llandovery.

Description

At the north-west end of the site (Figure 2.12A and B), regularly bedded, south-east dipping, Hawick greywackes and siltstones young consistently upwards, interrupted rarely by fold pairs verging to the north-west. Two distinctive red mudstone beds occur near the top of the exposed succession (Figure 2.12A). Some 20 m to the east of the red mudstones, a zone, about 10 m wide, is traversed by five steep fracture planes trending north-east (Figure 2.12B). The fractures are not associated with any of the usual fault-plane features suggesting major movement, except possibly thin mylonitic banding. The slices between the fractures usually retain some coherence of bedding, although a 1 m-wide central slice contains strikingly lensoid beds of greywacke. One syncline and one anticline core are evident elsewhere in the slices. To the south of the fractures, the first coherent greywackes, again clearly young to the south-east, but are immediately involved in a tight syncline. The north-west-younging continues through beds containing graptolitic mudstones of Wenlock age (see Rust, 1965, Figure 2), but is reversed again to the south-east after 20 m by the complementary anticline. The Wenlock rocks continue to dip and young to the south-east for at least another 200 m towards Burrow Head, with rare interruption by north-west-verging fold pairs. 2.12A & B

Interpretation

This site demonstrates that the junction between the Wenlock and Hawick Rocks, at least locally, is a fault zone. Apart from the physical evidence of fracture planes separating the two units, there is no match of lithology across the zone. As the sense of shear and the precise stratigraphical separation across the zone are as yet unknown, its significance can only be speculated on from regional considerations. Detailed structural investigation of the site itself and of the rocks immediately north and south could provide an answer to the debate as to whether the Hawick Rocks are younger (Craig and Walton 1959) or older (Rust, 1965) than the Wenlock.

Although recent opinion favours the view that the Hawick Rocks are attributable to the Llandovery Series (Kemp, 1986; Kemp and White, 1985; Barnes *et al.*, 1987), the opposing view still has the merit that it requires the least displacement on the fault zone at Burrow Head. Thus, if the red mudstone lithologies in the greywacke of the local Hawick Rocks were transitional downward to the Wenlock, as Craig and Walton (1959) propose, then the Wenlock would lie hidden in the core of the anticline to the north of the fault zone illustrated in Figures 2.12A and 2.12B. The red mudstones, to the south of the fault, would lie above the Wenlock in the core of the synclinal complex which lies south of the site. Displacement on the fault zone might then be a few hundred metres, but downwards on the north side.

