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The lost Lower Old Red Sandstone of England and Wales: a record of post-Iapetan flexure or Early Devonian transtension?

N. J. SOPER* & N. H. WOODCOCK†

*Gams Bank, Threshfield, Skipton, BD23 5NP, UK and Department of Geology, National University of Ireland, Galway, Ireland
†Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

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Abstract – Illite crystallinity data from the Silurian slate belts of England and Wales indicate anchizone to low epizone metamorphism during the Acadian deformation in late Early Devonian time. This metamorphic grade implies a substantial overburden, now eroded, of Lower Devonian non-marine sediments of the Old Red Sandstone (ORS) magnafacies. A minimum 3.5 km pre-tectonic thickness of 'lost' ORS is estimated in the southern Lake District and comparable thicknesses in North Wales and East Anglia. Tectonically driven subsidence of the underlying Avalonian crust is required to accommodate such thicknesses of non-marine sediment. One proposed mechanism is flexure of the Avalonian footwall during convergence that continued from Iapetus closure in the Silurian until Acadian cleavage formation in the Emsian. The evidence for this model in the critical area of northwest England is reviewed and found to be unconvincing. An alternative model is developed following a recent suggestion that the Early Devonian was a period not of continued convergence but of orogen-wide sinistral transtension. Transtensional accommodation of the lost ORS is evidenced by Early Devonian extensional faults, by synchronous lamprophyric magmatism, and by compatibility with previously diagnosed sediment provenance patterns. A summary of Siluro-Devonian tectonostratigraphy for Britain south of the Highland Border emphasizes that, unlike the Scottish Highlands, this area was not affected by the Scandian Orogeny, but was by the Acadian. An important period of sinistral transtension in the Early Devonian (c.420–400 Ma) was common to both regions. This was a time of high heat flow, lamprophyric and more evolved magmatism, and major southward sediment transport, involving mainly recycled metamorphic detritus from the Highlands and from contemporaneous volcanicity. Old Red Sandstone, deposited in coalescing transtensional basins over much of Britain from the Midland Valley to the Welsh Borders, was largely removed and recycled southward during Acadian inversion.

Keywords: Old Red Sandstone, Devonian, Acadian, transtension, lamprophyre.

1. Introduction

Deformation of the Early Palaeozoic slate belts of England and Wales was traditionally ascribed to an end-Silurian phase of the Caledonian Orogeny, because it mainly affected marine Lower Palaeozoic strata and was followed by continental 'molasse' sediments of the Old Red Sandstone (ORS) magnafacies (e.g. Powell & Phillips, 1985). It is now recognized that this deformation took place towards the end of the Early Devonian and forms part of the Acadian Orogen that extends from the NE Appalachians through western Europe to Poland (Soper, Webb & Woodcock, 1987; McKerrow, 1988*b*). This timing raises a problem about the tectonic setting of the Old Red Sandstone. Can it still be regarded as a classic example of post-orogenic molasse, derived from erosion of the Caledonides and prograding southwards through Devonian time (e.g. Allen, 1979; Friend *et al.* 2000), even though, as originally recognized by Jones (1956), its lower part predates the (Acadian) deformation of the Welsh slates?

† Author for correspondence: nhw1@esc.cam.ac.uk

In this paper we first report evidence that the Lower Old Red Sandstone was thicker and more extensive across England and Wales than usually portrayed. Focusing on northwest England, we recognize the need for substantial tectonic subsidence to accommodate this sediment, and critically assess the current flexural model for this Early Devonian tectonic regime. We then develop an alternative transtensional basin model, particularly highlighting evidence from minor intrusive suites and fault patterns. We argue that this transtensile phase was a critical interlude between the closure of the Iapetus Ocean and the later Acadian Orogeny.

2. The lost Old Red Sandstone

2.a. Regional evidence

This paper focuses on that part of the former continent of Avalonia comprising England, Wales and the southeastern half of Ireland, south of the Iapetus Suture (Fig. 1). Avalonia rifted from the major Gondwana continent in early Ordovician time (e.g. Prigmore, Butler & Woodcock, 1997) and impinged on Laurentia

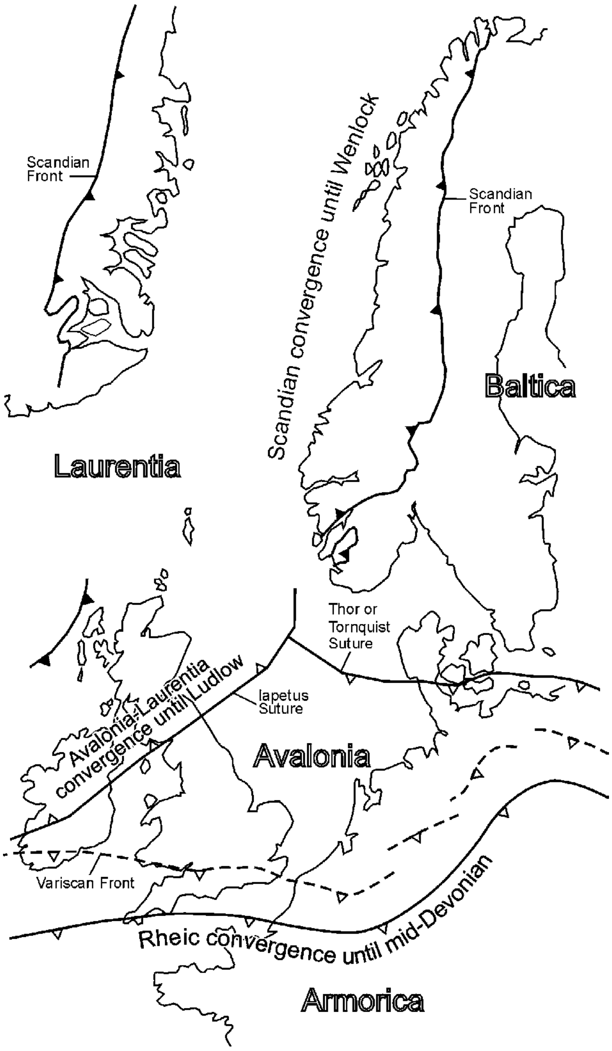

Figure 1. Mid-Palaeozoic plate configuration. The time of final suturing between Avalonia and Baltica is debated (see text).

during the early to mid-Silurian (Soper & Woodcock, 1990). By Ludlow time, there was continuous sedimentary linkage across the Iapetus Suture that marks the trace of the ocean destroyed between Avalonia and Laurentia (Figs 1, 2).

Marine Silurian rocks crop out, south of the suture, over much of the southern Lake District and Wales. However, extensive outcrop of the succeeding non-marine Lower ORS (predominantly Lower Devonian) is restricted to South Wales and the adjacent Welsh Borderland (Fig. 2). Boreholes in central and eastern England suggest that patches of Lower ORS are preserved here beneath post-Acadian cover (Allen, 1979). Further south, Lower Devonian non-marine intercalations occur in the predominantly marine successions deposited on the southern margin of Avalonia. To the north, however, only isolated remnants hint at a more extensive ORS cover between South Wales and the Iapetus Suture. These remnants comprise sandstone-dominated fluvial sequences on the Isle of Man (Peel) and in North Wales (Anglesey), and more conglomeratic alluvial fan and fluvial facies in western Ireland (Dingle Group).

Allen (e.g. 1962) appreciated from provenance and palaeoflow studies that a substantial cover of Lower ORS must have existed above the marine Silurian in the Welsh Basin, a cover which was eroded and recycled southwards during later Devonian uplift. Subsequent studies of the Acadian metamorphism in Wales, mainly using white mica crystallinity in cleaved mudrocks, have confirmed this hypothesis (e.g. Roberts, Merriman & Pratt, 1991). A section across North Wales (Fig. 3) shows the required sediment overburden assuming a thermal gradient of 36 °C per kilometre (see discussion in Roberts *et al.* 1996). A substantial Lower Devonian component to this overburden is implied, most persuasively by the upper anchizone grade of Ludlow rocks of the Denbigh Moors. The lost Lower ORS thickens from about 2 km at outcrop in the Welsh Borderland to a tectonic thickness of around 5 km over North Wales. A comparable thickness of missing ORS has been deduced from crystallinity data over the concealed Anglian Basin (Merriman *et al.* 1993) and in the Ribblesdale inlier of northwest England (Merriman *et al.* 1995). Perhaps significantly, thick Lower Old Red Sandstone is not required by the lower metamorphic grades in Mid-Wales (based on sections of Roberts *et al.* 1996).

2.b. Evidence from the Lake District

The possibility of a lost Old Red Sandstone cover to the Silurian slates of the southern Lake District is worth more detailed analysis because of the crucial role of this area in tectonic models of Iapetus closure and Acadian deformation. Figure 4 is an interpretive section showing minimum overburden at the time of peak Acadian metamorphism, constructed along the line of the deep section accompanying the BGS 1:50 000 Ambleside Sheet (British Geological Survey, 1998).

In burial metamorphism, overburden can be estimated directly from knowledge of lithostatic pressure and rock density, or indirectly from palaeotemperature if the geothermal gradient is known. No estimates of pressure or gradient are currently available for the Lake District slates, although fluid inclusion studies on syntectonic quartz veins are in progress to this end (M. Feeley, pers. comm. 2002). However, illite crystallinity data are available for the Ambleside area (Millward *et al.* 2000 fig. 63).

