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Chapter 7. Middle Ordovician to mid-Silurian active margin geology of the Southern Uplands and southern Midland Valley

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Running Head: Southern Uplands and southern Midland Valley

The Southern Uplands Terrane is the southernmost of the major tectonic units that make up Scotland. Its Ordovician and Silurian strata were incorporated into an accretionary complex formed above a north-directed subduction zone consuming the Iapetus Ocean beneath the continental margin of Laurentia and the accreted Midland Valley Terrane. The obduction of the ophiolitic, Lower Ordovician Ballantrae Complex, preceded initiation of the accretionary complex, and the ophiolitic rocks are unconformably overlain by a forearc basin succession deposited between a supra-subduction volcanic arc in the Midland Valley Terrane, and, to the south, the developing Southern Uplands accretionary complex. By the mid-Silurian, small depositional basins had formed more widely along the southern margin of the Midland Valley, with their strata now seen in a series of inliers.

The obduction of the Ballantrae Complex ophiolite as the Iapetus Ocean began to close was followed by the establishment of north-directed subduction beneath the Midland Valley Terrane, effectively the leading edge of Laurentia. As described in Chapter 6, the assembly and emplacement of the Ballantrae Complex was a polyphase process during Early to Middle Ordovician times, culminating during the Darriwilian Stage. Thereafter, obduction, uplift and erosion proceeded rapidly, with the oldest part of the unconformably overlying sedimentary succession, now cropping out to the south of Girvan, deposited at about 463 Ma (Stone & Rushton 2018). At that time (mid-Darriwilian), the Scottish sector of the southern Laurentian continental margin probably lay in sub-tropical latitudes south of the equator.

The Ordovician sedimentary rocks overlying the Ballantrae Complex accumulated in a forearc setting, oceanward of a supra-subduction magmatic arc that was developing in the Midland Valley Terrane (Chapter 8). There was strong fault control on the character and location of deposition resulting in an upward transition from shallow to deep marine lithologies – conglomerate, sandstone, siltstone, mudstone and minor, but stratigraphically crucial, reef limestone – and a northerly transgressive onlap as faulting stepped back into the continental interior. To the south, at the margin of the Iapetus Ocean, submarine fans of sandstone and conglomerate encroached onto oceanic crust and its cover of deep-marine lithologies.

As subduction of Iapetus Ocean lithosphere progressed during the Late Ordovician the accumulating clastic successions were stripped from the descending oceanic slab and incorporated into a growing imbricate thrust complex. The Southern Uplands Terrane preserves parts of this accretionary complex and demonstrates the continuation of active subduction through into the mid-Silurian. It was finally terminated by the complete closure of the Iapetus Ocean and the migration of the depositional basin into a foreland tectonic setting on what had been the southern continental margin of the Iapetus Ocean. That, together with the penecontemporaneous thrusting of the northern margin of the accretionary complex onto the Midland Valley Terrane, resulted in the accretionary complex becoming entirely allochthonous The southern margin of the Iapetus Ocean, now underlying northern England, is commonly ascribed to the Avalonia continent, a rifted fragment of Gondwanan origin. Waldron *et al*. (2014) included Avalonia within the larger Ganderia continent, but for simplicity and continuity, Avalonia will be used in this account to encompass the peri-Gondwanan terranes of England and Wales.

Progressive uplift of the Southern Uplands accretionary complex accentuated a forearc basin at the margin of the Midland Valley. Silurian marine strata unconformably overlie the Ordovician succession in outcrops near Girvan, but for several other Silurian inliers seen further to the NE, the stratigraphical base is not exposed. They probably developed as isolated basins in a transtensional tectonic regime, and their sedimentary fill shows an overall upward progression from marine to terrestrial lithofacies.

This chapter will first consider the Upper Ordovician succession at Girvan, then the Upper Ordovician to mid-Silurian accretionary complex forming the Southern Uplands, before returning to the Silurian of Girvan and the inliers of the Midland Valley's southern margin: for locations and outline geology see Fig. 7.1. It owes much to its predecessors in the 4th edition of the Geology of Scotland – Chapter 5 for the Midland Valley inliers (Bluck 2002) and Chapter 6 for the Southern Uplands (Oliver et al. 2002) – and to other more recent reviews of Southern Uplands geology (Stone *et al*. 2012; Stone 2014).

The Ordovician–Silurian succession of the Girvan district

Ordovician (Darriwilian–Hirnantian)

The outcrop of Ordovician sedimentary rocks at Girvan is one of the classical areas of British stratigraphy and of international importance. Its interpretation is founded on the work of Williams (1959, 1962), supplemented by Ince (1984), who demonstrated that sedimentation was largely controlled by active faulting, with downthrow to the south, which progressively stepped back northwards into the continental hinterland, so creating an overall northwards sedimentary transgression (Fig. 7.2). The succession ranges in age through the Late Ordovician from a mid-Darriwilian base high in the Middle Ordovician; it rests unconformably on eroded rocks of the obducted Ballantrae Complex. It is a continent-derived, clastic-dominated succession wherein boulder-bearing conglomerate with well-rounded clasts passes transitionally southwards into thick accumulations of sandstone. The conglomerates terminate towards the NW against contemporaneous faults that cut through the Ballantrae Complex and made its ophiolitic lithologies available for erosion. The limestones and coarse clastic deposits rest on, or were developed just above, the ophiolitic 'basement' suggesting that they accumulated on fault-controlled topographic highs (Williams 1962; Ingham 1978; Ince 1984). The limestone beds are richly fossiliferous with corals and the abundant calcareous alga *Girvanella*.

South of Girvan in the valley of the River Stinchar, limestones low in the Barr Group (Fig. 7.2) contain shallow-water shelly faunas of broadly Middle Ordovician aspect (Ingham 2000) and conodonts representative of the *Pygodus serra* and *P. anserinus* biozone (Bergström 1990). Based on Cooper & Sadler (2012, fig. 20.1) the mid-Darriwilian *serra* biozone ranges from about 462.5 Ma to 460.5 Ma; the *anserinus* biozone extends through the later Darriwilian to above the base of the Sandbian, from 460.5 Ma to about 458 Ma. These data place the onset of Barr Group sedimentation at about 463 Ma (Fig. 7.2).

The conglomerates of the Barr Group, and farther north of the Ardmillan Group (Fig. 7.2) contain clasts, up to 3 m in diameter and mostly well-rounded, of ophiolitic and acid to intermediate igneous rocks. The composition and size of these clasts suggests that, in addition to erosion of the underlying Ballantrae Complex, there was also unroofing of a major volcanic/plutonic arc, situated only a short distance to the north and shedding detritus into its proximal forearc (Bluck 1983). From radiometric dating (Rb-Sr, whole rock and feldspar) of granite clasts (most of which were boulder size), Longman *et al*. (1979) derived cooling ages close to the ages of the sediment from which the clasts were recovered. The ages of the youngest granite clasts decrease upwards in the sequence from about 481 Ma to 451 Ma implying a coeval evolution of the sedimentary system and the continuous intrusion, cooling and erosion of the magmatic arc, for possibly 30 million years or more (Bluck 1983, 2013).

Above the Barr Group and Ardmillan Group limestones and conglomerates, the successions in the Stinchar Valley and closer to the south of Girvan are dominated by immature, turbidite sandstones, which follow the general pattern and become progressively younger when traced towards the NW (Williams 1962; Ingham 2000) (Fig. 7.2). There is a widespread graptolite fauna, but in places there are also abundant and diverse shelly faunas, some of which are probably derived by slumping (Ingham 1978, 1992a). Another illustration of syn-sedimentary movement is an array of folds affecting the Ardwell Farm Formation and exposed on the coast to the north of Kennedy's Pass (about 5 km SW of Girvan). Originally thought to be tectonic in origin, the restriction of folds to a limited part of the succession and the details of the fold hinges have led to the reinterpretation (Bluck in Ingham 1978).

Of the shelly faunas, most of the brachiopods are indicative of unstable outer shelf and slope environments but some deep-water species are also present (Harper 2001). The trilobite fauna is of particular interest. It includes shallow-water assemblages of the illaenid–cheirurid association but also representatives of the cyclopygid biofacies, pelagic trilobites and blind benthic species (Ingham & Tripp 1991; Ingham 1992). This combination indicates alternating episodes of shallow-water sedimentation and deeper-water conditions where sedimentation failed to keep pace with subsidence. Another important palaeontological aspect of the Girvan succession that arises from this environmental variation is the interbedded presence of both shelly and graptolitic faunas, a valuable aid to wider correlation.

The most northerly of the Ordovician successions in the vicinity of Girvan crops out in the Craighead inlier, about 7 km NE of the town (Fig. 7.1). At the base is the Craighead Limestone which built-up around reefs on slight topographic rises in an underlying basement of basalt pillow lava. There is some uncertainty over the age of the basalt basement and its relationship to closely adjacent cherts. The lavas are commonly assumed to form the northern exposed extremity of the Early–Middle Ordovician Ballantrae Complex and whilst the chert may have been coeval with the lavas it has also been interpreted as a younger unconformable cover infiltrated into them or subsequently infolded with them, and of an age with the immediately overlying Craighead Limestone. The uncertainty arises in part from the disputed age of conodonts recovered from the chert (Ingham 1978; Bergström 1990). The age of the Craighead Limestone is firmly established as Sandbian. The reef limestone lithofacies is enclosed in interbedded, inter-reef limestone and mudstone with varied and abundant fossils: the brachiopods (Williams 1962), trilobites (Tripp 1980) and ostracods (Williams & Floyd 2000) are of particular importance for regional correlations.

The succession overlying the Craighead Limestone contains a high proportion of shelf deposits, including sheets of storm-generated sediment, and contemporaneous tectonic activity has been deduced from the presence of mass-flow deposits (Ingham 1992). In general, the Craighead lithologies demonstrate a significant contrast in sedimentation pattern compared to the stratigraphically equivalent parts of the more southerly Girvan successions; deep-water turbidites dominate in the south but are less abundant to the north. This may be explained by the position of the Craighead area, close to the southerly margin of a widespread, intermittently developed shelf that continued to the north, further into the Midland Valley Terrane.

The rich and varied Craighead fauna has been extensively studied for more than a century and is regarded as an Ordovician assemblage of global importance (Ingham 2000). Along with the other Late Ordovician faunal assemblages from the outcrops around Girvan, they were amongst the first to be recognized as having affinities with Appalachian faunas and are therefore of historical importance. Of especial interest are the three world-famous Lady Burn starfish beds (within the Farden Member of the South Threave Formation) of late Katian age (Donovan *et al*. 2002) (Fig. 7.3a). Although the faunas are of shallow-water origin, they are in many, if not most cases, clearly displaced into deeper-water deposits, although with little sign of reworking. Ingham (1978, 2000) and Harper (1982) consider at least some of these displaced faunas to have been transported by large-scale slumping of large blocks of sediment from the shelf edge, their enclosed fossils afforded protection and so retaining fine preservation. As a result, parts of the succession locally show alternations of indigenous deep-water fossils and transported shallow-water forms.

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From a consideration of the full Ordovician succession, it is notable that there appear to be cycles of initially shallow water sediment (limestone and conglomerate) that are followed by an abruptly deepening sandstone-mudstone lithofacies, which in turn is overlain by more conglomerate that may fill channels in the underlying strata. In detail there are large local differences in thickness between successive conglomerate units and in their provenance as indicated by the clast compositions. Many clasts are of locally derived spilite and serpentinite, clearly derived from the underlying Ballantrae Complex and set in a mafic volcaniclastic matrix of the same provenance. But in addition, the size and ages of the large granite boulders (c. 481 Ma to 451 Ma as described above) indicate proximity to a contemporaneous, Ordovician magmatic arc located not far to the north (Bluck 1983). Support for the existence of such an arc in the Midland Valley Terrane during the Late Ordovician was provided by Badenszki *et al*. (2019) who used U-Pb dating of zircons to show a protolith age of about 453 Ma for metatonalite basement xenoliths recovered from Permo-Carboniferous volcanic rocks.

A more complex picture of the sedimentary provenance arises from consideration of the accessory metamorphic detritus in the conglomerate and sandstone units. For example, Oliver (2001) described three distinct garnet populations in the detrital heavy-mineral fraction from the matrix of both conglomerate and sandstone. Most of the garnet grains had chemistry that matched that of garnet formed in Barrovian metamorphic rocks as seen in the Dalradian of the Grampian terrane. Oliver also reported other garnets with chemistry typical of examples sourced from S-type granites, and a third set likely derived from a high-pressure, low temperature, blueschist–eclogite facies subduction zone. Clearly, when deposition of the Girvan succession commenced in the mid-Darriwilian, sand-size detritus derived from high grade metamorphic rocks was available to mix with the locally sourced, coarser material of ophiolite and volcanic arc origin. Hutchison & Oliver (1998) contended that the sand was introduced by large river systems originating far to the north within the mountainous Grampian terrane. Then, flowing across the Midland Valley Terrane, the rivers picked-up plutonic and volcanic detritus, and eroded the obducted Ballantrae Complex. The resulting mix of sediment was deposited in the fault-controlled basins elucidated by Williams (1962) and Ince (1984) within the proximal forearc shelf environment proposed by Bluck (1983), to build up the Barr and Ardmillan groups (Fig. 7.2).

When considering the likely size of the arc-forearc system, Bluck (1983, 2013) stressed that the Girvan Ordovician succession represented but a fragment of what must have been a large shelf basin extending to the south. By comparison with the scale of mature, present-day forearc basins he suggested that that southward extension may have been as much as 250 km. Armstrong et al. (1996) preferred a narrower, collapsing shelf, but neither model accommodates the current proximity of the Girvan succession and the northern components of the Southern Uplands Terrane, juxtaposed across the Stinchar Valley Fault, the local representative of the Southern Upland Fault. Clearly a considerable area of the original forearc has been lost to view, either excised by strike-slip tectonics or overthrust by the Southern Uplands. There is evidence for both processes, with NW-directed thrusting evident from the structural histories of the Ordovician strata (Williams 1962; Ince 1984) and the Stinchar Valley Fault (Floyd 1994).

The unconformity and short depositional hiatus at the base of the overlying Silurian successions suggests some deformation of the Ordovician Barr and Ardmillan groups very early in the Silurian. However, the principal deformation episode occurred later, late in the Silurian, when the Ordovician succession was folded along with its overlying Silurian cover. The principal structures affecting the Ordovician strata around Girvan are large asymmetric folds overturned towards to NW, in several of which the NW limb has been replaced by a major NW-directed thrust. The dominant sense of vergence towards the NW is in marked contrast to the orientation of structures in the neighbouring Southern Uplands Terrane and may be the result of the reactivation of the earlier normal faults as back thrusts in response to the wholesale northwards emplacement of the Southern Uplands onto the Midland Valley forearc (Bluck 1983). Badenszki *et al*. (2019) have linked that overthrusting to metamorphism in the Midland Valley basement at *c*. 411 Ma, which they detected during dating of xenoliths found in Permo-Carboniferous igneous rocks, but that date seems a little too young to correlate with the deformation at Girvan. These issues of terrane relationships will be revisited later in this chapter.

Silurian (Llandovery–Wenlock)

The Silurian strata at outcrop around Girvan are disposed in three areas (Fig. 7.1): small outcrops on the coast to the south of the town, the main Girvan outcrop extending inland, and in the Craighead Inlier, to the NE of the town, where the strata are folded into a broad anticline plunging to the NE which introduces younger rocks in that direction. The base of the Silurian succession rests with gentle unconformity on Ordovician strata in the coastal section and in the main, inland outcrop to the south of the town. At Woodland Point, on the coast, although the angle of unconformity is only about 8°, a significant part of the Ordovician Ashgill succession (the entire Drummuck Subgroup) is missing. In the Craighead Inlier the stratigraphical break is smaller, but the unconformity is more abrupt (Fig. 7.2). Detailed stratigraphical reviews have been provided by Cocks & Toghill (1973), Clarkson et al. (1998) and Floyd & Williams (2003). The succession contains a rich variety of fossils and is well-known for the mixture of shelly and graptolitic faunas that facilitates correlation of different biostratigraphical schemes.

All the Silurian strata are included within the Girvan Group (Floyd & Williams (2003), which comprises about 2 800 m of sandstone, siltstone, mudstone and conglomerate (with rare, minor limestone). The succession arose from two major shallow- to deeper-water transgressive cycles during the Llandovery, followed by a marine regression during the early Wenlock. This depositional pattern is reflected by the arrangement of the three subgroups of the Girvan Group: Newlands, Dailly and Straiton (Fig. 7.4). The lowest of these, the Newlands Subgroup, contains all of the units in the first of the major transgressive cycle and crops out in three distinct areas: in the coastal section, inland to the SE of Girvan, and in the Craighead Inlier; there are subtle differences in lithofacies between the three areas. Strata deposited during the second of the major transgressive cycles make up the Dailly Subgroup which is fully developed in the inland outcrop, but elsewhere has only its basal division preserved in the Craighead Inlier. A brief depositional hiatus between the Newlands and Dailly subgroups is not accompanied by any signs of unconformity. At the top of the Girvan Group, the Straiton Subgroup occurs only inland within the inland outcrop and includes the strata deposited during marine regression and the transition to terrestrial conditions: red sandstone and conglomerate of earliest Wenlock age (Floyd & Williams 2003).

In the coastal section and at Craighead, Llandovery (Rhuddanian) conglomerates lie unconformably on the Ordovician succession described previously. The Craigskelly Conglomerate Formation at the coast is variably clast- to matrix-supported and contains interbedded sandstone lenses. Its rounded pebbles and cobbles show the same wide compositional range as the underlying Ordovician conglomerates but with a higher proportion of quartzose clasts. As with the Ordovician conglomerates, abundant detrital, high-grade Barrovian metamorphic garnet was described by Oliver (2001) from the matrix of the Craigskelly Conglomerate and thought to favour a Dalradian provenance. In contrast, Phillips *et al*. (2009) found the age population of detrital zircons in the sandstone interbeds to be incompatible with a Dalradian, Grampian Terrane, provenance, despite their agreed derivation from the north. Phillips *et al*. also presented zircon age data for several of the other Midland Valley inliers, discussed in more detail later in the chapter.

The basal Silurian conglomerate in the Craighead Inlier, although again derived from the north, contains mostly quartzose clasts, but the base of the inland outcrop at Girvan is faulted and no basal conglomerate is preserved. The conglomerates higher in both the inland and Craighead successions, together with the associated shallow marine sandstones and mudstones, show much variability in lithology and thicknesses over short distances, a feature attributed to local fault movements that perhaps arose from reactivation of the normal faults that controlled Ordovician sedimentation.

Much of the Llandovery successions in the inland Girvan and the Craighead outcrops are made up of transgressive marine deposits: sandstone, siltstone, mudstone and sporadic conglomerate. A noteworthy feature is the hummocky cross-stratification seen at several levels, indicating storm layers and deposition above wave base, that contrasts with deeper-water turbidite deposits. In detail, sequences of strata show repeated gradations from fine grained, sediment-starved, graptolitic mudstone, through sandstone and to conglomerate. Throughout the succession there is an abundance of both shelly and graptolitic faunas, the former (e.g. Fig. 7.3b) commonly derived from shallow-water shell banks and redeposited in deeper water. Cocks & Toghill (1973) have correlated the vertical lithological changes with faunal changes and related both to water depth fluctuations, extending the use of animal communities established in the Silurian rocks of Wales that were thought to be water depth related: *Lingula*, *Eocoelia*, *Pentamerus* and *Clorinda* communities, representing progressively deepening water assemblages, have been identified.

The inland Girvan succession terminates in rocks of earliest Wenlock age which are faulted against Llandovery strata, but with a minimal biostratigraphical break (Floyd & Williams 2003). The highest part of the Llandovery succession exposed comprises thinly bedded sandstone and graptolitic mudstone indicative of a marine transgression. The overlying Wenlock succession of the Straiton Subgroup then shows that the depositional environment shallowed enough to allow accumulation of sandstone and mudstone at or near to sea-level, with the development of the *Howellella–Protochonetes* brachiopod community (Cocks & Toghill 1973; Clarkson *et al*. 1998). Clarkson *et al*. (1998, 2001) identified the following lithofacies: a shallow-water prodelta facies, intertidal deposits subject to intermittent storm surges, nearshore delta-front sediment, and a coarse-grained back barrier facies. The youngest Wenlock strata preserved show a continuation of the shallowing trend. A brackish, lagoonal environment with a low-diversity acritarch flora and fresh-water bivalve and ostracod faunas (Floyd & Williams 2003) is succeeded by unfossiliferous, coarse red sandstone and conglomerate marking the onset of terrestrial conditions.

