7 Sedimentation and tectonics at a mid-Ordovician to Silurian active margin

7.1 Introduction

In mid-Ordovician to Silurian times, the Grampian mountains underwent exhumation, uplift and erosion, and shed debris into the surrounding basins. While the mountains were being exhumed an active margin was developing to the south. At this time, continued plate convergence led to closure of the Iapetus Ocean and development of a northwards-dipping subduction zone, above which a series of island arcs and an accretionary prism developed. The Ordovician and Silurian rocks of the Midland Valley and Southern Uplands Terranes record the development of this active margin, which is the subject of this Section. Section 7.2 outlines the mid-Ordovician to Silurian sedimentary history of the Midland Valley Terrane. Section 7.3 concentrates on the sedimentary and tectonic evolution of the Southern Uplands Terrane. Section 7.4 gives a reconstruction of the regional geological framework for the mid-Ordovician to Silurian active margin.

7.2 Mid-Ordovician to Silurian sedimentation in the Midland Valley Terrane

The Middle Ordovician and Silurian rocks of the Midland Valley of Scotland are exposed in a series of small inliers in the southern part of the Midland Valley, shown in Figure 6.3. Although fragmentary in nature, a sedimentary history has been constructed by linking the information from these inliers.

7.2.1 Ordovician sedimentation

Middle Ordovician rocks rest unconformably on the Ballantrae Complex (Figure 5.5). Recalling Section 5.2.2, the lowermost units comprise Llanvirn to Caradoc (*c.* 470–450 Ma) conglomerates that were deposited from submarine fans into a subsiding basin. These conglomerates pass upwards and laterally into deeper-water turbiditic mudstones and sandstones. Lateral facies changes, thickness variations and palaeocurrent data indicate that sedimentation was partly fault-controlled, and of northerly derivation. The conglomerates contain a variety of clasts that originated from several sources. Clasts of ultrabasic and basic rocks were derived from the underlying Ballantrae Complex. There is also a suite of igneous clasts, ranging in composition from granites to diorites, whose geochemistry is consistent with an origin in a calc-alkaline magmatic arc. These clasts have been dated and give ages of *c.* 560–450 Ma. In addition, a considerable metamorphic component is represented by clasts of low-grade mica schists and abundant detrital garnets. As we saw in Section 6.4, the compositions of these garnets suggest that the metamorphic detritus was derived from the erosion of Dalradian metasediments. Taken together these data suggest that the Ordovician rocks of the Midland Valley were sourced from the erosion of the Grampian mountains, an active magmatic arc and the Ballantrae Complex.

7.2.2 Silurian sedimentation

The Silurian rocks of the Midland Valley comprise Llandovery turbidites that pass upwards into shallow-water fluvial deposits. Conglomerates were then deposited from terrestrial fans in Wenlock times. The lowermost units are dominated by clasts of volcanic rocks. Higher up in the succession the conglomerates contain predominantly metaquartzite clasts; at the highest levels exposed the clasts are mainly greywackes. Interestingly, palaeocurrent analysis and the northward thinning of these sequences suggest a southerly source for some of these deposits, a point we will return to in Section 7.4.3.

A similar history is recorded from the Silurian rocks (Wenlock to Ludlow in age) of Ireland (Figure 6.3) that lie unconformably on the ophiolite fragments and sediments of the South Mayo Trough (Section 5.2.2). Sedimentation started in mid-Llandovery times with a fluvial sequence of red cross-bedded sandstones, conglomerates and breccias deposited by braided rivers that flowed southwards. These sediments are overlain by marine sandstones and conglomerates deposited in delta-fan environments. Lithic clasts in the sandstones include metaquartzites, similar to those from Scotland, and porphyritic volcanic rocks. Volcanic ash layers are also present in the succession, and imply the presence of a nearby arc. Shallow-water sedimentation may have occurred in a series of small inter-arc basins.