Illite crystallinity in mudrocks (crystallite thickness in authigenic clay micas) increases during diagenesis and low grade metamorphism due to recrystallization driven by thermal and strain energy (e.g. Roberts, Merriman & Pratt, 1991). Small wavelength map-scale variations in crystallinity might thus reflect changes in cleavage intensity while regional trends should reflect real changes in burial temperature. The Silurian slates exposed in the southern Lake District show a regional

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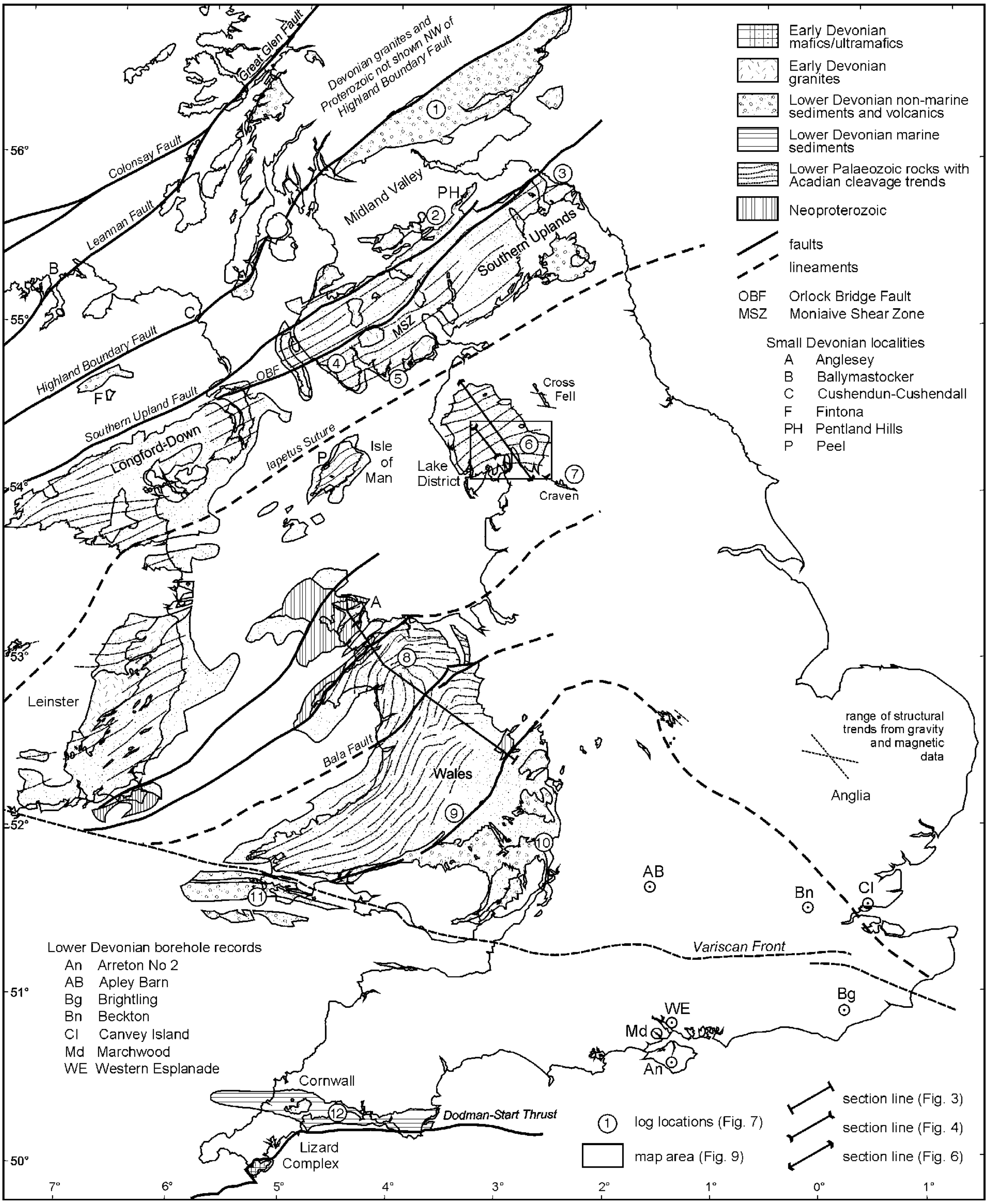

Figure 2. Geological map of southern Britain and Ireland highlighting outcrops of Lower Palaeozoic and Lower Devonian rocks. Also located are the section lines for Figures 3, 4, and 6, the stratigraphic columns for Figure 7 and the map in Figure 9.

trend from low anchizone-diagenetic grade in the east (Cautley area) to epizone grade in the southwest (Low Furness area: R. J. Merriman, pers. comm.). On the Ambleside cross-section (British Geological Survey, 1998), it is evident that the Acadian mid-anchizone isocryst lay close to the present erosion level. This corresponds to a palaeotemperature of about 250 °C (Kisch, 1987).

Maximum and minimum estimates of the overburden in the core of the Bannisdale Syncline (Fig. 4) can be made on the basis of the likely range of field gradients during Acadian metamorphism. Millward *et al.* (2000)

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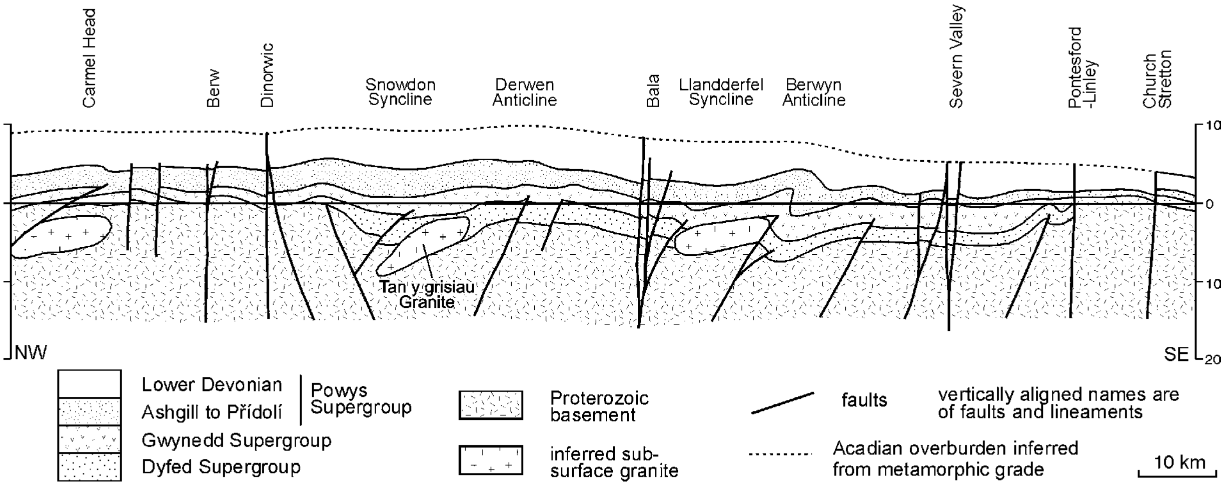

Figure 3. Tectonic cross-section across North Wales showing lost ORS overburden (section shown line on Fig. 2). Section modified from Shackleton (1954), with overburden deduced from metamorphic grade map of Robinson & Bevins (1986) and, at the SE end, from thickness at outcrop.

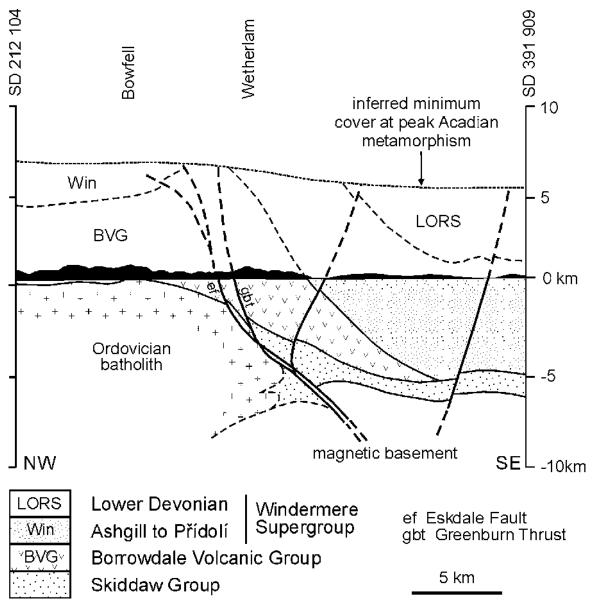

Figure 4. Tectonic cross-section across the southern Lake District showing the minimum thickness of the lost ORS overburden required above the southern part of the section. Based on the deep section accompanying BGS 1:50 000 geological map sheet (Ambleside) (British Geological Survey, 1998). Section line shown on Figure 2.

estimated at least 8 km of overburden assuming a gradient of 25 °C km^{-1} appropriate to a flexural basin setting. However, the Acadian deformation is unlikely to have taken place under such ‘cold basin’ conditions, and this thickness must represent a substantial over-estimate. ‘Thermal history modelling of the southern Lake District indicates that a low geothermal gradient of less than 20 °C km^{-1} during the Silurian was followed by higher gradients of 25–30 °C km^{-1} in the Lower Devonian’ (A. D. Carr and R. J. Merriman, pers. comm. 2003). A *minimum* overburden estimate can be made by assuming that an even steeper gradient had been attained by the time of peak metamorphism, comparable to that determined by Bottrell *et al.* (1990) for the Harlech Dome area: 36 °C km^{-1} at a depth equivalent to a lithostatic pressure of 3.0–3.6 kbar. However, the transient gradient was likely to have been non-linear within the ORS overburden, because the thermal conductivity of sedimentary rocks, particularly sandstones, diminishes markedly in the uppermost few kilometres (Holliday, 1999, fig. 3). Set against that, account must be taken of the erosion of weakly lithified sediments prior to the attainment of peak metamorphic conditions. Arbitrarily, we have assumed a linear gradient of 35 °C km^{-1} below 4 km depth, steepening to 50 °C km^{-1} at the surface. This steeper gradient is more in line with the findings of Bevins & Merriman (1988). It requires the presence of 4.9 km of overburden on the Bannisdale slates preserved at the present surface. This overburden consisted of about 1 km of uppermost Silurian strata (latest Ludlow and Přídolí, present to the east in the Kendal–Kirkby Lonsdale area) and 3.9 km of ORS. To this must be added about 0.6 km eroded during the build-up to peak metamorphic conditions. The 4.5 km tectonic thickness of ORS unstrains to about 3.5 km, assuming an Acadian vertical stretch of $e = 1.3$ in these high level rocks.

