Changing Silurian–Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension

Abstract: The late Silurian to mid- or late Devonian interval in the Caledonides was a period dominated, sequentially, by sinistral transpression, strike-slip and transtension during the development of mainly non-marine ‘red-bed’ basins following the Ludlow–Pridoll transition from marine to terrestrial sedimentation. The tectonic event that led to and generated the sinistral Devonian basins was the highly oblique sinistral closure of the Iapetus Ocean between Laurentia and Baltica and between Laurentia and Avalonia. We examine the diachronous closure of Iapetus, the contrasting tectonic modes arising from that closure, and the nature and origin of subsequent Devonian deformation north and south of the Iapetus Suture in the context of progressively changing, sinistrally dominated relative plate motion between Laurentia and Avalonia–Baltica. We suggest that, from about 435 to 395 Ma, there was about 1200 km of sinistral strike-slip relative motion between Laurentia and Baltica. Our lower and upper estimates of Silurian–Devonian relative plate motion rates of 30 mm a$^{-1}$ and 67 mm a$^{-1}$ based upon geological data, are similar to present rates.

Keywords: Silurian, Devonian, Caledonides, transpression, transtension.

The North Atlantic Caledonides are believed to have developed as a result of the closure of a major Lower Palaeozoic ocean, Iapetus, and its eastern arm, Tornquist’s Sea (Fig. 1). Closure of Tornquist’s Sea in the late Ordovician was associated with collision of the continent Baltica and a microcontinent, Eastern Avalonia (Trench & Torsvik 1992). Baltica and Avalonia then collided with Laurentia in the mid- to late Silurian to form the Caledonian orogenic belt and the supercontinent Laurussia (Soper et al. 1992, and references therein). Palaeomagnetic and structural evidence indicates that Eastern Avalonia and Baltica docked sinistrally against Laurentia as a result of oblique plate convergence (Soper et al. 1992; Torsvik et al. 1996). The final stages of the Caledonian orogenic event were associated with sinistral strike-slip movements along major transcurrent faults such as the Great Glen Fault (Scotland) and Billefjorden Fault Zone (Svalbard). However, the magnitude of late Caledonian displacements along these structures, and the possible implications for palaeogeographical reconstructions have been contentious issues (see Harland & Wright 1979; Ziegler 1982; Soper et al. 1992). Furthermore, previous syntheses of the Caledonian orogen have mainly focused on the evidence for oblique collision but, mostly, have not examined in detail the kinematic evolution of the late to post-orogenic Old Red Sandstone sedimentary basins and the consequent implications for continued relative plate motions.

In this paper, we re-examine old data and synthesize recently published information relevant to the geometry of sinistrally transpressive Caledonian collision during the Silurian at c. 435–425 Ma. We show that major left-lateral displacement along the Great Glen Fault and related transcurrent structures is necessary in the time period c. 425–410 Ma to juxtapose contrasting crustal blocks in the Scottish Highlands, and to assemble the disparate terranes of Svalbard. Finally, we review the geometry and probable kinematic evolution of the early to mid-Devonian (c. 410–395 Ma) Old Red Sandstone basins and associated deformation in underlying basement rocks and suggest that, in most cases, these probably resulted from sinistral transtension. Therefore, we conclude that the closure of Iapetus, the contrasting tectonic modes arising from that closure, and the nature and origin of subsequent Devonian deformation north and south of the Iapetus Suture can all be interpreted in the context of progressively changing, sinistrally dominated relative plate motion between Laurentia and Avalonia–Baltica during the Silurian and early–mid-Devonian.

Sinistral transpressive closure of Iapetus: the Avalonia–Laurentia collision

Southern Uplands–Lake District

A precise time of closure of Iapetus between Laurentia and Avalonia along the Solway Line in northern Britain can be determined from the stratigraphy of the Southern Uplands and the Lake District. The southward-growing subduction–accretion prism origin of the Southern Uplands from Llandeilo to late Wenlock (M. lundgreni) times (Fig. 2) is demonstrated by the progressively later, southward transition from the oceanic Moffat Shale facies to trench turbidites and the in tandem progressively later termination of turbidite deposition. South of the Garlieston Fault in the outcrop of the Hawick Group, the turbidite magnafacies still becomes younger southwards but without a Moffat Shale oceanic substrate (Floyd 2001). Detritus from the Southern Uplands first arrived in the Lake District Windermere Group in late Wenlock (M. lundgreni) time (Soper & Woodcock 1990), although the Lake District had earlier become part of a ‘foreland basin’ subsiding beneath the load of the Southern Uplands prism in the late Llandovery deepening episode recorded by the Stockdale Group (Kneller 1991; Kneller et al. 1994). In Ireland, the first arrival of detritus in basins south of the Iapetus Suture from sources north of the suture was during the Wenlock (Hutton &
Murphy 1987), suggesting a slightly diachronous collision, possibly a result of irregular colliding margins. Probably, the absence of the Moffat Shale south of the Garlieston Fault indicates the time of subduction of the last traces of Iapetus sensu stricto, when the tapered northern edge of continental Avalonia collided with and underthrust the Southern Uplands by at least 50 km (Freeman et al. 1988). Thus, the subduction–accretion prism became the pre- and post-collisional load that caused the Silurian flexural ‘foreland’ basin of the Lake District, the load of the accretionary prism causing flexural downbending well before collision. The dominant structures within the Southern Uplands sequence formed during accretion (e.g. Needham 1993). A switch from early, approximately orthogonal shortening to sinistral transpression within the accretionary prism is thought to have occurred in the late Llandovery at c. 430 Ma (Stone 1995).

