Chapter 1

Introduction to the Old Red Sandstone of Great Britain

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From:
Barclay, W.J., Browne, M.A.E., McMillan, A.A., Pickett, E.A., Stone, P. and Wilby, P.R. (2005) *The Old Red Sandstone of Great Britain*, Geological Conservation Review Series, No. 31, Joint Nature Conservation Committee, Peterborough, 393 pages, illustrations, A4 hardback, ISBN 1 86107 543 X
For more information see: http://www.jncc.gov.uk/page-2936

INTRODUCTION

The Old Red Sandstone is one of the two major 'red-bed' sequences of sedimentary rock in Great Britain, the other being the younger Permo–Triassic rocks that were formerly termed the 'New Red Sandstone' (see the companion GCR volume by Benton *et al*., 2002) to distinguish them from the *Old* Red Sandstone, rocks that are about 150 million years (Ma) older. In the early days of geological research in the 1830s, the Old Red Sandstone was included in the Carboniferous System, but soon after was given separate status and accorded a Devonian age, in recognition of its equivalence to the marine Devonian rocks of south Devon and Cornwall.

The GCR sites described in this volume are representative of the continental Old Red Sandstone facies in Great Britain. The rocks are mainly of what is now formally defined as Devonian age (about 418 to 362 million years (Ma) old), but according to modern definitions extend back into the Silurian Period, perhaps locally into the Wenlock Series (424 Ma). They also extend upwards into what is now defined as the early Carboniferous at less than 362 Ma (see Figure 1.4, 'Stratigraphical framework for the Old Red Sandstone', this chapter).

The Old Red Sandstone crops out principally in five areas in Great Britain (Figure 1.1), which

Figure 1.1 Simplified sketch map showing the principal Devonian outcrops of Great Britain. Marine Devonian strata are confined to south-west England, the remainder being sedimentary rocks of Old Red Sandstone facies and volcanic rocks. Caledonian (Ordovician to Late Devonian) intrusive rocks are not shown.

broadly reflect the original sedimentary basins in which they were deposited. These are:

- the Orkney and Shetland islands and north-east Scotland (the Orcadian Basin);
- the Midland Valley of Scotland (in an amalgamation of several basins of which the largest was the Strathmore Basin);
- the Scottish Borders and Northumberland (the Scottish Border Basin);
- the southern Lake District (the Mell Fell Trough); and
- south Wales, the Welsh Borderland and Bristol (the Anglo-Welsh Basin).

Figure 1.2 shows the stratigraphical distribution of the main Old Red Sandstone sequences.

Traditionally, the base of the Old Red Sandstone in the Anglo-Welsh Basin was placed at the base of the Ludlow Bone Bed, a thin, lenticular, phosphatized 'lag deposit' marking the top of the Silurian Ludlow Series. However, the international agreement at the Montreal Devonian Symposium in 1972 to define the base of the Devonian System in the fully marine, graptolite-bearing succession exposed at Klonck in the Czech Republic, at the base of the *Monograptus ultimus* Biozone (e.g. House, 1977) now places the basal parts of the Old Red Sandstone in the modern Silurian System. The strata from the Ludlow Bone Bed up to the base of the modern Devonian System, which is as yet poorly defined in the Old Red Sandstone, belong to the Přídolí Series, the fourth, uppermost series of the Silurian System (White and Lawson, 1989). The age intervals (or stages) of the Devonian Period, also defined in the *marine* rocks of Europe, are applied to the *terrestrial* Old Red Sandstone succession with some difficulty because of its absence of marine fossils.

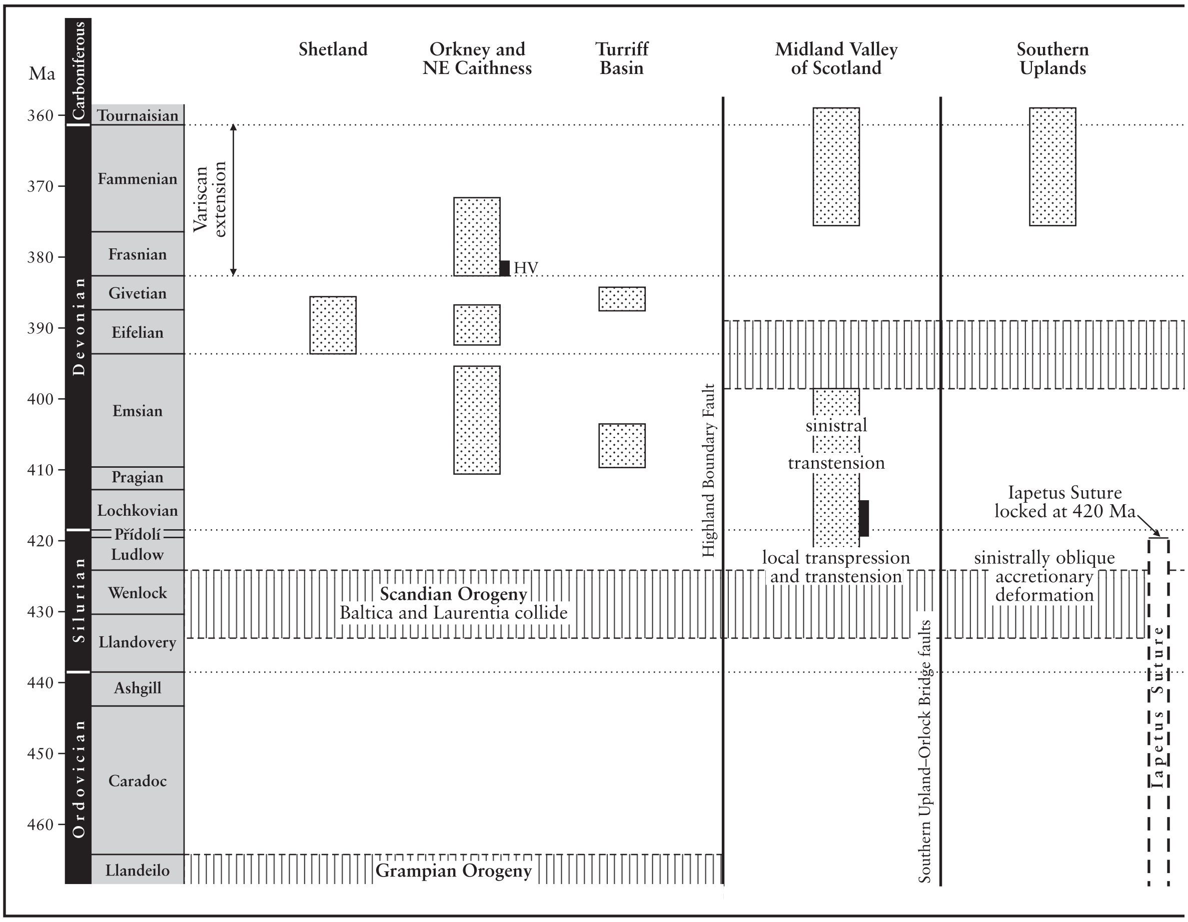


Figure 1.2 Stratigraphical distribution of the main Old Red Sandstone sequences of Great Britain. Tectonic events and their timing are from Soper and Woodcock (2003). Ages are from Williams *et al.* (2000). Small solid bars indicate the principal volcanic rocks. Individual chapter introductions provide more detailed stratigraphical distribution charts. (HV – Hoy Volcanic Member; MF – Mell Fell Conglomerate Formation; RC – Ridgeway Conglomerate Formation.)