2.c. Tectonic implications of the lost Lower Old Red Sandstone

Our minimum estimate of the compacted, pre-tectonic thickness of Lower ORS cover required above the Silurian in the Windermere Supergroup basin is therefore about 3.5 km. Comparable minimum thicknesses of unstrained section are also required above North Wales. Even this conservative estimate of basin fill is too great to be accounted for by sediment loading alone. In a water-filled basin, a simple isostatic balance would require about 1.2 km of initial accommodation space,

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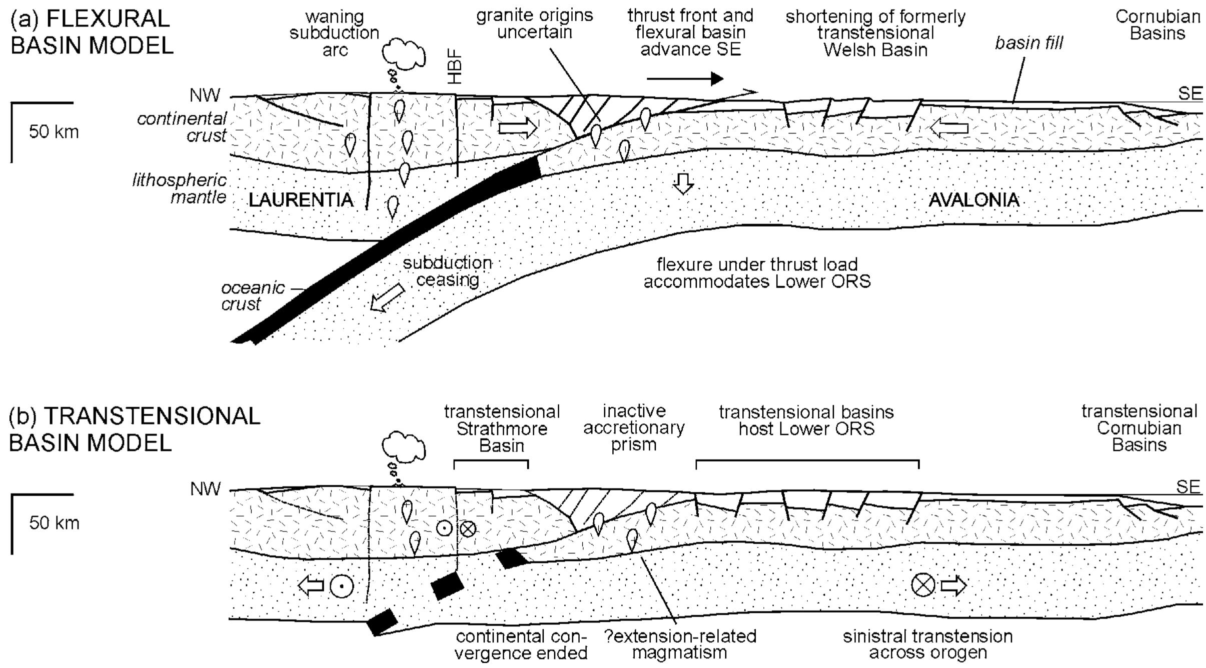

Figure 5. Cartoon lithospheric cross-sections for Early Devonian time showing (a) the flexural 'southward progradation' model and (b) the regional transtensional model.

which is incompatible with the evidence for shallow marginal marine facies by Přídolí time (King, 1994*b*). More appropriately, modelling of a non-marine alluvial basin suggests that the depositional surface would need to reach an implausible 0.9 km above sea level to deposit a sediment thickness of 3.5 km. The conclusion must be that a substantial component of tectonically driven subsidence was necessary to accommodate the lost Lower Old Red Sandstone.

Two alternative interpretations of Early Devonian tectonics in southern Britain are extant (Fig. 5). The flexural 'southward progradation' model of Barnes, Lintern & Stone (1989) and Kneller & Bell (1993) in essence proposes that Avalonia/Laurentia convergence continued after Iapetus closure in the mid-Silurian (Fig. 5a). The accretionary deformation of the Scottish Southern Uplands prograded southwards through the Avalonian lithosphere of England and Wales, progressively creating a flexural basin and then inverting it (King, 1994*a*; Woodcock & Strachan, 2000, fig. 12.13). The other view is that southern Britain was part of the wide region of the north Atlantic Caledonides affected by sinistral transtension during the Early Devonian (Fig. 5b), following the sinistrally transpressive Scandian Orogeny but pre-dating the Acadian Orogeny (Dewey & Strachan, 2003).

It is of some importance to resolve the issue of Early Devonian tectonic setting, because it bears on current problems other than that of the lost ORS, for example on the origin of Devonian 'Newer Granite' magmatism, the thermal structure of the low grade slate belts and the history of sediment recycling during exhumation of the orogen.

3. The flexural basin model

3.a. Regional context

The flexural model links some well-established tectonic scenarios: progressive imbrication of the Southern Uplands accretionary prism in the hangingwall of the Iapetus suture (Leggett, McKerrow & Eales, 1979), northward underthrusting of this prism by the Avalonian footwall (Leggett, McKerrow & Soper, 1983), and development of the Windermere Supergroup foreland basin in northwest England in Wenlock and Ludlow time (Kneller, 1991). The British Geological Survey has adopted the model as the preferred interpretation of Acadian tectonics in northern England (e.g. Kirby *et al.* 2000; Millward *et al.* 2000). In a regional review of ORS basin dynamics, Friend *et al.* (2000) inferred collapse, extensional or transtensional settings generally throughout the northeast Atlantic region, but a flexural origin for the Lower ORS basins south of the Iapetus suture in Britain, largely following King (1994*a*).

Despite its attraction as a unifying hypothesis, the flexural model does not satisfy several key regional constraints. It fails to account for the apparent synchroneity of the Acadian Orogeny through Britain and Ireland in Emsian time (McKerrow, 1988*b*). It does not explain how a convergence rate that decelerated to zero through Early Devonian time (Kneller & Bell, 1993) could lead to climactic crustal shortening in the late Emsian. Crucially, it does not allow a thick Lower ORS succession to be deposited in northwest England in a foreland basin that had begun to invert by the end of Silurian time (Kneller & Bell, 1993). These

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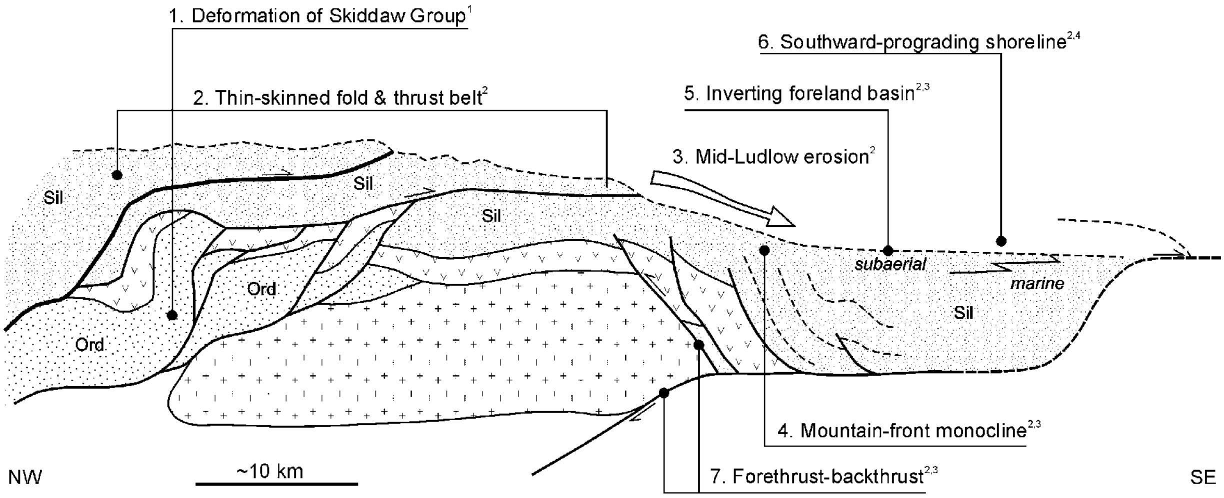

Figure 6. Cartoon cross-section across the Lake District, showing the southward-progradation tectonic model. Section line shown on Figure 2. Superscripts ascribe components of the model to (1) Hughes, Cooper & Stone (1993), (2) Kneller, King & Bell (1993), (3) Kneller & Bell (1993), and (4) King (1994*b*).

problems invite a reappraisal of the evidence from northwest England on which the flexural model was based.

3.b. Critique of the flexural model in northwest England

Following the initial proposal of Barnes, Lintern & Stone (1989), which was made from a Southern Uplands viewpoint, the flexural model was developed during a multidisciplinary re-survey of the English Lake District (Fig. 2). This survey was undertaken from 1982 by the British Geological Survey with participation by NERC-funded university geologists, including the authors. While expressing reservations about some of the resulting tectonic interpretations, we wish to acknowledge the contribution made by all participants in this collaborative project. Figure 6 is a cartoon cross-section illustrating the structural evolution of the Lake District in late Silurian and Early Devonian time according to the southward progradational flexure hypothesis (Kneller & Bell, 1993, fig. 4). It shows the main elements on which the model is based, which we discuss below as a series of propositions. To avoid repetition, primary references are included in the caption to Figure 6.

(1) *The main deformation of the Skiddaw Group was late Silurian.* According to this proposition the main cleavage (S1) and associated folding took place in late Wenlock or early Ludlow time, followed by thrusting and superimposed cleavage development from mid-Ludlow time onwards. While this structural sequence is correct, evidence from the aureole of the Skiddaw granite shows that the whole deformation took place late in the Early Devonian. Formation of the main cleavage overlapped the time of granite emplacement (Soper & Roberts, 1971), which has a K–Ar biotite age of 399 ± 8 Ma (Shepherd *et al.* 1976).

(2) *A thin-skinned fold and thrust belt developed over the central Lake District from mid-Ludlow onwards.* Deformation of the Skiddaw Group does not show genetic linkage of the folding and thrusting: the thrusts are superimposed on the 'D1' folds (Hughes, Cooper & Stone, 1993) and disrupt the metamorphic pattern (Fortey, Roberts & Hirons, 1993). Nor is there compelling evidence that the structure is thin-skinned: exposed thrusts in the Skiddaw Group are steeply inclined, as shown correctly in the cartoon. Emplacement of the thrust sheets requires a very large displacement on the most northerly thrust shown in the cartoon, which is a hypothetical structure, hidden beneath Carboniferous cover.

(3) *Emergent thrust sheets shed sediment into the foreland basin from mid-Ludlow time.* Turbidite sedimentation in the Ludlow was mainly sandy in the Coniston Group followed by mixed sand, silt and mud in the Bannisdale Formation, all with dominantly southwestward palaeoflow, and inferred Scandian provenance (McCaffrey *et al.* 1992; McCaffrey, 1994). Lack of marginal facies suggests that these units were continuous across the central Lake District, an idea supported by the predominance of locally derived Silurian clasts in the Devonian Mell Fell conglomerate (Capewell, 1955). Crucially, there is no record of a mid-Ludlow change to proximal SE-directed conglomerate fans with reworked Silurian detritus. A change in provenance parameters is only recorded in the regressive sequence at the *end* of the Ludlow (McCaffrey & Kneller, 1996), presumably associated with the orogen-wide change from dominantly marine to fluvial facies.

(4) *The Westmorland Monocline began to develop as a mountain front structure in the Přídolí.* This structure was invoked to explain the similar grade of Acadian metamorphism in the central and southern

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Lake District despite a difference in stratigraphic level of some 8 km, which had to be eliminated by erosion of the upper limb of the monocline before the Acadian. In fact the problem is the reverse. A cover of Windermere Supergroup is adequate to produce prehnite–pumpellyite facies metamorphism in the Borrowdale Group (Thomas, Harmon & Oliver, 1985; Millward *et al.* 2000) but extra cover is required over the younger Silurian rocks to raise them to anchizone grade, and this could only have been provided by Lower Devonian strata.

(5) *Inversion of the foreland basin commenced in the Přídolí.* Sedimentary facies in the regressive sequence preserved at the exposed top of the Windermere Supergroup have been described in detail by King (1994*b*). They show that sediment input began to exceed subsidence in late Ludlow time. However, this shallowing and overfill did not herald contractional inversion because, again, several kilometres of Lower Devonian sediment were subsequently deposited.

