8 Multiple plate collisions and the end of the Iapetus Ocean

8.1 Introduction

Sections 4 to 7 outlined the evidence and possible plate-tectonic explanations for the formation and partial closure of the Iapetus Ocean. Section 4 showed that a prolonged period of rifting that started in late Precambrian times culminated in plate separation and led to the opening, to the south of Laurentia, of the Iapetus Ocean. The initial stage of ocean closure was by subduction of oceanic crust and the collision of an island arc with Laurentia, which caused the Grampian phase of the Caledonian Orogeny (Section 5). Ocean closure continued with the development of a northwards-dipping subduction zone on the southern margin of Laurentia (Section 7). This Section concentrates on establishing the plate-tectonic causes for the demise and eventual closure of the Iapetus Ocean in the early Palaeozoic. Section 8.2 presents a broad, plate-scale view of the causes of the closure, whereas the later Sections give the geological evidence upon which these plate models are based. Section 8.8 summarizes the closure of the Iapetus Ocean.

8.2 Palaeocontinental reconstructions

8.2.1 The global view

Palaeocontinental reconstructions of plate movements since the late Precambrian are based in part on palaeomagnetic pole positions, and partly on studies of fossils that allow palaeogeographically separate faunal provinces to be recognized. The palaeogeographic reconstructions that are relevant to events associated with the Caledonian Orogeny were illustrated in Section 1 (Figure 1.5) and involve many continental fragments that bordered Iapetus and which were converging during the early to mid-Palaeozoic. Of these continental fragments, Baltica and Eastern Avalonia were directly involved in the geological evolution of Scotland. Further to the west, Western Avalonia collided in mid-Silurian times with Laurentia, and Armorica collided with the assembled northern fragments to the south-east, forming a palaeocontinent informally termed Laurussia, in the Early Devonian. In mid-Devonian times Iberia collided with Armorica.

8.2.2 A model for the closure of the Iapetus Ocean

In recent years a detailed evaluation of the causes and nature of the closure of the Iapetus Ocean has been based on a multidisciplinary approach incorporating stratigraphic, structural and isotopic dating methods applied to rocks from a huge area. Figure 8.1 shows the sequence of convergence of continental fragments onto the Laurentian margin during Silurian to Early Devonian times.

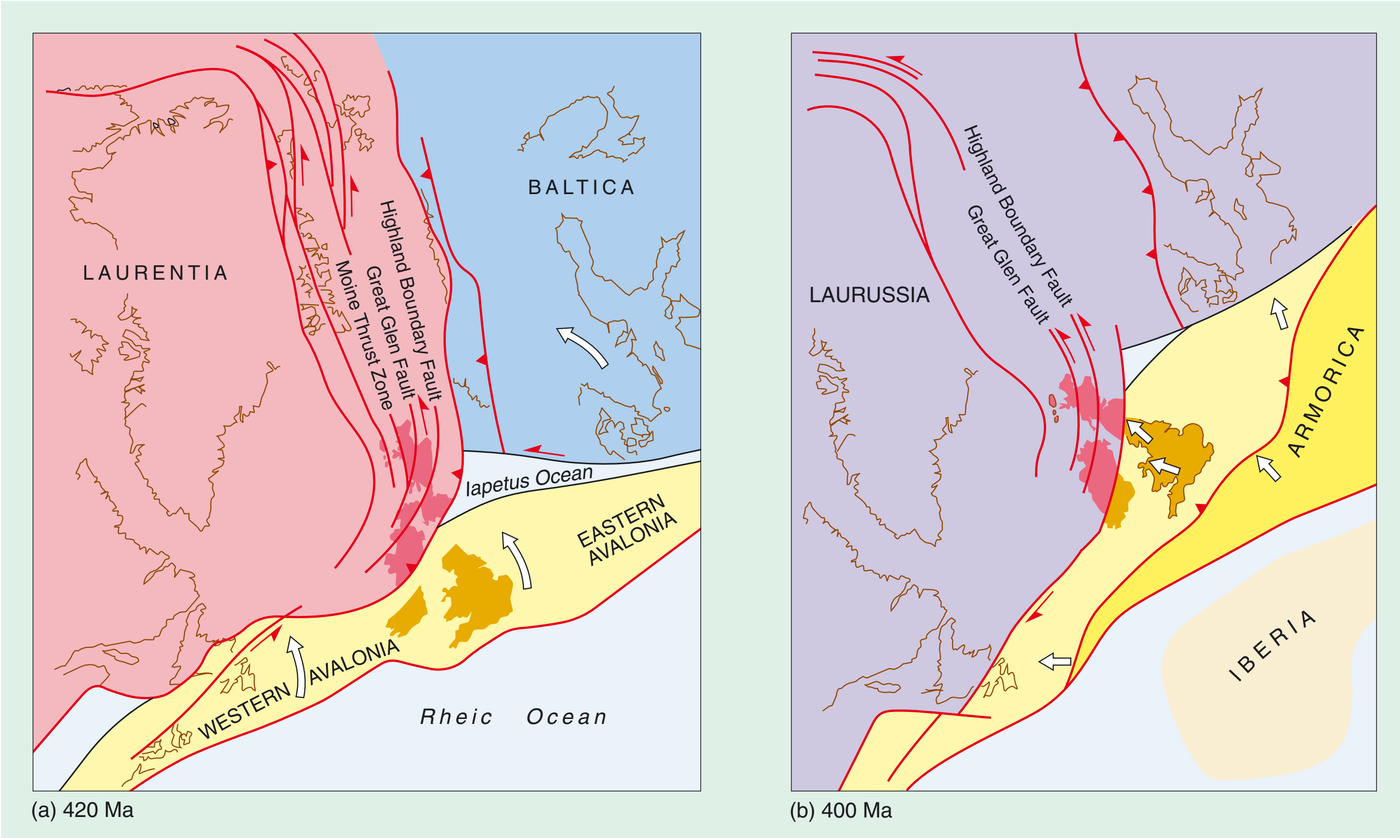


Figure 8.1 Reconstruction of multiple plate collisions and the Silurian closure of the Iapetus Ocean. (a) 420 Ma, at about the Wenlock–Ludlow boundary. Large arrows indicate the convergence directions of Baltica and Eastern Avalonia with the Laurentian margin. (b) 400 Ma, Early Devonian, showing the Acadian convergence directions. Also shown is the impending collision of Iberia with Armorica, which occurred in Mid-Devonian times. These diagrams illustrate the progressive restriction and closure of the Iapetus Ocean.

- Study Figure 8.1a. Does it indicate orthogonal plate convergence (i.e. perpendicular to plate boundaries) with the Laurentian margin?

- No. Examination of the plate convergence directions indicates that in mid-Silurian times (Figure 8.1a) Baltica collided obliquely with the north-eastern part of the Laurentian margin.

The collision of Laurentia and Baltica led to the closure of the northern arm of the Iapetus Ocean, an event called the Scandian orogenic phase, and was responsible for mountain building in Norway, Sweden and East Greenland. Further south, and at the same time, Eastern Avalonia collided obliquely with the Laurentian margin. In both cases a significant component of anticlockwise rotation was involved in the displacement. One of the major consequences of oblique collision was that major plate movements were accommodated along a series of major strike–slip faults and shear zones (Box 8.1).

