9 Sedimentation at the end of the Caledonian Orogeny

9.1 Introduction

The normal consequence of crustal thickening and mountain building is uplift and erosion. As long as uplift is faster than erosion, mountains will continue to grow, but once uplift slows, erosion eventually leads to the exhumation of the deeper roots of mountain belts. The exposure of these deep roots has allowed geologists to investigate the processes that led to crustal thickening and mountain building, as we have seen in this book. But what of the sediments that result from uplift and erosion during and after a period of prolonged mountain building? In this Section, we consider the drainage and sediment dispersal pattern associated with the final stages of the Caledonian Orogeny, as recorded by Devonian sedimentary rocks.

9.2 The Old Red Sandstone and the Devonian Period

The term Old Red Sandstone is the name given to the non-marine clastic sediments of approximately Devonian age that were deposited in the region where Baltica, Laurentia and Avalonia had collided during the Ordovician and Silurian Periods. These sediments are often brown to red in colour and comprise conglomerates (such as those shown in Figure 9.1), sandstones and siltstones

Figure 9.1 A bedding plane in an Upper Old Red Sandstone conglomerate that contains clasts of Dalradian metasediments, near Loch Lomond.

that are readily interpreted to be late- to post-orogenic sedimentary successions formed by intense erosion of the recently-built Caledonian mountains.

The Old Red Sandstone (ORS) is conventionally divided into the Lower, Middle and Upper Old Red Sandstone, but these only crudely equate with subdivisions of the Devonian. Furthermore, many Lower Old Red Sandstone successions were actually deposited during the Late Silurian, when the transition from marine to non-marine environments occurred. Some Upper Old Red Sandstone successions include rocks deposited in the Early Carboniferous.

9.3 Distribution and stratigraphy of the Late Silurian to Devonian Basins

The distribution of Late Silurian to Devonian sedimentary basins is illustrated in Figure 9.2a. The basins are classified according to whether they lie to the north or south of the Iapetus Suture; those to the north are termed internal basins, those to the south are external basins.

The history of sedimentation in these basins is reflected in the stratigraphic logs in Figure 9.2b, which show that the most continuous record of sedimentation is found in the south, in the Cornubian Basin of Cornwall and Devon. To the north, as far as the Highland Boundary Fault, Middle Devonian sediments are missing, and a major unconformity separates Lower and Upper Devonian successions. A near-complete succession is preserved in the Orcadian Basin. The