(6) *A shoreline prograded southwards during the Přídolí and Early Devonian.* King (1994*b*) demonstrated that sediment dispersal in the foreland basin during Ludlow time was from the northeast and locally the northwest and that there is limited evidence, following Shaw (1971), of southeasterly progradation of shallow over deeper water facies, suggesting that the basin filled from the north. By analogy with southeast Wales, it is also reasonable to suppose that fluvial sedimentation succeeded marine, indicating emergence. However, no shoreface facies are present in the preserved section, so it is not possible to infer that the shoreline migrated in any particular direction, or to link emergence with inversion. All that can be said is that the Windermere basin became overfilled towards the end of the Silurian.

(7) *The deep structure of the southern Lake District is thin skinned.* The interpretation involving a crustal ramp and backthrust (Fig. 6) was developed by M. K. Lee and one of the authors (NJS) in an attempt to model the deep structure of the Lake District from geophysical potential field data. A flat detachment beneath the foreland basin was added by Kneller & Bell (1993) to accommodate southward propagation of the deformation. With the exception of the Greenburn Thrust, which is exposed (Fig. 9), the existence of all these structures is speculative.

The tectonostratigraphic model illustrated by Figure 6 is thus based on data that are at best equivocal, or on permissive interpretations that do not in themselves constitute evidence. The southward progradation model for deformation on Avalonia is thus questioned, as is a predominantly flexural origin for the basins that accommodated the missing Old Red Sandstone. Before considering an alternative transtensional tectonic model we first review the constraints on timing of tectonic events through the Silurian and Devonian.

4. Timing of Silurian to Devonian deformation

4.a. Ending of Iapetan convergence

There has been much debate, which need not be reviewed here, on the timing of Iapetus closure between Eastern Avalonia and the southern margin of Laurentia and consequently on the tectonic setting of Silurian sedimentation in the Southern Uplands. It is now widely agreed that the Central and Southern belts of the Southern Uplands do represent a SE-vergent accretionary prism and that a hemipelagite- then turbidite-dominated deposystem was established across the suture by Wenlock time. The question is for how much longer did convergence continue? There are two lines of evidence.

Kemp (1987*a*,*b*) recorded a decrease in the intensity of accretionary deformation between the early Wenlock Ross Formation and the mid- to late Wenlock Raeberry Castle Formation. The change occurred between the *M. atennularius* and *C. rigidus* biozones (*c.* 426 Ma) and Kemp attributed it to a slowing in accretion rate and hence of subduction. The youngest accreted package in the Riccarton Group contains *C. lundgreni* Biozone strata, implying that convergence continued at least until the late Wenlock (Fig. 7).

The end of accretion-related deformation in the Southern Uplands is also marked by a suite of late Caledonian dykes and subvolcanic minor intrusions, ranging from K-lamprophyres to rhyolitic porphyries, that are concentrated in the Hawick Group rocks of the Central Belt (Barnes, Rock & Gaskarth, 1986; Rock, Gaskarth & Rundle, 1986). Emplacement of these intrusions began before the end of accretionary deformation, as early members were deformed by D2, although most are post-tectonic. Eight K–Ar ages from unfoliated lamprophyres (Rock, Gaskarth & Rundle, 1986) span the period 400–418 Ma (Fig. 7) and, together with a similar date along-strike in Ireland (Anderson & Oliver, 1996) average 410 ± 3 (Fig. 8). When the important dating by Rock, Gaskarth & Rundle was undertaken, difficulties arose in reconciling isotopic and biostratigraphic ages using the timescales available at the time. For example post-tectonic dykes appeared to have been emplaced contemporaneously with Wenlock sedimentation and therefore during accretion. On the current timescale (Tucker *et al.* 1998; Williams, Friend & Williams, 2000) the Siluro-Devonian boundary is placed at 418 Ma: the undeformed dykes are thus Early Devonian and the problem is resolved. Combined with the stratigraphic evidence above, the dykes constrain the end of accretionary deformation to latest Wenlock, Ludlow or Přídolí time (Fig. 7).

The end of accretion implies also the end of convergence across the British sector of Iapetus unless, as suggested by Barnes, Lintern & Stone (1989), displacement was transferred to a more southerly decollement within the Avalonian footwall of the

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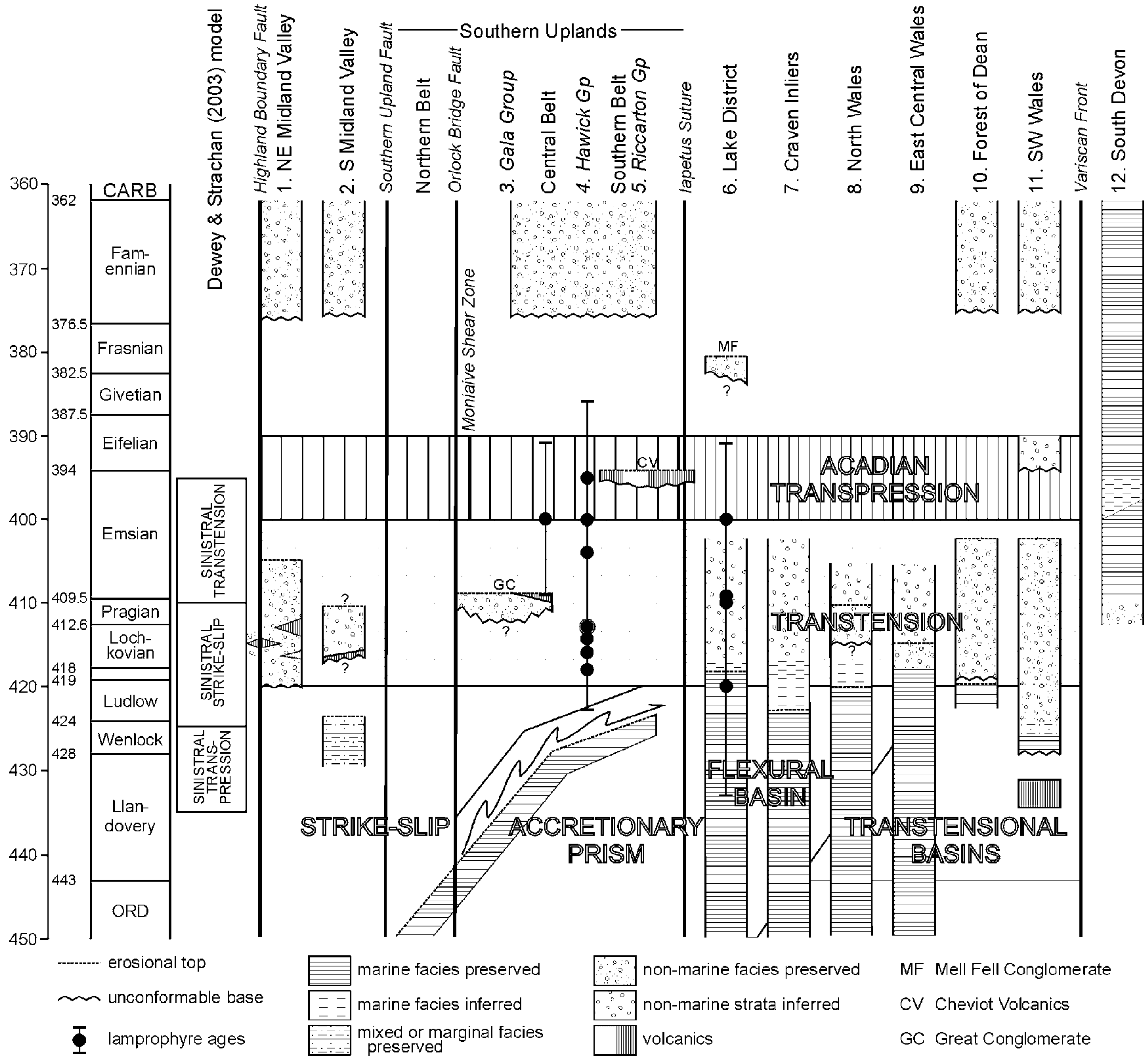

Figure 7. Stratigraphic columns across Britain south of the Highland Boundary. Locations are shown on Figure 2. Lamprophyre dates from Rock, Gaskarth & Rundle (1986), Rundle (1979) and Nixon, Rex & Condliffe (1984).

suture. Difficulties with this southward propagation model in the Lake District (Kneller & Bell, 1993) have already been detailed. Additionally, although subsidence curves from the Windermere Supergroup in this region (King, 1994*a*) record a flexural response to a southward-migrating load through early and mid-Silurian time, decreasing subsidence rates in the late Ludlow and Přídolí (King, 1994*a* fig. 4, curves 3, 4) suggest that this load then ceased to advance further. To the south, the Welsh Basin was dominated by transtension through Silurian time, and King (1994*a*, p.654) observed that possible flexural responses in the subsidence curves here are difficult to pick. Persuasive evidence against any southward wave of subsidence and deformation is provided by the generally synchronous rather than diachronous change, close to the Silurian/Devonian boundary, from marine to non-marine facies across Avalonia (Fig. 7). This change is more compatible with a synchronous end to Iapetus convergence, combined with the regressive effects of falling global sea-level (Johnson, 1996).