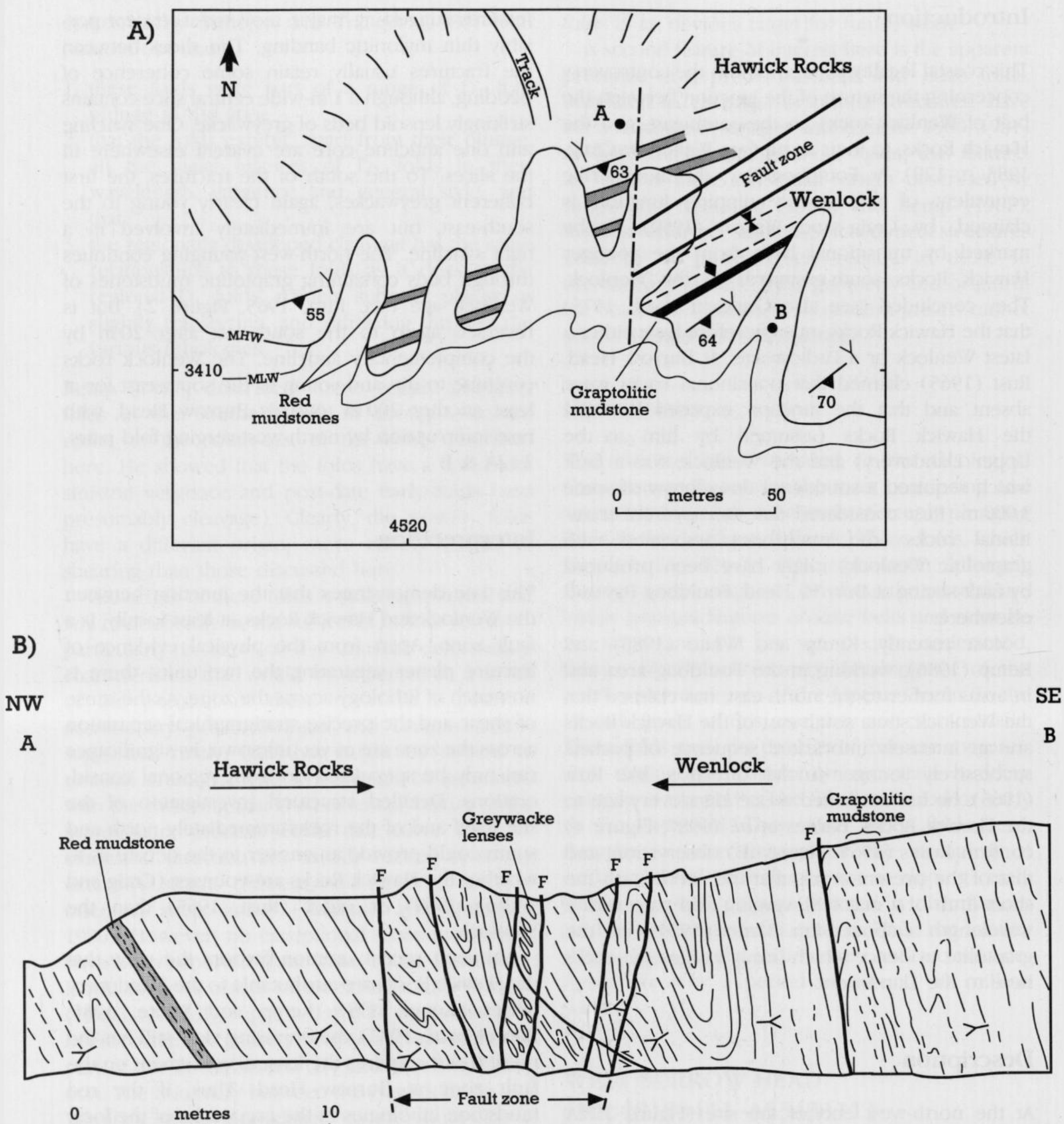


Figure 2.12 West Burrow Head. (A) Geological map of site. (B) Sketch cross-section along line A–B of Figure 2.12A).

On the other hand, if Rust (1965) is correct in his view that north of the anticline (north-west of the site) there is a sequence of Hawick Rocks (Rust's Carghidown and Kirkmaiden Formations) uniformly dipping and younging to the north-west as far as Kirkmaiden, then a 2–3 km displacement would be necessary, downwards on the south side of the fault zone shown in Figures 2.12A and 2.12B. The magnitude of the displacement, in the latter hypothesis, depends very much on the stratigraphical and structural arrangement of the Carghidown and Kirkmaiden Formations. Information relating to this is given in the Geological Survey Memoir (Barnes, 1989). Barnes *et al.* (1987) suggest that the Carghidown Formation (with red-beds) is younger than the Kirkmaiden Formation (with a gradational boundary between them) and may be stratigraphically overlain by the Wenlock rocks at Burrow Head. The structural arrangement, whereby this stratigraphy is obtained, is not yet published, but must involve a new interpretation of folding and/or faulting in the Hawick Rocks.

Thus the Burrow Head site is potentially of great importance, in the resolution of two issues in Southern Upland geology. Firstly, there is the question of the age of the Hawick Rocks and all that it implies for the palaeogeography. If the interpretation of a transitional junction is correct then only a small displacement, down on the north side of the fault zone, would be required. Such a fault would not be a major down-to-the-south thrust associated with the accretionary process. On the other hand, a smaller displacement, possibly of D_1 age would explain the lack of high-strain features associated with the fault zone. Secondly, there is the question of the position, age and displacement of the faults which are critical to the interpretation of the structural evolution.