GCR SITE SELECTION

The selection of Geological Conservation Review (GCR) sites described in this volume was carried out in the 1980s and 1990s, following the criteria set out in Ellis *et al*. (1996). The main reasons for qualification of a site for a particular GCR site selection category are:

- international importance – for example, the site may be important because it is a type locality for a geological time period, rock unit or fossil species, or is of historical importance in the development of geological science;
- possession of unique or exceptional geological features;
- national importance because a site is representative of a feature, event, process or rock body that is fundamental to the understanding of the geological history of Great Britain.

SCOPE

The GCR sites were selected according to thematic GCR 'Blocks', the present volume describing the 'Non-marine Devonian' GCR Block, which consists of 64 ratified GCR sites, together with a small number of potential GCR sites. The site descriptions are arranged geographically, from north to south, in areas that correspond to the original depositional basins. The sites are listed in Table 1.1, together with the principal criteria for their selection. Many of the sites have features that satisfy several selection criteria. Furthermore, there are numerous Old Red Sandstone sites that have been independently selected for other GCR palaeontological 'Blocks'. These sites are described in the companion GCR volumes on fossil fishes (Table 1.2; Dineley and Metcalf, 1999) and Palaeozoic palaeobotany (Table 1.3; Cleal and Thomas, 1995).

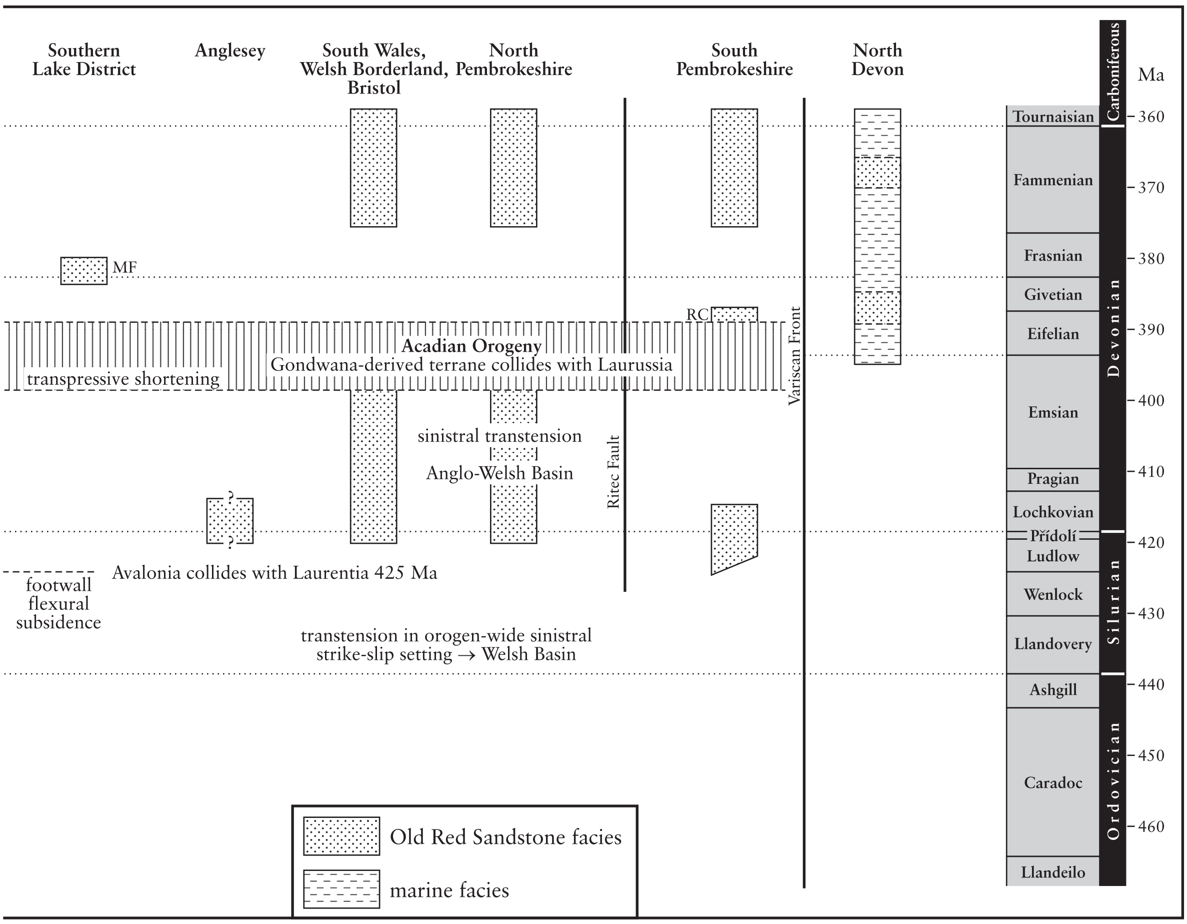


Table 1.1 GCR Old Red Sandstone sites and proposed sites, with main criteria for their selection. Continued on page 7.

