
Chapter 1 Introduction to the Silurian

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Introduction

The aim of stratigraphy is to study rock successions preserved from the past and to bring them to life as sequences of events through geological time. By correlating events such as sea-level changes, climatic variations and crustal deformation against the standard geological timescale, stratigraphical methods can reconstruct a moving picture of Earth history in time and place. The time in this volume is the Silurian Period, from about 440 to 410 million years ago (Ma), and the place is the fragment of continental crust that was destined to become Britain.

The enterprise of reconstructing part of Britain's geological history would, in itself, be important enough to justify a network of field reference sites at which components of this history are well preserved in the rock record. However, Silurian sites in Britain have a more fundamental role, as the basis for part of the global standard stratigraphical scale itself. By historical precedent and by recent formal international agreement, Britain has become the guardian of seven boundary stratotypes, geological sections that define key points on the geological timescale. Furthermore, it was the historic investigation of British Silurian strata and their characteristic fossils that helped to lay the scientific foundations of stratigraphical procedure in Palaeozoic rocks, especially, as in the Southern Uplands of Scotland, where they have been tectonically deformed. These sites must remain accessible, well preserved and properly supported by stratigraphical information from related sites. What before was a national interest has now become an international duty.

Stratigraphy is done in four dimensions, one of time and three of space. In this chapter, the *Stratigraphical Framework* section first concentrates on the time dimension, as deduced from the vertical succession of rocks in one-dimensional space. A section on *Geological Controls on Silurian Stratigraphy* then outlines some of the real earth processes that modulate and punctuate this temporal record. The *Palaeogeographical Framework* section has map views of the other two spatial dimensions of the Silurian, showing its main geographical components and their modification through time. The *Silurian Palaeontology* Chapter outlines the important role played by fossils, both now and in the past, in the stratigraphical endeavour and in the description of Earth history. These framework sections provide the space–time *Rationale for Site Selection*, described in the final section of this chapter.

Stratigraphical framework

The early development of Silurian stratigraphy

The Silurian System of rocks was named by Roderick Murchison in July 1835. He derived the term Silurian from the name of a British hill tribe, the Silures, who lived in part of the Welsh Borderland during the Roman occupation. Murchison first envisaged the system as a major rock unit encompassing four of the thinner mapping units that he had traced through the Borderland in the preceding four years: the Llandeilo Flags, Caradoc Sandstone, Wenlock Rocks and Ludlow Rocks (Figure 1.1). However, during the second half of the 1830s, Murchison came to see that his new system might be applicable not just to the Welsh Borderland but to rocks with particular fossils, and therefore implied stratigraphical age, wherever else they were found. This important trend towards modern stratigraphical practice was already well advanced by the time that Murchison's *The Silurian System* was published (Murchison, 1839).

By creating a Silurian division of geological time, within what had previously been regarded as the Welsh *terra incognita* of the Transition Series of rocks, Murchison (1835) defined the first of the Lower Palaeozoic systems to gain widespread recognition. Part of the international recognition of the British-based Silurian System was due to Murchison's active promotion of 'his' system. That the Silurian System has survived subsequent redefinitions is a tribute to the generations of British geologists who have reworked and refined our understanding of one of the most intensively studied outcrops of strata in the world.

At the beginning of the 19th century, the definition and subdivision of crustal strata into successions of named units was still at an early stage of development. This was especially true within the older, more highly deformed rocks. By contrast, the gently deformed younger strata of the great sedimentary basins of continental Europe and southern England were amongst the first to be mapped and subdivided into major units still used today, such as the Quaternary (by Desnoyers in 1829) and Cretaceous (by d'Halloy in 1822). The geological methods of mapping and characterizing these younger strata on the basis of their contained fossils had been pioneered by British and French geologists independently.

In the early 1830s, Roderick Murchison, a 'gentleman of independent means', had joined forces with a young Cambridge academic, Adam Sedgwick. They had decided to map the distribution of the Transition strata within Wales and to attempt to subdivide them using the 'Smithian' principles of characterization by diagnosis of successive fossil assemblages. Murchison started his traverse in the south, from the base of the known outcrop of the distinctive Old Red Sandstone in the Wye Valley. He worked through the Welsh Borderland outcrops into the stratigraphically older Transition Series below, which are still relatively undeformed. He had the advantage of building on a considerable body of detailed knowledge, which was available from local investigators such as the Rev. T.T. Lewis. Sedgwick, the more experienced geologist, had the much more difficult task of starting in North Wales, amongst highly folded and faulted strata, which contained very few fossils.

The constituent rock units of Murchison's Silurian System (Figure 1.1) already showed the developing practice of naming rocks '...from places in England and Wales, where their succession and age are best proved by order of superposition and imbedded organic remains' (Murchison, 1839, p. 195). This concept of geographical 'type sections' for rock units has recently been developed to define the global standard stratigraphy. Murchison's choice of the names of Wenlock and Ludlow has been enshrined in two of the series names of the global stratigraphical scale. The term 'Llandovery' is of only slightly younger vintage (Murchison, 1859).

Murchison's endeavours in the Silurian rocks were part of a decade of intense stratigraphical activity in other parts of the Palaeozoic (itself named by Sedgwick in 1838). Sedgwick and Murchison defined the Devonian System (1839), effectively redefining Conybeare and Phillips' earlier (1822) concept of a Carboniferous System. Murchison himself was to name the Permian System in 1841. Most significant of all, for understanding of Silurian stratigraphy, was the definition by Sedgwick of the Cambrian System in September 1835 (Sedgwick and Murchison, 1835).

In the 1830s, Sedgwick and Murchison visualized the Silurian of the Welsh Borderland as overlying the Cambrian of North Wales along a boundary that they had roughly traced through mid-Wales in 1834. When, in the 1840s, this region was surveyed more accurately by the Geological Survey, it was found to comprise entirely Murchison's Silurian System. As the mapping reached North Wales, these 'Silurian' rocks were seen to strike directly into units of Sedgwick's Cambrian System. These observations provoked the celebrated 'Cambrian-Silurian controversy', setting the two former collaborators against each other and spawning two competing schemes of Lower Palaeozoic stratigraphical nomenclature (Figure 1.1).

The ensuing debate has been comprehensively reviewed by Secord (1986) and summarized by Bassett (1991). The seeds of a stratigraphical resolution to the controversy had, in fact, been sown by Murchison himself in defining distinct Lower and Upper divisions to his Silurian System (Figure 1.1). The effective three-fold division of Lower Palaeozoic rocks was increasingly used through the second half of the nineteenth century. It was formalized by Lapworth (1879), after the deaths of both Murchison (in 1871) and Sedgwick (in 1873), in the definition of an Ordovician System roughly equivalent to Murchison's Lower Silurian. Even then, diehard 'Sedgwickians' and 'Murchisonians' continued to use the old schemes. It was not until Sir Archibald Geikie retired from the Geological Survey in 1901 that the Ordovician replaced Lower Silurian on official maps, and that the Silurian System edged closer to its modern meaning.

Silurian time defined: chronostratigraphy

The 19th century debates served to demonstrate that the subdivisions of geological time (chronostratigraphy), in contrast to those of rock units (lithostratigraphy), need to have boundaries that are widely agreed. Inter-regional and international correlations would at best be imprecise if, for instance, Silurian time was differently defined in each region or country.

Consequently, the 20th century has seen increasing rationalization of stratigraphical procedure and practice, and in the last quarter of the 20th century a global standard stratigraphy has begun to be formalized. These developments have been chronicled for the Silurian by Holland (1989).

The global standard stratigraphical scheme has a hierarchy of divisions (Figure 1.2). Systems, series and stages are the divisions of rock bodies, whereas periods, epochs and ages are the corresponding divisions of geological time. The Silurian System is divided into four series, and all but one series into a number of stages. The benchmarks in this hierarchy are the internationally agreed positions for the base of each division, located at a particular point in a specified local rock succession. These boundary stratotypes (Figure 1.2) comprise the strategy for achieving stability in international stratigraphy. Future debates may arise over correlation of local successions with the type section, but not over the meaning of the system, series and stage names in the type sections themselves.

Because of the uncertainties in correlation, some authors (e.g. Holland, 1985, 1989) hold to the philosophically correct view that systems, series and stages can only be translated into valid time units (periods, epochs and ages) in the boundary stratotype section. The more pragmatic school of thought (e.g. Whittaker *et al.*, 1991) accepts that correlations beyond the stratotype have an inherent imprecision, but regards such correlations as the practical basis for *chronostratigraphy*, the best approximation to a working global timescale. This less perfect but more practical definition of chronostratigraphy will be adopted in this chapter.

Of the eight stratotypes that define the bases to the Silurian stratigraphical divisions, seven are in Britain (Figure 1.2). The one exception is the base to the Pridoli Series, the only major addition to the Silurian System since the time of Murchison. The need for this series arose because of previous erroneous international correlations. The chosen level for the base of the Devonian System in the Czech Republic (McLaren, 1977) is considerably higher than the base of the 'Old Red Sandstone', which had traditionally been regarded as the Silurian-Devonian boundary in the Welsh Borderland. The new Pridoli Series, also defined in a graptolitic Czech section, therefore correlates with the lowest part of the Old Red Sandstone. Sites in this stratigraphical interval are included in this volume.