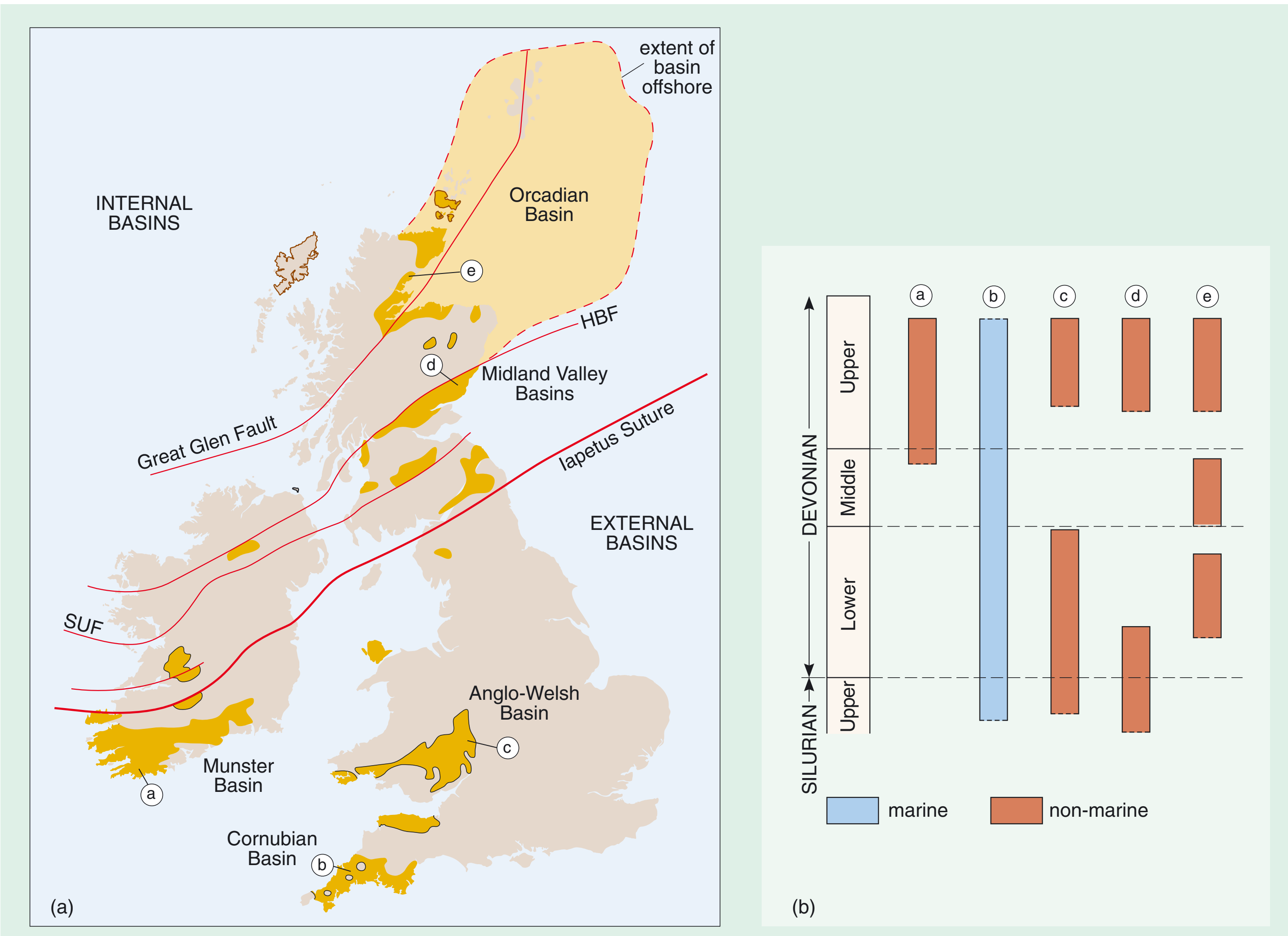

Figure 9.2 (a) The distribution of Late Silurian to Devonian basins. (b) Representative stratigraphic logs for the main basins a–e.

separate and distinct histories of different sedimentary basins indicate that individual basins were separated by topographic highs that acted as major drainage divides.

With the exception of the Cornubian Basin, the Late Silurian to Devonian basins preserve a record of non-marine sedimentation. The implications are that any residual marine Iapetan basins had been uplifted well above sea-level, and were either exposed and being eroded, or accumulating non-marine sequences. The mid-Devonian unconformity marks the period of maximum uplift and erosion. It was only in the south of the region, in the Cornubian Basin, that subsidence and deposition of marine sequences persisted.

9.4 Sedimentation and tectonics in the Midland Valley

9.4.1 Structure of the Midland Valley in the Devonian Period

The Midland Valley contained two Early Devonian basins, the Strathmore and Lanark Basins, which were separated by a central zone or axis of active volcanism (Figure 9.3). The Upper Silurian to Lower Devonian sediments laid down in these two basins are unconformably overlain by Upper Devonian sediments deposited in a larger basin, the Midland Valley Basin; Middle Devonian rocks are absent (Figure 9.2b). Outliers of Upper Silurian to Lower Devonian sediments and associated volcanics are found within the adjacent Grampian Highlands and Southern Uplands. The depositional age of the sedimentary rocks is constrained by the eruption ages of the contemporaneous basaltic, andesitic and dacitic volcanic rocks, radiometrically dated at *c.* 423–396 Ma (Figure 9.3).

