Excursion 17 The Orlock Bridge Fault and The Moniaive Shear Zone: sinistral displacement and high strain at the Ordovician–Silurian boundary structure

By R.P. Barnes, M.P. Boland, E.R. Phillips and P. Stone

OS 1:50 000 sheets 82 Stranraer & Glen Luce, 77 Dalmellington to New Galloway, 78 Nithsdale & Annandale, 72 Upper Clyde Valley

BGS 1:50 000 sheets 1 & 3 Rhins of Galloway, 4W Kirkcowan, 8E Loch Doon, 9W New Galloway, 15E Leadhills, 24W Biggar

Route map: (Figure 55)

Main points of interest This excursion examines the range of structures developed along the trace of the Orlock Bridge Fault and within the adjacent Moniaive Shear Zone across southern Scotland. In Northern Ireland and south-west Scotland the Orlock Bridge Fault forms the boundary between Ordovician and Silurian turbidite sequences although this relationship may not hold further east. The fault zone, originally described in Ireland, shows evidence for major post-D1 sinistral displacement and has been proposed as a terrane boundary of regional significance. This interpretation has not been universally accepted although recent work in the Southern Uplands has defined a zone of ductile deformation (the Moniaive Shear Zone) associated with part of the fault.

Logistics This is a two-day excursion, with localities spread along the length of the Southern Uplands (Figure 55). New Galloway is a convenient break with Localities 1 to 4 (or 5) on the first day and localities 5 (or 6) to 9 on the second. Alternatively some of the localities described here could be linked with other excursions. Localities 1–3 are easily accessed using the A75 from Stranraer to Newton Stewart, the A712 via New Galloway and the A702 to Moniaive. Thence the A702 leads past locality 7 through the Dalveen Pass to Elvanfoot and, after 10 km southwards on the A74, the B719 links to the A701 from which Localities 8 and 9 are easily reached. Locality 1 is coastal, but most of the exposure there is accessible at all but very high tides. At some of the localities parking and access are on private land and appropriate permission should be sought.

Introduction

The strike-fault at the boundary between the Ordovician and Silurian turbidite sequences in the Southern Uplands was termed the Kingledores Fault by Leggett et al. (1979), from a major feature in the central Southern Uplands. Anderson and Oliver (1986) subsequently described the equivalent structure in the Longford—Down inlier of Northern Ireland, where a 200 m wide fault zone is exposed on the coast at Orlock Bridge. To the SW, a 1 km wide shear zone is associated with the fault at Slieve Glah. They correlated the 'Orlock Bridge Fault' with the Kingledores Fault in the Southern Uplands, describing exposures of a narrow zone of deformation at Cairngarroch Bay on the Scottish coast (Locality 1) and near Garvald east of Edinburgh. A high strain zone up to 5 km in width (the Moniaive Shear Zone, Lintern et al., 1992; Barnes et al., 1995; Phillips e$_t$ al., 1995), comparable with the Slieve Glah shear zone, has since been recognised in the Southern Uplands. The Orlock Bridge Fault in Scotland can be divided into five distinct sectors from west to east as follows:

Glenluce sector: Cairngarroch Bay to the River Cree near Newton Stewart. The fault zone is relatively narrow (up to 50 m), and is marked by predominantly brittle structures except in the immediate vicinity of the fault where more ductile fabrics may occur in a very narrow zone.

Talnotry sector: Newton Stewart to New Galloway. Several anastomosing faults are marked by narrow outcrops of Moffat Shale Group in this complex sector. These faults occur near the northern edge of a wide zone of ductile deformation partly contemporaneous with the early stages of contact metamorphism. This subsequently overprinted all the fabrics as the Cairnsmore of Fleet pluton was emplaced.

Moniaive sector: New Galloway to Thornhill. The fault forms the sharp, northern margin to a zone of locally intense ductile deformation up to 5 km wide. Both planar and linear fabrics are well developed.

Durisdeer sector: Thornhill to Peebles. The shear zone narrows eastwards from about 2 km width east of Thornhill. Brittle and ductile components are present and as the shear zone narrows it bifurcates with discrete strands affecting Ordovician and Silurian strata on either side of the Orlock Bridge Fault.

Garvald sector: Peebles to Dunbar (not shown in (Figure 55)). A narrow fault zone at the boundary between the Ordovician and Silurian strata is known at one locality only, where mainly brittle shearing and sinistral refolding of S1 cleavage structures were described by Anderson and Oliver (1986).

In the Glenluce sector the Orlock Bridge Fault can be examined at Cairngarroch Bay and Wood of Dervaird (Localities 1 and 2). At the eastern margin of the Glenluce sector a cross-cutting NNW-trending fault along the River Cree at Newton Stewart effectively marks the start of the Moniaive Shear Zone. A large down-west displacement across the NNW fault causes an abrupt eastward increase in the grade of regional metamorphism (BGS 1992c, inset map), accompanied by the appearance of an unusually intense bedding-parallel foliation in the massive sandstone of the Silurian Gala Group. The foliation is characteristic of the Moniaive Shear Zone, a major, regional high-strain zone up to 5 km wide, which extends for over 50 km to the NE, with the Talnotry and Moniaive sectors of the Orlock Bridge Fault forming its northern boundary. The occurrence of Moffat Shale in the Talnotry sector indicates that the Orlock Bridge Fault is essentially comparable to the other tract bounding faults in the Southern Uplands (see Introductory chapter) but is associated with an unusual degree of post-D1 reactivation.

In the aureole of the Cairnsmore of Fleet granite pluton (Localities 3 and 4), the Moniaive Shear Zone fabric is characterised by an intense bedding-parallel foliation with fine, parallel quartz segregations. Outwith the aureole the shear zone is best developed around Moniaive (e.g. Localities 5 and 6) where the planar foliation is intermittently developed but the shear zone includes a strong linear component. Farther east the shear zone narrows (e.g. Locality 7) and breaks into at least two strands (Localities 8 and 9) where the close association between the Orlock Bridge Fault and the Ordovician/ Silurian boundary is lost. In the most easterly Garvald sector the fault becomes a narrow zone of brittle deformation; it is poorly exposed and correlation of its various possible strands is uncertain.

In Northern Ireland, the belt of fault-deformation associated with the Orlock Bridge Fault ranges in width from 200 m to 1 km and typically comprises three structural zones (Anderson and Oliver, 1986). These contain increasingly intense deformation fabrics in sequence from 1 to 3.

Zone 1 The regional 51 cleavage is overprinted by a phyllonitic fabric and sandstone beds are cut by numerous sinistral extensional shear fractures at an acute angle to bedding.

Zone 2 Bedding and cleavage are transposed by a strongly developed foliation subparallel to the fault. Numerous quartz segregations, of variable thickness, occur parallel to the fabric and increase in intensity towards the boundary with Zone 3. An S-C fabric is develped usually.

Zone 3 Abundant, discontinuous, tightly folded quartz segregations are embedded in intensely foliated phyllonite.

These zones are best developed at Slieve Glah where the fault zone is up to 1 km wide; zone 1 forms broad areas of shearing at the margins of the fault zone and zones 2 and 3 occur in the central part. At Orlock Bridge the fault-associated deformation is about 200 m wide, although it is very asymmetrical and affects the formations on either side of the fault in different ways. Zone 1 is recognisable south of the fault but cannot be distinguished to the north where the regional DI deformation is relatively intense. Zone 2 deformation occurs north of the fault in a number of bands, 1–10 rn wide, which coalesce southward towards the fault-trace. Zone 3, about 16 m wide, is coincident with the fault trace and has a sharp boundary with zone 1 to the south; a lamprophyre dyke at this boundary postdates most of the fault-related deformation.

Fault-deformation is thus apparent on both sides of the Orlock Bridge Fault in Northern Ireland and a comparable situation occurs in the Glenluce sector in the Southern Uplands, with the most intense deformation (Zone 3) along the

trace of the fault. However, in the Talnotry and Moniaive sectors the Moniaive Shear Zone, essentially a major development of Zone 2, is situated south of the fault and may be very wide, encompassing at least two tectonostratigraphical tracts and one other tract-bounding fault. Deformation continues north of the fault for a short distance at Talnotry (Locality 4) before dying out gradually northwards.