The original selection of Silurian GCR sites was made over 15 years ago and did not take into account the significance of sites of Pridoli age within the British outcrop. Since that original selection, considerable biostratigraphical work has demonstrated the importance of Pridoli age strata at a number of sites in Wales and Cumbria. A selection of these sites has been included for stratigraphical completion even though they are not yet confirmed GCR sites.

Correlating Silurian rocks and time: biostratigraphy

The task of correlating rock successions from any region in the world with the type sections can, in principle, be done using a variety of indicators such as radiometric ages, palaeomagnetic polarity, geophysical rock properties, geochemical signatures, and seismic character. In practice, fossil content has proved to be the most widely applicable method for Silurian rocks, resulting in *biostratigraphical* zonations, keyed to the chronostratigraphical scale in the type areas. The evolving assemblages of each group of organisms are divided into *biozones*, named after an abundant or characteristic species. Graptolites and conodonts have yielded the most refined Silurian zonations (Figure 1.2), but analogous schemes exist for other groups, notably brachiopods, acritarchs and chitinozoans.

The Silurian stage boundaries have been chosen with reference to the bases of specific graptolite biozones in the boundary stratotypes or in nearby sections. True time correlation with other sections presumes synchronicity of the biozones. This presumption is difficult to test on a global scale, although it is supported by the generally consistent results of biostratigraphical correlation using different fossil groups and by comparison with other dating methods.

Calibrating Silurian time: radiometric dates

The global standard stratigraphy (Figure 1.2) does not depend, for its definition or application, on its calibration against the numerical age scale derived from radiometric dating. The philosophy of chronostratigraphy is that it can stand alone as a practical reference scale. In the Silurian, radiometric ages are still an imprecise correlation tool by comparison with graptolite biozones. This point is emphasized by comparing two recent calibrations of the standard stratigraphy (Figure

1.2). The Harland *et al.* (1989) and Tucker and McKerrow (1995) timescales give significantly different ages at each series boundary. The discrepancies, ranging from 1 Ma up to 8.5 Ma at the base of the Devonian, are large by comparison with the average duration of graptolite biozones — estimated at between 0.5 Ma and 1.2 Ma. A chronometric scale that incorporates the data of Tucker and McKerrow into the Harland *et al.* scale has been prepared by Gradstein and Ogg (1996).

The continuing discrepancy between Silurian timescales results partly from acquisition of new data and partly from the methodological approach to the radiometric database. The Harland *et al.* (1989) scale results essentially from averaging a large number of ages from this database. By contrast, the Tucker and McKerrow (1995) timescale is hung on a few high quality U-Pb (uranium-lead) ages in sequences well tied to the standard chronostratigraphy. Either methodology is dependent on the maintenance of an accessible network of reference sections in Britain, comprising both the world stratotypes and supplementary well-correlated sections, particularly those containing volcanic horizons amenable to dating. The numerical calibration of the timescale may not be vital for correlation, but it is essential for proper discussion of the durations and rates of geological processes.

Silurian rock units: lithostratigraphy

Before a local rock succession can be correlated with the standard chronostratigraphy, it must first be defined in terms of its component lithostratigraphical units. These units are the natural subdivisions based on readily observable characters such as rock composition, texture and depositional structure. Most rock successions are laterally variable, certainly in the British Silurian. Consequently, there are numerous lithostratigraphical schemes in use, each applying to a restricted area of outcrop. As knowledge increases of the three-dimensional geometry of the component rock units, it is possible to discard redundant terms and reduce the number of lithostratigraphical schemes. Five lithostratigraphies are summarized in this chapter (Figure 1.3)a, b, representing the major palaeogeographical provinces during Silurian time. Other relevant local schemes are referred to in individual chapters or site descriptions.

Prevailing lithostratigraphical practice can be demonstrated by the recently revised column for the Lake District ((Figure 1.3)b; Kneller *et al.*, 1994). The basic rock units are *formations*, which are lithologically distinctive enough to be mappable over most of the region in question. An example is the Skelgill Formation, a generally black, carbonaceous, graptolitic mudstone or shale. Some formations contain *members*, which may be impersistent or mappable only in favourable exposures. So, the Skelgill Formation contains a Spengill Member at its base, comprising paler graptolitic mudstone with a nodular limestone band. Such a band, if it were useful in regional correlation might be designated as a named *bed*, though this level of the lithostratigraphical hierarchy is infrequently used.

Hierarchical levels above that of the formation are useful in inter-regional correlation. So, the Skelgill Formation and the overlying Browgill Formation together constitute the Stockdale Group, and the uppermost Ordovician and Silurian groups and formations in the Lake District are gathered into a Windermere Supergroup.

Implicit in the lithostratigraphical schemes (Figure 1.3)a, b is the practice, inherited from Murchison's time, of naming units after a locality where they are well exposed. Typical localities may be formally designated as type sections, although it is more common for units to be defined by geological maps or measured stratigraphical logs in type areas (e.g. Kneller *et al.*, 1994). The geographical name attached to each rock unit may be supplemented by a lithological descriptor. Examples in the Welsh Borderland sequence are the Much Wenlock Limestone Formation and the Temeside Shales Formation. Such lithological qualifiers may be added to continue a traditional usage or simply to provide lithological reminders in a long sequence of otherwise bland unit names.

Not all the lithostratigraphical units mentioned in this volume comply strictly with modern practice. Examples occur at the base of the Midland Platform succession (Figure 1.3)b. Here 'Beds', as in Pentamerus Beds, is used roughly in the sense of a formation. Similarly the Hughley Shales and the Kenley Grit are units of approximate formation status, awaiting formal designation as such.

A striking feature of the generalized British Silurian lithostratigraphies (Figure 1.3)a, b is the lack of lithological similarity between regions at most times on the chronostratigraphical scale. This lateral variability results from the contrasting

palaeogeographical, tectonic and sedimentological settings of these regions during Silurian time. The variability underlines the need for a network of well-documented stratigraphical sites, not just in the type areas for the global chronostratigraphy, but in representative areas across the whole country. These sites underpin the local lithostratigraphical schemes and, through correlation with global stratotypes, serve to support them and enhance the international value of the British Silurian.

Geological controls on Silurian stratigraphy

Silurian event stratigraphy

The chronostratigraphical scale is intentionally defined without reference to the geological events that shape rock successions, such as sea-level and climate changes, and tectonic and volcanic episodes. Lithostratigraphical units record such events more closely, but the response to an event varies between different palaeogeographical settings. So, a sea-level fall might produce an unconformity in a shallow marine area, but a burst of turbidite sandstones in an adjacent deep marine setting. The aim of *event stratigraphy* is to recognize and correlate the signatures of real geological events, rather than the more arbitrary time-related surfaces of chronostratigraphy. Event stratigraphy provides the framework of a regional geological history. Some events, such as sea-level changes, may be recognizable globally and their pattern through time may eventually be refined sufficiently to provide a reliable correlation tool.

The main types of event that influence Silurian successions are summarized in the following sections.

Global sea-level change

Changes in sea level relative to the contemporary sediment surface are most easily deduced from rock successions deposited in shallow marine environments. The Welsh Borderland succession provides an example (Figure 1.3)b. No rocks of early Llandovery age are preserved *in* this area, suggesting a time of non-deposition or erosion during relatively low sea level. A fining-up sequence in the middle to upper Llandovery suggests sea-level rise. Limestone units in the lowest and uppermost Wenlock can be interpreted as short episodes of low sea level during a time of predominantly high sea level. Limestones within the Leintwardine Group may indicate a similar sea-level low during Ludlow time. The formerly fully marine sequences show increasing faunal and facies evidence of freshwater influence during Pridoli time, consistent with a sea-level fall transitional to the fluvial sequences of the Devonian.

Such a local analysis of relative sea-level changes cannot be interpreted directly in terms of global or *eustatic* changes. There is the possibility that some or all of the relative change is caused by the *tectonic* or *isostatic* uplift and subsidence of the crust on which the sediments were being deposited. Comparison of the relative changes between different areas and regions provides the test of eustatic change, particularly if these areas were situated on widely separated continental blocks.

The sea-level curve in (Figure 1.4) has been derived from comparing the stable platform areas of Silurian Gondwana (Australia), Laurentia (North America), Avalonia (Wales and England), Baltica (Norway and Estonia), South China and Siberia (Johnson *et al.*, 1991). Refined depth estimates are derived from faunal communities, most usefully from brachiopods. After a lowstand during the latest Ordovician (Hirnantian) ice age, the Llandovery was a time of spasmodically rising sea level, including at least four identifiable highstands. The Wenlock saw generally high sea levels, but with marked lowstands early and late in the epoch. A further major lowstand in mid-Ludlow time was superimposed on a generally falling global sea level into the Pridoli. Many of the variations in the global sea-level curve, postulated from data on other continents, can be matched with shallow-ing and deepening events on the Midland Platform. This correlation suggests relative tectonic stability of this area through much of Silurian time.

