Llandovery (LDY)

Block Description

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Introduction

The GCR sites selected for this GCR Block represent the British geological record of Earth history from about 440 to 428 million years ago (Ma). This interval is the first epoch of the the Silurian Period (440 to 410 Ma).

Rocks that formed during the Llandovery Epoch form the Llandovery Series (part of the Silurian System). The Silurian System is divided into four series (Llandovery, Wenlock (see Wenlock (WEN)), Ludlow (see (LUD)) and Prídolí (see PRIDOL)) and all but one series (the Pridoli) into a number of stages. The Llandovery Epoch is divided into three ages.

Of the eight stratotypes that define the bases to the Silurian stratigraphical divisions, seven are in Britain. The one exception is the base to the Prídolí Series. The chosen level for the base of the Devonian System in the Czech Republic 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 Prídolí Series therefore correlates with the lowest part of the 'Old Red Sandstone' (see **Non-Marine Devonian (NMAR-DEV)**). Graptolites and conodonts have yielded the most refined Silurian zonations, but analogous schemes exist for other groups, notably brachiopods, acritarchs and chitinozoans.

Palaeogeographical framework

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. This subdivision of Britain provides the template against which the network of important stratigraphical sites can be compared.

Laurentian elements

The Scottish Highlands have their south-eastern limit at the Highland Boundary Fault. Non-marine sedimentary rocks of probable Ludlow and Prídolí 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.

The Southern Uplands of Scotland now lie between the Southern Uplands fault and the Iapetus Suture. Their formation is interpreted as a thrust stack of deep-water sediments.

Avalonian elements

The Midland Platform is the stable core of the Eastern Avalonia continent lying south-east of the Welsh Borderland fault system. During Silurian time it was flooded more persistently by shallow seas but accommodated only modest thicknesses of sediment. In latest Silurian (Prídolí) 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. Ithosted deep marine environments, and accumulated some kilometres of sediment. In late Ludlow and Prídolí 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 boreholes, but its sedimentary history has the same shallowing upwards character as that of Silurian Wales.

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 sequence 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 sequences 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. Sedimentary environments became shallower during Prídolí time as sediment input exceeded subsidence, and in Early Devonian time the area was uplifted in the culminating events of the Acadian Orogeny.

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 Early Palaeozoic time. 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. 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 (Prídolí) time into the Devonian. The continental collision culminated in strong deformation, uplift and erosion of the basinal sediments during Early and Mid-Devonian time, an event termed the ‘Acadian Orogeny’.

Palaeogeographical elements of Silurian Britain

Early to Mid-Llandovery: Subduction of Iapetus oceanic lithosphere beneath Laurentia continued from Ordovician time. Deep-marine mudstones (Moffat Shale Group) deposited on the oceanic crust were overlain by turbidite sandstones (Gala Group) as the crust neared the trench. Segments of this sedimentary sequence 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 clastic 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. 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). The pulsed nature of the transgression 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, 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. 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) at least into late Wenlock time (Riccarton Group). 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 sequence, dominated by mudstones (e.g. Coalbrookdale Formation). Shorter periods of limestone deposition (Woolhope, Buildwas and Much Wenlock Limestone formations) coincide with postulated lowstands on the eustatic sea-level curve. 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 Prettania. The sediment was accommodated by an episode of crustal stretching and subsidence in the basin.

The Lake District Basin accumulated mostly mudstones until early Wenlock time (e.g. Brathay Formation), receiving the first substantial turbidite sands into its south-eastern part in the mid-Wenlock. The main influx of sand was not until early Ludlow time (Coniston Group). 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 Prídolí

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 clastic 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 Prídolí, 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 (**see Marine Devonian (MAR-DEV)**).

GCR site selection

Three criteria have been particularly important in choosing the GCR sites:

• The chronostratigraphical position of rocks at each site.

• The palaeogeographical setting of each site.

• The international importance of each site. The key sites here are the boundary stratotypes of the global chronostratigraphical scheme

For site selection, the subdivision into palaeogeographical areas, each with a distinctive Silurian record of subsidence or uplift, sedimentation or erosion, was an important consideration. The areas, described above, provide the framework within which stratigraphical sites can be compared.

Although the relatively common invertebrate fossils do not have a separate selection category in the GCR in their own right, the scientific importance of many stratigraphy sites lies in their fossil content. Therefore, some of the GCR sites are selected specifically for their fossil fauna, which facilitates stratal correlation and enables the interpretation of the environments in which the animals lived. Moreover, some sites have international significance because they have yielded fossils that are the 'type' material for a taxonomic group.

Palaeontology

Silurian times are now known to have been occupied, from the beginning, by representatives of most of the major groups (phyla) of extant marine animals. From free-swimming fish and cephalopods to sedentary bottom dwelling corals, clams and actively burrowing worms, the Silurian biota has some taxonomic familiarity to us today. However, there are also many important differences: almost all of the organisms belong to different genera and most belong to extinct family groupings; a significant number of the important marine groups, such as the trilobites, graptolites and conodonts are members of the distinctive and extinct Palaeozoic fauna. The dominant shelly macro-invertebrates of Silurian times were brachiopods, a relatively uncommon group today, whose habitats have been taken over by the bivalved molluscs. The main biological 'innovations' of the Silurian are associated with the radiation of the fish and the invasion of the land by animals and plants.

The late Ordovician glaciation, with its lowered sea levels and major changes in ocean circulation, produced a significant marine extinction at that time. Many invertebrate groups were severely affected but most made fairly rapid recoveries in early Silurian time. However some, notably the trilobites, never fully recovered.

The typical Lower Palaeozoic biota includes brachiopods, trilobites, graptolites, cephalopods (important in stratigraphic correlation) conodonts, bivalved molluscs and gastropods, but

important microfossils in Silurian strata include acritarchs, chitinozoans, plant spores, scolecodonts, radiolarians and foraminiferans.

Also important were the sessile, bottom-dwelling invertebrates, of which many secrete preservable siliceous or calcareous skeletons such as the sponges, stromatoporoids, corals and bryozoans.

The fossil record of arthropods in Silurian times was almost entirely marine, but for the very rare remains of some of the earliest known land-living animals. The marine forms are dominated by two groups, the extinct trilobites and the crustacean ostracods. Of lesser biostratigraphic important are numerous other arthropod groups, such as the phyllocarids, xiphosurans, eurypterids, scorpions and myriapods.

The Silurian fossil record of the echinoderms contains sporadic remains of the main living and extinct groups from the blastoids, cystoids, crinoids, asteroids, holothurians and echinoids to the ophiuroids.

Somewhat like jellyfish in life habits, the graptoloid graptolites (with millimetre wide branches and an overall colony diameter of up to a metre) were, for the most part, free-living animals that probably fed on the plankton and followed its diurnal migration within the surface waters of the oceans. They are an important group stratigraphically.

The land-plant fossils are, at first glance, unspectacular in that they are generally small (1–4 cm high), carbonized thin stems with simple dichotomous branches, terminated by globular reproductive organs. This plant fossil evidence from the British sites has been of international importance in developing our understanding of early vascular plant evolution. The most commonly preserved plant fossils are their microscopic reproductive spores, which are produced in great numbers. The abundance, wide dispersal and evolution in morphology of these plant spores has made them very useful biostratigraphical markers and has led to the development of spore-based biozonal schemes.