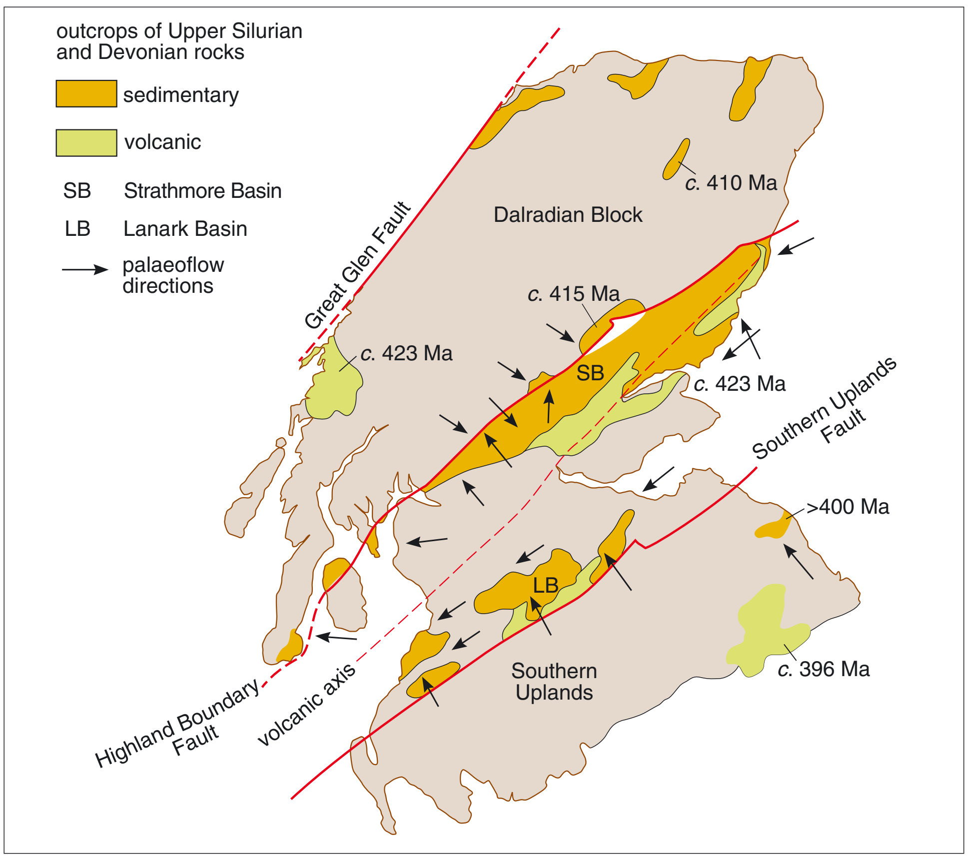

Figure 9.3 Map showing the distribution of Old Red Sandstone (Upper Silurian and Devonian) outcrops in the Midland Valley and adjacent areas. Arrows show the Lower Old Red Sandstone palaeoflow directions.

- What significant magmatic and tectonic events were happening at this time in this region? (Refer back to Section 8.)
- The Newer Granites were emplaced at *c.* 440–390 Ma, and important sinistral strike–slip displacements were occurring along NE–SW-oriented fault systems at *c.* 430–425 Ma and *c.* 410–390 Ma.
- What information in Figure 9.3 indicates that some fault displacements outlasted sedimentation?
- The Highland Boundary Fault truncates the margin of the Strathmore Basin and the adjacent outliers to the north; in addition, the Southern Uplands and Great Glen Faults also cut Devonian rocks. (These observations also suggest that the Early Devonian basins originally extended beyond their present outcrop.)

The outliers of sedimentary and volcanic rocks to the north of the Midland Valley sit directly on Dalradian sediments that attained some of the highest metamorphic grades during the Grampian event, as can be seen by comparing their positions in Figure 9.2a with the metamorphic map of Figure 5.12.

- What are the implications of these observations?
- The fact that the sediments and volcanics sit directly on the highest-grade rocks suggests that the deepest levels of the Grampian mountains had been exposed and the region was essentially eroded to a peneplain by at least *c.* 425 Ma.

This is not unlikely, because Ordovician and Silurian sediments from the Midland Valley and Southern Uplands have been shown to contain Dalradian metamorphic minerals, implying that the Grampian mountains had been supplying debris to the surrounding areas since *c.* 465 Ma (Section 6.4). Likewise, uplift and erosion of the Southern Uplands before deposition of the Old Red Sandstone is indicated by the unconformable bases of the Old Red Sandstone outliers.

In Late Silurian to Early Devonian times the Midland Valley and its neighbouring areas had the structure summarized in Figure 9.4. This provided the setting for the accumulation of the Old Red Sandstone in the Midland Valley.