Conclusions

This site is an example of one of the major, steep, strike-parallel fault lines that form an important part of the structural framework of the Southern Uplands. It has been claimed that the fault has a very large displacement of 3000 m, bringing mid-Silurian aged rocks (Wenlock) against early Silurian Hawick Rocks; this dating is based on sparse fossils found in these marine sediments. The displacement of the fault depends on the precise dating of the rocks on its two sides, and an alternative 'structural' interpretation has been proposed which would make the fault a far less important structure. The settlement of the controversy over this major Southern Uplands discontinuity, will have considerable repercussions on the study of the geological framework of southern Scotland.

BACK BAY, MONREITH (NX 36783947–36943930)

J. E. Treagus

Highlights

Back Bay, Monreith has the most dramatically exposed cliff section of large-scale folding in the Southern Uplands (Figure 2.13). Two large-scale, D_1 fold pairs are completely exposed in the 30 m-high cliffs, with an excellent example of D_2 structures superimposed. The geometry of these features is characteristic of the deformation style in the Central Belt of the south-west Southern Uplands.

Introduction

The rocks of this site display a typical range of lithologies in the Hawick Rocks, including some massive greywackes, as well as thinner-bedded greywackes, siltstones, and mudstones. The principal feature of the site is the refolding of the north-westerly fold pairs by a D_2 fold pair with a flat-lying south-easterly dipping axial surface and crenulation cleavage. The style of this D_2 deformation is typical of its local development throughout the Central Belt, but here is part of a 2.3 km-wide zone that crosses the Whithorn Peninsula and can be traced to the north-east coast of Wigtown Bay (Figure 2.1). The D_2 deformation is locally associated here with minor north-west directed thrusting, but regionally appears to result from subvertical shortening of the D_1 fold stack.

The site is part of the Whithorn area described by Rust (1965) in which he recognized four phases of deformation related to folds and cleavage. The F_1 folds of Rust are the D_1 folds of the West Burrow Head site 10 km to the south, and of the present description. Superimposed on this phase Rust recognized two sets of folds, his F_2 and F_4

Figure 2.13 Type-D_1 syncline in massive Silurian greywackes, Back Bay, Monreith. View to the north-east, with figure for scale. (Photo: J. Treagus.)

phases, and the Back Bay locality is quoted (Rust, 1965, p. 14 and Plate 2) as an example of the F_4 folding with accompanying cleavage. The distinction of F_2 and F_4 appears to be partly on the flatter dips of the axial surfaces of the latter and also on the superimposition of F_4 on the locally developed, steeply plunging F_3 folds.

Stringer and Treagus (1980, 1981), recognized one dominant phase of deformation, D_1, with its associated (but non-axial planar) cleavage. This is locally affected by a D_2 deformation (incorporating Rust's F_2 and F_4) particularly in one 2 km-wide, NE-trending belt (labelled A on Figure 2.1), on which the Back Bay site lies in a median position.

Description

The north-western half of the section (Figure 2.14) is dominated by a spectacular profile of a large open D_2 fold (minimum amplitude 5 m) superimposed upon a tight upright D_1 anticline (at NX 36823942) and a syncline (at NX 36853940) of *c.* 30 m amplitude (Rust, 1965, Figure 1 and Plate 2). The folds plunge gently to the north-east. At the north-west end of the section, steep NW-dipping strata and S_1 cleavage are deformed by smaller-scale, D_2 'step' folds with axial surfaces and sporadic, D_2 crenulation cleavage inclined gently to the south-east (Stringer and Treagus, 1981, Figure 3A). Minor thrust faults, with small north-westerly displacements and a zone of quartz veins, are associated with the D_2 folds.

The south-eastern half of the section (Figure 2.14) comprises a D_1 anticline (at NX 36913937) and syncline (at NX 36933936, see Figure 2.13) forming an asymmetrical D_1 fold pair (Folds 3 and 4 in Stringer and Treagus, 1981, Figure 3A) which verges to the south-east. The folds are tight (interlimb angle 20–35°); overturned strata in the common short limb (15 m wide, measured horizontally) dip steeply to the north-west, and strata in the long limbs (50 m wide) dip moderately to steeply to the north-west. The D_1 fold pair