4.b. Acadian deformation

Contrary to previous views that the Acadian deformation on Avalonia was temporally continuous with deformation related to Iapetus closure (Barnes, Lintern & Stone, 1989; Woodcock & Strachan, 2000), evidence is accumulating for a significant time gap between the two events (Fig. 7). Stratigraphic evidence for Acadian timing has been summarized by McKerrow, MacNiocall & Dewey (2000). It indicates an Emsian (latest Early Devonian) age in Britain, Ireland and maritime Canada, though possibly somewhat later in the northern

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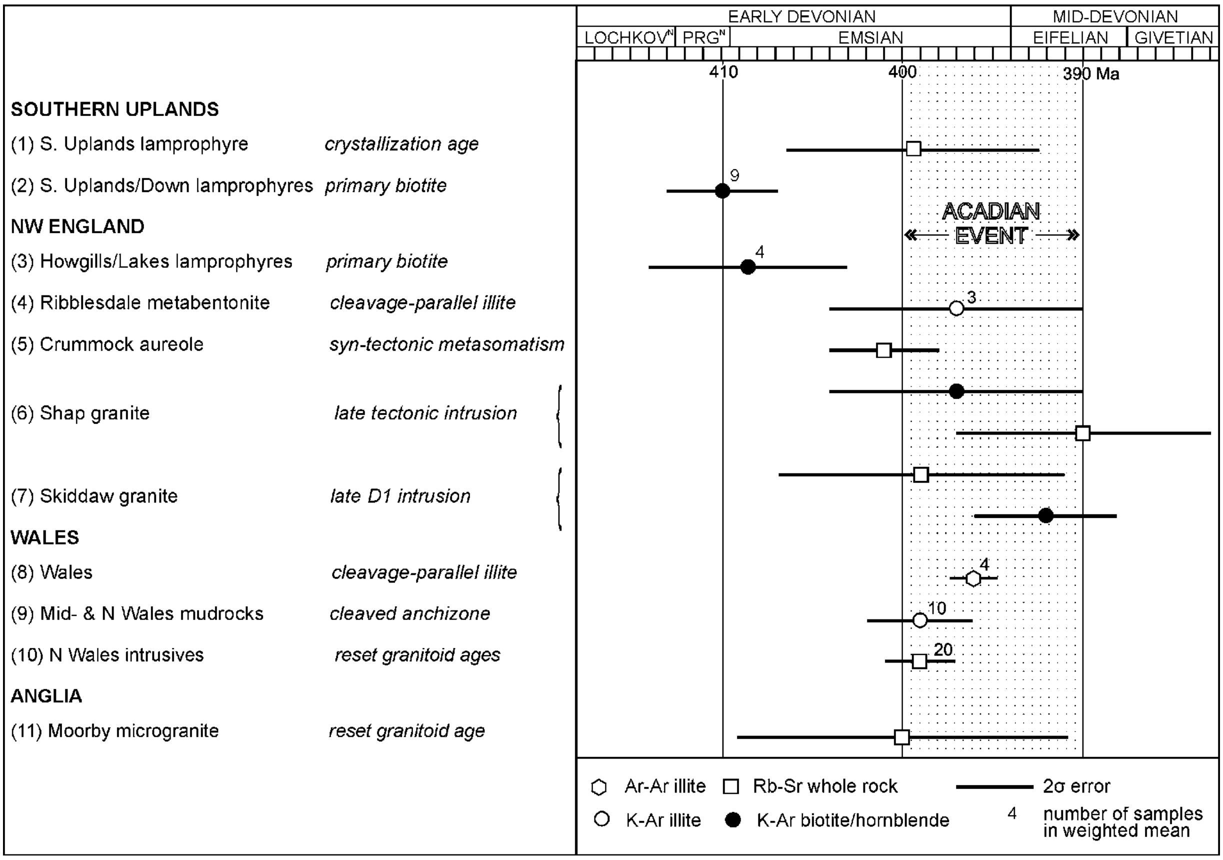

Figure 8. Radiometric ages relevant to Devonian tectonics in southern Britain. The timescale is that of Tucker *et al.* (1998), as modified by Williams, Friend & Williams (2000). Data sources are (1) Macdonald *et al.* (1986); (2) Rock, Gaskarth & Rundle (1986); (3) Nixon, Rex & Condliffe (1984) and Rundle (1979); (4) Merriman *et al.* (1995); (5) Cooper *et al.* (1988); (6) Rundle (1992), Pidgeon & Aftalion (1978); (7) Rundle (1981), Shepherd *et al.* (1976); (8) Sherlock *et al.* (2003); (9) Evans (1996); (10) Evans (1991); (11) Pharaoh *et al.* (1997).

Appalachians. This conclusion is supported by the clarification of Richmond & Williams (2000) that, on the Dingle Peninsula, western Ireland, the Acadian unconformity occurs between the Dingle and Smerwick groups, of late Silurian to Pragian or early Emsian age, and the overlying Eifelian Pointagare Group.

Geochronometric evidence from Eastern Avalonia (Fig. 8) also favours a later Emsian or earliest Eifelian age, in the period 390–400 Ma. Direct K–Ar dating of illites from cleaved anchizonal mudrocks yields mean ages of 397 ± 7 Ma in northwest England (Merriman *et al.* 1995) and 399 ± 3 Ma in the Welsh Basin (Evans, 1996). Most reliably, Ar–Ar dating of cleavage-parallel micas in strain fringes has given an average age of 396.1 ± 1.4 (Sherlock *et al.* 2003). Similar deformation ages are suggested by textural relations around dated intrusions in the Lake District. The Skiddaw granite was emplaced into Skiddaw Group mudrocks late in the formation of the main cleavage: chiastolite in the aureole overgrows components of the S1 fabric but is weakly wrapped by it, and is crenulated by S2 (Soper & Roberts, 1971). The aureole of the Shap granite overprints cleavage in the Borrowdale and Windermere rocks but some cogenetic dykes are cleaved at their margins (Soper & Kneller, 1990). The metasomatic aureole of the concealed Crummock intrusion overprints cleavage in the Skiddaw Group but pre-dates movement on the Causey Pike Thrust (Cooper *et al.* 1988). The mean of the five ages from these late tectonic intrusions is 397 ± 2 Ma. Isotopic closure is thought to have taken place within a few million years of granitoid emplacement, as erosional unloading and cooling appear to have been rapid. The date may therefore approximate that of peak Acadian metamorphism.

Pre-dating the inferred Acadian climax are some age determinations of debatable reliability or tectonic significance which are therefore not shown on Figure 8. Rb–Sr whole rock and Ar–Ar ages (422–417 Ma) from mudrocks in both Wales and the Lake District all date prograde mineral reactions, probably during pre-tectonic subsidence (e.g. Evans, 1996; Dong *et al.* 1997). The resetting of Rb–Sr systems averaging 426 ± 2 Ma in Lake District granitoids and volcanics has been ascribed to thrust-induced crustal uplift (Stone, Cooper & Evans, 1999), although the Causey Pike thrust, at least, moved during or after the ∼400 Ma event: this resetting event is more likely associated

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with regional subsidence during the flexural basin phase.

Of more certain significance are the Early Devonian (420–402 Ma, average 409 ± 6 Ma) dates from a lamprophyre dyke suite in northwest of England. Members of the suite bear the Acadian cleavage in areas such as the Cross Fell inlier (Burgess & Wadge, 1974; Arthurton & Wadge, 1981). However, in areas of lower deformation, such as the Howgill Fells where most of the radiometric ages were obtained (Nixon, Rex & Condliffe, 1984), the dykes show only foliated margins (Bonney & Houghton, 1878) whose origin could be primary or tectonic. On balance, the current evidence is that the lamprophyre suite pre-dates the Acadian deformation. These lamprophyres provide a petrogenetic link with Southern Uplands intrusions of similar age (Fig. 7), a link that merits later discussion.

Three important conclusions may be drawn from the stratigraphic and radiometric results. First, within error, the Acadian tectono-metamorphism occurred synchronously through England and Wales, beginning late in Early Devonian time. Second, the spatial pattern of stratigraphic and radiometric dates lends no support to the idea that the Acadian deformation front prograded southwards through England and Wales. Indeed, and thirdly, there was a sizeable time gap between the inferred end of Iapetus convergence (about 420 Ma) and the apparent onset of Acadian deformation (about 400 Ma). Active lithospheric extension during this period is suggested by the widespread intrusion of lamprophyre dykes and other minor intrusions during Early Devonian times. Is this extension or, most likely, transtension responsible for creating the basins in which the lost ORS was deposited?

5. The transtensional basins model

5.a. Regional evidence

The case for an orogen-wide sinistrally transtensional regime in the Caledonides has most recently been compiled by Dewey & Strachan (2003). They review the well-established scenario of sinistrally oblique convergence of Baltica and Avalonia with the Scoto-Greenland margin of Laurentia, recognizing three main phases:

(1) Scandian transpression between 435 and 425 Ma, apparently evidenced in Britain only north of the Great Glen;

(2) a period of sinistral strike-slip from 425 to 410 Ma, with substantial displacement on the Great Glen, Highland Boundary and Southern Upland fault systems;

(3) sinistral transtension in the Early Devonian, 410–395 Ma

The observational evidence cited by Dewey & Strachan (2003) for Early Devonian transtension was drawn largely from former Laurentia and Baltica. We augment this evidence below with observations from Avalonia. It seems entirely reasonable that southern Britain, the area of concern here, should experience similar transtension while interacting with the 'Scottish promontory' of Laurentia (Dalziel & Soper, 2001) which provides a releasing bend for obliquely accreting terranes.

Dewey and Strachan (2003) adopted Trench & Torsvik's (1992) interpretation of a combined Baltica–Avalonia continent created by late Ordovician collision before it accreted to Laurentia in the Silurian. However, they expressed reservations about this model for the obvious reason. No common rotation pole can accommodate both the vigorous collision of Baltica, with major imbrication and development of an eclogite root, and weak convergence of Eastern Avalonia, with the purely flexural footwall response discussed in this paper. We prefer a three-plate model for the Silurian (e.g. Soper *et al.* 1992) with Avalonia and Baltica juxtaposed, to satisfy the palaeomagnetic and faunal evidence, but structurally decoupled along a Tornquist plate boundary (Fig. 1). The Avalonian system had a more northerly and probably slower convergence vector than the Scandian, and continued longer. This kinematic pattern has important implications for southern Britain. The Scandian and Avalonian convergence regimes were independent, and Britain and Ireland south of the Highland Boundary Fault *did not participate in the Scandian Orogeny*. Silurian deformation in southern Britain does not fit neatly into the regional pattern of transpressive convergence followed by strike-slip; strain partitioning was both spatial and temporal. Additionally, the subsequent Early Devonian period of transtension was terminated by a further compressive event, the Acadian, whose effects were concentrated south of the Highland Border.

5.b. Stratigraphic evidence from the southern Scotland

The nearest substantial Lower Old Red Sandstone sequence to the Lake District is preserved in the southern Midland Valley of Scotland (Bluck, 1983; 1984; Smith, 1995). Here clastic sediments and volcanic rocks of ORS magnafacies succeed mixed marine and red beds of Wenlock age; marine Ludlow strata have not been recognized (Fig. 7). In the Pentland Hills and at Girvan, the basal ORS Greywacke Conglomerate Formation rests unconformably on folded Wenlock strata, while in the central inliers there is a non-angular erosional contact. Smith (1995) attributed the localized deformation of the Silurian rocks to sinistral strike-slip with restraining-bend fault geometry, which was followed by a period of sinistral transtension during ORS sedimentation and volcanicity. This timing is compatible with a latest Silurian end to Iapetan convergence in the Southern Uplands to the southeast (Fig. 7).

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In the northeastern part of the Southern Uplands, Lower ORS conglomerates sit unconformably on Gala Group (Silurian) rocks bearing accretionary deformation. A lamprophyre dyke, dated at 400 ± 9 Ma, cuts the conglomerate and confirms its Early Devonian age, (Rock & Rundle, 1986). This relationship implies that deposition of the Lower ORS overlapped in time with the intrusion of the regional lamprophyre suite in the Southern Uplands, mostly dated between 418 and 400 Ma (Fig. 7) (Rock, Gaskarth & Rundle, 1986). The original thickness of Lower ORS in the Southern Uplands cannot be constrained by the metamorphic grade in the underlying Silurian units, because of the intervening unconformity, nor can any required extensional subsidence. However, the lamprophyre suite itself provides critical evidence.