Site	Age	Selection criteria
Orcadian Basin		
Easter Rova Head	Mid-Devonian	Spectacular sea-cliff exposures of conglomerates.
Footabrough to Wick of Watsness	Mid-Devonian	Continuous sea-cliff exposures of Walls Formation.
The Cletts, Exnaboe	Mid-Devonian	Continuous sea-cliff exposures of cyclic lacustrine, fluvial and aeolian facies of the Brindister Flagstone Formation. Also a fossil fish GCR site.
Melby: Matta Taing to Lang Rigg (P)	Mid-Devonian	Fossil fish GCR site. Spectacular sea-cliff and foreshore exposures of lacustrine Melby Formation.
South Stromness Coast Section	Mid-Devonian	Best section in Orkney through the Caithness Flagstone Group.
Taracliff Bay to Newark Bay	Mid-Devonian	Thickest, best-exposed section of the Eday Group.
Greenan Nev Coast, Eday	Mid-Devonian	Best section through the Eday Marl Formation in Orkney.
South Fersness Bay, Eday	Mid-Devonian	Well-exposed, accessible section of the Eday Group.
Yesnaby and Gaulton Coast Section	Early Devonian	Superb sea-cliff sections of the Yesnaby Sandstone Group, including unique aeolian facies. Also sections in the Lower Stromness Flagstone Formation containing the best stromatolites in the Orcadian Basin.
Old Man of Hoy Coast	Late Devonian	Spectacular sea cliffs of the Hoy Sandstone Formation, including the Hoy Volcanic Member.
Bay of Berstane (P)	Mid-Devonian	Unique onshore evidence of marine-influenced deposition in the Middle Devonian Eday Marl Formation.
Red Point	Mid-Devonian	Spectacular lake-margin deposits and basement-cover topography.
Pennyland (Thurso–Scrabster)	Mid-Devonian	Well-exposed lacustrine cycles of the Orcadian lake (Upper Caithness Flagstone Group). Also a fossil fish GCR site.
John o'Groats (P)	Mid-Devonian	Fossil fish GCR site. Type locality of John o'Groats Sandstone Group.
Wick Quarries	Mid-Devonian	Spectacular exposures of fish-bearing lake deposits and shrinkage cracks in the Lower Caithness Flagstone Group in an otherwise poorly exposed part of the Orcadian Basin.
Achanarras Quarry (P)	Mid-Devonian	Fossil fish GCR site, the richest locality in Great Britain. Type locality of Achanarras Limestone Member (Fish Bed), of importance regionally as a marker horizon between the Lower Caithness Flagstone Group and Upper Caithness Flagstone Group.
Sarclet (P)	Early Devonian	Sea-cliff sections in the Lower Devonian Sarclet Group.
Tarbat Ness	Mid-Devonian and Late Devonian	Complete section of the Balnagown Group and of the apparently conformable junction with the Strath Rory Group.
Loch Duntelchaig (Dun Chia Hill)	Mid-Devonian	Dramatic exposure of Middle Old Red Sandstone conglomerates resting unconformably on Dalradian metasedimentary rocks and late Caledonian granites in the south-west of the Orcadian Basin.
Tynet Burn (P)	Mid-Devonian	Fossil fish GCR site. Classic fossil fish locality yielding whole, well-preserved specimens, and important evidence on the nature of the southern margin of the Orcadian Basin at the time of maximum (Achanarras) lake extent.
Den of Findon, Gamrie Bay and New Aberdour (P)	Mid-Devonian (also Early Devonian)	Fossil fish GCR site, with superb coast sections at Gamrie Bay, Pennan (Lower ORS–Middle ORS unconformity), New Aberdour and Quarry Haven.
Rhynie (P)	Early Devonian	Fossil plant GCR site. World renowned floral and arthropod lagerstätte. Exceptional preservation in a hydrothermal spring deposit.
Midland Valley of Scotland and adjacent areas		
The Toutties (P)	Mid-Silurian	Fossil fish GCR site. Oldest (Mid-Silurian) Old Red Sandstone facies in Scotland containing fish and important arthropod fauna.
Dunnottar Coast Section (P)	Mid-Silurian–Early Devonian	Magnificent exposures in dramatic sea cliffs of conglomerates and sandstones.
Crawton Bay	Late Silurian–Early Devonian	Fine coastal sections of conglomerates and volcanics. Also a Caledonian igneous rocks GCR site
North Esk River	late Early Devonian	Best sections of the Strathmore Group
Milton Ness (P)	Late Devonian–Early Carboniferous	Sea cliffs exposing one of the best sections of mature calcrete development in Scotland in the Kinnesswood Formation.
Aberlemno Quarry (P)	Early Devonian	Fossil fish and Palaeozoic palaeobotany GCR site. Also important for arthropod fossils. Important for Dundee Flagstone and Scone Sandstone formations.
Tillywhandland Quarry (P)	Early Devonian	Fossil fish GCR site. Unique lacustrine facies in the Midland Valley of Scotland in the Dundee Flagstone Formation containing fish, arthropods and trace fossils.
Whiting Ness	Early and Late Devonian	Sea cliffs exposing Early Devonian sandstones unconformably overlain by Late Devonian sandstones, the units being separated by a spectacular unconformity.

Table 1.1 – *continued*.

Site	Age	Selection criteria
Tay Bank	Early Devonian	Type locality of the Campsie Limestone Member, including the Stanley Limestone, representing mature calcrete development and providing an important stratigraphical marker horizon.
Glen Vale (P)	Late Devonian	Important sandstones (the Knox Pulpit Sandstone Formation) of aeolian origin.
Wolf's Hole Quarry (P)	Early Devonian	Fossil fish GCR site exposing the highest lava on the southern side of the Strathmore Basin.
Auchensail Quarry (P)	Early Devonian	Fossil plant GCR site yielding a well-preserved assemblage of land plants in the Teith Sandstone Formation.
Siccar Point to Hawk's Heugh (E)	Late Devonian–Early Carboniferous	Classic section at Siccar Point (Hutton's Unconformity). Fossil fish GCR site at Hawk's Heugh. Proposed extension to include the intervening superb sections of fluvial and ?aeolian sandstones at Pease Bay.
Largs Coast, Ayrshire	Late Devonian	Important coastal exposures in sandstones illustrating fluvial, braided river sandbody morphologies.
North Newton Shore, Arran	Late Devonian	One of the three classic Old Red Sandstone unconformities recognized by James Hutton.
Southern Scotland and the Lake District		
Palmers Hill Rail Cutting	Late Devonian	Exposures of calcrete in the Scottish Border Basin.
Pooley Bridge	Early Devonian	Best section of Old Red Sandstone facies conglomerates in north-west England.
Anglo-Welsh Basin		
Porth-y-Mor	Early Devonian	One of the best, most accessible Old Red Sandstone sections in the Anglo-Welsh Basin.
Devil's Hole (P)	Late Silurian–Early Devonian	Historically important fossil fish GCR site, with important 'Downtonian'–'Dittonian' boundary exposure.
Oak Dingle, Tugford (P)	Early Devonian	Fossil fish GCR site with well-documented sedimentological analysis.
The Scar	Late Silurian	Good inland exposure of the Raglan Mudstone Formation.
Cusop Dingle (P)	Late Silurian–Early Devonian	Best, most complete inland section through topmost Přídolí and lowermost Devonian strata.
Sawdde Gorge (E)	Late Silurian–Early Devonian	Proposed extension of GCR site to include higher Přídolí and basal Devonian strata.
Pantymaes Quarry (P)	Early Devonian	Excellent exposure of Lochkovian channel sandstones and floodplain mudstone facies, internationally known for its arthropod trackways.
Heol Senni Quarry	Early Devonian	GCR fossil fish site. Also representative of the Senni Formation.
Caeras Quarry	Early Devonian	Best exposure of local pebbly facies in the Brownstones Formation.
Craig-y-Fro Quarry (P)	Early Devonian	Classic fossil plant GCR site. Also important for exposure of the Senni Formation.
Abercriban Quarries	Late Devonian–Early Carboniferous	Type locality of the Grey Grits Formation.
Afon y Waen (P)	Late Devonian	Potential fossil fish GCR site. Also important for exposure of the Plateau Beds Formation.
Duffryn Crawnon (P)	Late Devonian	Type locality of the Plateau Beds Formation, including possible aeolian facies.
Craig-y-cwm (P)	Late Devonian–Early Carboniferous	Representative section of the Quartz Conglomerate Group.
Ross-on-Wye, Royal Hotel	Early Devonian	Excellent, well-documented, accessible section of the Brownstones Formation.
Wilderness (Land Grove) Quarry	Early Devonian	Fossil fish GCR site with superb exposure of the lowermost strata of the Brownstones Formation.
Lydney	Late Silurian–Early Devonian	Fossil fish GCR site with good section of the Psammosteus Limestone horizon.
Albion Sands and Gateholm Island (P)	Late Silurian–Early Devonian	Magnificent sea-cliff and foreshore exposures of Wenlock marine strata and the overlying Old Red Sandstone.
Little Castle Head (P)	Late Silurian–Early Devonian	Reference section of the Přídolí Sandy Haven Formation and of the Townsend Tuff Bed.
West Angle Bay (North)	Late Silurian–Early Carboniferous	Continuous section of the entire Old Red Sandstone succession and of the underlying and overlying strata.
Freshwater West (P)	Late Silurian–Early Carboniferous	Superb, accessible dip section exposing the entire Old Red Sandstone succession.
Freshwater East–Skrinkle Haven ('Tenby Cliffs')	Late Silurian–Early Carboniferous	Excellent strike section of the entire Old Red Sandstone succession.
Llansteffan	Late Silurian–Early Devonian	Superb exposures of stacked carbonate palaeosols of the Chapel Point Calcretes Member (Psammosteus Limestone).
Portishead	Early and Late Devonian	Best section of the Old Red Sandstone succession east of Severn Estuary.
Glenthorne	Mid-Devonian	Best section of Old Red Sandstone facies south of the Bristol Channel.