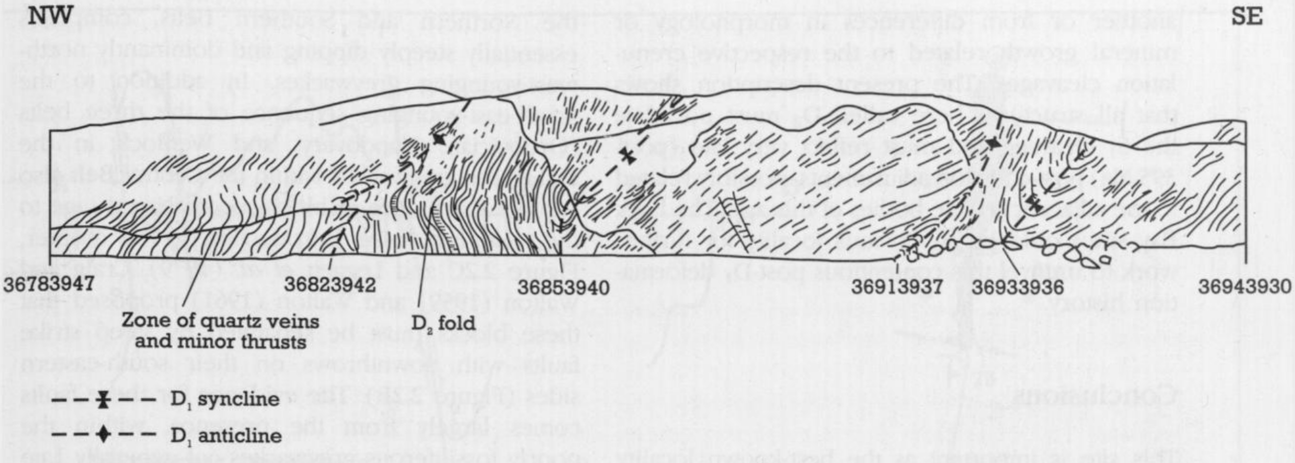


Figure 2.14 Sketch of the Back Bay site, drawn from photographs. Horizontal scale is not linear; total length is approximately 200 m.

(wavelength *c.* 75 m, amplitude *c.* 30 m) is probably intermediate in scale to larger scale, 0.25–3.0 km, D_1 folds. Gentle curvature of the north-westerly-dipping axial surfaces indicates large-scale D_2 folding. The D_1 cleavage in mudstone and sandstone beds strikes close to 070° and 090° respectively, markedly oblique to the north-easterly strike of the D_1 fold axial surfaces.

The site generally offers the opportunity to examine all aspects of the D_1 and D_2 deformations, including the relative thickening of fold hinges compared with limbs, boudinage of limbs, the variable development of the S_2 cleavage, and the associated quartz veining and thrusting.

Interpretation

The interest of the site lies in the scale and geometry of both D_1 and D_2 folds, and the fact that it affords the rare opportunity to observe one phase superimposed on the other.

The D_1 folds give a glimpse of the amplitude and wavelength of this phase of folding, although the first-order D_1 folds in the Central Belt are thought by Stringer and Treagus (1983) to be of the order of 0.25–3.0 km. The section (see Figure 2.14) also reveals the south-east vergence of these second-order folds, as seen by the relative thickness of the north-west- and south-east-younging limbs respectively. In fact, the north-west-younging limb, between the north-west and south-east fold pairs, is uncharacteristically gently dipping, presumably as a consequence of D_2 deformation. A 30° sheet-dip to the north-west would probably represent the pre-D_2 value, seen here interrupted by major folding. In the accretionary model, these folds would be interpreted as having a primary attitude with gentle landward-dipping (NW) axial planes and south-east vergence. Their rotation to their approximate present attitude would have taken place during thrusting, possibly exemplified at the West Burrow Head site. Finally, the transecting cleavage would have been impressed on the folds during the late Silurian closure of the Iapetus and before dykes were emplaced, the latter dated by Rock *et al.* (1986) at 418–395 Ma.

