Southern Uplands accretionary complex

Introduction

Stages in the closure of the Iapetus Ocean.
P912315.
Summary of the regional controls on the timing of deformation across the Southern Uplands accretionary complex. P912335.

Migration of the Southern Uplands accretionary complex onto the Avalonian continental margin as a foreland fold and thrust belt. P912336.
Deep crustal sections across the Iapetus Suture Zone. P912318.

Representative structural-stratigraphical profile for the Queensberry Formation and the Ettrick Group. P912331.
Geochemical variation shown by sandstones from the Ettrick, Gala and Hawick groups. P912332.

Representative structural-stratigraphical profile for the Ross and Raeberry Castle formations in the Kirkcudbright area. P912334.
Variation in structural style seen in the Southern Uplands. P912337.

Examples of $D_1$ folding in the Kirkcolm Formation, Rhins of Galloway: a) A large-scale overturned anticline. P008502.

Upright, tight, D, anticline-syncline fold pair affecting thinly bedded strata of the Carghidown Formation (Hawick Group).
P220420.

Examples of D₁ cleavage development. An anticline with an axial cleavage fan.
P220411.

Variations in the relationship between folding and cleavage developed during the D₁ phase of accretionary deformation.
P912338.
Examples of D$_2$ refolding of D$_1$ structures affecting Kirkmaiden Formation at Craigmore Point. P220404.

Examples of D$_2$ refolding of D$_1$ structures affecting Kirkmaiden Formation at Isle Mouth. P220407.

Steeply plunging D$_3$ fold affecting Garheugh
A stratigraphical paradox was identified in the Southern Uplands at an early stage of its geological exploration. At outcrop, most of the steeply inclined beds face northward so that the sequence becomes younger in that direction, yet the oldest strata are found in the north of the terrane and the youngest in the south. To explain this apparent contradiction various models of folding and faulting were proposed, but it is now generally accepted that the Southern Uplands terrane formed as an accretionary thrust complex above the northward-dipping subduction zone that carried Iapetus Ocean crust beneath the Laurentian continental margin. It was built by a series of southward-propagating, imbricate thrusts that sequentially stripped the oceanic sedimentary cover from the descending plate and stacked-up the ensuing, fault-bounded strips, each strip being inserted at the base of a stack of previously accreted strips (P912315c, d). The original thrust faults would have advanced at a relatively low angle. As the complex developed, the faults and their enveloped strata were structurally rotated to become near vertical, but at depth they remained listric, merging into a subhorizontal décollement surface. Their near-vertical attitude is now exposed across the Southern Uplands and defines the tracts as described in Chapter 3.

Only one phase of ductile deformation (D₁) is evident throughout the Southern Uplands. It is related to thrust propagation and the folds produced are hence diachronous, becoming younger southwards (P912335). Later phases of deformation are apparent locally, associated either with accommodation in the thrust hinterland commensurate with D₁ deformation at the thrust front (and so likely to be equally diachronous) or with intermittent sinistral shear imposed across the entire belt but focused into major strike-fault zones. These post-D₁ deformation phases have been referred respectively to D₂ (co-axial with the gently plunging D₁ folds) and D₃ (sinistral, steeply plunging folds) but their relationship may not be the same everywhere.

One caveat should be attached to the interpretation of the entire Southern Uplands terrane as an accretionary complex. There is much evidence for a change in structural style in the late Llandovery, as manifest in the Ettrick and Hawick groups. The sequential southward younging of the structural tracts, established through the Barrhill and Scaur groups and the lower part of the Gala Group, is replaced in the Ettrick Group by the repetition of narrow tracts all with similar ages. The Gala 8 tract, the likely equivalent on the Rhins of Galloway of the Ettrick Group farther east, and the Hawick Group tracts to the south of it, show a reversal of the structural pattern with north-directed thrusts imbricating a succession that becomes younger southward. Elsewhere, and more generally, the Hawick Group tracts are much folded and affected by a stronger cleavage than is apparent to the north. These changes are most probably linked to the effective closure of the Iapetus Ocean with the younger Llandovery to Wenlock turbidite successions deposited in a relict basin above the suture (P912315d).

