Stratigraphy and plate tectonic models 1

In North Wales we can identify three geologically distinct **terranes** which developed before the Ordovician period:

- Deformed and metamorphosed rocks of late Precambrian to Cambrian age forming the north-western part of the ***Lleyn peninsula***. These include gneiss, schist and tectonically deformed slump deposits known as mélange. This is known as the **Monian terrane**.
- A thick sequence of Cambrian sediments dominated by coarse grits and sandstones in the central ***Harlech Dome*** and ***St Tudwal's peninsula*** of Lleyn. These rocks were formed in a marine basin, mainly by turbidity currents, and are relatively undeformed. This is known as the **Megumia terrane**.
- Cambrian rocks in the ***Arfon*** area of northern Snowdonia containing large thicknesses of muds, now converted to slate, which contrast with the coarser sediments of the Harlech Dome. This is known as the **Arfonian terrane**.

These early terranes developed separately but were brought together at the end of Cambrian times by lateral movements along the major crustal fractures of the Menai Strait Fault Zone.

Throughout the Ordovician and Silurian periods, North and Mid-Wales formed a single terrane, with similar geological processes operating simultaneously across the whole of the region. Much of the Ordovician was dominated by the eruption of volcanics, whilst the Silurian saw a return to the quiet deposition of great thicknesses of sediment.

In the following sections, we outline the general stratigraphy of each of the terrane blocks, then discuss plate tectonic models which could account for their origin.

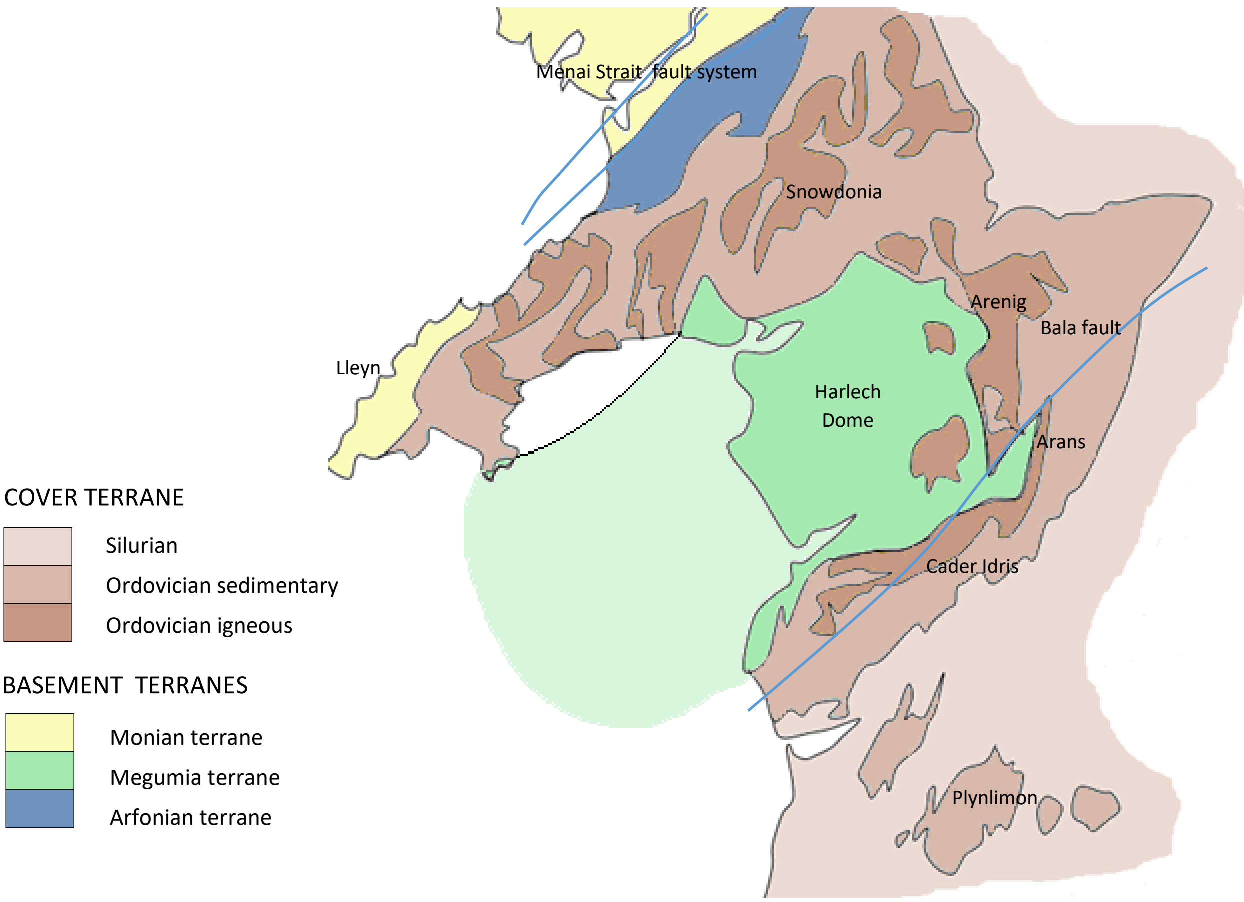


Figure 2: Terranes of North Wales

Monian of the Lleyn peninsula

A sequence of heavily deformed sedimentary and igneous intrusive and extrusive rocks are found in Anglesey and the Lleyn peninsula. All show some degree of metamorphism, reaching schist and gneiss grade in places. This whole sequence has been termed the ***Mona Complex***. The group was originally considered to be Precambrian, but some components have now been shown to be Cambrian in age.

The lowest grade of metamorphism is seen in rocks of the ***Gwna Group***, exposed in a series of spectacular cliffs and bays along the north-west coast of the Lleyn peninsula.

The rocks of the Gwna Group can be divided into two contrasting types:

- ***Ocean plate stratigraphy***: basalt pillow lavas and related deep ocean floor sediments, thought to represent remnants of ancient oceanic crust which were scraped from a descending oceanic plate at a subduction zone.
- ***Mélange***: disturbed large scale conglomerates showing evidence of unstable conditions. These deposits originated as bedded shelf sediments along a continental margin, then slumped into the deep marine trench along a subduction zone.

In contrast to the low grade metamorphic rocks of the Gwna Group, a band of high grade gneisses and associated igneous rocks crosses central Lleyn, where unfortunately the exposure of outcrops is poor. These rocks, known as the ***Sarn Complex***, have been shown by radiometric dating to be Precambrian in age. They represent the continental crust of the early island arc of Avalonia, below which the later subduction of oceanic crust took place during Gwna Group times.

An unusual rock type observed in the Mona Complex of Lleyn is a schist showing a strong deformation fabric and containing minerals formed under very high pressure. It is thought that the metamorphism took place as sediments were dragged downwards by the subducting plate, but later returned to the surface due to buoyancy of the rock slab.