The effects of changes in sea level on basinal, deeper water, successions are more subdued or at least more cryptic than in shallow water successions. Lowstands can result in greater erosion on platform areas and higher sediment input into basins. This effect is not conspicuous in the British Silurian basins. A more prominent signature is the inferred variation in the oxygenation of bottom waters in the basins. During rises and highstands in sea level the basin mudstones tend to be laminated and rich in organic matter, implying anoxic conditions. During falls and lowstands, mudstones are more likely to

be bioturbated and poor in organic carbon, indicating oxygenated bottom waters. For example, the early Llandovery (Rhuddanian and early Aeronian) mudstones of central Wales, the Lake District and the Southern Uplands are predominantly anoxic, recording a rapid sea-level rise.

Climate change

Although apparently responsible for some Silurian facies changes, global sea-level variations are themselves driven by other Earth processes. Long-period sea-level changes — over some tens of millions of years — can be forced by the varying rate of sea-floor spreading. However, shorter-period changes are probably linked to processes within the complex ocean–atmosphere system. On these timescales, it is not always clear that changes in sea level are any more important in modulating sedimentary facies than some of the other parameters associated with changing climate: the organic productivity of ocean waters, the intensity of weathering on land, the degree and cause of stratification in basinal marine-water bodies, or the CO₂ content of the atmosphere and oceans.

Models involving these climatic influences do not all predict the same type of correlation between eustatic sea-level cycles (Figure 1.4) and sedimentary facies, on scales of a few million years. For example, some hypotheses link limestone deposition on shelves with sea-level rise rather than sea-level lowstand. One such model (Jeppsson, 1990; Aldridge *et al.*, 1993a; Jeppsson *et al.*, 1995) identifies *primo* (P) episodes, approximately coinciding with sea-level lowstands, alternating with *secundo* (S) episodes approximating to sea-level highstands. During *primo* episodes (alternatively called *icehouse states*, Tucker 1992), the ocean bottoms were kept oxygenated by input of dense water from cold high-latitude seas. Corresponding upwelling of nutrient-rich deep water promoted high phytoplankton productivity, drawdown of CO₂ from the atmosphere, and the consequent enhancement of a cold global climate. Carbonate deposition in shallow water was reduced. During *secundo* episodes (or *greenhouse states*), high-latitude water was too warm to sink and the oceans became salinity-stratified with anoxic conditions at depth. Weak upwelling of nutrients resulted in low phyto-plankton productivity, the release of CO₂ to the atmosphere, and the consequent enhancement of a warm global climate. Reefs and rich benthic faunas characterized the shelf areas.

Models such as this should eventually provide a rationale for the observed correlations between sea level and basin oxicity. Less clear is the primary forcing mechanism for the climatic cycles. They are at least an order of magnitude too long to be attributed to the Milankovitch cycles in the Earth's orbital parameters. They might be related to some, as yet unproven, variation in the heat output of the sun. More likely is that they are feedback cycles within the ocean-atmosphere system itself, caused perhaps by the finite size of the ocean reservoir for dissolved CO₂.

Tectonic influences

Tectonic influences on stratigraphical sequences are, by their nature, of regional or local rather than global extent. Their importance is readily seen by comparing rock successions in different areas of Silurian Britain (Figure 1.3)a, b. For instance the Welsh Borderland Silurian succession, deposited on the relatively stable Midland Platform, is about 1.5 km thick. The Central Wales succession, deposited on the more rapidly subsiding crust of the Welsh Basin, contains at least 4 km of Llandovery and Wenlock rocks alone, with a comparable thickness of Ludlow and Pridoli rocks probably having been eroded, except at its south-east margin, off the top. The thickness of sedimentary sequences is constrained by the rate of crustal subsidence. The balance of the rates of subsidence and sediment supply determines whether the available accommodation space is kept filled close to sea level, or whether deeper water facies predominate.

Various tectonic influences operated in Silurian Britain.

Lithospheric extension

Episodes of lithospheric extension produce an initial phase of rapid crustal subsidence due to thinning of the lithosphere, followed by a long period of slowing subsidence as the lithosphere regains its thermal equilibrium. These episodes can potentially be recognized on subsidence curves (Figure 1.5) derived from cumulative plots of stratigraphical thickness against time. Such plots must be corrected, firstly for the subsequent compaction of each rock unit and secondly for the extra subsidence produced by the weight of sediment itself. Uncertainties of the depth of water in which each

stratigraphical unit was deposited limit the accuracy of the plots. Fuller explanations of the method applied to British Lower Palaeozoic sequences are given by King (1994) and Woodcock *et al.* (1996).

A significant subsidence episode ascribed to lithospheric stretching can be recognized in the late Llandovery and early Wenlock of the Welsh Basin and Midland Platform (Figure 1.5)a. This is a time when large thicknesses of turbidite sandstones were deposited in central Wales (Figure 1.3)b, accommodated in sedimentary basins bounded by active extensional faults (Woodcock *et al.*, 1996). This extension is recorded by steep segments of the subsidence curves (Figure 1.5)a followed by progressively shallower segments representing the later thermal subsidence phase. Further steep segments, of possible extensional origin, occur in the Pridoli and earliest Devonian record.

Lithospheric flexure

Sedimentary basins can also be formed by down-bending or *flexure* of the lithosphere under a superimposed load. An example is the Lake District Basin, which was formed in front of a stack of crustal sheets being thrust southwards from the region of the Southern Uplands of Scotland. The flexural basin in the Lake District subsided increasingly rapidly as the thrust load advanced towards it. The resulting subsidence curves (Figure 1.5)b begin with gentle segments representing the early Silurian, but become steeper through the Silurian record (King, 1994).

Subduction accretion

The most intimate control of sedimentation by tectonic events in any British Silurian basin is seen in the Southern Uplands of Scotland. Here, sedimentary packets deposited on downbent lithosphere were periodically overthrust from the north by a stack of faulted sheets. One view is that this stack is a *subduction accretion complex* formed by offscraping of sediments from a northward-subducting slab of oceanic lithosphere (Leggett *et al.*, 1979a). An alternative view is that the subducting lithosphere floored a back-arc basin rather than a major ocean (Stone *et al.*, 1987). On either model, the result is a stack of thrust sheets in which the stratigraphy in each sheet youngs northward, but where the stack as a whole youngs southward ((Figure 1.6) inset).

This southward younging is clearly shown in a series of stratigraphical columns across the Southern Uplands (Figure 1.6). A typical column preserves deep marine mudstones overlain by turbidite sandstones deposited as that segment of lithosphere neared the front of the thrust stack and the basin margin. The stratigraphy on (Figure 1.3)a is a simplified representation of this diachronous system.

Palaeogeographical framework

The Silurian world

Silurian stratigraphy must be interpreted in terms of an arrangement of continental fragments quite different from that of the present day. Palaeocontinental positions can be estimated from the extents of faunal provinces, from latitude-sensitive sediments such as reefs, and most accurately from palaeomagnetic data (e.g. Pickering and Smith, 1995; (Figure 1.7)).

Until late Ordovician time, northern and southern Britain had been separated by the wide *Iapetus Ocean*. Scotland, together with the north and west of Ireland, were part of the south-eastern margin of the major continent of *Laurentia*, which straddled the equator through much of the Early Palaeozoic. England and Wales, together with south and east Ireland, lay on the smaller continent of *Avalonia*, which also included parts of mainland Europe to the east and fragments of the maritime states of North America to the west. Avalonia had originated on the northern margin of *Gondwana*, the major continent straddling the Early Palaeozoic south pole. Avalonia had rifted from Gondwana early in Ordovician time and moved northwards towards Laurentia, the Iapetus Ocean closing ahead of it and the *Rheic Ocean* opening in its wake. The continent of *Baltica* had a broadly similar drift history to Avalonia, so that the two continents amalgamated and moved northwards together from Late Ordovician time onwards.

During early Silurian (Llandovery) time both Baltica and Avalonia began to impinge on the Laurentian continent. Continental crust started to choke the northward-dipping subduction zone beneath Laurentia, which had formerly subducted only Iapetus oceanic lithosphere (Figure 1.7). By late-Silurian (Ludlow) time, the last remnant of the Iapetus Ocean had been destroyed and the Laurentian margin was being overthrust onto the British segment of Avalonia. This thrusting and associated crustal compression rapidly obliterated the marine Silurian basins and began to uplift parts of them above sea level. Consequently, marginal marine and non-marine facies dominate the stratigraphical record from latest Silurian (Pridoli) time into the Devonian. The continental collision culminated in strong deformation, uplift and erosion of the basinal sediments during the Early and Mid-Devonian, an event termed the *Acadian Orogeny*.

Geological investigation, ever since Murchison began his investigations in Wales, have transformed our understanding of the Silurian Period in geological history. Murchison's vast Silurian Period, which was thought to contain the fossil evidence for the origin of life, has now been considerably reduced in duration, to some 30 Ma. However, the Silurian has re-emerged as an equally momentous period in the geological history of Britain, but for different reasons. At the dawn of the Silurian, Britain comprised two separate halves originating thousands of kilometres apart. By its close, these halves were united into more or less their present form. Silurian stratigraphy preserves the record of this act of union. So, by accident of its geology and despite a small geographical area of outcrop, the Silurian of Britain and its detailed investigation has played a significant role in the development of methods of investigation and the actual reconstruction of this major phase in Earth history.