Some convergence of Laurentia and Avalonia continued after the elimination of the Iapetus Ocean, with the Laurentian margin overriding that of Avalonia. In this situation, deformation of the Ettrick-Hawick-Riccarton successions occurred in a foreland fold and thrust belt setting, with the deformation front migrating southward towards the Avalonian hinterland. Sedimentary links, particularly clear for the hemipelagite facies of the Ross and Raeberry Castle formations (Hawick and Riccarton groups respectively), suggest that in time this basin extended to the Isle of Man and into the south of the English Lake District (P912336). The final stage of this process is seen in the southern Lake District, where loading by the advancing Southern Uplands thrust belt caused an acceleration of subsidence and the deposition of the thick, Ludlow turbidite sequence of the Coniston Group. Convergence stalled at this point and the Coniston Group basin had stabilised and filled by Pridoli times. Acadian deformation did not follow for about another 10 million years.
A possible tectonic outcome of the Laurentia–Avalonia collision at the northern margin of the accretionary complex was its northward emplacement onto Laurentian crystalline basement (P912318). Such large-scale northward thrusting of the accretionary complex perhaps accompanied the demonstrable north-directed thrusting of the Girvan succession during the mid to late Silurian. The considerable horizontal shortening of the accretionary complex that would have been likely in such circumstances could have been accommodated by the widespread rotation of bedding towards the vertical, an attitude hard to attain across the whole terrane only by accretionary activity.

**Major faults**

The northern boundary of the Southern Uplands terrane is formed by the Southern Upland Fault (= the Stinchar Valley Fault in the west), a long-lived and much reactivated structure marked by a gouge and breccia zone that may reach several tens of metres in width. Significant sinistral movement has occurred along the Southern Upland Fault and this process may have truncated the older part of the Southern Uplands accretionary complex as it was juxtaposed against the Midland Valley terrane. Up to about 1500 km of lateral movement has been proposed, based on the correlation of boulders in the Corsewall Conglomerate with a provenance in Newfoundland. This correlation now seems tenuous and a more likely limit of several hundred kilometres of post-Caradoc movement is suggested by the similarities between the derived fauna in slump conglomerates within the Kirkcolm Formation and the in situ fauna in Upper Ordovician limestone in the Midland Valley terrane, at Girvan and at Pomeroy in Northern Ireland. In this situation, ophiolitic detritus in the northernmost of the Southern Uplands tracts may have been derived from obducted masses now represented by the Ballantrae Complex, though the provenance is not definitive. In northern and central parts of the Southern Uplands, the thin, discontinuous and lenticular inliers of Moffat Shale Group mudstone define lineaments that divide the turbidite succession into the strike-parallel tracts. Individual tracts so established range from a few tens of metres to several kilometres in outcrop width. The mudstone sequence is commonly disrupted but in places a stratigraphical transition from mudstone to turbidite sandstone is preserved at its northern margin. The southern mudstone–sandstone junction in each inlier, typically juxtaposing older mudstone against younger sandstone, is interpreted as a major, steeply dipping, strike-parallel fault that originated as an accretionary thrust, as discussed above. In some cases, closely spaced repetitions of the mudstone at the base of the sandstone tracts show these bounding structures to be anastomosing fault zones. There is rarely much associated fault rock preserved but breccia and gouge may locally reach a few metres in width.

The recognition of faults is largely dependent on the preservation of the inliers of the Moffat Shale Group. Apparent fault density is highest in the central Southern Uplands, in a zone of about 10 km across-strike width spanning the Gala and Ettrick groups in the Moffat- Ettrick area (P912331), where fifteen or more faults occur spaced from 100 m to 1.5 km, commonly anastomosing to define laterally discontinuous, lenticular tracts. Elsewhere, the recognised faults appear as subparallel structures spaced up to about 5 km, although in the north-west the tract containing the Kirkcolm and Galdenoch formations is up to 16 km wide. It is very likely that these broader tracts are compound, with internal strike-parallel faults that are not currently recognisable.