7.2.3 Summary of Section 7.2

- The mid-Ordovician rocks of the Midland Valley were deposited in a subsiding fore-arc or inter-arc basin (the Midland Valley Basin). The sediments were derived from the north and were sourced from the Ballantrae Complex, the eroding Grampian mountains and an active magmatic arc.
- Silurian sedimentation occurred in a series of shallow-water inter-arc basins.

7.3 Sedimentation and tectonics in the Southern Uplands Terrane

The Southern Uplands Terrane comprises a series of SW–NE-striking slices of Ordovician and Silurian rocks. On a large scale the Southern Uplands is divided into three major fault-bounded blocks, the Northern, Central and Southern Belts (Figure 7.1). As a whole, there is an overall younging of the rocks from north to south across the terrane, with the Northern Belt containing Ordovician rocks, the Central Belt Ordovician and Silurian rocks, and the Southern Belt being entirely Silurian in age. Each of these belts is further subdivided into slices or tracts that are bounded by reverse faults or thrusts. The succession within each of these tracts generally youngs towards the north (Figure 7.1).

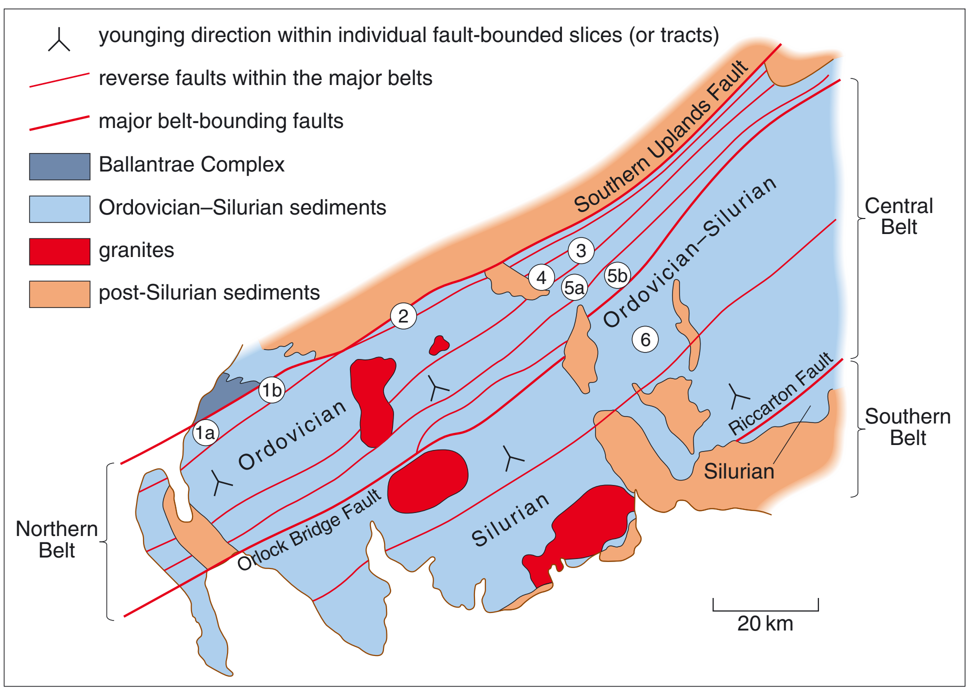

Figure 7.1 Simplified geological map of the Southern Uplands. The numbered units refer to the individual fault-bounded tracts in the Northern and Central Belts.

7.3.1 Sedimentation

The Northern Belt is bounded to the north by the Southern Uplands Fault and to the south by the Orlock Bridge Fault (Figure 7.1). The succession within each of the individual tracts of the Northern Belt is illustrated in Figure 7.2.