The Girvan Silurian succession is unconformably overlain by Siluro-Devonian rocks of Old Red Sandstone lithofacies. To create the late Silurian unconformity, the Girvan succession, along with its underlying Ordovician sedimentary strata were folded into large asymmetrical structures verging NW. This dominant sense of vergence may be the result of the reactivation as back thrusts, during the late Silurian, of the earlier normal faults that controlled Ordovician sedimentation, in response to the northwards emplacement of the Southern Uplands Terrane onto the Midland Valley forearc as a culmination of the closing of the Iapetus Ocean (Bluck 1983). Interpretation of deep seismic data supports the idea that the Southern Uplands Terrane has been overthrust onto the southern margin of the Midland Valley Terrane (Hall *et al*. 1984) and is discussed in more detail later in the chapter.

The Midland Valley Silurian inliers

Along the southern margin of the Midland Valley of Scotland, Silurian strata occupy a series of inliers extending from Girvan in the SW to the Pentland Hills in the NE (Fig. 7.1). They form part of a long belt of such rocks that extends from western Ireland to Scandinavia (Clarkson *et al*. 2001). Throughout the whole of this belt the overall succession is regressive, commencing with relatively deep-water lithofacies and terminating with red beds of semi-arid, continental type. Only at Girvan is the base of the Silurian succession preserved. There, and in the Pentland Hills, the Silurian strata are unconformably overlain by rocks of Old Red Sandstone lithofacies with marked angular discordance. In the central inliers the relationship is gently disconformable or parallel, but the base of the Old Red Sandstone is still erosive and unconformable (Smith 1995; Phillips *et al*. 1998; Mitten *et al*. 2022). The basal conglomerate of the Old Red Sandstone – the Greywacke Conglomerate Formations of the Lanark Group – may have begun to accumulate in places as early the Wenlock, although Thirlwall (1988) obtained Early Devonian ages of about 412 Ma (Lochkovian) for interbedded lavas higher in the Lanark Group succession. Correlations between the inliers following Cocks *et al*. (1992) and Phillips *et al*. (2004) are summarised in Fig.7.4.

There are five main inliers, and all show the upward transition from marine to continental sedimentation associated with widespread marine regression evident across large areas of Laurentia, Baltica, Ganderia and Avalonia at that time (Clarkson *et al*. 2001). Across the transition, deltaic, lagoonal and lacustrine depositional environments developed, whilst shoreline facies have been described from some of the inliers. Most of the inliers are richly fossiliferous in places and are particularly well known for their fine assemblages of well-preserved arthropods and fish. Llandovery, shallow-marine sedimentation persisted into the earliest Wenlock in the Girvan area, but in the other inliers there was a change to mainly terrestrial sedimentation at about the Llandovery – Wenlock boundary. Thereafter, fluvial, red-bed sequences of sandstone and mudstone with intermittent coarse conglomerate dominate the Wenlock successions.

Although the overall pattern of regression is evident in all the inliers there is much local variation in lithostratigraphy; interpretation has also been made more complicated by the effects of variable tectonism. The successions have been viewed as a record of the final stages of infilling of the forearc basin between the supra-subduction, volcanic arc in the Midland Valley and the advancing Southern Uplands accretionary complex (Bluck 1983). At a larger scale, the Silurian inliers and their westward extension into Ireland can be seen as originating in a continuous sedimentary basin, now fragmented, that ranged along the SE coastline of Laurentia (Williams & Harper 1988). More local control on sedimentation was emphasised by Smith (1995) and Phillips *et al*. (1998) who described the main areas of Silurian deposition, now preserved in the principal inliers, as small, fault-defined, strike-slip sub-basins which opened in response to a sinistral transtensional regime active during the later stages of closure of the Iapetus Ocean. There is no single structural pattern common to the inliers and the localised fault activity may have controlled the different cycles of deepening and shallowing seen in the different successions, although such local effects would have interacted with intermittent, eustatic sea level changes (Williams & Harper 1988).

The relatively abundant fossil faunas, both shelly and graptolitic, allow a degree of biostratigraphical correlation between the different inliers, whilst distinctive conglomerate units are important lithostratigraphical markers. Another common factor is the presence of metabentonite ash layers, with rhyodacitic and intermediate to mafic compositions, in the Llandovery successions (Batchelor 1999). The associated lithic arenites with degraded ash fragments attest to far more widespread volcanic activity during Llandovery and later times, and the preserved metabentonites are likely to record only that fraction of ash fall deposited in favourable environments free of reworking.

The central inliers

Strata of Llandovery and Wenlock age are exposed in several inliers along the central southern side of the Midland Valley, namely the Lesmahagow, Hagshaw Hills, Eastfield and Carmichael inliers (Figs 7.1). In general, their lithostratigraphy follows the pattern established for the Girvan successions, being characterized by the same upward change from Llandovery marine turbidites and storm deposits to littoral and then terrestrial deposits in the Wenlock. But in the central inliers marine conditions appear to have lasted intermittently well into the Wenlock where they alternated with the terrestrial conditions that gave rise to red beds of fluvial aspect. Examples of overstep, non-sequences and lateral change in sediment thickness suggest deposition in relatively small basins where changes in water depth and sediment supply were dominant influences (Rolfe 1960, 1961; Smith 1995); strike-slip control of basin development has been proposed (Phillips *et al*. 1998; 2004).

The largest of the central inliers is that at Lesmahagow, where about 2 500 m of Llandovery to Wenlock strata are preserved in a broad anticline. The depositional environments, biofacies and faunas have been reviewed by Rolfe (1992). At the base of the succession, the Llandovery strata of the Priesthill Group comprises sandstone, siltstone and mudstone, of marine turbidite origin in the lower part of the group but with an increasingly non-marine aspect in its upper part. The turbidite sandstones contain a redeposited shelly fauna derived from shallow water, but the palaeontological renown of the Lesmahagow inlier rests on the agnathan fish, eurypterid and associated faunas from laminated siltstone interbedded with the marine turbidites. The fish are amongst the oldest complete examples known and include *Jamoytius* and *Logania*. The spectacular eurypterids, such as the large forms *Slimonia* and *Erettopterus* are equally renowned, whilst the fauna also includes the earliest known scorpions.

A trend towards shallower-water deposition in the upper part of the Priesthill Group is continued into the Wenlock Waterhead Group, which comprises red, green and variegated sandstone and mudstone deposited in shallow marine, deltaic and lagoonal environments. Fossils are rare, mostly sporadic *Lingula* brachiopods, but there are two important fish beds noted for the agnathans *Birkenia*, *Lanarkia, Lasanius* and *Logania* amongst others; the accompanying fauna includes eurypterids and pod-shrimps (Rolfe 1992). The succeeding Dungavel Group is an unfossiliferous succession of conglomerate and brown, micaceous sandstone.

A similar stratigraphical pattern to that seen at Lesmahagow is also present in the Hagshaw Hills inlier where the succession, in total about 1500 m thick, is disposed in an asymmetrical anticline trending NE–SW with the SE limb overturned; bedding dip is commonly steep (Rolfe 1961, 1992). The succession begins with turbidite sandstone and sparsely graptolitic mudstone – the Llandovery Hagshaw Group. An extensive and varied shelly fauna within the turbidites is of shallow water aspect but mostly fragmentary or disarticulated. As with the fauna from the Girvan succession, it has been displaced and redeposited in deep water and the assemblage appears identical to that found in the Straiton Subgroup at Girvan, a *Howellella–Protochonetes*, shallow-water shelf assemblage (Rolfe 1992). The palaeoenvironment envisaged is one in which a shallow-water, carbonate platform supplied bioclastic material to turbidites and storm deposits that accumulated in the deeper water regions of a small fault-bounded basin.

The Wenlock succession in the Hagshaw Hills inlier commences with the basal conglomerate of the Glenbuck Group followed by its shelf and intertidal deposits of grey and red sandstone and calcareous mudstone. In this transition from open marine to continental sedimentation there was much opportunity for the development of lagoons and lakes and renowned faunas are well-preserved in the resulting finely laminated lagoonal to lacustrine strata. Fish, eurypterids and pod-shrimps are amongst the best-known fossils (Rolfe 1992); nautiloids and plant material are also present. Like the higher of the fish beds at Lesmahagow, the Hagshaw Hills fish fauna includes the agnathans *Birkenia*, *Lanarkia*, *Lasanius* and *Logania*, whilst the eurypterids present include *Lanarkopteris* and *Erettopterus*. Many of the species appear to have been endemic, their distribution controlled by variations in depositional facies. The stratigraphically higher part of the Wenlock succession, the Monks Water Group, comprises conglomerate and sandstone, the lowermost of which contain a terrestrial palynomorph assemblage indicative of a Sheinwoodian, early Wenlock age (Wellman & Richardson 1993).

The two other small inliers of the central association, Carmichael and Eastfield, contain successions with many similarities to that in the Hagshaw Hills inlier. At Carmichael, the mudstones at the base of the Carmichael Group are locally fossiliferous, with a varied shelly fauna plus graptolites confirming a Late Llandovery age (Rolfe 1960). The upper, Wenlock part of the group is a coarser-grained succession of conglomerate and sandstone. The small, Eastfield inlier, contains sandstone and conglomerate most probably equivalent to that in the upper part of the Carmichael Group.

The eastern, Pentland Hills inliers

Of the three Silurian inliers in the Pentland Hills, the two small, northeastern examples, Bavelaw and Loganlea, contain sparsely fossiliferous siltstone and mudstone. In contrast, the much larger North Esk inlier contains an extensive and varied succession that is richly fossiliferous and has been much studied (Tipper 1976; Robertson 1989; Clarkson *et al*. 2001). For the North Esk inlier, the first point of note is that its beds are near vertical, strike NE-SW, and young to the NW. All of the succession is included within the North Esk Group which may be as much as 2 500 m thick and shows transition from marine conditions, up through an offshore barrier system impounding a sheltered, shoreward lagoon, and finally into fluvial and terrestrial depositional settings (Clarkson *at al*. 2001).

At the base of the North Esk Group is a thick sequence of marine mudstone and sandstone (Reservoir Formation). It is sparsely graptolitic (confirming a Telychian age: Bull & Loydell 1995) and with a broken, derived shelly fauna at a few points close to the upward transition into a more fossiliferous sandstone-dominated succession (Deerhope Formation). Some of the sandstone beds contain an abundant and varied fauna that includes corals, brachiopods, bivalves and trilobites. Through the middle part of the group, the upward-shallowing trend continues into unfossiliferous and extensively cross-bedded sandstone and pebble-conglomerate, interpreted as offshore barrier and beach deposits (Cock Rigg Formation); they are abruptly succeeded by sandstone and fossiliferous mudstone deposited in a brackish, lagoonal environment (Wether Law Linn Formation). One notable feature of the latter is a 10 cm thick layer of bentonitic clay above which the fossil fauna is much diminished, demonstrating the adverse environmental effects of a volcanic ash-fall (Clarkson et al. 2001). The uppermost part of the North Esk Group comprises red aeolian sandstone and fluvial conglomerates (Henshaw Formation), indicating the onset of terrestrial conditions. A brief marine incursion is marked by siltstone contain fish scales, crinoids and sponges (Robertson 1989) and rare acritarchs (Wellman & Richardson 1993) from which a Wenlock age was established.

Conglomerates, correlation and provenance

Although there are broad similarities in the depositional environments and lithofacies between the Midland Valley inliers, each succession accumulated in its own separate basin. Nevertheless, they share distinctive Wenlock conglomerates (Fig. 7.4) and are overlain by the Greywacke Conglomerate Formation at the base of the Lanark Group. That unit rests on marked angular unconformities at Girvan and the Pentland Hills, but in the central inliers has disconformable relationships with the underlying strata, erosive but with minimal structural discordance. Each of the conglomerates is characterized by a particular clast type and their provenance has been the subject of a long-running debate over terrane relationships across the Southern Upland Fault (Bluck 1983, 2002; Smith 1995; Phillips *et al*. 2004).

The lowest conglomerate, marking the base of the Wenlock, is characterized by abundant clasts of igneous rock. It has been informally referred to as the ‘Igneous Conglomerate’ but is locally defined as named formations or members. Many of the clasts in the ‘Igneous Conglomerate’ appear to be first cycle, and in the Hagshaw Hills inlier the overall thinning of the conglomerate and the cross-lamination in associated sandstone, evidence reviewed by Bluck (1983, 2013), suggested derivation from the SE. Fine-grained igneous clasts dominate, peralkaline rhyolites and lithologies indicative of a calc-alkaline to high-K arc complex (Heinz & Loeschke 1988). Also present are granites, wackes (up to 10%), cherts and mica schists, this lithological assemblage is very different to that seen in the currently adjacent Southern Uplands Terrane.

A higher conglomerate within the Wenlock succession is characterised by quartzite clasts. It is informally known as the ‘Quartzite Conglomerate’ but has also been locally defined as either a formation or a member. Its palaeoflow was broadly towards the NNW quadrant based on a thickness and grain size decline which radiates outward from a point midway between the Carmichael and North Esk inliers (Bluck 1983). It is an upward fining wedge of sediment which is at its thickest, *c*. 100 m, in the ESE where also are found the largest clasts, *c*. 1.5m diameter. These large clasts are dominantly well-rounded and may be polycyclic. Within the smaller and generally less-well-rounded clast population, fine-grained igneous lithologies (predominantly rhyolite) and vein quartz are common.

Bluck (1983) regarded the ‘Quartzite Conglomerate’ as an alluvial fan that possibly built into a coastal environment as some of the underlying beds in the Hagshaw Hills inlier are lagoonal and contain fish and eurypterid faunas. This interpretation envisages an alluvial fan with estimated radius exceeding 35 km, in its proximal parts containing substantial rounded boulders. Clearly that would require a source area with some considerable topographic relief and so again raised the possibility of a contemporary uplifted source block to the south, where the present-day Southern Uplands Terrane provides no suitable provenance for the range of clast lithologies seen.

The highest of the three regional conglomerates, the Greywacke Conglomerate Formation, has clasts dominantly of wacke-type sandstone. It is an alluvial fan and talus cone deposit up to 500 m thick with much more variable sedimentology and palaeoflow patterns than the ‘Igneous and Quartzite conglomerates’ (Mitten *et al*. 2022). In the Hagshaw Hills inlier, the Greywacke Conglomerate Formation appears to thin and become finer grained to the NW and so Bluck (1983, 2013) made a case for a provenance to the south. The composition of the clasts with this apparent southern derivation were inconsistent with a source in the Southern Uplands. As will be shown later in the chapter, the exposed Southern Uplands wackes have a wide range of compositions, but the clasts are notably richer in quartz and acid rock fragments than *in situ* Southern Uplands wackes. An additional, but related problem is the source of Ordovician limestone clasts described from the Greywacke Conglomerate Formation in the Pentland Hills (Armstrong & Owen 2000; Armstrong *et al*. 2000). The limestone contains conodonts with a colour index suggesting thermal alteration prior to erosion and redeposition but, again, there is no known source for this lithology in the Southern Uplands.

Phillips et al (2004) approached the problem from the perspective of the Silurian sandstones rather than the conglomerates. They established that the sandstone-dominated sequences in the Silurian inliers and the lower part of the overlying Lanark Group are petrographically and compositionally similar and share the same provenance. Minor differences in sandstone composition between the Carmichael, Eastfield and North Esk inliers were interpreted as reflecting their deposition within individual, fault-controlled sub-basins. The lithologies present as sand grains indicated a provenance that included a granitic igneous suite, volcanic to hypabyssal igneous rocks, and a wacke-dominated sedimentary succession, all founded upon an older metamorphic basement. The location of this geological assemblage, still envisaged as lying to the south of the Silurian inliers, remained uncertain.

The Southern Uplands accretionary complex

The Southern Uplands Terrane occupies about 10 000 km^2 of southern Scotland and has a westward correlation into the Down-Longford massif of Ireland (approximately 6 000 km^2). Its northern boundary with the adjacent Midland Valley Terrane, the Southern Upland Fault (SUF), is represented to the south of Girvan by the Stinchar Valley Fault that also marks the southern limit of the Ballantrae Complex. Traced to the eastern side of Scotland, the SUF continues through the Midlothian coalfield as the controlling structure, at depth, of the Crossgatehall Fault, and thence into the Firth of Forth graben (McKerrow & Elders 1989; Floyd 1994). The apparent terrane boundary at outcrop steps SE to the Lammermuir Fault which, farther SW, forms an internal structural boundary within the Southern Uplands (Fig. 7.1).

The Southern Uplands Terrane is characterised by Ordovician and Silurian turbidite successions of sandstone, siltstone and mudstone that have been deformed such that bedding dip commonly approaches vertical or is overturned. Most of the sandstones can be classified as varieties of wacke, the 'greywackes' of the older literature. A superficial uniformity of lithology and structure camouflages the terrane's complexity, and its understanding has only been achieved relatively recently by the integration of a range of geological techniques within the framework of plate tectonics.

A regional overview

Whilst the Ballantrae Complex was being buried beneath the thick, Ordovician forearc shelf succession now seen around Girvan, a different process was operating farther south. As Iapetus oceanic crust was subducted beneath the margin of Laurentia, sections of its uppermost volcanic rocks and their sedimentary cover were intermittently stripped from the subducting plate and thrust beneath a stack of similarly stripped-off slices to form an accretionary complex (Fig. 7.5). The Southern Uplands Terrane represents the eroded remains of this accretionary complex, which developed along the northern fringe of the Iapetus Ocean sequentially from late Darriwilian to mid-Wenlock times. The accretionary complex is often referred to as an accretionary prism, following the introduction of the concept by McKerrow *et al*. (1977) and Leggett *et al*. (1979), but complex is preferred in this account.

In general, the clastic sedimentary units incorporated into the accretionary complex originated as sediment carried by turbidity currents from the continental shelf and deposited in submarine fans. These turbidite deposits encroached onto an oceanic succession of hemipelagic mudstone (the graptolitic Moffat Shale Group), radiolarian chert and pillow lava (Crawford Group) but, in so doing, overstepped progressively younger oceanic rocks that were continually approaching the continental margin as the oceanic plate was subducted. The oceanic succession and its cover of turbidite sandstone was sequentially stripped from the subducting oceanic plate, thrust beneath a growing stack of similar stripped-off slices, and structurally rotated to the vertical or beyond. This structural configuration gave rise to the characteristic pattern of elongated, NE-SW-striking tracts, delineated by major strike-parallel faults (originally accretionary thrusts) that define the Southern Uplands lithostratigraphical outcrop pattern (Fig. 7.6). Graptolite biostratigraphy in a series of tract profiles is shown in Figs 7.7 and 7.8. From SW (Fig. 7.7) to NE (Fig. 7.8) the tract arrangement is modified by a tendency for the Ordovician tracts to thin and for some to be eliminated, whilst there is increased structural repetition of the Silurian tracts.

At its simplest, each Southern Uplands tract comprises a steeply inclined succession that youngs towards the north. The Moffat Shale and Crawford groups form the base of the succession, faulted at its southern margin. Above these thin, basal groups, a thick succession of turbidite sandstone is terminated at each northern tract margin by a fault contact with the base of the adjacent, structurally higher tract. Cumulatively, this produces the paradox of Southern Uplands stratigraphy: despite an overall sense of younging to the north within individual tracts, the oldest Southern Uplands tracts are found in the north of the terrane whilst the youngest tracts crop out in the south (Fig. 7.9).

Although the Moffat Shale Group underlies most of the Ordovician and earliest Silurian turbidite sandstone successions, it is not seen beneath the oldest of the Ordovician tracts (the Tappins Group) nor the younger of the Silurian tracts; in these cases, the age control is provided by sporadic interbeds of graptolitic mudstone. In those tracts where the Moffat Shale Group does occur, in addition to the internal sense of younging towards the north and the decrease in minimum age southwards, the time interval represented by the Moffat Shale Group within each tract increases southward (Figs 7.7 & 7.8).