Western Ireland

Along the Iapetus Suture to the west, the late Silurian collision between Avalonia and Laurentia was ‘harder’. In western Ireland (Fig. 3), a complex polyphase sinistral transpressive deformation sequence deformed the Ordovician and Silurian strata of the South Mayo Trough (Dewey et al. 1997), where the deformation is dated, by unconformity, as post-Wenlock–pre-Lower Devonian (Fig. 2). The South Mayo Trough shows a multiple clockwise-transecting cleavage sequence related to transpressional shortening. The sinistrally transtensional Louisburgh Basin contains Prídolí fluvialite sediments and, probably, dates the end of transpressional deformation (Dewey et al. 1997). The Corvock and Slieve Gamph Granites were emplaced in rhombohedral sinistral pull-aparts during transpression (Dewey et al. 1997).

What caused the mid-Devonian Acadian Orogeny?

The Iapetus Suture in northern Britain defines an important difference in the timing of penetrative deformation of Lower Palaeozoic strata. To the north, the dominant structures within the Southern Uplands were acquired in the accretionary prism before end-Wenlock collision (see above). In contrast, to the south, continuous sedimentation through the late Silurian into the early Devonian in the Lake District, Anglo-Welsh Basin and SW Ireland (Fig. 2) indicates the ‘soft’ nature of the Avalonia–Laurentia collision. The Lower Palaeozoic and lower Devonian successions of Avalonia were not deformed until mid-Devonian (Late Emsian) times (Fig. 2) when the Acadian orogenic event imposed regionally clockwise-transecting sinistrally transpressive cleavages (Soper et al. 1987). It is not clear what caused the Acadian deformation. It was, probably, a continent–continent collision to the south of Wales and the Brabant Massif, perhaps a....

Fig. 1. Outline palaeogeographical reconstructions of the Caledonides for (a) 440 Ma, (b) 420 Ma and (c) 400 Ma (Torsvik, pers. comm.). They depict the general disposition of the various continental blocks and the location of the Iapetus Ocean; they differ in detail, however, from the reconstructions presented in this paper. Avalonia is shown as a rigid prong of Baltica (following Trench & Torsvik 1992) but this cannot have been its relationship during the late Silurian (see discussion in text). It should be noted that before the reconstruction depicted in (a), the Iapetan margins of Laurentia and Baltica had already been affected by arc–continent collisions that occurred during initial ocean closure in early to mid-Ordovician time. These early orogenic events include the Grampian event in the Scottish Highlands (Lambert & McKerrow 1976) and the Finmarkian event in Norway (Dallmeyer 1988).
westward continuation of the Armorican and Bohemian Massifs, like that of the Northern Appalachians (Soper et al. 1992). The evidence is now disjunct, because, from Cornubia to the Ardennes, deep-water sedimentation was continuous through the Devonian and early Carboniferous. A line through the Bristol Channel to between the Brabant Massif and the Ardennes must mark a major terrane boundary along which a continental fragment, whose collision with the Midland Craton and Wales caused the Acadian deformation south of the Iapetus Suture, was excised and replaced with Cornubia. Nutman et al. (2000) described Emsian thrusts in the Lizard Peninsula that followed an earlier period of extensional peridotite diapirism, supporting the notion of a period of Early Devonian extension (transtension) between the Silurian closure of Iapetus and the Acadian Orogeny.

Sinistrally transpressive closure of Iapetus: the Laurentia–Baltica collision

The continental collision between Laurentia and Baltica generated the Silurian Scandian Orogeny in Scandinavia, East Greenland, Svalbard and NW Scotland (e.g. Gee 1975; Hossack & Cooper 1986), to form an orogenic belt that has regional dimensions and geometries similar to those of the modern Himalayan–Tibetan system (Fig. 3). Structural evidence reviewed by Soper et al. (1992) was interpreted in terms of initial sinistrally oblique collision followed by more nearly orthogonal convergence. Here we summarize data acquired more recently and suggest an alternative kinematic interpretation.

Scandinavia

In Scandinavia, the Scandian Orogeny began with the eastward obduction of a supra-subduction-zone ophiolite complex and developed into the Laurentia–Baltica continental collisional stacking of a nappe pile onto Baltica (Dewey et al. 1993). The lower- to intermediate-level thrust sheets comprise basement complexes and sedimentary cover rocks derived mostly from the passive margin of Baltica; higher thrust sheets are a mix of ocean-derived allochthons and continental basement derived possibly from Laurentia (Roberts & Gee 1985; Hossack & Cooper 1986; Stephens & Gee 1989). Isotopic age data indicate an early Silurian age for the onset of Scandian thrusting (Dallmeyer 1988) with foreland-propagating thrusting continuing until c. 410 Ma (Fossen & Dunlap 1998). Development of the Scandian nappe pile from c. 430 to 410 Ma was accompanied by deep burial (80–100 km) of the Baltica basement rocks of the Western Gneiss Region, which contain coesite eclogites with, locally, microdiamonds (Griffin et al. 1985; Smith & Lappin 1989; Dobrzhinetskaya et al. 1995; Wain 1997).