Regional constraints on the timing of movement on the Orlock Bridge Fault

Evidence for the timing of movement on the Orlock Bridge Fault is at present contradictory and may indicate a long history, with phases of movement from Wenlock to early Devonian times (Barnes et al., 1995; Lintern et al., 1992). The structures in the Glenluce sector have features in common with the D3 deformation elsewhere and thus the main phase of movement may have occurred in the Wenlock (c.425 Ma; (Figure 1), (Figure 2), (Figure 3), (Figure 4) and Lintern et al., 1992). It is unclear to what extent the origin of the Moniaive Shear Zone is related to that of the Orlock Bridge Fault but there are certainly geometrical affinities with the structures developed in the Slieve Glah Shear Zone, regarded by Anderson and Oliver (1986) as being formed before 400 Ma. The shear zone foliation apparently represents a progressive development of the S1 cleavage. Local refolding of the shear zone foliation by structures similar in style to D2 is also consistent with it being related to S1. However, the shear zone foliation locally deforms dioritic intrusions of probable late Silurian or early Devonian age, and cordierite and garnet porphyroblasts in the thermal aureole of the Cairnsmore of Fleet granite pluton (see Excursion 16, Locality 5) also predate at least part of the development of the foliation. An overlap between the development of foliation and thermal metamorphism is indicated, although subsequent biotite hornfelsing overprints the foliation. The granite itself is largely undeformed and cuts the foliation in the host rocks (see Excursion 16, Localities 5, 6 and 7). The cooling age of the granite is 392 ± 2 Ma by the Rb-Sr method (Halliday et al., 1980), a date recently confirmed by U-Pb on zircon (J.A. Evans written communication, 1994). This places a minimum age limit on the ductile deformation in the high-strain zone although it also suggests that significant deformation occurred in the late Silurian (Figure 4). At its northern margin the Orlock Bridge Fault was probably reactivated as a brittle structure during the late Palaeozoic.

Kinematic indicators

Interpretation of the movement direction of the fault zone depends on identification of minor structural features. The four main shear criteria encountered in this excursion are described below and summarised diagrammatically in (Figure 56).

1. Asymmetry of steeply plunging folds Steeply plunging fold pairs may be described as having sinistral or dextral vergence, the description being based on the sense of rotation of the short limb (sinistral = anticlockwise) but also applying to the overall sense of the lateral component of movement on the zone in which they were formed.
2. S–C mylonites An S–C fabric represents the development of two foliation surfaces within a shear zone (Berthe et al., 1979). The C-surfaces develop parallel to the shear zone boundary while the S-surfaces are initiated at 45° to the boundary and rotate towards the C-surfaces as deformation progresses. The C-surfaces have the same sense of shear as the overall zone and this can be determined from the rotation of the S-surfaces (Lister and Snoke, 1984).
3. Asymmetric augen structures These develop where resistant particles, such as feldspar and quartz grains or cordierite and garnet porphyroblasts, are contained within a more ductile matrix. The foliation may be asymmetrically distributed around the augen and recrystallised grains of the porphyroclast extend along the foliation plane forming 'tails'. The asymmetry of these tails defines the sense of shear (Passchier and Simpson, 1986).
4. Extensional crenulation cleavage Extensional crenulation cleavages form oblique to the shear zone boundary and develop after the main shear zone fabric (Platt, 1984; Platt and Vissers, 1980). The sense of movement is such as to cause extension along the older foliation, the new fabric forming along the limbs of open folds of the foliation.

1 Cairngarroch Bay

OS 1:50 000 Sheet 82 Stranraer & Glen Luce

BGS 1:50 000 Sheet 1 & 3 The Rhins of Galloway

The most westerly manifestation of the Orlock Bridge Fault within the Southern Uplands can be seen on the coast about 10 km SE from Portpatrick. The locality may be reached from the A75 by travelling westward past Glenluce and turning left on the A715 towards Sandhead. This road links with the A716 just north of Sandhead; continue south towards the village but at its outskirts turn right (west), initially on the B7042 but thereafter utilising a network of minor roads towards Cairngarroch. Continue straight on at the Cairngarroch crossroads to West Cairngarroch Farm. Access and parking arrangements should be agreed at the farm. Walk down the rough track leading south from the road about 300 m east of the farm near Cairngarroch Croft. After a short distance the track swings WSW to follow a narrow valley for 1 km down to the shore.

Much of Cairngarroch Bay is underlain by granodioritic intrusive rocks (Stone, 1995), intruded subsequent to movement on the Orlock Bridge Fault. The fault itself forms a narrow inlet at Calves Hole, about 100 m SW of the cottage on the south margin of Cairngarroch Bay. Scramble over the rocky cliffs until a narrow gully leads down to the WSW. The belt of fault-associated deformation is about 50 m across with structures typical of Zones 1 and 2; the following description is based on Anderson and Oliver (1986, p.217 and (Figure 8)).

The Orlock Bridge Fault is represented by a few square metres of intensely foliated and quartz-veined strata in Calves Hole which show an S-C fabric referable to Zone 2. Closely spaced upright S-surfaces trending 065°, together with quartz segregations, are clearly cut by steeply inclined C-surfaces with approximately 3 mm spacing and at some 10° to 30° anticlockwise of the S-surfaces. There are other, less regular, shear planes and some local refolding of the fault fabric. Late carbonate veins cut across both S- and C-surfaces. South of the Calves Hole gully, sandstone and mudstone (Gala Group) are sheared into lenses characteristic of Zone 1. Bedding becomes obvious about 10 m south of Calves Hole and the intensity of shearing and density of fractures both decrease rapidly southward, with the fault-associated deformation ceasing to be distinguishable from the regional S1 cleavage.

The north side of Calves Hole is a cliff 4 m high formed by a fault trending about 070°. This forms the northern margin of the Zone 2 outcrop and separates it from a complex of felsite sills and numerous lenticular screens of hornfelsed Shinnel Formation sandstone which are moderately NW-dipping. The lowest sill is clearly truncated by the fault. The felsite sills are foliated approximately parallel to their margins but this fabric is not obviously tectonic and is clearly not related to fault movement. In the hornfelsed sandstone at the base of the 4-m cliff, tight folds with a strong axial-planar cleavage are probably products of the main DI regional deformation. Local refolding of that cleavage may be due to fault movement or may be a consequence of felsite intrusion. The relationship between intrusion and faulting is complex but it seems likely that the intrusion post-dated the main fabric-generating movement on the Orlock Bridge Fault but was followed by one or more phases of brittle movement.

2 Wood of Dervaird

OS 1:50 000 Sheet 82 Stranraer & Glen Luce

BGS 1: 50 000 Sheet 4W Kirkcowan

Return eastwards on the A75 and, near the east end of the Glenluce bypass, turn right into a gated farm track 2 km after the junction with the A747 to Port William. Drive 600 m south along the track, keeping right at the intersection with a forestry track, and park near the Wood of Dervaird Farm buildings [NX 226 578]. Permission for access should be sought at the farm if not already arranged in advance.

The ENE-trending Orlock Bridge Fault passes a few metres south of the farmhouse, separating a thick unit of laminated silty mudstone at the base of the Ordovician Shinnel Formation (to the north) from thickly bedded greywacke of the early Llandovery Gala Group (to the south). Deformation is largely concentrated in thesiltstone and is best seen in exposures which extend over a distance of about 200 m west from the farm before the Orlock Bridge Fault is displaced southwards by a cross-fault. Fault-related deformation in the Gala Group is restricted to the immediate vicinity of the fault where intensely foliated sandstone containing suggestions of an S-C fabric is exposed at the southern edge of the farmyard near the gate.

Proceed through the sheep pens west of the farm track and follow the wall to the right for about 50 m. Exposures in small knolls to the left and just beyond the sharp angle in the wall are composed of grey silty mudstone with a distinct cleavage and thin quartz veins parallel to the steeply dipping bedding-lamination. The lamination, cleavage and veins are distorted by numerous sinistral minor folds with axial plunge ranging from moderate to vertical. Walk SE to a small WSW-trending and N-facing bank with small exposures at the base. These show intensely foliated silty mudstone with abundant parallel quartz veins up to 2 cm thick. The veins are folded by small, steeply plunging, sinistral fold pairs. The overall characteristics are of Zone 3, suggesting that these exposures and the bank feature mark the trace of the fault.