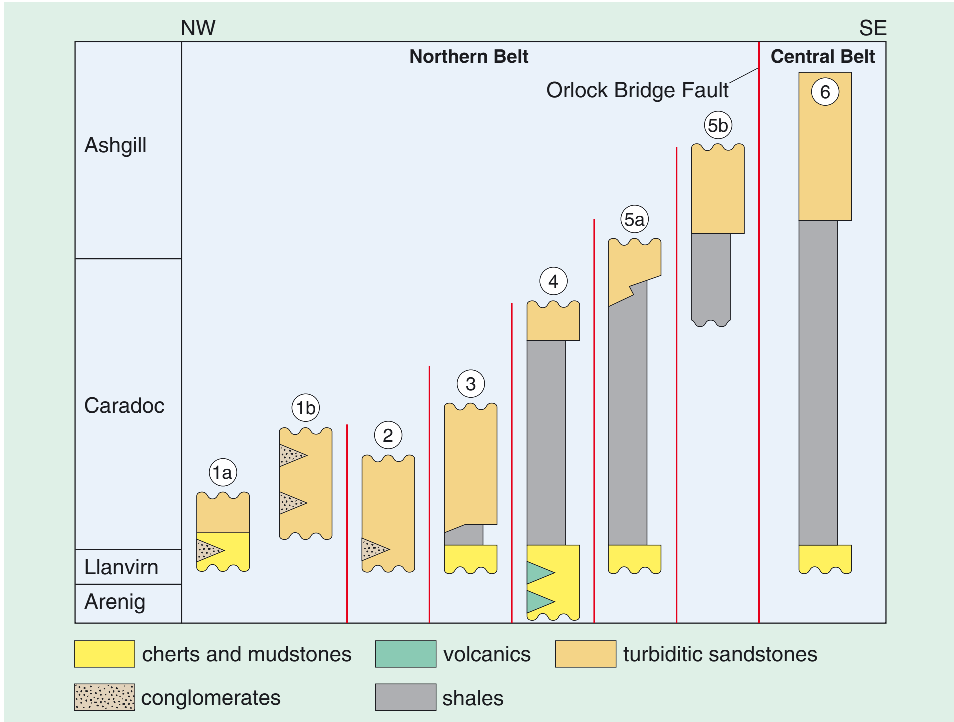

Figure 7.2 Ordovician stratigraphy of the Southern Uplands showing the fault-bounded tracts within the Northern and part of the Central Belt. The numbered columns relate to the tracts located in Figure 7.1.

Overall the succession comprises three distinct sedimentary units, although not all of them are found in every tract. The lowermost unit comprises pillow lavas and cherts that are interpreted as the uppermost part of the oceanic crust. These are overlain by deep-water black shales. The oceanic crust and black shales are overlain by conglomerates and turbiditic sandstones, which were deposited in submarine fans. Within the individual tracts, and from north to south, the influx of these turbidites occurs at progressively later times. In the northernmost tracts, the turbidites rest directly on the oceanic crust, and the shales are absent.

Petrographic studies of the major conglomeratic units have found that clasts of granites, volcanics, basalts and microgabbros are present. Many show similarities to the arc-related igneous rocks from the lowermost conglomerates that overlie the Ballantrae Complex. Turbidite sandstones are grey, quartz-rich and contain metamorphic detritus. The composition of detrital garnet is consistent with a Barrovian-type source; the presence of compositions typical of low-grade metamorphism in the older rocks and high-grade metamorphism in younger rocks is typical of unroofing sequences (Section 6.4). Ar-isotope dating of detrital micas gives ages of *c.* 480–460 Ma. These are similar to cooling ages from the Dalradian metasediments that were being uplifted to the north-west (Section 6.2). Palaeocurrent data point to a derivation from both the north-west and north-east.

Although the oldest sediments in the Central Belt are Caradoc to Ashgill, these are only a minor component, and the Central Belt mostly comprises Silurian greywackes and conglomerates deposited in submarine fans. The Southern Belt comprises Wenlock turbidites and thin siltstones.

7.3.2 The Southern Uplands as an accretionary prism?

The generally accepted interpretation of the Southern Uplands is that it represents an accretionary prism that developed in the fore-arc region of a convergent plate margin (Figure 7.3).