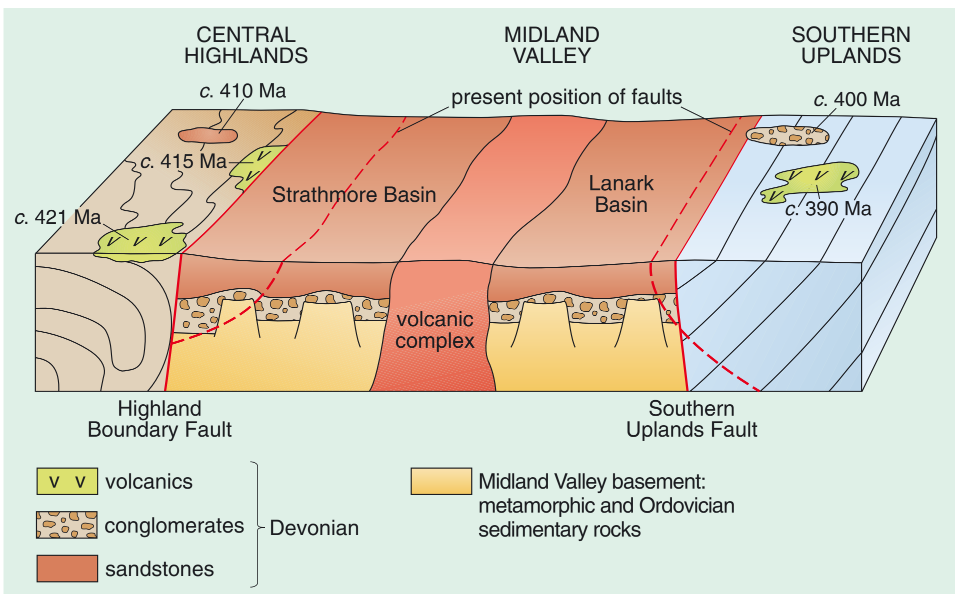

Figure 9.4 Schematic block diagram of the structure of the Midland Valley and adjacent regions in Late Silurian to Early Devonian times. The present positions of the major faults may reflect later compression of the Midland Valley.

9.4.2 Late Silurian–Early Devonian sedimentation

The early basin fill comprised conglomerates and breccias deposited in alluvial fans (Figure 9.5). The debris mainly consisted of reworked quartzites, granitic boulders, abundant andesitic volcanics, gabbros and dolerites. The gabbros and dolerites were probably sourced from remnant ophiolitic rocks that may underlie the Midland Valley. Detritus of Dalradian origin accounts for only a limited amount of these sediments. Palaeocurrent data (Figure 9.3) indicate that the sediments were sourced from several regions: from the NE and SW, from the adjacent blocks of the Grampian Highlands and Southern Uplands, and from the volcanic axis. It has been suggested that deposition occurred in a set of transtensional basins bounded by a series of active strike–slip faults (including the Highland Boundary and Southern Uplands Faults). The changing pattern of fault movements caused uplift in some areas and erosion in others, and led to the recycling of earlier deposits as areas of deposition became uplifted blocks. The early sediments were progressively recycled and reworked.

Figure 9.5 Near-vertical Lower Old Red Sandstone conglomerates in the northern limb of the Strathmore Syncline, Dunnottar Castle, south of Stonehaven.

By late Early Devonian times sedimentation in the basin had changed. The coarse conglomerates and breccias gave way to finer sands. Palaeocurrent data suggest a south-westerly flow along the axis of the basin, and indicate that the sediment was derived from the north-east. One possible explanation is that the sediments were sourced from the rising Scandian mountains and transported by major trunk rivers that flowed south-west along the axis of the basin. The fining-upwards of the sequence and the absence of significant Dalradian metamorphic debris suggest that the basin flanks or rift shoulders were no longer uplifting and providing debris to the basin.

9.4.3 A Mid-Devonian hiatus

Sedimentation in the Midland Valley ceased in Mid-Devonian times. Several lines of evidence point to a phase of convergence or transpression at this time. For example, the Early Devonian basins are folded on a regional scale, with NE–SW-striking fold axes. In addition, the Early Devonian basin-bounding faults may have been reactivated as thrusts, a process which led to truncation of the basin margins. The possible effect of the displacement on the positions of the major faults is illustrated in Figure 9.4.

