Chapter 2 Southern Uplands

Introduction — A structural perspective

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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 cgricemed 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.

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 2.6)A). 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 2.6)B, from parallelism with fold hinges.

The D2 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.

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 northwest, 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 southeasterly (oceanward) asymmetry being regarded as a result of deformation above the north-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.

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. 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.

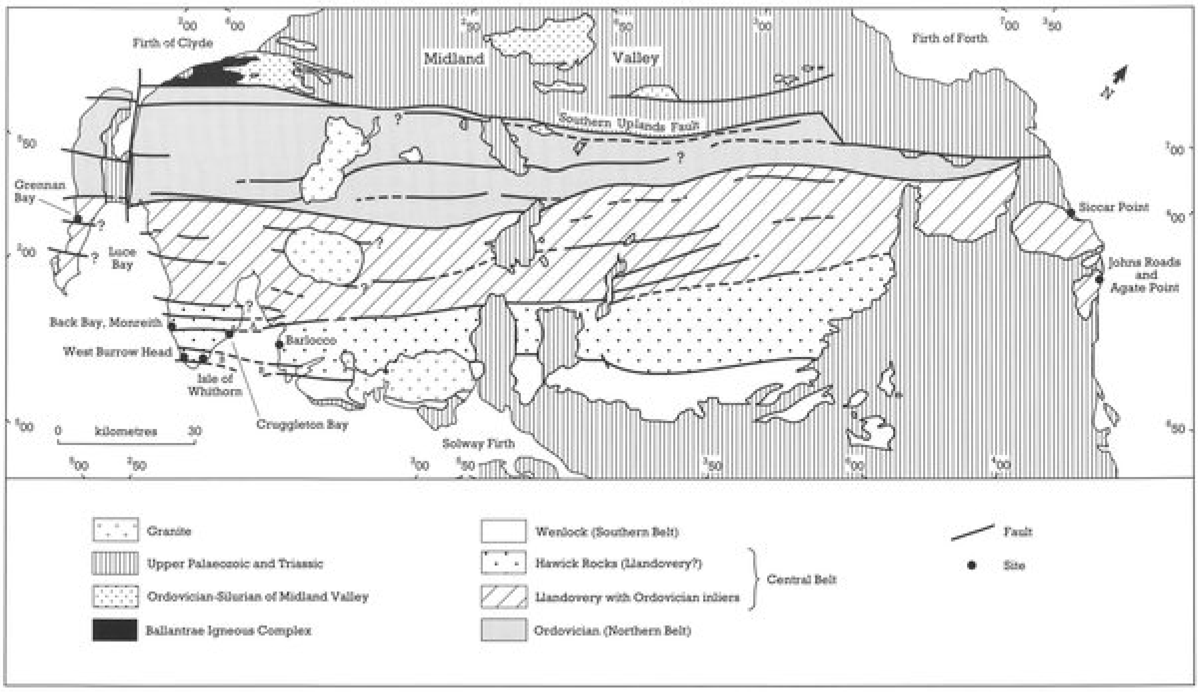
Timing of deformation

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.