Although thrust sheets were, overall, translated SSE–ESE across the Baltic Craton, broadly normal to the trend of the orogen, there is, in detail, variation in transport direction of up to 45° (Fig. 3; Soper et al. 1992). The outboard, ophiolite-bearing nappes in the hinterland around Bergen show orogen-parallel lineations (Fossen 2000). Further north, thrust sheets at a high level within the nappe stack appear to have a consistent transport direction of c. 160°, sinistrally oblique to the Baltic margin. In general, transport directions rotated anticlockwise to become more nearly orthogonal to the margin as the foreland-propagating thrust sheets overrode the Baltic foreland during the latest Silurian to early Devonian (Soper et al. 1992).

East Greenland

In East Greenland, the Neoproterozoic strata of the Eleonore Bay Supergroup and its underlying Archaean–Palaeoproterozoic basement record a Silurian to early Devonian orogenic history dominated by the interaction between compressional and gravitational forces during sinistrally oblique plate convergence. Early crustal thickening was associated with high-grade metamorphism of the basement (Brueckner et al. 1998; White et al. 2002) and is kinematically complex (Fig. 3). Parts of the basement are dominated by Caledonian orogen-parallel extension lineations; in central East Greenland, these are not associated with any consistent kinematic indicators (White et al. 2002), but in NE Greenland they are widely associated with subhorizontal, top-to-the-north shear (Holdsworth & Strachan 1991; Strachan et al. 1992, 1995). Late Silurian, orogen-parallel, north-directed flow within the middle crust was coeval with east–west shortening at higher crustal levels, implying a crustal-scale partitioning of deformation (White et al. 2002). The simplest interpretation is...
that the direction of orogen-parallel flow was constrained by sinistral transpression during oblique convergence (Strachan et al. 1992; White et al. 2002). East–west crustal shortening was synchronous with gravitationally driven extension in the upper crust as the orogenic wedge re-equilibrated to a steady-state configuration (Hartz et al. 2000, 2001; White et al. 2002).

Renewed shortening during the late Silurian–early Devonian was associated with the final emplacement of thrust sheets onto the Laurentian foreland. In central East Greenland, transport directions are west-trending, approximately orthogonal to the belt (Higgins & Leslie 2000). In NE Greenland, shortening was dominated by sinistral transpression (Holdsworth & Strachan 1991; Strachan et al. 1992). Thrust transport directions show an arcuate, anticlockwise swing with early sinistrally oblique thrusting succeeded by orogen-normal thrusting (Fig. 3). Thrusting and associated upright folding was accompanied by ductile, sinistrally transpressive shear along the Storstrommen Shear Zone.

**NW Scotland**

In NW Scotland, the Neoproterozoic metasedimentary strata of the Moine Supergroup are deformed by a series of major foreland-propagating thrusts; the western margin of this part of the Caledonian belt is defined by the Moine Thrust Zone (Fig. 3). Isotopic dating of mylonites and synkinematic igneous rocks within the Moine Thrust Zone indicates that thrusting occurred during the Scandian Orogeny at c. 435–425 Ma (van Breemen et al. 1979; Johnson et al. 1985; Kelley 1988; Freeman et al. 2001). It had been considered for many years, on the basis of rather sparse isotopic evidence, that the internal ductile thrusting of the Moine rocks was kinematically unrelated and had occurred during the Ordovician Grampian Orogeny (Powell & Phillips 1985). However, a series of synkinematic granites that were emplaced during ductile displacement along the Naver Thrust in Sutherland have yielded Silurian emplacement ages (U–Pb zircon, sensitive high-resolution ion microprobe) of c. 435–425 Ma, indicating that much of the internal nappe stacking and associated deformation must have occurred during the Scandian Orogeny (Kinny et al. 2003). Scandian transport lineations in Ross-shire and Sutherland show an arcuate swing (Fig. 3; Kinny et al. 2003): early ductile thrusting in the internal part of the belt was oblique top-to-the-NNW or -NW, indicating sinistral transpression. Transport directions rotated progressively anticlockwise to a more orthogonal top-to-the-WNW direction in the vicinity of the Moine Thrust Zone.

**Svalbard**

The Svalbard Archipelago comprises three terranes that were juxtaposed by major strike-slip movements during the late Silurian–Devonian (Fig. 3; Harland 1985, and references therein; Gee & Page 1994). Indications of substantial lateral displacements rest on the differences in the tectonic evolution of these terranes, and their close affinities with contrasting parts of Laurentia. The pre-Devonian geology of NE Svalbard is dominated by the Hecla Hoek Sequence, a succession of Neoproterozoic to Ordovician strata over 18 km thick, parts of which correlate closely with the Eleonore Bay Supergroup of central East Greenland (Harland & Wright 1979). The tectonic histories of the Caledonian complexes in NW and SW Svalbard are different. In both terranes, there is evidence for high-pressure subduction-related metamorphism; of Vendian to Cambrian age in NW Svalbard (Peucat et al. 1989) and of mid-Ordovician age in SW Svalbard (Dallmeyer et al. 1990). It seems unlikely that the passive margin succession of NE Svalbard was ever separated from Laurentia by a subduction complex (Gee & Page 1984); the Caledonian complexes of NW and SW Svalbard probably originated close to Ellesmere Island (Ohta et al. 1989).