Despite turbidite sandstones comprising by far the greater part of the succession – sandstone formations range up to 3 000 m in thickness whereas the Moffat Shale Group is nowhere more than about 80 m thick – those in any one tract are generally either of the same biostratigraphical age as, or only slightly younger than, the youngest part of the underlying Moffat Shale Group (Figs 7.7 & 7.8). Locally, the Crawford Group ranges down to the Early Ordovician, whilst the overlying Moffat Shale Group is restricted to the Late Ordovician in the northern tracts but extends into the Llandovery in the southern tracts. The age of the turbidite successions tracks that of the Moffat Shale Group in becoming younger southwards: Late Ordovician in the north of the terrane in the tracts comprising the Tappins, Barrhill and Scaur groups, Llandovery in the older tracts of the Gala Group**;** farther south the trend is confirmed by the graptolitic interbeds in the Llandovery (and early Wenlock locally), younger tracts of the Ettrick and Hawick groups, and the entirely Wenlock, Riccarton Group, which comprises the southernmost tracts.

The definition of the individual tracts may also be assisted by marked compositional differences in their component sand grain populations (and hence their provenance), a dominance of quartzo-feldspathic grains in some tracts contrasting with a dominance of andesitic and lithic grains in others. This effect is most apparent in the Ordovician part of the terrane, where sandstone units of contrasting composition are also interbedded in some tracts. Compositional contrasts are maintained into the earliest Silurian Gala Group tracts but thereafter, southwards, the sandstones become more uniformly mature in character and in general are finer grained than those to the north. There are many local exceptions to this general trend.

The model of the Southern Uplands as a forearc accretionary complex is now generally accepted, following much discussion of possible alternative models that arose, in part, from the provenance contrasts evident between different sandstone tracts. In particular, the apparent introduction of volcanic detritus from the south, from the oceanic plate rather than the continental margin, was cited in support of a back-arc origin for at least the Ordovician sector of the terrane (Morris 1987; Stone *et al*. 1987); analyses of basin thermal history have now ruled out that proposal (Stone & Merriman 2004). There has also been some discussion of the possible extension of the Girvan depositional setting into an extending and subsiding continental margin basin before the tectonic incorporation of its strata into the northern part of the Southern Uplands Terrane (Armstrong et al. 1996; Armstrong & Owen 2001). Nevertheless, whilst this introduces a measure of unresolved uncertainty, the development of the Southern Uplands Terrane as a supra-subduction-zone accretionary complex is now the consensus view: key references include McKerrow *et al*. (1977), Leggett *et al*. (1979), Leggett (1987) and Stone (2014). Examples of the Southern Uplands graptolite fauna are shown in Figure 7.3c and d.

Building on biostratigraphy

Early attempts at determining the overall geological structure of the Southern Uplands had foundered on the apparently intractable monotony of the succession. Graptolite biostratigraphy provided the crucial breakthrough (Rushton 2001) and in his seminal contribution Lapworth (1878) defined the internal stratigraphy of the 'Moffat Shale' and established a regionally applicable succession of biozones based on meticulous fieldwork. He recognised and named, in upward succession, the Glenkiln, Upper and Lower Hartfell and Birkhill shales, now formalised as formations (Figs 7.7 & 7.8). Lapworth's insights led to a regional reappraisal in a monumental Geological Survey memoir (Peach & Horne 1899): a classic of Victorian science, it remains a valuable source of geological data.

At Dob's Linn, 15 km NE of Moffat, Lapworth (1878) detailed the Moffat Shale Group mudstones striking broadly NE–SW in one of the most continuous basal successions seen in any of the Southern Upland tracts. Illustrating the regional pattern, the SE limit of the mudstones is marked by a major strike-parallel fault, whilst at their NW limit the mudstones are abruptly and conformably succeeded by Gala Group (Queensberry Formation) sandstone beds. In this section, the mudstone succession spans 18 graptolite biozones from the early Sandbian (Late Ordovician) to the mid-Llandovery (early Silurian) in about 80 m of strata (Fig. 7.10). In other Moffat Shale Group outcrops there are rare sandstone interbeds (Rushton & Stone 1991), a significant concentration locally forming the Ettrickbridge Formation (Fig. 7.8) (Floyd 2001). These indicate periodic incursion of turbidity flows from the forearc region to the north. The closely defined graptolite biostratigraphy at Dob's Linn has enabled the section to be established as the 'Global Stratotype Section and Point' (GSSP) for the base of the Silurian System (Williams, S.H. 1988; Rong *et al*. 2008), now defined 1.6 m above the base of the Birkhill Shale Formation at the base of the *Akidograptus ascensus* Biozone (Fig. 7.10). Pannell *et al*. (2006) demonstrated the possibility of achieving even finer-scale biostratigraphical resolution at Dob's Linn.

Although black, graptolitic mudstone with thin chert interbeds is characteristic of the Moffat Shale Group as a whole, the Upper Hartfell Shale Formation contains only a very sparse graptolite fauna and is dominated by grey, rather than black mudstones. This variation has been widely ascribed to the cooling effect of the Hirnantian glaciation, although a recent trace element geochemical study at Dob's Linn has instead favoured the warming effect of large-scale volcanicity, with resulting anoxia, as the primary cause of the lithological variation (Bond & Grasby 2020).

Numerous thin layers of volcanic ash (metabentonites) interbedded within the mudstones provide ample confirmation of volcanicity contemporaneous with deposition of the Moffat Shale Group. Merriman & Roberts (1990) described 138 metabentonite layers from the Upper Hartfell Shales and Birkhill Shales, typically comprising 5–10 % of the compacted succussion but rising to 20% of the total in the *convolutus* to *sedgwickii* biozones (Fig. 7.10). It is possible that the repeated volcanic ash falls had an impact on the graptolite populations. Pannell *et al*. (2006) described taxonomic richness decreasing upwards through the *sedgwickii* Biozone and suggested that the ash falls might have led to local extinctions of graptolite populations. Unsurprisingly, Llandovery metabentonites also occur sporadically within the turbidite sandstone successions of the Southern Uplands and have been regionally correlated with their Irish equivalents (Batchelor *et al*. 2003).

As a useful complement to the graptolite biostratigraphy at Dob's Linn, radiometric dates from zircon in the metabentonites (Tucker *et al*. 1990) bracket the Ordovician-Silurian boundary (Fig. 7.10). A U-Pb age of 445.7 ± 2.4 Ma was obtained from the *anceps* biozone (revised to 448.88 ± 1.17 M by Melchin *et al*. 2012, p. 546), and of 438.7 ± 2.0 Ma from the *revolutus* biozone (cited as 439.57 ± 1.13 Ma by Melchin *et al*. 2012, p. 545). Note that the age from the *revolutus* biozone is slightly young relative to the internationally accepted age for the Aeronian–Rhuddanian boundary.

Current concepts of Southern Uplands geology have built, *inter alia*, on turbidite sedimentology, fold vergence, and sandstone petrography, but it was the biostratigraphy of the Moffat Shale Group that catalysed recognition of the major strike-parallel faults within the terrane as imbricate thrust zones (Toghill 1970; Fyfe & Weir 1976), and so played into a wider, regional interpretation in plate tectonic terms. For the Southern Uplands, the origins of an 'accretionary prism' model can be traced back to a landmark paper by Dewey (1971) who discussed the Early Palaeozoic evolution of the Scotland-Ireland sector of the Laurentian margin as the Iapetus Ocean closed. Dewey identified the Southern Upland succession as a wedge of clastic sediment that initially built up in a continental margin trench, but then extended out across the subducting oceanic plate. Deformation arose from shortening of the sedimentary succession in response to segmentation of the oceanic crust. Presciently, figure three of Dewey's paper showed a stratigraphical correlation chart within which eight Southern Uplands columns form a time-stratigraphical series in which each column showed the onset of turbidite sedimentation, conformably succeeding graptolitic mudstone, becoming progressively younger southward. Dewey's interpretation foreshadowed the evolution of the 'accretionary prism' model (Fig. 7.5) through a series of papers by McKerrow, Leggett and co-workers (McKerrow *et al*. 1977; Leggett 1980, 1987; Leggett *et al*. 1979, 1982).

The progress in biostratigraphy that has made possible the detailed interpretations of Figs 7.7 and 7.8 has been reviewed by Rushton (2001). Most notable since the pioneering work of Lapworth, Peach and Horne is the increasing refinement of biozonation, which has resulted in a doubling of the recognised divisions relative to the twelve in Lapworth's original (1878) scheme (Zalasiewicz *et al*. 2009). In the Southern Uplands, the principal effect of the biostratigraphical refinement has been to allow the recognition of a more detailed arrangement of structural tracts, a process complemented by new fossil discoveries. For example, the Katian (and possibly Hirnantian) faunas of the Glenlee Formation, the southernmost of the Ordovician tracts in the SW of the Southern Uplands (Fig. 7.7), were only identified relatively recently (Floyd & Rushton 1993). More widely, along-strike variations have also become more apparent with the profiles across different parts of the Southern Uplands now seen to be significantly different (Figs 7.7 & 7.8). This has important structural implications, showing individual tracts being excised or repeated and, in some cases, appearing to be out-of-sequence.

The cross-strike, time-stratigraphic profiles now used to illustrate the Southern Uplands tract assemblage show a much greater level of detail than was possible in the early expositions by Leggett *et al*. (1979, 1982). Nevertheless, the same limitations are still imposed by the restricted nature of the faunas at any one locality. The cross-strike profile is determined by the youngest graptolite fauna obtained from the Moffat Shale Group, from beds immediately beneath the overlying turbidite sandstone, in each structural tract. It is always possible that the truly youngest fauna has been missed during collecting, or that the strata containing it have been tectonically excised; most Moffat Shale outcrops are indeed sheared and disrupted. However, except in the youngest, southernmost tracts, graptolitic interbeds within the overlying turbidite successions have always indicated either the same biozone as proved from the youngest part of the underlying Moffat Shale Group, or the next younger biozone. In the southern part of the terrane, Moffat Shale is not seen to underlie much of the Hawick Group or the Riccarton Group, and for these divisions the biostratigraphical control is limited to fossiliferous interbeds. These are rare and so provide only sparse biostratigraphical control in the Hawick Group but are relatively abundant in the Riccarton Group, for which the control is, accordingly, better.

Conodonts were used by Armstrong *et al*. (1996) to supplement the graptolite biostratigraphy of the Northern Belt and to strengthen correlation with the coeval Midland Valley successions. Their interpretation, and the broader regional synthesis by Armstrong & Owen (2001), was also aided by correlations of the shelly fauna, notably brachiopods. Within the Kirkcolm Formation of the Northern Belt, shelly fauna, comprising trilobites, gastropods and corals (Fig. 7.3e) as well as the brachiopods, is not *in situ* but is instead, at several localities to the NE of Abington, contained within mass flow deposits interbedded with the sandstone succession (Clarkson *et al*. 1992). The fauna is of Sandbian or earliest Katian age and is equivalent to *in situ* shelly faunas known from the southern margin of the Midland Valley Terrane at Girvan (Scotland) and Pomeroy (Northern Ireland). Despite its relative proximity to Girvan, the Kirkcolm Formation fauna compares most closely to that of Pomeroy, a correlation best established for the brachiopods by Candela & Harper (2010). The conclusion drawn was that any sinistral displacement along the Southern Upland Fault was more limited than that required in earlier speculation linking Southern Uplands conglomerates to a source in or near Newfoundland (Elders 1987; McKerrow & Elders 1989).

Oceanic crust and intra-basinal volcanic suites

The oldest rocks known from the Southern Uplands Terrane are the Middle Ordovician mudstones, cherts and basaltic lavas of the Crawford Group. They represent the oceanic substrate on which the pelagic mudstones of the Moffat Shale Group were deposited. Within that group (and sporadically within the coeval sandstone-dominated formations), metabentonite interbeds range up into the late Llandovery, becoming most common around the *sedgwickii* Biozone. Their geochemistry ranges from subalkaline to peralkaline, indicative of eruption in an ensialic volcanic arc or possibly a back-arc setting (Merriman & Roberts 1990; Batchelor & Evans 2004).

The oldest volcanic rocks, the basalt lavas of the Raven Gill Formation (Crawford Group), have a restricted outcrop in the Abington area, adjacent to the Leadhills Fault. There, the lavas are closely associated with blue-grey radiolarian chert and brown mudstone for which a probable Floian–Dapingian age is indicated by conodonts (Armstrong *et al*. 1990). A mixture of within-plate lava types and tholeiitic basalts of possible mid-ocean affinity has been reported by Phillips *et al*. (1995a) and Barnes *et al*. (1995a), who note that some sheet-like doleritic bodies could be intrusions rather than extrusive lavas.

Basaltic lavas also form the base of the succession in several of the northern Ordovician tectonic slices in the Northern Belt. Some are overlain by mudstone of the early Sandbian *gracilis* Biozone which, together with associated chert, make up the Kirkton Formation (Crawford Group). Armstrong *et al*. (1996) assigned conodont faunas from Kirkton Formation chert and mudstone intimately associated with the lavas to the *anserinus* conodont Biozone, which spans the Darriwilian – early Sandbian interval. Further, at several localities, the lavas are interbedded with the lowermost part of the sandstone succession and so are more probably of Sandbian age (Floyd 1982). This association of *anserinus* Biozone conodonts immediately overlain by *gracilis* Biozone graptolites supports a common, earliest Sandbian age for the volcanic rocks preserved in several successive thrust slices within the Northern Belt. Some are subjacent to the Marchburn Formation and others either underlie or are interbedded with the basal sandstone of the Kirkcolm Formation on the Rhins of Galloway (Fig. 7.1) (Kelling 1961; Stone 1995).

A different relationship is possible farther south, at Gabsnout Burn near Glenluce, where volcanic rocks occur beneath the base of the Portpatrick Formation. These basalt and dolerite bodies have been described by Phillips *et al*. (1995a) as allochthonous blocks within *gracilis* Biozone Moffat Shale Group mudstone. Their age, their source, and the mechanism of their emplacement are not entirely clear, but Barnes *et al*. (1995a) interpreted their geochemistry as indicating island arc volcanicity. Barnes (2008, p. 25) noted the difficulty in reconciling the presence of volcanic olistoliths derived from an island arc with the oceanic depositional setting of the Moffat Shale Group even allowing the possibility that the olistoliths may be significantly older than the Moffat Shales in which they are now enclosed.

Stratigraphical uncertainty also surrounds the Downan Point Lava Formation (Tappins Group) in the NW of the terrane, south of Ballantrae, and adjacent to the Stinchar Valley Fault. This unit of tholeiitic basalt lava has geochemistry indicative of within-plate, oceanic island eruption (e.g. Thirlwall & Bluck 1984). It preserves spectacular arrays of pillow forms and was originally thought to be part of the Early to Middle Ordovician Ballantrae Complex. However, Walton (1961) noted the apparent interbedding of similar pillow lavas with the structurally adjacent Tappins

Group, of Darriwilian to Sandbian age. This raised the possibility that the Downan Point lavas are significantly younger than those of the Ballantrae Complex. A poorly constrained Sm–Nd age of 468 ± 22 Ma (Thirlwall & Bluck 1984) did not resolve the issue. Nevertheless, the Downan Point Formation now usually included within the Tappins Group as one of the oldest (Darriwilian–Sandbian) tracts of the accretionary complex (Floyd 2001).

The largest coherent volcanic assemblage unequivocally within the Southern Uplands Terrane is the Bail Hill Volcanic Group which crops out over about 4 km^2 in the central part of the Ordovician Leadhills Supergroup. It is a mildly alkaline, oceanic seamount assemblage, a product of within-plate volcanism (Hepworth *et al*. 1982; Phillips *et al*. 1999). It comprises a heterogeneous succession of submarine lavas and volcaniclastic rocks up to 2 km thick, cut by a vent breccia and several minor intrusions. The volcanic rocks range in composition from alkali basalt to trachyandesite. The oldest part of the volcanic succession rests on Moffat Shale Group mudstone of *gracilis* Biozone age whilst younger parts laterally interdigitate with and overlie turbidite sandstone beds of the Kirkcolm Formation, also of *gracilis* age. These biostratigraphical controls indicate early Sandbian volcanicity.

Another likely manifestation of Late Ordovician volcanism is seen within the eastern part of the terrane as the Tweeddale Member of the Shinnel Formation. The member is a heterogeneous assemblage of limestone blocks (the Wrae Limestone) and peralkaline rhyolitic lavas (the Tweeddale lavas) regarded by Leggett (1980) as a submarine slide deposit. The host Shinnel Formation contains an *anceps* Biozone graptolite fauna and overlies Moffat Shale Group strata ranging up to the *linearis* Biozone (Floyd & Rushton 1993) so is largely Katian in age. However, the exotic limestone blocks contain conodonts of the *anserinus* Biozone, Darriwilian–Sandbian (Armstrong *et al*. 1996), so the associated volcanic rocks may also be of that age. Hence, the Tweeddale Member lavas could be coeval with the other Sandbian volcanic units within the Northern Belt of the Southern Uplands. The Tweeddale lavas were described by Thirlwall (1981) as peralkaline rhyolites of likely oceanic-island origin.

In summary, there are two important aspects of the Southern Uplands volcanism. Firstly, it is likely that there were two distinct episodes of eruption, one Floian–Dapingian and the other in the early Sandbian. Secondly, the Sandbian lavas are in places interbedded with the sandstone succession, showing that eruption and turbidite deposition overlapped in time. The Floian–Dapingian volcanic rocks, the substrate to the Moffat Shale Group, have diverse origins with possible mid-oceanic basalts, within-plate/ocean island lavas and perhaps even arc-related rocks all represented. The *in situ* Sandbian volcanic rocks are all within-plate or ocean-island types associated with cherts of the *anserinus* conodont Biozone and/or mudstones of the *gracilis* graptolite Biozone. These lavas are also interbedded locally with the sandstone sequences of the Marchburn and Kirkcolm formations establishing that eruption occurred within the main depositional basin and over an area wide enough to span turbidite fan systems derived contemporaneously from contrasting provenances.

Finally, a puzzling epilogue to the Sandbian lavas is provided by the REE chemistry of associated cherts. Owen *et al*. (1999) reported its close similarity to that of recent cherts from continental-margin settings and discounted the deep-ocean origin most readily compatible with interpretation of the Southern Uplands as an accretionary complex. The uniformity of age seen across the Sandbian volcanic rocks, their likely eruption in an extensional environment, and their relationship with the turbidite sequences was also thought by Armstrong *et al*. (1996) to be incompatible with a uniformly accretionary model of the Southern Uplands. They preferred an extensional environment developed within a narrow continental shelf for the volcanicity, and hence for the subsequent accumulation of Upper Ordovician sediment. These uncertainties remain.

Lithostratigraphy: sedimentary characteristics

The thin successions of pelagic mudstone and chert within the Crawford Group and Moffat Shale Group accumulated very slowly across the broad expanse of the Iapetus Ocean, laid down on the volcanic rocks of the oceanic crust. Thick, Sandbian to Wenlock turbidite successions transgressively overlie the Moffat Shale Group and dominate the Southern Uplands succession. An overall assessment of lithostratigraphy was provided by Floyd (2001), whilst considerable local detail is available in a series of BGS memoirs: Stone (1995), Floyd (1999), Lintern & Floyd (2000), McMillan (2002), Barnes (2008). Stratigraphical variation in the dominant lithofacies, both vertically and lateral, is characterised by changes in individual bed thickness and the range of turbidite features present: sole structures on bed bases, grading, and cross- and planar-lamination. For the younger Southern Uplands tracts comprising the Gala, Hawick and Riccarton groups, the assemblages of sedimentological features are an important element in the definition of the lithostratigraphical divisions. For the older tracts of the Leadhills Supergroup, the sedimentary features supplement divisions defined by variable detrital grain populations.