P Potential site (most of these sites are confirmed GCR sites for their palaeontology)
E Proposed extension to site

Table 1.2 GCR sites in the Old Red Sandstone described in the fossil fishes GCR volume. After Dineley and Metcalf (1999). Continued on page 9.

Site	Stratigraphy	Criterion	Treatment in this volume Full description FD Summary description SD Not described ND
Orcadian Basin			
Westerdale Quarry	Mid-Devonian; Eifelian	One of oldest fish-bearing horizons in Orcadian Basin; complete specimens	ND
Achanarras Quarry	Mid-Devonian; Eifelian–Givetian boundary	Richest Old Red Sandstone fish site in Britain	FD
Cruaday Quarry	Mid-Devonian; Eifelian–Givetian boundary*	Best Old Red Sandstone fish site in Orkney	ND
Black Park, Edderton	Mid-Devonian; Eifelian–Givetian boundary*	Fish well preserved in three dimensions	ND
Den of Findon, Gamrie	Mid-Devonian; Eifelian–Givetian boundary*	Prolific fish fauna	SD
Tynet Burn, Elgin	Mid-Devonian*	Rich fish fauna and historically important	FD
Melby	Mid-Devonian; Eifelian–Givetian boundary*	Northernmost occurrence of Achanarras horizon	FD
Papa Stour	Mid-Devonian; Eifelian–Givetian boundary*	Fish in sedimentary rocks in predominantly volcanic sequence	ND
Dipple Brae	Mid-Devonian	Fish fauna younger than that of the Achanarras horizon	ND
Spittal Quarry	Mid-Devonian	Rare fish fauna, including only Mid-Devonian cephalaspid	ND
Banniskirk Quarry	Mid-Devonian	First ORS site to yield fishes	ND
Holborn Head Quarry	Mid-Devonian; mid-Givetian	10–11 fish species, including *Osteolepis panderi*	ND
Weydale Quarry	Mid-Devonian	Well-preserved *Osteolepis panderi* and *Dipterus valenciennesi*	ND
Pennyland	Mid-Devonian; Givetian	Many fish specimens from several fish-bearing horizons	FD
John o'Groats	Mid-Devonian; late Givetian	Youngest fish fauna in Caithness	SD
The Cletts, Exnaboe	Mid-Devonian; late Givetian	Northernmost late Givetian fish site	FD
Sumburgh Head	Late Mid-Devonian; late Givetian	Possibly youngest fish fauna of the Orcadian Basin	ND
Midland Valley of Scotland			
The Toutties	Late Wenlock	Oldest Old Red Sandstone facies rocks in Scotland; unique fish fauna	FD
Tillywhandland Quarry	Early Devonian	One of best Early Devonian fish sites in Scotland	FD
Aberlemno Quarry	Early Devonian	Best surviving of the famous Turin Hill fish sites; also a fossil plant GCR site (Table 1.3)	FD
Wolf's Hole Quarry	Early Devonian	Unique pteraspid fish fauna	FD
Whitehouse Den	Early Devonian	Fossil acanthodian fish	ND
Grampian Highlands			
Ardmore–Gallanach	Late Silurian–Early Devonian	Unique early fish fauna in sediments associated with Lorne lavas	ND
Bogmore, Muckle Burn	Earliest Late Devonian (Frasnian)	Diverse fish fauna with over 15 species	ND
Scaat Craig	Late Devonian	Diverse late Devonian fish fauna and a distinctive tetrapod	ND

* Achannaras Fish Bed horizon

Table 1.2 – *continued*.

Site	**Stratigraphy**	**Criterion**	**Treatment in this volume** Full description FD Summary description SD Not described ND
Southern Uplands			
Oxendean Burn	Late Devonian	Abundant fragments of *Bothriolepis*	ND
Hawk's Heugh	Late Devonian	Only British occurrence of *Remigolepis*	FD
Anglo-Welsh Basin			
Ludford Lane and Ludford Corner	Silurian; Přídolí	Internationally renowned for rich fish fauna; see also Table 1.4	ND
Ledbury cutting	Silurian; Přídolí	Historical site yielding complete specimens of *Auchenaspis* and *Hemicyclaspis*	ND
Temeside, Ludlow	Silurian; Přídolí	Historical site in Temeside Mudstone Formation yielding a rich fish fauna including *Hemicyclaspis murchisoni*	ND
Tite's Point (Purton Passage)	Silurian; Ludlow–Přídolí	*Thelodus parvidens* fish fauna, allowing correlation with Ludlow Bone Bed, and source of *Cyathaspis*	
Lydney	Late Přídolí–Early Devonian	Sequence of vertebrate faunas, including specimens of *Sabrinacanthus*	FD
Downton Castle area (network of 4 sites)	Early Přídolí	Several quarries in Downton Castle Sandstone yielding vertebrate remains	ND
Bradnor Hill Quarry	Late Přídolí	Late Přídolí thelodont fauna	ND
Devil's Hole	Přídolí–Lochkovian	Fish fauna straddling Downtonian–Dittonian boundary	SD
Oak Dingle, Tugford	Lochkovian (Dittonian)	Near-strike section of fish-bearing beds; earliest record of *Weigeltaspis*	SD
Cwm Mill	Lochkovian (Dittonian)	Unique preservation of complete cephalaspids, including three new species; also specimens of *Rhinopteraspis crouchi*	ND
Wayne Herbert Quarry	Lochkovian (Dittonian)	Well-preserved, diverse fish fauna	ND
Besom Farm Quarry	Lochkovian (Dittonian)	Rich, diverse fish fauna, including 7 type specimens and sole occurrence of 5 of them	ND
Heol Senni Quarry	Lochkovian–Pragian	Only occurrence of *Althaspis senniensis*	FD
Portishead	Late Devonian	Unique fish fauna, including only British occurrence of *Groenlandaspis*	FD
Prescott Corner	Late Devonian (Frasnian)	Extensive Late Devonian fish fauna	ND
Afon y Waen	Late Devonian	*Bothriolepis* and *Holoptychius* in Upper Old Red Sandstone	FD

Table 1.3 GCR sites in the Old Red Sandstone described in the Palaeozoic palaeobotany GCR volume. After Cleal and Thomas (1995).