The Hecla Hoek Sequence was deformed and metamorphosed during the Silurian Ny Friesland Orogeny (Harland et al. 1992; Gee & Page 1994). Early, westward-directed translation of recumbent fold nappes was followed, in the late Silurian, by an intense sinistral transpression that was associated with upright foliations and strongly developed subhorizontal extension lineations. Much of this deformation was focused along the western...
margin of the NE Svalbard Terrane, in the vicinity of the Billefjorden Fault Zone (Fig. 3). Early amphibolite-facies fabrics were progressively overprinted, in the greenschist facies, implying a prolonged history of transpression that accompanied the left-lateral transtension of the NE Svalbard Terrane relative to central East Greenland.

**Transpression: concluding remarks**

The sinistrally transpressive nature of the Baltica–Laurentia collision deduced by Soper et al. (1992) is confirmed. Scandia-
via, East Greenland and NW Scotland all display kinematically similar, foreland-propagating, deformation sequences, whereby early orogen-parallel or oblique translations were succeeded, progressively, by anticlockwise rotation of transport directions to culminate in orogen-normal thrusting. This regional variation in transport directions has been interpreted previously as indicating a progressive change in relative plate or block movement from highly oblique to orthogonal to the trend of the orogen (Soper et al. 1992). The alternative interpretation that we suggest here is that the overall kinematic framework was dominated by sinistral transpression that became progressively partitioned into orogen-orthogonal components and orogen-parallel left-lateral strike-slip. There remains, however, a difficult problem of kinematics and timing in the Silurian collisional relationship between Laurentia, Baltica and Avalonia. The Laurentia–Baltica collision produced an orogen of Himalayan proportions with a 50% horizontal shortening and sufficient crustal thickening or subduction to generate coesite eclogites. In contrast, the roughly coeval Laur-
entia–Avalonia collision generated deformations varying from shortening and sufficient crustal thickening to orogen-normal thrusting. This regional variation in transport directions has been interpreted previously as indicating a progressive change in relative plate or block movement from highly oblique to orthogonal to the trend of the orogen (Soper et al. 1992). The alternative interpretation that we suggest here is that the overall kinematic framework was dominated by sinistral transpression that became progressively partitioned into orogen-orthogonal components and orogen-parallel left-lateral strike-slip. There remains, however, a difficult problem of kinematics and timing in the Silurian collisional relationship between Laurentia, Baltica and Avalonia. The Laurentia–Baltica collision produced an orogen of Himalayan proportions with a 50% horizontal shortening and sufficient crustal thickening or subduction to generate coesite eclogites. In contrast, the roughly coeval Laur-
entia–Avalonia collision generated deformations varying from extremely weak (Southern Uplands) to low-grade, polyphase, clockwise-transsecting, steep cleavages. We cannot find a pole of rotation that allows this contrast in deformation with Avalonia attached as a prong of Baltica in its present configuration (Fig. 1) forming the Balonia of Trench & Torsvik (1992). We conclude that Avalonia must have occupied a position or orientation that allowed the deformation contrast. Perhaps Avalonia was only loosely coupled with Baltica across the Tornquist Zone, or rotated clockwise with dextral motion during the early Devonian transtensional period. It seems unlikely that Avalonia would have survived as a rigid prong of Baltica during the Scandian, Acadian and Hercynian orogenies. Continental collision generally involves the fragmentation, rotation and smearing out of blocks, terranes and zones caught up in collision (Van Staal et al. 1998).

**Late Caledonian orogen-parallel displacements**

In Scotland, the Scandian event did not affect the Neoproterozoic Dalradian rocks of the Grampian Terrane (Fig. 3). Before the collisional events described in this paper, the Moine and Dalradian rocks of Scotland and Ireland had been regionally deformed and metamorphosed during arc–continent collision and orophistic obduction during early Ordovician time (Dewey & Ryan 1990; Ryan & Dewey 1991; Dewey & Mange 1999; Soper et al. 1999; Oliver 2000). Isotopic evidence from metamorphic rocks as well as syn- to late tectonic plutons indicate that in both Scotland and Ireland the Grampian event was well under way by 470 Ma and essentially complete by c. 460 Ma (Friedrich et al. 1999; Kinny et al. 1999; Oliver 2000; Rogers et al. 2001; Strachan et al. 2002). The Moine Supergroup of NW Scotland was later deformed extensively during the Scandian event as described above. Scan-
dian crustal shortening in NW Scotland may well have been of the order of several hundred kilometres given the likely displacements on the Moine and Sgurr Beag–Naver thrusts (e.g. Barr et al. 1986). However, in marked contrast, there is no field or isotopic evidence that the Dalradian rocks of the Grampian Terrane were affected subsequently by regional-scale deformation and meta-
morphism that can be related unambiguously to the Scandian collision. Therefore, it follows that a minimum of about 700 km left-lateral motion on the Great Glen Fault is needed to restore the Grampian Terrane to a position to the SW where it could have escaped the Scandian collision. Restoring this amount of left-
lateral slip on the Great Glen Fault brings southern Scandinavia into congruence with NW Scotland and northern Scandinavia with central east Greenland. This is in addition to the sinistral motion on the Highland Boundary Fault. We also suggest that this major, orogen-parallel, strike-slip relative motion was a phase of transition from sinistral transpression to sinistral transtension.