Palaeogeographical elements of Silurian Britain

The *Iapetus Suture*, trending NE–SW close to the England–Scotland Border, marks the former site of the Iapetus Ocean between Laurentia to the north-west and Avalonia to the south-east. It is helpful to further subdivide these two regions into palaeogeographical areas, each with a distinctive Silurian record of subsidence or uplift, sedimentation or erosion (Figure 1.8). This subdivision of Britain provides the template on which Silurian geological history was overlain, and against which the network of important stratigraphical sites can be compared. The palaeogeographical elements of Ireland are broadly the south-western continuation of those in Britain and are only referred to here in passing.

Laurentian elements

The *Scottish Highlands* have their south-eastern limit at the *Highland Boundary Fault*. The record of Silurian sedimentation in this area is sparse and poorly dated. Non-marine sedimentary rocks of possible Ludlow and Pridoli age are locally preserved, and late Silurian granitic intrusions imply an original volcanic superstructure. The area probably lacked marine basins, and comprised actively deforming, uplifting and eroding continental crust throughout Silurian time.

The *Scottish Midland Valley* is the area between the Highland Boundary Fault and the *Southern Uplands Fault*. During Silurian time it accumulated shallow marine to non-marine sediments, implying an underlying normal-thickness continental crust. Some of these sediments were derived from the south, but with compositions incompatible with erosion from the present Southern Uplands. This mismatch suggests that there are missing palaeogeographical elements or *terranes* between the Midland Valley and the Southern Uplands (Bluck, 1983). These probably included an active volcanic arc above the subduction zone dipping northward beneath Laurentia. The missing terranes have either been obscured by northward overthrusting of the Southern Uplands rocks or removed laterally by strike-slip fault displacements.

The *Southern Uplands* of Scotland now lie between the Southern Uplands Fault and the *Iapetus Suture*. Their formation as a thrust stack of deep-water sediments has already been discussed. The persistent deep-marine Silurian environment is compatible with deposition on oceanic crust, subsequently removed down the Laurentian subduction zone. Sedimentation in the Southern Uplands persisted only into late Wenlock time, after which the thrust stack began to override the advancing Avalonian continental margin.

Avalonian elements

The *Midland Platform* is the stable core of the Eastern Avalonia continent lying south-east of the *Welsh Borderland Fault System*. The platform had been delineated during early Ordovician rifting from Gondwana and had accumulated thin patches of upper Ordovician sediment. During Silurian time it was flooded more persistently by shallow seas but accommodated only modest thicknesses of sediment, implying underlying continental crust of near-normal thickness. In latest Silurian (Pridoli) and Early Devonian time the platform accumulated a thick prism of sediment shed southwards from the newly uplifting areas to the north. The platform was only weakly deformed during the Acadian Orogeny.

The *Welsh Basin* borders the north-west edge of the Midland Platform, as far as the *Menai Strait Fault System*. During the Ordovician the basin had been the site of numerous volcanic centres associated with a south-dipping subduction zone beneath Avalonia. For most of Silurian time it subsided more rapidly than the Midland Platform, due to stretching and thinning of its continental basement. It therefore hosted deep marine environments, and accumulated some kilometres of sediment. In late Ludlow and Pridoli time, the basin shallowed as subsidence gave way to uplift, and by Early Devonian time the former basin was an eroding source area.

The *Anglian Basin* had a similar tectonic setting on the north-east side of the Midland Platform. Its rocks are known only from bore-holes, but its sedimentary history has the same shallowing upwards character as that of Silurian Wales (Woodcock and Pharaoh, 1993).

The *Irish Sea Platform* is a small elongate area of Precambrian and Early Palaeozoic crust forming the north-west margin of the Welsh Basin. A thin Silurian succession is preserved on it, but it may have been emergent for much of Silurian time.

The *Lake District Basin* is the most northerly component of Avalonian palaeogeography and was probably continuous with the Leinster Basin of Ireland. The uppermost Ordovician and Silurian successions were built on the eroded remnants of a volcanic arc formed above the south-dipping Ordovician subduction zone beneath Avalonia. This old arc terrane subsided rapidly enough to give deep-marine environments by earliest Silurian (Llandovery) time. Subsidence was progressively enhanced by flexure of the Avalonian lithosphere as Laurentian crust was thrust onto it from the north (Kneller 1991, Kneller *et al.*, 1993). Many kilometres of Silurian sediment were deposited. Sedimentary environments became shallower during Pridoli time as sediment input exceeded even this rapid subsidence, and in Early Devonian time the area was uplifted in the culminating events of the Acadian Orogeny.

Changing palaeogeography: a brief history of Silurian time

The Silurian palaeogeography of the British Isles is represented on three sequential maps (Figure 1.9)a-c focussing on areas where Silurian rocks are preserved. The present coastline on these maps is shown as discontinuous across zones of large Silurian or post-Silurian displacement. However, the relative positions of the crustal fragments across these zones are largely diagrammatic, either through lack of data, or for graphical convenience. Particularly uncertain are the separation across the Iapetus Suture in earliest Silurian time and the amounts of strike-slip displacement along the major Laurentian faults.

Early to mid-Llandovery

The geography of the earliest Silurian is shown with a remnant of the Iapetus Ocean still separating Eastern Avalonia from Laurentia (Figure 1.9)a. Estimates of the precise time of initial continental impingement vary through the late Ordovician (Pickering *et al.*, 1988) into the early Silurian (Llandovery; Soper and Woodcock, 1990). Such estimates are complicated by the diachroneity of the collision along the margin, and the progression from 'soft' collision of the sediment prisms on the two margins to the 'hard' collision of their crystalline basement rocks.

Subduction of Iapetus oceanic lithosphere beneath Laurentia continued from Ordovician time. Deep-marine mudstones (Moffat Shale Group, (Figure 1.3)a, (Figure 1.6)) deposited on the oceanic crust were overlain by turbidite sandstones (Gala Group, (Figure 1.3)a, (Figure 1.6)) as the crust neared the trench. Segments of this sedimentary succession were periodically scraped off the downgoing slab and accreted to the base of the thrust stack on the Laurentian margin. The trench turbidites were supplied in part from the missing southern segment of the Midland Valley, probably including

volcanic arc rocks. Farther north, the preserved part of the Midland Valley received elastic debris from both the south and the north, probably in a relatively shallow marine basin. North of the Highland Boundary Fault were the uplands of the Scottish Highlands, possibly cut by active major faults.

The shallowest parts of Avalonia were still emergent in earliest Silurian time, following the lowering of sea level during the late Ordovician glaciation (Figure 1.4). On the Midland Platform, the unconformity produced during this regression is overlain by sequences of shallow marine mudstones and limestones, often with transgressive sandstones at the base e.g. Kenley Grit–Pentamerus Beds–Hughley Shales, (Figure 1.3)b. The pulsed nature of the transgression (Figure 1.4) is reflected in the diachroneity of the sediments overlying the unconformity, varying up to upper Llandovery (Telychian). In the basinal areas, the same transgression is recorded by a blanket of carbonaceous mudstones (e.g. Cwmere and Skelgill Formations, (Figure 1.3)b, the signature of anoxic bottom waters in a stratified basin during a secundo (greenhouse) climate. In the Welsh Basin this mudstone deposition was punctuated by sandstones and conglomerates transported by turbidity currents from the edge of the Midland Platform.

Late Llandovery to early Ludlow

The Iapetus oceanic remnant separating the two halves of Britain seems to have closed diachronously from south-west to north-east during late Llandovery and Wenlock time (Soper and Woodcock 1990). This convergence progressively linked the geological histories of Laurentia and Avalonia, and began to restrict the connections between their marine basins and the open ocean system.

Offscraping of deep-marine turbidites at the Laurentian margin continued from late Llandovery (Hawick Group, (Figure 1.3)a, (Figure 1.6)) at least into late Wenlock time (Riccarton Group, (Figure 1.3)a, (Figure 1.6)). Shallow marine environments in the upper Llandovery of the Midland Valley gave way to subaerial alluvial fans in the Wenlock, supplied from the missing terrane to the south. The Scottish Highlands remained an upland area, its north-western part now undergoing strong deformation and granite intrusion.

On Avalonia, the Midland Platform accumulated a continuous upper Llandovery to Ludlow succession, dominated by mudstones (e.g. Coalbrookdale Formation, (Figure 1.3)b. Shorter periods of limestone deposition (Woolhope, Buildwas and Much Wenlock Limestone formations, (Figure 1.3)b coincide with postulated low-stands on the eustatic sea-level curve (Figure 1.4). The Welsh Basin received large volumes of south-west-derived turbidite sand from late Llandovery time onwards, possibly sourced from newly uplifted areas in the Laurentia–Avalonia collision zone. This source area has been termed Pretannia (Cope and Bassett, 1987). The sediment was accommodated by an episode of crustal stretching and subsidence in the basin ((Figure 1.5)a.

The Lake District Basin accumulated mostly mudstones until early Wenlock time (e.g. Brathay Formation, (Figure 1.3)b), receiving the first substantial turbidite sands into its southeastern part in the mid-Wenlock. The main influx of sand was not until early Ludlow time (Coniston Group, (Figure 1.3)b). The signature of flexural subsidence suggests that the Laurentian thrust stack was substantially loading the northern edge of Avalonia by then, and that the Ludlow turbidite fans of the Lake District represent the encroachment of the Southern Uplands fans onto Avalonian crust.