The turbidite sandstone successions comprise varying proportions of three dominant lithofacies: channel-fill sequences of massive sandstone, coarse-grained, thickly bedded and locally associated with intraclast (sandstone) breccia and conglomerate; lobe or unconfined sheet flow deposits of well-bedded, fine- to medium-grained sandstone with subordinate mudstone; and interchannel or interlobe deposits of siltstone and silty mudstone. These lithofacies are interbedded in vertical alternations that range in thickness from a few tens of metres to several hundred metres, but they also pass laterally from one to another on a scale of hundreds of metres to several kilometres. Most of the sandstones contain a high proportion of fine-grained matrix enclosing poorly sorted grains and are classified as wackes, greywackes in the older literature.

Individual beds may display a complete or partial array of the characteristic turbidite features. Where substantial turbidity flows closely followed each other, a thick succession of amalgamated, graded sandstone beds resulted, with only subtle variations in grain size determining the margins of each bed. For more distal deposits, or those arising from small, low-density flows, thin and fine-grained sandstone beds may be pervasively laminated and separated by thicknesses of silty mudstone, the finest-grained part of the submarine-fan succession deposited in areas that were spatially or temporally removed from most of the depositional activity. In these parts of the succession trace fossils may be locally abundant. Benton (1982) described a range of meandering tracks, feeding trails and burrow networks, mostly from Silurian strata; environmental control dictated the assemblage present.

Where the base of a turbidite sandstone bed overlies the fine-grained top of its predecessor, it is usually sharp and clearly defined, though load structures and groove and flute casts are common on many of the bed bases (Fig. 7.11). If the bed is rotated back to the horizontal, the orientations of the groove and flute casts indicate the flow direction of the original turbidity current (the palaeocurrent), which also influenced the geometry of the ripples that show up in section as cross-lamination. This becomes an important interpretational tool when linked with the distinctive compositions of the sandstones forming some tracts, particularly those of the Ordovician, Leadhills Supergroup.

Given the structural setting of the Southern Uplands succession the general coherence of the strata is somewhat unexpected. In many other accretionary situations there was considerable disruption of the accreting strata to produce an abundance of mélange, but this lithology is generally scarce in the Southern Uplands. Mélange or 'mélange-like' lithologies have been described by Kemp (1987) and Needham (1995) from the Hawick Group, and by Ogawa (1998) from the Tappins Group, but all would be more properly termed 'broken formations' and still represent only a very minor component of the overall sedimentary assemblage.

Leadhills Supergroup
The Tappins Group turbidite successions form the most northerly structural tracts of the Ordovician, Leadhills Supergroup. Limited biostratigraphical (graptolite and conodont) evidence indicates a Sandbian age for all the component formations but, unlike the situation in other Ordovician tracts, they do not rest on Moffat Shale Group strata (Figs 7.7 & 7.8). The successions comprise red and green mudstone, chert, turbidite sandstone and conglomerate. Most of the sandstones were derived from the north and NW and are immature (Fig. 7.12); they contain a high proportion of igneous detritus, much of it likely to have been derived from ophiolitic rocks similar to those forming the Ballantrae Complex. The conglomerates form stacked, lenticular bodies interpreted by Kelling *et al*. (1987) as proximal or inner-fan features deposited in laterally migrating channels with a minimum width of 2–3 km. They invite comparison with the conglomerates of the Barr and Ardmillan groups in the Girvan succession. Like those, the Corsewall Formation conglomerates may be either clast- or matrix-supported and contain rounded boulders up to 1.5 m in diameter with a range of compositions (Fig. 7.13): various granitic and granodioritic lithologies (some with an apparently tectonic foliation), felsite, spilite, wacke, chert and polymict conglomerate. A U-Pb monazite age from a granite boulder of 474 ± 2 Ma (Bluck *et al*. 2006) is within the 481 Ma to 451 Ma range of ages obtained from granitic boulders in the Girvan conglomerates, as is an imprecise Rb-Sr date of 475 ± 20 Ma from another granite boulder (Elders 1987). Another similarity to the Girvan conglomerates is the scarcity of metamorphic clasts.

To the south of the Tappins Group tracts, the Moffat Shale Group underlies thick turbidite sandstone successions with ages that range southward through the Sandbian and up into the Katian (Figs 7.7 & 7.8). These comprise the Barrhill and Scaur groups, the latter extending south to the Orlock Bridge Fault. Thickly to thinly bedded sandstone dominates all the component formations but there are marked variations in the compositions of the sandstones in each tract, indicating derivation from a range of different provenance regions. These compositional differences are not only on a tract scale, but also appear as the interbedding of differently sourced sandstone units. So, within the Barrhill Group, the quartzo-feldspathic wacke succession of the Kirkcolm Formation has interbeds of volcaniclastic wacke assigned to the Galdenoch Formation and polymict wacke and conglomerate of the Blackcraig Formation; within the Scaur Group, the volcaniclastic wackes of the Portpatrick Formation have interbeds of quartzo-feldspathic wacke assigned to the Glenwhargen Formation, and the Glenlee Formation has quartzose and andesitic components. The overall range of Leadhills Supergroup sandstone composition is illustrated in Fig. 7.12, with additional details summarized in Table 1.

There is abundant evidence for the direction of palaeocurrent flow from flute and groove casts on the bases of sandstone beds (Fig. 7.11), and from cross-lamination in their silty upper parts. For most formations, the directions indicated are quite variable, the likely result of deposition in meandering channels within submarine fans derived from the NW that were themselves deviated into a basin-axial, NE or SW trend (Kelling *et al*. 1987; Smith *et al*. 2001). The exception is the Portpatrick Formation, the most extensive of the Ordovician volcaniclastic divisions, which was consistently derived from the SW quadrant. This contrast was one of the features that prompted the back-arc depositional model for parts of the Leadhills Supergroup (Morris 1987; Stone *et al*. 1987), now invalidated by the accumulation of evidence in favour of accretion as reviewed by Stone (2014).

Marking the southern boundary of the Leadhills Supergroup, the Orlock Bridge Fault has traditionally been seen as one of the more important Southern Uplands strike-parallel faults simply because it separated strata of Ordovician and Silurian ages. Whilst its major structural importance remains (Anderson & Oliver 1986; Barnes *et al*. 1995b; Phillips *et al*. 1995b), the biostratigraphical break across the fault is within the range seen across most of the other tract boundary faults (Figs 7.7 & 7.8), an apparent contradiction that will be returned to later in this chapter.

Gala Group

The Gala Group combines the sandstone-dominated tracts between the Orlock Bridge Fault and, to the south, the faulted boundary with the Ettrick and Hawick groups. Tracts range from a few hundreds of metres to a few kilometres in outcrop width and their age becomes progressively younger southwards, with an overall range spanning the Llandovery *acuminatus* to *guerichi* biozones (Figs 7.7 & 7.8). From SW to NE there is a tendency for the older and younger tracts to be repeated by faulting, with the middle tracts eliminated.

Palaeocurrent indicators show that sediment transport during deposition of Gala Group sandstones was predominantly towards the SW. Sandstone composition is typically quartzo-feldspathic (Fig. 7.12), with quartz forming up to 55% and feldspar (plagioclase and K-feldspar in varying proportions) 20–30% of the rock. Mica generally forms a minor component but is more abundant in fine-grained sandstone. Detrital pyroxene and amphibole occur sporadically in the older formations where, together with andesitic and basaltic grains, they may locally make up 20% of the population. Other lithic grains comprise clastic sedimentary, felsic igneous, and spilitic volcanic rocks, the latter becoming more abundant in the younger part of the group. Grains of garnet, tourmaline, zircon and epidote are present in the sandstones of all tracts, with chrome spinel a characteristic feature in the older Gala Group sandstones.

Mudstone and siltstone are commonly interbedded with the Gala Group sandstones and represent fine-grained elements of the submarine fan succession laid down in areas sheltered from sandstone deposition. They may dominate the succession locally. In the older tracts, dark grey graptolite-bearing mudstone commonly forms units up to 10 m thick, and locally up to 80 m, which are effectively interbedded, lateral equivalents of the pelagic Birkhill Shale Formation. In younger tracts, massive or laminated siltstone dominates units that are tens, and locally hundreds, of metres thick and which contain only a small proportion of medium- to coarse-grained sandstone in thin beds.

Ettrick Group

In the western part of the Southern Uplands the Laurieston Fault forms a relatively well-defined boundary between the Gala and Hawick groups (Fig. 7.1), but eastwards the distinction is less clear and is further complicated by additional structural imbrication which has the effect of progressively broadening the Llandovery outcrop (e.g. Akhurst *et al*. 2001). To address this issue and to resolve stratigraphical difficulties eastward from the Moffat–Ettrick area, the Ettrick Group was introduced relatively recently (Stone *et al*. 2012) so was not included in the otherwise comprehensive review by Floyd (2001). It incorporates strata lying to the south of the Moffat Valley Fault that had been formerly assigned to the Gala Group, and some strata lying to the south of the Laurieston Fault that had been previously included within the Hawick Group.

The Ettrick Group is characterised by a turbidite lithofacies of well-bedded sandstone, locally coarse-grained, with mudstone interbeds up to about 40 cm thick. Very thick sandstone beds and thick massive siltstone units occur sporadically. Sole marks are common on the base of the turbidite sandstone beds with linear grooves and flute casts establishing a palaeocurrent flow dominantly towards the SW. One division, the Grieston Formation, forms a narrow outlier within the Gala Group around Innerleithen, to the north of the main Ettrick Group outcrop, and is largely composed of laminated to thin-bedded alternations of fine-grained sandstone, siltstone and mudstone. In addition to control provided by the underlying Moffat Shale Group, the biostratigraphical age of the Ettrick Group is defined by graptolite faunas from mudstone interbedded within the turbidite succession. It is unusual for the Southern Uplands in that within individual tracts it spans several Telychian graptolite biozones, from *guerichi* to *spiralis* (Fig. 7.8), and so overlaps with the range established for the very youngest part of the Gala Group, and the oldest part of the Hawick Group.

Quartz and feldspar (mostly plagioclase) dominate the detrital grain population in the sandstones. Garnet is common locally in coarse-grained sandstone and tourmaline, zircon and epidote are widely present as minor accessory mineral grains. A variable proportion of lithic detritus includes grains of clastic sedimentary and metasedimentary rock, fine- and coarse-grained felsic igneous lithologies and, conspicuously, mafic volcanic/spilitic rocks. Some carbonate (CaO up to 7%) is usually present as replacement of matrix or framework grains. Whole-rock geochemical analyses of the Ettrick Group sandstones show them to have a relatively homogeneous compositional character and allow them to be readily distinguished from both the Gala Group and Hawick Group sandstones (Fig. 7.14).

In the central Southern Uplands, the Ettrick Group outcrop is characterized by relatively closely spaced tract-bounding faults that define numerous anastomosing tracts. Farther NE, Moffat Shale outcrops become relatively rare and the tracts that can be recognised appear correspondingly broader, although a similar level of cryptic tectonic imbrication may well be present. However, the tract arrangement of the Ettrick Group is in some respects unusual, since the oldest strata in every formation are of *guerichi* or early *turriculatus* Biozone age, and the same base level is repeated across several adjacent tracts in the closely faulted areas (Fig. 7.8).

Hawick Group

The Hawick Group comprises the late Llandovery (Telychian) to early Wenlock (Sheinwoodian), sandstone-dominated turbidite strata that crop out between the Ettrick Group to the north and the Riccarton Group to the south. The steeply dipping fault-bounded tracts that characterise the structural pattern in the older Southern Uplands divisions are identifiable only in the oldest part of the Hawick Group in SW Scotland, where narrow slivers of the underlying Moffat Shale Group are locally preserved. For the central part of the Hawick Group outcrop, it is evident only that the succession is much folded, but at its southern margin the distribution of graptolites found in the Ross Formation has allowed definition of four narrow tracts, albeit much disrupted internally (Fig. 7.15).

All formations of the Hawick Group are composed of alternating turbidite lithofacies. The succession is dominated by well bedded sandstone (bed thickness most commonly in the 20–60 cm range) with interbeds of silty mudstone up to about 30 cm thick. Interspersed are units of thinly interbedded sandstone, silty mudstone and sporadic thick sandstone beds. Thin red mudstone beds are common in the Llandovery part of the succession but are replaced in the upper, mainly Wenlock part by beds of hemipelagic, laminated and carbonaceous siltstone. On this basis, a stratigraphical contact has been defined between the Carghidown and Ross formations (Barnes 2008). The Ross Formation siltstone beds are locally fossiliferous, with graptolite faunas proving the *centrifugus* to *riccartonensis* biozones (Fig. 7.15). In the earlier, Llandovery part of the succession, graptolite faunas are very sparse, ranging from the *guerichi* to the *insectus* biozone (Figs 7.7 & 7.8).

The sandstone is typically fine- to medium-grained with beds graded only in the upper part to siltstone that may be cross-laminated; thinner beds may be laminated or cross-laminated throughout. Sandstone beds have sharply defined bases commonly carrying sole marks, mostly linear grooves and flute casts that generally indicate axial sediment transport towards the SW. Trace fossils, usually small burrows or feeding traces, are abundant in places.

Petrographically, the sandstone is lithic wacke, with angular to sub-rounded grains and up to 40% silt-grade matrix. The sand fraction is dominated by quartz with up to about 10% feldspar, mainly plagioclase (Fig. 7.12). Mica contributes about 3–15% depending on grain size, with reddened, haematite-coated mica grains conspicuous in younger parts of the group. Carbonate is a significant component, forming up to 15%

of the rock, and though now extensively recrystallised it probably originated largely as detrital bioclastic material. The high carbonate content of the rocks is shown by the whole-rock sandstone geochemistry (Fig. 7.14), which also demonstrates the relatively homogeneous compositional character of the group, and its contrast with sandstones from both the Gala and Ettrick groups. The lithic grain assemblage in the sandstone (variable around 15%) consists mainly of mafic-volcanic and sedimentary rocks, polycrystalline quartz and granitic material. Accessory minerals include green tourmaline, zircon and garnet.

Riccarton Group
The Riccarton Group, the southernmost part of the Silurian succession, is in fault contact with the Hawick Group to the north and is unconformably overlain by Lower Carboniferous strata to the south. It includes a range of turbidite lithofacies interbedded with finely laminated carbonaceous siltstone, most probably a hemipelagic deposit. Wenlock graptolite faunas are common in the latter, ranging in age from the *riccartonensis* Biozone to the *lundgreni* Biozone in the Kirkcudbright coastal outcrop (Raeberry Castle Formation – Fig. 7.7), but ranging no higher than the *rigidus* Biozone farther NE (Fig. 7.8). The distribution of graptolites in the Raeberry Castle Formation has allowed three narrow tracts to be identified (Kemp 1986, 1987), which are internally coherent, in marked contrast to the disrupted Ross Formation tracts immediately to the north (Fig. 7.15).

Palaeocurrents were variable but with a modal flow towards the NE quadrant (Lintern & Floyd 2000). The turbidite sandstones, variably fine- to coarse-grained, are quartz-rich (up to 67% of the grains) and may include 5–10% feldspar (predominantly K-feldspar) (Fig. 7.12). Locally they contain abundant carbonate, largely as an alteration product but also as rock fragments and bioclastic debris. Lithic grains form a significant component of coarser sandstone and include quartzite, chert, limestone and acid and basic (spilitic) igneous material; some grains of sedimentary rock are likely to be of intra-basinal origin or were perhaps eroded from previously accreted tracts.

Trench-slope basin deposits
So far, the discussion of the Southern Uplands geological architecture has been in terms of deep-water, submarine fan successions sequentially incorporated into the active front of a growing accretionary complex. Exceptions to this pattern are preserved in the extreme east of the terrane where the Coldingham and Linkim formations crop out on the North Sea coast between St Abb’s Head and Eyemouth in a small inlier surrounded by Devonian volcanic rocks (Fig. 7.1). Although still composed of turbiditic strata they have several unique characteristics.

The Linkim Formation occupies the southern part of the inlier. It is a succession of turbiditic sandstone and mudstone and is pervasively reddened. Beds generally range from 10 to 60 cm in thickness. The detrital clast assemblage is dominantly quartzose with only accessory feldspar and lithic grains. Sedimentary structures, including cross-lamination and bottom structures are well preserved, and although the approximately 200 m of strata exposed are relatively coherent with a low dip, they are inverted. A sparse and low-diversity acritarch assemblage suggests an early Wenlock (Sheinwoodian) age (Molyneux 1987).

The thinly interbedded sandstone and siltstone of the Coldingham Formation form the northern part of the inlier. The detrital grains in the sandstone are largely quartzose with only minor, accessory feldspar, muscovite and lithic fragments. A high proportion of carbonate is common in the matrix, the rocks have a characteristic ochreous weathering, and they are intensely veined by quartz and carbonate. The strata have been pervasively and chaotically deformed by slumping and there is no biostratigraphical control on the age of the formation. Nevertheless, the high matrix carbonate invites comparison with the Hawick Group, of Llandovery age, whilst association with the adjacent Linkim Formation suggests a Wenlock age.

Despite the extreme disruption of the Coldingham Formation and the inversion of the Linkim Formation neither has a well-developed cleavage. Further, the metamorphic grade is amongst the lowest in the Southern Uplands, so countering any tectonic interpretation of the complex structure (Oliver *et al*. 1984). Instead, deposition of both formations was accommodated in trench-slope basins perched on the top of the Southern Uplands accretionary thrust stack. Deformation and overturning were caused by slumping soon after deposition, followed by down-faulting into the body of the accretionary complex.

Lithostratigraphy: the contribution of provenance

However the stratigraphy is defined, one of the more remarkable aspects of the Southern Uplands Terrane is the along-strike continuity of the component structural tracts of steeply dipping, turbidite lithofacies beds. Some individual tracts can be traced across the full width of the Southern Uplands, from the North Sea coast to the Rhins of Galloway (Figs 7.1 & 7.6), and thence into the Down–Longford inlier in Ireland (Barnes *et al*. 1987), despite cross-strike widths that are generally less than 10 km and may be as little as 2 or 3 km. Together with the age difference between adjacent tracts the variation in sandstone composition, particularly marked in the Ordovician Leadhills Supergroup, is a key regional parameter. It enables lithostratigraphical discrimination to be aided by measurement of magnetic susceptibility, the andesite-rich sandstones showing much higher values than the more mature sandstones (Floyd 1999, table 2). Compositional differences in dominant grain populations are less obvious in the Silurian tracts but more subtle variations, probably controlled by matrix compositions, have been revealed by a range of geochemical techniques. They first became evident in a pioneering application of whole-rock geochemistry by Duller & Floyd (1995) who characterised different assemblages of cratonic- and volcanic-derived sandstones but found mismatches with what might have been predicted from the sandstone petrography.

On a regional scale, compositional contrasts between the different tracts of the Southern Uplands are sufficiently strong to be reflected in the geochemistry of stream sediment sampled within their boundaries (the G-Base dataset: BGS 1993). For individual elements, contoured maps of element concentration in stream sediment commonly show steep gradients coincident with or parallel to the tract boundary faults: two examples are shown in Fig. 7.16. The dominant feature in the distribution of strontium (Fig. 7.16a) is a marked decrease in its abundance across a narrow zone coincident with the Laurieston – Moffat Valley Fault. The change probably reflects variation in the plagioclase to K-feldspar ratio in the detrital grain population: more detrital plagioclase in the sandstones to the NW of the fault, more detrital K-feldspar in the sandstones to the SE. The distribution of chromium (Fig. 7.16b) is dominated firstly by the effects of the ophiolitic Ballantrae Complex, and secondly by a broad zone of very high values running parallel to, but NW of, the Laurieston – Moffat Valley Fault. Detrital chrome-spinel in the Gala Group sandstones underlying this part of the Southern Uplands is the likely cause of this second anomalous zone. In detail, there are cryptic complications in the regional geochemistry data which suggest that Southern Uplands geology has not been fully resolved by field studies (Stone *et al*. 2004, 2006).