Box 8.1 Contrasting the effects of orthogonal and oblique convergence

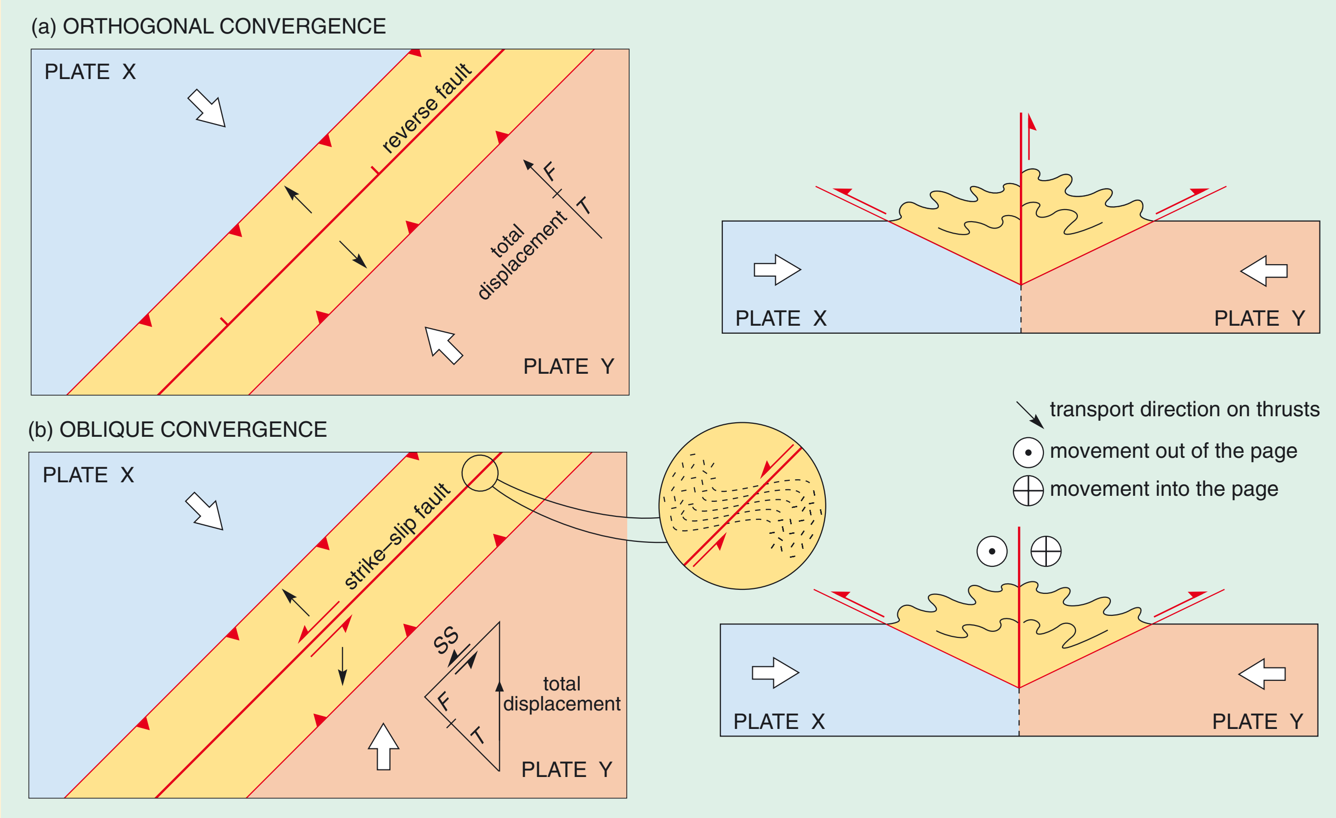


Figure 8.2 Models of collision between two plates X and Y: (a) orthogonal convergence; (b) oblique convergence in map view (left) and cross-section (right). The total amount of shortening accommodated by thrusting (*T*), folding (*F*) and strike–slip displacements (*SS*) is shown by the vector diagrams. The symbols in circles indicate sinistral strike–slip displacement. The inset shows how the sense of displacement along the fault is indicated by the rotation of fabric components.

In a simple model of plate convergence, two blocks representing two plates X and Y collide in an orthogonal manner, essentially head-on (Figure 8.2a). In this model, crustal shortening across the orogen is accommodated by reverse and thrust faulting, and by folding. During an orthogonal collision, shortening is perpendicular or normal to plate boundaries (termed orogen-normal shortening) such that the transport directions on faults are perpendicular to the plate margin.

But what would happen if plates X and Y collided obliquely? This situation is illustrated in Figure 8.2b. One of the major consequences of oblique collision is that plate movements can be resolved into two components, a component of orogen-normal shortening and a component of orogen-parallel displacement or shear. In this case, the orogen-normal shortening is accommodated by folding and thrusting (which may be dip–slip or oblique), whereas an orogen-parallel component is accommodated along strike–slip faults or shear zones. In Figure 8.2b, an anticlockwise shear is imposed on the orogen because of the angular relationship between the plates, and strike–slip faults will have a sinistral sense of displacement. The sense of displacement on these structures can be determined from the sense of rotation of fabric components into the fault or shear zone. During oblique convergence or collision, material is moved along the orogen.

In reality, the style and location of structures that develop along a collisional plate boundary are a function of a variety of factors, including the angle of convergence, the shape of the plate boundary, the existence of pre-collisional weaknesses (e.g. faults) and the nature and strength of the crust. For instance, Figure 8.3 shows the effects of an orthogonal plate convergence in which the plate boundary has a promontory and re-entrant.

Note how the sense of displacement is different on either side of the promontory and re-entrant, being either sinistral (anticlockwise) or dextral (clockwise). The relative displacements on the strike–slip faults indicate that material is transferred away from the promontory and towards the re-entrant.

The combination of compression (shortening) and strike–slip displacement is called transpression; likewise a combination of extension and strike–slip displacement is called transtension. In the example in Figure 8.3, the formation of structures on both sides of the promontory would result from either dextral or sinistral transpression, yet plate convergence is, overall, orthogonal. This example shows that the relative motion of the plates cannot simply be established from the kinematics of fault displacement from different parts of a collision zone. Independent information such as the results of palaeomagnetic studies must be considered.

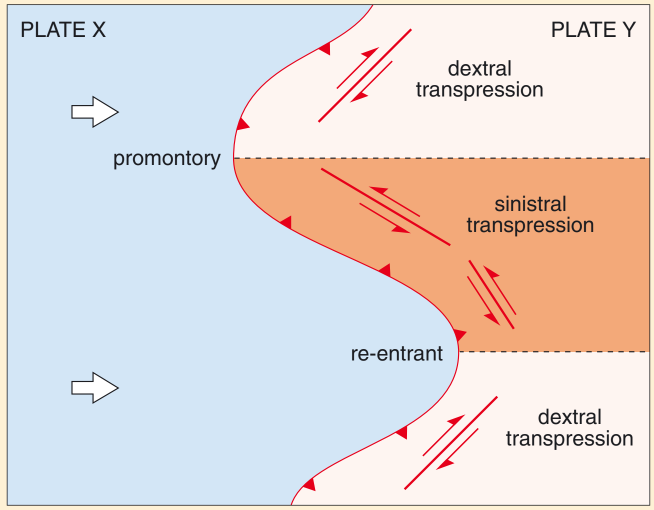


Figure 8.3 Orientation and sense of displacement along structures developed during orthogonal convergence involving a plate with an irregular boundary, containing a promontory and a re-entrant.

By Late Silurian–Early Devonian times (Figure 8.1b) the extent of the Iapetus Ocean was severely restricted and, with respect to Britain and Ireland, was essentially closed. It is clear from the comparison of Figures 8.1a and b that the Iapetus Ocean closed in a scissor-like manner, with closure first in the south-west and progressing north-eastwards. This closure was a consequence of the oblique convergence and anticlockwise rotation of Eastern Avalonia into a re-entrant along the Laurentian margin. In Early Devonian times (*c.* 400 Ma) further compression between Eastern Avalonia and Laurentia led to the Acadian orogenic phase. The cause of this event is uncertain, but two possibilities have been put forward: either convergence of Eastern Avalonia with Laurentia continued for some time after ocean closure, or this compression was enhanced by the collision of Armorica with Eastern Avalonia in Early Devonian times.

The change in displacement along major strike–slip faults with time indicates an anticlockwise change in convergence directions. Evidence for this change can be seen in Figure 8.1, where the direction of displacement along the strike–slip fault in Newfoundland, associated with collision of Western Avalonia and Laurentia, changes from sinistral (Figure 8.1a) to dextral (Figure 8.1b). In essence, the convex shape of the Laurentian margin controlled the direction of displacements along the strike–slip faults. In Britain and Ireland, the Acadian compression induced further sinistral strike–slip displacements along major faults, e.g. the Highland Boundary Fault, and in some cases reactivation of older faults, e.g. the Great Glen Fault, a feature that is accentuated around the 'convex corner' of the Laurentian margin.