Constraints on the timing of orogen-parallel, strike-slip motion are provided mainly by structural and geochronological studies of members of the subduction-related Newer Granite suite. The Newer Granites are mainly calc-alkaline, I-type plutons (Brown 1979) that are scattered across most zones of the British Caledonides like an accidentally spilled bottle of red ink. Emplacement levels vary from mid-crustal to subvolcanic; by mid-Devonian time, erosional and tectonic denudation had reduced the surface of the Caledonides to about its present level. The present consensus is that the Newer Granite Suite was derived mainly from the melting of lithospheric mantle and lower-crustal sources (Stephens & Halliday 1984; Halliday et al. 1985; Tarney & Jones 1994; Fowler et al. 2001), perhaps initiated by introduction of fluids derived from subducting oceanic slabs into overlying mantle wedges. The emplacement of the suite was principally in transtensional pull-aparts and dilational splays on sinistral strike-slip faults (Hutton 1982, 1988; Hutton & McEr-
leen 1991; Hutton & Reavy 1992; Jacques & Reavy 1994; Stewart et al. 2001). It is notable that the major strike-slip faults with inferred displacements larger than their observed strike lengths, such as the Great Glen, Highland Boundary and Southern Uplands Faults, are clean narrow displacement zones with no transtensional or transpressive jogs. Granite emplacement was mainly in transtensional pull-aparts on faults with relatively small sinistral displacements, such as those in the Ox Mountains, Donegal, and the Scottish Highands. Many of these faults are, probably, splays of the large-displacement faults; some, in the Grampian Highands, may be Riedel shears to the Great Glen and Highland Boundary Faults (Johnson & Frost 1977).

The most reliably dated Newer Granite plutons (U–Pb zircon, thermal ionization mass spectrometry) in the Scottish Highlands were emplaced, mostly, at or around 425 Ma (e.g. Rogers & Dunning 1991; Stewart et al. 2001) and we take this to date the onset of orogen-parallel, strike-slip motion. Newer Granite magmatism in the SW Grampian Terrane continued into the early Devonian (Thirlwall 1988) but the bulk of left-lateral displace-
ment along the Great Glen Fault must have occurred before the deposition of the Old Red Sandstone (Emsian?) sedimentary rocks that lie within the fault zone and are relatively undeformed compared with the Moine basement (Stewart et al. 1999). There-
fore, we conclude that the major orogen-parallel, strike-slip motion along the Great Glen Fault Zone and related structures in Scotland occurred between c. 425 and 410 Ma. A similar age is inferred for left-lateral movement along major strike-slip faults in Svalbard and East Greenland.

**Post-Caledonian sinistral transtension**

Caledonian sinistrally transpressive crustal thickening with thrust–wrench fault combinations and major strike-slip faulting
was followed by deposition of the late Silurian to Devonian Old Red Sandstone continental sedimentary successions in a series of basins (Fig. 4) that combined normal and wrench faults along the length of the orogen (Friend & Williams 2000, and references therein). The overall tectonic controls on the development of these basins and their associated structures have been the subject of much debate. Although basin development, in some areas, has been related to sinistral trancurrent movements (e.g. Svalbard, Vogt 1936; Harland 1985, and references therein), in other areas it has been suggested that basins resulted from regional extension with little or no control by strike-slip movements (e.g. Orcadian basin, Scotland, McClay et al. 1986; Norton et al. 1987; Rogers et al. 1989). Many of the Old Red Sandstone successions are folded and contain important unconformities, features that, in some places (e.g. Scotland), have been ascribed, commonly, to the Acadian transpressional event. The parallelism in some areas (e.g. Svalbard, Midland Valley of Scotland) of fold traces and strike-slip faults has been interpreted in terms of alternating phases of lateral movement and orthogonal compression. We draw together and, in some cases, reinterpret information from a number of areas and propose that the time period from about 410 to 395 Ma was dominated by sinistral transtension, although, in some places, this may have continued until late Givetian times (c. 380 Ma).

**SW Norway**

In SW Norway (Fig. 4), the tectonic exhumation of eclogite gneisses (Dewey et al. 1993) was accomplished by sinistral transtension (Krabbendam & Dewey 1998) that generated a bulk constrictional strain with a 430% east–west stretch, a vertical shortening of 75%, and a north–south horizontal shortening of 25% with a bulk $K$ value of three (Dewey 2002). Gently west-dipping extensional detachments were shortened north–south as they slipped westward. The Kollstraumen Detachment (Braathen et al. 2000) dips east and has a top-to-the-east sense of displacement thus disallowing a buoyant wedge mechanism for the exhumation of the eclogites. This transtension lasted from about 420 to 390 Ma. The main early stages may have been accomplished by orthogonal orogenic collapse, partly balanced by marginal thrusting, combined with sinistral axial motion and in the mid-Devonian stage by trans-orogenic transtension.