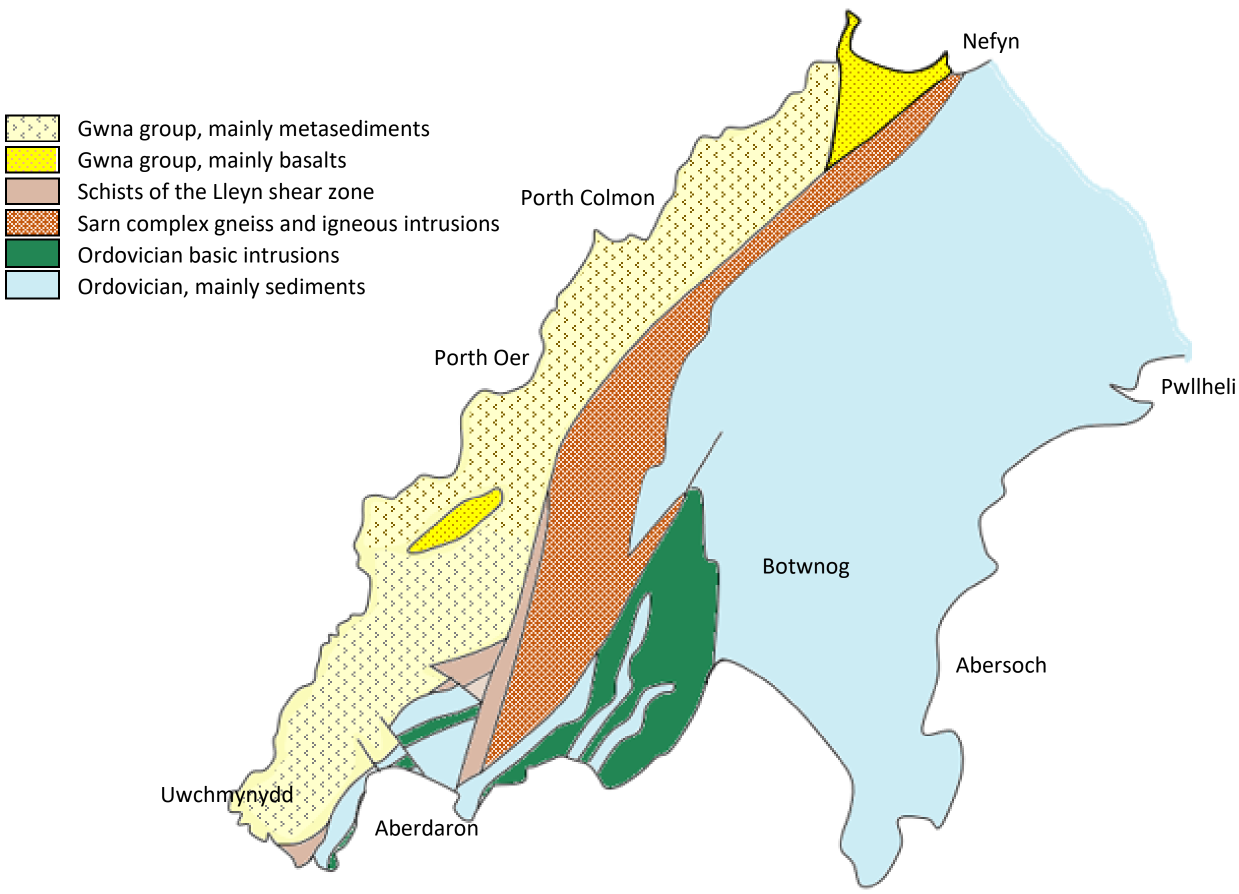


Figure 3: Geological structure of the western Lleyn peninsula

Figure 4: Rocks of the Mona Complex, Lleyn peninsula:

(upper left) Basalt pillow lavas of the Gwna Group

(upper right) Large scale slump deposits of the Gwna Group, known as mélange.

(lower left) Deformed schist rocks of the Lleyn shear zone.

(lower right) Mafic gneiss.

Cambrian of the Harlech Dome and St Tudwal's peninsula

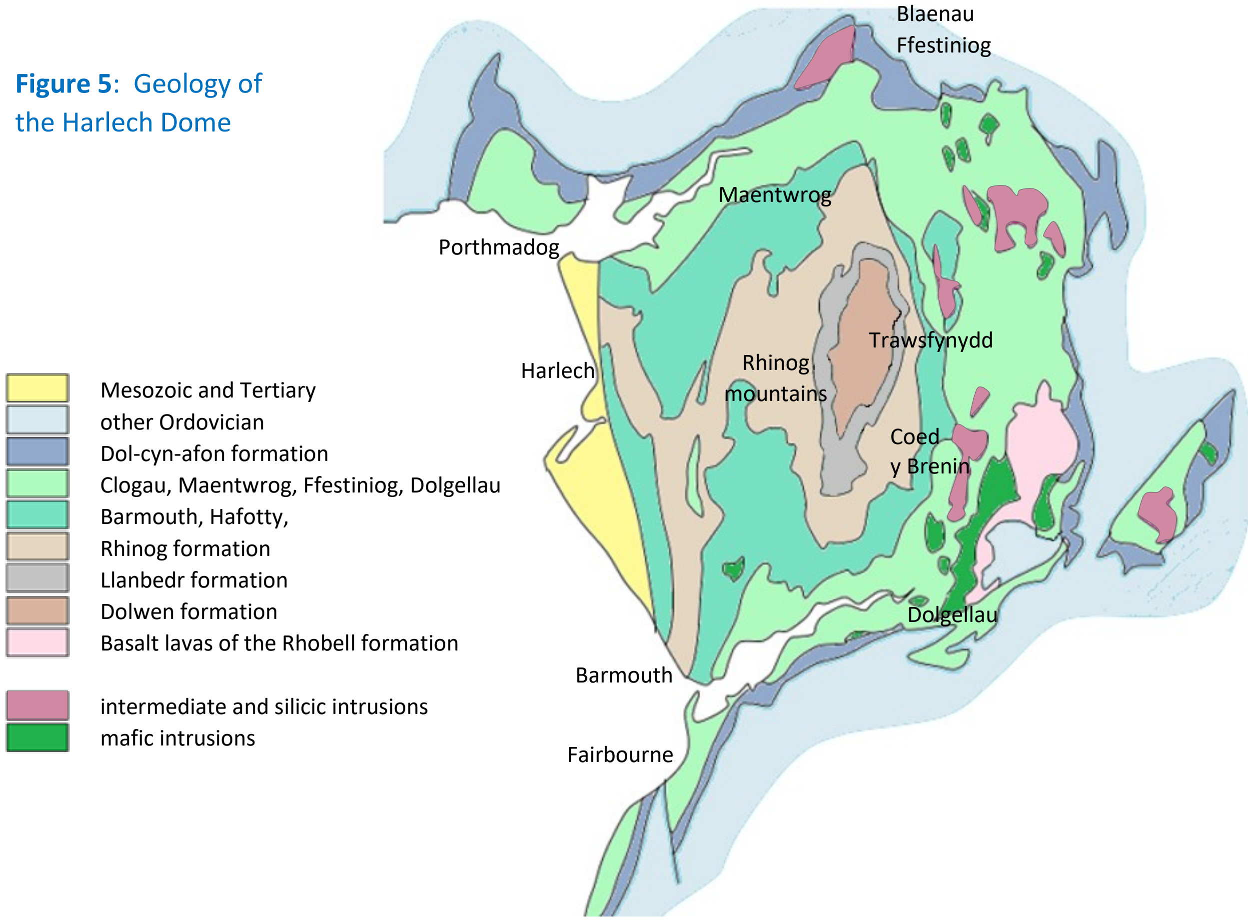
The main Cambrian outcrop lies inland from the coast of Cardigan Bay in a region known as the Harlech Dome, extending from Barmouth in the south to Porthmadog in the north, and inland to Trawsfynydd (fig. 5).

During Cambrian times, much of North Wales was occupied by a marine basin into which sediments were deposited from the surrounding landmasses. The Cambrian rocks in this area can be divided into a lower sequence, the ***Harlech Grit Group***, and an upper sequence, the ***Mawddach Group*** (fig. 6).

The Harlech Dome has been deeply eroded after uplift, exposing the oldest rocks of the Harlech Grits Group at its core. Within this group, the massively bedded and resistant Rhinog Grits form a range of high mountains. Folding complicates the outcrop pattern to some extent, but there is a general progression outwards towards the younger Cambrian sediments of the Mawddach Group. These thinly bedded and finer grained rocks have been eroded into deep river valleys in the picturesque forested area of Coed y Brenin.

Typical lithologies of Cambrian rocks are shown in fig. 7, representing a general progression in the Harlech Dome from coarse sandstones, often containing pebble conglomerates, through bedded siltstones, to fine grained mudstones.