3 Murray's Monument, Talnotry

OS 1:50 000 Sheet 77 Dalmellington to New Galloway

BGS 1:50 000 Sheet 8E Loch Doon

Return to the A75 and proceed east to the junction with the A712, 1.5 km beyond the roundabout south of Newton Stewart; turn left on to the A712 and continue for about 9 km towards New Galloway. Murray's Monument [NX 488 719] is a monolith situated on a knoll named Big Doon to the left of the road and is served by a car park [NX 491 721] a little further on at the foot of the Grey Mare's Tail waterfall (Locality 4). From the car park, follow the path which leads SW to the top of Big Doon. The monument was erected in honour of the self-educated son of a local shepherd who became a professor in oriental languages at Edinburgh University.

A number of exposures in meta-greywacke near the top of Big Doon are characteristic of the Zone 2 style of deformation immediately south of the Orlock Bridge Fault in this northern part of the Cairnsmore of Fleet aureole. An intense foliation, dipping moderately NW, transposes all original structure and carries fine, parallel quartz veins. Conjugate kink bands are locally well developed.

4 Grey Mare's Tail Burn, Talnotry

OS 1:50 000 Sheet 77 Dalmellington to New Galloway

BGS 1:50 000 Sheet 8E Loch Doon

A series of waterfalls in the Grey Mare's Tail Burn [NT 18328 14908] and forest trails through the adjoining woodlands (described in a leaflet available from the nearby campsite) are situated close to the A712 and are served by the same car park as Murray's Monument (Locality 3). The burn provides a discontinuous section across the relatively narrow aureole in the deformed Moffat Shale and interfaulted greywackes north of the Cairnsmore of Fleet granite and into the much less deformed Shinnel Formation outwith the aureole to the north. The Orlock Bridge Fault has at least two branches here. The intrusive granite contact, visible to the NE on Craigdews Hill (Excursion 16, Locality 6b), is not exposed here but probably passes beneath the burn just north of the A712. The three characteristic features of the western part of the aureole, the moderate dip, intense foliation and the contact alteration itself, die out gradually to the north.

From the car park, cross the burn by the road-bridge and walk along the east side of the burn. The exposures in the lower part of the burn are a fine-grained rock seen in thin-section to be a brecciated mylonite. This lithology can be traced for some distance either side of this locality and may represent the locus of ductile movement adjacent to the Orlock Bridge Fault. Its junction with the overlying metasandstone is a gently dipping fault exposed low in the steep bank on the opposite side of the stream. Near the waterfall scramble up the steep bank in front of the cliff, or walk back a few metres andfollow the main path which climbs more gently. The cliff is in metasandstone with an intense foliation marked by 1–2 mm quartz veins which are moderately NW-dipping. Near the top of the slope the fabric is folded by an open recumbent fold, similar in style to the D2 folds well developed to the south in the Hawick Group (Excursion 13). Continuing up the path, there are small exposures of metamorphosed black mud-stone (which may mark a branch of the Orlock Bridge Fault) and then another large exposure in the foliated metasandstone. The path continues alongside the burn for a further 200 m to the intersection with a forestry track. North of the track, about 30 m east of the burn, a clearing is partly floored by intensely foliated metasandstone with uneven, fabric-parallel veining and alteration. In thin-section the latter is seen to

be caused by replacement of the biotite in the hornfels by delicate, radiating arrays of sillimanite needles, indicating that no deformation has occurred after their formation in the aureole.

Return to the burn and continue upstream towards the steep bank visible to the north, which marks the main strand of the Orlock Bridge Fault. Exposure in the burn resumes near the foot of the bank, about 100 m north of the track. About 4 m of pyritous black mudstone/siltstone, with a foliation dipping 45° NW and a gently SW-plunging crenulation lineation, is followed by grey silty mudstone with medium to thick sandstone beds to the foot of a series of waterfalls. The lower waterfall cascades over a cliff in about 8 m of metamorphosed black mudstone. Two large greywacke lenses in the mudstone at the base of the cliff show no sign of the pervasive foliation seen hitherto. A zone of intensely brecciated mudstone 1–1.5 m thick, on both sides of the stream by the waterfall is probably a fault gouge formed by relatively late reactivation of this part of the fault. East of the burn the interbedded transition between the Moffat Shale and the greywacke of the overlying Shinnel Formation, dipping moderately north, is exposed above the path where it turns abruptly along the base of the slope.

Exposure in the deeply incised burn above is best accessed from the west bank, although this involves a scramble through the trees. Alternatively the path can be followed to the top of the waterfalls where massive, thickly bedded greywacke alternates with medium- to thin-bedded greywacke and interbedded silty mudstone. This assemblage is typical of the Shinnel Formation locally. Initially the pervasive foliation is still apparent in the metasandstone, dipping moderately NW and parallel to bedding, but northwards it weakens and within 100 m dies out. Evidence of the contact metamorphism, small dark cordierite spots and the purple colouration characteristic of the biotite hornfels, dies out about 250 m north of the waterfall.

The dip of bedding in the 300 m section north of the waterfall is variable between 60° and 80°NW. The burn then turns along strike for a short distance and the next exposure northwards, where its NW course is regained, shows bedding dipping steeply south and overturned. North of this point bedding displays its regional attitude, being near vertical or dipping steeply SE. This moderate NW dip of bedding and foliation is characteristic of the western part of the Cairnsmore of Fleet aureole but the reason for the departure from the regional attitude is unknown. The effect is approximately coincident with the western part of the thermal aureole so it may be related to the emplacement of the granite. This is consistent with the rotation of the dip of the foliation, confirming other evidence that the shear zone pre-dates the final emplacement of the granite.

5 Bread and Beer Cottage to Troquhain Hill

OS 1:50 000 Sheet 77 Dalmellington to New Galloway

BGS 1: 50 000 Sheet 9W New Galloway

Route map: (Figure 57) with locality numbers referenced in the text

East of New Galloway the Moniaive Shear Zone causes locally intense deformation of the early Llandovery greywacke of the northern tract of the Gala Group (see below and Phillips, 1992; Barnes et al., 1995; Phillips et al., 1995). A variably developed penetrative planar fabric and subhorizontal stretching lineation are characteristic. On its north side the Shear Zone is bounded by the Orlock Bridge Fault, beyond which the pyroxene-bearing greywacke sequence of the Ordovician Glenlee Formation is at very low regional metamorphic grade and is only weakly deformed.

The section between Bread and Beer Cottage [NX 698 792] and Troquhain Hill [NX 695 816] lies on the south (Silurian) side of the Orlock Bridge Fault and entirely within the Moniaive Shear Zone. Follow the A712 east from New Galloway, through Balmaclellan, towards Corsock. Bread and Beer Cottage is located approximately 6 km from New Galloway, near the junction of a single-track road. Turn left at this junction and park after the cattle grid (Locality 5a). Space is available for a small number of vehicles at the side of the road, but please avoid blocking access to the cottage. The section follows a northward route, across country, to the summit of Troquhain Hill (5f). Total walking distance is about 5 km. There is no footpath across the open and relatively featureless moorland so this section should not be attempted in poor visibility.

From the road (5a) walk northwards across scattered small exposures of Gala Group quartzose greywacke. Bedding and way-up evidence can be locally identified showing that the sequence dips and youngs NW. Clasts of quartz and feldspar plus various rock fragments are recognisable in the sandstone, despite a variably developed planar foliation and locally developed linear fabric. The foliation, typically steeply NW-dipping, is represented in places (5b) by a fine S-C fabric which yields a consistent sinistral sense of shear. The stretching lineation, plunging gently NE, is defined by highly attenuated lithic quartz and mudstone. Within the more pelitic bands the foliation takes the form of a weak to moderate slaty cleavage.

Proceed north, following the line of the exposures on to the slightly higher ground on the southern slopes of Troquhain Hill where the intensity of foliation and linear fabric in the metasandstone decreases. An altered apinitic lamprophyre dyke is poorly exposed (5c) but is seen to contain a variably developed foliation dipping steeply NW. The strike of this foliation is broadly parallel to the shear zone fabric developed within the country rocks, indicating that intrusion of the dyke occurred before or during, ductile deformation.