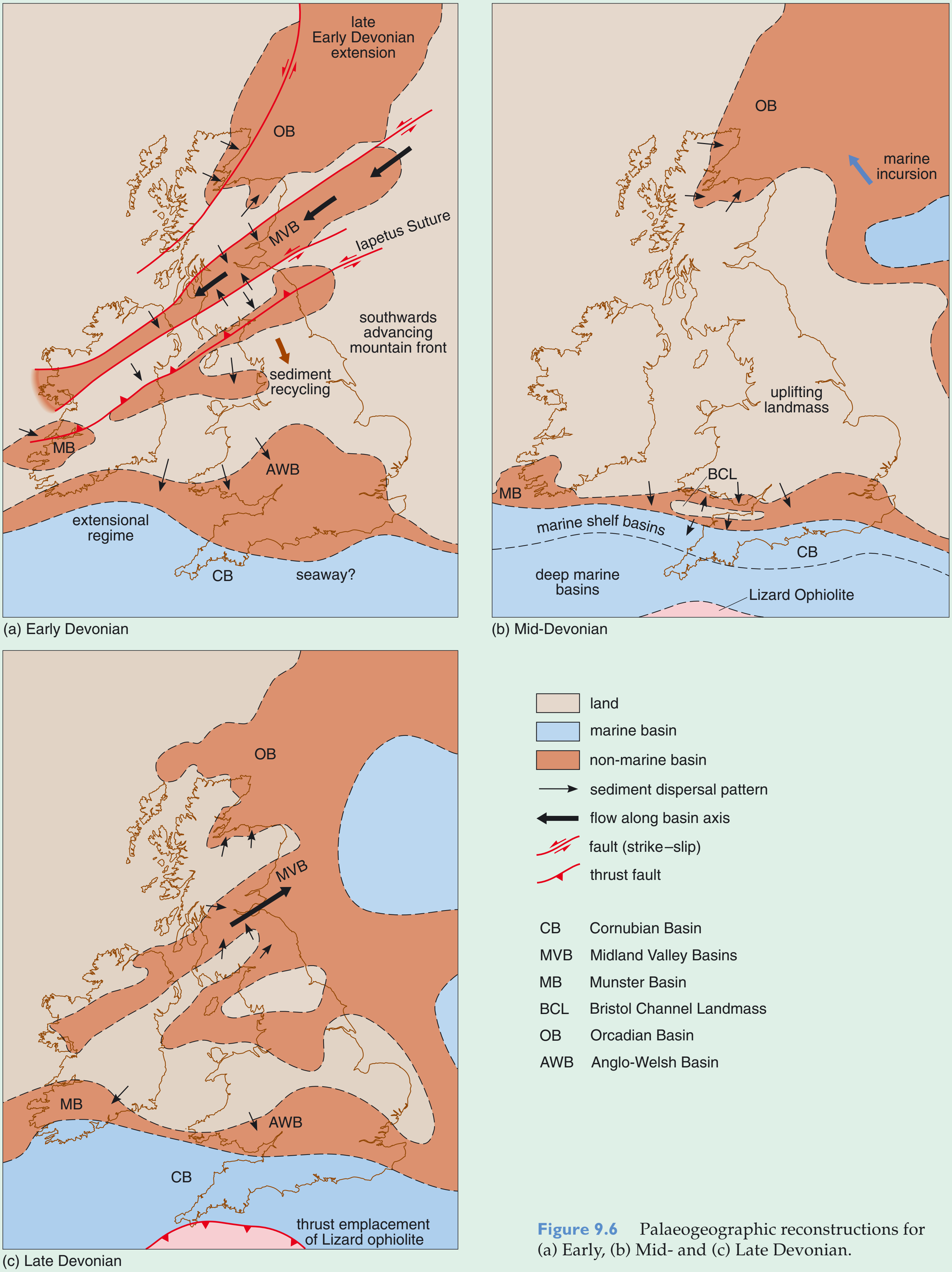

Figure 9.6 Palaeogeographic reconstructions for (a) Early, (b) Mid- and (c) Late Devonian.

9.4.4 Renewed deposition in the Late Devonian

Sedimentation in the Midland Valley resumed in the Late Devonian. A series of northerly-derived alluvial fans, which deposited conglomerates fining upwards into muds, bordered an alluvial plain crossed by meandering rivers, from which essentially fine-grained sediments were deposited. Deposition was slow and allowed the development of calcareous cements and carbonate evaporites (caliches). Palaeocurrents indicate that the rivers flowed roughly NE, opposite to the Early Devonian drainage system, probably as a result of uplift in the SW. The changing pattern of sedimentation in the Midland Valley (and across the mountain belt) is illustrated in Figure 9.6, which shows a series of palaeogeographic reconstructions for Early to Late Devonian times.