Accretionary prisms develop when trench-fill turbidites, ocean sediments and underlying oceanic crust are scraped from the descending oceanic plate by the leading edge of an overriding plate and become accreted to it. The internal structure of the prism therefore consists of a series of thrust-bounded slices that dip towards the arc and define wedge-shaped packets (Figure 7.3b). As subduction continues, the older thrusts and packets are gradually moved upwards and rotated as new wedges are added to the base of the prism. The older thrusts rotate to become steeper with time and may become inactive. Within each slice the sediments young towards the continent, whereas overall the age of sediments in the slices gets progressively younger towards the oceanward side. The different stratigraphies observed within each slice are consistent with deposition in widely separated parts of the ocean floor; eventually these are juxtaposed as they are progressively accreted to the subduction complex. During this deformation a fore-arc basin may develop between the trench and island arc.

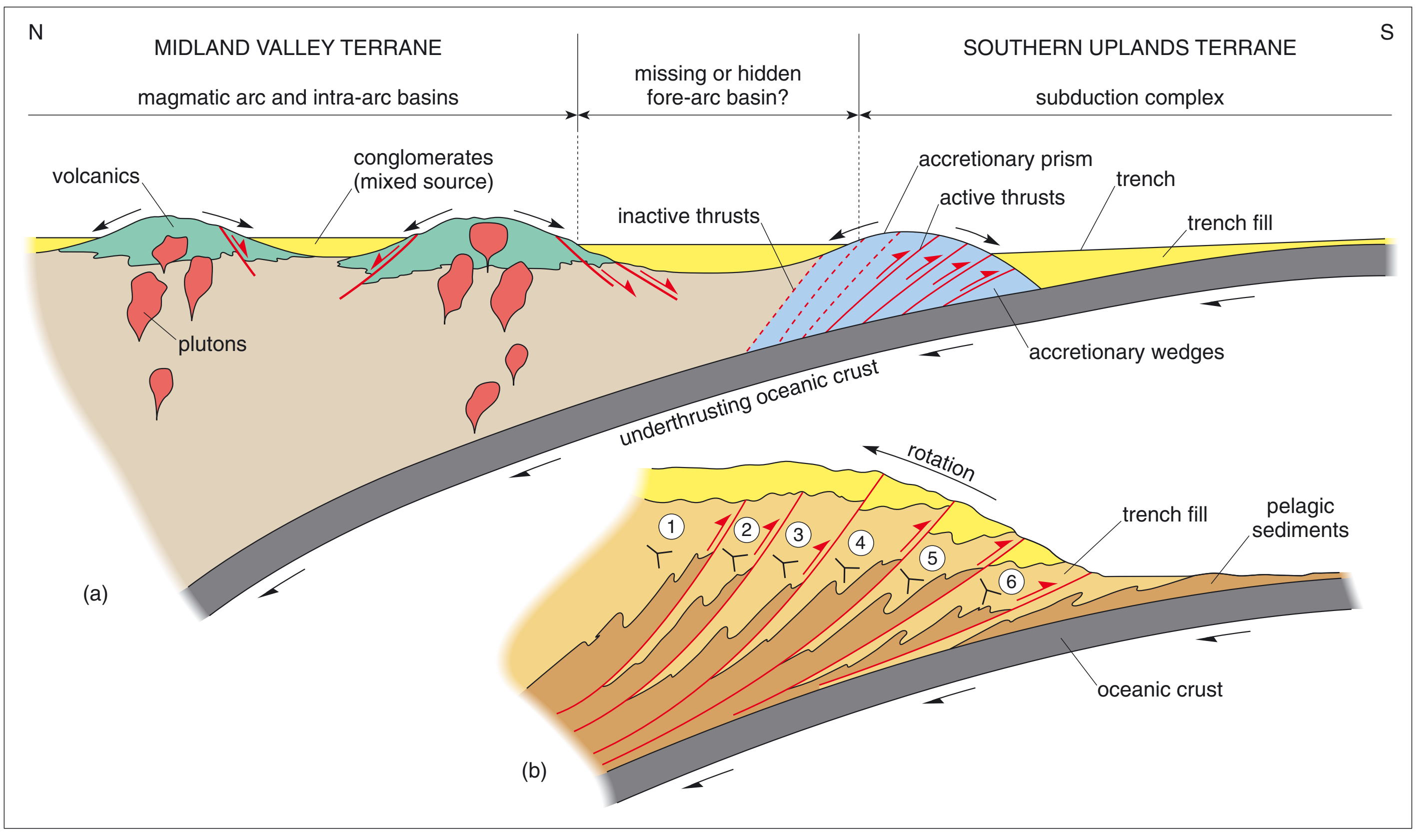

Figure 7.3 (a) A schematic tectonic reconstruction of the Midland Valley and Southern Uplands Terranes during Silurian times. (b) A model for the development of an accretionary prism at a convergent plate margin. The numbers refer to the order in which each tectonic slice was accreted.

7.3.3 Summary of Section 7.3

- The Southern Uplands comprises a series of Ordovician to Silurian sediments in a series of fault- or thrust-bounded slices.
- The sediments consist of a sequence of ocean-floor rocks that were progressively swamped by a turbidite apron. The petrology of clasts within the turbidites points to a significant component being derived from the erosion of Dalradian metasediments.
- The structure and sedimentology of the Southern Uplands is comparable to modern accretionary prisms that develop in convergent plate margins.

7.4 Interpretation: regional tectonic framework for the Midland Valley and Southern Uplands

7.4.1 Introduction