Figure 5: Geology of the Harlech Dome



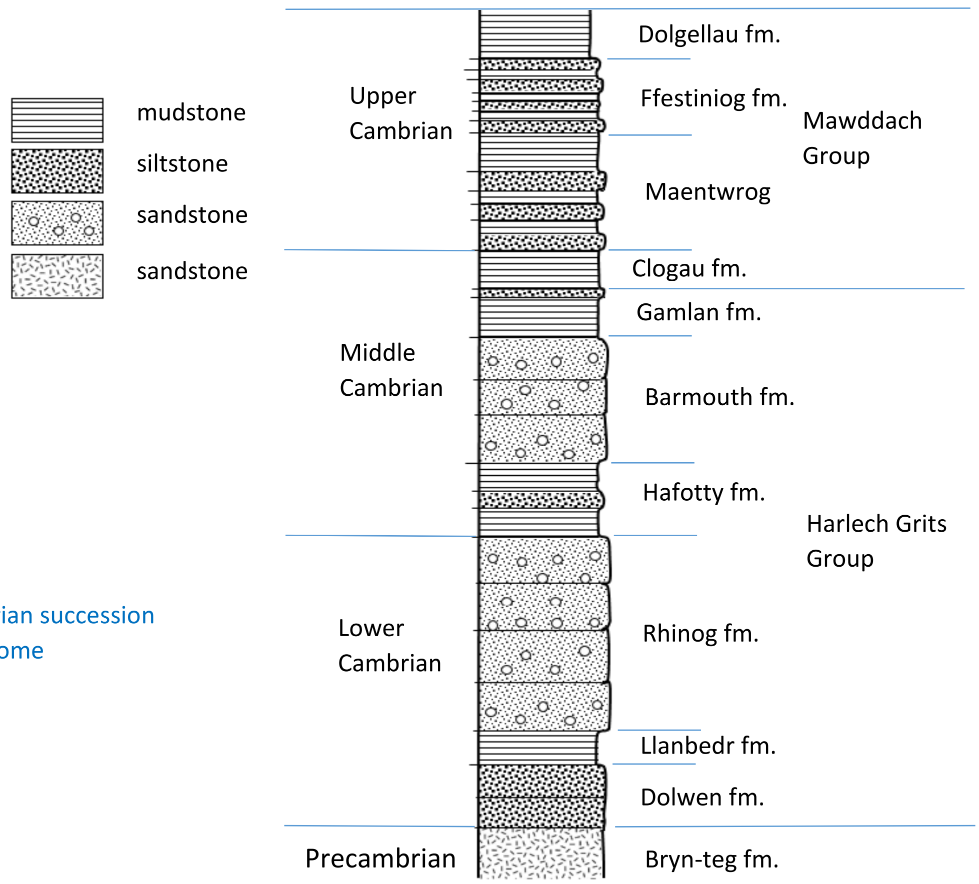


Figure 6: Cambrian succession in the Harlech Dome

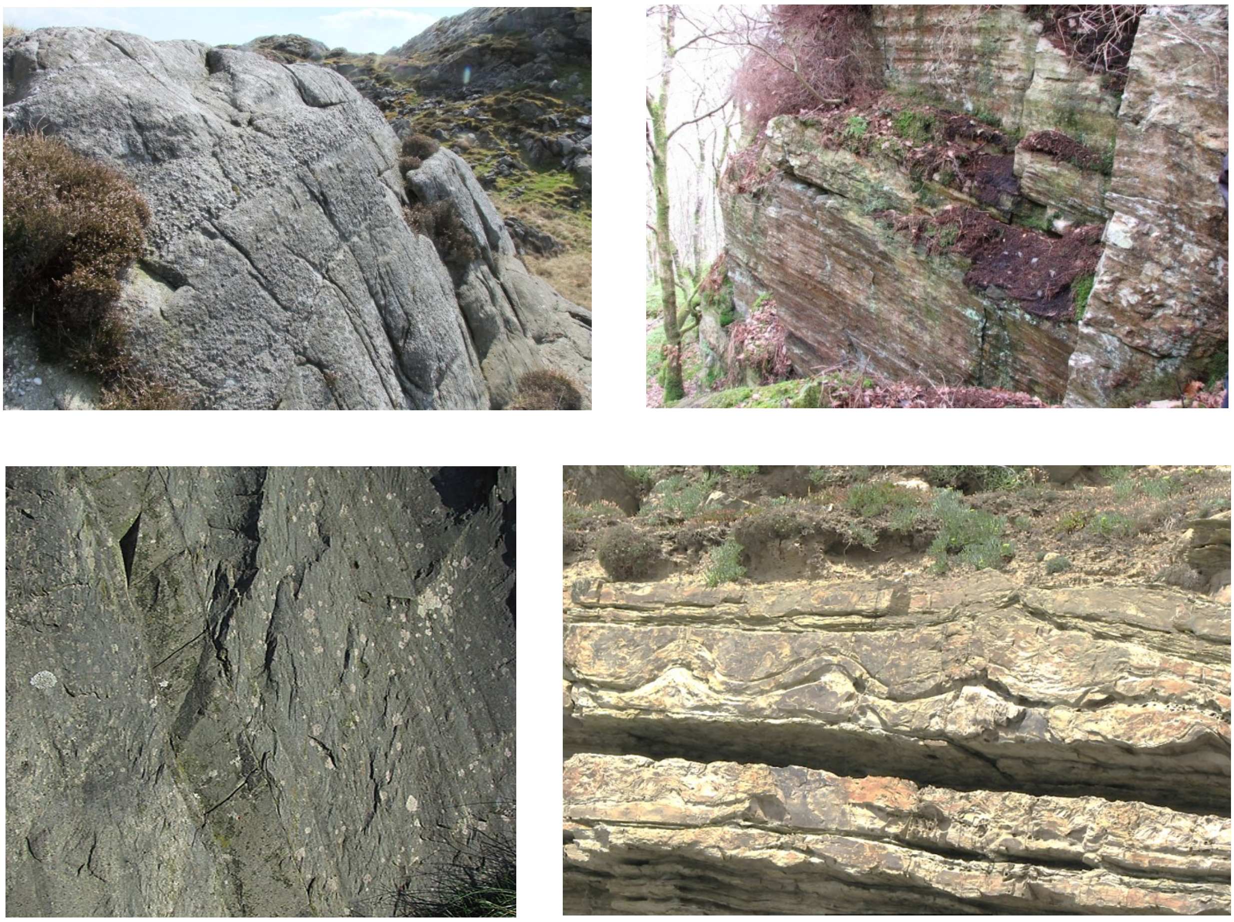


Figure 7: Cambrian rocks of the Harlech Dome and St Tudwal's peninsula:

(upper left) Sandstone and conglomerate of the Barmouth Grit, Barmouth
(upper right) Thinly bedded mudstone and siltstone of the Maentwrog formation, Barmouth.
(lower left) Mudstones showing slaty cleavage, Dolgellau formation, Barmouth.
(lower right) Ripple bedded sandstone, Ffestiniog formation, St Tudwal's peninsula.

A small outcrop area of the Cambrian marine basin sediments also occurs on the southern coast of Lleyn at St Tudwal's peninsula. Some upper Cambrian sediments in this area show characteristics of deposition in shallow water, so the coastline of the basin may have been near to the west of Lleyn at this time.

The Arfon Basin

Another succession containing Cambrian rocks outcrops in the north of Snowdonia, but has very different characteristics to the sediments of the Harlech Dome and St Tudwal's peninsula. This succession, in an area known as the ***Arfon Basin***, is dominated by a large thickness of high quality slate which has been extensively quarried in Nantlle, Llanberis and Bethesda.

The succession begins with the Padarn **tuff**, a volcanic ash deposit which has been radiometrically dated as Precambrian age.

The overlying Fachwen formation is a sandstone and conglomerate derived largely from erosion of the volcanoes which formed the Padarn tuff, and is again of Precambrian age. These beds are overlain by the Llanberis Slates formation of definite Cambrian age.

The muds which produced the Llanberis slates were deposited in a down-faulted marine basin. This basin was probably separated to the north-east of the Harlech basin along the line of the Menai Fault zone. The Arfon basin succession forms a distinct terrane block which has been moved to its present position by transverse faulting along the fracture zone.