What, then, are the tectonic implications for the Scottish Highlands of significant displacements (>*c.* 100 km) along the Great Glen and Highland Boundary Faults? An important consequence of significant sinistral displacements along these major faults is that during Silurian times the Northern Highlands lay further to the north-east and were located opposite Scandinavia. This palaeogeography makes it likely that the deformation in the Moine Thrust Zone may have resulted from the collision of Baltica with Laurentia, and did not form in response to the collision of Eastern Avalonia and Laurentia.

8.2.3 Summary of Section 8.2

- Plate reconstructions indicate that the closure of the Iapetus Ocean in the early Palaeozoic resulted from multiple plate collisions.
- Plate-tectonic models suggest that plate collision was predominantly oblique. As a consequence, Iapetus closed in a scissor-like manner.
- The combination of oblique collision and the shape of the plate boundary ultimately controlled the nature of the deformation, in particular the sense of displacement along major strike–slip faults.
- Given the suggested magnitude of the sinistral displacements along some of these faults, it seems likely that the Northern Highlands lay within the Baltica–Laurentia collision zone.

8.3 Tectonics of the Northern Highlands

The geology of north-west Scotland provides a glimpse into the processes active during the early Palaeozoic collision of Baltica and Laurentia. This Section describes the structures, metamorphism and magmatism that resulted from this collision.

8.3.1 Structure and metamorphism of the Northern Highlands

Although complex in detail, the main lithotectonic units and structures of the Northern Highlands can be traced along strike over great distances. These structures are illustrated in Figure 8.4, where they are seen to separate major lithotectonic units.

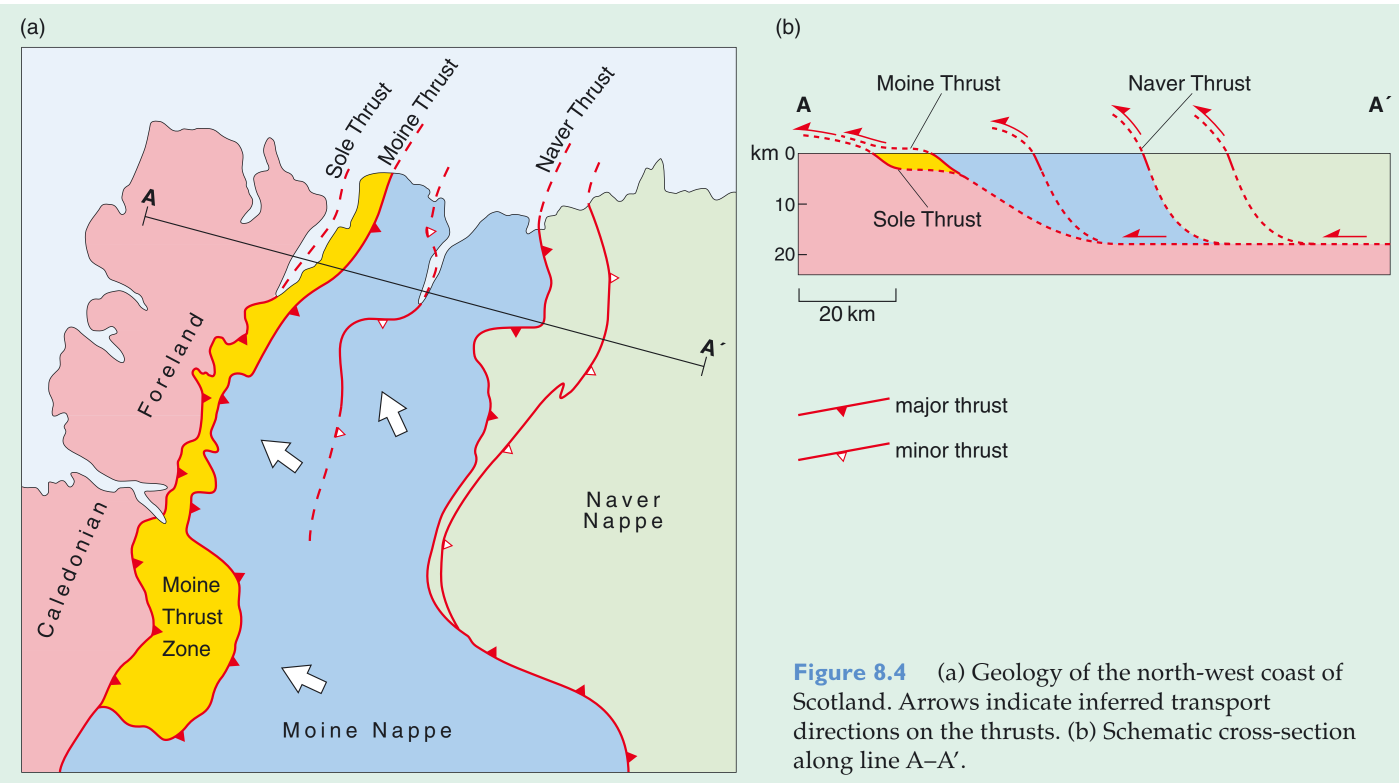
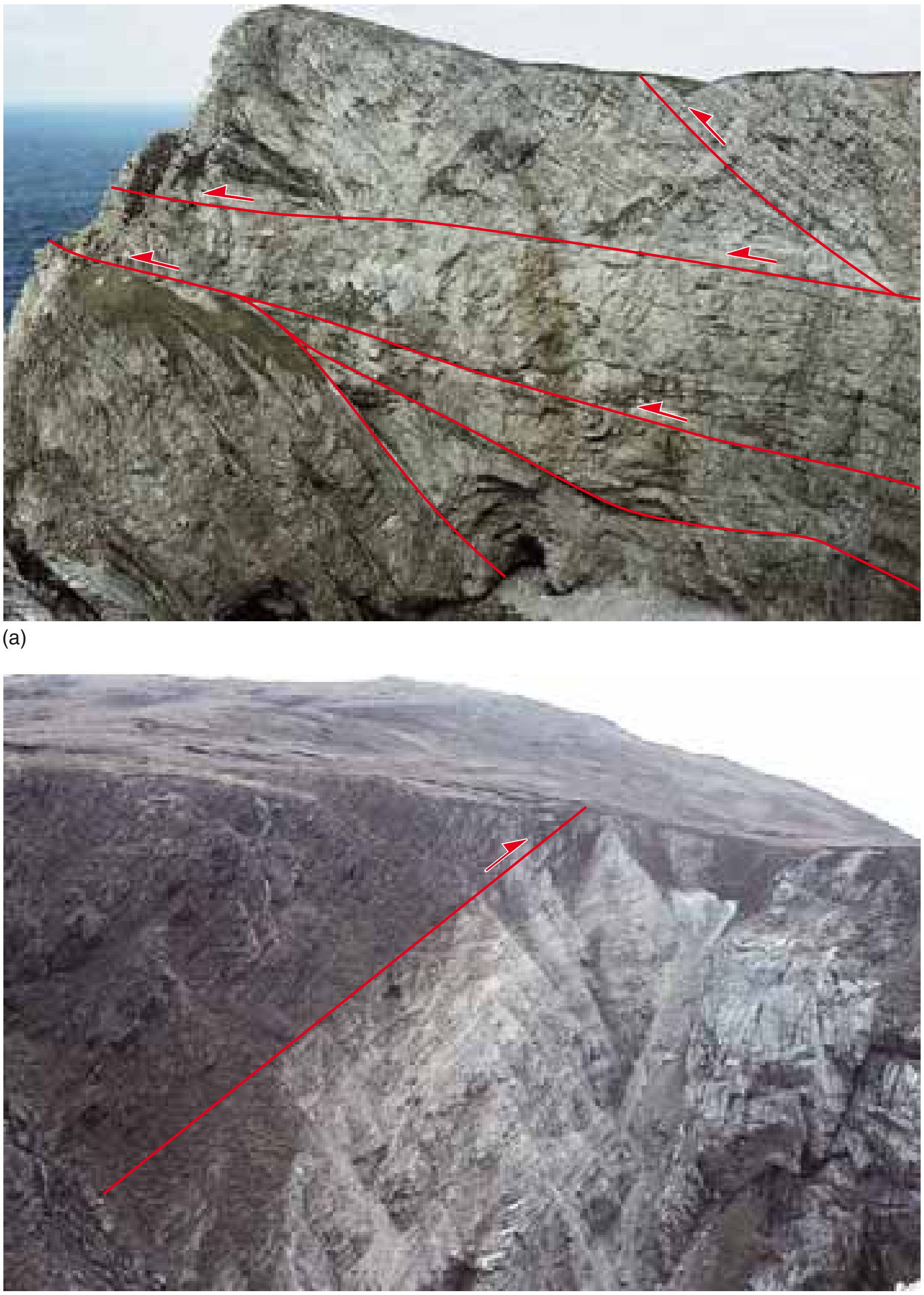


Figure 8.4 (a) Geology of the north-west coast of Scotland. Arrows indicate inferred transport directions on the thrusts. (b) Schematic cross-section along line A–A′.