In mid-Ordovician to Silurian times an active margin developed to the south of the Grampian mountains. Several lines of evidence indicate that a volcanic arc developed in the Midland Valley, and was probably built on an older remnant Ordovician arc (Section 5.2.2) and metamorphic basement. The arc developed in response to northwards-directed subduction as indicated by the geometry of the Southern Uplands accretionary prism. Large amounts of sediments derived from the uplifting Grampian mountains and the volcanic arc were shed southwards into intra-arc basins and submarine fans, and ultimately incorporated into a growing accretionary prism. A simplified tectonic reconstruction of the active margin is presented in Figure 7.3a. Two important problems arise if this reconstruction is accurate. Firstly, what caused a reversal in the polarity (i.e. the direction) of subduction at the end of the Grampian phase? Secondly, where is the missing fore-arc basin?

7.4.2 What caused a subduction zone reversal?

In Figure 5.1 we saw that the Grampian phase resulted from the collision of an island arc with the Laurentian margin and that at this time the subduction zone dipped southwards. Given the evidence outlined above for the development of a N-dipping subduction zone it follows that at some point in the early Ordovician the subduction zone must have changed polarity. One possible explanation is that the collision of an island arc with the Laurentian margin led to jamming or blocking of the S-dipping subduction zone (Figure 5.1c). As a consequence of continued convergence, a second N-dipping subduction zone developed on the oceanward side of the island arc complex (Figure 5.1d).

7.4.3 A missing fore-arc basin?

The close proximity of the magmatic arc of the Midland Valley and the accretionary prism of the Southern Uplands causes a space problem for tectonic and palaeogeographic reconstructions if modern-day analogues are taken into consideration. In active modern-day intra-oceanic subduction zones the distance between the magmatic arc and the trench is at least *c.* 90 km, and this gap is normally occupied by a fore-arc basin (Figure 7.3a). In Scotland this fore-arc basin is missing. Additional evidence for a piece of missing crust comes from the study of the Silurian conglomerates of the Midland Valley (Section 7.2.3). The southerly-derived mixed metaquartzite and volcanic clasts could not have come from the Southern Uplands, as rocks of this type are not present there. They were probably derived from a volcanic arc built on a metamorphic basement (a Midland Valley-type crust) that is no longer exposed.