Further north, in central Norway, a comparable network of extensional shear zones and detachments (e.g. Nesna Shear Zone, Kollstraumen Detachment, Fig. 4) show a consistent WSW bulk stretching axis sinistrally oblique to orogenic strike, and are thought to have formed through the early to mid-Devonian (Osmundsen et al. 2003). The subsequent folding of the Nesna Shear Zone along hinges parallel to the extensional transport direction was interpreted by Osmundsen et al. (2003) as indicating a continued phase of shortening and plate convergence. However, there is no evidence to preclude our alternative view; namely, that sinistrally oblique transtension and folding of the shear zone resulted from the same bulk constrictional strain field as demonstrated for SW Norway (Krabbendam & Dewey 1998).

**East Greenland**

In central East Greenland (Figs 2 and 4), thick successions of continental sediments were deposited on eroded segments of the Caledonian orogen during the Mid-Devonian (e.g. Friend et al. 1983; Larsen & Bengaard 1991; Hartz 2000). Sedimentation was controlled, in part, by sinistral displacements along the prominent Western Fault Zone, which Larsen & Bengaard (1991) linked speculatively with the Storstrømmen Shear Zone to the north and the Great Glen Fault Zone to the south. The Devonian strata are deformed by a series of upright, open, north-trending folds that parallel the orogen and developed during sedimentation, contemporaneously with a series of north- and south-dipping normal faults (Hartz 2000). This structural pattern was interpreted by Hartz (2000) as indicating that Devonian sedimentation occurred during east–west shortening (to produce the folds) that was accompanied by orogen-parallel extension (to produce the faults). Because continued convergence of Baltica and Laurentia through the Devonian as part of the Caledonian plate cycle seems unlikely, these structures were thought to represent the far-field effects of the closure of the Rheic Ocean or early stages of the Variscan–Alleghanian Orogeny (Hartz 2000). We suggest an alternative interpretation that is also consistent with the observed structural pattern; namely, that the Devonian structures in central East Greenland were produced by extremely oblique sinistral transtension. Transtension involves a combination of zone-orthogonal coaxial extension (pure shear), which generates vertical...
shortening and part of the horizontal extension, and zone-parallel non-coaxial strain (simple shear), which generates the vorticity, horizontal shortening, and part of the horizontal extension. These components combine to generate bulk constriction, which is expressed, in the brittle regime, by a combination of normal and wrench faults and, in layered sequences, by fold hinges parallel to the finite stretching direction (Dewey 2002).

Svalbard

In north–central Svalbard, mainly continental Devonian basins are bounded, largely, by the Raudfjorden and Billefjorden Fault Zones (Fig. 4). Deposition of late Silurian to early Devonian Old Red Sandstone sedimentary sequences (Fig. 2) was influenced strongly by sinistral strike-slip displacements along these important terrane boundaries. The late Silurian or Lochkovian Skt – jet Group was deposited in a sinistrally transtensive pull-apart basin before final terrane amalgamation (McCann 2000). Continued sinistral shear has been invoked to explain subsequent folding (Haakonian Phase) of the succession during the early Devonian juxtaposition of terranes (McCann 2000). Deposition of the unconformably overlying Red Bay Group was terminated in latest Lochkovian times by renewed sinistral strike-slip faulting. This was followed, very rapidly, by regional shortening (Monacobreen Phase) that formed a series of upright open folds trending parallel to the major strike-slip faults (McCann 2000). Whether these also formed by extremely oblique sinistral transtension, as proposed above for East Greenland, or as a result of the initiation of Ellesmerian orogenic activity, as suggested by McCann (2000), is uncertain.

Shetland

Shetland (Figs 2 and 4) contains the northernmost exposures of the Old Red Sandstone Orcadian Basin, where Seranne (1992) has shown that the deposition of Devonian sediments was influenced strongly by sinistral transtension. In west Shetland, Givetian strata of the Walls Formation occupy a pull-apart basin developed between the approximately north-trending Melby and Walls Boundary Faults. The succession is deformed by the major NE-trending Walls Syncline that is strongly oblique to the bounding faults (Mykura 1976; Seranne 1992). The Devonian strata contain numerous internal unconformities, and older horizons are more tightly folded than younger ones, supporting a synsedimentary origin for the fold. In the SE Shetland Devonian (Givetian) basin, structures and distribution of sedimentary facies also indicate that deposition was controlled by sinistral transtension with an overall NE direction of extension, oblique to the regional-scale transcurrent faults (Seranne 1992). The Devonian strata are deformed into a series of open folds, most of which trend nearly parallel to the lateral ramp faults that, in part, define the western margin of the basin. These folds were interpreted by Seranne (1992) as forced folds formed by faulting in the underlying basement. However, no observations preclude the alternative interpretation that they formed as a result of sinistral transtension during sedimentation.