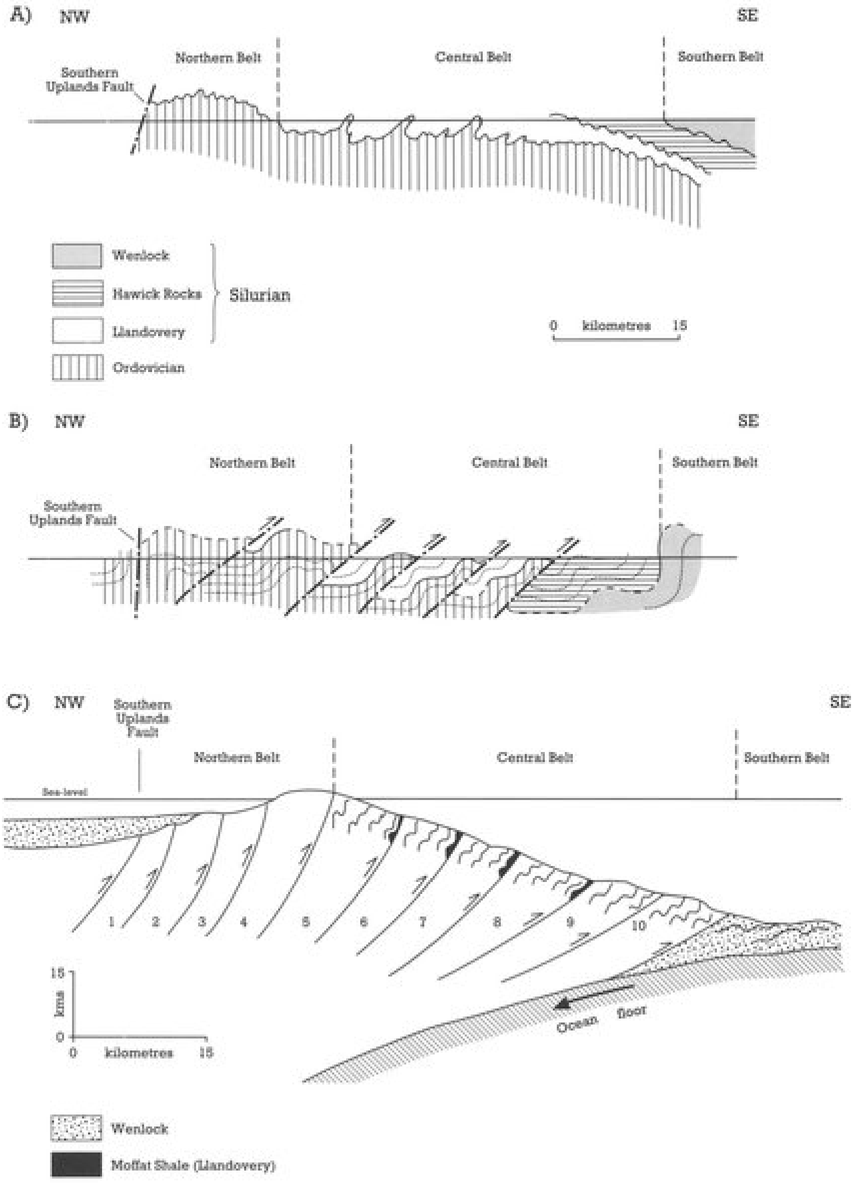
The selected sites are shown in (Figure 2.1). In spite of the detailed sections of the Northern Belt by Kelling (1961), it was not possible to select any site in these rocks which would illustrate their typical D_1 style. It is hoped that future work will especially clarify the relationships of the cleavage 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.