Figure 8: Geology of the Arfon basin

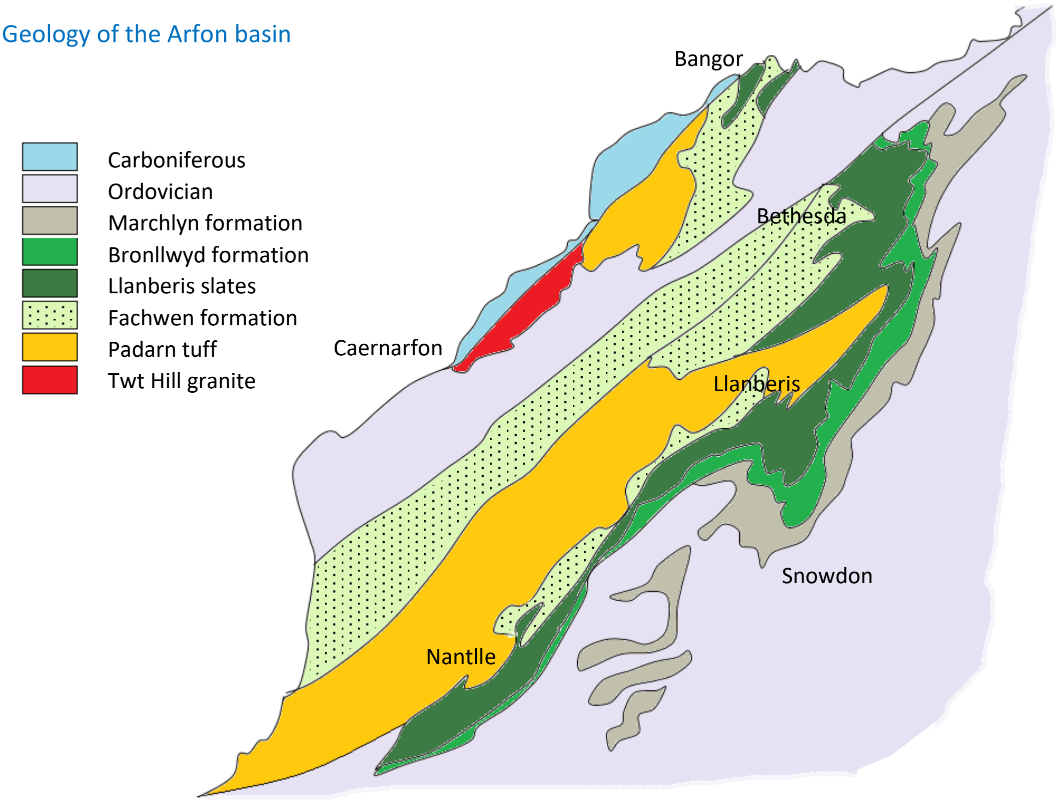


Figure 9: Rocks of the Arfon basin:

(upper left) Padarn tuff, Llanberis

(upper right) Conglomerate of the Fachwen formation, Moel Tryfan.

(bottom left) Llanberis slate, Llanberis

(bottom right) Bronllwyd Grit, Cwm Grainog

The upper Cambrian rocks of the Arfon basin, the ***Bronllwyd*** and ***Marchlyn*** formations, are composed of coarser sediments. They have some similarity to the Ffestiniog formation of the Harlech Dome, so there is a possibility that the fault movements which brought the basins together occurred in upper Cambrian times before deposition of the Bronllwyd and Marchlyn formations.

Ordovician volcanics

By the end of the Cambrian period, the contrasting terranes of the Harlech Dome, the Arfon basin and the Monian of Lleyn had moved into their present relative positions. North and Mid-Wales experienced a shared sequence of events during subsequent geological periods.

At the start of the Ordovician, during the **Arenig series**, the region was covered by shallow seas and widespread deposition of sandstones and conglomerates occurred. A localised volcanic centre developed at ***Rhobell Fawr*** near Dolgellau, erupting basalt lavas and giving a first indication of the volcanic activity which was to extend widely across the region and dominate the Ordovician geology of North Wales.

Following the Rhobell event, a series of volcanic centres became active around the Harlech Dome. Activity was initially focussed on ***Cader Idris*** and the ***Aran mountains***, close to the lines of the Rhobell and Bala-Mawddach fault zones which provided easy routes for magma to rise through the crust.

Volcanic activity spread progressively northwards to the ***Arenig*** and ***Moelwyn*** areas, culminating in a major phase of eruptions in central Snowdonia during the **Caradoc epoch** of the later Ordovician.

The Ordovician volcanic rocks around the south and east of the Harlech Dome are known as the ***Aran Volcanic Group***. A simplified outcrop map is given in fig. 11, and comparative stratigraphic sequences in fig. 12.

The Aran Volcanic Group is thickest and most complete at Cader Idris, with some of the central formations absent from outcrops in the Aran and Arenig mountains.

A wide variety of extrusive rock types are present in the Aran Volcanic Group; some examples are shown in fig. 13. An important characteristic is that the rocks are strongly bimodal. Low silica basalts and high silica rhyolites are well represented, but few rocks of intermediate silica content are present. Basalt magma was erupted as pillow lavas and bedded ashes. Rhyolitic rocks include **ignimbrite** deposits in which particles of hot ash became welded together to produce massive solid layers.

The Aran Volcanic Group was deposited almost entirely under water, either directly by eruptions from sea floor vents, or in the shallow waters surrounding volcanic islands. The sequence shows many sedimentary features, including volcanic ashes redistributed by water currents, and sands and muds laid down in the intervals between eruptions. Particularly spectacular are volcanic mudflows, produced as ashes and larger blocks of debris slumped into the waters around a volcanic cone.

Figure 10: Early Ordovician rocks of the Dolgellau area:
(left) Sandstone of the Arenig stage, Rhobell Fawr.
(right) Basalt lava flows with a rubbly texture, Rhobell Fawr.