Substantial intercalations of volcanic rock within lower Silurian sedimentary sequences point to isolated volcanic centres across the southern part of the Midland Platform. These centres neither overlie extinct Ordovician volcanoes, nor have rocks of the same subduction-related composition. The Silurian volcanism seems to represent a weak episode of crustal rifting, of uncertain origin, within Avalonia.

Late Ludlow to Pridoli

As Avalonia and Laurentia were driven ever more tightly together, the subsidence of most of their marine basins was curtailed, as any crustal extension gave way to shortening. This shortening began to create new uplands, which shed increasing amounts of sediment into the remaining basins. Deep marine environments were replaced by shallow marine and continental conditions. Even the Lake District Basin, whose flexural subsidence was maintained by the load of the advancing Laurentia, was filled to sea level by sediment before the end of Silurian time.

The former Laurentian margin was cut by many active faults with sinistral strike-slip or thrust displacements. Remnants of non-marine elastic sediments suggest a scatter of small, locally sourced alluvial basins controlled by these faults. These basins occurred in the Scottish Highlands as well as the Midland Valley and on the uplifted remnants of the Southern Uplands thrust stack. Some basins contain substantial thicknesses of lavas, and contemporaneous granitoid intrusions imply further superjacent volcanic piles. Mismatches between clast compositions in alluvial conglomerates and the source areas implied by palaeocurrent data suggest substantial post-Silurian displacement on some Laurentian faults. In particular, the Southern Uplands may have been thrust back over the persistent source area to the south of the Midland Valley at this time.

The Lake District and Welsh Basins were rapidly filling with sediment and the marine shoreline was moving quickly south-eastward. By the end of the Pridoli, the basins were emerging above sea level and were starting to be eroded themselves. River systems took the sediment southwards to be deposited first in a marginal marine embayment and then on alluvial plains on the site of the old Midland Platform.

The 30 Ma of Silurian time had seen the total demise of the marine Silurian basins over most of Britain. An extensive sequence of non-marine sediments, the 'Old Red Sandstone', was laid down on the newly consolidated continent during Devonian time. The marine focus shifted farther south, to the Cornwall–Rhenish Basin developed along the south edge of the Midland Platform. This basin was to close progressively during later Devonian and Carboniferous time to generate the Variscan orogenic belt.

Rationale for site selection

Sites for the Geological Conservation Review have been selected to provide a network that is representative of British Silurian stratigraphy. This network is listed in (Table 1.1) and displayed on maps in (Figure 1.10). Three criteria have been particularly important in choosing sites:

- (a) The *chronostratigraphical position* of rocks at each site. The proportion of sites in each constituent rock series of the Silurian reflects its stratigraphical importance and the geographical extent of its outcrop. This criterion results in fewer sites for the Pridoli than for other series, reflecting its abundant outcrop only on the Midland Platform and its margin.
- (b) The *palaeogeographical setting* of each site. Stratigraphical sequences vary markedly between the different palaeogeographical areas of Silurian Britain. This variety is captured by the spread of sites across each of these areas.
- (c) The *international importance* of each site. The key sites for this criterion are the boundary stratotypes of the global chronostratigraphical scheme, shown in bold typeface on (Table 1.1). There is an international obligation to maintain the accessibility and quality of these sites for future scientific work. Moreover, there is an expectation that the value of these stratotypes should be enhanced by maintenance of a local network of related sites that provide comparative sections through the same horizon or through intervening horizons. This criterion explains the disproportionate density of sites on the Midland Platform and its transitional margin with the Welsh Basin (Table 1.1).

(Table 1.1) GCR sites arranged by palaeogeographical setting and stratigraphical age. Bold typeface denotes a basal boundary stratotype for the global standard stratigraphy.

	Llandovery	Wenlock	Ludlow	Pridoli
	Gutterford Burn			
	Birk Knowes	Lyne water and Lynslie		
Midland Valley	Roughneck Quarry	Burn		
	Blair Farm	Ree Burn–Glenbuck		
	Penwhapple Burn	Loch Knockgardner		
	Woodland Point			

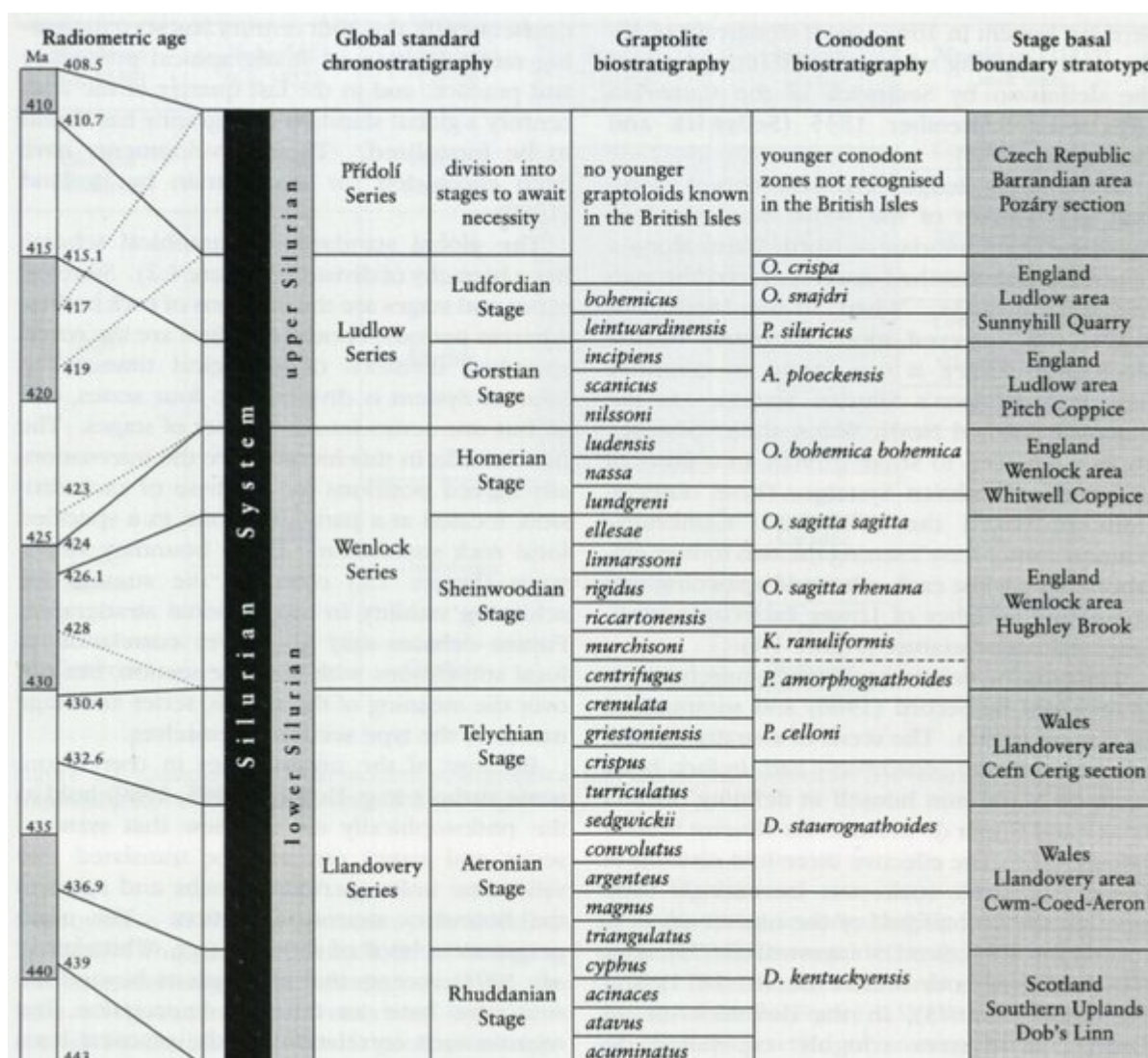
Southern Uplands	Old Cambus Quarry	Balmae Coast		
	Thornylee Quarry			
	Grieston Quarry Dob's Linn	Meikle Ross		
Lake District Basin	Brow Gill Beck	Brathay Quarries	Tebay Cuttings	
	Skelghyll Beck	River Rawthey	Benson Knott	The Helm
	Spengill	Torver–Ashgill	Hills Quarry	
	Yewdale Beck Meifod	Arcow Quarry		
Welsh Basin	Craigyfulfran		Ty'n-y-Ffordd Quarry	
	Rheidol Gorge	Penstrowed Quarry	Clogau Quarry	
	Caban Côch	Ty Mawr	Dinas Brân	
	Aberarth–Morfa Banwy River			
Welsh Basin	Buttington Brickworks	Trewern Brook		
	Cwm Clyd Quarry	Buffington Brickworks		
	Scrâch Track	Banwy River		
	Trefawr Track	Trecoed–Castle Crab	Beacon Hill	Lower Wallop Quarry
		Dulas Brook		
		Coed-mawr	Meeting House Quarry	Capel Horeb Quarry
Margin	Cwm-Coed-Aeron	Pen-cerig	Mithil Brook and Cwm Blithus	Little Castle Head
	Coed Glyn Moch Track	River Irfon		Albion Sands and Gateholm Island
	Fron Road	Sawdde Gorge	Sawdde Gorge	
	Cilgwyn-Ydw Valley	Wernbongam Marloes		
	Gasworks Lane	Freshwater East (south)		
	Marloes			