Site	Stratigraphy	Criterion	Treatment in this volume Full description FD Summary description SD Not described ND
Orcadian Basin			
Sloagar	Mid-Devonian; Late Givetian	Only occurrence of *Svalbardia* in Britain	ND
Bay of Skaill	Mid-Devonian	Important floral assemblage in Sandwick Fish Bed; type locality of *Protopteridium thomsonii*	ND
Rhynie	Early Devonian	Renowned Devonian palaeobotanical site; 22 species unique to this site	FD
Midland Valley of Scotland			
Turin Hill	Early Devonian	Best example of *Zosterophyllum* Zone flora in world and type locality of *Cooksonia caledonica*	FD (as 'Aberlemno Quarry')
Ballanucater Farm	Early Devonian; Emsian	Best Emsian floral assemblage in Britain	ND
Auchensail Quarry	Early Devonian; Emsian	Well-preserved Emsian floral assemblage	FD
Anglo-Welsh Basin			
Targrove Quarry	Early Devonian; Gedinnian	Most diverse rhyniophytoid plant assemblage in world	ND
Capel Horeb Quarry	Late Silurian; Ludfordian–Přídolí	Oldest vascular plants in world in Ludlow Series; Long Quarry Formation yielded some rhyniophytoids including *Cooksonia*	ND
Perton Lane	Late Silurian; Přídolí	Classic locality and type locality of *Cooksonia*	ND
Freshwater East	Late Silurian; Přídolí	Most diverse Silurian flora in the world	FD
Llanover Quarry	Early Devonian; Siegenian	Classic locality yielding one of most diverse *Psilophyton* Zone flora in Britain	ND
Craig-y-Fro Quarry	Early Devonian	Some of best preserved Devonian plants in Britain; locality second only to the Rhynie site in Britain	SD

The GCR sites provide representative localities for the entire stratigraphical range of the Old Red Sandstone. The initial selection of GCR sites for the 'Non-marine Devonian' GCR Block included sites in the Anglo-Welsh Basin in strata that extended down from the base of the Devonian System to the Ludlow Bone Bed. These strata, comprising the Downton Group (the former Downtonian Stage), are of Silurian (Přídolí Series) age and the sites (Table 1.4) are described in the GCR volume on Silurian stratigraphy (Aldridge *et al*., 2000). The GCR volume on Caledonian igneous rocks (Stephenson *et al*., 1999) includes sites (Table 1.5) in which Old Red Sandstone strata are present in addition to the contemporaneous igneous rocks for which they are cited. All of the Old Red Sandstone sites described in the other GCR volumes are listed in Tables 1.2, 1.3, 1.4 and 1.5, along with the level of detail in which they are described in the present volume. Only some of these 'overlapping' sites are given full descriptions in the present volume, which emphasizes the sedimentological and lithostratigraphical features. The **Freshwater West** potential Old Red Sandstone GCR site, and part of the **Freshwater East–Skrinkle Haven** GCR site are also Variscan to Alpine structures GCR sites.

Table 1.4 GCR sites in the Old Red Sandstone described in the Silurian stratigraphy GCR volume. After Aldridge *et al*. (2000).

Site	Stratigraphy	Criterion	Treatment in this volume Full description FD Summary description SD Not described ND
Anglo-Welsh Basin			
Marloes	Wenlock–Přídolí	Classic site showing early transition from marine to Old Red Sandstone facies	ND (included with report for Albion Sands and Gateholm Island)
Albion Sands and Gateholm Island	Ludlow–Přídolí–Lochkovian	Complete, conformable succession from Ludlow into early Devonian	SD
Freshwater East (South)	Wenlock–Přídolí	Wenlock marine strata overlain by Old Red Sandstone; faulted/ unconformable relationship	ND
Ludford Lane and Ludford Corner	Ludlow–Přídolí	Classic, internationally renowned site traditionally regarded as reference section for Silurian–Devonian boundary; earliest known land animals, early plants (see Table 1.3), unusual arthropods and fish remains in Ludlow Bone Bed	ND
Brewin's Bridge/Canal	Ludlow–Přídolí–Carboniferous	One of few sites in central England exposing marine Silurian–Old Red Sandstone junction, including Ludlow Bone Bed	ND
Capel Horeb Quarry	Ludlow–Přídolí	Good section of unconformity between Ludlow and Přídolí; internationally important plant site (Table 1.3)	ND
Little Castle Head	Přídolí	Old Red Sandstone facies rocks; Townsend Tuff Bed	SD
Lower Wallop Quarry	Ludlow–Přídolí	Marine to Old Red Sandstone transition later here, well into Přídolí	ND

Site selection is inevitably subjective, but the aim of the GCR is to identify the minimum number and area of sites needed to demonstrate the current understanding of the diversity and range of features within each GCR 'Block'. The preferred sites are generally those that are least vulnerable to the potential threat of destruction, are more accessible and are not duplicated elsewhere (Ellis *et al*., 1996). The original selection of sites was made over 20 years ago, and all of these sites are included in this volume. In addition, a small number of sites were identified during the course of the compilation of the volume as representing stratigraphical units or unique features not included in the original GCR site selection, and are described as 'potential' GCR sites.

HISTORY OF RESEARCH

The name 'Old Red Sandstone' appears to have been first applied to the red rocks below the Mountain (Carboniferous) Limestone in the mistaken belief that they were the equivalents of the Permian Rotliegendes of Germany (Jameson, 1821; Simpson, 1959). It was initially mapped and named in southern Wales and the Welsh Borderland (Phillips, 1818; Conybeare and Phillips, 1822) and included as the lowermost part of the Carboniferous System. Murchison was the first to champion the Old Red Sandstone as a separate geological entity. According to Miller's account (1841), a visiting foreign geologist advised Murchison that 'you must inevitably give up the Old Red Sandstone:

Table 1.5 GCR sites with Old Red Sandstone sedimentary rocks described in the Caledonian igneous rocks volume. After Stephenson *et al*. (1999).

Site	Stratigraphy/ radiometric age	GCR selection criteria
Eshaness Coast	Mid-Devonian	Representative of Eifelian Eshaness volcanic succession, NW Shetland.
Ness of Clousta to the Brigs	Mid-Devonian	Representative of Givetian Clousta volcanic rocks, Walls, Shetland.
Point of Ayre	Mid-Devonian	Representative of Givetian Deerness Volcanic Member, mainland Orkney.
Too of the Head	Mid-Devonian	Representative of Givetian Hoy Volcanic Formation, Isle of Hoy, Orkney.
South Kerrera	Late Silurian to Early Devonian	Representative of Lorn Plateau Volcanic Formation. Exceptional examples of subaerial lava features and interaction of magma with wet sediment.
Ben Nevis and Allt a'Mhuilinn	Mid-Silurian 425 Ma	Representative of Ben Nevis Volcanic Formation. Exceptional intrusive tuffs. Internationally important as example of exhumed root of caldera, and historically for development of cauldron subsidence theory.
Stob Dearg and Cam Ghleann	Mid-Lochkovian 421 ± 4Ma	Representative of succession in eastern part of Glencoe caldera, including basal sedimentary rocks. Exceptional rhyolites, ignimbrites and intra-caldera sediments. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian–Devonian boundary.
Crawton Bay*	Late Silurian–Early Devonian	Representative of Crawton Volcanic Formation.
Scurdie Ness to Usan Harbour	Early Devonian	Representative of 'Ferrydean' lavas and 'Usan' lavas, comprising lower part of Montrose Volcanic Formation.
Black Rock to East Comb	Early Devonian	Representative of 'Ethie' lavas, comprising upper part of Montrose Volcanic Formation.
Balmerino to Wormit	Early Devonian (Lochkovian) 410.6 ± 5.6 Ma	Representative of eastern succession of Ochil Volcanic Formation. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian–Devonian boundary.
Sheriffmuir Road to Menstrie Burn	Early Devonian 416 ± 6.1 Ma	Representative of western succession of Ochil Volcanic Formation. Exceptional topographic expression of Ochil fault-scarp.
Tillycoultrie	Early Devonian 415–410 Ma	Representative of diorite stocks, intruded into Ochil Volcanic Formation, surrounded by thermal aureole and cut by radial dyke swarm. Exceptional examples of diffuse contacts due to metasomatism and contamination, with 'ghost' features inherited from country rock.
Port Schuchan to Dunure Castle	Early Devonian	Representative of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Culzean Harbour	Early Devonian	Representative of inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Turnberry Lighthouse to Port Murray	Early Devonian	Representative of most southerly inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Pettico Wick to St Abb's Harbour	Early Devonian *c*. 400+ Ma	Representative of volcanic rocks in the SE of the Southern Uplands. Exceptional vent agglomerates, block lavas, flow tops and interflow high-energy volcaniclastic sediments.