Figure 11: Outcrop of the Aran Volcanic Group

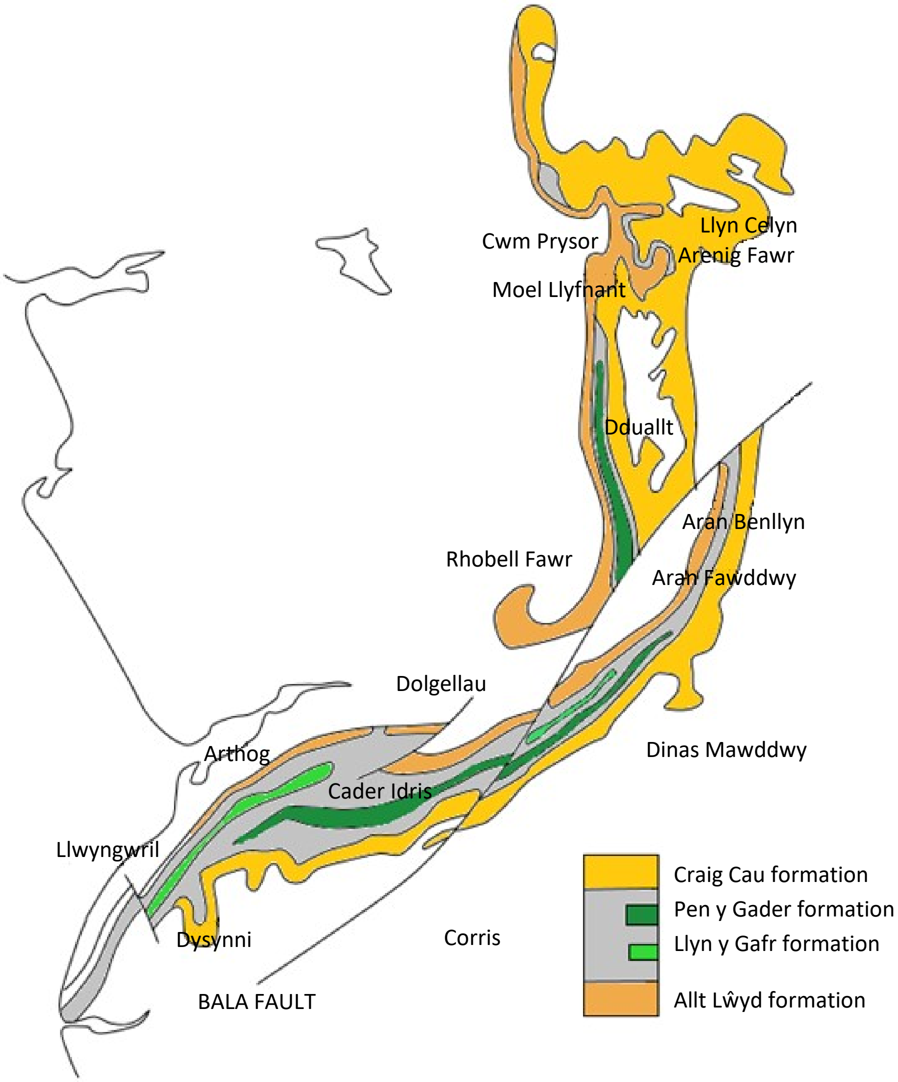


Figure 12: Stratigraphy of the Aran Volcanic Group

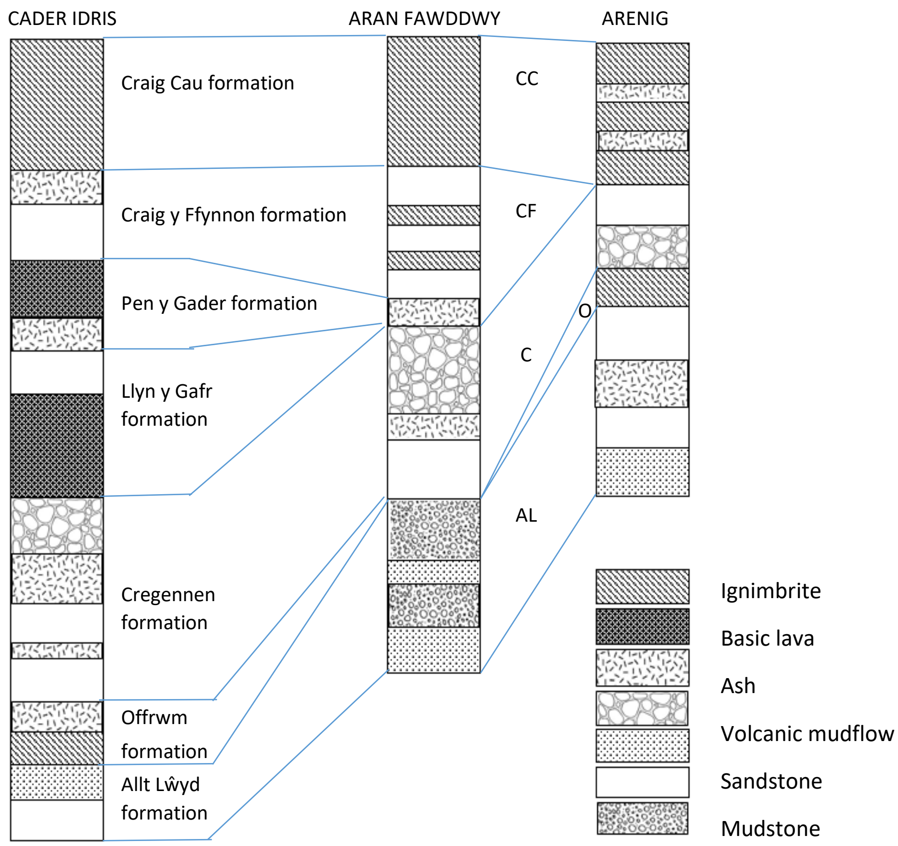


Figure 13: Extrusive rocks of the Aran Volcanic Group:

(upper left) Rhyolitic ignimbrite, Mynydd Moel, Cader Idris.

(upper right) Basalt pillow lavas, Pen y Gader, Cader Idris.

(bottom left) Basaltic ashes, Cregennen.

(bottom right) Volcanic mud flow, Cregennen.

Volcanic activity reached its maximum intensity during the Caradoc epoch, towards the end of the Ordovician period. Eruptions of great thicknesses of ignimbrite ashes continued at the Cader Idris, Aran and Arenig volcanic centres. However, the most extensive volcanism occurred in the Snowdon area (Woodcock, N. H. (2009).

Two phases of volcanic activity have been identified around Snowdon. The first, the ***Llywelyn Volcanic Group***, was erupted to the east of the region at a number of centres from Conwy to Nant Ffrancon. The second phase, producing the ***Snowdon Volcanic Group***, was localised in the current mountain area between Beddgelert and Capel Curig.

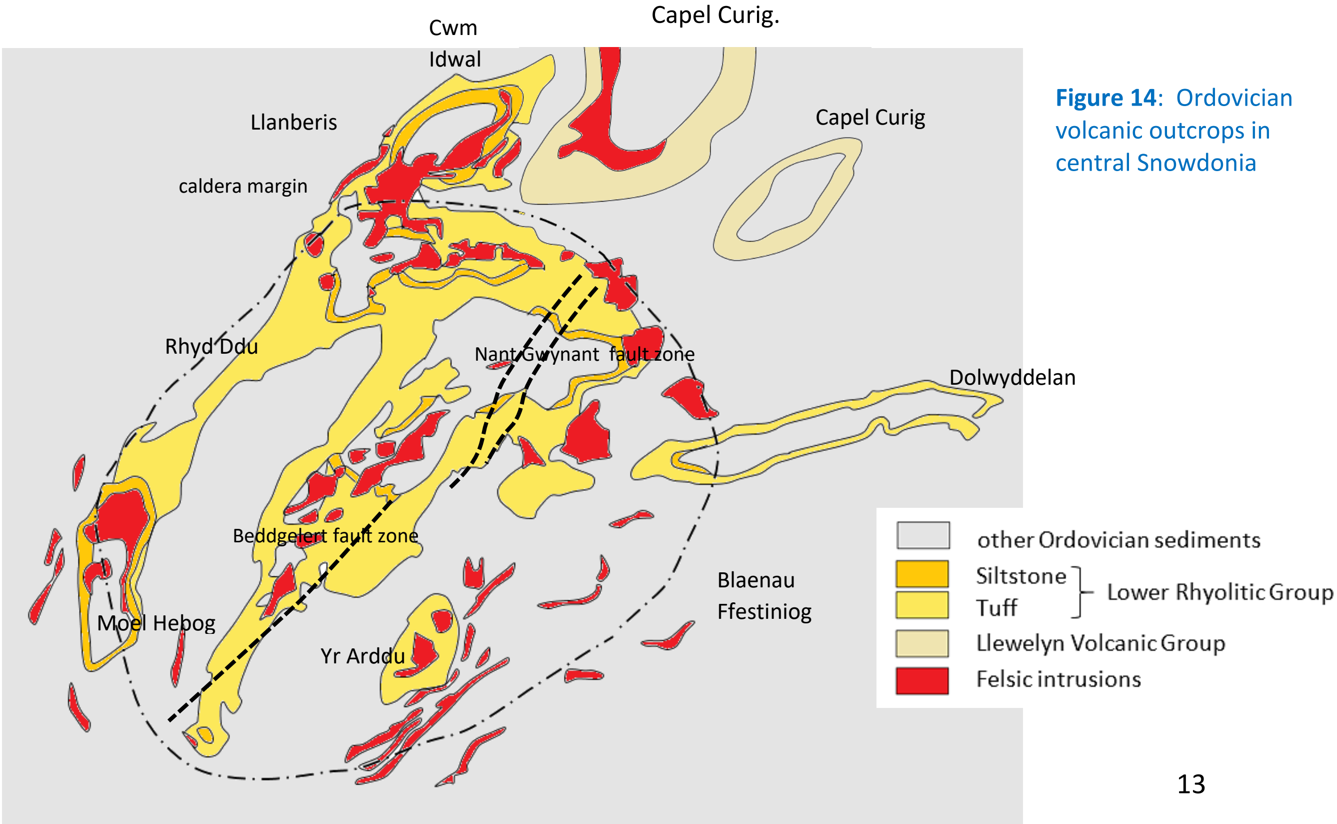


Figure 14: Ordovician volcanic outcrops in central Snowdonia

Figure 15: Rocks of the Snowdon Volcanic Group:

(upper left) Bedded ashes, Moel Hebog
(upper right) Ignimbrite flow, Yr Arddu.
(lower left) Flow banded rhyolite intrusion, Yr Arddu

Eruptions of the Snowdon Volcanic Group began along the deep crustal fractures of the ***Beddgelert*** and ***Nant Gwynant fault zones***, which provided an easy route for magma to rise to the sea bed of the Ordovician Welsh basin. Over a period of time, however, magma accumulated in large quantities at shallow depth below the fault zones to produce an extensive magma chamber roughly circular in plan. Eventually the crust above the magma chamber subsided as a caldera, allowing eruptions to take place at a series of centres around the circular fracture. Igneous intrusions representing the cores of these eruptive centres can be found at ***Yr Arddu***, ***Moel Hebog***, and on Snowdon itself.