Traverse eastwards across two small streams to a group of exposures at the base of a cairn and proceed towards the summit of Troquhain Hill. In the vicinity of the cairn only a weak fabric is apparent but the intensity of ductile deformation progressively increases up the hill, resulting in the development of a locally intense lineation (5d) as well as a steep SE-dipping planar foliation which, in places, forms a sinistral S-C fabric (5d and 5e). Preserved detrital clasts are attenuated and the resulting augen may exhibit a pronounced sinistral asymmetry. At the top of Troquhain Hill (5f) the shear zone fabric is quite well developed, dipping NW. Minor variations in the intensity of the fabric occur, even within a single exposure, and may be related to the small-scale partitioning of deformation and/or a lithological control, with shearing being concentrated along the more pelitic partings. The same effect is seen regionally; variation in the intensity of ductile shearing can be related to the partitioning of deformation into a number of discrete belts of high strain within the Moniaive Shear Zone.

Return to the parking place by the most direct route down the hill.

6 Corriedoo Forest

OS 1:50 000 Sheet 77 Dalmellington to New Galloway

BGS 1:50 000 Sheet 9W New Galloway

Return towards New Galloway on the A712 but at Balmaclellan turn right to join the A702 and continue NE from St John's Town of Dairy towards Moniaive. Approximately 7 km from Dairy, past Corriedoo Farm, there is a forest track on the right hand side of the A702 immediately after a sharp right hand bend. Parking is provided by a large lay-by (a section of the old A702) [NX 689 836] immediately before the right hand bend (Figure 57). Locality 6 is situated approximately 100 m southwards along the forest track and about 20 m off to the left within Corriedoo Forest.

Coarse-grained Silurian (Gala Group) greywacke is exposed beside the track butthe best exposures form a small rocky knoll about 20 m farther to the NE. There, large clasts of quartz, feldspar and lithic fragments are clearly recognisable. Mudstone clasts are locally flattened into the plane of a steeply NW-dipping foliation which wraps around the more rigid quartz and feldspar clasts with the development of asymmetric pressure shadows. Within the mudstone clasts the foliation takes the form of a variably developed slaty cleavage. Quartz and lithic clasts are also highly attenuated, the latter up to 10 cm in length, defining an exceptionally well-developed stretching lineation plunging gently NE and providing a spectacular illustration of a linear fabric. This locality is at the northern margin of the Moniaive Shear Zone and the Orlock Bridge Fault probably occupies the valley immediately to the north of the A702.

7 Durisdeer

OS 1:50 000 Sheet 78 Nithsdale Annandale

BGS 1:50 000 Sheet 15E Leadhills

Route map: (Figure 58) with locality numbers referenced in the text

This section provides an opportunity to examine the variation in intensity of fabric within the shear zone, the nature of the shear zone margins, and the relationship between the shear zone fabric and the regional folds. Kinematic indicators can also be seen within the highest strain segments of the zone. Follow the A702 to the NE, including its offset by a short section of the A76 from north of Thornhill to Carron-bridge, following signs for Elvanfoot. Four kilometres NE from Carronbridge the small settlement of Durisdeer is signposted on the right; take this road and park in front of Durisdeer Kirk [NS 895 038]. Walk along the road which runs NE past the Kirk and then follow the Roman Road (now a farm track) on to the valley bottom and along to the Roman fortlet (7a).

Silurian greywacke of the Gala Group is exposed in a number of places on the flanks of the mound on which the fortlet was built. A well-developed penetrative cleavage, slaty in places, has a moderate dip NW and includes a stretching lineation plunging gently NE. Within the phyllosilicate-rich layers the slaty fabric is deformed by an extensional crenulation cleavage. Open crenulation folds, with wavelengths of 1–3 cm, have zones of intensified cleavage associated with their limbs. The main cleavage rotates into these discrete zones, the sense of rotation indicating extensional displacement on the secondary cleavage and an overall sinistral sense of shear.

Following the Roman Road further up the valley an outcrop of mylonite can be seen above the road where it passes through the field boundary wall (7b). The fabric here is folded by open to close asymmetric folds with wavelengths of 2–30 cm. The axial surface of the folds dips moderately SW, the fold hinges having a moderate plunge NW These folds are comparable in style and orientation to the widespread D3 structures and indicate further shear reactivation after the formation of the main fabric zone.

Proceed north on to the slightly higher ground above the Roman Road where two small exposures occur approximately 150 m SW of a sheepfold (7c). Here a penetrative cleavage and stretching lineation in silty mudstone are folded by open to close folds with wavelength of approximately 30 cm. The folds have a subhorizontal axial surface, marked by a weak axial planar crenulation cleavage, and plunge gently SW. These folds are comparable in style to the recumbent D2 structures seen elsewhere in the Southern Uplands and suggest a complex relationship between the sinistral strike-slip folding (D3) and the regional D2 event. Both fold episodes were probably polyphase, diachronous and overlapping.

Follow the small stream (Glenhourie Burn) on to Stonycleuch Rig (7d). Coarse-grained massive sandstone beds form a small waterfall where the stream bifurcates. No cleavage is apparent within the sandstone here but it is intensely fractured and a narrow zone of quartz- cemented fault breccia is developed. The fracturing is probably a consequence of late, brittle deformation on the Orlock Bridge Fault, the trace of which probably runs along the break of slope at the NW side of the valley, marking the northern extent of the shear zone.

The variation in fabric development towards the southern margin of the shear zone can be examined by traversing east into the valley of the Gana Burn. A strong fabric is present within the greywacke exposed in the burn (7e) and a slaty foliation in the mudstone units is accompanied by fabric-parallel, mm-scale quartz veins. Both the cleavage and the veins are folded by close asymmetric folds, similar to those at Locality 7c, but here with a wavelength of about 2 cm and subhorizontal axial surfaces.

An initial expression of the domainal nature of fabric development can be seen on the NW flank of Durisdeer Hill (70, these exposures being easily accessible from the track from Durisdeer where it passes through the col at the head of Kirk Burn. There, coarse-grained, thick-bedded to massive greywackes show a weakly developed planar fabric in zones 50 cm wide. Outside these narrow zones the greywackes are undeformed but the whole assemblage is interleaved between the zones of intense fabric development exposed to the north and south, by the Roman Road (Localities 7a, b and c) and in Gana Burn (7e) respectively. This contrast within the broad Moniaive Shear Zone may be a precursor to its bifurcation farther east (Localities 8 and 9).

8 Hearthstane

OS 1:50 000 Sheet 72 Upper Clyde Valley

BGS 1:50 000 Sheet 24W Biggar

This and the next locality (9) examine the north-easterly continuation of the Moniaive Shear Zone in an area where two separate belts of ductile deformation have been identified, one on each side of the Orlock Bridge Fault. At Hearthstane (Locality 8), deformation in the Silurian Gala Group appears to have a sinistral sense of displacement, continuing the character of the western part of the Moniaive Shear Zone; further north, at Drumelzier (Locality 9) a narrow zone of deformation in Ordovician rocks shows clear evidence of dextral movement. It is not yet clear whether these two belts, about 2.5 km apart, represent branches of a single zone or whether they were produced by two separate kinematic events.

From Durisdeer, return to the A702 and continue east to Elvanfoot, from where the southbound A74(M) should be followed for about 10 km before turning left on to the B719 signposted Greenhillstairs. Turn left at the junction with the A701 and continue for about 20 km towards Edinburgh. Hearthstane [NT 113 260] is situated on the right, 1.5 km north of Tweedsmuir; permission for parking and access should be sought at the farm house.

This section provides an opportunity to examine shear zone fabrics correlated with those within the Moniaive Shear Zone, last seen 50 km to the SW.

A well-developed fabric can be seen in the section exposed in Hearthstane Burn downstream from the small dam behind the farm buildings. A strong linear fabric, plunging gently NE, is present in the thick-bedded greywacke of the Gala Group which crops out immediately downstream of the dam. The fabric is largely caused by quartz grains with a preferential elongation. In thin section they show evidence of both ductile and brittle deformation with undulose extinction and sub-grain development around grain boundaries; mica beards form tails to the elongate quartz grains and show a sinistral sense of shear. Brittle desegregation of grains has also occurred, with fractures perpendicular to the stretching direction.