NW Scotland

The main outcrops of the Orcadian sedimentary basin occur in Caithness and the Orkneys (Fig. 4). Offshore seismic data west of the Orkney Islands and in the Moray Firth image arrays of small half-graben basins, suggested to be reactivated Caledonian thrusts (Enfield & Coward 1987; Norton et al. 1987; Coward et al. 1989). These basins were interpreted to contain thick Old Red Sandstone sediments and to have resulted from the extensional collapse of thinned Caledonian crust. However, much of the basin fill is now known to be of Permo-Triassic age (Stoker et al. 1993), thus calling this interpretation into question. The Lower Old Red Sandstone in the onland basin is Emsian and mainly restricted to the western Moray Firth. It occupies a series of small basins consisting of alluvial fan and local lacustrine deposits (Rogers et al. 1989). The Middle Old Red Sandstone is of Eifelian and Givetian age and is dominated by a lacustrine fill that was deposited close to sea level (Rogers et al. 1989).

Previous descriptions suggest that the boundary between the Lower and Middle Old Red Sandstone successions is mainly conformable with local minor angular unconformities (Mykura 1983) attributed to extensional block-faulting (Rogers et al. 1989) or an increase in extension-related subsidence (Norton et al. 1987). However, recent re-examination of the Old Red Sandstone strata onland on the NW side of the Moray Firth (Fig. 4; British Geological Survey 1998, 2002) confirms the existence of a major Lower–Middle Old Red Sandstone unconformity (Read 1931). The Lower Old Red Sandstone crops out in the cores of two major, close to open synforms; the northern fold is located along the core of an older Scandian cross-fold in the underlying Moine rocks. The Lower Old Red Sandstone is overlain with angular unconformity by Middle Old Red Sandstone strata that transect both folds but are gently folded along the same NE trend. Critically, these folds appear to die out rapidly near the base of the main Middle Old Red Sandstone succession to the NE. We interpret these field relations to indicate that the folds developed during Lower and very early Middle Old Red Sandstone sedimentation as a result of extremely oblique sinistral transtension in a zone parallel to the Great Glen Fault Zone to the SE.

Midland Valley of Scotland

In the Midland Valley of Scotland, there is only local discordance between upper Silurian marine strata and overlying lower Old Red Sandstone sequences (Fig. 2), further testifying to the ‘soft’ nature of the Avalonia–Laurentia collision to the south. Local unconformities between the two successions in the southern Midland Valley have been attributed to ‘forced folding’ during sinistral displacement along the adjacent Southern Uplands Fault (Smith 1995). Bluck (1984) showed that early Devonian deposition in the Midland Valley was accompanied and controlled by sinistral strike-slip and normal faulting (i.e. transtension), a conclusion further substantiated by Smith (1995).

In the Midland Valley, early Devonian strata are disposed in pre-late Devonian folds (e.g. Strathmore Syncline, Fig. 4) that give a combined shortening of about 25%, similar to that in Norway. Many of these folds have a NE trend, parallel to the Highland Boundary and Southern Upland Faults. Some of the folds in the southern Midland Valley have a slight anticlockwise obliquity with respect to the adjacent Southern Uplands Fault (Smith 1995). The folding of the early Devonian has been ascribed to the Acadian orogenic event (e.g. Friend et al. 2000, and references therein). However, this is difficult to reconcile with the flat-lying and almost undeformed early Devonian strata that lie unconformably on the Southern Uplands accretionary wedge a short distance to the south, and the subhorizontal Old Red Sandstone that is unconformable on the Dalradian to the north of the Highland Boundary Fault. Therefore, we suggest that the Midland Valley shortening can be explained by Emsian–Frasnian sinistral transtension in a zone parallel to the NE-
trending Highland Boundary and Southern Uplands Faults. The vertical to locally overturned disposition of the early Devonian strata adjacent to the Highland Boundary Fault may be part of a flower structure along this major lineament.

**Western Ireland**

The Lower Devonian strata of Ireland (Fig. 4), from Mayo to Antrim, consist of red-bed–volcanic sequences of Islandeady, Curlew, Fintona and Cushendun, which unconformably overlie deformed Silurian strata and are deformed by NE-trending folds with limb dips of up to 70° and horizontal shortening values of up to 30% (Holland 1981; Max et al. 1992). Middle Devonian red beds (Beltra Group) unconformably overlie the Islandeady Group, are folded with limb dips up to 40° and shortening values of up to about 20%, and are overlain unconformably by gently dipping Upper Devonian and Carboniferous strata (Holland 1981; Max et al. 1992). It is not clear how this complicated sequence of unconformities and decreasingly deformed rocks developed, whether in transpression or transtension, but, by analogy with other areas north of the Iapetus Suture, the post-Islandeady, pre-late Devonian deformations were probably sinistrally transtensional.