	Buildwas River Section	Turner's Hill	
	Lincoln Hill	Upper Millichope	
	Daw End Railway Cutting	View Edge	
	Farley Road Cutting	Mocktree Quarries	
	Whitwell Coppice	The Whiteliffe	
	Hay Head Quarries	Church Hill Quarry	
	Hughley Brook	Wigmore Road	
	Hughley Brook	Deepwood	
	Easthope–Harley Hill	Mary Knoll Valley	
	Longville–Stanway Road Section	Pitch Coppice	
	Hope Quarry and Hope Brook	Bow Bridge	
	Hughley Brook	Wren's Nest	
	Hillend Farm	Eaton Track	
Midland Platform	Wistanstow Gullet Quarry	Burrington	Burrington Farm Stream Section
	Damery Bridge	Dolyhir Quarries	Sunnyhill, Mary Knoll Valley
	Cullimore's Quarry	Little Hill	Brewin's Canal Ludford Lane and Ludford Corner
		Scutterdine Quarry	Goggin Road
		Linton Quarry	Deer Park Road
		Hobbs Quarry	Elton Lane
		Cwm-Ton Area	Aymestrey Quarries
		Cilwrgi Quarry	Woodbury Quarry
		Brinkmarsh Quarry	Perton Road and Quarry
		Buckover Road Cutting	Gurney's Quarry
		Rumney River	Linton Quarry
		Rumney Quarry	Longhope Hill
		Pen-y-Lan Quarry	Wood Green
		Moons Hill Quarry	Tites Point
			Brook House

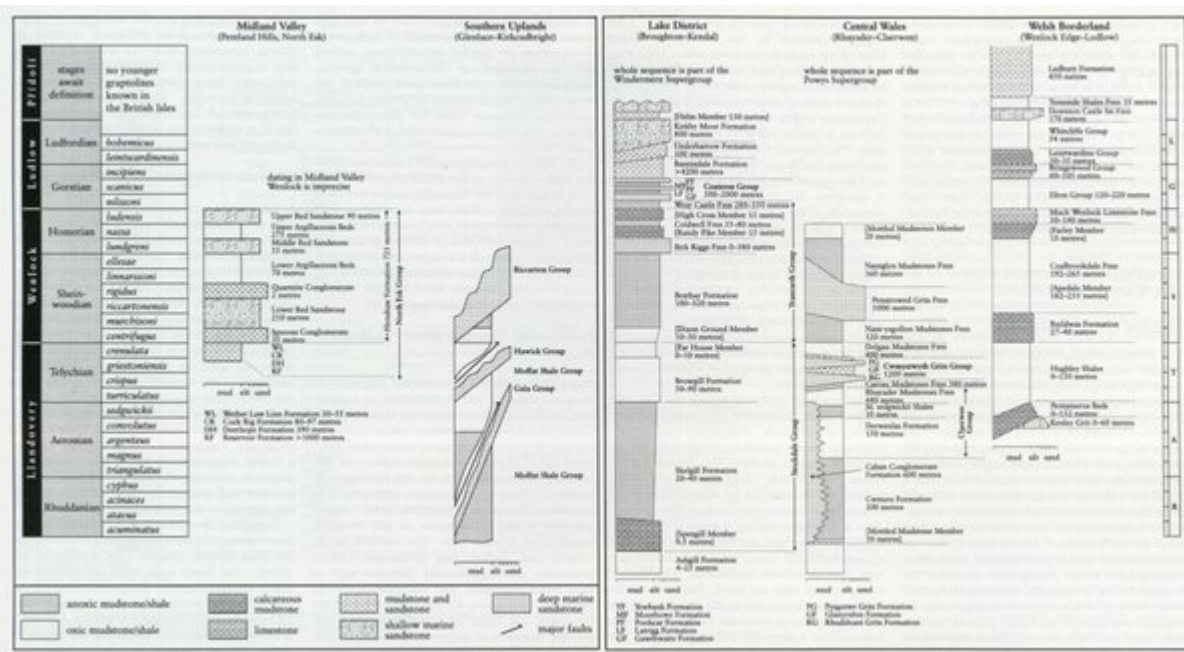
[References](#)

Murchison (e.g. 1839)	Sedgwick (e.g. 1852)	Lapworth (1879)	Modern Systems	Modern Series	Murchison's (1839) rock units	
Old Red Sandstone	Old Red Sandstone	Old Red Sandstone	Silurian	Přídolí	Cornstone and Marl Tilestone	
Upper Silurian	Silurian	Silurian		Ludlow	Upper Ludlow Rock Middle Ludlow Rock Lower Ludlow Rock	
					Wenlock	Wenlock Limestone Wenlock Shale
						Llandovery
Lower Silurian	Upper Cambrian	Ordovician		Ordovician	Ashgill Caradoc	
			Middle Cambrian		Cambrian	Cambrian
Cambrian						

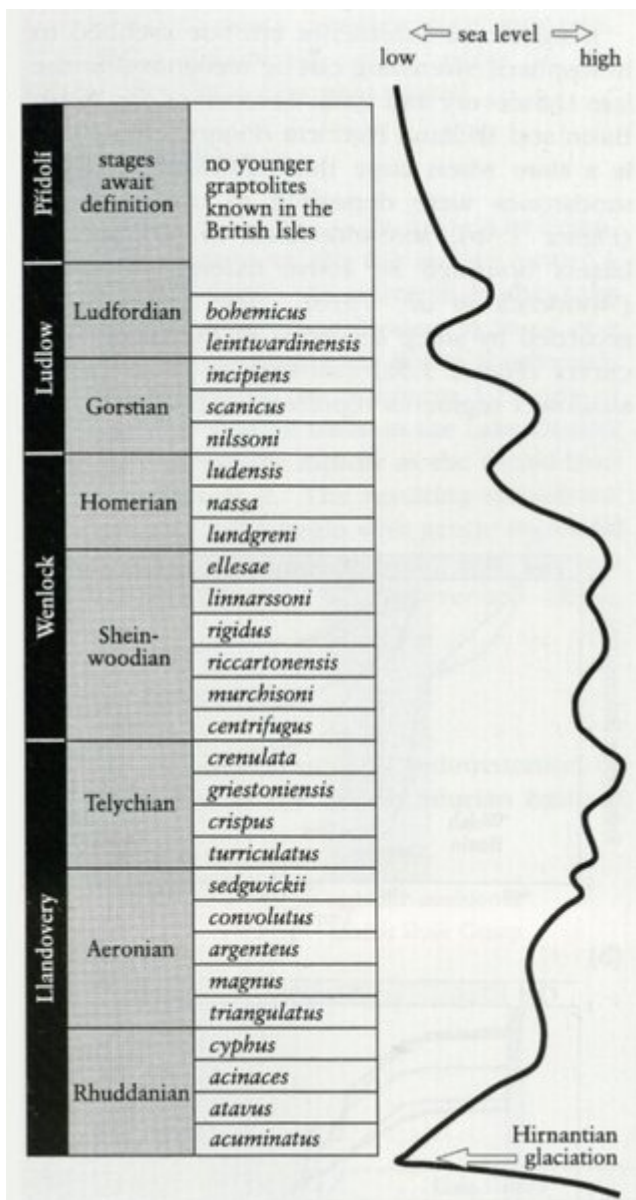
(Figure 1.1) Comparison of the modern stratigraphical scheme for the Ordovician and Silurian with the stratigraphical usage of Murchison, Sedgwick and Lapworth.



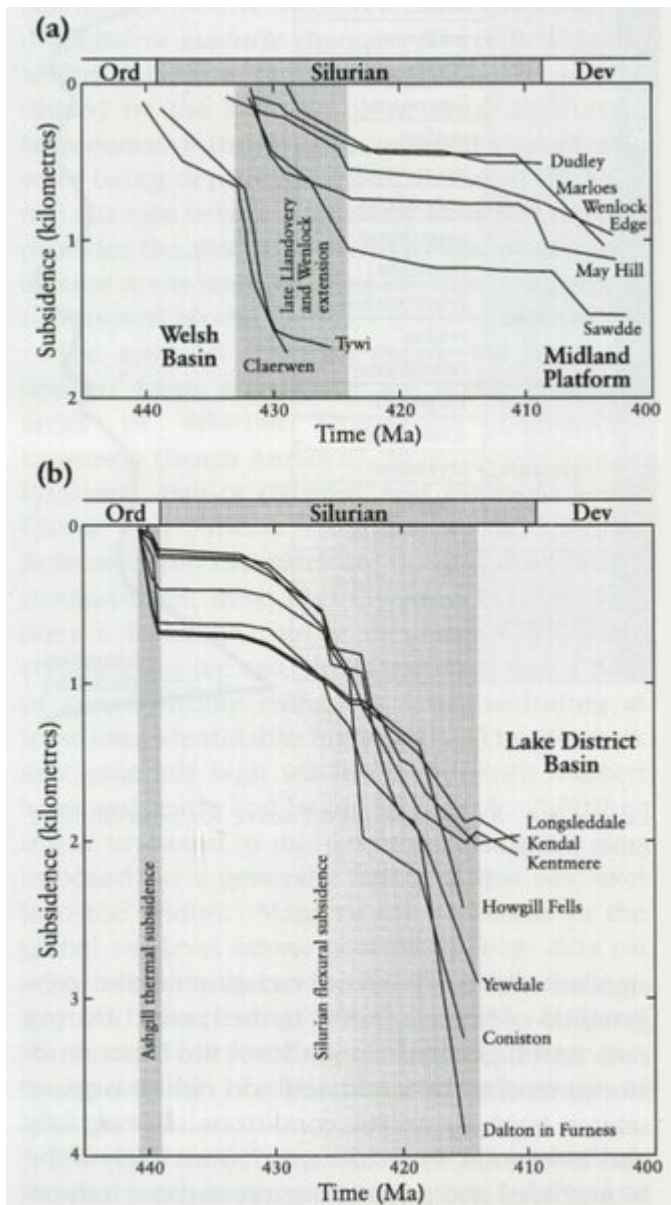
(Figure 1.2) The global standard stratigraphy and a graptolite biostratigraphical zonation, calibrated against two recent chronometric scales derived from radiometric age determinations.