The southernmost inliers of the Moffat Shale Group lie within the outcrops of the Ettrick or Hawick groups or at the boundary between them. Only a few strike-parallel faults are recognised south of this limit, substantiated either by extrapolation from limited local exposure of fault-related fabrics or by abrupt changes in sandstone composition. So, for example, east of Moffat the faulted boundary between the Ettrick and Hawick groups is identified by the marked increase in carbonate in the Hawick Group sandstone (P912332). Coincident with this ‘carbonate lineament’ is an outcrop of
north-east-trending fault gouge and breccia at Buck Cleuch (NT 334 145). Tract boundaries within the Hawick Group are particularly problematical, as discussed in Chapter 3, due to the highly folded nature of the succession and the biostratigraphical overlap between adjacent tracts. Hence, whilst the boundary between the Carghidown and Ross formations might appear to be faulted due to the conundrum of apparently younger strata appearing southwards in a northward-younging succession, there is some conflicting biostratigraphical evidence to suggest that the two units are partially coeval; locally (at Burrow Head (NX 457 340), Ross Bay (NX 647 448) and south of Hawick) the boundary appears to be a stratigraphical transition. The fault thought to separate the Hawick Group from the younger Riccarton Group to the south is deduced largely from an abrupt decrease in deformation into the latter but, in the Kirkcudbrightshire coastal section, abundant biostratigraphical data within the Riccarton Group does establish a sequence of narrow tracts repeated by closely spaced faults (P912334).

Although the major strike-parallel faults are thought to have developed as thrusts with a ‘top to the south’ sense of displacement, many have experienced different senses of reactivation with widespread evidence for significant sinistral lateral displacement during the later stages of ductile deformation of the terrane (the D$_3$ episode, see below). Many of the strike-parallel faults were then reactivated during later tectonic episodes, with variable amount and sense of displacement along their lengths due to their segmentation by cross-strike faults. These disrupt the tract fault system and are typically associated with narrow zones of gouge that may weather recessively, forming marked features. The cross faults are concentrated on two trends: north-west to south-east and north-north-east to south-south-west. It is evident from their close relationship with minor intrusions that many of them pre-existed, or were active during, the approximately 400 Ma intrusive episode.

It is generally difficult to quantify vertical displacements on most of the cross-strike faults, although some larger examples were reactivated as major bounding structures to the post-Silurian basins that cut across the Southern Uplands terrane. Offsets in metamorphic grade, such as that affecting the thermal aureole of the Cairnsmore of Fleet granite pluton, or abrupt changes in the low-grade metamorphic pattern (see below) also point to vertical movement on cross faults transferring onto reactivated segments of the strike-parallel fault system. Lateral offsets are more commonly identifiable with north-west-trending structures, with most proving to have a dextral sense; where north-north-east-trending faults show evidence for lateral movement it is usually sinistral. In general, any lateral movements on the cross faults are relatively small, but in a few cases they appear to reach several kilometres.

**Early, thrust-related deformation (D$_1$)**

D$_1$ folds were developed variably throughout the Southern Uplands. Many occur as gently plunging, south-verging anticline-syncline pairs compatible with the ‘top to the south’ movement on the thrusts, with which the folds may be intimately connected via hanging-wall detachments (P912337). Fold structures occur on all scales, with congruous minor fold pairs in the limbs of the larger structures (P008502 and P008464). Across-strike, highly folded zones occur interspersed with long homoclinal sections, usually of steeply inclined, north-younging strata. This variation in structural style is, at least in part, related to the nature of the strata, with thickly bedded, massive greywacke less likely to be intensely folded than more thinly bedded strata. Slickensides or slickenfibres in thin veins along bedding surfaces, perpendicular to the fold axial orientation, demonstrate early fold growth by flexural slip, although the veins were themselves folded in the later stages of deformation. Individual tracts are commonly marked by subtle variations in the style, orientation and intensity of D$_1$ folding. The D$_1$ deformation was particularly intense in the generally finer-grained rocks of the
Hawick Group (P220420), in the southern part of which many fold hinges become strongly curved to steeply plunging and are locally downward facing. This phenomenon suggests that a significant component of sinistral shear was involved in D₁ as the Hawick Group tracts were deformed, and this may well have coincided with the onset of D₃ in the thrust hinterland (see below).