In the eastern Southern Uplands, Late Devonian sedimentation deposited sandstones and conglomerates on upturned Silurian turbidites to produce the Siccar Point unconformity, famously recognized by James Hutton in 1788 (Figures 1.1 and 9.7).

Figure 9.7 The unconformity at Siccar Point, showing shallowly-dipping Upper Old Red Sandstone resting on steeply-dipping Llandovery turbidites.

9.4.5 Summary of Section 9.4

- Late Silurian to Early Devonian non-marine sedimentation in the Midland Valley occurred in a series of transtensional basins. It has been suggested that deposition was controlled by major strike–slip faults.
- By *c.* 425 Ma the mountains of the Grampian Highlands had been eroded down to their roots and the highest-grade metamorphic rocks were exposed.
- Initially, locally-derived detritus was supplied from the basin flanks. Later, externally-derived sediment was supplied by major SW-flowing trunk rivers.
- Mid-Devonian sediments are absent from the Midland Valley. Late Devonian sediments were deposited under conditions in which the regional drainage pattern flowed north-eastwards.

9.5 Sedimentation and tectonics in the external basins

9.5.1 A southward-migrating mountain front

Data from the external basins provide a picture of sedimentation and tectonics that is different from that obtained from the internal basins. In Late Silurian to Early Devonian times debris was shed southwards from the rising mountains and was deposited either in rapidly subsiding foreland basins or in fault-bounded extensional basins. It was only in the very south that the marine basins on the southern edge of Eastern Avalonia persisted. Figure 8.12 and Figure 9.6 show the overall tectonic and palaeogeographic contexts in which these basins developed.

Close to the Iapetus Suture, in the Lake District, Isle of Man and Ireland, Late Silurian deposition of debris occurred in rapidly subsiding foreland basins that developed as the Avalonian crust was depressed beneath the southwards-advancing load of Laurentia. In these basins, subsidence quickly gave way to uplift, shortening and erosion in the Early Devonian. As a result these early sediments were recycled and transported further south. A similar picture is observed in south-west Ireland (the Munster Basin) where gravels and coarse sandstones were deposited in a rapidly subsiding fault-controlled basin (Figure 9.6a).

In the Anglo-Welsh Basin, Upper Silurian marine sequences were replaced by non-marine deposits as sediment supply outweighed subsidence and basins rapidly filled. The composition of the Upper Silurian to Lower Devonian detritus suggests derivation from a metamorphic source, probably the Grampian and Northern Highlands. By Early Devonian times this source was waning and the majority of the deposits were derived from uplifting and eroding regions in northern England and North Wales, in essence recycling the earlier deposits. Deposition occurred in alluvial fans and flood-plains. Coarsening-upwards sequences indicate the southwards migration or advance of the mountain front.

By Early Devonian times, uplift and erosion was affecting all areas except Cornubia (Figure 9.6a). Maximum uplift was reached in mid-Devonian times and resulted in the widespread mid-Devonian unconformity. A periodically emergent landmass, the Bristol Channel Landmass, shed debris both north and south at this time (Figure 9.6b).

Alluvial and marginal marine deposition began again in Late Devonian times as a global sea-level rise caused the upwards transition into marine Lower Carboniferous sediments.

9.5.2 A short-lived mid-Devonian ocean basin?

In the south, the Cornubian Basin records the development of a small ocean basin. In the Early Devonian, fluvial sequences are thought to have covered most of Cornubia, the rivers flowing south into a marine basin (Figure 9.6a). In mid-Devonian times crustal extension led to the formation of a series of fault-bounded basins that developed on a marine shelf (Figure 9.6b). The most northerly of these basins periodically received sediments brought in from the north by rivers eroding the emergent Bristol Channel Landmass.

These southern basins had a history of fault-controlled sedimentation, indicated by debris flows, slumps and active volcanism sited along major fracture zones, with extension possibly continuing until the Early Carboniferous. Although the *c.* 400 Ma Lizard ophiolite may represent a fragment of oceanic crust, the basin was probably of limited extent and short-lived. By the mid-Devonian the basin was being filled by clastic sediment derived from the south, in response to the flexural subsidence ahead of the northward-migrating Variscan thrust pile. By the Late Devonian to Early Carboniferous, this small basin was being deformed by thrusting associated with the early stages of the Variscan Orogeny (Figure 9.6c).