The traditional position of the Gala-Hawick boundary, at the northern limit of carbonate-rich sandstones thought characteristic of the Hawick Group, meant that, by default, the rocks to the north of this line were assigned to the Gala Group. However, assessment of the G-Base dataset identified the Moffat Valley Fault (Fig. 7.1) as a major compositional boundary with an abrupt change across it in Rb/Sr ratio, a key feature amongst several steep element-distribution gradients coincident with the fault. To the south of the fault, the area that displays Rb/Sr ratios similar to those of the Hawick Group rather than the Gala Group, but lacks the characteristic high carbonate content of the former, is coincident with the newly defined Ettrick Group, the outcrop of which was extended eastward based largely on the regional geochemical data (Stone & McMillan 2013).

Various geochemical investigations, reviewed by Stone (2014), addressed one of the fundamental points at issue between the different evolutionary models for the Southern Uplands Terrane: the provenance of the volcanic detritus characteristic of some Ordovician and older Silurian tracts. Was the volcanic source north of a forearc accretionary complex (McKerrow *et al*. 1977; Leggett *et al*. 1979) or was it south of a back-arc depositional basin (Morris 1987; Stone *et al*. 1987)? The nature of the volcanic material was established as juvenile and calc-alkaline to tholeiitic, but those characteristics could be accommodated within both models. Stone & Evans (2001) attempted to track the juvenile influence through time using Nd isotope data, with results suggesting progression of the provenance bipolarity seen in the Leadhills Supergroup, mature cratonic versus juvenile volcanic, into an arc unroofing trend during deposition of the Gala Group; a resurgence of juvenile input followed during deposition of the Hawick and Riccarton groups. But this work did not establish the absolute age of the volcaniclastic material.

The Portpatrick Formation, with its dominant palaeocurrent flow from the SW, was of particular interest. Was there active volcanicity contemporaneous with the Late Ordovician sedimentation, as required by the back-arc model? When the age of the Portpatrick Formation volcanic detritus was established, that proved not to be the case. Ar-Ar dating by Kelley & Bluck (1989) of rhyolite and andesite clasts suggested that the volcanic source rocks had an age range of about 560-530 Ma and so were Late Neoproterozoic to Early Cambrian rather than Late Ordovician. Kelley and Bluck's results were relatively imprecise but were subsequently vindicated by U-Pb dating of detrital zircons by Phillips *et al*. (2003), who found a zircon population peak in Portpatrick Formation sandstone at around 557 Ma.

Waldron *et al*. (2008) presented zircon age data from five of the lithostratigraphic divisions of the Leadhills Supergroup where, within sandstones from the Kirkcolm, Galdenoch, Glenwhargen and Shinnel and Glenlee formations an abundance of Archaean and Proterozoic zircons were related to potential sources within the

Laurentian basement. More data in support of a Laurentian origin were subsequently presented by Waldron *et al*. (2014) which, taken in conjunction with their 2008 results, provided detrital zircon distributions from the full range of Southern Uplands divisions including the Portpatrick Formation, although the Ettrick Group was not differentiated from the Gala Group. The results showed a consistent dominance of Mesoproterozoic zircons in all samples, whilst the proportion of Archaean zircon decreased into the younger rocks. Most samples also contained some late Cambrian and/or Early Ordovician zircon grains (*c*. 490–467 Ma) thought to have originated from a combination of Laurentian margin, rift-related and volcanic arc magmatism, or from erosion of obducted ophiolite bodies such as the Ballantrae Complex. These younger zircons are more abundant in the younger tracts of the Southern Uplands, reaching a maximum in the Hawick and Riccarton groups, as predicted by the Nd isotope results of Stone & Evans (2001). For the older zircons, Waldron *et al*. (2014) accommodated their results within an entirely Laurentian provenance, principally by a progressive change in source from younger to older parts of the Dalradian succession.

A broadly Laurentian/Dalradian provenance for much of the Southern Uplands ‘continental’ sediment had also been favoured by Hutchison & Oliver (1998) on the basis of a close similarity between detrital garnet grains from Southern Uplands sandstones (mostly from the Corsewall (Tappins Group) and Kirkcolm (Barrhill Group) formations and ‘Barrovian’ metamorphic garnet from the Dalradian (Grampian Terrane). An alternative, preferred by Kelley & Bluck (1989) was a source for Southern Uplands sandstones within a separate Midland Valley Terrane, where early Palaeozoic arc magmatism – now confirmed by Badenszki *et al*. (2019) – was thought to have been responsible for the uplift of continental basement, allowing its rapid erosion. Bluck (2001) reviewed mica ages then available for the Southern Uplands and the Dalradian and emphasised that the modal age of dates from the detrital micas in the former terrane was some 30 Ma older than the modal age from the Dalradian. Radiometric dating of a granite boulder from a Corsewall Formation (Tappins Group) conglomerate (U-Pb monazite: 474±2 Ma) was also cited by Bluck *et al*. (2006) as evidence for a ‘Midland Valley arc’ provenance for the Southern Uplands sediment, with additional emphasis placed on palaeogeographical objections to a relatively distant, Dalradian provenance. Conversely, the Dalradian provenance for Northern Belt sandstones received strong support from a detrital heavy-mineral study by Mange *et al*. (2005) that demonstrated the progressive unroofing and erosion of a Barrovian-type metamorphic complex.

Accretionary deformation

The simplest concept of the Southern Uplands accretionary complex is that it was built by a series of south-propagating, imbricate thrusts that sequentially stripped the oceanic sedimentary cover from the descending plate and stacked-up the ensuing, fault-bounded tracts, each tract being inserted at the base of a stack of previously accreted tracts: the accretionary model (Fig. 7.5). The true picture is probably more complicated, with frontally accreted thrust units riding above one or more décollement levels below which underplated duplex structures developed (Fig. 7.17).

Polyphase folding was imposed as the accretionary complex built up. Early folds were formed in association with thrusting during the subduction process as each individual tract was accreted. Subsequent folds developed as accommodation structures when the early-formed part of the accretionary complex adjusted to continued subduction at its leading edge and responded to intervals of lateral transpression. However, there is an important difference between the early and late stages in the tectonic development of the accretionary complex. The older tracts were accreted from subducting oceanic crust, but by mid-Wenlock times the Iapetus Ocean had effectively closed and the complex, at the leading edge of Laurentia, over-rode the margin of Avalonia. There was no climactic deformational event associated with this continental collision, and instead the accretionary complex continued to advance through the foreland basin that now formed ahead of it, above Avalonian continental crust depressed by the encroaching mass of Laurentia. The Hawick and Riccarton groups may have been initially deformed in this transitional regime. Convergence of the two continental plates ceased in Ludlow times, but intermittent lateral movement throughout the Southern Uplands Terrane continued into the Devonian and spread north into the southern margin of the Midland Valley. The situation there will be returned to later in this chapter.

In both frontal accretion and underplating situations, the original thrust faults would have initially advanced at a relatively low angle but were structurally steepened, together with the strata between them, as the complex developed. But this would have occurred progressively, the older strata (in the north) becoming steeply rotated whilst younger strata (in the south) remained at a shallow angle. Hence it is difficult to envisage the currently uniform arrangement of steeply dipping and locally overturned strata, consistently present across the entire width of the exposed accretionary complex, being created by the accretionary process alone. Post-accretion compression and steepening would also seem to be required. At depth the tract-bounding faults have been generally illustrated as listric, dipping and merging northwards into a major regional décollement; again, the reality was probably more complicated.

An early phase of deformation (D_1) seen throughout the Southern Uplands was active during thrust propagation; hence the folds produced are diachronous, becoming younger southwards. Later phases of more localised deformation were associated either with accommodation in the thrust hinterland commensurate with D_1 deformation at the thrust front (and so likely to be equally diachronous as D_1 but less systematically so) or with intermittent sinistral shear imposed across the entire belt but focused into major strike-parallel fault zones. It is convenient to describe these post-D_1 deformation phases, respectively, as D_2 (co-axial with the gently plunging D_1 folds) and D_3 (sinistral, steeply plunging folds), but their relationship is not everywhere strictly sequential (Barnes *et al*. 1989).

The Tappins Group contains the earliest accreted tracts. They show evidence of stratal disruption; chaotic bedding is common and scaly cleavage is locally developed (Ogawa 1998). These features were thought by Merriman & Roberts (2001) to be characteristic of frontal accretion in and above a zone of décollement, and they also noted a cryptic disruption of the sedimentary microfabric by bedding-plane slip. Further south, thrust units containing relatively coherent bedding and more widely developed slaty cleavage probably passed beneath the décollement and accumulated as a series of underplated thrust duplexes. Where present, the Moffat Shale Group provided an ideal décollement horizon, allowing the overlying turbidite successions to be stripped from the subducting basement of oceanic crust. Needham (2004) investigated structures within the décollement zones and described different structural assemblages thought to have arisen from deformation at different depths within the accretionary complex. These may correspond to frontal accretion and underplating or to underplating at different structural levels.

There is a variable development of D_1 folds, but throughout the northern and central Southern Uplands tracts gently plunging, south-verging anticline-syncline pairs are typical, compatible with the 'top to the south' movement on the accretionary thrusts (Fig. 7.18). They occur on all scales, with congruous minor fold pairs in the limbs of the larger structures. An axial-planar slaty cleavage is widely developed and in places is refracted into cleavage fans where it passes between sandstone and mudstone. Across-strike, folded zones are interspersed with long, homoclinal sections of steeply inclined, mostly north-younging sandstone beds. This variation in structural style is, at least in part, related to the nature of the strata, intervals of thickly bedded, massive sandstone being less likely to be intensely folded than zones of more thinly bedded strata. Slickenlines along bedding surfaces are mostly perpendicular to the fold hinge orientation, demonstrating early fold growth by flexural slip,

Individual tracts are commonly marked by subtle variations in the style, orientation and intensity of D_1 folding. Notably, the D_1 deformation was particularly intense in the generally finer grained rocks of the Hawick Group, in the southern tracts of which many fold hinges become strongly curved to steeply plunging and are locally downward facing. This phenomenon suggests that significant transpression was involved in D_1 as the Hawick Group tracts were deformed. Further, there is a tendency for the penetrative slaty cleavage to be clockwise transecting by up to 20° locally (Fig. 7.19), an effect of strain rotation between fold initiation and the imposition of cleavage. (Stringer & Treagus 1980).

The extent and character of post-D_1 deformation varies widely across the Southern Uplands. Within the Leadhills Supergroup tracts south of the Tappins Group and those forming the northern (older) part of the Gala Group, the accretion-related folds (D_1) are mostly south-verging (commensurate with the south-directed, accretion-related thrusting) and display axial planar cleavage. Superimposed D_2 structures are relatively rare and localised and generally co-axial with the D_1 folds. Where they do occur, D_2 folds may be associated with a crenulation cleavage and locally with minor north-directed thrust movement (Barnes *et al*. 1989; Needham 1993). To the south, D_2 effects increase in the southern Gala Group tracts and through the Hawick Group outcrop are relatively widespread. Gently plunging, minor to mesoscale folds, coaxial with but refolding D_1 structures, occur in two styles, upright to inclined and recumbent (Fig. 7.20). These have conjugate geometry and locally occur together as open box folds suggesting that they formed together; consequently, both are classified as D_2. Small recumbent folds, verging down the dip of bedding, are most common and are associated with a widely developed, gently dipping, S_2 crenulation cleavage. The orientation and geometry of the D_2 structures suggests that they formed through a continuation of 'D_1' strain after locking of the original D_1 folds, and (or alternatively) by subsequent renewal of shortening on the tract-bounding faults. The recumbent folds could also have formed by sub-vertical 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.

Steeply plunging sinistral folds (D_3) are developed locally throughout the Southern Uplands, affecting bedding and the D_1 cleavage (Fig. 7.21). They are typically found in narrow zones of shearing adjacent to tract-bounding faults and may therefore be associated with reactivation of these structures. The general relationships of D_3 folds to those assigned to D_2 are ambiguous in places, with indications of sinistral shear influencing development of D_1 folds at various times. For example, it is very likely that the sinistral shear associated with D_1 deformation in parts of the Hawick Group – variable fold hinge plunge, transecting cleavage etc. – manifested as D_3 in the older, northern hinterland of the accretionary complex. It also seems likely that there were several episodes of sinistral shear superimposed on the diachronous D_1 and D_2 folds at different times. This means that in some localities in the south of the terrane, folding of 'D_3' style and origin preceded that with 'D_2' character.

In terms of the overall tract geometry, there is a change in D_1 structural style in the southernmost Gala Group that thence carries southward through the Ettrick and Hawick groups. The tract biostratigraphy shows the change in style to have occurred from the late Llandovery onwards. The sequential southward younging of the structural tracts, established through the Leadhills Supergroup and in much of the Gala Group, is replaced in the Ettrick Group by the repetition of narrow tracts all with very similar ages, an outcrop pattern that hints at duplex structure (Fig. 7.6). Southwards through the Ettrick and Hawick groups, there is also increased complexity and asymmetry in the D_1 fold pattern, which features variably plunging fold hinges, north-verging folds and thrusts (McCurry & Anderson 1989; Holdsworth *et al*. 2002) and out-of-sequence thrusts (Rushton *et al*. 1996; McMillan. 2002). These effects cause local irregularities in the otherwise regular pattern of overall younging seen in successive tracts and locally result in successions of steeply inclined beds younging to the south.

The changes in the intensity and combination of structural features from north to south across the Southern Uplands tracts indicates that, from the mid-Llandovery onwards, a significant component of sinistral shear was intermittently present during the accretionary D_1 deformation, at the same time generating D_3 folds within the thrust hinterland. The domainal nature of this transpressive deformation was stressed by Holdsworth *et al*. (2002) who described, from the Berwickshire coastal sections, its partitioning into strike-slip and contraction-dominated zones. The approximate temporal coincidence of this increase in transpression affecting the Hawick Group, with back-thrusting and out-of-sequence thrusting affecting the southernmost (youngest) Gala Group tracts, led to the suggestion by Rushton *et al*. (1996) that during the late Llandovery the accretionary thrust belt had to accommodate to an obstacle to its forward propagation. A basement ramp was modelled by Akhurst *et al*. (2001) but the process might have arisen from the arrival at the subduction zone of a small continental fragment that had rifted from the Avalonian margin (Fig. 7.22a); geophysical evidence in support of this possibility is discussed later in the chapter. Alternatively, the change in structural style may mark the effective closure of the Iapetus Ocean, implying that the subsequent, youngest Llandovery to Wenlock turbidite successions (Hawick & Riccarton groups) were deposited in a foreland basin developed above Avalonian continental lithosphere. Other variables that may have been influential include a change in plate convergence parameters or in sediment input rate. Whatever the cause, by the time of the Wenlock deposition of the

Riccarton Group, the forward-breaking, sequential thrust pattern characteristic of the earlier phase of accretion appears to have been re-established.

The end of the Iapetus Ocean

By the late Wenlock the Iapetus Ocean had closed and a foreland fold and thrust belt migrated across the sutured remains of the Iapetus Ocean and then farther south onto its southern continental margin (Fig. 7.22b). Ahead of the deformation front, sedimentary links suggest that by Wenlock times the foreland basin extended to the Isle of Man and into the south of the English Lake District (Kemp 1991; Kneller *et al.* 1993). A particularly clear correlation is provided by a distinctive laminated hemipelagite facies seen in the Ross and Raeberry Castle formations (Hawick and Riccarton groups respectively) in the Southern Uplands, in the Brathay Formation in the Lake District, and in the Niarbyl Formation in the Isle of Man (Morris *et al.* 1999). By Ludlow times, loading by the advancing Southern Uplands thrust belt had caused an acceleration of subsidence on the Avalonian margin, with deposition of a thick Ludlow turbidite sequence now preserved in the southern Lake District as the Coniston Group. Thereafter, convergence stalled and by the end of the Silurian the post-Iapetus depocenter had stabilised and filled.

The Southern Uplands accretionary complex appears not to have been affected by any substantial internal deformation as a result of the collision of Laurentia with Avalonia, and the southernmost tracts, now forming the Riccarton Group, were incorporated without the development of a pervasive cleavage (Kemp 1986). Accordingly, the collision has been widely described as ‘soft’, final closure of the Iapetus Ocean being largely effected by markedly oblique convergence (Soper *et al.* 1992a). It is hard to distinguish any collisional strike-slip effects, *sensu stricto*, from the D_3 manifestations of strike-slip tectonics, the steeply plunging folds and fold-transecting cleavage.

Despite the lack of ‘collisional’ deformation, and arguments in favour of strike-slip tectonics, there is evidence at the northern margin of the accretionary complex for its northward emplacement onto Laurentian basement (Fig. 7.22b). North-directed thrusting of the Girvan succession during the mid- to late Silurian was demonstrated by Williams (1959) and incorporated into an overall regional structure portrayed by Needham & Knipe (1986) as a large-scale pop-up. In this model, the Iapetus Suture (as defined at the ‘Solway line’) formed the forethrust, and the backthrust zone now manifest at Girvan was responsible for obducting the rear of the accretionary complex northwestward onto the Laurentian margin. An important observation by Floyd (1994) was that, on the south side of the Stinchar Valley Fault, small inliers of ophiolitic rocks were overthrust by Tappins Group strata of the Southern Uplands Terrane. Named by Floyd the Pyet Thrust, this structure formed the original terrane boundary, carrying the northern margin of the Southern Uplands onto the southern margin of the Midland Valley, but it has been mostly eliminated by post-Silurian fault movements. With overthrusting regimes active at both its southern and northern margin, considerable horizontal shortening within the main body of the accretionary complex, orthogonal to strike, would have been accommodated by the widespread rotation of bedding towards the vertical, an attitude hard to attain across the whole terrane solely by accretionary activity.

The last of the 'Caledonian' structural features imposed on the Southern Uplands was a regional, conjugate set of cross-cutting strike-slip faults; sinistral faults trend NNE-SSW whilst dextral faults trend NW-SE. Individual faults have mostly small displacements but they are widespread and numerous so may have a considerable cumulate effect (Anderson 1987; Stone 1995). Reactivation of this fault pattern subsequently defined the marginal orientations of Devonian and Permo-Carboniferous graben and half-graben extensional basins.

The Moniaive Shear Zone

The Moniaive Shear Zone (MSZ) is a major example of sinistral transpression at the northern margin of the Gala Group tract assemblage (Fig. 7.1). It is a zone of high strain, up to 5 km wide, extending over a strike length of c.100 km across the central Southern Uplands (Phillips *et al*. 1995b). It narrows and dies out to both the NE and the SW, although in the latter direction it reappears in Ireland as the substantial Slieve Glah Shear Zone (Anderson & Oliver 1986). In the Southern Uplands, along most of its length the MSZ is truncated abruptly to the NW by the Orlock Bridge Fault but dies out southward within the Gala Group. The exception is in the NE, where the shear zone narrows and diverts southwards, away from the Orlock Bridge Fault, before dying out. The MSZ is characterised by a pervasive foliation accompanied locally by a sub-horizontal, linear extension fabric. The planar shear fabric is sub-parallel to the relatively weaker D_1 cleavage and transposes all earlier structure.

The timing of final shear zone development can be established from relationships in the thermal metamorphic aureole of the Early Devonian Cairnsmore of Fleet granite (Fig. 7.1). Cordierite porphyroblasts are deformed by the shear zone foliation, but the foliation is overprinted by biotite hornfels and the later stages of thermal metamorphism. These relationships constrain the timing of final development for the MSZ to granite intrusion, around 395–400 Ma (U-Pb: Evans in Barnes 2008, Appendix 7; Miles *et al*. 2014), an interval contemporaneous with the Acadian Orogeny in Avalonia. Elsewhere in the Southern Uplands an Acadian association has been assigned to white mica ages of 390 ± 6 Ma (K-Ar, Ar-Ar) from Llandovery metabentonites (Huff *et al*. 1991). In the Midland Valley, metamorphic effects detected in basement xenoliths have been assigned an age between about 400 and 391 Ma (U-Pb, zircon) and described as Acadian (Badenszki *et al.* 2019).

Regionally, the MSZ has been thought to separate pluton suites of differing age and composition (Thirlwall 1988; Brown *et al*. 2008) but more recent work reduced those differences (Miles *et al*. 2016), leaving the issue unresolved. In the NE of the Southern Uplands, the top surface of the unexposed but geophysically modelled, Tweeddale granitic pluton (Lagios & Hipkin 1979) is about 2–3 km below ground level at its shallowest. Its margins lie between the surface traces of the Orlock Bridge and Moffat Valley faults (Fig. 7.1), suggesting a spatial association between intrusion and the MSZ.