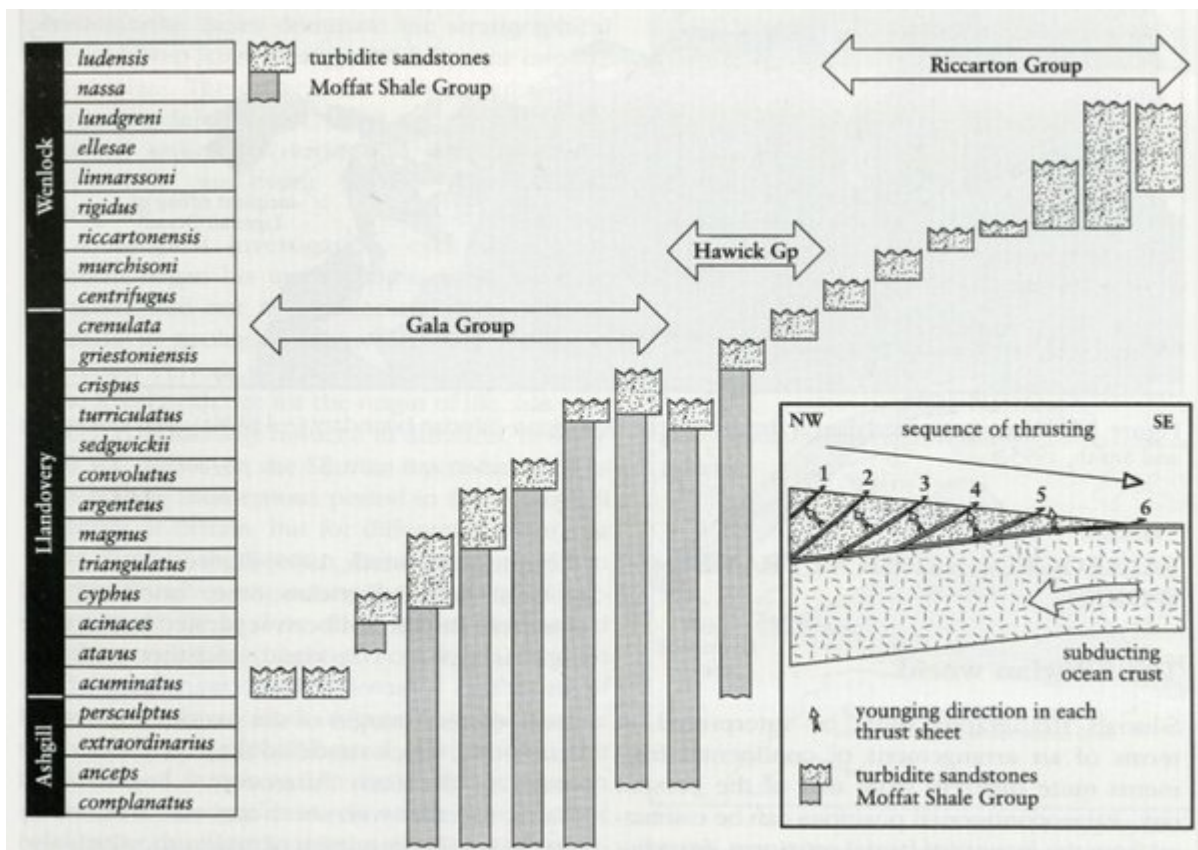
(Figure 1.3) a. Representative lithostratigraphical columns from the main palaeogeographical areas of Silurian Britain: Midland Valley from Bull and Loydell (1995) and Robertson (1989), Southern Uplands from Rushton et al. (1996). b. Representative lithostratigraphical columns from the main palaeogeographical areas of Silurian Britain: Lake District from Kneller et al. (1994), central Wales from British Geological Survey (1993), Welsh Borderland from Cocks et al. (1993).



(Figure 1.4) A global sea-level curve for Silurian time (after Johnson et al., 1991).



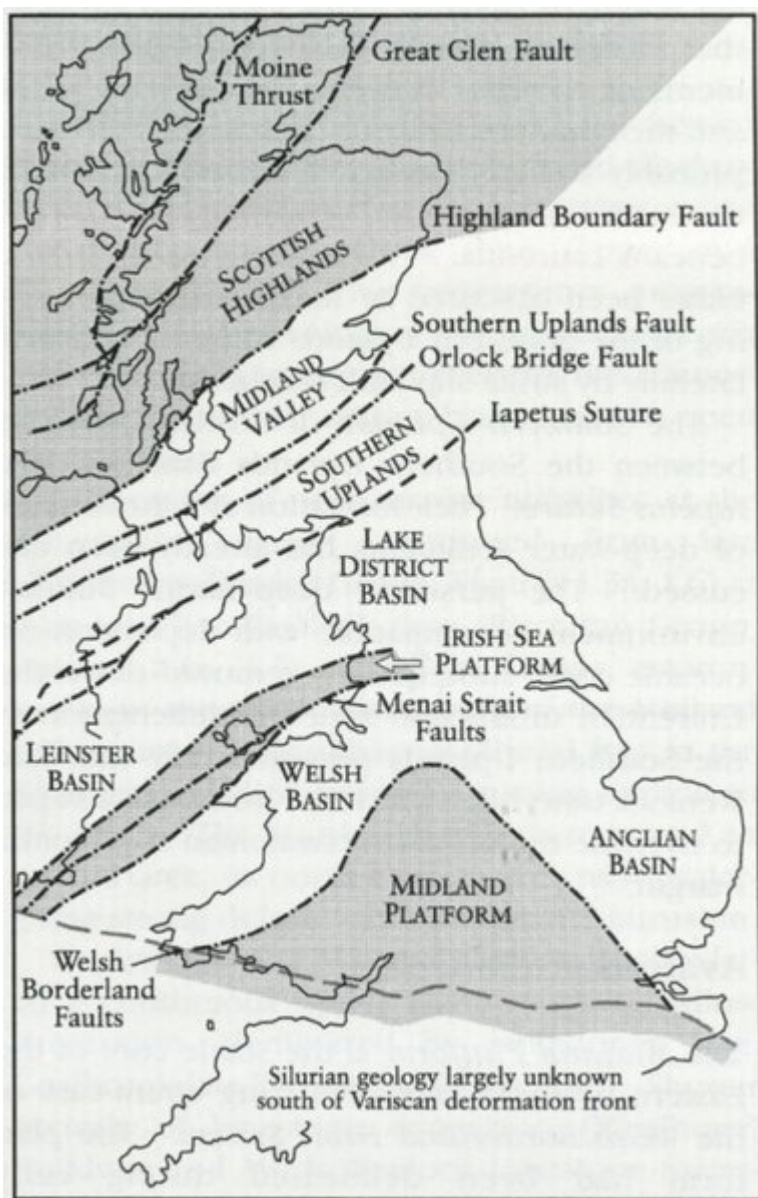
(Figure 1.5) Backstripped, water-loaded subsidence curves for the Silurian of (a) the Midland Platform and central Welsh Basin (From Woodcock et al., 1996), and (b) the Lake District (from King, 1994). The time scale is that of Tucker and McKerrow (1995).