9.5.3 Summary of Section 9.5

- By Early Devonian times, the Late Silurian marine basins had been uplifted above sea-level and non-marine sedimentation was occurring. As the Caledonian mountain front migrated south, early deposits were reworked by erosion and transported in river systems that drained into a marine basin. Sedimentation occurred in a series of fault-bounded basins that developed in response to the flexural loading of the crust.
- By mid-Devonian times, uplift and erosion had reached a maximum, as indicated by the absence of mid-Devonian deposits and the development of a major unconformity. In the south, continued extension-related rifting formed a mid-Devonian oceanic basin, which culminated in the development of oceanic crust.
- In Late Devonian times, the ocean basin closed by thrusting and renewed sedimentation resulting from pulsed marine transgression.

9.6 Orogen-scale drainage and sediment dispersal patterns

By Early Devonian times, the basement rocks of the Laurentian and Avalonian crust had been considerably shortened, the Lower Palaeozoic sedimentary successions had been folded, deformed and weakly metamorphosed, and the Silurian marine basins had been uplifted well above sea-level. As a result of the uplift a regional drainage pattern developed and rivers transported detritus away from the growing mountain belt. The palaeocontinental reconstructions shown in Figure 9.8 illustrate the changing pattern of the drainage system out of the orogen from Early to Late Devonian times. In the Early Devonian, an axial drainage pattern developed in response to uplift in the Scandinavian and Greenland segments of the orogen. This uplift generated a major drainage divide from which rivers shed sediment both NW and SW. These rivers transported sediment into the transtensional basins of the Midland Valley. Rivers originating in the Southern Uplands and northern England transported sediments towards the SE across the Iapetus Suture into the extensional fault-bounded external basins and into a marine basin, located along the southern margin of Avalonia. In mid- to Late Devonian times the drainage system changed as the centre of major uplift shifted south-westwards, and as a result rivers in the Midland Valley drained northwards and the mid-Devonian hiatus and regional unconformity developed across most of the region. Sedimentation only continued throughout the Devonian in the extensional fault-controlled Orcadian and Cornubian Basins.

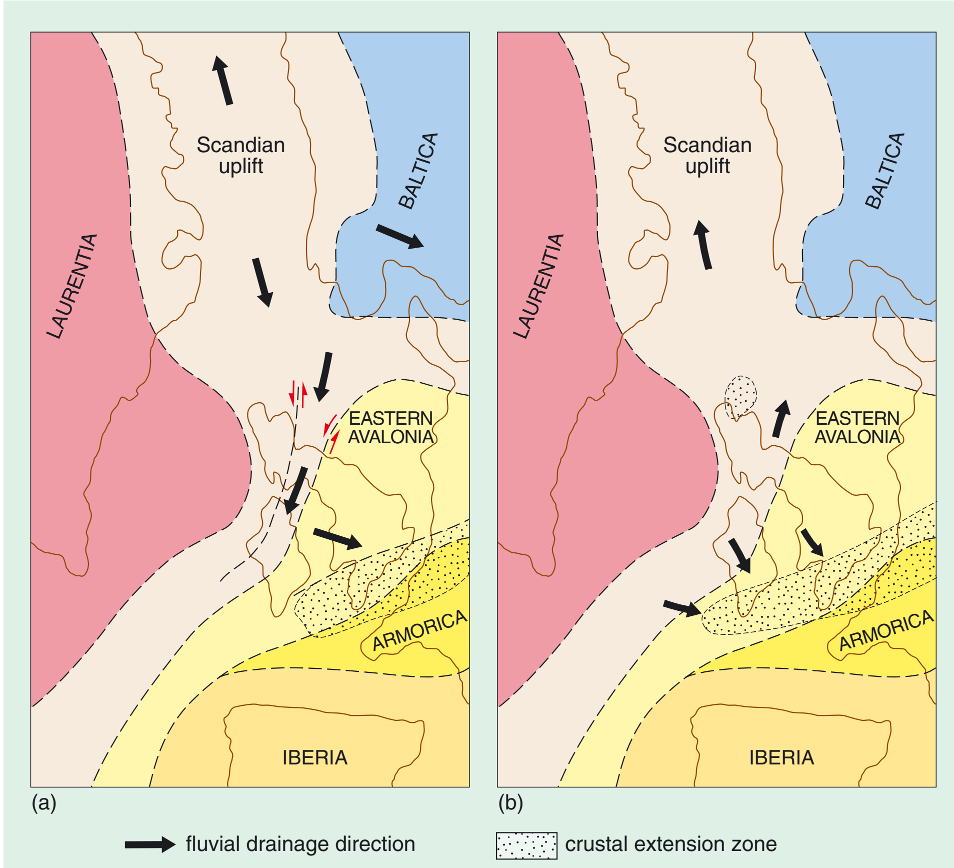

Figure 9.8 Late Caledonian orogen-scale drainage and sediment dispersal pattern for (a) Early Devonian, and (b) Late Devonian times.