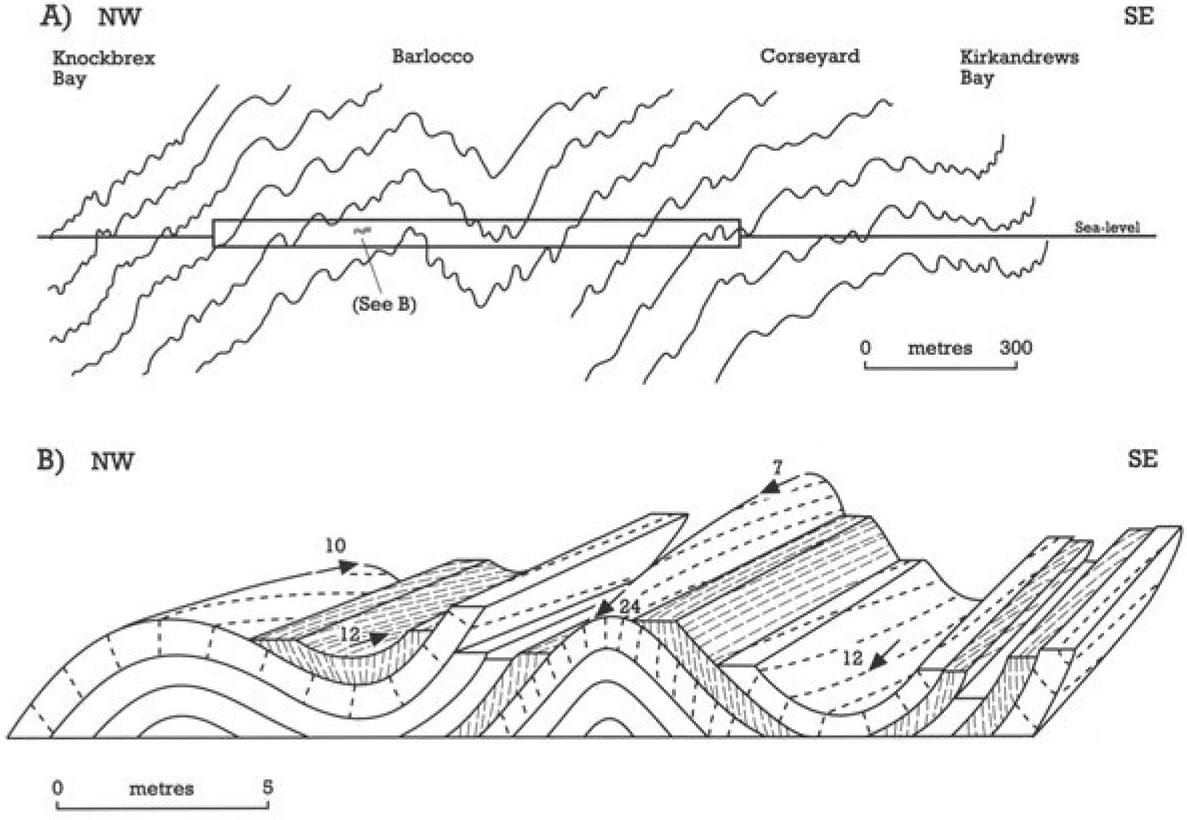
References



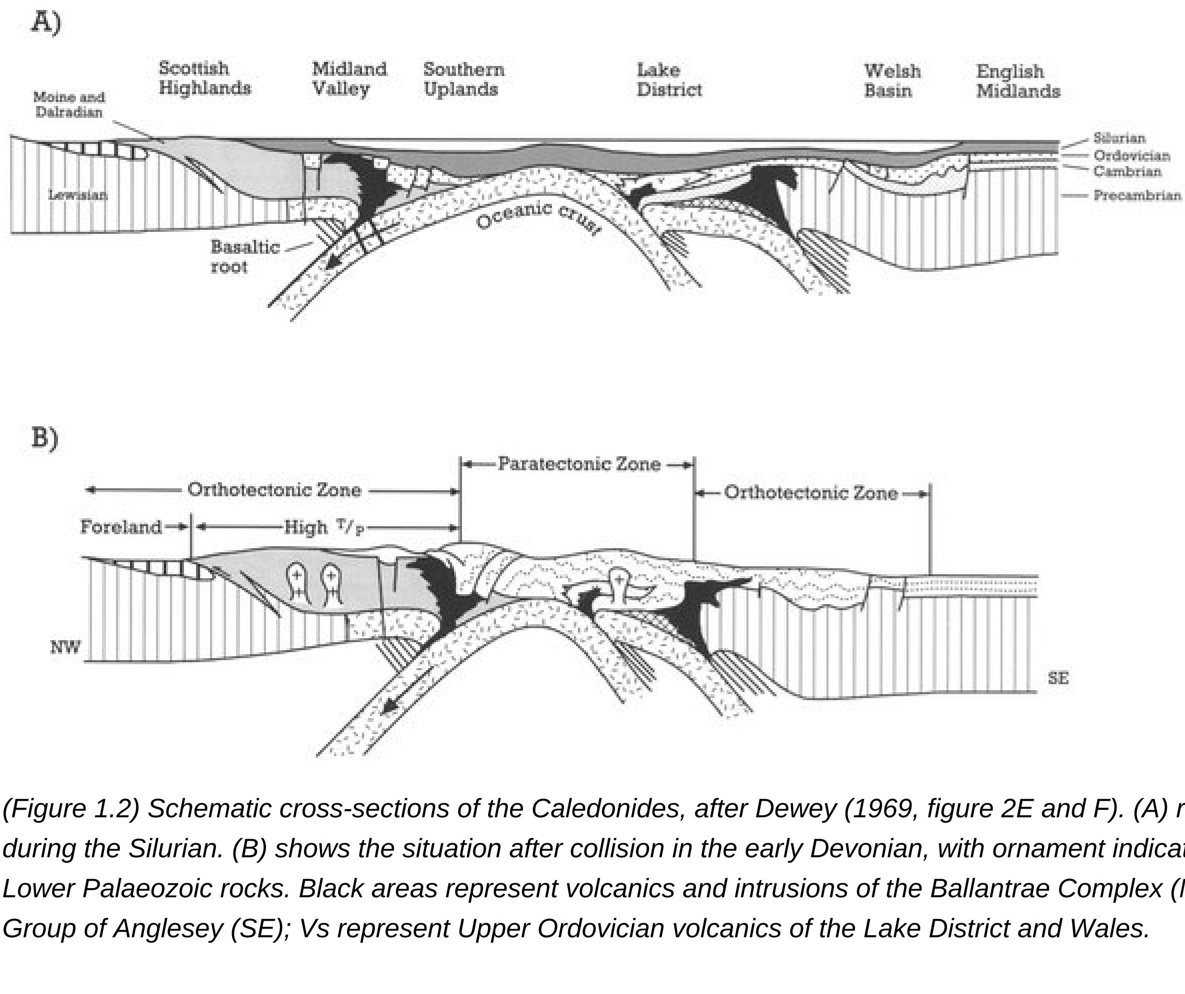
(Figure 2.1) Geological map of the Southern Uplands, showing the distribution of the three main belts, some of the steep faults that bound these belts, and subsidiary tracts. The positions of the sites discussed are also shown. A and B, in the south-west, show the zones of D_2 folding and steep D_1 plunge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



(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).



(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).



(Figure 1.2) Schematic cross-sections of the Caledonides, after Dewey (1969, figure 2E and F). (A) represents Iapetus during the Silurian. (B) shows the situation after collision in the early Devonian, with ornament indicating fold style in Lower Palaeozoic rocks. Black areas represent volcanics and intrusions of the Ballantrae Complex (NW) and Gwna Group of Anglesey (SE); Vs represent Upper Ordovician volcanics of the Lake District and Wales.