The D_2 folding shows the typical (but often steeper) dip to the south-east of the axial surfaces of the folds and their consequent south-easterly vergence. Like Rust (1965), but for different reasons, Knipe and Needham (1986), elsewhere, distinguished two generations of folds with this geometry. The earlier, with steeper axial surfaces, they ascribe to pre-accretion rotation and associate with continuing oceanward rotation from D_1 (Knipe and Needham, 1986, Figure 11). The second set, with flatter, south-easterly-dipping axial surfaces like those at Back Bay, they attribute to post-accretion rotation and note the association with minor thrusting directed to the north-west. They associate this structure with shortening in the collision related to the closure of the Iapetus. Stringer and Treagus (1980, 1981) were unable to distinguish these two sets of post-D_1 structures, either on the basis of interference of one set with another or from differences in morphology or mineral growth related to the respective crenulation cleavages. The present description shows that all structures here called D_2 must post-date the S_1 cleavage and must reflect very late (post-395 Ma) post-collision adjustments, possibly related to the adjacent granite bodies of this age. The Back Bay site would be an obvious locality for further work to unravel this contentious post-D_1 deformation history.

Conclusions

This site is important as the best-known locality where the Caledonian D_2 folds of the Southern Uplands can be clearly seen to be superimposed D_1 folds, formed earlier in that mountain-building phase. Large, upright asymmetrical folds with amplitudes up to 30 m, associated with steeply inclined cleavage (fine, closely spaced, parallel fractures), are refolded by a second generation of smaller folds orientated almost at right-angles to the first. The first generation (D_1) of folds is thought to result from the subduction of oceanic crust during the closure of the Iapetus Ocean, whereas the cleavage probably relates to eventual continental collision in the end-Caledonian mountain-building episode. The second generation of folds (D_2) is possibly related to uplift. As well as providing an unequalled view of the style and scale of D_1 folds, this locality must rank as one of the most dramatic large-scale exposures of major refolded folds anywhere in the British Isles.

GRENNAN BAY (NX 07754373)

J. E. Treagus

Highlights

This site exposes one of the 'inliers' of Moffat Shales within the Llandovery greywackes of the Central Belt. Here the contacts between the two units are unusually well displayed. The Moffat Shale inliers have played a central role in the debate over the structure and geological history of the Southern Uplands, for more than a century.

Introduction

The Central Belt of the Southern Uplands, like the Northern and Southern Belts, comprises essentially steeply dipping and dominantly north-west-younging greywackes. In addition to the south-east-younging sequence of the three belts (Ordovician, Llandovery, and Wenlock in the main), the greywackes within the Central Belt also exhibit a sequence of blocks decreasing in age to the south-east – see 'Introduction' to this chapter, Figure 2.2C and Leggett *et al.* (1979). Craig and Walton (1959) and Walton (1961) proposed that these blocks must be separated by steep strike faults with downthrows on their south-eastern sides (Figure 2.2B). The evidence for these faults comes largely from the presence, within the poorly fossiliferous greywackes (of generally Late Llandovery age), of the graptolitic Moffat Shales, (Hartfell, Birkhill, and Glenkiln Shales, of Llandeilo to Llandovery age). The juxtaposition of Moffat Shale slices above, and to the north-west of, the greywackes in the Grennan Bay site requires faults with substantial throws. Lapworth (1889) and Peach and Horne (1899) in the earliest interpretation of the Moffat Shale strips within the greywacke, saw them as anticlinal inliers of the Ordovician, although they fully appreciated their faulted nature (Figure 2.2A). This site is important in its bearing on the structural relationships between the Moffat Shale 'inliers' and the younger Llandovery greywackes of the Central Belt. At its southern margin, this site exposes a gradational contact between the Moffat Shales and these greywackes to their north. The northern half of the site consists of a 100 m-thick slice of Moffat Shales, with fault contacts with the greywackes to their north and south (Figure 2.15). The latter fault is an example of one of the steep 'thrusts' which, in the accretionary interpretation of the Southern Uplands, would be consequent to the north-westerly subduction of the Iapetus Ocean crust.

The area of the Rhinns of Galloway in which the Grennan Bay site lies, had not been studied since the original Geological Survey mapping (Peach and Horne, 1899). However, it has recently been the subject of resurvey by J. A. McCurry (Barnes *et al.*, 1987), who provided much of the background information for the present description.