As in the Aran Volcanic Group, the volcanics of Snowdon show a strong bimodal distribution. Basalts, and rhyolitic ashes and ignimbrites, are well represented but extrusive rocks of intermediate silica content are rare.

Upper Ordovician and Silurian of mid-Wales

Volcanic activity died out in North Wales by the end of the Caradoc epoch of the Ordovician. The final events of the Ordovician were dominated by the deposition of large thicknesses of mud in a subsiding Welsh marine basin. This mud was later converted into slate, creating the economically important quarrying areas of Blaenau Ffestiniog and Corris.

The Silurian in Wales was a period of continuing marine sedimentation, when large thicknesses of muds and fine silts were deposited, along with some coarser sands and pebbly grits. The originally flat lying beds were subsequently folded into a series of dome structures around Plynlimon , which have been eroded to expose older Ordovician sediments in their cores.

The Welsh marine basin of the later Ordovician and throughout the Silurian appears to have been an area of crustal tension, allowing faulted blocks of the sea bed to subside to produce a deep elongated trough. This had a controlling effect on sedimentation, with sand, silt and mud discharging laterally into the deeper waters from the shallow trough margins, then carried both along the axis of the deeper trough (Schofield, 2009).

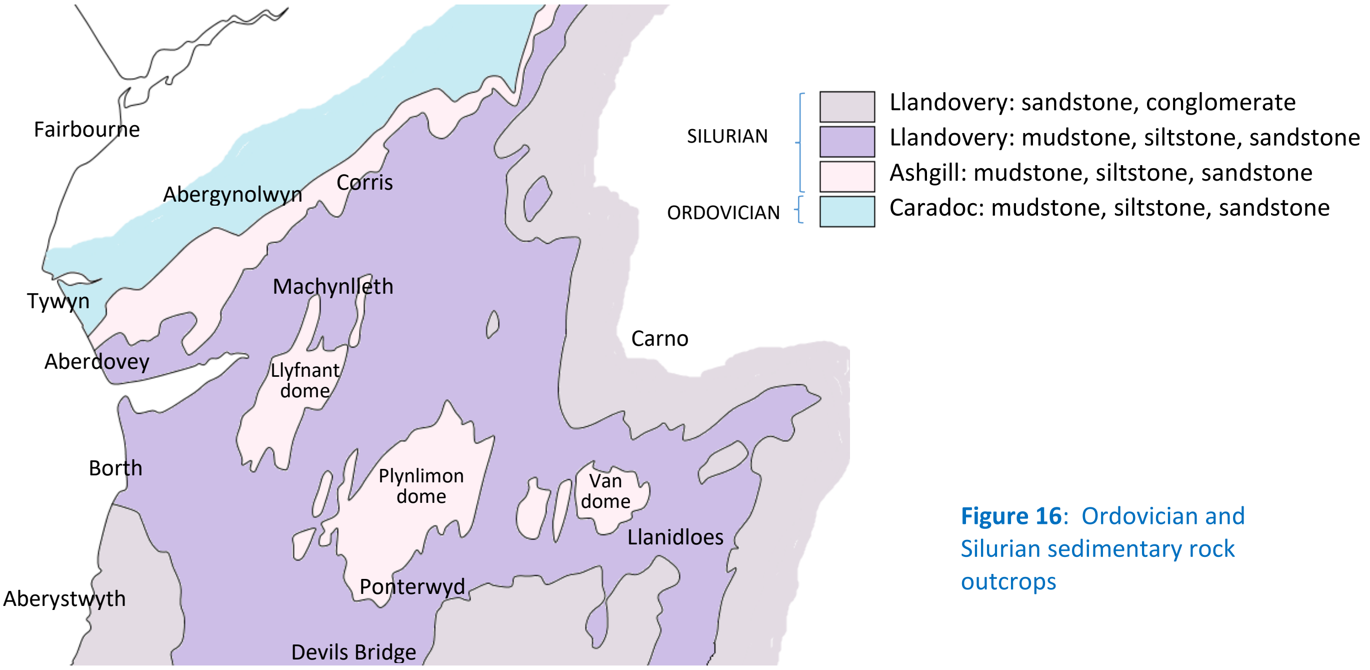


Figure 16: Ordovician and Silurian sedimentary rock outcrops

Figure 17: Ordovician and Silurian sedimentary rocks of Mid-Wales:
(upper left) Ordovician slate, Corris.
(upper right) Ordovician Sandstone, Plynlimon.
(bottom left) Silurian mudstones and grits, Aberystwyth.
(bottom right) Soft sediment deformation in slumped Ordovician strata, Plynlimon.

A plate tectonic model for the early development of Wales

To gain an understanding of the present-day geology of North and Mid-Wales, we need to begin by examining the plate tectonic history of the region.

Several specialist techniques have been used to develop plate tectonic models:

- Palaeomagnetic studies, combined with radiometric dating, can determine the latitude and orientation of crustal plates at particular geological times. However, the range of rocks suitable for palaeomagnetic measurement and radiometric dating is limited, so data on plate movements may be incomplete.
- Palaeontological studies can identify crustal areas where similar marine faunas have developed, or where evolutionary pathways diverge. Where shallow water fauna were unable to cross an extensive ocean basin, evidence of similar or separate evolution can determine the closeness or separation of blocks of continental crust at different geological times.
- Detrital zircon analysis, which can determine the age of grains in sandstones. The mineral zircon is a minor constituent of igneous rocks such as granite. It is highly resistant to weathering, so can persist in the environment for many millions of years as sand grains, which may then be incorporated into younger sedimentary rocks. When the age of zircon grains in a sandstone is known, geologists can look for igneous rocks of the same age which could have provided a source for the sediment.

Figure 18: Plate tectonic reconstruction for the late Precambrian

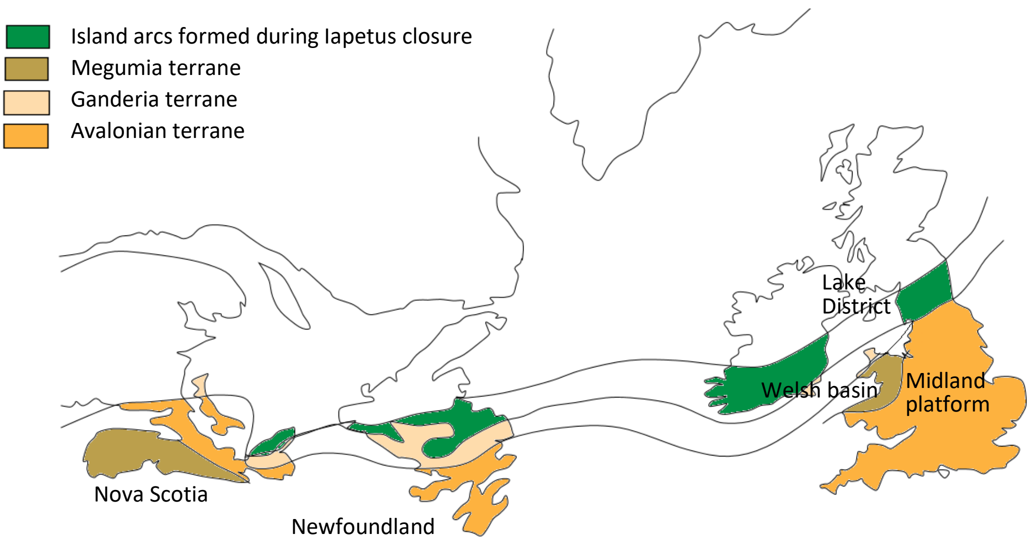


Figure 19: Geological terranes of Britain and the Atlantic provinces of Canada.

Using palaeomagnetic evidence for the late Precambrian, it is thought that Wales formed part of a microplate known as Avalonia which was positioned alongside the major continent of Gondwana. At this time, Gondwana lay far to the south, close to the South Pole (fig. 19).

Scotland and the north of Ireland formed part of a different plate, Laurentia, which was separated from Gondwana by the Iapetus ocean. The story of late Precambrian to Silurian evolution of Wales will chart the breaking away of Avalonia from Gondwana, and the movement of the microcontinent across the Iapetus ocean to dock with Laurentia and finally bring together northern and southern Britain.