A planar fabric, dipping moderately NW, is developed within siltstone interbeds exposed in small cuttings beside the track running east along Hearthstane Burn. A gently NE-plunging stretching lineation is developed within the foliation. The southeastern margin of the zone cannot be located precisely, due to lack of exposure, but a linear fabric is present in loose scree blocks as far as the confluence of Glenheurie and Hearthstane burns approximately 1 km farther east.

9 Drumelzier Place

OS 1:50 000 Sheet 72 Upper Clyde Valley

BGS 1:50 000 Sheet 24W Biggar

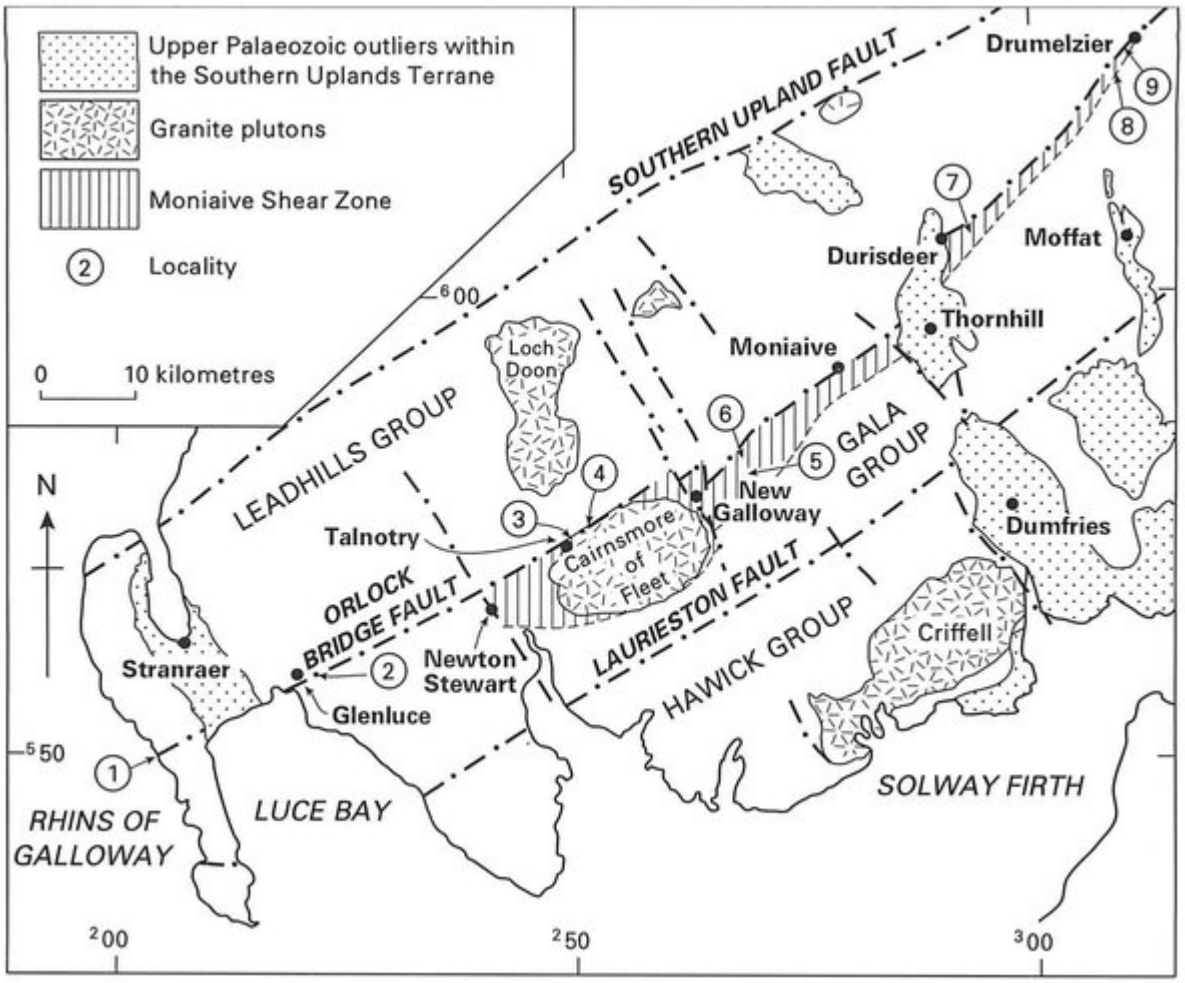
From Hearthstane continue towards Edinburgh on the A701 and at Rachan Mill turn right on to the B712, which is signed for Drumelzier. The road takes a sharp left turn after it crosses the River Tweed; at the bend turn right, following the sign for Drumelzier Place, and follow this minor road to the turn off to Drumelzier Place Farm [NT 125 336], where permission should be sought for parking and access.

Above the road to the SE, opposite the farm drive entrance, are a number of exposures of rhyolitic tuff forming interbeds in the Ordovician greywacke sequence. The tuff contains both scoria and crystals, the former up to 5 cm across, in a fine-grained chloritic matrix; the vesicles in the scoria are mulled with quartz, chlorite and calcite. The tuff horizons are closely associated with a limestone breccia, the Wrac Limestone, interpreted as a debris flow transported into deep water. The limestone has been worked in a small quarry a few hundred metres along strike to the SW. More extensive workings are present on Wrae Hill directly to the SW across the River Tweed (Floyd and Stone, 1992). Within the tuff both the clasts and crystals show chloritic deformation tails, though little desegregation of the crystals has occurred. A penetrative foliation is developed but there is no sign of the stretching lineation seen within the Moniaive Shear Zone further west. Shear sense indicators visible on near-horizontal surfaces include augen asymmetry, long-axis alignment of feldspar grains, and localised development of secondary cleavages. These dominantly indicate a dextral sense of movement but contradictory evidence is also apparent and a complex shear history seems likely.

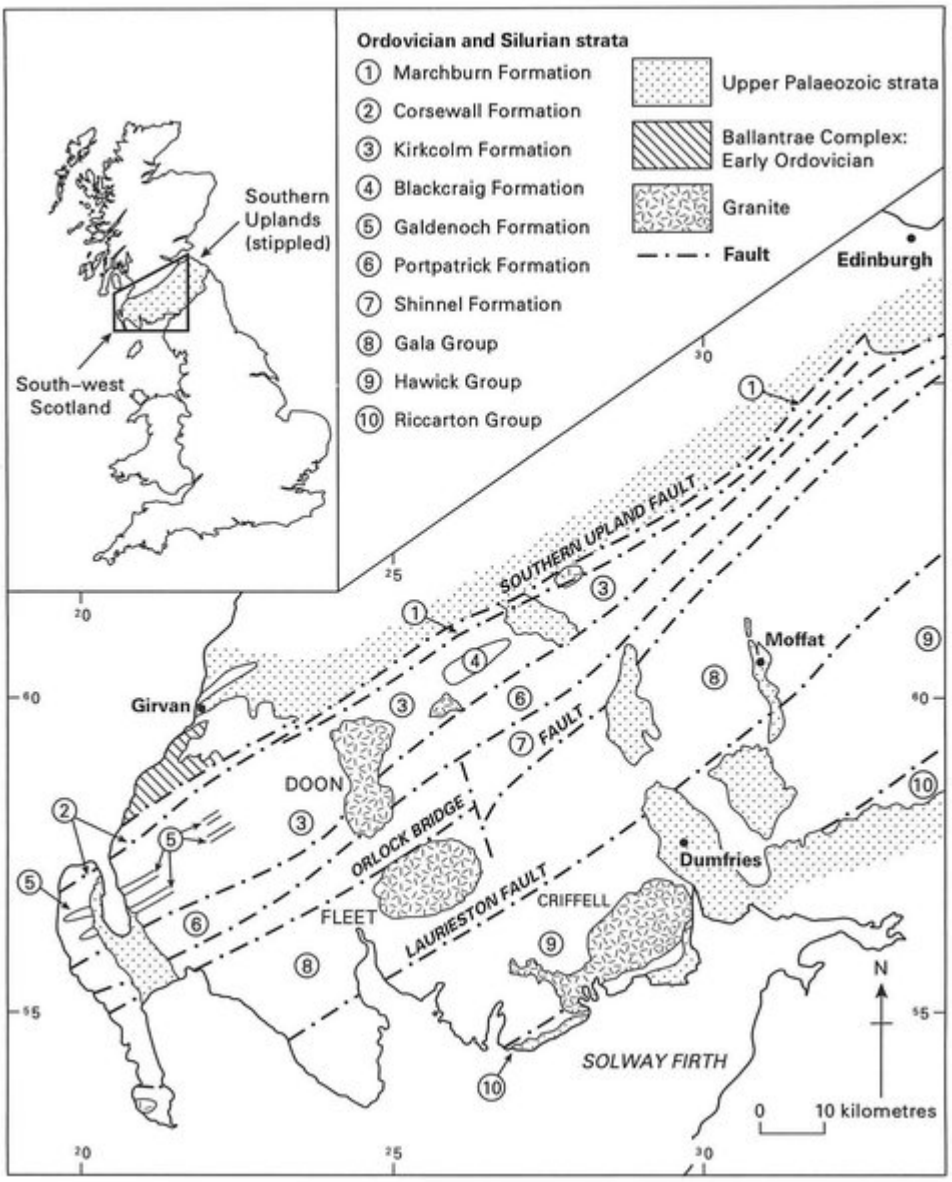
Further up-slope, medium-bedded greywacke sandstones can be seen in a number of small exposures. The sandstone shows no indication of penetrative deformation and its position thus limits the southern extent of the shear zone. This strand of the shear zone lies entirely within the Ordovician sequence and it is clear that the close relationship seen farther SW between the Orlock Bridge Fault, the Moniaive Shear Zone and the Ordovician—Silurian boundary, is not maintained at this more easterly outcrop.