* described in this volume

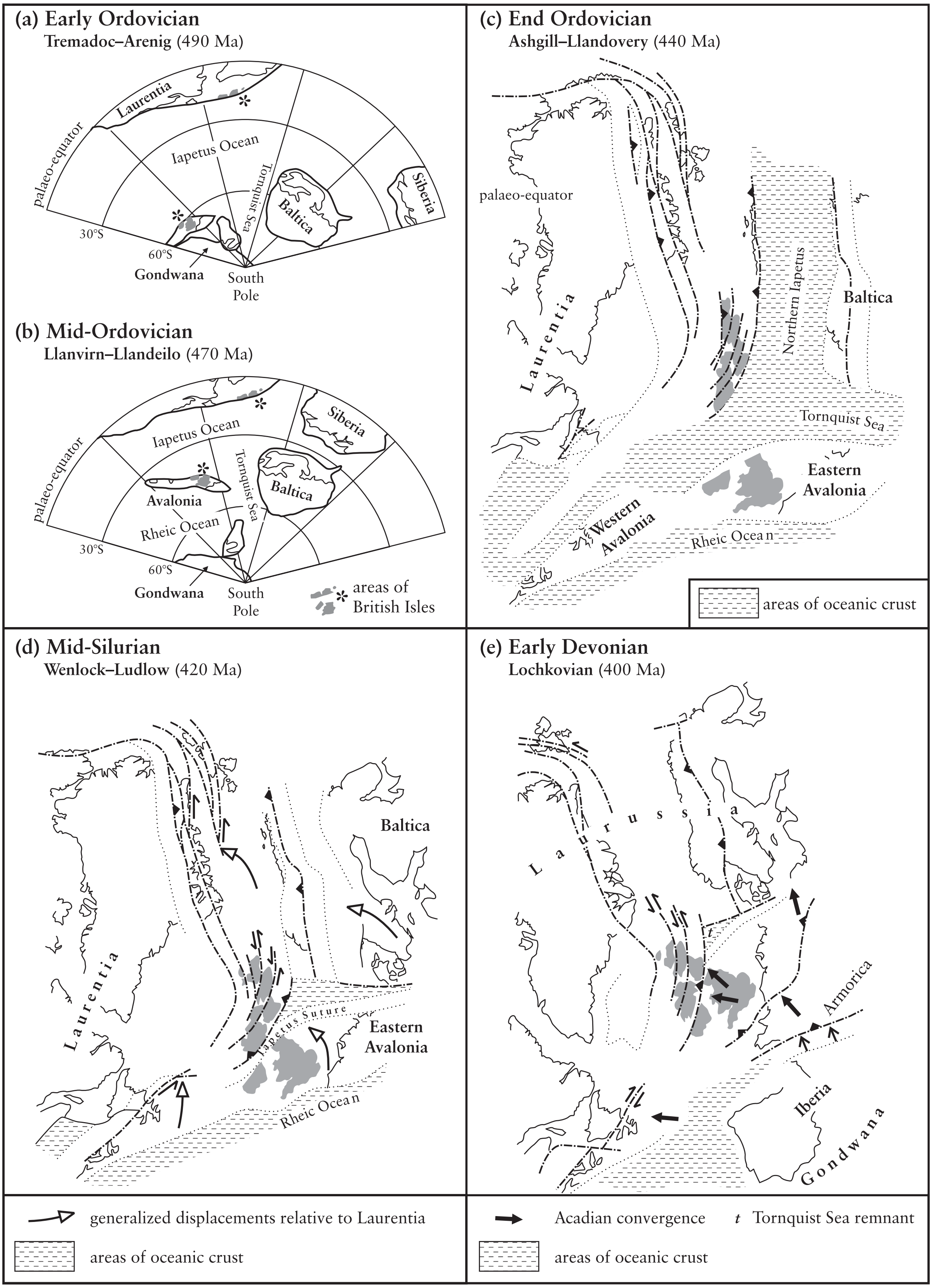
it is a mere local deposit, a doubtful accumulation huddled up in a corner, and has no type or representative abroad.'

'I would willingly give it up if Nature would,' replied Murchison, 'but it assuredly exists, and I cannot'. Compared to the richly fossiliferous rocks of the Silurian System below and the Carboniferous System above, the Old Red Sandstone seemed relatively barren to the early Victorian workers, but as the remains of early fishes were discovered, first in Scotland by the young Swiss naturalist Louis Agassiz, and later in south Wales and the Welsh Borderland, interest gradually increased.

The Devonian System was established by Sedgwick and Murchison (1839) for the pre-Carboniferous marine rocks of Devon. These rocks were readily correlated with the Rhenish nearshore rocks and the Bohemian deep-water rocks of mainland Europe (House, 1977). With the recognition of large tracts of Old Red Sandstone in North America, Norway, Siberia, Poland and Russia (the last containing many of the same fish species as Great Britain), the strata assumed a new importance (Geikie, 1879). At the same time, Murchison (1839), impressed by the great thickness of Old Red Sandstone strata in the Welsh Borderland, and the difference between them and the overlying Carboniferous rocks, with which they had hitherto been merged, applied the status of 'system' to the Old Red Sandstone. This situation held, in the UK at least, for over 130 years, with the term used in a quasi-chronostratigraphical sense for rocks of continental facies and Devonian age. However, with the advent of more precise stratigraphical procedures and classification, and, in 1972, the new definition of the base of the Devonian System at a higher level, equivalent to a horizon within the Old Red Sandstone (see below), the term is now no longer used in a quasi-chronostratigraphical sense. Biostratigraphers tend not to use the term at all; the glossary in the companion GCR volume on Silurian stratigraphy, for example (Aldridge *et al*., 2000), defines the Old Red Sandstone as 'a classic term still applied to the terrestrial, largely clastic facies of the late Silurian to earliest Carboniferous in Britain'. Sedimentologists retain the name as a facies (or magnafacies) term for all the terrestrial red beds and lacustrine deposits of Silurian to early Carboniferous (but predominantly Devonian) age (e.g. Friend and Williams, 2000). The term 'Old Red Sandstone' is also applied in an informal lithostratigraphical sense. The three subdivisions of the Old Red Sandstone recognized by Murchison – Lower, Middle and Upper – are similarly retained as informal, but long-established lithostratigraphical terms onshore in the United Kingdom and as formal groups offshore in the North Sea.