To develop a model for the early plate tectonic history of southern Britain, it is necessary to consider not only the British Isles but also the Canadian provinces of Newfoundland and Nova Scotia (Waldron et al., 2011). These areas were geographically close before the opening of the Atlantic Ocean in relatively recent geological times.

Across central England, southern Ireland, and into Newfoundland are found outcrops of island arc volcanic and intrusive rocks of late Precambrian age. These were formed as subduction in the Cadomian Ocean carried the ***Avalonian microcontinent*** towards the coast of Gondwana (fig 20a). Late Precambrian basalts are found in the the Gwna Group of Lleyn, and may represent remnants of the Cadomian ocean floor preserved at the subduction trench during this event.

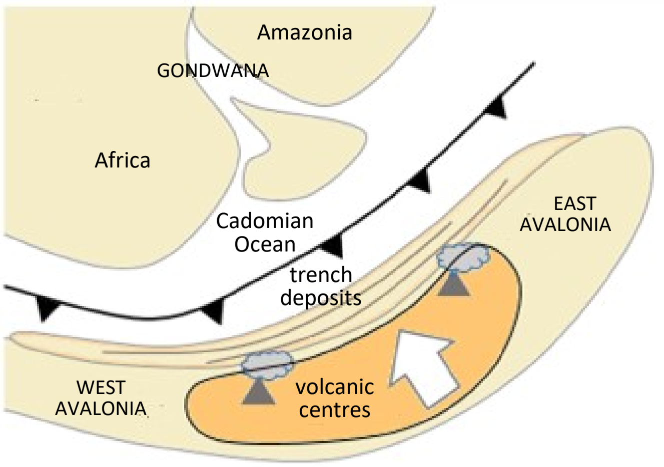


Figure 20(a): Late Precambrian development of the Avalonian microcontinent

We now move forward to the Cambrian period. Rocks formed at this time in the Harlech Dome area of North Wales appear very similar to rocks of the Meguma region of Nova Scotia, Canada, and it is likely that both sequences were deposited within a single marine basin. Together, the fragments form the ***Megumia terrane*** (fig.20b) of sedimentary strata relatively unaffected by metamorphic processes.

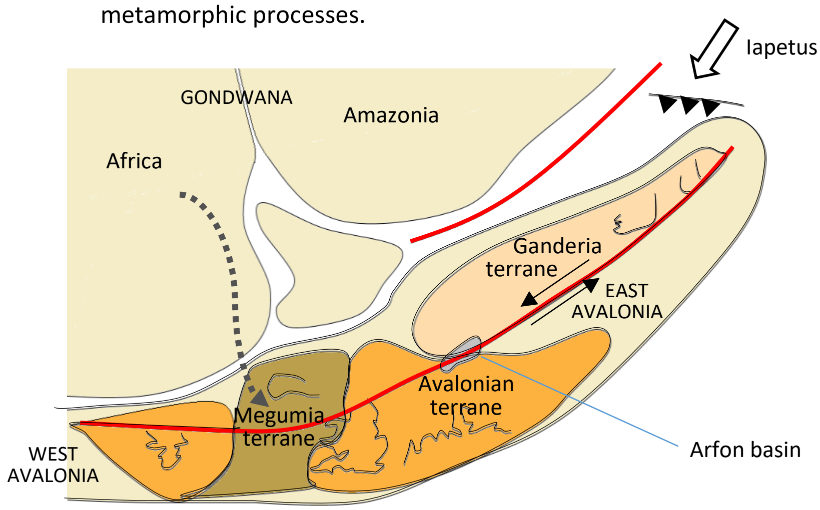


Figure 20(b): Early Cambrian development of the Avalonian microcontinent

By contrast, the Gwna Group of rocks in Anglesey and the Lleyn peninsula are often highly fragmented and metamorphosed. These strata have a strong similarity to outcrops in central Newfoundland and Nova Scotia, and are together known as the ***Ganderia terrane***.

We now need to explain how these various terrane fragments have moved into their present-day relative positions. A plausible model has been proposed by Pothier et al. (2015) which is outlined here. Please be aware that other models are possible, and these will be discussed later in chapter 24.

Let us first consider the relatively undeformed sedimentary successions of the Megumia terrane. After accreting to the coast of Gondwana, a section of the Avalonian microcontinent may have subsided to produce a marine trough into which the Cambrian sediments of Megumia were deposited. Detrital zircon analysis is consistent with a source area on the African continent (fig.20b).

By early Cambrian times, ocean floor spreading in the Iapetus basin initiated the break-away of Avalonia from Gondwana. Ocean floor rocks accreted at the subduction margin of Avalonia to

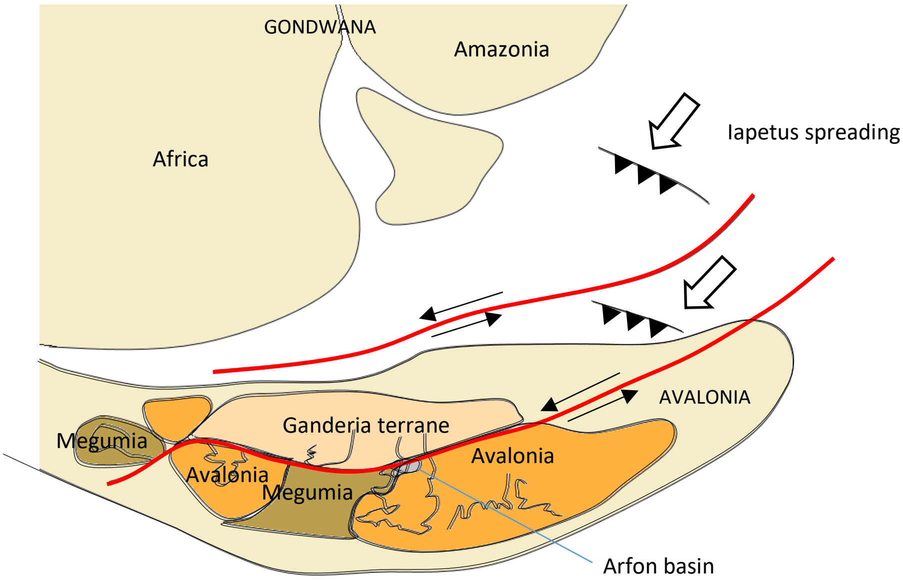


Figure 20(c): Break away of Avalonia from Gondwana in the late Cambrian

produce the Ganderia sequence of basalt pillow lavas and deep sea bedded cherts, now represented within the Gwna Group of Lleyn. Lateral stresses led to the development of a series of fractures, along which fragments of Avalonia were able to move sideways.

The separation of Avalonia continued through late Cambrian times, with movement along the fault zones causing a rotation of the microcontinent and displacement of terrane fragments. The Megumia marine basin was split, with a section moving to its present position in Nova Scotia. The Ganderia terrane came to rest as outcrops in Anglesey and the Lleyn peninsula, as well as in central Newfoundland. The rocks of the Arfon basin of North Wales may have been originally deposited in a small marine basin within the wide fracture zone, and were then moved laterally to their present geographical position in North Wales (fig.20c).

By earliest Ordovician times, Avalonia had broken away completely from Gondwana, and followed a track across the Iapetus ocean (fig. 21). This movement was accompanied by subduction-related volcanicity.

The model outlined above requires that southern Britain was 'upside down' during the Cambrian period relative to its present geographical orientation. The Avalonian microcontinent would need to have rotated by 180° before reaching its final docking position alongside the Laurentian continent. Geomagnetic studies return a wide variety of compass orientations for Avalonia during the Ordovician, so this model is certainly plausible.

Avalonia continued to move northwards throughout the Ordovician, arriving off the coast of the Laurentian continent (fig. 22).