Description

The stratigraphy at Grennan Bay, together with post-cleavage lamprophyre dykes and faults, is demonstrated at eight localities within the site (a–h; Figure 2.15); these are discussed in detail

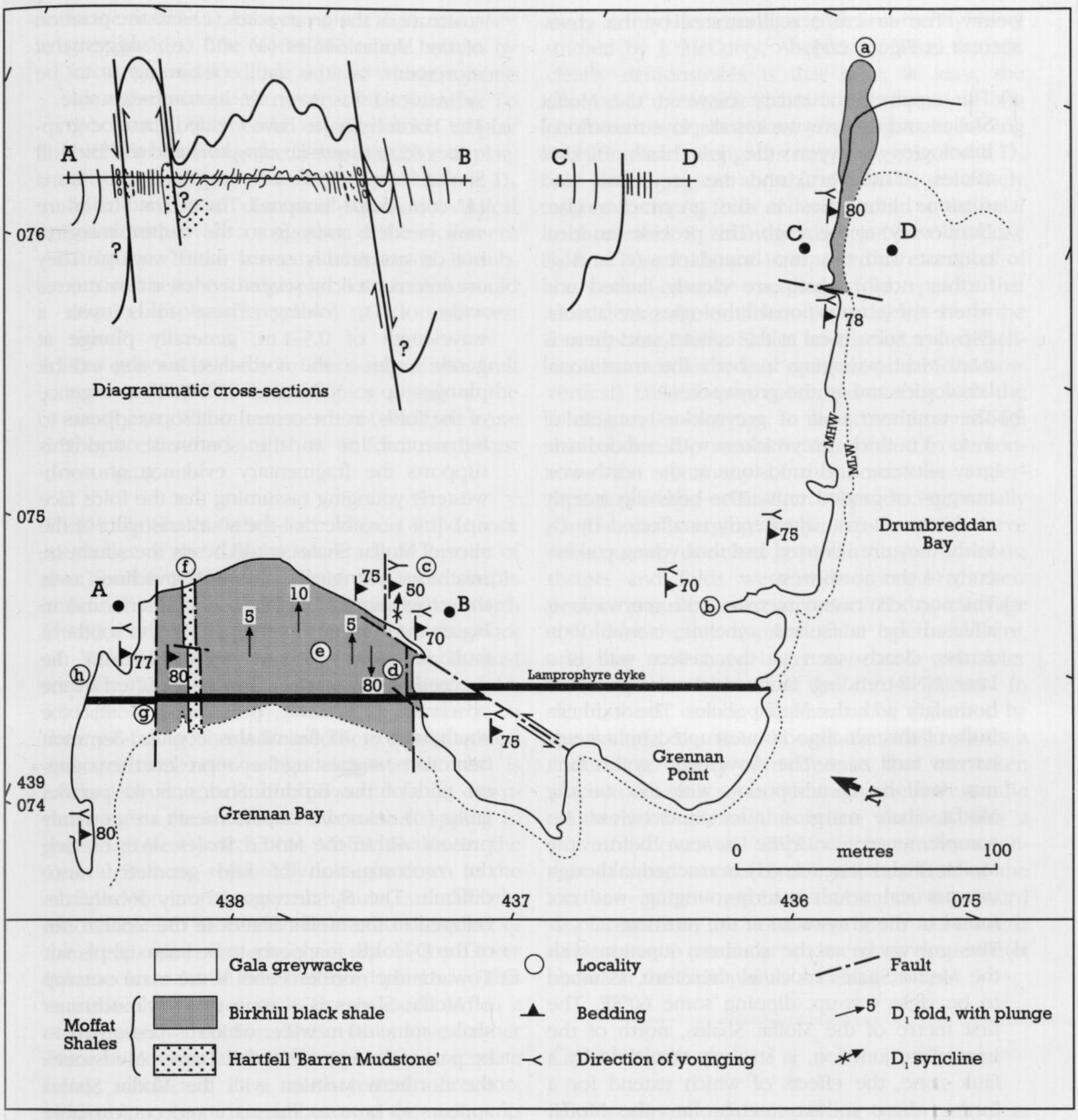


Figure 2.15 Geological map and cross-sections (inset) of the Grennan Bay site (after J. A. McCurry, unpublished).

below. The structure is illustrated by the cross-section in Figure 2.15.