**Summary**

Relative plate motion, in a three or more (n) global plate mosaic, must continuously and smoothly change across at least n – 1 plate boundaries (Dewey 1975). This involves the instantaneous pole of relative plate motion continuously shifting its position with respect to the plate boundary across which relative motion is described by that pole. Also, the rapid migration of triple junctions can cause extremely large changes in relative motion across plate boundaries (Dewey 1975). Furthermore, continental collision causes drastic changes in relative plate motion (Dewey et al. 1989) by blocking and terminating the subduction of oceanic lithosphere. Changes in the direction and rate of relative plate motion are necessary consequences of the evolution of plate mosaics (Dewey 1975). There appears to have been an orogen-wide transition in the Caledonides from sinistral transpression to sinistral transtension at about 400 Ma in mid-Emsian time. We suggest that this was the result of a change in relative plate motion between Laurentia and Baltica from oblique sinistral convergence through orogen-parallel motion to oblique sinistral divergence, caused by the Scandian collisional orogeny. During sinistral transpression, from about 435 to 425 Ma, Baltica collided with Laurentia to generate the Scandian Orogen in which partitioning into zone-orthogonal thrusting and zone-parallel strike-slip faulting progressively increased. At about 425 Ma, Avalonia collided, in highly oblique sinistral transtension, with Laurentia, a soft collision across the Iapetus Suture in Scotland and a harder collision in western Ireland.

At about 425 Ma, relative motion between Laurentia and Avalonia–Baltica became orogen parallel, which lasted until about 410 Ma. In Scotland, the Great Glen Fault appears to have been the principal structure on which sinistral displacement occurred. It may have continued northwards, via the Walls Boundary Fault, into East Greenland as the Western Fault Zone (Larsen & Bengaard 1991), or alternatively have linked with the Billefjorden Fault Zone in Svalbard. During this phase, the bulk of the Newer Granite Suite was emplaced mainly in transensional strike-slip pull-aparts. From about 410 Ma, the Caledonides went into regional sinistral transtension when transtensional Old Red Sandstone basins formed with combinations of normal and wrench faults and constrictional strains deforming their red-bed sequences.

During the transcurrent and transtensional phases, at least 700 km of sinistral motion occurred on the Great Glen Fault and its continuation in East Greenland with an unknown combined sinistral motion on the Highland Boundary Fault and Southern Uplands Fault. The Great Glen Fault post-dates the Moine Thrust (425 Ma) and largely predates the Eifelian Middle Old Red Sandstone Orcadian Basin (395 Ma). If we take the lengths of these faults as a minimum displacement, the total minimum sinistral displacement between Laurentia and Avalonia–Baltica was about 1200 km, giving a relative plate motion rate of 40 mm a⁻¹. A more conservative estimate of a total displacement of 900 km gives a rate of 30 mm a⁻¹ which places SW Norway against Scotland during the Scandian Orogeny. If we use 30 mm a⁻¹ as an approximate rate of the orogen-parallel strike-slip component of the motion of Laurentia with respect to Baltica from about 435 to 395 Ma, the outline reconstructions of Figure 5. (a) Silurian (435–425 Ma) reconstruction of the Caledonides with 700 km of sinistral motion on the Great Glen Fault removed, showing principal Scandian transpressional collisional structures referred to in the text. Abbreviations and symbols as in Figure 3. (b) Late Silurian–Devonian (425–395 Ma) reconstruction of the Caledonides showing principal transtensional structures referred to in the text. Abbreviations and symbols as in Figure 3.
5 can be achieved. Figure 5a portrays the Scandian Orogen with 900 km of sinistral motion on the Great Glen Fault and other faults restored. A 50% shortening across the Scandian Orogen (Hossack & Cooper 1986; Higgins & Leslie 2000) gives 600 km of orthogonal convergence between Laurentia and Baltica at a rate of 60 mm a\(^{-1}\). Combining the orogen-parallel and orogen-normal components of relative motion, Laurentia moved relative to Baltica, sinistrally obliquely, at about 67 mm a\(^{-1}\) (Fig. 5a). At 425 Ma, Laurentia–Baltica convergence ceased and the sinistral strike-slip component remained from 425 to 410 Ma to generate major orogen-parallel transient faults such as the Great Glen Fault. From 410 to 395 Ma, continuing transient motion combined with a modest orogen-orthogonal extension to generate a sinistral transtensional milieu in which many Old Red Sandstone basins developed (Fig. 5b). An implication of these rough and ready calculations is that, from 435 to 395 Ma, there was about 1200 km of sinistral strike-slip relative motion between Baltica and Laurentia. This large displacement appears to conflict with, by being outside the limiting error of, palaeomagnetic data (Torsvik et al. 1996); the trend of the Caledonides was at a high angle to Silurian–Devonian palearcticlal and there appears to have been little Devonian orogen-parallel offset between Laurentia and Baltica. However, we can see no escape from a bare minimum 700 km sinistral offset on the Great Glen Fault from the absence of Scandian deformation in the Dalradian from Connemara to Banffshire. If we add a further bare minimum 200 km of sinistral displacement on the Highland Boundary and Southern Uplands Faults, we obtain a minimum relative plate motion rate of 30 mm a\(^{-1}\). These lower and upper estimates of Silurian–Devonian relative plate motion rates of 30 mm a\(^{-1}\) and 67 mm a\(^{-1}\) based upon geological data are similar to present rates based upon global positioning system data, offsets across plate boundary zones, and finite-difference studies from magnetic anomaly fitting.