5.c. The 'Late Caledonian' lamprophyres

It has been argued by Barnes, Rock & Gaskarth (1986) and Vaughan (1996) that the late Caledonian lamprophyre suite records a component of lithosphere-scale extension, or more specifically sinistral transtension, in the Early Devonian. The argument is as follows. Calc-alkaline lamprophyres require a deep mantle source, most probably K-rich melt-metasomatized subcontinental lamproitic material, and their generation commonly results from small amounts (or the early stages) of lithospheric extension (Harry & Leeman, 1995). Transtensional displacements on lithosphere-penetrating shear zones provide a viable trigger for decompression melting and can generate through-going fractures that provide conduits for the necessarily rapid rise of magma (Vaughan, 1996, and references therein).

Vaughan inferred that a deep shear zone underlies the 10 km wide swarm of mica lamprophyres that extends across the southern part of the Southern Uplands into eastern Ireland (Rock, Gaskarth & Rundle, 1986). The intensity of this zone in well-exposed coastal sections indicates upper crustal extension averaging 1% and locally as much as 6% (Barnes, Rock & Gaskarth, 1986). The late Caledonian lamprophyres and related dykes with more evolved compositions extend cross-strike from northern England to the north of Scotland, intruding all the recently assembled Caledonian terranes, so their tectonic setting is a regional-scale phenomenon. Almost all the published dates on the lamprophyres (Figs 7, 8) fall within the 400–420 Ma interval between the end of Iapetus convergence and the Acadian Orogeny. They are evidently the igneous fingerprint in northern Britain of the orogen-wide transtensional event proposed by Dewey & Strachan (2003) – a hypothesis presciently suggested in general terms by Watson (1984).

Dyke orientations confirm the sinistral sense of this transtensional episode. The lamprophyre-rich zone trends somewhat anticlockwise of the Southern Uplands/Longford-Down regional strike, straddling the trace of the Iapetus suture (Fig. 10; Vaughan, 1996, fig. 4). Vaughan showed that at Clogher Head in eastern Ireland, dykes strike on average 35° anticlockwise of primary sinistral shears, interpreting them as hosted by sinistral Riedel shears.

Dewey (2002) has modelled transtension from a strain viewpoint, as a combination of zone-normal coaxial extension (pure shear with an instantaneous extension direction normal to the zone) and zone-parallel rotational strain (simple shear with an instantaneous extension direction at 45° to the zone: Dewey, 2002 fig. 3). In general transtension, dyke-hosting fractures are likely to be initiated normal to the combined instantaneous stretch. Thus sinistral transtension in a 'Caledonoid' 060° orientation would generate a combined stretch with an azimuth somewhere between 150° and 105° depending on the relative magnitude of the irrotational and rotational components respectively. Dykes intruded normal to this direction would have strikes initially between 060° and 015°, and then rotate passively anticlockwise in the rotational strain field.

In the Wigtown peninsula (Fig. 10), Barnes, Rock & Gaskarth (1986) have described two modes of dyke emplacement. In a southern subarea, the majority of dykes were emplaced parallel to well-developed bedding or in pre-existing NW-trending fractures. In a northern sub-area the turbidite country rocks tend to be massive, and the dykes were interpreted as invading new fractures and thus likely to reflect the regional strain field. These have a pronounced maximum azimuth between 020° and 030°, supporting the idea that they were emplaced during regional sinistral transtension, in which the non-coaxial component perhaps predominated. Similarly, the Clogher Head dykes, interpreted as invading sinistral R-shears by Vaughan (1996, fig. 2), have mean strikes of $030 \pm 22°$ and $040 \pm 20°$, again compatible with sinistral transtension. These models are of course non-unique: a purely extensional or even dextral geometry could be devised; but given the sinistrally oblique nature of Caledonian deformation generally, and in the Southern Uplands in particular, it is our preferred interpretation.

Mention must be made of the Black Stockarton Moor subvolcanic dyke complex in Galloway (Fig. 10) which is of Early Devonian age, pre-dating the c.397 Ma Criffel pluton. The dyke swarm has a complex sigmoidal geometry (Leake & Cooper, 1983). At a time when Iapetus convergence was thought to be dextral (Phillips, Stillman & Murphy, 1976), Leake and Cooper interpreted the main phase of dykes (D2) as emplaced during dextral shear. However, these dykes form an *en echelon* S-sigmoidal array, suggesting lateral propagation under sinistral Caledonoid shear, together with substantial anticlockwise passive rotation of the inner dyke segments. A modern structural/geochronological

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study of the complex would throw light on the evolving Early Devonian stress field.

5.d. Early Devonian extensional faults?

Our proposal is that subsidence during the Early Devonian period of transtension created accommodation space to host the lost Old Red Sandstone, which on our estimate attained a minimum thickness of about 3.5 km in the southern Lake District and possibly more over North Wales. Attempting to model a basin whose fill has been lost is an unrewarding task, but some comments about tectonic controls can be made.

There is ample time within the period from 420 to 400 Ma to deposit 3.5 km of sediment in an extensional setting. Under the boundary conditions adopted by Ryan & Soper (2001), the accumulation of 3 km of synrift deposits would require about 15 Myr of lithospheric stretching at a standard strain rate of 10^{-15} $\sec^{-1}$ to which must be added about 0.5 km of concomitant thermal subsidence (Ryan & Soper, 2001, figs 3, 4). In the upper crust, this stretch component of about $\beta = 1.5$ was presumably achieved by displacement on normal faults, which should be preserved in the Lower Palaeozoic rocks that underlie the basin fill. We attempt to identify some of these in the Lake District, then more widely.

A map of the southern Lake District, based on the recent re-survey (Fig. 9), shows the principal faults, which we assign to three groups on the basis of age, reactivation history and less importantly, trend. To the north, within the Borrowdale Volcanic Group, are faults of variable orientation, many of which were active during the volcanism (Millward, 2002). Of these, some important NNE-trending faults (e.g. Coniston, Brathay, Troutbeck, Fig. 9) offset the base of the Windermere Supergroup and were reactivated after deposition of the Silurian. They are considered below.

In the Borrowdale Volcanic Group there are also 'Caledonoid' faults located close to the southeastern flank of the Ordovician subvolcanic batholith. The Haweswater fault system forms the northern margin of the Kentmere volcanic basin (Millward, 2002, fig. 7), throws down to the southeast and could well have been reactivated in that sense during the Early Devonian. In contrast, the Greenburn Fault, which had thrust-sense displacement during the Acadian, appears to have been initiated as an extensional fault on the batholith flank in the Early Devonian, linking displacement on the pre-existing Eskdale and Grassguards faults (Fig. 9). We suggest that these 'Caledonoid' faults marked a hinge during Early Devonian transtension between the buoyant batholith in their footwall and the subsiding ORS basin to the southeast.

The southeastern part of the map area in Fig. 9 is dominated by faults that displace Lower Carboniferous strata and were probably either initiated or reactivated during Permo-Triassic extension. A prominent set of arcuate faults, concave towards the Southwest (for example, the Grayrigg, Skelsmergh, Kendal and Lyth Valley faults on Fig. 9) may well represent listric extensional faults initiated at that time. Together with members of the northerly group described below, into which they transfer displacement, they control the pattern of easterly dipping Carboniferous tilt-blocks characteristic of the southern Lake District. If entirely post-Carboniferous, the arcuate faults cannot have participated in Early Devonian extension.

The dominant fault system within the Windermere Supergroup consists of mainly NNE-trending faults that often anastomose with NNW strands, and have an interesting reactivation history. As shown by Moseley (1968) and confirmed by the recent re-survey, these faults commonly separate tracts with mismatching patterns of Acadian folds and cleavage. However, their orientation suggests that they were not initiated during the Acadian; rather they appear to represent pre-existing fractures along which the Acadian strain was partitioned. They show variable displacements along their length and sometimes tip-out via minor splays. The few well-exposed examples (usually in working roadstone quarries) are inclined steeply to the west, with a dominant normal displacement but much evidence of reactivation.

We infer that many of these NNE-trending faults represent pre-existing fractures in the sub-Windermere basement that propagated up into the Silurian cover as normal faults during Early Devonian sinistral transtension, for which their orientation was ideal. Extensional displacement on these faults (of which the major examples are named in Fig. 9) accommodated deposition of the Lower ORS basin fill. They were thus already present as tract-bounding fractures in the Silurian rocks before the Acadian deformation was imposed almost parallel to their strike, and some were reactivated again as west-down normal faults during post-Carboniferous extension.

The most important of the NNE group is the Dent Fault Zone which additionally saw compressional reactivation as a major east-down monocline during the Variscan (Woodcock & Rickards, 2003). Despite its straight trace, the Dent Fault shows westward dips as low as 70° and in our view is likely to represent the eastern bounding fault of the inferred ORS basin against the Askrigg block. This block is underpinned by the Wensleydale Granite which on the grounds of chemical composition and heat flow characteristics is thought to be of Ordovician age (Millward, 2002). Early Devonian lamprophyre dykes to the west of the Dent Fault have a mean NNW strike, compatible with sinistral transtension locally resolved onto the Dent Fault Zone (Fig. 9; Woodcock & Rickards, in press).