a) The southern boundary between the Moffat Shales and the greywackes displays transitional lithologies between the grey/black Birkhill Shales (Llandovery) and the grey shale and siltstone lithologies in the greywackes (late Llandovery) to the north. This provides an ideal contrast with the two boundaries (d and g) further north, which are clearly faulted and where these transitional lithologies are absent. Dips are subvertical at the contact, and there is north-west younging in both the transitional lithologies and in the greywackes.
b) The southern unit of greywackes consists of 1 to 3 m-thick greywackes with subordinate grey siltstone and mudstone at the north-west margins of graded units. The beds dip steeply to the south-east, apparently unaffected by D_1 folds; they are inverted and thus young consistently to the north-west.
c) The northern twenty metres of the greywacke is affected by a faulted syncline, some 10 m across, clearly seen on the eastern wall of a later NNE-trending fault which also cuts the boundary with the Moffat Shales. The southern limb of this syncline is interrupted by a steep, narrow fault zone. The movement on this fault may well be contemporary with that on the Moffat Shale margins, mentioned below. No complementary anticline is seen before the Moffat Shales junction (d) is reached, although unequivocal south-easterly-younging was not found in the greywacke at the junction.
d) The greywacke at the southern junction with the Moffat Shales block is, therefore, assumed to be right way-up, dipping some 60°SE. The first metre of the Moffat Shales, north of the immediate junction, is strongly disturbed by a fault zone, the effects of which extend for a further three to five metres into the Moffat Shales to the north. Within this first metre, lenses of greywacke, up to a metre in length, occur in sheared black shale and the Moffat Shales beyond are broken by anastomosing fracture planes. The actual junction with the Moffat Shales is generally sharp and planar (dipping steeply to the south-east), but in detail it is often undulating. Some striations are subvertical within the fault zone, but there is no other obvious indication of direction, or amount of movement. Some movement disturbs, and thus post-dates, the S_1 cleavage. The simple structure of the greywackes (c) and the position of the Moffat Shales (a) and (e), suggest that movement on this fault (assuming it to be subvertical) was down on its south-east side.
e) The Hartfell Shales have yielded Caradoc graptolites *(C. wilsoni–D. clingani)* and the Birkhill Shales have yielded a Lower Llandovery fauna (*M. convolutus* biozone). The Moffat Shales are well bedded, away from the faulted margins, but do not readily reveal their 'way-up'. They are interrupted by several zones, a few metres wide, of D_1 folding. These folds, with a wavelength of 0.5–1 m, generally plunge at gentle angles to the north-east, but also exhibit plunges up to 50°NE and 80°SW. The vergence of the folds, in the central outcrops, appears to be neutral, or to the south-east, and this supports the fragmentary evidence of north-westerly younging (assuming that the folds face up). It is possible that the south-east part of the slice of Moffat Shales could be on the southern, south-east-younging, limb of an anticline (as in the cross-sections of Peach and Horne and in Figure 2.15 herein) interrupted by the southern fault (at point d) and separated from the succeeding greywackes; this is supported by the observation (McCurry, pers. comm.) that the southernmost Moffat Shales contain common bentonites, suggesting they represent the youngest part of the Birkhill Shales. Strike-parallel faults (of unknown displacement) are certainly present within the Moffat Shales slice, making the reconstruction of fold geometry more difficult. The S_1 cleavage is only locally developed in the Moffat Shales in the axial zones of the D_1 folds; it appears to be subaxial planar.
f) Towards the northern end of the main outcrop of Moffat Shales is a zone of grey mudstone/shale, some 10 m wide, which is presumed to be part of the upper Hartfell 'Barren Mudstone'; the northern junction with the Moffat Shales appears to be a sedimentary and conformable junction younging northwards, but the southern junction is probably a fault. Since the southerly junction is followed by a syncline in the Moffat Shales, the outcrop of the Barren Mudstone may well be anticlinal with a thinned and faulted southern limb, as shown in Figure 2.15.
g) The junction of the Moffat Shales with the greywackes to the north is, again, clearly a fault zone. The actual junction was only seen in one place (but this is dependent on the movements of material on the foreshore), over a distance of 1 m, where it is a sharp plane, steeply dipping

to the south-east, between black shale and platy grey siltstone. The Moffat Shales are broken by fractures, and bedding is lost within a zone some 3 m-wide to the south of the junction. To the north, thin beds of greywacke display excellent lensoid structure in a matrix of platy siltstone and grey shale for several metres; D_1 folds have been disrupted. Again, subvertical striations provide a suggestion of the movement direction. If the movement direction is subvertical then the stratigraphical separation would require displacement down on its north-west side.

h) The greywacke beds to the north of the fault zone are 0.5–2 m thick, dipping steeply to the south-east. Within ten metres of the fault zone they are inverted and show uniform north-west younging.