The Moine Thrust separates the Moine rocks of the Moine and Naver Nappes from the deformed Lewisian, Torridonian and Cambrian–Ordovician rocks of the Moine Thrust Zone. The Sole Thrust, the lowermost thrust of the Moine Thrust Zone, separates the rocks of the Moine Thrust Zone from the essentially undeformed rocks exposed further west. The Moine Thrust Zone directly underlies the Moine Thrust and comprises a series of major thrusts and smaller imbricate thrusts that are stacked on top of each other and carry deformed Lewisian, Torridonian and Cambrian–Ordovician rocks towards the west (Figure 8.5). Thrusting was active at shallow levels in the crust, as indicated by syn-kinematic lower greenschist-facies assemblages.



(a)

(b)

Figure 8.5 Structures within the Moine Thrust Zone at Whitten Head, north-west Scotland. (a) Internal imbrication of Cambrian quartzites of the Pipe Rock (Eriboll Sandstone Formation). View looking north, height of cliffs 150 m. (b) Thrust placing Lewisian basement over Cambrian quartzites of the Pipe Rock (Eriboll Sandstone Formation). View looking south, height of cliffs 150 m.

The Moine and Naver Nappes are internally imbricated by a series of lesser thrusts. These structurally higher-level (and earlier) thrusts are ductile structures that were active at higher metamorphic grades (deeper levels in the crust), as indicated in Figure 8.4b. Syn-kinematic temperatures obtained from the thrusts decrease from east to west, a feature consistent with deformation progressing from deeper to shallower levels as rocks were transported towards the west. Microstructure and fabric analysis indicates that Barrovian-type metamorphism was syn-kinematic with the ductile thrusting. The sequence of mineral growth of garnet→staurolite→kyanite is consistent with increasing P and T resulting from crustal thickening by ductile thrusting.

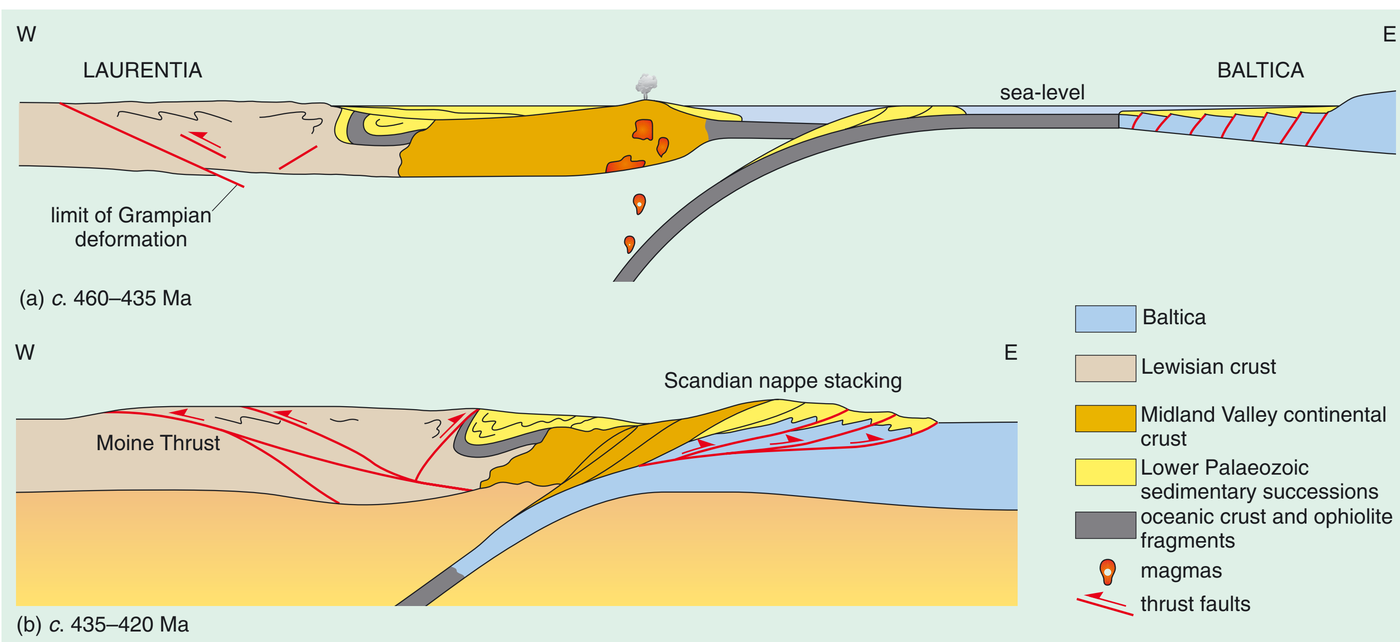
8.3.2 Magmatism and the timing of deformation

A series of intrusive bodies are found above and below the Naver Thrust. These occur as a series of branching sheets and lenses that are sub-concordant with the major thrust planes. They comprise medium- to coarse-grained granites, granodiorites and diorites. The sheets cross-cut early fold structures and fabrics that developed in response to the initial stages of crustal shortening, yet are themselves deformed and carry fabrics that resulted from tectonic strains induced during the later stages of thrusting. As such, these granites are thought to have been emplaced synchronously with ductile thrusting. Radiometric dating of the syn-kinematic intrusions has given ages in the range *c.* 435–420 Ma. Mica cooling ages (Rb–Sr method) from the various nappes indicate a range of *c.* 440–410 Ma and cooling ages on micas (formed during thrusting) from the Moine Thrust Zone are *c.* 428–413 Ma. The similarity between these ages suggests that the metamorphism, magmatism and displacement along the ductile thrusts and the Moine Thrust Zone belong to the same sequence of deformation. These ages are a good deal younger (by at least 30 million years) than those of the Grampian phase and indicate that these events belong to the younger mid-Silurian Scandian phase of the Caledonian Orogeny.

8.3.3 Regional implications

The Moine Thrust and its associated ductile thrusts formed at *c.* 435–420 Ma during the Scandian phase, which resulted from the collision of Baltica and Laurentia. A similar history of thrusting, Barrovian-type metamorphism and

Figure 8.6 A simplified tectonic model for the Scandian phase of the Caledonian Orogeny (*c.* 435–420 Ma) in northern Scotland. (a) Development of an active margin in post-Grampian times by westwards subduction of the northern arm of Iapetus beneath Laurentia. (b) Underthrusting of Baltica beneath Laurentia and the development of both E- and W-directed thrust systems.



magmatism is recorded in both East Greenland and Scandinavia, where the Scandian phase lasted until *c.* 390 Ma. The Scandian event was initiated by westward subduction of the northern arm of the Iapetus Ocean beneath the Laurentian margin (Figure 8.6a). Continued compression led to continental collision with crustal shortening being accommodated by thrusting towards both the west and east (Figure 8.6b).

8.3.4 Summary of Section 8.3

- Thrusting, metamorphism and magmatism in north-west Scotland (*c.* 435–420 Ma) are attributed to the Scandian phase of the Caledonian Orogeny.
- Crustal thickening was achieved by thrusting and resulted in Barrovian-type metamorphism.

8.4 Silurian–Devonian strike–slip displacements on the Laurentian margin

Section 8.2.2 pointed to the importance of strike–slip faulting during multiple plate collisions. In this Section we describe the nature and establish the timing of these displacements on the Laurentian margin.

8.4.1 Geometry and amount of displacement

The Laurentian margin is cut by a series of steeply-dipping faults that strike roughly NE–SW, and cut most of the other Caledonian structures (e.g. the Great Glen Fault and the Highland Boundary Fault – Fair Head–Clew Bay Line, Figure 8.7).