One possible explanation is that the missing crust now lies below the Southern Uplands accretionary prism. Two lines of evidence support this concept. Firstly, the presence of xenoliths of granulite-facies rocks that occur in Carboniferous volcanic vents in the Southern Uplands lends support to the existence of continental basement at depth. Secondly, a large scale S-dipping reflector identified in geophysical profiles taken across the Southern Uplands has been interpreted as a large-scale thrust that translated the accretionary prism northwards during the later collision of Avalonian fragments with the Laurentian margin (Figure 7.4).

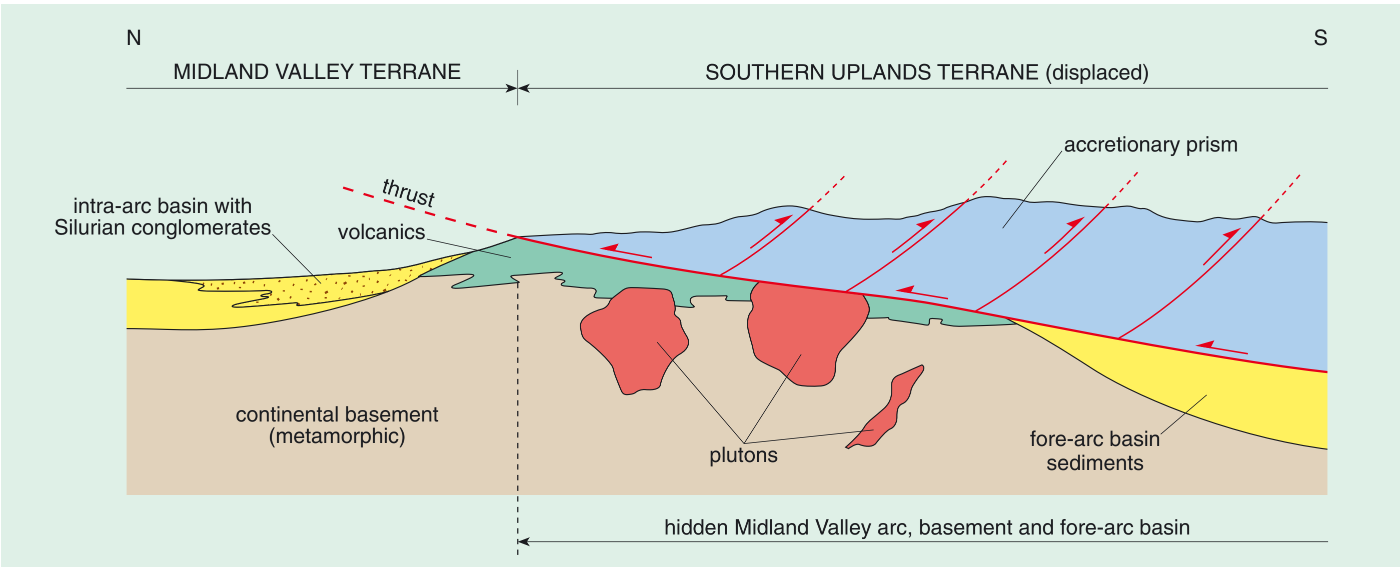

Figure 7.4 A tectonic reconstruction explaining the present juxtaposition of the Midland Valley arc and the Southern Uplands accretionary prism.

7.5 Summary of Section 7

- In mid-Ordovician to Silurian times an active margin developed on the southern side of the Laurentian margin.
- The continued closure of the Iapetus Ocean was achieved by the development of a second, N-dipping, subduction zone on the oceanward side of an island arc that collided with the Laurentian margin.
- A series of magmatic arcs, fore-arc and intra-arc basins formed in the Midland Valley, and in the Southern Uplands an accretionary prism developed as a result of the continued northwards subduction.