The N–S pattern of faults in the southern Lake District can be traced westwards into faults with clear later reactivation, such as the Lake District Boundary

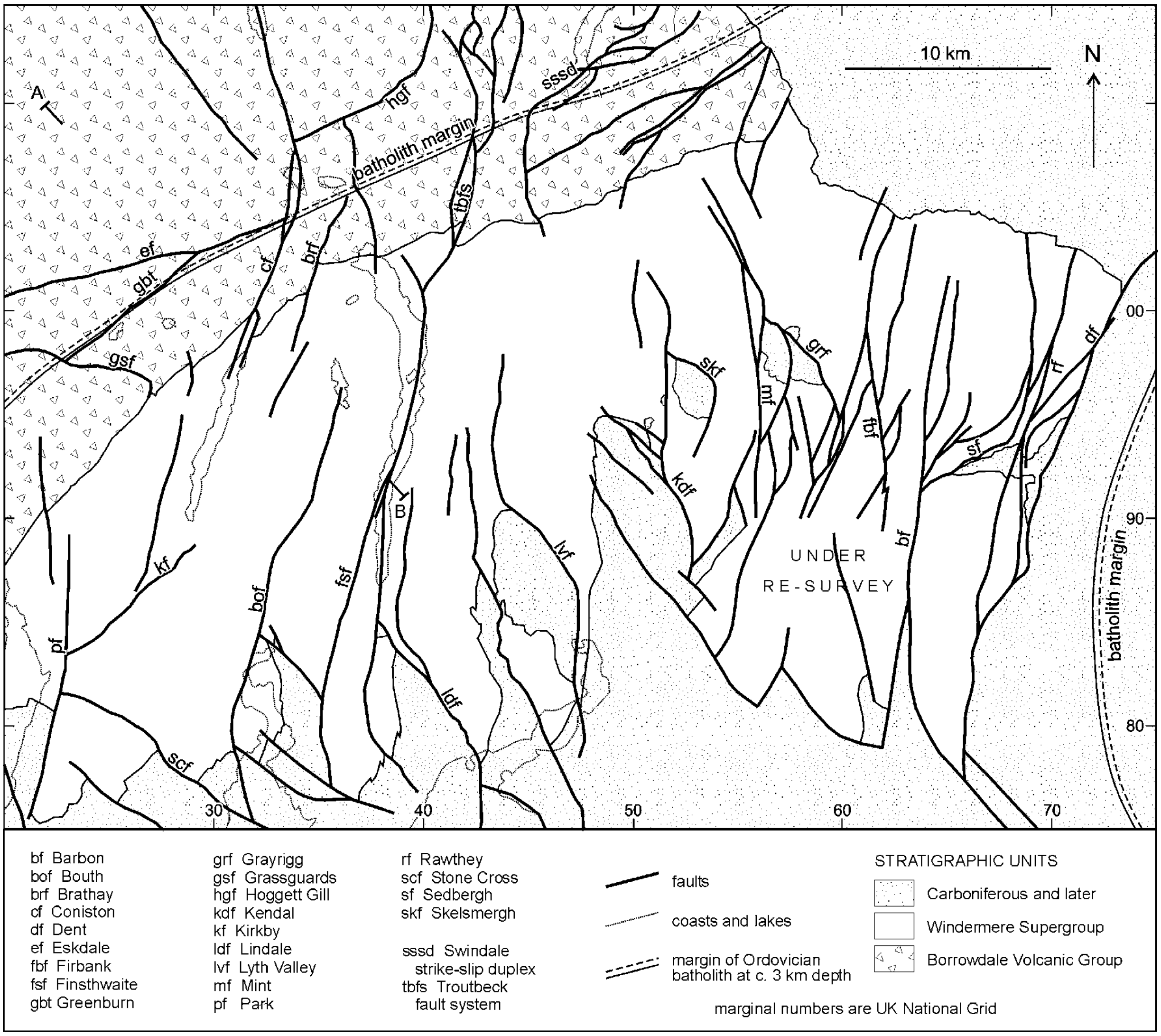

Figure 9. Simplified structural map of the southern Lake District, emphasising main faults. Based mainly of published BGS maps and author's own mapping. Map location shown on Figure 1. A–B is section line of Figure 4. Faults in Borrowdale Group after Millward (2002). Some faults in southern Lake District from data supplied by Iain Burgess (pers. comm. 2003).

Fault, then offshore into the East Irish Sea Basin (Fig. 10). The mapped faults here have conspicuous Permo-Triassic or Carboniferous displacement. However, Jackson & Mulholland (1993) and Needham & Morgan (1997) argue that the N–S fault pattern is mismatched to primary Permo-Triassic extension directions, and is instead inherited from the pre-Carboniferous subcrop. Faults with this N–S strike certainly cut Lower Palaeozoic rocks in North Wales, where Wilkinson & Smith (1988) argue their pre-Acadian ancestry. South of the Bala Fault, in Mid-Wales, NNE-striking normal faults had been operating as turbidite-basin bounding faults in sinistral transtension for much of Silurian time (e.g. Woodcock *et al.* 1996; Davies *et al.* 1997). Continued displacement on these faults into the Early Devonian is possible, though metamorphic grades suggest that only a thin cover of Lower ORS was deposited (Fig. 10).

In summary, whilst in the absence of preserved Lower ORS strata contemporaneous activity cannot be proved on any of the faults that cut Lower Palaeozoic rocks in northwest England and North Wales, many examples of the regional northerly trending group were probably present in the Silurian rocks before the Acadian, and were favourably oriented to accommodate the extensional component of Early Devonian sinistral transtension.

5.e. Provenance evidence

Provenance studies on the preserved Lower ORS of south Wales and the Welsh Borderland (Figs 2, 7) provide important evidence on the depositional setting of the formerly more extensive Anglo-Welsh basin (Allen, 1962). We have argued for its existence on the basis of metamorphic grade of Silurian slates, but

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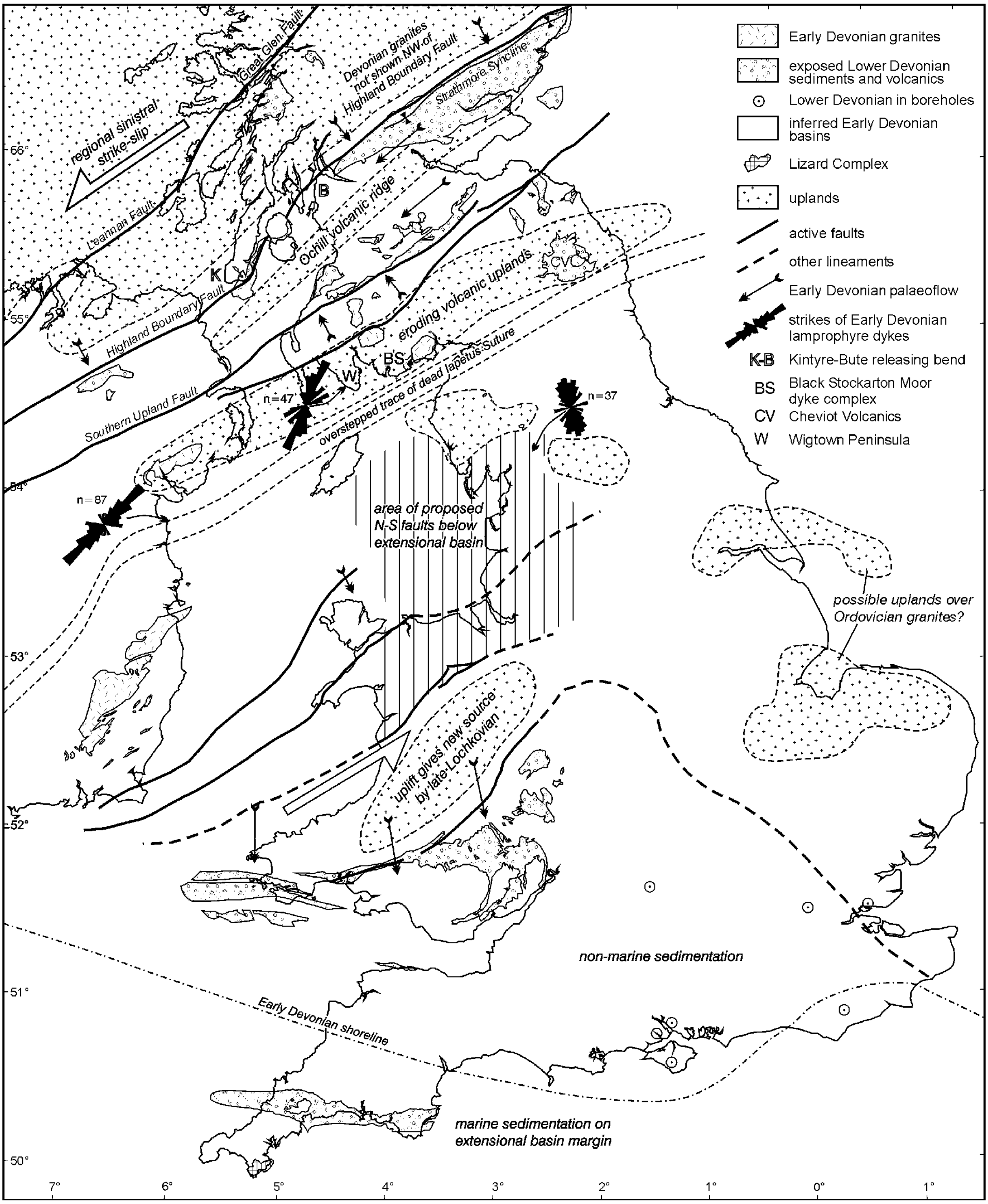

Figure 10. Palaeogeographic map for Early Devonian time, highlighting areas of outcropping and inferred thick Lower Old Red Sandstone, possible areas of uplift and erosion, and speculative drainage patterns. Modal strike of Early Devonian lamprophyre dykes are shown in selected areas; discussion and data sources in the text.

an appreciation of its former extent had already been gained by Allen (1974, 1979) from provenance and palaeoflow data.

The lower part of the Welsh Borderland succession, the Downton Group (Přídolí to lower Lochkovian), contains predominantly medium-grade metamorphic debris. Allen (1974) and Allen & Crowley (1983) inferred a continuous SE-draining fluvial basin fed by rivers carrying detritus from the eroding Caledonian uplands north of the Highland Border. This metamorphic source was cut off abruptly in early Lochkovian time and the succeeding Ditton and Abdon

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groups (Lochkovian to mid-Pragian) are dominated by igneous debris and pebbles of Lower Palaeozoic sedimentary rocks. The Woodbank Group (mid-Pragian to mid-Emsian) contains pebbles recycled from the lower part of the ORS succession. Allen (1974) explained these changes by 'Caledonian' uplift in Wales and NW England which severed the through-going fluvial system and created more local drainage patterns and source areas. The palaeogeographic maps of Bluck, Cope & Scrutton (1992, figs D1, D2) however show continuous southeasterly palaeoflow from the Highlands and Midland Valley into the Welsh Basin until the early Emsian, implausibly crossing a 'zone of transpressional convergence' along the Iapetus suture, reflecting the flexural progradation hypothesis. The composition of garnets in the Anglo-Welsh Basin precludes such a direct connection with Scotland after Lochkovian time (Haughton & Farrow, 1989).

Allen's interpretation supports the alternative concept of regional transtension in the Early Devonian. A major SE-sloping alluvial system was established at the end of the Silurian after Iapetus convergence ceased, spreading fluvial Highland detritus over the filled marine basins. The abrupt disruption of this drainage system in the early Lochkovian is less compatible with a steady southward progradation of flexure than with the onset of transtensionally driven basin subsidence and flank uplift (Fig. 10).

6. Synthesis

Below and in Figures 7 and 8 we offer a tectono-stratigraphic outline of Britain south of the Scottish Highlands. Figure 7 differs from earlier stratigraphic summaries by McKerrow (1988*a*, fig. 4) and King (1994*a*, fig. 6) in that it includes the inferred Lower Devonian cover to the Silurian slate belts, with implications for the timing of tectonic and depositional events. Detailed departures from Dewey & Strachan's (2003) model for the Scandian part of the orogen are also evident. Broadly, four discrete tectonic regimes can be recognized in southern Britain during the Silurian and Devonian.