This completes the itinerary and the A701 may be followed south towards Moffat and the A74 or north towards Edinburgh. The only known outcrop of the Orlock Bridge Fault farther to the NE is the Garvald locality originally described by Anderson and Oliver (1986). This is near Haddington, about 70 km farther NE where the trace of the Orlock Bridge Fault is marked by a few metres of mainly brittle deformation. Anderson and Oliver (1986) describe anastomosing shear planes similar in some respects to their Zone 1 fabrics, and note that in the vicinity of the fault the SI cleavage is refolded about steeply plunging sinistral hinges.

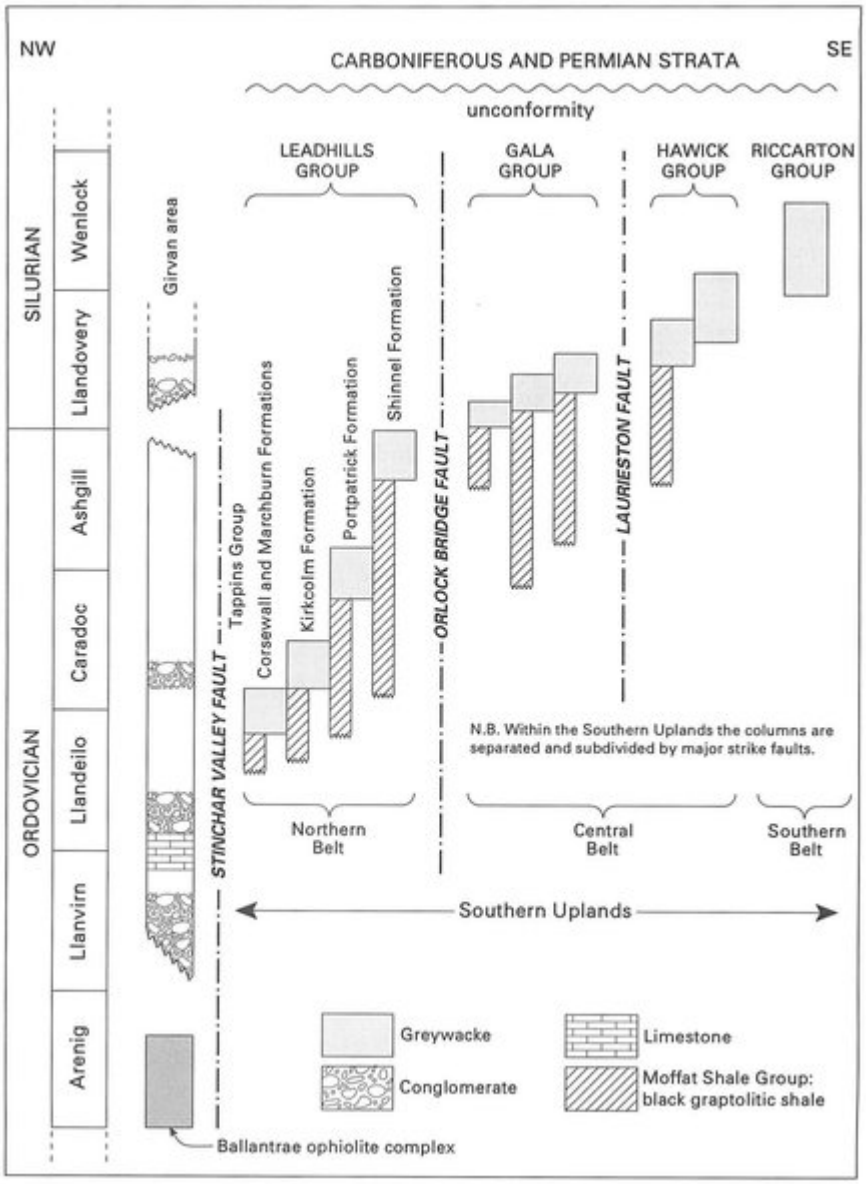
References



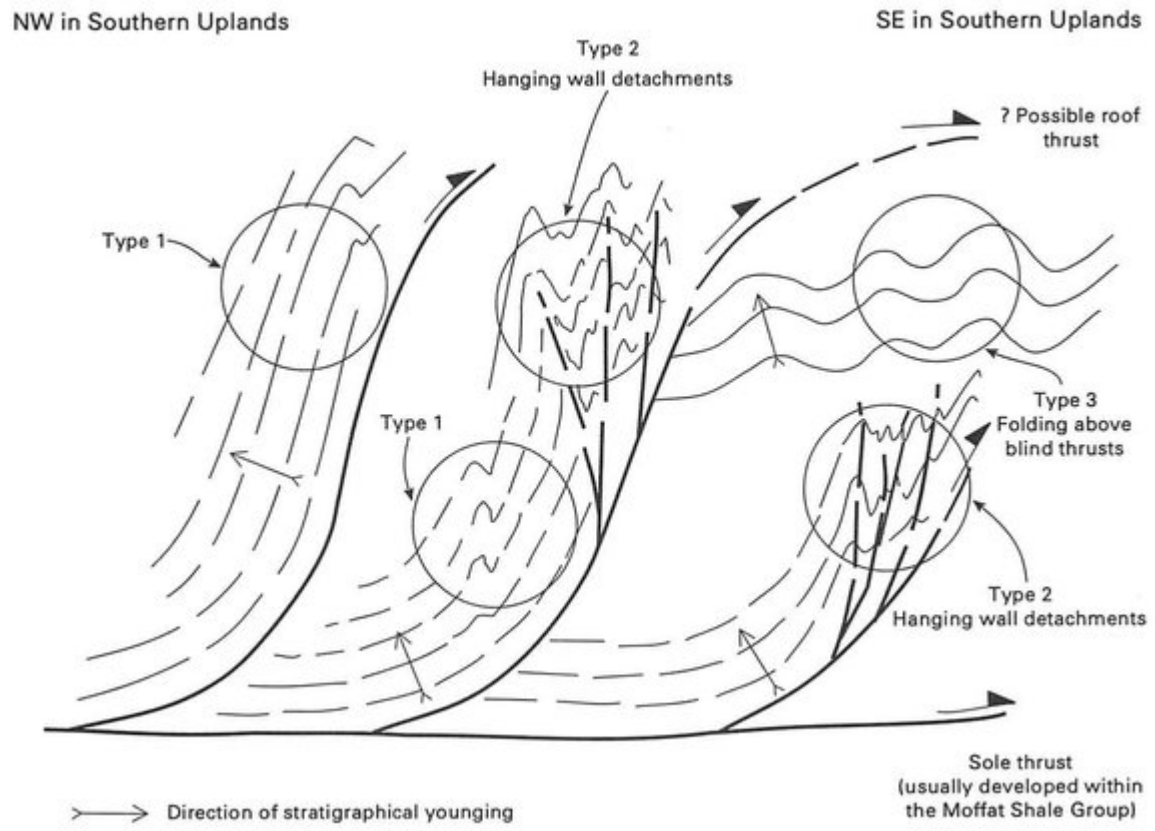
(Figure 55) Locality map and outline geology For the Moniaive Shear Zone excursion.