A widespread, regional manifestation of D₁ is the penetrative cleavage (S₁). It is commonly developed as an axial planar fabric to the major folds, but in cross-section may be slightly fanned (P220411). In northern and central parts of the Southern Uplands, S₁ is best developed in the fine-grained, silt- and mud-rich lithologies, though even there it can be quite weak. It is much less apparent macroscopically in sandstone, and when present may be strongly refracted across the sandstone-mudstone contact (P220143) and also with grain size in the graded sandstones. It is more widely seen in thin sections of sandstone as an irregular anastomosing fabric. In parts of the Hawick Group, however, the foliation is more pervasive and is well developed in sandstone, where it is strongly refracted through graded beds. Significantly for the timing of deformation, the cleavage is also commonly developed in felsic and lamprophyre dykes intruded into the Hawick Group. Cleavage is only very weakly developed in strata of the Riccarton Group.

The S₁ cleavage is typically axial planar to the folds in the north-western tracts of the Southern Uplands (P912338a) but in the south-eastern tracts, and in particular those containing Hawick Group strata, it may locally show a clockwise transection in plan view of up to 20° relative to the fold axial traces (P220414 and P912338b). Where folds are overturned, and such overturning is generally towards the north-west, the cleavage may cut across the inverted fold limb (P912338c) so that there the bedding faces downward on cleavage whilst in the opposing limb of the same fold the bedding is normal relative to the same cleavage. As a consequence of this confusing effect, the assessment of way-up or vergence from bedding-cleavage relationships alone is generally unreliable in the south-eastern tracts of the Southern Uplands. The transecting cleavage is undoubtedly a result of the D₁ deformation and can be explained as resulting from rotation of the D₁ stress field between initiation of folding and imposition of cleavage. An added complication in some sections is the alternation of zones of axial planar and transecting cleavage, apparently partitioned by major north-east-trending faults and providing further evidence for a variable stress regime during accretion.

Late, superimposed deformation (D₂ and D₃)

The extent and character of post-D₁ deformation varies widely across the Southern Uplands. In northern and central parts, post-D₁ structures coaxial with D₁ tend to occur only very locally and are difficult to correlate. To the south, in central and southern parts of the Hawick Group outcrop, coaxial post-D₁ deformation is widespread. Gently plunging, minor to mesoscale folds, coaxial with but refolding D₁ structures, occur in two styles, upright to inclined and recumbent (P220404 and P220407). These have conjugate geometry and locally occur together as open box folds suggesting that they formed together; consequently both are classified as D₂. Small recumbent folds, verging down the dip of bedding, are most common and are associated with a widely developed, gently dipping, S₂ crenulation cleavage. The orientation and geometry of the D₂ structures suggests that they formed either through a continuation of ‘D₁’ stress after locking of the original D₁ folds, or by subsequent renewal of shortening on the tract-bounding faults. Alternatively, the recumbent folds may have been formed by subvertical shortening of bedding in more or less its present attitude, causing down-dip vergence, rather than by a consistent sense of shear on tract-bounding or other faults.

The steeply plunging sinistral folds (D₃) developed locally throughout the Southern Uplands are
usually in narrow zones of shearing adjacent to tract-bounding faults and may therefore be associated with reactivation of these structures (P008491). The relationships of the putative D₃ folds to D₂ are ambiguous with indications of sinistral shear or refolding co-axial with development of D₁ folds at various times. It also seems likely that there were several episodes of sinistral shear superimposed on the diachronous D₁ and D₂ folding at different times. This means that in some localities in the south of the terrane, folding of 'D₃' style and origin preceded that with 'D₄' character (P912335).