The Moffat Shales 'inliers' are of great importance in studies of the Caledonian structural history of the Southern Uplands. They are not simple anticlinal inliers as envisaged initially by Lapworth (1889), but have come to be seen, from the work of Walton (1961), Toghill (1970), and, most recently, Webb (1983), as the expression of D_1 fold pairs modified by faulting, particularly on their SE-facing short limbs. Their stratigraphical and structural relationships suggest that each is marked by one, or more, powerful faults downthrowing to the south-east ('thrusts' if dipping to the north-west), such that Moffat Shales in the Central Belt are repeatedly brought down to the surface. More importantly, such faults, cumulatively, are believed to more than counteract the effect of the steep north-westerly sheet-dip of the Lower Palaeozoic rocks of the Southern Uplands, so that successively younger rocks are encountered in a south-easterly direction. These faults have further come to be seen as the effect of an oceanic plate being subducted, in a north-westerly direction, beneath an oceanic trench, causing the sediments to be sliced and accreted on to the forearc prism to the north-west (Figure 2.2C and Leggett *et al.*, 1979, 1983).

The Grennan Bay site offers clean, almost continuous exposure across three junctions in two inliers. It is superior, in this respect, to any of the exposures of the inliers that have been described already (for instance, Toghill, 1970; Fyfe and Weir, 1976). Although the displacement on the bounding faults are yet to be proved and the internal structure and stratigraphy of the Moffat Shales has not been mapped in detail, the potential for future study at this site is very great (it is currently being studied by J. McCurry, Aberdeen). What the site clearly demonstrates is that here, at least, the outcrop of the Moffat Shales is a consequence of a combination of north-west younging, tight folding and complex faulting. It strongly suggests that a D_1 fold pair is present and that the faults are closely related to the D_1 folds and subparallel to the axial surfaces and S_1 cleavage associated with those folds. These folds are interpreted as examples of the south-easterly verging fold pairs that characterize the Southern Uplands, but here the incompetent Moffat Shales have acted as a detachment horizon for at least one substantial (and now vertical) fault, in part contemporaneous with the folding and/or cleavage. In the accretionary model this relationship would be interpreted to demonstrate the continuity of the north-west underthrusting of the oceanic crust, producing initially south-easterly-verging flat-lying folds which were subsequently detached at Moffat Shales horizons; thrusts and folds were then rotated to their present attitude during accretion. The S_1 cleavage should be the last imprint of the Iapetus closure, and may well have been associated with later strike-dip movement on the thrust planes. In detail, the S_1 cleavage appears to be disturbed by the faulting, but it is thought that this reflects a continuing history of movement that has taken place in the fault zones. Although one fault, on the southern margin of this inlier, certainly has a powerful downward displacement to the south-east (a steep normal fault), another fault at the northern margin must have a substantial downward displacement to the north-west. More work needs to be done, in particular to determine the sense of shear on the fault planes and fault zones.

Conclusions

This locality affords outstanding opportunities to study sections in one of the Moffat Shales 'inliers' of the Southern Uplands, with faulted and unfaulted contacts between the Upper Ordovician to lowermost Silurian Moffat Shales and the surrounding Lower Silurian greywackes. These inliers (that is, areas of older rocks surrounded by younger ones) are now regarded as first-generation (D_1) folds, formed during the early stages of Caledonian mountain building and modified by later faulting. Both the folding and faulting are thought to result from the descent of ocean crust beneath the continent (subduction) on the north-west margin of the Iapetus Ocean: a situation similar to that seen today just east of Japan where the Pacific oceanic plate plunges beneath the Asian continental plate. When this happened in the Southern Uplands during late Silurian to early Devonian times the rocks and sediments were added (accreted) on to the continental margin in a sliced (faulted) wedge or prism.