The MSZ is likely to be a composite feature, representing progressive but intermittent deformation over a long period from its initiation during D_1 (accretionary) deformation early in the Silurian until the possibly Acadian effects in the Early to Middle Devonian. Despite the possible long duration of deformation, there is no evidence from Scotland for a large lateral displacement, although movement of several hundred kilometres has been proposed for the Slieve Glah Shear Zone, along-strike to the west in Ireland (Anderson & Oliver 1986). Remarkably, across the MSZ and the adjacent, tract-bounding Orlock Bridge Fault, there is no greater biostratigraphical break than is seen across the other tract-bounding faults of the Southern Uplands (Barnes *et al*. 1995b).

Topic box about here

The Southern Uplands accretionary complex: archetype or anomaly?

The biostratigraphical resolution provided by graptolite faunas has enabled the structure of the Southern Uplands Terrane to be resolved in fine detail, so much so that it has become a classic case study in accretionary tectonics. The Moffat Shale Group is the key and remarkably, given the structural setting, has at Dob's Linn, Moffatdale, retained sufficient stratigraphical integrity to allow definition of the Global Stratotype Section and Point (GSSP) for the base of the Silurian (Rong *et al*. 2008). This is the only System/Period-level GSSP defined from British geology.

When the 4th edition of Geology of Scotland was published there was still active debate over the origins of the Southern Uplands with contrasting back-arc and forearc tectonic settings under consideration (Oliver et al. 2002; Stone 2014). Since then, the back-arc alternative has been eliminated through basin thermal history analysis (Stone & Merriman 2004) and the age range of detrital zircons (Waldron *et al*. 2008), with structural complexity addressed by the pattern of burial metamorphic grade at outcrop (Merriman & Roberts 2001) and by additional biostratigraphic data (summarised by Stone *et al*. 2012). Now, whilst acknowledging alternative views on the origin of its northern, Ordovician part (Armstrong & Owen 2001), the Southern Uplands Terrane is widely accepted as an archetypal, supra-subduction, accretionary thrust complex.

Nevertheless, despite the achievement of this near-consensus, the along-strike continuity of well-defined, stratigraphically coherent, structural tracts, and the regularly sequential cross-strike change in age between those tracts, are unexpected features in what is normally a highly disruptive setting. Much disordering of strata would be expected during accretion accompanied by the production of abundant mélange, but this lithology is generally scarce in the Southern Uplands.

An underplating regime, for example as described by Sample & Moore (1987) from the Kodiak complex (Alaska), was thought by Leggett *et al*. (1982) to be the most conducive environment for the accretion of the coherent tracts of strata that characterise the Southern Uplands. However, invoking an underplating regime introduces another complicating factor. The grade of burial metamorphism commonly shows abrupt changes at Southern Uplands tract boundaries (Merriman & Roberts 2001), and so requires the structural juxtaposition of tracts derived from different depths, some frontally accreted, others underplated (Topic Box, Fig. 7.23). There would have been movement on any underplating décollement planes within the accretionary complex, such that an age difference would develop between the strata accreted above and below. Yet structural juxtaposition of tracts across one or more of those décollements has apparently occurred without disrupting the regularly incremental progression in the ages seen at outcrop (Figs 7.6 and 7.7). This puzzle has still to be solved.

To explain the scarcity of mélange, Leggett *et al*. (1982) invoked slow subduction coupled with a high sedimentation rate, a likely combination for the Southern Uplands where accretion was relatively long-lived and the sediment supply consistently abundant. It would have required about 30 million years of subduction to incorporate the Late Ordovician and early Silurian tracts now forming the Southern Uplands Terrane. At its maximum the Iapetus Ocean was probably at least 1 000 km wide, a figure supported by an area balancing assessment by Anderson (2001) that calculated a width in excess of 1 000 km for the Moffat Shale Group depositional basin. Taking from these figures the approximation that 500 km of oceanic crust were subducted at the Laurentian margin whilst the Southern Uplands accretionary complex developed over 30 million years, a very slow subduction rate of less than 2 cm/year is implied, a result compatible with the coherent internal stratigraphy of most Southern Uplands accretionary tracts.

But the issues discussed above must also be set against the enormous scale and complexity of subduction-accretion systems, from one of which the Southern Uplands Terrane represents only a tiny segment. During plate-scale oblique convergence or terminal collision, the thrust-related or strike-slip excision or duplication of terrane elements is highly likely if not inevitable. Against this background the Southern Uplands Terrane stands out as a remarkably complete and well preserved, thirty-million-year record of accretionary geological processes.

End of Topic Box

Metamorphism and thermal history

The Southern Uplands strata experienced only limited metamorphism during development of the accretionary complex and its subsequent burial beneath an unconformable sedimentary cover. The crystal thicknesses of white mica (illite crystallinity) in mudstone (Merriman & Roberts 2001) establishes a range from the deep diagenetic zone, up through the anchizone and locally into the epizone. in the vicinity of intrusions or where cleavage is strongly developed. The prehnite-pumpellyite facies (approximately equivalent to the anchizone) has been widely detected in volcaniclastic sandstones (Oliver *et al*. 1984).

Assuming a relatively low geothermal gradient typical of subduction settings ($<20°C\ km^{-1}$), the depth of burial of the Southern Uplands strata would have ranged from about 6 or 7 km for those rocks now in the deep diagenetic zone, up to about 13 km for some of the epizonal rocks (Merriman & Roberts 2001). Some of this burial depth would have arisen from the likely post-accretionary cover of Devonian sediment but this alone would not have resulted in the metamorphic relationships now preserved. Most significantly, 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) are found in the Hawick Group. In a number of cases the metamorphic grade increases sequentially into younger tracts. As an additional complication, in places the grade changes abruptly along strike at major NW–SE cross faults (Merriman & Roberts 2001, fig. 3; Stone *et al*. 1995, fig. 4), 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 post-metamorphic reactivation of those faults, and in some cases the change in grade indicates downthrow to the north, the reverse effect of that imposed during accretion.

To explain the geometry of the metamorphic pattern found in the Southern Uplands, Merriman & Roberts (2001) utilised the analogy of the Kodiak accretionary complex (Sample & Moore 1987) to explore the consequences of two levels of accretion, separated by a zone of décollement (Fig. 7.17 and Topic Box Fig. 7.23). Southern Uplands strata accreted to the front of the complex were stacked above the décollement and were probably metamorphosed only in the late diagenetic zone and with a weak development of the D_1 cleavage. Below the décollement, in a region of underplating, strata were accreted in a series of duplexes, were metamorphosed typically in the anchizone, and show a moderate to well-developed slaty cleavage. At both levels, coherent, thrust-enclosed tracts of strata were rotated and buried to produce a syn-D_1, depth-dependent pattern of approximately horizontal metamorphic zones that intersect moderately to steeply dipping strata.

Post-accretion, intermittent Devonian through to Permian uplift reactivated the near-vertical tract boundary faults to juxtapose different levels of the metamorphic sequence. The greatest displacement is seen along parts of the Orlock Bridge Fault, where Ordovician rocks in the Late Diagenetic Zone are juxtaposed against epizonal Silurian rocks in the Moniaive Shear Zone. Even allowing for the effects of tectonic shearing, downthrow to the north may have been as much as 4 km, which raises another problem. There would have been movement on any décollement plane within the accretionary complex, such that an age difference would develop between the strata accreted above and below. Yet even at the Orlock Bridge Fault there is no disruption of the biostratigraphic relationships between the tracts, which maintain a pattern of southward younging by small increments despite the abrupt changes in metamorphic grade.

The very small crystal size and chemical-crystal structure of clay minerals makes them sensitive to the differences in basin thermal histories of contrasting geotectonic settings (Merriman 2002), so their characteristics enable the thermal conditions of low-grade metamorphism to be assessed. Stone & Merriman (2004) utilised this feature to test the relative merits of the back arc (extensional) and fore-arc (convergent) depositional basin settings inherent in the different tectonic models for the terrane. A relatively high heat flow would be expected in the extensional setting, a much lower heat flow in the compressional setting, and the clay mineral structures formed in each environment would vary accordingly.

Using the clay mineralogy of mudstones, Merriman (2002) had shown that the geotectonic setting of early Palaeozoic basins in the British paratectonic Caledonides had strongly influenced clay reactions during diagenesis and low-grade metamorphism. The result was a broader range of clay minerals in the extensional basins of Wales, the northern Lake District (Skiddaw Group) and the Isle of Man (Manx Group) when compared to the convergent (foreland) basin of the southern Lake District (Windermere Supergroup). Stone & Merriman (2004) demonstrated that

Southern Uplands data matched that for the convergent basin of the southern Lake District and, importantly, showed no variation across the width of the accretionary complex. This made unlikely any progression from back arc (extensional) to fore-arc (convergent) basin settings across the Southern Uplands, so eliminating the models proposed by Morris (1987) and Stone *et al*. (1987); the extensional continental margin origin proposed by Armstrong *et al*. (1996) was also thought incompatible with the clay data. In contrast, an accretionary interpretation was matched by the uniform clay mineral data across the full width of the Southern Uplands.

Regional terrane relationships

Two lines of evidence independently demonstrate that the Southern Uplands accretionary complex is now allochthonous and is underlain by crystalline basement rocks extending southward from the Midland Valley Terrane and northward from Avalonia. The evidence is provided by xenoliths carried from depth by igneous intrusions, and by regional geophysical modelling.

The range of xenoliths contained in Carboniferous volcanic rocks led Upton *et al*. (1983) to infer that the northern margin of the Southern Uplands Terrane was underlain by a similar magmatic basement to that of the Midland Valley. Xenoliths have also been recovered from the widespread lamprophyre dykes that were intruded during the Early Devonian. Floyd & Phillips (1998) and Barnes (2008) report variably foliated dioritic and granodioritic xenoliths in dykes intruded into the Gala and Hawick groups in Galloway. Farther to the SW, in the extension of the Southern Uplands Terrane into Northern Ireland, Anderson & Oliver (1996) have interpreted xenoliths of mylonitized andesitic rock as having been derived from the partly subducted Avalonian plate. They suggest a source akin to the Borrowdale Volcanic Group of the English Lake District which, by Early Devonian times, had been over-ridden by the advancing Southern Uplands accretionary complex.

Pioneering seismic interpretations established crystalline basement beneath the Southern Uplands but did not reach a structural consensus. Bamford *et al*. (1977) described a marked southward increase in the depth to basement (to as much as 15 km) across the Southern Upland Fault, although a subsequent reinterpretation of the same data (Barton 1992) smoothed and reduced the basement topography. Whilst noting an apparent change in lower crustal properties at the Southern Upland Fault, Barton (1992, p. 382) was unequivocal that there “is no indication of a crust-penetrating feature connecting surface and deep structures”. Conversely, marked positive aeromagnetic anomalies associated with the Ballantrae Complex suggest that it extends vertically to a substantial depth and may therefore separate two blocks of ‘Midland Valley-type’ basement (Fig. 7.22c and d) which came together, trapping the Complex, in the mid-Ordovician (Stone 2014 and see Chapter 6). Other seismic interpretations modelled overthrusting onto the southern margin of the Midland Valley with crystalline basement at unexpectedly shallow depths of 3 – 5 Km beneath the Southern Uplands (Hall *et al*. 1984). For comparison, the modelling of geomagnetic and gravity data suggested a crystalline basement at about 10 km (Kimbell & Stone 1995) (Fig. 7.24).

To the south of the Southern Uplands, several seismic lines have shown a moderately NW-dipping, reflective zone projecting to the surface close to the northern coast of the Isle of Man and thence striking NE beneath northern England, as summarised by Soper et al. (1992b). This has been taken as the suture zone between Laurentia and Avalonia, but when the seismic results are integrated with regional interpretations of gravity and magnetic data a rather more complicated picture emerges. The potentially Avalonian crust appears caught up in a compound suture zone that extends well to the north beneath the Southern Uplands Terrane, whilst Midland Valley crust continues south to underlie the northern Southern Uplands. This situation is encapsulated in the interpretation of the long wavelength magnetic anomaly over SW Scotland known as the 'Galloway High' (Fig. 7.24). Kimbell & Stone (1995) modelled relatively magnetic continental crust beneath the English Lake District Terrane divided from similar crust beneath the Silurian tracts of the Southern Uplands by a zone of less magnetic crust interpreted as sedimentary rock of Avalonian affinity carried to deep structural levels within the Iapetus Suture Zone. The northern margin of the Southern Uplands magnetic basement coincides, at depth, with the surface trace of the Moniaive Shear Zone; to the north, the basement is of non-magnetic crust sharing properties with that underlying the Midland Valley. This magnetic basement unit beneath the southern Southern Uplands was subsequently designated 'Novantia' by Armstrong & Owen (2001).

As noted above, the Southern Upland Fault, at outcrop the terrane boundary with the Midland Valley, has no consistent geophysical expression at depth except where the Ballantrae Complex appears to extend to depth as a vertical zone on its northern side (Fig. 7.22c and 22d). Floyd (1994) has described a plexus of fault strands along the length of the fault with a long history of post-Silurian movement. That post-Silurian faulting has modified the original terrane boundary, which is now preserved only as the Pyet Thrust (Floyd 1994) which isolates small ophiolitic inliers on the south side of the Stinchar Valley Fault. The Pyet Thrust is the surviving vestige of the terrane boundary structure(s) that carried the northern margin of the Southern Uplands onto the southern margin of the Midland Valley. Nevertheless, there is no geophysical evidence for any substantial, hidden extension of the Ballantrae Complex south of the Stinchar Valley Fault although at depth it extends along the north side of the fault to the NE (Fig. 7.24) and offshore to the SW (Stone 1995). As a further complication, Floyd (1994) suggested a linked partitioning of sinistral strike-slip displacement between the Stinchar Valley Fault and the Glen App Fault, the southern boundary of the Tappins Group tracts.

Although substantial lateral displacements along the Southern Upland Fault have been proposed, for example by Elders (1987), Ordovician sedimentary links – coeval conglomerates and, particularly, derived fossil faunas (Clarkson *et al*. 1992; Candela & Harper 2010) – limit strike-slip movement between the terranes to a maximum of a few hundred kilometres. That may be sufficient to resolve the provenance problem posed by the conglomerates in the Midland Valley's Silurian inliers, which require a source to the south comprising rocks dissimilar to those currently seen in the Southern Uplands.

As an alternative solution, Bluck (1983, 2013) developed the concept of a southern Midland Valley extension, now hidden, that separated by inter-arc rifting to create an inter-arc basin along the line of the current Southern Upland Fault. This separated Midland Valley sliver, comprising a felsic plutonic basement and a cover of sedimentary rocks including wacke-sandstone and quartzite-bearing conglomerate, was then the southern source of the conglomerates in the Silurian inliers. It was subsequently over-ridden and lost to view as the Southern Uplands accretionary complex as a whole was thrust northwards. There is geophysical evidence to support this model (Hall *et al*. 1984), it is inherent in the back thrusting model proposed by Needham & Knipe (1986) although with conflicts of timing, and back-thrusting was confirmed by Floyd's (1994) observations of relationships between the Stinchar Valley Fault and the Pyet Thrust. More recently, Badenszki *et al*. (2019) have linked the proposed overthrusting to metamorphism in the Midland Valley basement at *c*. 411 Ma which they detected during dating of xenoliths found in Permo-Carboniferous igneous rocks. It is tempting to associate this separated Midland Valley sliver with that required for the collisional interpretation of the Ballantrae Complex (Fig. 7.22c and 22d) but there are spatial and temporal difficulties with any direct comparison.

In a different approach to provenance difficulties posed by the Silurian inliers, Phillips *et al*. (2009) utilised detrital zircon ages from sandstones. They found a paucity of Archaean zircons and a bimodal distribution of Mesoproterozoic (ca 1000 Ma) and Early Ordovician (ca 475 Ma) ages. All of the younger zircons were assigned a relatively local provenance within a Midland Valley, Early Ordovician volcanic arc and its putative basement. If zircon populations in wackes from the Southern Uplands Terrane were derived from Dalradian sources within the Grampian Terrane (Waldron *et al*. 2014), either their host sediment would have had to bypass the Midland Valley Terrane, or those terranes had a very different spatial relationship to that currently seen. These issues remain unresolved, compounded by the results of Badenszki *et al*. (2019) which would seem to rule out any ancient basement beneath the Midland Valley.

Summary

At the southern margin of the Midland Valley Terrane, Middle to Late Ordovician sedimentary rocks unconformably overlie the ophiolitic Ballantrae Complex in the vicinity of Girvan. They accumulated in a forearc shelf setting and show an upward transition from shallow to deep-marine lithologies. There was strong fault control on deposition; downthrow to the south and a northward migration of faulting resulted in a northerly transgressive onlap. The succession is largely clastic but reef limestones built-up locally on the ophiolitic 'basement'. Coarse conglomerates were deposited adjacent to the faults and transition into thick sequences of sandstone both stratigraphically upwards and geographically southwards.

During the Silurian, sinistral strike-slip tectonics resulted in the development of a series of small transtensional basins along the southern margin of the Midland Valley Terrane. The sedimentary infill of these basins, including the Silurian part of the Girvan succession, is regressive, their successions commencing with relatively deep-water lithofacies and terminating with continental, semi-arid red beds. The upward transition from marine to continental sedimentation commonly spans the Llandovery–Wenlock boundary.

Late Ordovician deposition of sandstone and some conglomerate, coeval with that at Girvan, extended southwards from the forearc shelf into the Iapetus Ocean. Following obduction of the Ballantrae Complex, northward subduction of the Iapetus Ocean had been established and successions of sandstone, with a thin underlying veneer of oceanic rocks were sequentially stripped from the descending plate and incorporated into the accretionary thrust complex that now defines the Southern Uplands Terrane (Fig. 7.22a). Polyphase folding developed as the accretionary complex built up. The burial metamorphic grade ranges from the late diagenetic zone to the epizone and was imposed on strata that were already steeply inclined.

Despite its ocean margin origin, the Southern Uplands Terrane is allochthonous, underlain by continental crust. In part this is the result of deposition of the southernmost (mid-Silurian) part of the terrane in a foreland basin setting as the accretionary complex over-rode Avalonia following the closure of the Iapetus Ocean (Fig. 7.22b). At the northern margin of the Southern Uplands Terrane, late in the Silurian, the accretionary complex was thrust northwards onto the margin of the Midland Valley Terrane. In response, the Ordovician sedimentary succession at Girvan, along with its unconformable cover of Silurian strata, was folded into large asymmetric structures verging towards to NW in association with a series of NW-directed thrusts. Corresponding, late Silurian deformation within the accretionary complex, was largely restricted to sinistral strike-slip movements, with strain localised into structures such as the Moniaive Shear Zone. At depth, this tectonic feature is underlain by a major crustal break: Laurentian (Midland Valley) to the north, Avalonian to the south (Fig. 7.22b).

A unifying feature across the Silurian inliers of the Midland Valley is a series of distinctive Wenlock to Early Devonian conglomerates derived from the south, but with clast compositions dissimilar to lithologies currently exposed in the Southern Uplands Terrane. The original provenance was probably lost by a combination of the late Silurian strike-slip faulting and the penecontemporaneous north-directed, thrust emplacement of the Southern Uplands accretionary complex onto the margin of the Midland Valley Terrane.