- Do these faults have a consistent strike along their length?
- These faults exhibit major strike swings from N–S in Shetland to E–W in Ireland.

As we have seen, this strike swing may be linked to the deformation around the convex corner of the Laurentian margin. Geophysical evidence indicates that these faults extend to depths of at least 40 km. Many have a protracted history. For example, the Highland Boundary Fault – Fair Head–Clew Bay Line may originally have defined the southern limit of rifted Proterozoic crust, and represents a site of collisional suture during the Grampian event. In the Late Silurian to Early Devonian, displacements along the fault led to juxtaposition of the Midland Valley Terrane against the Central Highlands Terrane. The use of structural analysis on granitic plutons, along with the correlation of distinct geological features across these faults, indicates they have undergone significant sinistral displacements. Estimates for the amount of displacement range from *c.* 10 km on the Strathconan Fault, to *c.* 40 km on the Leannan Fault to hundreds of kilometres for the Great Glen and Highland Boundary Faults.

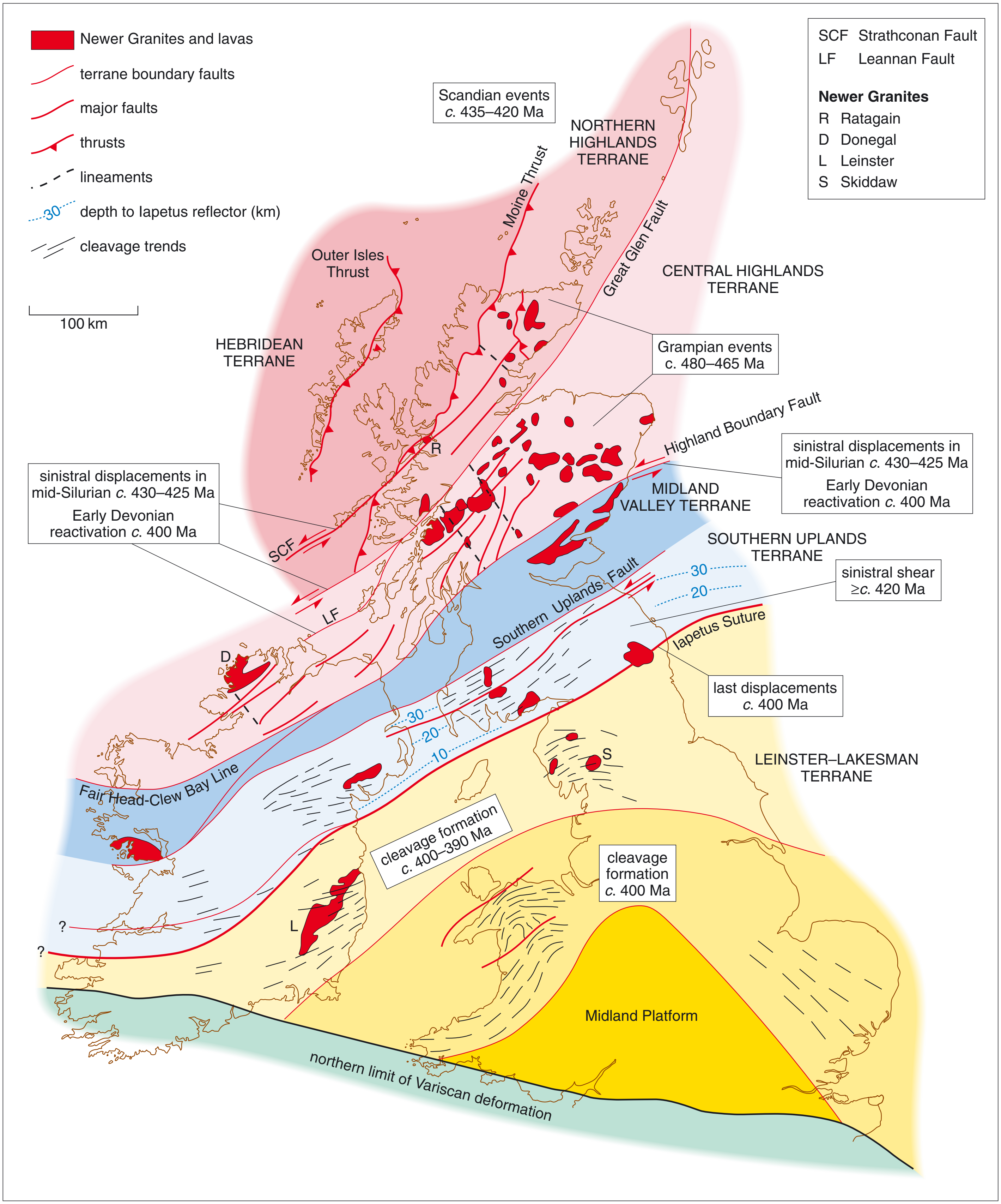


Figure 8.7 Map of Britain and Ireland showing Caledonian structures based on surface geology, borehole data and geophysical studies. The timing of deformation and the location of the Newer Granites is also shown.

8.4.2 Time constraints on fault zone displacements

Early displacements on the Great Glen Fault and associated faults are constrained by the ages of syn-kinematic intrusions. Figure 8.8 shows an example of one of these granites, the Ratagain granite, which is found adjacent to the Strathconan Fault (for location see Figure 8.7).

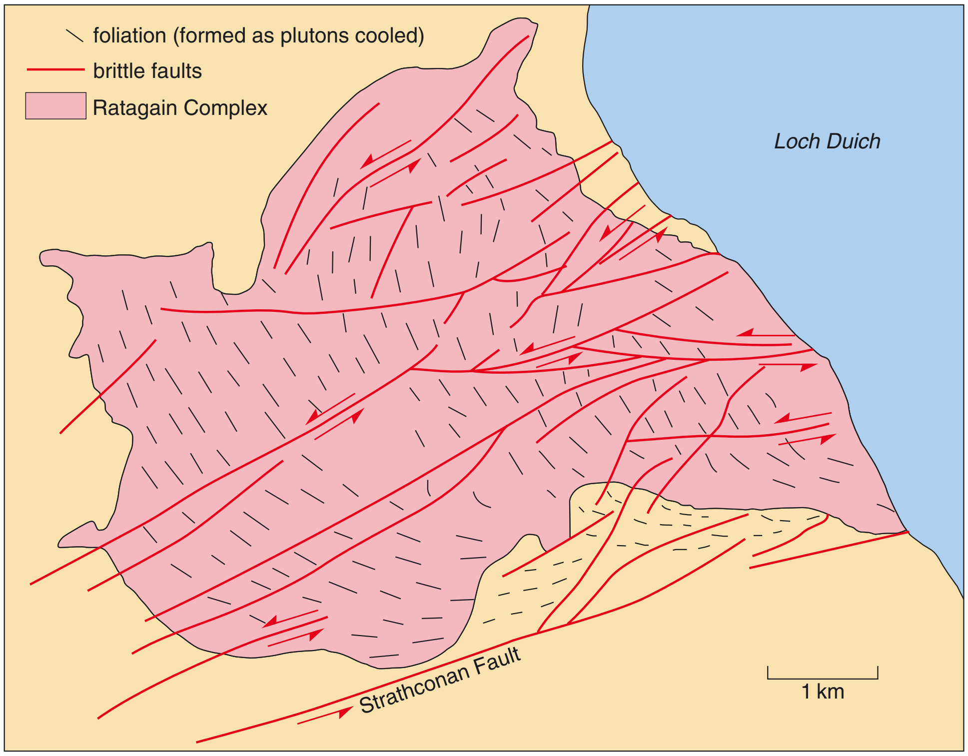


Figure 8.8 Relationship of the Ratagain granite to the Strathconan Fault.