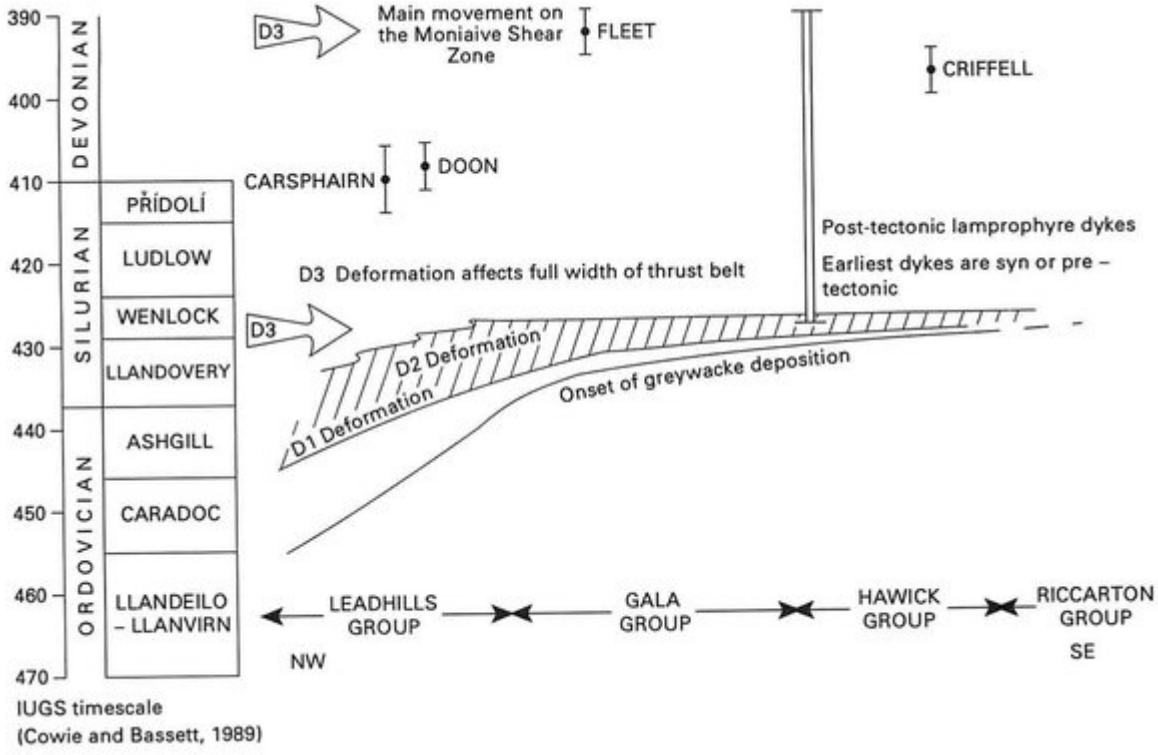
(Figure 1) Principal features of Lower Palaeozoic geology in south-west Scotland.



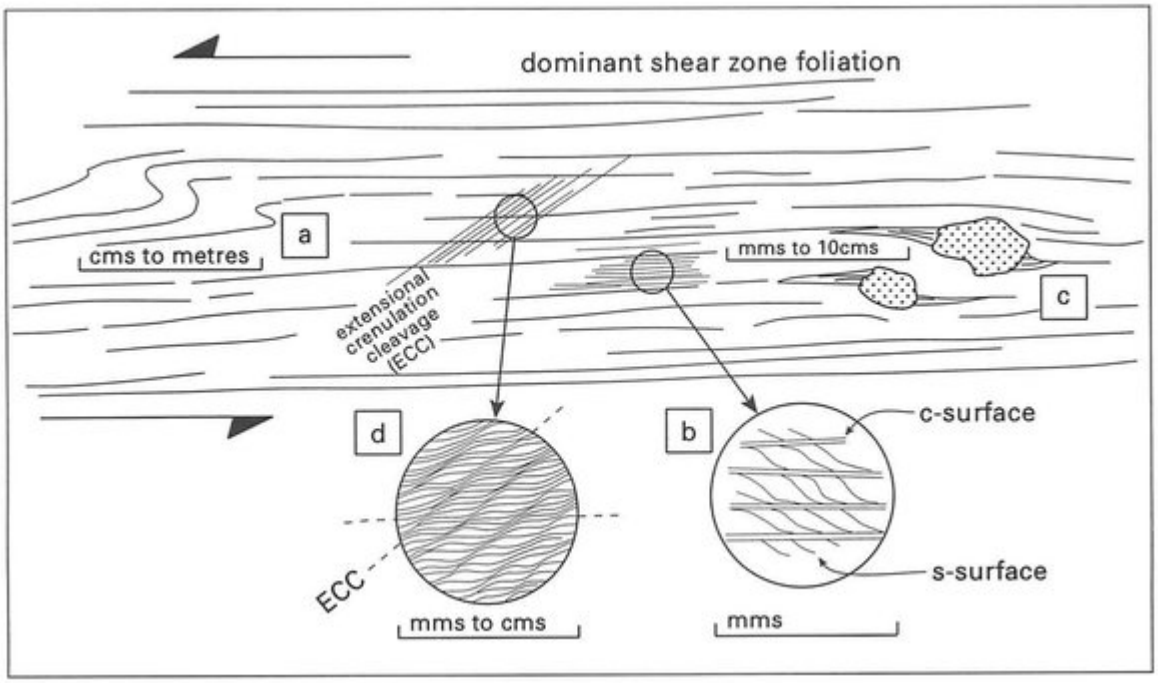
(Figure 2) Schematic representation of stratigraphical relationships in south-west Scotland.



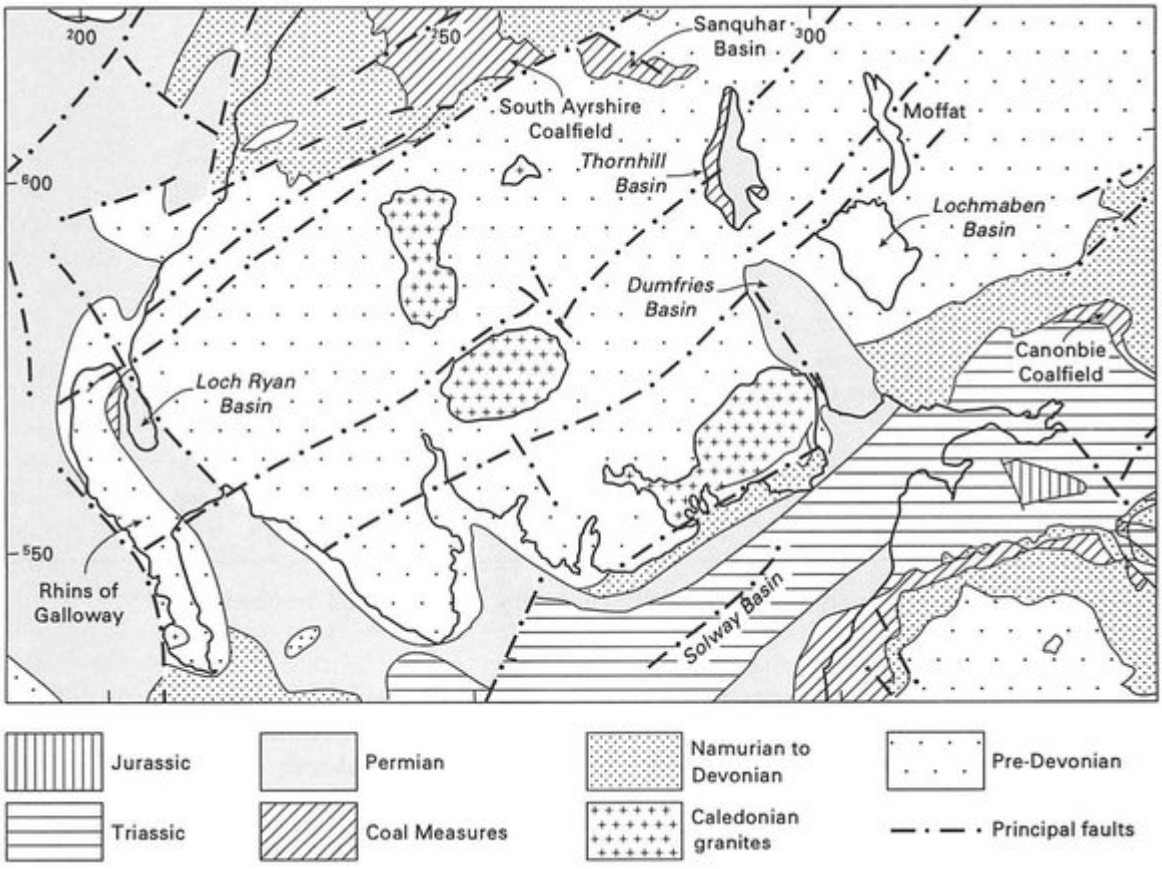
(Figure 3) Variable fold style developed within an idealised thrust sequence: examples are seen in the Southern Uplands.