OLD RED SANDSTONE PALAEOGEOGRAPHY

The Old Red Sandstone represents a period when ocean closure and continental collisions resulted in a world geography vastly different to that of much of early Palaeozoic times. The drift of the early Palaeozoic continents and their relative positions can be estimated from the correlation of geological successions and their faunas, with palaeomagnetism providing data on palaeolatitudes. The Iapetus Ocean, which separated the northern (Laurentian) and southern (Gondwanan) continents, closed throughout the Ordovician and Silurian periods as the smaller continent of Avalonia fragmented from Gondwana and drifted northwards (Figure 1.3). As the Iapetus Ocean closed north of Avalonia, the Rheic Ocean opened behind it. To the east, the continent of Baltica also drifted northwards and eastwards and the Tornquist Sea, an arm of the Iapetus Ocean, slowly closed. The timing and nature of the convergence of the three components that were to make up the Old Red Sandstone continent remain matters of debate. Trench and Torsvik (1992) considered that Baltica and the eastern part of the Avalonia microcontinent collided first, in late Ordovician times, moving northwards together to make first contact with Laurentia by late Silurian time at about 420 Ma (Torsvik *et al*., 1996; see Dewey and Strachan, 2003, fig. 1). However, Dewey and Strachan (2003) interpret the Scandian Orogeny as the result of collision, by sinistral transpression, of Baltica and Laurentia from about 435 Ma to 425 Ma, with a soft collision between Avalonia and Laurentia/Baltica (Laurussia) at about 425 Ma (Soper and Woodcock, 2003). By late Silurian (Ludlow) time, the continents had fully docked, with the Iapetus Ocean closed along the


(a) Early Ordovician
Tremadoc–Arenig (490 Ma)
Laurentia
Iapetus Ocean
palaeo-equator
Tornquist Sea
Baltica
Siberia
30°S
60°S
Gondwana
South Pole
(b) Mid-Ordovician
Llanvirn–Llandeilo (470 Ma)
Iapetus Ocean
Siberia
palaeo-equator
Tornquist Sea
Baltica
Avalonia
Rheic Ocean
30°S
60°S
Gondwana
South Pole
areas of British Isles
(c) End Ordovician
Ashgill–Llandovery (440 Ma)
palaeo-equator
Laurentia
Northern Iapetus
Baltica
Tornquist Sea
Eastern Avalonia
Western Avalonia
Rheic Ocean
areas of oceanic crust
(d) Mid-Silurian
Wenlock–Ludlow (420 Ma)
Baltica
Laurentia
Iapetus Suture
Eastern Avalonia
Rheic Ocean
generalized displacements relative to Laurentia
areas of oceanic crust
(e) Early Devonian
Lochkovian (400 Ma)
Laurussia
Armorica
Iberia
Gondwana
Acadian convergence
t Tornquist Sea remnant
areas of oceanic crust

◂**Figure 1.3** Sketch maps showing the movements and amalgamation of the early Palaeozoic continents that produced the Old Red Sandstone (Laurussia) continent. (a) and (b) are global views to illustrate the fragmentation of Avalonia from Gondwana and its drift northwards as the Iapetus Ocean closed (adapted from Torsvik *et al.*, 1992, by Trench and Torsvik, 1992). (c), (d) and (e) show the later stages of the Caledonian Orogeny. Sinistral strike-slip movements in relation to the Laurentian margin culminated in the Acadian Orogeny in late Early Devonian (Emsian) times (after Stephenson *et al.*, 1999, adapted from Soper *et al.*, 1992).

line of subduction (the Iapetus Suture) under the Southern Uplands. Thus, the Caledonian–Appalachian Orogen (or North Atlantic Caledonides) and the newly amalgamated Old Red Sandstone continent (Laurussia or Euramerica) were formed. Continuing compression and shortening of the continental crust resulted in the filling to sea level of the Silurian marine basins, their inversion to upland areas and the establishment of terrestrial conditions in newly developing basins.

Palaeogeographical reconstructions (e.g. Scotese, 2001) suggest that the continent lay in tropical to sub-tropical latitudes from the equator to about 30°S, with the Anglo-Welsh Basin lying approximately 5°S to 15°S. Palaeomagnetic data from the Lower Old Red Sandstone in southern Wales suggest a latitude of 17 ± 5°S (Channell *et al.*, 1992). Sedimentological studies of the Old Red Sandstone, and particularly of its fossil carbonate soils (calcretes) confirm, by analogy with modern calcretes, a warm to hot, semi-arid tropical to sub-tropical setting (e.g. Allen, 1986) with rainfall confined to wet seasons (e.g. Marriott and Wright, 1993). Uplift of the orogen may have caused broad variations in the rainfall pattern, producing periods of wetter and drier climate.

Woodcock (2000a), Friend *et al.* (2000), Dewey and Strachan (2003) and Soper and Woodcock (2003) presented recent overviews of the tectonics and kinematics of Old Red Sandstone basin formation. Superimposed on the broadly compressive stresses associated with convergence of the Avalonian and Laurentian continental margins, the oblique angle of closure produced strike-slip transpressive and transtensional movements. The nature and extent of these movements remain the matter of debate, largely centred on whether there was a major, orogen-wide sinistral megashear or whether basins were controlled by strike-slip movements of different sense and at different times during the Caledonian orogenic cycle. Another debate concerns the possible role of gravitational collapse of the uplifted, granite-buoyed Caledonian Orogen in the formation of some at least of the internal basins (e.g. Woodcock, 2000a). Dewey and Strachan (2003) conclude that the diachronous closure of Iapetus, and subsequent deformation and basin formation were controlled by sinistrally dominated relative movement between the Laurentian and Avalonia–Baltica plates. The Old Red Sandstone basins probably formed as a result of sinistral transtension, with an estimated 1200 km of strike-slip movement between Laurentia and Baltica. Rheic convergence in the Emsian Age (late Early Devonian) from 400 Ma to 390 Ma resulted in the Acadian Orogeny, which affected the basins south of the Highland Boundary Fault (Soper and Woodcock, 2003).

The Old Red Sandstone basins were formerly divided into two main groups on the basis of their positions relative to the Caledonian Orogen (e.g. Allen, 1977; Woodcock, 2000a). Those within it (internal or intramontane basins) include the Orcadian Basin, the basins of the Midland Valley of Scotland (but see below) and the Scottish Border Basin. The Anglo-Welsh Basin was regarded as an external, or extra-montane basin, open to the sea to the south. However, the recent models, invoking major orogen-parallel, sinistral movement and three separate, temporally discrete collision events (Grampian, Scandian and Acadian) collectively making up the Caledonides have revised the former view of a continuously prograding Caledonian mountain front.

The recent models (Dewey and Strachan, 2003; Soper and Woodcock, 2003) envisage that the highly oblique, sinistral closure of the Iapetus Ocean resulted in, sequentially, transpression, strike-slip and transtension. The area of maximum uplift in the Scandian Orogen was to the north of Britain, in Scandinavia, in an orogen of Himalayan proportions (Dewey and Strachan, 2003). The compression in the Laurentian crust, of which the Scottish

Highlands were part, caused thrusting along major NE-trending faults, granitic intrusion, andesitic volcanicity and low-grade metamorphism in northern Britain (Stephenson *et al.*, 1999). The volcanic rocks were probably extensive, their eroded remnants being seen at Ben Nevis, Glen Coe, Lorn and just north of the Highland Boundary Fault. Volcanic rocks also occur extensively within the Midland Valley of Scotland, at Montrose, in the Sidlaw, Ochil and Pentland hills, and in Ayrshire. They also occur more locally in the Southern Uplands, where granitic intrusions such as the Cheviot were emplaced.