The *c.* 425 Ma Ratagain granite has been deformed by both ductile and brittle structures (Figure 8.8). The first deformation produced a strong ductile foliation that formed as the granite was cooling and crystallizing. The anticlockwise swing of this foliation towards the fault is consistent with a sinistral sense of displacement within a ductile shear zone. The Ratagain granite and its ductile foliation are cut by a network of later brittle faults that exhibit a sinistral offset. These faults were active during the emplacement of a series of mafic dykes that have been dated at between *c.* 410 Ma and *c.* 395 Ma (Early Devonian). The conclusion from this is that a mid-Silurian (*c.* 425 Ma) shear zone was reactivated as a brittle fault during later Early Devonian (*c.* 410–395 Ma) displacements. Data from other syn-kinematic granites, including the Donegal granite (Figure 8.7), support the conclusion that sinistral strike–slip displacement occurred in two distinct episodes, at *c.* 430–425 Ma and *c.* 405–390 Ma.

8.4.3 Sinistral displacements in the Southern Uplands

Limited constraints can also be placed on the timing of deformation across the Southern Uplands accretionary prism. As we saw in Section 7.3.2, the progressive accretion of thrust slices to the toe of the accretionary prism led to the steepening and rotation of earlier thrusts (Figure 7.3). Many of these steepened thrusts (including the Orlock Bridge Fault) record later sinistral strike–slip reactivations. Time constraints on these displacements are provided by the age of post-kinematic granites (*c.* 410–390 Ma), and of mafic dykes (*c.* 420–398 Ma), which can only provide a minimum age for the last sinistral strike–slip displacements along these faults.

8.4.4 Summary of Section 8.4

- A series of major sinistral strike–slip faults cuts the Laurentian margin.
- Age constraints from syn-kinematic intrusions suggest that sinistral displacement occurred in two discrete episodes, in mid-Silurian and in Early Devonian times.

8.5 Collision of Eastern Avalonia with the Laurentian margin

The model presented in Section 8.2 suggests that Eastern Avalonia collided obliquely with the Laurentian margin and that this led to a scissor-like closure of the Iapetus Ocean. This Section outlines the history of convergence and collision as seen in the sedimentary record of rocks on the Eastern Avalonian margin. The location of the Iapetus Suture Zone is also discussed.

8.5.1 The sedimentary record of a far-felt collision

The initial impingement of Eastern Avalonia on the Laurentian margin occurred somewhere to the south-west of Britain and Ireland in late Llandovery times (Figure 8.9), and the first effects of this collision are preserved in sedimentary basins along the Eastern Avalonian margin. Collision led to the reactivation of pre-existing fault systems causing compression, uplift and renewal of sedimentary sources in some areas, and extension, subsidence and deposition in others. Active basin-bounding faults became localized sites for late Llandovery turbidite sedimentation. The influx of turbidites began in late Llandovery times from a westerly source as collision somewhere to the south-west of Britain led to uplift and erosion. A major sedimentary influx was also derived from the south and was sourced from the erosion of uplifting crustal blocks. The relative timing of the turbidite influx is illustrated in Figure 8.10. This pattern of faulting and sedimentation was a response to the flexing of the crust in front of the collision zone, a direct result of thrust loading and subduction along the collision zone.

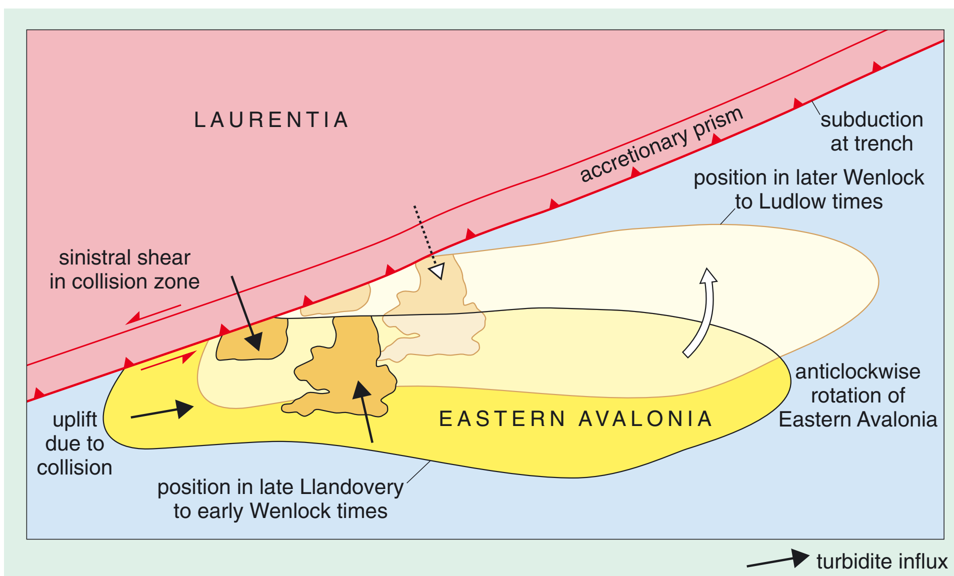


Figure 8.9 The palaeogeography of the Laurentian margin in Silurian times.

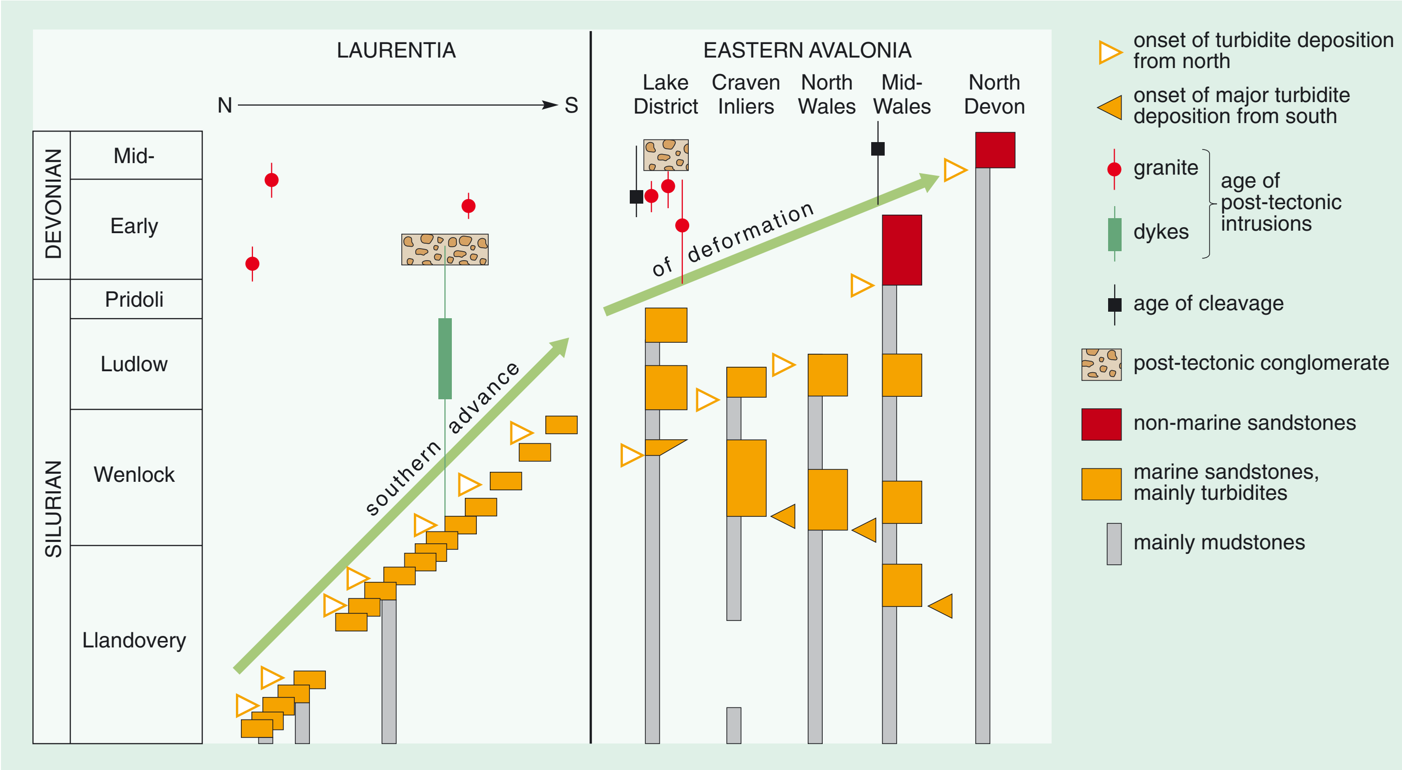


Figure 8.10 Timing of key events on the Laurentian and Eastern Avalonian margins during and after closure of the Iapetus Ocean.