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Figures and Table

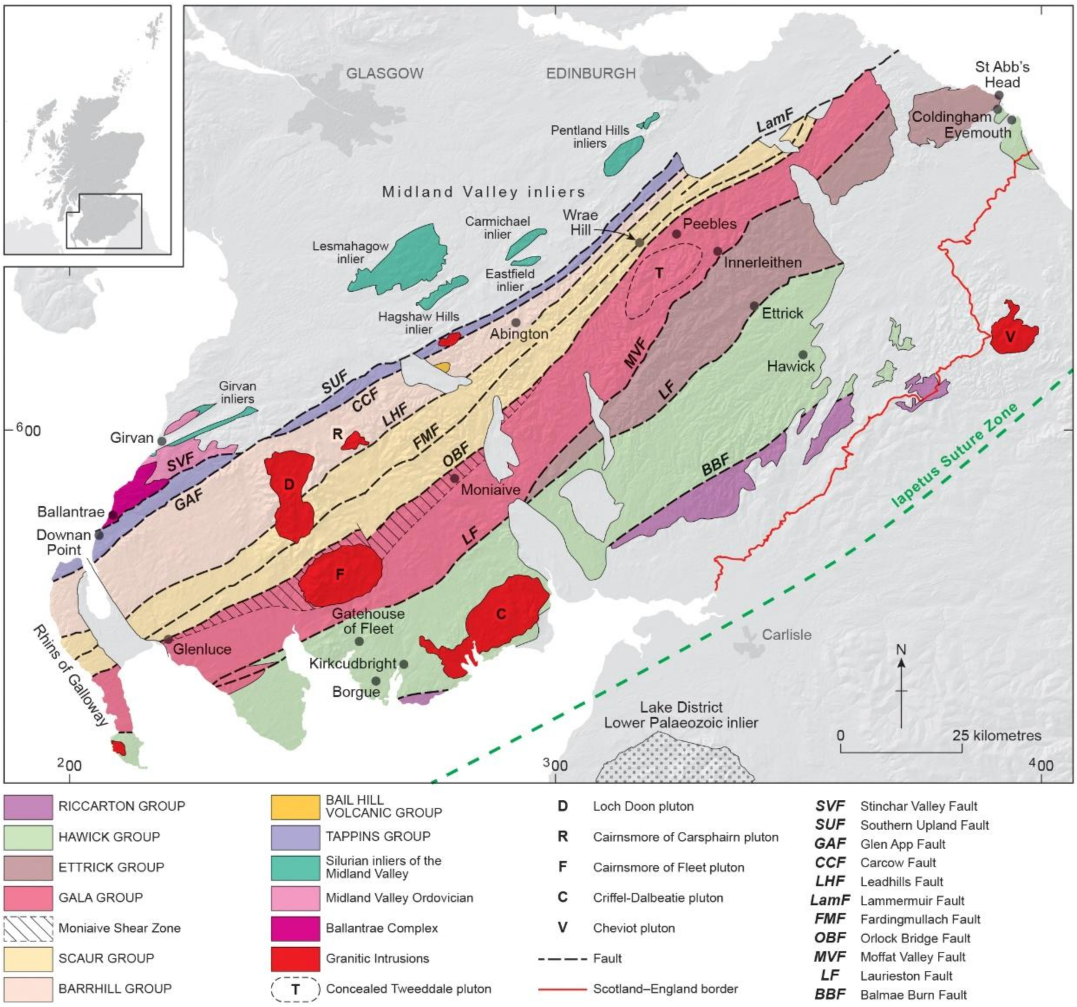

Figure 7.1

Outline Lower Palaeozoic geology of the south of Scotland locating the inliers within the Midland Valley terrane and the principal faults and lithostratigraphic divisions of the Southern Uplands accretionary complex. BGS © UKRI 2023. This figure is based on Stone *et al*. (2012, fig 2) and Stone (2014, fig. 1).

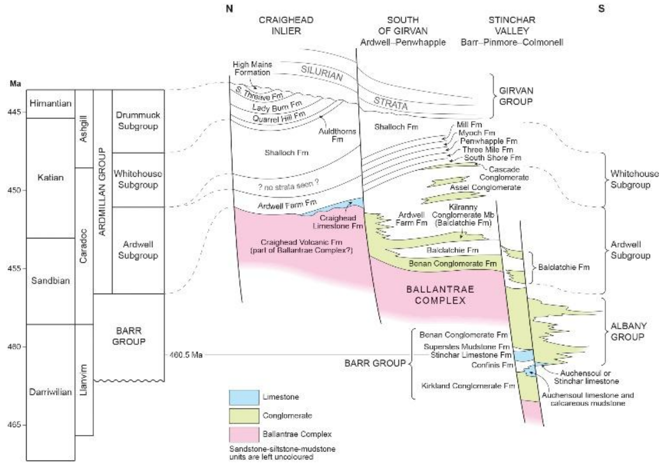

Figure 7.2
Schematic cross-section showing the fault control on Llanvirn to Ashgill sedimentary patterns in the Girvan area, after Williams (1962) and Ingham (2000) correlated with the regional and international chronostratigraphy. BGS © UKRI 2023.

Figure 7.3
Examples of the Ordovician–Silurian fossil fauna from the Midland Valley and Southern Uplands terranes. See also the GeoScenic Home Page, British Geological Survey (geoscenic.bgs.ac.uk). BGS images © UKRI. (a) Starfish: *Tetraster sp*. Ordovician (Katian). South Threave Formation, Drummuck Subgroup, Armillan Group. Lady Burn, Craighead inlier [NS245037]. Source: BGS image P740610. (b) Trilobite: *Acernaspis woodburnensis* Clarkson, Eldredge and Henry. Silurian (Telychian). Dailly Subgroup, Girvan Group. Bargany Burn, Barr [NX250990]. Source: BGS image P521140. (c) Graptolite: *Torquigraptus linterni* Williams, Zalasiewicz *et al*. Silurian (Aeronian–Telychian, sedgwickii–halli biozones). Birkhill Shale Formation, Moffat Shale Group. Pot Burn, Ettrick Valley [NT180090]. Source: BGS image P521147. (d) Graptolite: *Diplograptus truncatus* Lapworth var. *pauperatus* Elles and Wood. Ordovician (Sandbian–Katian). Lower Hartfell Shale Formation, Moffat Shale Group. Dob's Linn, Moffatdale [NT196157]. Source: BGS image P521143. (e) Coral: *Kilbuchophyllia clarksoni* Scrutton. Late Ordovician. Allochthonous in the Kirkcolm Formation (Sandbian–Katian), Barrhill Group. Wandel Burn, Abington [NS968262]. Source: BGS image P521144.

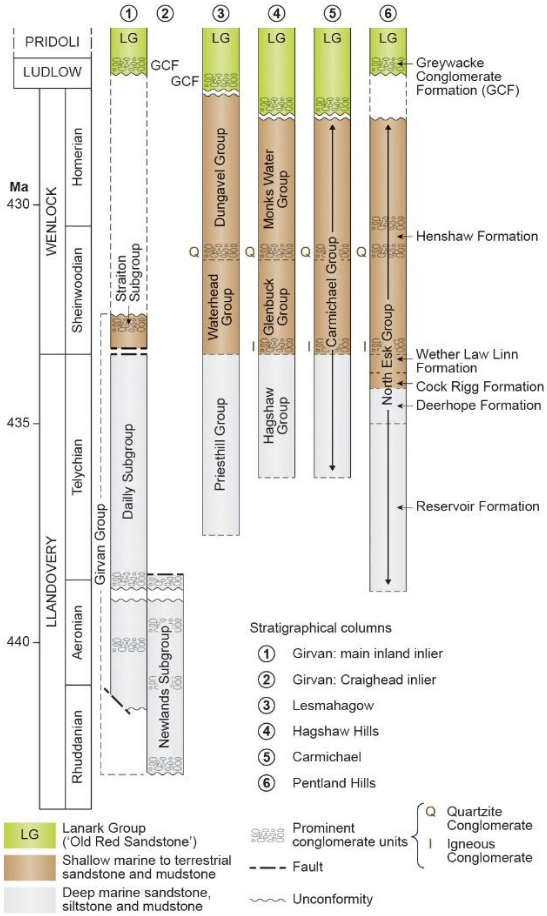

Figure 7.4
A correlation of the Silurian successions seen at Girvan and in the inliers of the Midland Valley utilising data from Cocks *et al*. (1992) and Floyd & Williams (2003). BGS © UKRI 2023.

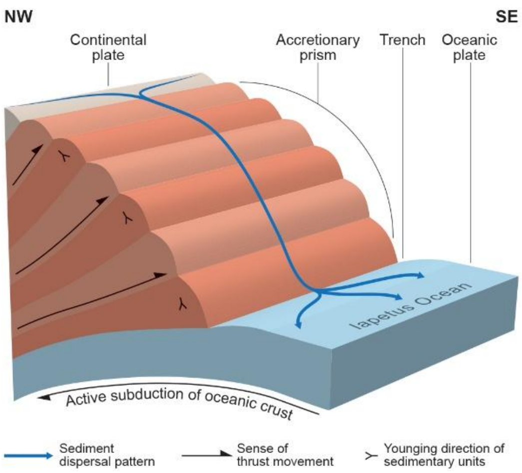

Figure 7.5
An idealised representation of the accretionary prism model for the Southern Uplands terrane proposed by McKerrow *et al*. (1977) and Leggett *et al*. (1979), after Stone (1995, fig 3). BGS © UKRI 2023.

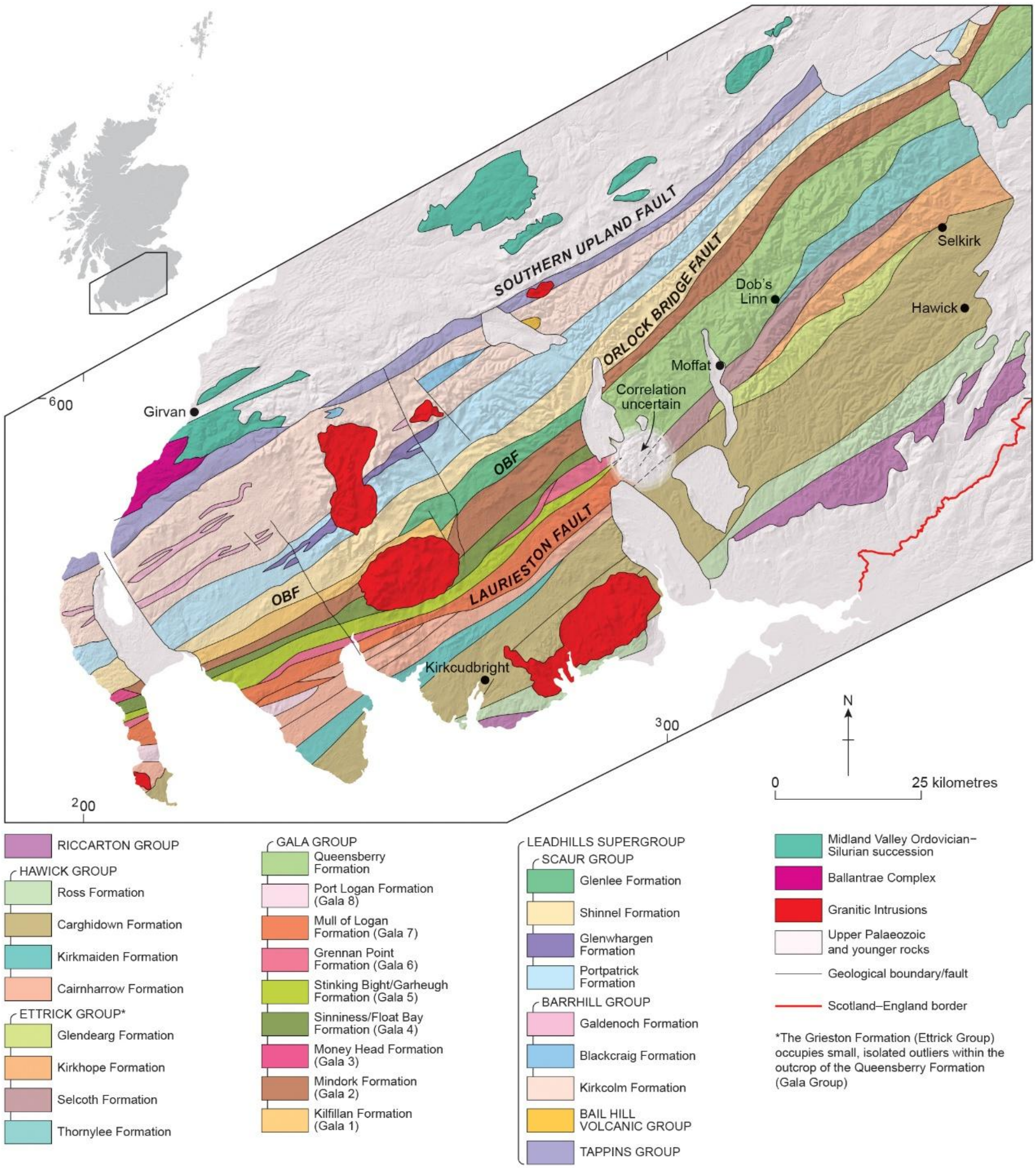

Figure 7.6
A generalised representation of the principal mid-Ordovician to mid-Silurian structural tracts of the Southern Uplands terrane, which form the basis of the regional lithostratigraphy, after Stone *et al*. (2012, fig.14). Gala Group tract numbers are included to aid correlation with the earlier literature. For chronostratigraphical correlation see Figs 07.06 and 07.07. BGS © UKRI 2023.

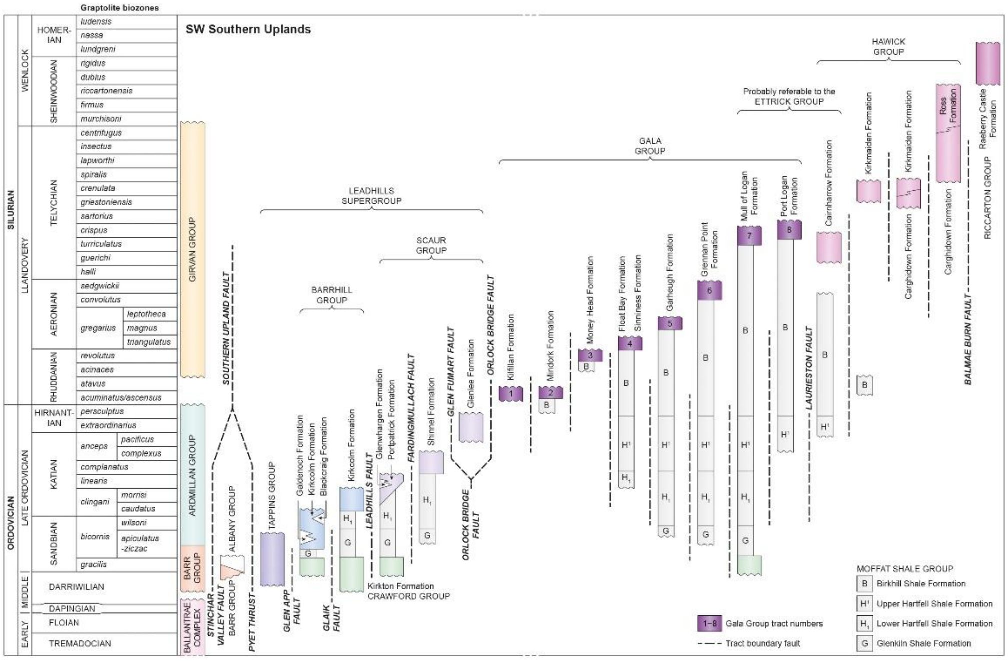

Figure 7.7
Representative structural-stratigraphical tract profile for the SW Southern Uplands, after Stone *et al*. (2012, fig. 15b). Gala Group tract numbers are included to aid correlation with the earlier literature. BGS © UKRI 2023.

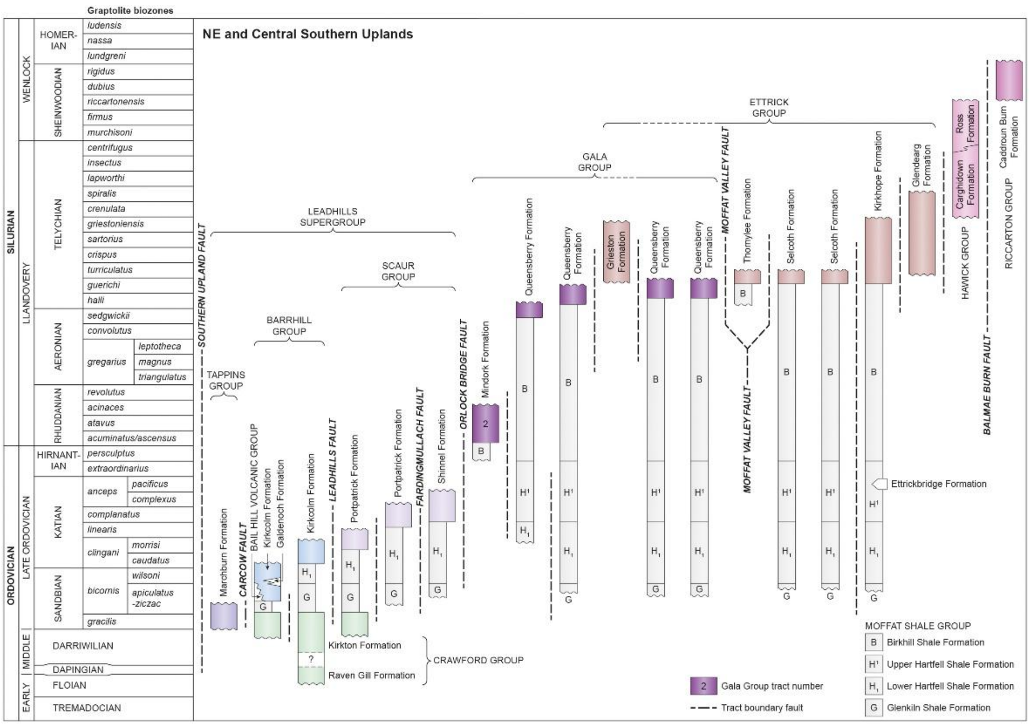

Figure 7.8
Representative structural-stratigraphical tract profile for the central and NE Southern Uplands, after Stone *et al*. (2012, fig. 15a). Gala Group tract numbers are included to aid correlation with the earlier literature. BGS © UKRI 2023.

Figure 7.9
The Southern Uplands stratigraphical paradox: A. Steeply inclined (slightly overturned) turbidite strata of the Kirkcolm Formation (Caradoc, Ordovician) on the NW coast of the Rhins of Galloway, northern Southern Uplands [NW 962 620] (BGS image P008483 © UKRI); B. Steeply inclined (slightly overturned) turbidite strata of the Carghidown Formation (Llandovery, Silurian) on the southern, Solway Firth coast of the Southern Uplands near Kirkcudbright [NX 632 453] (BGS image P220426 © UKRI). In both examples the strata young to the north (from right to left) despite the younger beds cropping out to the south of the older ones, a typical arrangement of the Southern Uplands tracts.

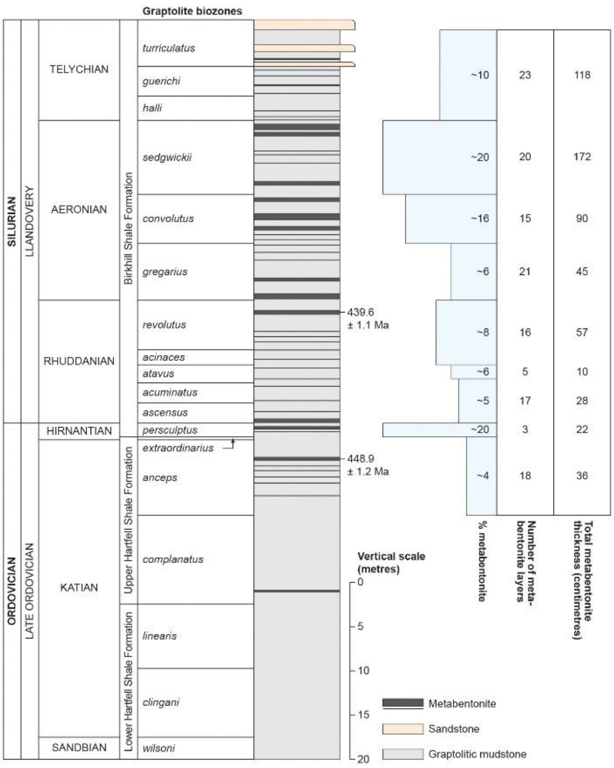

Figure 7.10
Stratigraphy of the Moffat Shale Group showing the distribution of metabentonite (volcanic ash) bands in the Dob's Linn (Moffatdale) defined by Merriman & Roberts (1990). The dates shown are those of Melchin *et al*. (2012) recalculated from the original data of Tucker *et al*. (1990). BGS © UKRI 2023.