Moniaive Shear Zone

One particularly important example of strike-parallel sinistral shear is the Moniaive Shear Zone, named from the area around Moniaive (NX 780 910), north-east of the Cairnsmore of Fleet pluton. It is a zone of high strain that shares structural characteristics with, but is much wider than, the narrow shear zones associated with a few of the tract-bounding faults. It has been recognised over a strike length of about 100 km through the central part of the Southern Uplands, where it is up to 5 km wide, and continues westward across Ireland as the Slieve Glah Shear Zone. In the Southern Uplands, the Moniaive Shear Zone is truncated abruptly to the north-west by the Orlock Bridge Fault but dies out southward within the northern tract of the Gala Group. It is characterised by the intermittent development of a pervasive foliation nearly parallel to bedding, locally with a strong linear component, which commonly transposes all original structure. Strain within the shear zone is very variable but a variety of structural indicators consistently show a sinistral sense of shear. Because the shear zone fabric is inseparable from the relatively weaker S₁ cleavage outwith the shear zone, the two cannot be differentiated and unequivocal relative age relationships are difficult to establish. Cordierite (and some garnet) porphyroblasts, widely distributed throughout the thermal metamorphic aureole of the Early Devonian Cairnsmore of Fleet Pluton (c. 397 Ma, see below), are deformed by the shear zone foliation but the latter is generally overprinted by the biotite hornfelsing and later stages of the thermal metamorphism. These relationships closely constrain the timing of final development for the Moniaive Shear Zone to around 397 Ma, which means that it could have been active during the Acadian deformational event.

It is likely that the Moniaive Shear Zone is a composite feature, representing progressive but intermittent deformation over a long time period from its initiation during D₁ (accretionary) deformation in the early Silurian until the possibly Acadian effects in the Early to Mid Devonian. Despite the possible long duration of deformation there are no grounds for assuming very large lateral displacement from evidence in Scotland. However, substantial movement has been proposed for the Slieve Glah Shear Zone, along-strike to the west in Ireland. In addition, the Moniaive Shear Zone lies above a deep crustal discontinuity (P912318) that may have focused movement during and after the collision of Laurentia and Avalonia.

Regional metamorphism

The thermal metamorphic aureoles surrounding the larger plutons are superimposed on low grades of regional metamorphism that were acquired by burial during development of the accretionary complex. The prehnite-pumpellyite facies can be established in some of the volcaniclastic sandstone beds, but elsewhere grades within the deep diagenetic zone and anchizone are shown by the crystal thicknesses of white mica from the mudstone — the illite crystallinity. Only locally does the grade rise to epizone, and mostly that is either in the vicinity of intrusions or where cleavage is unusually
well developed. There is no consistent pattern of increasing grade into older strata, which would be expected in normal sedimentary burial, and instead, some of the highest grades (though still mostly anchizonal) affect the Llandovery Hawick Group. In a number of cases the metamorphic grade increases sequentially into younger tracts. If the succession had initially acquired a pattern of normal burial metamorphism whereby grade increases into older strata, and had subsequently been imbricated and rotated, older strata would still be expected to show higher grades than younger strata; this is demonstrably not the case. As an additional complication, in places the grade changes abruptly along strike at major cross faults, with lower grade on the downthrow side. These relationships are most readily explained if a depth-related pattern of metamorphism was imposed on strata that were already steeply inclined. This would have been achieved after their incorporation in the accretionary complex. Abrupt changes in grade across some of the tract-boundary faults probably arose through their post-metamorphic reactivation. Assuming low to moderate heat flow (<25°C), the depth of burial within the accretionary complex, would have ranged from about 6 km, for those strata now in the deep diagenetic zone, up to about 13 km for some of the epizonal rocks.

The following are related articles:

- Obduction of the Ballantrae Complex, Southern Uplands
- Deformation of the Girvan succession, Southern Uplands
- Southern Uplands accretionary complex
- Late Caledonian dyke swarms, Southern Uplands
- Late Caledonian plutonic rocks, Southern Uplands

Bibliography


Retrieved from 'http://earthwise.bgs.ac.uk/index.php?title=Southern_Uplands_accretionary_complex&oldid=34824'

Category:
- South of Scotland

Navigation menu

Personal tools
- Not logged in
- Talk
- Contributions
- Log in
- Request account