8.5.2 Diachronous collision and terrane linkage

One estimate of the timing and nature of collision is provided by the date at which large volumes of sand-dominated turbidites first crossed the Iapetus Suture and were deposited on the Eastern Avalonian margin. The influx of northerly-derived sediments first occurred in Ireland in early Wenlock times and in north-west England in Wenlock–Ludlow times (illustrated schematically in Figure 8.9). These data suggest that closure of the Iapetus Ocean progressed from south-west to north-east; the closure was diachronous. By mid-Wenlock times, the trench was transformed into a foreland basin with the northern edge being marked by the Southern Uplands accretionary prism. Collision by the late Silurian (Wenlock to Ludlow) is indicated by a major reduction of convergence rates, as deduced from palaeomagnetic data, from *c.* 12 cm yr^{-1} to <6.3 cm yr^{-1}, as underthrusting of Eastern Avalonia under Laurentia began. This also coincided with a change in the character and a reduction in the rate of sedimentation in mid- to late Wenlock times in the Southern Belt of the Southern Uplands, a feature that resulted from the slowing of subduction as a result of the onset of collision.

8.5.3 Sediment dispersal and basin shallowing

A unified depositional system was established across Britain by Wenlock times, as coarse debris derived from the uprising collision zone spread progressively southwards (Figure 8.10). In the late Silurian, basin subsidence slowed and gave way to shortening and uplift, with marine sedimentary basins being transformed into areas of non-marine sedimentation. Basin shallowing probably resulted from a combination of factors including an overall fall in sea-level and an increased rate of sediment supply.

8.5.4 Where is the Iapetus Suture?

The suture zone between Laurentia and Eastern Avalonia is the least exposed of all the major Caledonian terrane boundaries, but is usually drawn along a line parallel with the Solway Firth (Figure 8.7). The position of the suture zone is based on several lines of evidence. The suture must lie to the south of the Southern Uplands accretionary prism, as these sediments were scraped off the ocean floor and onto the Laurentian margin before collision. Seismic surveys show a prominent northwards-dipping reflector that is interpreted as separating southern and northern crust and is consistent with the Eastern Avalonian crust having underthrust the Laurentian margin (Figure 8.11).

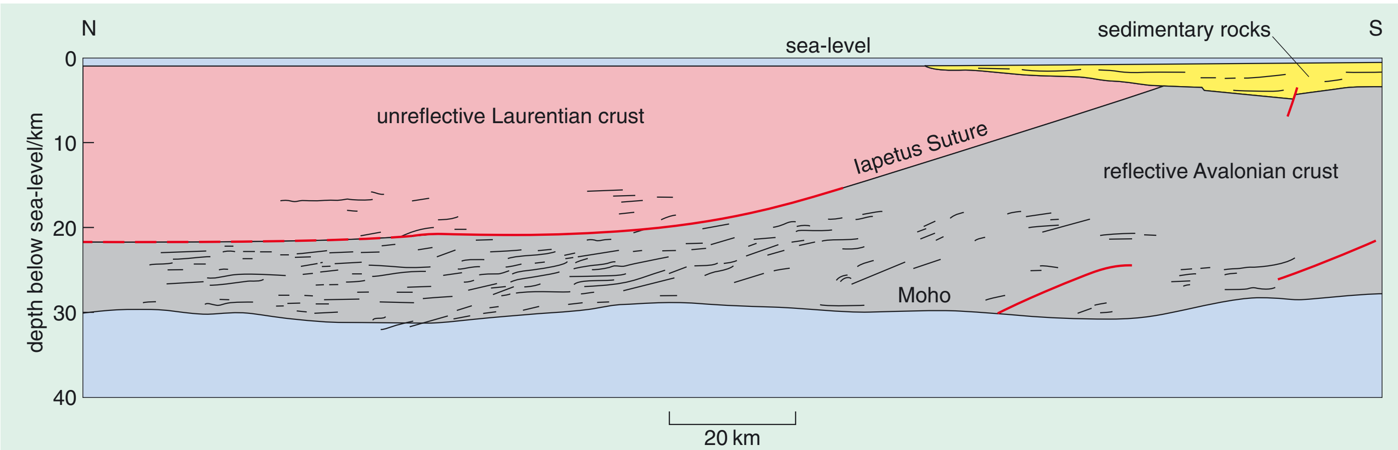


Figure 8.11 The interpretation of a N-dipping reflector from a seismic survey across the Iapetus Suture in the North Sea east of the Southern Uplands. The depth to this reflector is indicated in Figure 8.7.

In the north-west Isle of Man, Ordovician rocks of the Avalonian margin are overthrust by mid-Silurian strata akin to those of similar age in the Southern Uplands. The position of the suture across Ireland is less certain but is drawn between Ordovician inliers with either Laurentian or Avalonian faunal affinities. In south-west Ireland the suture is usually drawn along the Shannon Estuary, although a deep reflector has been located to the north of the Dingle Peninsula. These alternative locations are indicated in Figure 8.7. An age of *c.* 400 Ma obtained on volcanics from the Cheviot Hills that overlie the suture constrains the timing of final movements along this structure.

8.5.5 Summary of Section 8.5

- The collision of Eastern Avalonia with Laurentia initially occurred somewhere to the south-west of Britain and Ireland. Widespread turbidite sedimentation into basins on the Eastern Avalonian margin preserves a record of this collision.
- Collision was diachronous, with Iapetus closing in a scissor-like manner, progressing from south-west to north-east.
- After collision, northerly-derived detritus spread progressively southwards with time.
- Further or continued convergence led to basin shallowing and deposition of non-marine sedimentary sequences.

8.6 Late Silurian to Early Devonian deformation of Eastern Avalonia

The rocks on the Eastern Avalonian margin have been affected by a major deformation event that is referred to as the Acadian phase of the Caledonian Orogeny. The deformation is characterized by the regional development of folding, cleavage formation and associated low-grade, sub-greenschist facies (200–300 °C) metamorphism.

8.6.1 The cleavage pattern

The pattern of cleavage produced during the Acadian phase is illustrated in Figure 8.7.

- Is there a consistent trend to the cleavage?
- The general trend of the Acadian cleavage is NE–SW but significant deflections from this trend occur, e.g. around the Midland Platform, and in North Wales and the Lake District.

The general trend of the folds and cleavage is indicative of NW–SE crustal shortening across the orogen. The most obvious swing in the cleavage trend is around the old continental block of the Midland Platform. The platform is thought to have acted as an indenter against which the relatively ‘soft’, early Palaeozoic basins were moulded during shortening. A similar interpretation has been advanced for the arcuate swings in the cleavage pattern in North Wales and the Lake District. Here, older bodies of granite have acted as the rigid bodies around which the cleavage was moulded.

8.6.2 Time constraints on cleavage formation and deformation

The timing of cleavage formation is constrained by radiometric ages of syn-kinematic intrusions. The Skiddaw granite (*c.* 390 Ma) of the Lake District was emplaced during cleavage formation, as indicated by the timing of andalusite growth in hornfelses from its thermal aureole. In Ireland, the Leinster granite (*c.* 404 Ma) was intruded into an actively deforming sinistral shear zone. These data suggest that deformation and sinistral shear affected the Eastern Avalonian continental margin in Early Devonian times at *c.* 405–390 Ma.

Examination of Figure 8.10 indicates that deformation progressed from north to south with time during Late Silurian to Devonian times. An important point of this diagram is that at the same time as deformation was occurring in the Lake District, basins further south were shallowing and non-marine sediments were being deposited. Deformation of these non-marine sequences occurred somewhat later. Figure 8.10 also shows the timing of deformation across the Southern Uplands. One possible interpretation of this data set is that a wave of deformation spread southwards with time.

8.6.3 Summary of Section 8.6

- Eastern Avalonia was affected by the Acadian deformation event in the Late Silurian to Early Devonian.
- The timing of Acadian cleavage formation is constrained by the ages of syn-kinematic granites.
- Cleavage formation and deformation were diachronous. One interpretation is that a wave of deformation spread southwards with time.