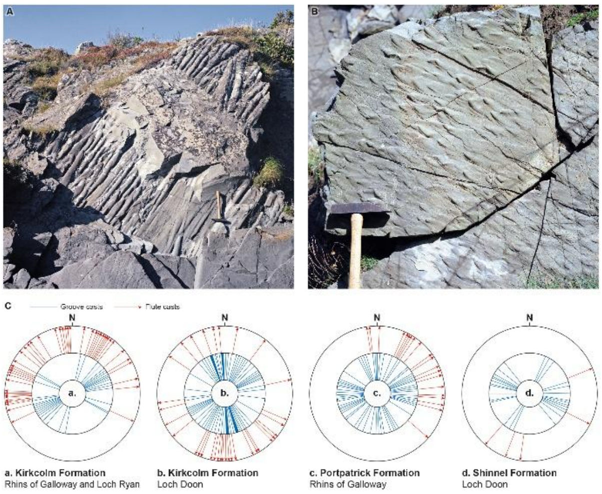

Figure 7.11
Palaeocurrent indicators and the range of flow direction indicated. A and B, flute casts, two examples from the Kirkcolm Formation showing different styles and current directions: A. Finnarts Bay [NX 053 722] BGS image P008425 © UKRI; B. Portobello [NW 960 665] BGS image P008463 © UKRI. The shape of the linear flute casts from Finnarts Bay indicates current flow from top right to bottom left; the linguiform flute casts from Portobello indicate current flow from top left to bottom right. In both cases the steeply inclined beds are slightly overturned and are viewed looking north. C. The range of palaeocurrent flow directions seen in three formations from the Leadhills Supergroup outcrop in the SW Southern Uplands; data from Stone (1995) and Floyd (1999). BGS © UKRI 2023.

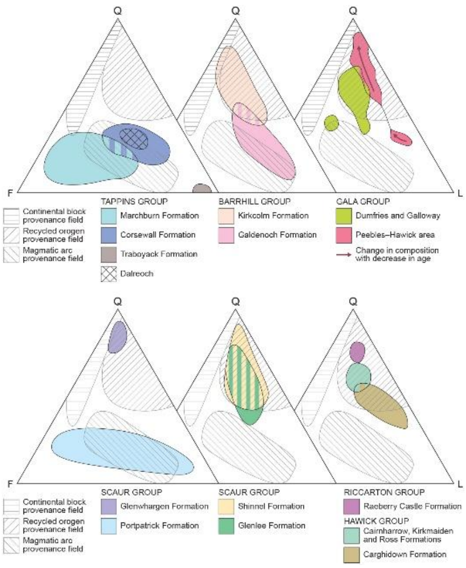

Figure 7.12
The compositional variation of sandstones with stratigraphy across the Southern Upland terrane. The triangular plots illustrate the relative abundance of quartzose grains (Q), feldspathic grains (F) and unstable (labile) lithic or mineral grains (L). The corner points of the triangles correspond to 100% Q, F or L, as indicated. Provenance fields from Dickinson & Suczek (1979). BGS © UKRI 2023.

Figure 7.13
One of the boulder conglomerate members from the younger part of the Corsewall Formation (Tappins Group) as exposed at Corsewall Point [NW 982 727], the northern extremity of the Rhins of Galloway. BGS image P008481 © UKRI.

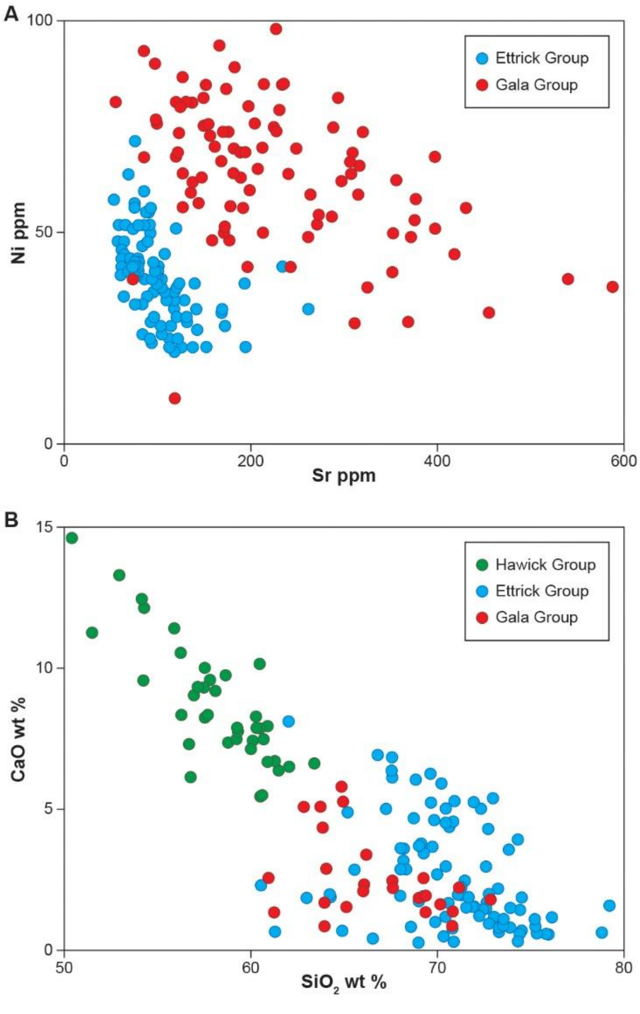

Figure 7.14
The geochemical variation shown by sandstones from the Ettrick, Gala and Hawick groups, after Stone *et al*. (2012, fig. 20). The Ni-Sr plot differentiates between sandstones of the Gala and Ettrick groups, the CaO-SiO_2 plot differentiates between these and sandstones from the Hawick Group. BGS © UKRI 2023.

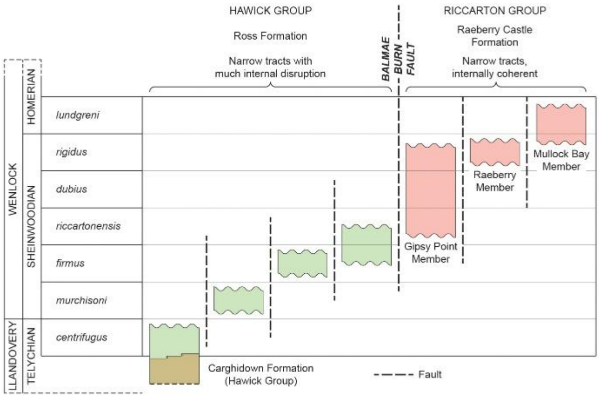

Figure 7.15

A representative structural-stratigraphical profile for the Ross Formation (Hawick Group) and Raeberry Castle Formations (Riccarton Group) in the Kirkcudbright area, after Kemp (1986) as updated in Stone *et al*. (2012, fig. 22) following Lintern & Floyd (2000). BGS © UKRI 2023.

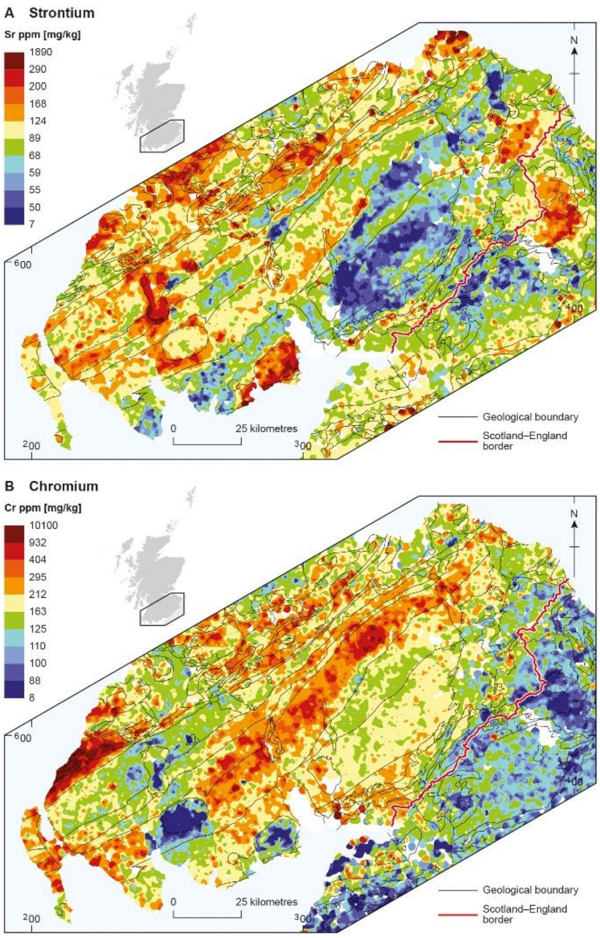

Figure 7.16

Regional geochemical images showing the distribution of strontium and chromium in the fine-grained fraction of stream sediment across the Southern Uplands terrane and adjacent areas: A. Strontium (Sr); B. Chromium (Cr). No data is available for those areas left uncoloured. G-Base data (BGS 1993) reprocessed for Stone *et al*. (2012, fig. 16). Compare the strontium distribution with the whole-rock geochemistry illustrated in Fig 7.13; the agreement is striking. BGS © UKRI 2023.

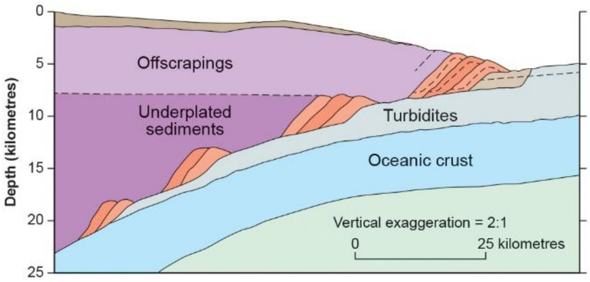

Figure 7.17
Frontal accretion and underplating differentiated in the accretionary model developed from the Kodiak complex, Alaska, by Sample & Moore (1987, fig. 3) BGS © UKRI 2023.

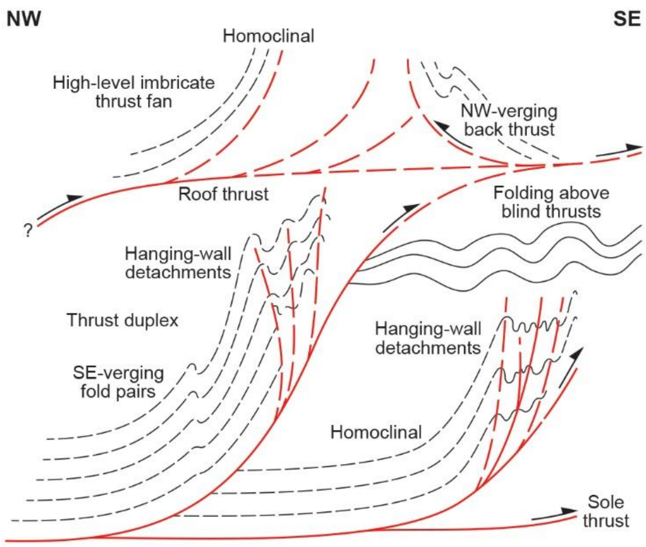

Figure 7.18
Variation in the structural style seen in the Southern Uplands diagrammatically illustrated as a consequence of position and thrust geometry within a developing accretionary complex, after Stone (1995, fig. 19). BGS © UKRI 2023.

Figure 7.19
Transecting cleavage (aligned with hammer handle) in a D_1 anticline affecting strata of the Kirkmaiden Formation (Hawick Group) at Corseyard Point [NX 591 481] near Borgue. BGS image P220414 © UKRI.

Figure 7.20
Examples of D_2 refolding of D_1 structures from the Kirkmaiden Formation (Hawick Group) to the west of Borgue: A. Craigmore Point [NX 572 517] BGS image P220404 © UKRI; B. Isle Mouth [NX 576 498] BGS image P220407 © UKRI.

Figure 7.21
Steeply plunging D_3 fold affecting Garheugh Formation (Gala Group) strata at The Hooies [NX 068 448] on the west coast of the Rhins of Galloway. BGS image P008491 © UKRI.

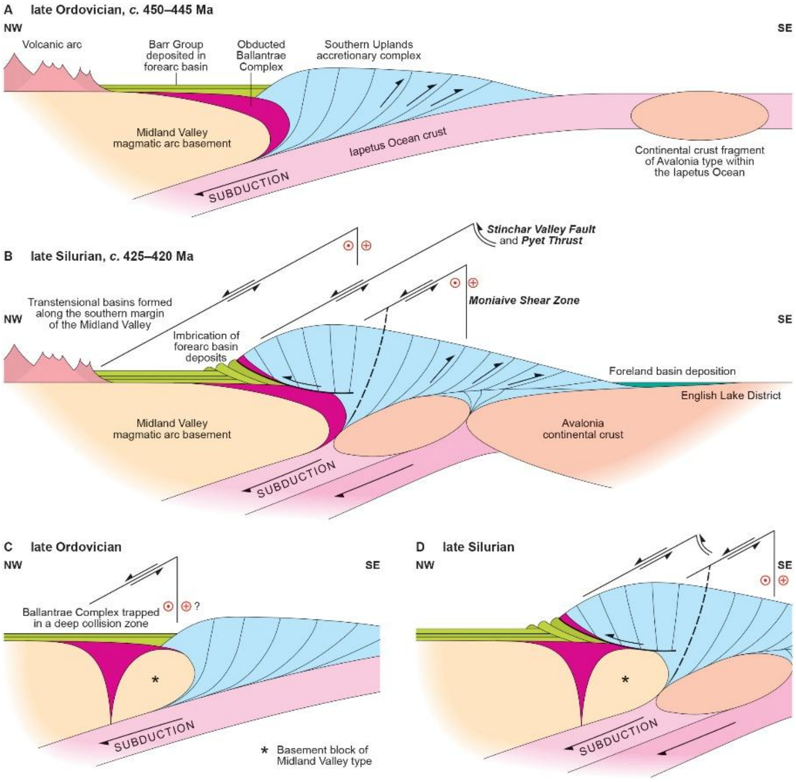

Figure 7.22
Two schematic and simplified cross-sections illustrating possible stages in the development of the Southern Uplands accretionary complex (A and B) following obduction of the Ballantrae Complex. Modifications (C and D) show alternative basement relationships of the Ballantrae Complex and the northern part of the Southern Uplands Terrane (after Stone 2014, fig 12). No scale is implied. Substantial post-Caledonian faulting and erosion is required to bring-about the current outcrop pattern. BGS © UKRI 2023.

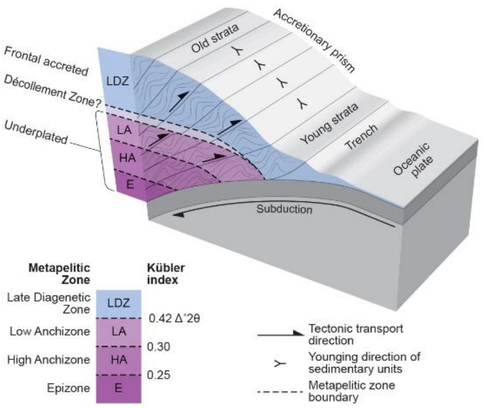

Figure 7.23 (Topic box)
An attempt to integrate structural and metamorphic patterns in a two-layer Southern Uplands accretionary complex (utilising a modified Fig. 07.04), after Stone & Merriman (2004, fig. 2). Lowest grade rocks are accreted, rotated and stacked above a major décollement; higher grade rocks are rotated and underplated below the décollement. Syntectonic burial generates a depth-dependent pattern of horizontal metamorphic zones intersecting the steeply dipping strata. BGS © UKRI 2023.

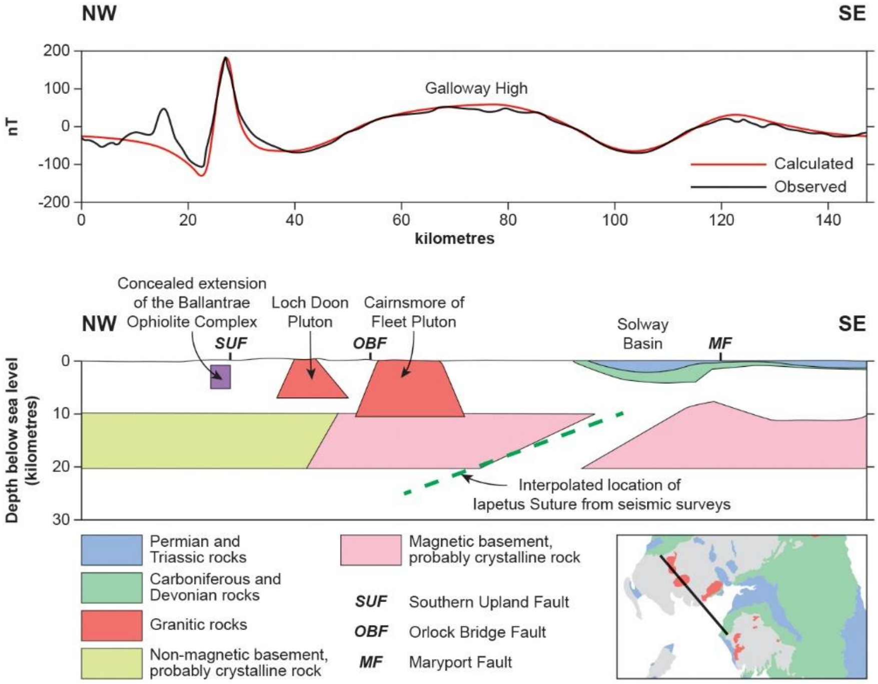

Figure 7.24
A deep crustal model interpreting long-wavelength magnetic anomalies across the Southern Uplands and the Iapetus Suture Zone: from Stone *et al*. (2012, fig. 7a) after Kimbell & Stone (1995). BGS © UKRI 2023.

Group	Formation	Detrital lithic material	Mineral grains
Scaur	Glenlee (andesitic)	Andesite, basalt, rhyolite, quartzite, chert	Quartz (24%), feldspar, augite, hornblende
Scaur	Glenlee (quartzose)	Basalt, rhyolite, quartzite, chert	Quartz (37%), feldspar
Scaur	Shinnel	Granodiorite, granophyre, rhyolite, microdiorite, basalt, quartzite, mudstone	Quartz (57%), feldspar, apatite, zircon
Scaur	Glenwhargen	Quartzite, mica-schist, microdiorite, basalt, chert	Quartz (67%), feldspar, zircon
Scaur	Portpatrick	Pyroxene/hornblende andesite, dacite, rhyolite, basalt, crossite- and garnet-schists, gabbbro, diorite, granite, mudstone	Quartz (15%), feldspar, augite, hornblende, garnet, crossite, spinel, zircon
Barrhill	Blackcraig	Granite, gabbro, rhyolite, basalt, quartzite, chert	Quartz (33%), feldspar, epidote, augite, hornblende
Barrhill	Galdenoch	Pyroxene/hornblende andesite, dacite, rhyolite, basalt, chlorite-schist	Quartz (18%), feldspar, augite, hornblende, apatite
Barrhill	Kirkcolm	Quartzite, basalt, garnet- and mica-schists	Quartz (45%), feldspar, garnet, zircon
Tappins	Corsewall	Granodiorite, quartz-porphyrite, chlorite-schist, microgranite, andesite, gabbro, basalt, serpentinite, chert	Quartz (14%), feldspar, apatite, augite, hornblende, spinel, epidote, biotite
Tappins	Marchburn	Basalt, serpentinite, chert	Quartz (15%), feldspar, hornblende
Tappins	Dalreoch	Serpentinite, basalt, chert, rhyolite	Quartz (26%), feldspar
Tappins	Traboyack	Serpentinite, basalt, chert, andesite, dolerite, gabbro	Quartz (2%), feldspar, epidote, chlorite

Table 7.1
Detrital grain characteristics defining provenance variation for the Ordovician turbidite sandstones of the Leadhills Supergroup, after Stone *et al*. (2012, table 2) with additional data from Floyd (1999, 2001). BGS © UKRI 2023.