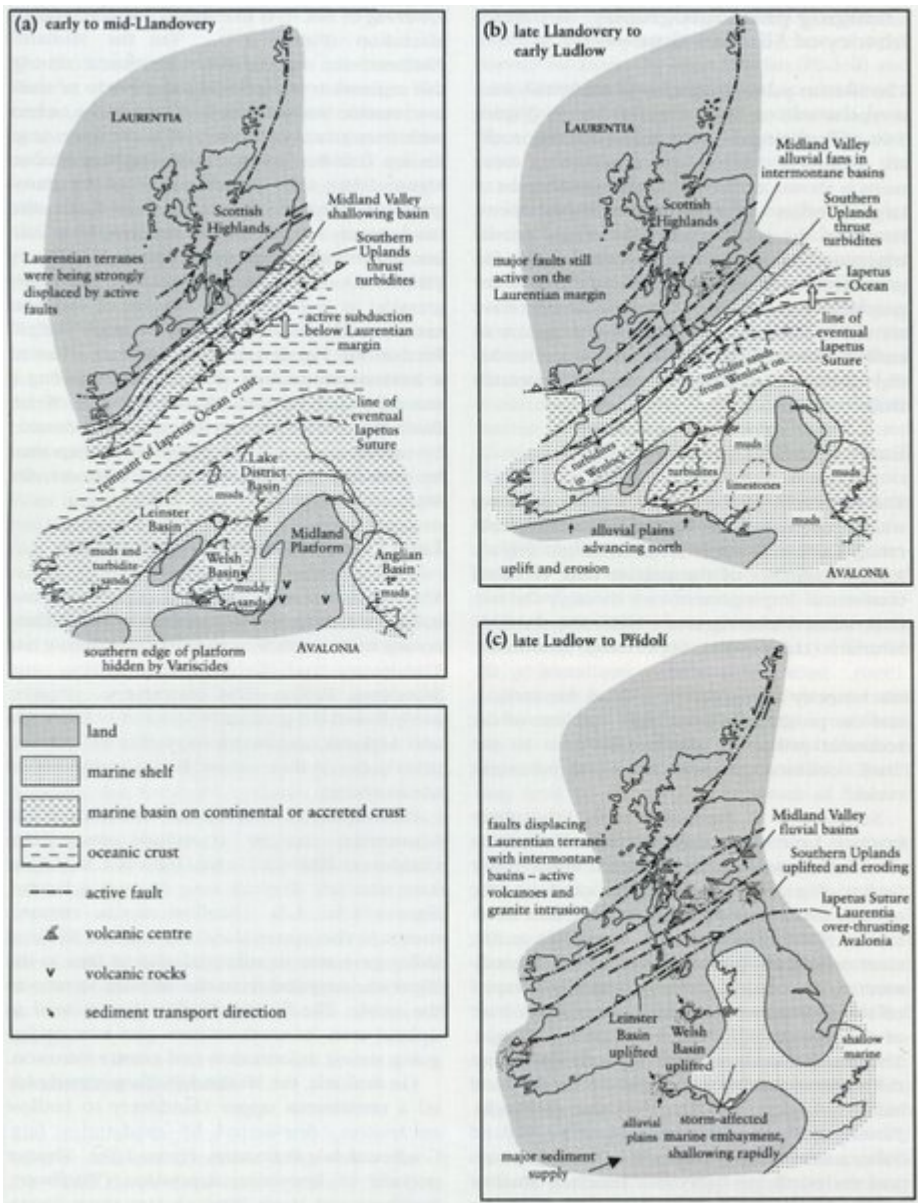
(Figure 1.6) The stratigraphical columns of successive tectonic slices across the south-west end of the Southern Uplands of Scotland (after Rushton et al., 1996). Inset shows the geometry of an accreting sedimentary prism.



(Figure 1.7) Palaeogeographic map at the time of the Ordovician–Silurian boundary (~440 Ma). (After Pickering and Smith, 1995.)



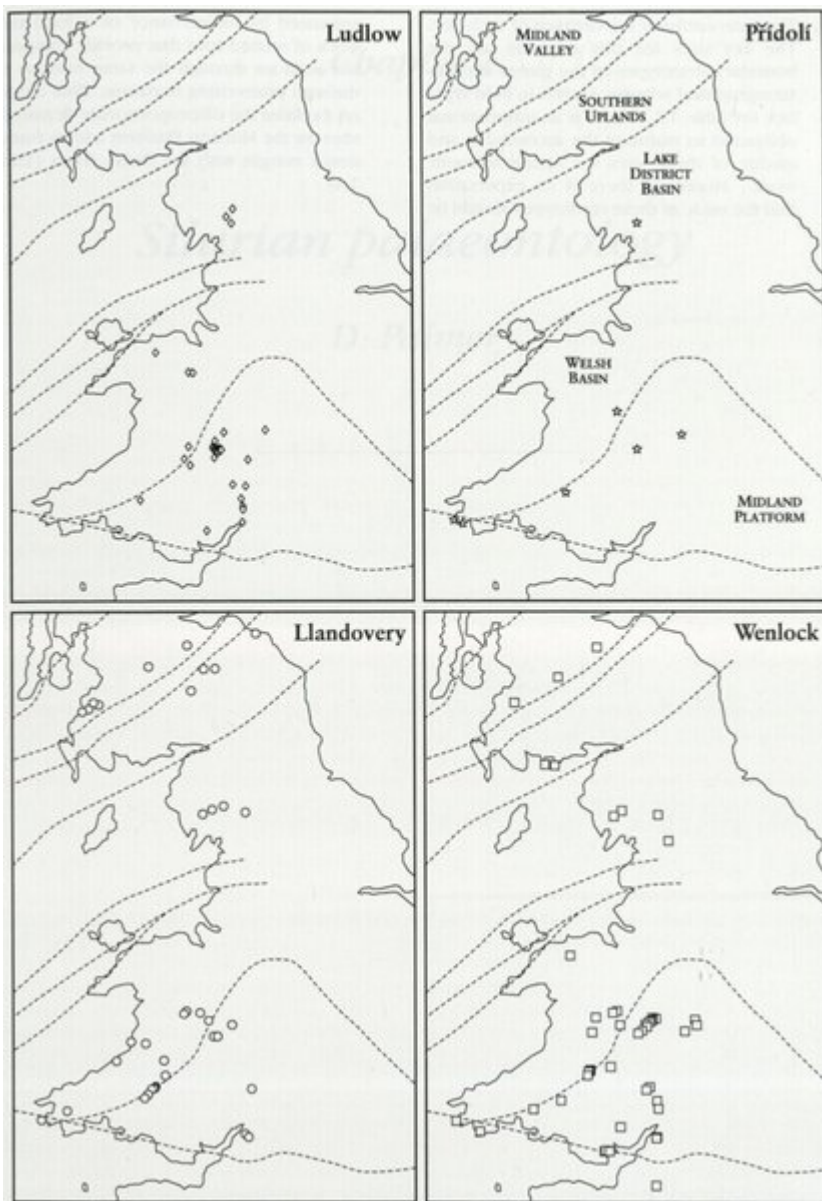
(Figure 1.8) Palaeogeographical elements of Silurian Britain.



(Figure 1.9) Palaeogeographical maps of Britain for three intervals of Silurian time: (a) early to mid-Llandovery, (b) late Llandovery to early Ludlow, (c) late Ludlow and Pridoli.

	Llandoverly	Wenlock	Ludlow	Pfidioli
Midland Valley	Gutterford Burn Birk Knowes Roughneck Quarry Blair Farm Penwhapple Burn Woodland Point	Lyne water and Lynsle Burn Ree Burn-Glenbuck Loch Knockgardner		
Southern Uplands	Old Cambus Quarry Thornylee Quarry Grieston Quarry Dob's Linn	Balmae Coast Meikle Ross		
Lake District Basin	Brow Gill Beck Skelghyll Beck Spengill Yewdale Beck	Brathay Quarries River Rawthey Torver-Ashgill Arcow Quarry	Tebay Cuttings Benson Knott Hills Quarry	The Helm
Welsh Basin	Meifod Craigyfulfran Rheidol Gorge Caban Coch Aberarth-Morfa	Penstrowed Quarry Ty Mawr	Tŷn-y-Floedd Quarry Clogau Quarry Dinas Brân	
Welsh Basin Margin	Banwy River Buttington Brickworks Cwm Clyd Quarry Scrâch Track Trefawr Track Cwm-Coed-Acron Coed Glyn Môch Track Fron Road Cilgwyn-Ydw Valley Gasworks Lane Marloes	Trewern Brook Buttington Brickworks Banwy River Treoed-Castle Crab Dulas Brook Coed-mawr Pen-cerig River Irfon Sawdde Gorge Wernbongam Marloes Freshwater East (south)	Beacon Hill Meeting House Quarry Mithil Brook and Cwm Blithus Sawdde Gorge	Lower Wallop Quarry Capel Ffloreb Quarry Little Castle Head Albion Sands and Gateholm Island
Midland Platform	Hope Quarry and Hope Brook Hughley Brook Hillend Farm Wistanstow Gullet Quarry Damery Bridge Cullimore's Quarry	Buildwas River Section Lincoln Hill Daw End Railway Cutting Farley Road Cutting Whitwell Coppice Hay Head Quarries Hughley Brook Easthope-Harley Hill Longville-Stanway Road Section Wren's Nest Eaton Track Burrington Dolyhir Quarries Little Hill Scutterdine Quarry Linton Quarry Hobbs Quarry Cwm-Ton Area Cibwrgi Quarry Brinkmarsh Quarry Buckover Road Cutting Rumney River Rumney Quarry Pen-y-Lan Quarry Moores Hill Quarry	Turner's Hill Upper Millichope View Edge Mocktree Quarries The Whitcliffe Church Hill Quarry Wignore Road Deepwood Mary Knoll Valley Pitch Coppice Bow Bridge Burrington Farm Stream Section Sunnyhill, Mary Knoll Valley Goggin Road Deer Park Road Elton Lane Aymestrey Quarries Woodbury Quarry Perton Road and Quarry Gurney's Quarry Linton Quarry Longhope Hill Wood Green Tites Point Brook House	Brewin's Canal Ludford Lane and Ludford Corner

(Table 1.1) GCR sites arranged by palaeogeographical setting and stratigraphical age



(Figure 1.10) Maps of the distribution of Geological Conservation Review sites from each Silurian series. For detail and site names see Figures 3.1 (Llandovery), 4.1 (Wenlock), 5.1 (Ludlow) and 6.1 (Pridoli).