8.7 Granite magmatism and convergence

So far we have seen that magmatism associated with the Scandian and Acadian phases spanned a time interval of *c.* 440–390 Ma. This extensive magmatic suite is collectively referred to as the Newer Granites. The distribution of the Newer Granites and associated lavas is presented in Figure 8.7. The age of the granites varies across the orogen. Granites in the Northern Highlands and Leinster–Lakesman Terranes range from *c.* 440–390 Ma whereas those in the Central Highlands, Midland Valley and Southern Uplands Terranes range from *c.* 420–380 Ma. But what can we learn from studying the geochemistry of these magmas?

8.7.1 Origin of the Newer Granites

In Figure 6.2 the initial $^{87}Sr/^{86}Sr$ ratios of the <*c.* 435 Ma Newer Granites and lavas is compared with those of the older >*c.* 435 Ma Ordovician (Grampian) granites from the Central and Northern Highlands.

- Can you suggest a reason for the differences in the initial $^{87}Sr/^{86}Sr$ ratios?

- The Newer Granites have very different isotopic signatures from the Ordovician granites in having lower initial $^{87}Sr/^{86}Sr$ ratios (0.704–0.708). These lower values are consistent with a major mantle component contributing to their genesis.

In addition, the Newer Granites have other geochemical characteristics, e.g. high Rb/Sr, high K/Na and low K/Rb ratios, that are indicative of calc-alkaline magmas produced in an Andean-type subduction zone, i.e. where oceanic lithosphere subducts below continental lithosphere. The Newer Granites probably owe their genesis to melting in response to the northwards-directed subduction of the Iapetus Ocean. Therefore, by *c.* 435 Ma the northwards-dipping subduction zone that started to form at the end of the Grampian phase had reached far beneath the Laurentian margin. However, the model of simple subduction and arc-related magmatism does not easily explain the plutons that occur close to the suture in the Southern Uplands and south of the suture in the Leinster–Lakesman Terrane. There is no general consensus as to the origin of these granites.

8.7.2 Summary of Section 8.7

- Magmatism spanning *c.* 440–390 Ma (the Newer Granites) probably resulted from melting in response to northwards-directed subduction of the Iapetus Ocean. By *c.* 435 Ma the subduction zone reached far to the north of the Central Highlands.

8.8 Summary of Section 8

The demise and eventual closure of the Iapetus Ocean resulted from a complex sequence of events caused by the accretion of several continental fragments to the Laurentian margin. A plate-tectonic model that attempts to summarize these events is presented in Figure 8.12 and a summary chronology is outlined below.

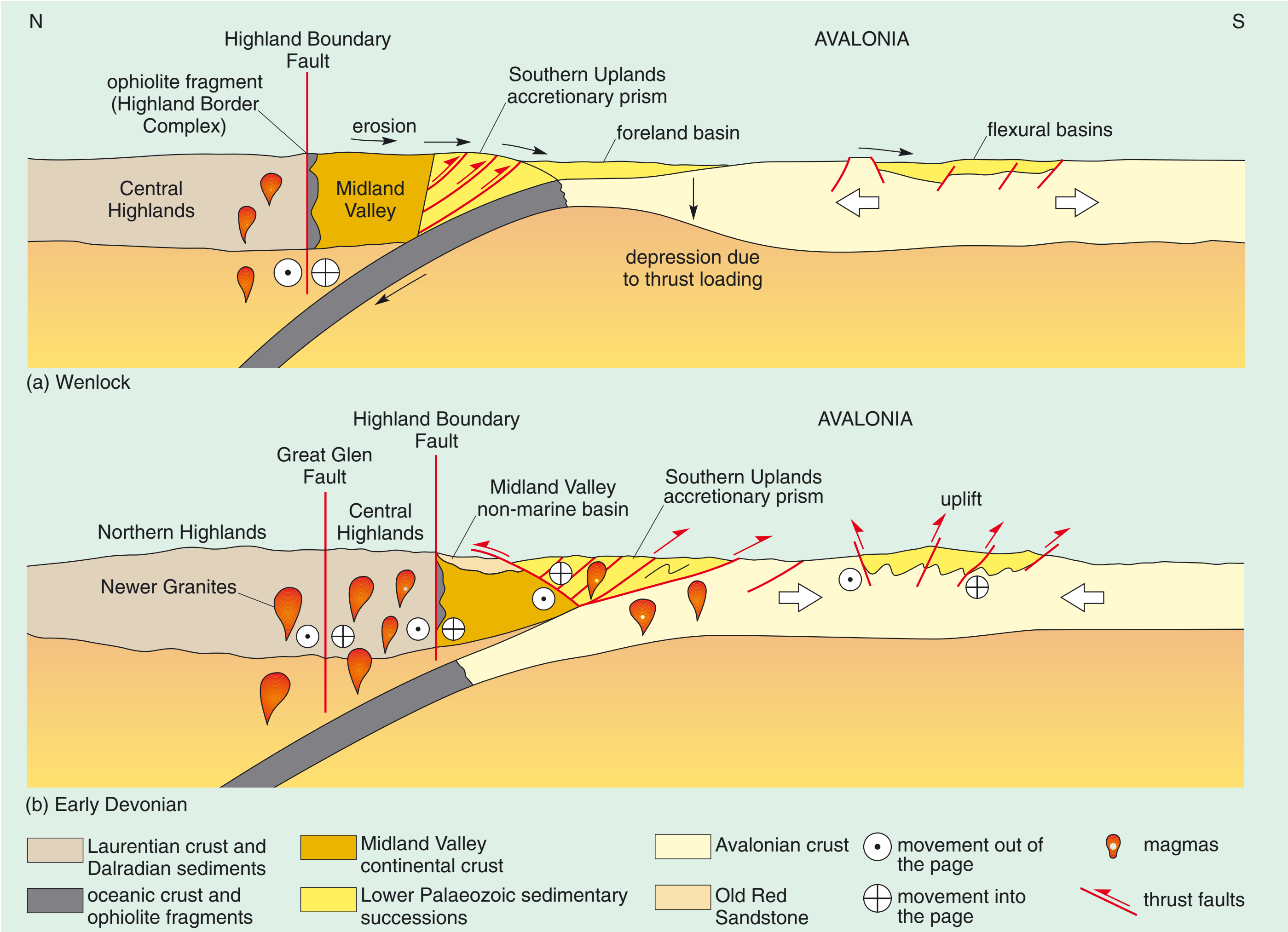


Figure 8.12 A plate-tectonic model for the Silurian–Devonian evolution of the Caledonian Orogen. (a) Mid-Silurian; (b) Early Devonian.

In Llandovery times, Baltica and Eastern Avalonia collided obliquely with the Laurentian margin. In north-west Scotland, the oblique collision with Baltica (the Scandian event) led to closure of the northern arm of the Iapetus Ocean by W-directed subduction. Continued convergence led to plate collision and resulted in NW-directed thrusting and the onset of sinistral strike–slip displacements. In the south, Eastern Avalonia was colliding with part of Laurentia south-west of the Southern Uplands. The Iapetus Ocean closed diachronously, progressing from south-west to north-east.

In Wenlock (Figure 8.12a) to Early Devonian times, strike–slip shear zones played a dominant role in the siting of granites on the Laurentian margin. The northern edge of Eastern Avalonia began to subduct beneath the accretionary prism of the Southern Uplands. A foreland basin developed in a depression in front of the loaded crust. Northerly-derived sediments spread progressively southwards.

Later, in the Early Devonian, the whole orogen underwent sinistral shear deformation (Figure 8.12b). On the Laurentian margin, deformation led to major sinistral reactivation of existing faults and juxtaposition of the southern terranes against the Central Highlands Terrane along the Highland Boundary Fault. In

Eastern Avalonia, deformation (referred to as the Acadian event) at this time led to cleavage formation and magmatism. Granites were emplaced synchronously with cleavage formation and sinistral displacements along shear zones. The Acadian event resulted from either prolonged post-collisional convergence between Eastern Avalonia and Laurentia, or was enhanced by further collision of Armorica with the southern edge of Eastern Avalonia. Non-marine Devonian sedimentation deposited the Old Red Sandstone, which is the subject of Section 9.