9.7 Summary of Section 9

- In Early Devonian times, non-marine sedimentation occurred during convergence, with deposition of the Lower Old Red Sandstone within internal, transtensional basins, and external, fault-controlled rift basins.
- In mid-Devonian times, movement along strike–slip faults had ceased and uplift was at a climax. Uplift led to the development of a major mid-Devonian unconformity. At this time most of Britain and Ireland was shedding rather than receiving detritus. It was only in northern Scotland and along the southern margin of Avalonia that subsiding basins persisted. By Early Carboniferous times, marine transgression occurred and most of southern Britain came under the influence of the early stages of the Variscan Orogeny.

10 Legacy

Sections 2 to 9 summarized the origin of the crustal blocks, or terranes, of which Scotland is built and the plate tectonic collisions and strike-slip movements that brought those terranes together. Our geological saga ended some 350 million years ago, with the first ripples of the Carboniferous marine transgression and the distant rumblings of the Variscan Orogeny developing in Armorica to the south. Later events in Britain's geological history involved sedimentation during its northward drift across the globe, with bursts of igneous activity during the Carboniferous, Permian and Tertiary Periods, the last being associated with continental rifting and the opening of the Atlantic Ocean. In the main, however, the Scottish bedrock is made of rocks that formed before or during orogenic collisions between plates and micro-plates in the Ordovician and Silurian Periods.

The geology of the Highlands and its influence on the lives of people are therefore the legacy of Precambrian and Palaeozoic events. For example, hot springs of mineralized sea-water that were discharged from the faulted, stretched crust of the Laurentian continental margin during mid-Dalradian times deposited baryte, and this mineral is now mined from the enclosing metasediments in central Perthshire (at Foss) and used in the oil production industry. Shallow marine sedimentation during Dalradian (Southern Highland Group) times produced limestones, such as the Loch Tay Limestone, which 19th century farmers quarried and burnt to make fertiliser for the typically acidic Highland soils. Once crustal stretching and continental break-up had led to the creation of the wide Iapetus Ocean, plate convergence then brought Avalonia and Laurentia, and intervening island arcs, together. A series of terrane collisions ensued, with the collision of the Midland Valley Terrane and Laurentia deforming and metamorphosing the Dalradian in the Grampian phase of the Caledonian Orogeny. This *c*. 480–465 Ma mountain-building event also left many a mark. It was at this time that Dalradian metasediments melted during exhumation of the roots of the Grampian mountains to form granite, the defining building stone of Aberdeen (the 'Granite City'). The reason that Aberdeen is one of the places in Britain with a higher than normal level of background radiation is that the Ordovician Aberdeen granite inherited and concentrated radioactive isotopes from its source metasedimentary rocks. Silurian to Early Devonian subduction-related magmatism associated with the convergence of Avalonia and Baltica on Laurentia produced the granites of Lochnagar and the Cairngorm plateau, the andesitic volcanics of Britain's highest peak Ben Nevis and the igneous rocks of Glen Coe as illustrated on the front cover. During the final stages of orogenesis, the erosion of the high mountain range during the Silurian and Devonian, the Old Red Sandstone was deposited in the Midland Valley, later giving rise to the rich soil that supports one of the most productive fruit-growing areas in the UK.

Music, poetry, art and science have all been inspired by the rocks of the Scottish Highlands, and the introduction to this book (Section 1.1) mentioned some of the 19th century scientists whose geological work in the Highlands earned them places in the history of science. Perhaps it is no wonder that Charles Lyell, often considered to have founded the science of geology, was born and grew up in the shadow of the Highlands, some two kilometres south of the Highland Boundary Fault at Kinnordy, near the town of Kirriemuir. Present-day geologists still find much to puzzle about and enjoy in the rocks of the Highlands; the rocks themselves may be old but they continue to inspire new ideas and fresh insights on the way that mountains are built.

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