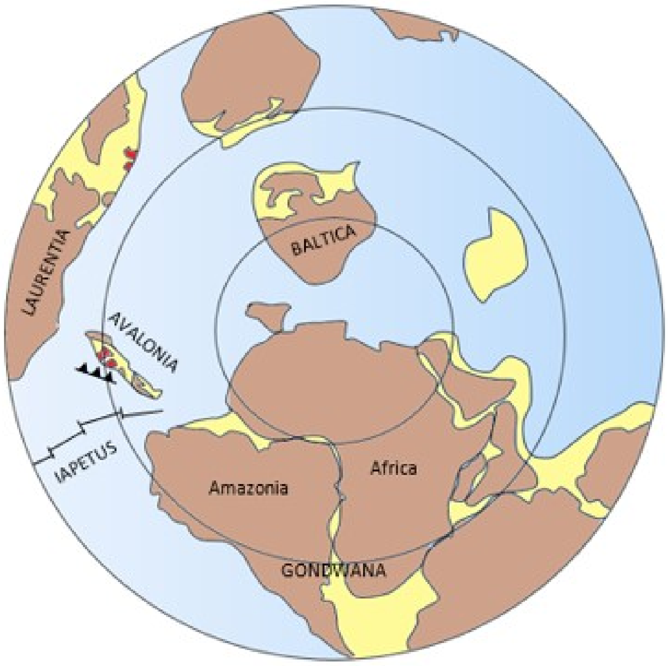


Figure 21: Plate tectonic reconstruction for the early Ordovician

Paleontological evidence supports this, with increasing similarities amongst the trilobite and brachiopod faunas of Avalonia and Laurentia at this time. Continuing subduction produced volcanism in both northern and southern Britain.

By the end of the Ordovician, Avalonia joined with the small continent of Baltica, and the combined land mass continued to move northwards. Collision with the coast of Laurentia first occurred in the Canadian section in the west of Avalonia (Soper & Woodcock, 1990). Closure moved progressively eastwards during the Silurian, with the northwards subduction of oceanic crust beneath Scotland coming to an end (fig. 23).

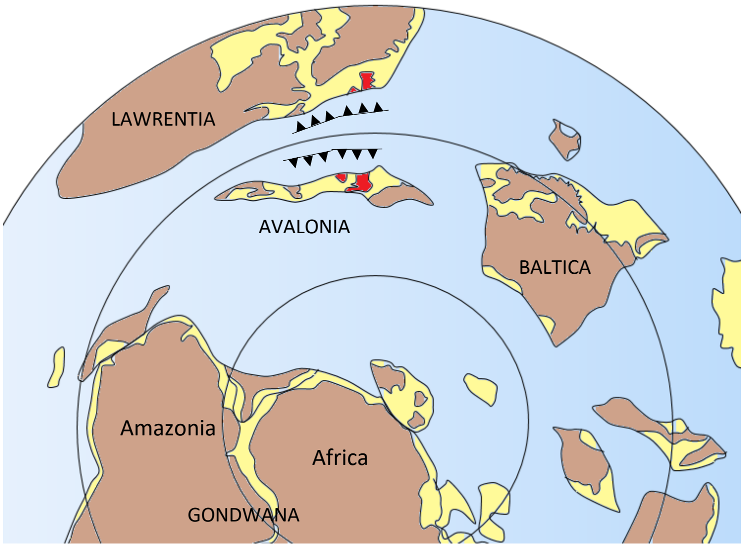


Figure 22: Plate tectonic reconstruction for the later Ordovician

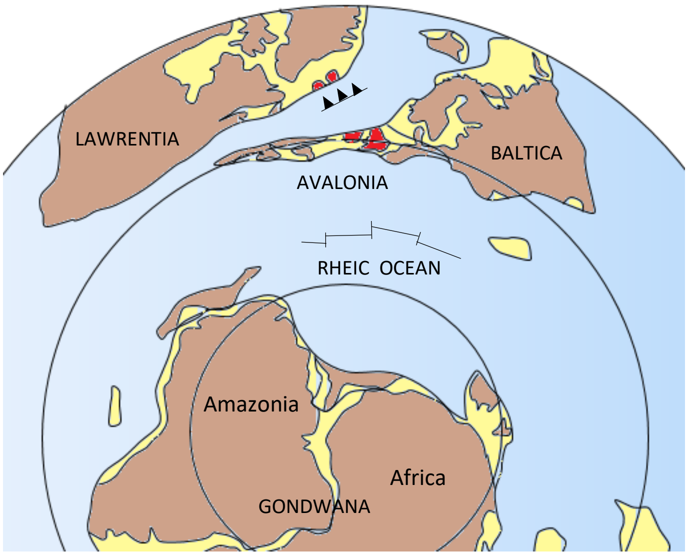


Figure 23: Plate tectonic reconstruction for the early Silurian

By late Ordovician times the Rheic Ocean to the south began to close, leading to the eventual elimination of the Rheic ocean basin and the collision of Gondwana with the Laurentian margin.

Convection currents in the hot fluid mantle below the Welsh area during Rheic subduction created an expanding **back arc basin.** Subsidence of blocks of the overlying crust allowed marine basins to form, in which extensive deposition of muds and sands occurred during the late Ordovician and throughout the Silurian period.

Final compression of Avalonia against Laurentia occurred in the Devonian, when the **Acadian orogeny** led to uplift of the marine basins, folding, low grade metamorphism in the thickened sedimentary sequence, and emplacement of lead and gold mineral deposits.

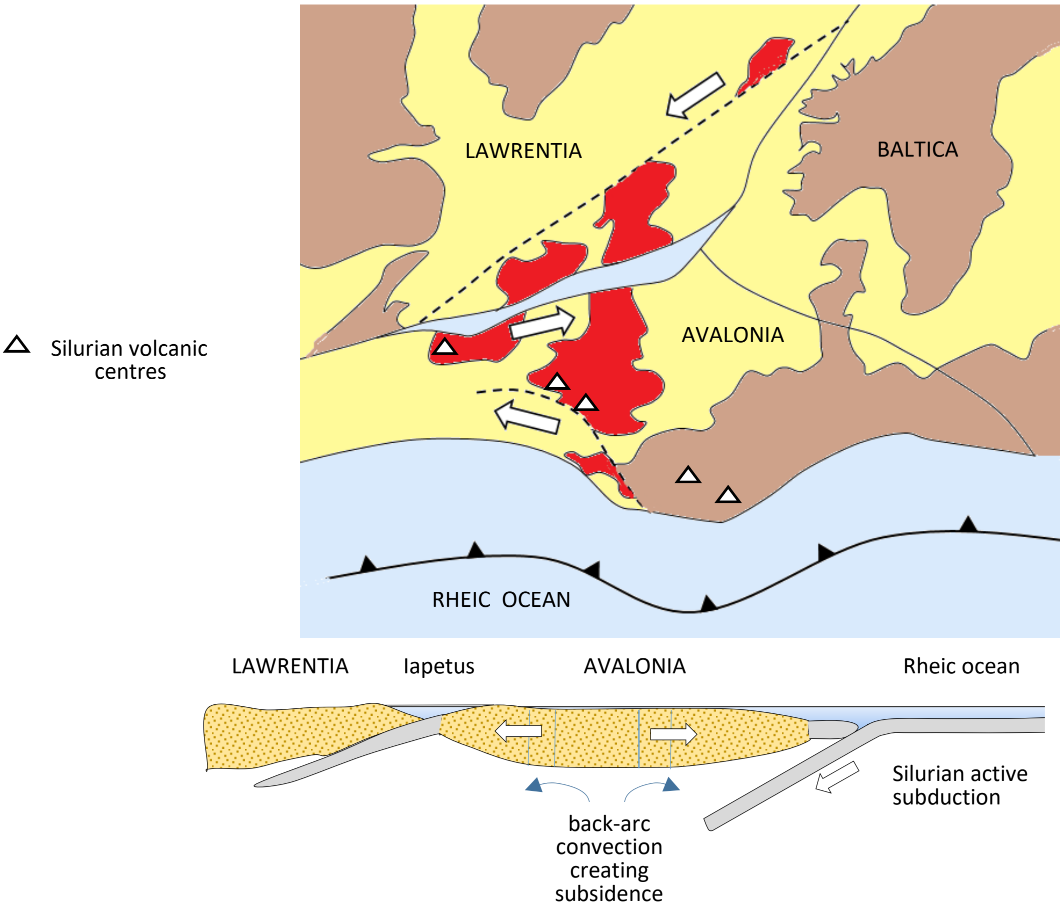


Figure 24: Closure of the Iapetus basin by Rheic Ocean subduction