6.a. Silurian to *c.*420 Ma: sinistrally convergent partitioned strain

Silurian Britain south of the Highland Border can be divided into four upper crustal tectonic zones reflecting the interaction of orogen-wide strike-slip with declining Iapetus convergence. Close to the surface trace of the suture, sinistrally oblique accretionary deformation of the hangingwall induced a flexural response in the footwall. Convergence slowed in the Wenlock (Kemp, 1987*b*) and ceased by the end of the Silurian. In the footwall, accelerating subsidence during the Wenlock and early Ludlow provides the best evidence for the flexural basin setting of the Windermere Supergroup (Kneller, 1991). Decelerating subsidence in the late Ludlow–Přídolí (King, 1994*a*) is compatible with termination of the flexural phase concomitantly with ending of accretionary deformation in the Southern Uplands. The convex-up pattern of subsidence is also evidenced in Craven inliers and into Denbighshire, where Wenlock stratigraphy is similar to that of the southwest Lake District (Cocks, Holland & Rickards, 1992), perhaps marking the southernmost extent of the Windermere foreland basin. The number of deeply penetrating faults in the Avalonian lithosphere probably limited its flexural rigidity and prevented further southward propagation of the flexural wave.

In the central Welsh Basin the Silurian curves become concave-up, interpreted by King (1994*a*) as indicating extension and thermal subsidence. In the context of orogen-wide sinistral strike-slip, a transtensional setting on the 'releasing' flank of the Midlands microcraton might be inferred for the Silurian Central Welsh Basin, with a degree of partitioning into narrow sub-basins due to local fault control (Woodcock *et al.* 1996).

To the north, between the Orlock Bridge and Highland Border faults, sinistral slip predominated, with local transpression and transtension controlled by pre-existing fault geometry (Smith, 1995).

6.b. Early Devonian transtension, *c.*420–400 Ma

Following the end of Iapetus convergence and locking up of the suture zone, the whole of Britain was subjected to sinistral transtension, emplacement of the regional lamprophyre suite and widespread fluvial sedimentation. An Early Devonian palaeogeography for the area of southern Britain flanking the suture is shown in Figure 10. Lower ORS sediments and volcanic rocks are widely preserved in the Midland Valley where the studies of Bluck (1984) and Haughton (1988) have established the palaeogeographic pattern shown; further south it is necessarily speculative.

A transtensional setting may be inferred for the great thickness of Lower ORS in the north-east Midland Valley, where more than 7 km of strata are preserved in the Strathmore basin (Fig. 7, col. 1; Mykura, 1991). A purely strike-slip setting, as has been suggested, is not supported by the way in which the Strathmore succession thins southwestwards towards the Kintyre–Bute releasing bend (Fig. 10). The basin fill is not first cycle 'Highland molasse'. It contains dominantly igneous and contemporary volcanic detritus, together with metamorphic clasts reworked from Silurian conglomerates that existed above the already deeply eroded Grampian terrane. More than 3 km of calc-alkaline volcanics were erupted in the Ochill area (Fig. 10), contemporaneous with volcanicity in Lorne and the Southern Uplands,

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where numerous subvolcanic intrusions are preserved.

We infer that volcanic detritus from the Southern Uplands formed a major component of the Lower ORS fluvial sediment that spread southward across the trace of the Iapetus suture into northwest England, forming the earliest post-closure overstep sequence. This was largely removed during the Acadian deformation and recycled southwards; the Peel Sandstone of the Isle of Man may represent a remnant (Piper & Crowley, 1999). The Mell Fell Conglomerate of the northeastern Lake District (Capewell, 1955), often assigned to the Lower ORS, is post-Acadian (Fig. 7, col. 7) and contains locally-derived detritus. The oldest overstepping rocks now preserved are the Cheviot volcanics; their Rb–Sr age of about 396 Ma (Thirlwall, 1988) indicates that they were erupted during the Acadian deformation. Their preservation, together with that of the Great Conglomerate (Fig. 7), of inferred Lower ORS age (Rock & Rundle, 1986), testify to the weak character of Acadian deformation in the Southern Uplands.

The extent of the Early Devonian basins in England and Wales can only be guessed at, particularly in areas where the metamorphic grade of Lower Palaeozoic rocks is unknown. The palaeogeographic map (Fig. 10) shows deposition as continuous from the southern Lake District through the East Irish Sea and at least North Wales, joining with the preserved Lower Devonian rocks of South Wales and the Welsh Borderland. However, the Ordovician granites below the Lake District and Askrigg blocks are shown as buoyant areas within or bounding the basins, and with little or no Early Devonian deposition. Similar positive areas undoubtedly existed elsewhere, perhaps above the Ordovician granites below eastern England. Barriers to long distance drainage into the Welsh Borderland must have been uplifted by later Lochkovian time. The area shown in Mid-Wales provides a local source and is compatible with metamorphic grade evidence.

The eastward extent of the Early Devonian basins is unconstrained by stratigraphic or metamorphic data as far as southern East Anglia, where crystallinity determinations suggest a substantial thickness of lost ORS (Merriman *et al.* 1993). The persistence of inherited N–S fault directions would suggest that the Devonian precursor basins were restricted to the western part of northern and central England (Fig. 10) and that the Anglian Basin might have been a separate entity. The Lower Devonian sediments this far south are assumed to have been continuous with the marginal marine then marine successions being continuously deposited on the assumed southern margin of Avalonia, and now preserved in southwest England.

6.c. Acadian Orogeny: *c.*400–390 Ma

In Britain south of the Highland Border, Early Devonian sinistral transtension was terminated by Acadian deformation, a brief episode that climaxed in the late Emsian. Transpressive shortening of the Early Palaeozoic basins flanking the Midlands Microcraton produced structural trends that were generally Caledonoid and sinistral in Wales, the Isle of Man and Lake District, arcuate in the easternmost Lake District and Ribblesdale, NW–SE and dextral in Charnwood and the subsurface Acadides of East Anglia (Fig. 2; Soper, Webb & Woodcock, 1987; Woodcock *et al.* 1988). Lower Devonian rocks overlying the Early Palaeozoic basins were also shortened, exhumed and eroded, with only those Lower ORS rocks lying on the Midland Microcraton being protected from Acadian shortening and uplift.

In the Early Palaeozoic basins the resulting slate-belt style of deformation involved ductile cleavage formation under very low metamorphic grade, generally anchizonal in Silurian slates exposed at the present surface. These conditions, about 200–300 °C and 1.0–1.5 Kbar, were induced, at least within the former flexural basin, during the preceding period of transtension. A significant cover of ORS was deposited over the filled flexural basin and the heat flux was enhanced, presumably by igneous advection. Without these changes there would have been no slates in the Lake District or North Wales; Acadian deformation would probably have been of thin-skinned style.

To the north of the slate belts, the Southern Uplands are commonly thought to have escaped Acadian deformation. However, the Moniaive shear zone, a major zone of sinistral ductile deformation that lies south of the Orlock Bridge Fault (Fig. 2) was active during emplacement of the *c.* 392 Ma Cairnsmore of Fleet granite (Phillips *et al.* 1995), and is thus in part of Acadian age. Late sinistral structures that post-date the Caledonian dykes in parts of the Southern Uplands (e.g. Barnes, 1989) may also be Acadian. An overstepping sub-Famennian unconformity is developed across southeastern Scotland (Fig. 8), testifying to post-Acadian uplift and erosion. Perhaps the Southern Uplands block transmitted Acadian stress into the Midland Valley with limited but strongly partitioned internal deformation.

The extent of Acadian deformation within the Midland Valley is controversial. Smith (1995) attributed *en echelon* folding of the Lower ORS in the southern Midland Valley to Acadian transpression, but Dewey & Strachan (2003) interpreted the Strathmore Syncline (Fig. 10) as part of a transtensional flower structure. The stratigraphical age of the syncline is post-early Emsian, pre-Famennian (Fig. 7, col. 1) and it has a substantial inverted northern limb against the Highland Boundary Fault. The evidence presented here shows that regional transtension ended by mid-Emsian time, so we would interpret the syncline as Acadian. However, we agree that the Highland Border zone may well have evolved into a complex flower structure through superimposed sinistral displacements during the Silurian and Early Devonian. Acadian movements may have produced transtension adjacent to the Kintyre–Bute releasing bend and transpression along the rectilinear Strathmore section (Fig. 10).

Displacement on the main sinistral faults in the Central Highlands was largely complete by Devonian time (Treagus, 1991). The Highland Boundary Fault may therefore mark the northern limit of significant Acadian deformation in Scotland, though reactivation of major, long-lived structures such as the Great Glen Fault cannot be ruled out.

The low-grade slate belts of southern Britain comprise only a small part of the Acadian Orogen, whose major expression is found in the Canadian maritime states. This orogeny resulted from Rheic convergence between Gondwana-derived continental terranes (Meguma, Armorica) with the previously amalgamated Laurussian continent (e.g. van Staal *et al.* 1998; Fig. 1). A fragment of the Rheic suture is thought to be preserved at the Lizard (Fig. 10), where Devonian mafic and ultramafic rocks, interpreted as an ophiolite, have been obducted northwards onto the Avalonian passive margin (Holder & Leveridge, 1986).

Recent dating has revealed a small but possibly significant mismatch between tectonic events at the Lizard and those in the slate belts to the north. The Lizard peridotite has been re-interpreted as a rift-related mantle diapir (Cook *et al.* 2000) with a possible igneous age of 397 ± 2 Ma (Clark *et al.* 1998), slightly younger than the cessation of Early Devonian transtension at *c.* 400 Ma. U–Pb zircon dating by Sandeman *et al.* (2000) and Nutman *et al.* (2001) has shown that thrust stacking of the peridotite, metamorphism and anatexis to produce the associated Kennack Gneiss took place in the period 390–377 Ma, again slightly younger than the slate belt deformation.

The significance of this mismatch, if real, is not understood. What is not in doubt is that the Acadian deformation in southern Britain was later than Iapetus closure and unrelated to it. Accepting the traditional Iapetan definition of the Caledonian Orogeny (McKerrow, MacNiocaill & Dewey, 2000), the slate belts of England and Wales are better seen as 'proto-Variscan' then 'late Caledonian'.

6.d. Post-Acadian exhumation: from *c.*390 Ma

The long break in deposition initiated by the Acadian Orogeny is reflected in the mid-Devonian (about 400–375 Ma) unconformity across Britain between the Highland Boundary Fault and southern England. During this time, much of the Lower Old Red Sandstone cover was removed and presumably deposited elsewhere as genuine Acadian molasse, though composed in part of recycled Highland metamorphic detritus. Southward recycling continued during periods of extension through later Palaeozoic and Mesozoic time (Sherlock, Jones & Kelley, 2002).

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