During the transcurrent and transtensional phases, much of the orogen-parallel, sinistral movement appears to have been taken up by the Great Glen Fault and its north-east continuation, with at least 700 km of displacement (Dewey and Strachan, 2003). The formation of the Late Silurian–Early Devonian Old Red Sandstone basins is also attributed to sinistral transtension (Dewey and Strachan, 2003; Soper and Woodcock, 2003). The Acadian Orogeny ended this phase of basin formation and caused transpressive shortening of the early Palaeozoic basins flanking the Midland Microcraton, as well as the inversion and erosion of the Old Red Sandstone rocks not underlain by the microcraton (Soper and Woodcock, 2003). The cause of the Acadian event was probably the collision of a Gondwana-derived continental fragment (Soper and Woodcock, 2003) with the Midland Microcraton segment of the amalgamated Laurussian continent. The evidence for the terrane boundary in the vicinity of the Bristol Channel is now confined to the Lizard mafic–ultramafic complex, interpreted as an ophiolite and a fragment of the Rheic suture (e.g. Soper and Woodcock, 2003).

The Orcadian Basin was a large Mid-Devonian intramontane lake basin, totally unconnected to the open sea, apart perhaps from a brief period. Its formation was probably due to a combination of both gravitational extension, and transtensional movements on basin-margin faults. The Midland Valley of Scotland was not a single discrete basin in the Devonian Period. Weakened by a long history of igneous activity, internal, transtensional fault movements opened pull-apart basins and transpressive movements subsequently inverted them, resulting in the recycling of the basin-fills and providing weak points for continuing volcanic extrusion (e.g. Bluck, 2000). The preserved sequences thus represent the deposits of separate pull-apart basins, formed and brought together in a strike-slip faulted collage. The Stonehaven Basin in the north-east is the earliest, its sedimentary fill dating perhaps from the Wenlock Epoch (Marshall, 1991). It and its larger successor basins, the Crawton and Strathmore basins, formed by sinistral strike-slip along the Highland Boundary Fault. The southerly Lanark Basin formed along the Southern Upland Fault. Large volumes of arc-related volcanic rocks were extruded along the central axis of the Midland Valley, on lines weakened by the transtensional stresses (e.g. Bluck, 2000). The late Devonian Scottish Border Basin formed after Acadian inversion in Mid-Devonian times and extended into the Midland Valley, Northumberland and the Solway Firth.

The Anglo-Welsh Basin was formerly interpreted primarily as the product of load-generated flexural subsidence of the Caledonian foreland (James, 1987; King, 1994; Friend *et al.*, 2000). Dewey and Strachan (2003) and Soper and Woodcock (2003) prefer a transtensional mechanism for its formation. Transtensional movement on faults produced variations in the basin-fill in Pembrokeshire (e.g. Marshall, 2000a,b) and introduced coarse, clastic, detritus farther north (Tunbridge, 1980a). The isolated succession in Anglesey was probably deposited contiguously with the Přídolí–Pragian sequences to the south, with which there are marked similarities, although the initial coarse conglomerates are unique and of local derivation, and lacustrine deposits suggest internal or impeded drainage.

STRATIGRAPHICAL FRAMEWORK FOR THE OLD RED SANDSTONE

Stratigraphical classification of the rocks in the geological record has traditionally fallen into two broad categories – lithostratigraphical and chronostratigraphical. Lithostratigraphical classification is based on the physical characteristics of a rock body, such as colour, rock type (lithofacies) and mode of formation. Chronostratigraphical classification is based on the relative age of a rock body, determined by its fossil content (biostratigraphy) as correlated with standard, defined and internationally agreed geological marker horizons (the 'golden spikes'), and in the case of igneous rocks, by radiometric age dating. Biostratigraphical classification is achieved by the study of component fossil and microfossil groups, with subdivisions based on marker species or assemblages of species. Thus, in the Devonian System, there are biostratigraphical zonal schemes for graptolites, ammonoids, brachiopods, fish, conodonts, microvertebrates and miospores.

The chronostratigraphical subdivisions of the Upper Silurian and Devonian (Figure 1.4) are internationally agreed and defined in fossiliferous marine strata in continental Europe. The Upper Silurian Přídolí Series (not yet divided into stages) and Lower Devonian Lochkovian and Pragian stages are defined in the deep-water, graptolite-bearing succession of the Prague Basin in the Czech Republic. The last two replace the previously used, but not completely equivalent Gedinnian and Siegenian stages defined in the nearshore succession of the German Rhenish Basin. The highest Lower Devonian stage is the Emsian, defined in Belgium. The Middle Devonian stages (Eifelian and Givetian) are defined in Germany, the Upper Devonian stages (Frasnian and Famennian) are named from the carbonate-bearing marine succession of southern Belgium.

The problems of classification and correlation of the Old Red Sandstone of Great Britain are inherent in its terrestrial origins and the patchy preservation of its non-marine fossils. The fossils that are present indicate that the Devonian Period was a time of profound changes in the evolutionary record, with the first significant colonization of terrestrial habitats by vascular plants (Edwards, 1979a), the rapid expansion of the first aquatic vertebrates, and their emergence onto land. However, no direct correlations can be made with the European marine successions and the internationally agreed stages. Because of this, a series of loosely defined local stages (Downtonian, Dittonian, Breconian and Farlovian) were erected for the Anglo-Welsh Basin, but now have been largely subsumed into the international stages as a result of increasing refinement in correlation. Figure 1.4 (based on House *et al*., 1977; and Marshall and House, 2000) shows the stages and their correlation.

		Period/ System	Epoch	Series	Stage	Age (Ma)
Old Red Sandstone	Upper	Carboniferous		Tournaisian	Courceyan	362
		Devonian	Late	Upper	Famennian	376.5
					Frasnian	382.5
	Middle		Mid	Middle	Givetian	387.5
					Eifelian	394
	Lower		Early	Lower	Emsian	409.5
					Pragian	413.5
					Lochkovian	418
		Silurian	Late	Přídolí		419
				Ludlow	Ludfordian	
					Gorstian	424
			Mid	Wenlock	Homerian	

Figure 1.4 Major subdivisions of the Old Red Sandstone and its chronostratigraphical classification. Ages from Williams *et al*. (2000).

The principal macrofossils are fish fragments. A biozonal scheme was erected for the Old Red Sandstone in the Anglo-Welsh Basin (see Figure 5.3, Chapter 5) and was extended to continental Europe. Refinement of the scheme continues (Blieck and Janvier, 1989; Blieck and Cloutier, 2000), but the occurrence of fish remains is patchy and of limited use in high-resolution correlation. Miospore classifications (e.g. Richardson *et al*., 2000; Streel *et al*., 2000) and microvertebrate classification (Vergoossen, 2000) also aid correlation and stratigraphical resolution. However, the problem of detailed correlation of the terrestrial Old Red Sandstone succession with the Bohemian, German and Belgian marine stages, in which miospores are rare, remains. Progress is, however, being made by chains of correlation involving miospores that are common to the Old Red Sandstone and the Rhenish marine succession, the latter then being correlated with the Bohemian stages. For example, the recognition of the *Breconensis-zavallatus* Zone in the Ardennes allows correlation of the Anglo-Welsh and Rhenish Gedinnian–Siegenian successions (Richardson *et al*., 2000) (Figure 5.3, Chapter 5). A widespread volcanic ash deposit (the Townsend Tuff Bed) and a basin-wide calcrete (the Psammosteus Limestone) are valuable marker horizons in the Anglo-Welsh Basin, providing lithostratigraphical correlation of the succession.