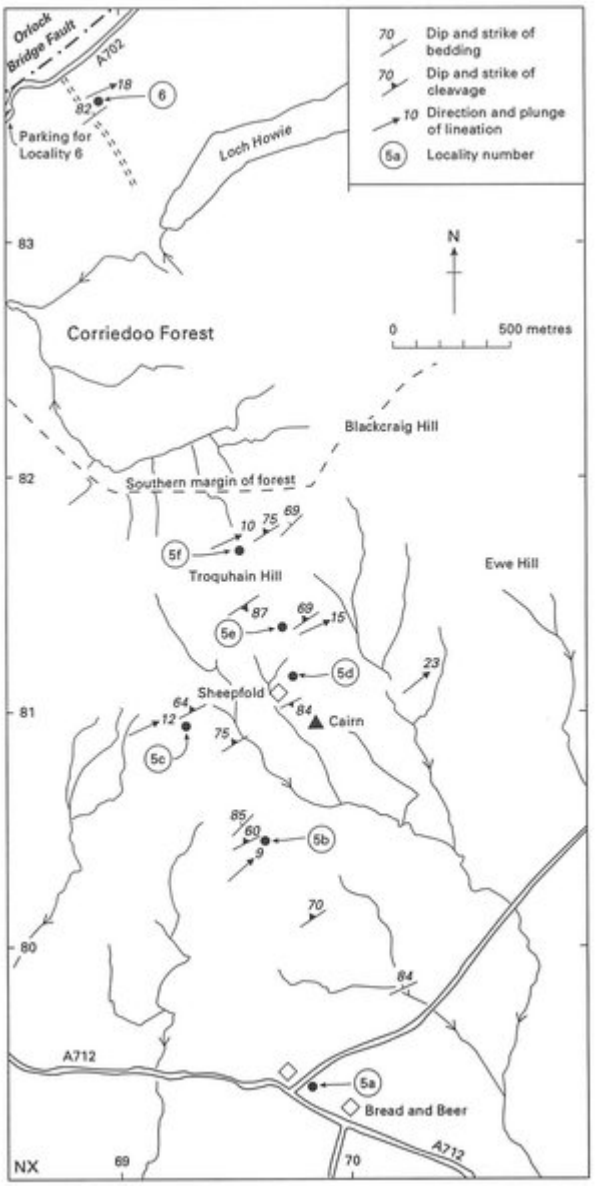
(Figure 4) Summary of information used to establish controls on the timing of Caledonian deformation in the Southern Uplands (cf. Barnes et al., 1989, fig. 1) Ages of post-tectonic plurons (in million years): Carsphairn: 410 ± 4, Rb-Sr, Thirlwall (1988). Loch Doon: 408 ± 2, Rb-Sr, Halliday et al. (1980). Fleer: 392 ± 2, Rb-Sr, Halliday et al. (1980). Criffell: 397 ± 2, Rb-Sr, Halliday et al. (1980). Dyke ages (range): Rb-Sr and K-Ar, Rock e. al. (1986b).



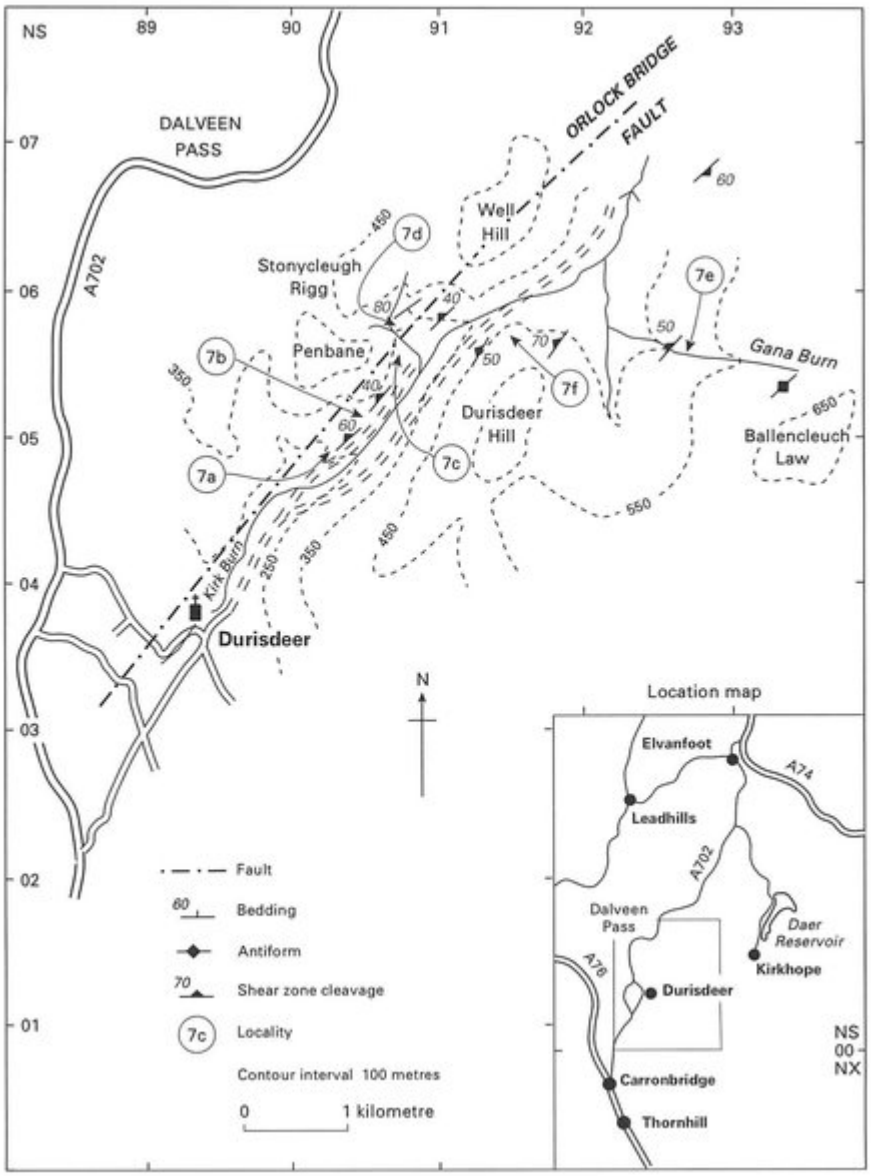
(Figure 56) Schematic illustration of kinematic indicators within a sinistral shear zone. For more detailed illustrations see White et al. (1986). a. asymmetry of steeply plunging folds. b. S-C mylonite. c. asymmetric augen structures. d. extensional crenulation cleavage. Scale range for each kinematic indicator shown.



(Figure 8) Upper Palaeozoic geology in south-west Scotland.



(Figure 57) Locality map for the section from Bread and Beer (Locality 5) to Corriedoo (Locality 6).



(Figure 58) Locality map for the Durisdeer section (Locality 7).