Discussion

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Our objective in this book has been to compile evidence from field observations. This evidence can then be used to evaluate plate tectonic models for the early geological evolution of North West Wales. In the sections which follow, figure numbers displayed in diagrams refer back to the outcrops examined during field excursions in earlier chapters.

We began in **Chapter 3** by considering the Monian rocks of the Lleyn peninsula. It was clear that the area represents a plate margin where subduction had taken place. Rock types characteristic of ocean plate stratigraphy and trench slump deposits were identified.

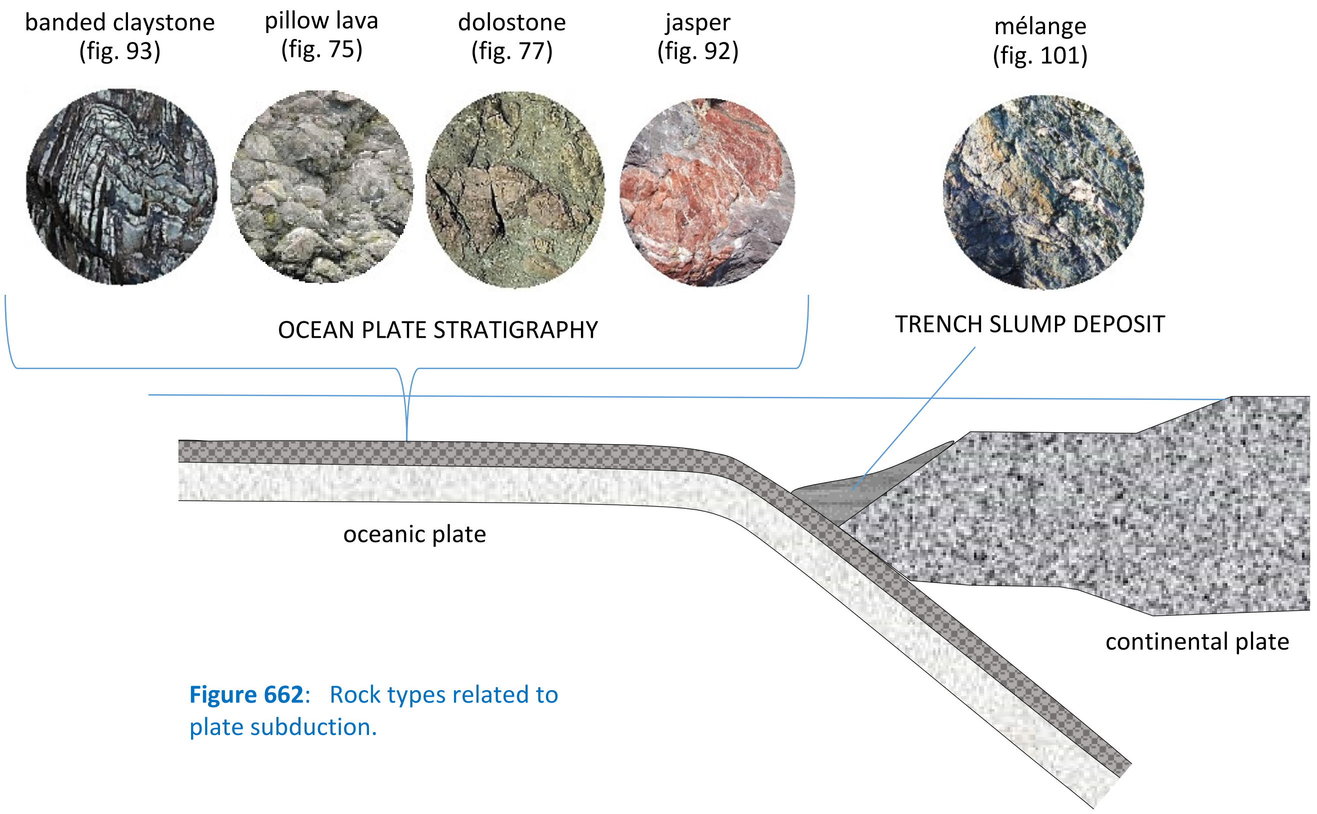


Figure 662: Rock types related to plate subduction.

A more difficult set of rocks to interpret are the schists and gneisses of the Lleyn peninsula.

The **gneiss** rocks of highest metamorphic grade appear to be the original island arc of the Avalonian microcontinent. This volcanic arc formed in the southern ocean during Precambrian times. Both high-silica and low-silica gneisses are found. They are likely to represent felsic and mafic igneous rocks and volcanogenic sediments deposited on and around the volcanic arc. The original rocks were metamorphosed during the intense plate tectonic activity which occurred in the late Precambrian, at a time when the Earth's interior was hotter and more fluid.

Contrasting with the gneisses are a varied group of **schists** showing fine banding which may be strongly contorted in places. Many of these rocks can be related to the metamorphism which occurs in a subduction zone. In particular, blueschist is known to form at very high pressure. After being carried downwards with the descending slab, slices of schist may become detached and return upwards towards the surface. This is due to their high temperature which creates buoyancy.

A further type of schist seen in Lleyn is mylonite, produced by mechanical fragmentation within the major fault zone which runs along the peninsula.

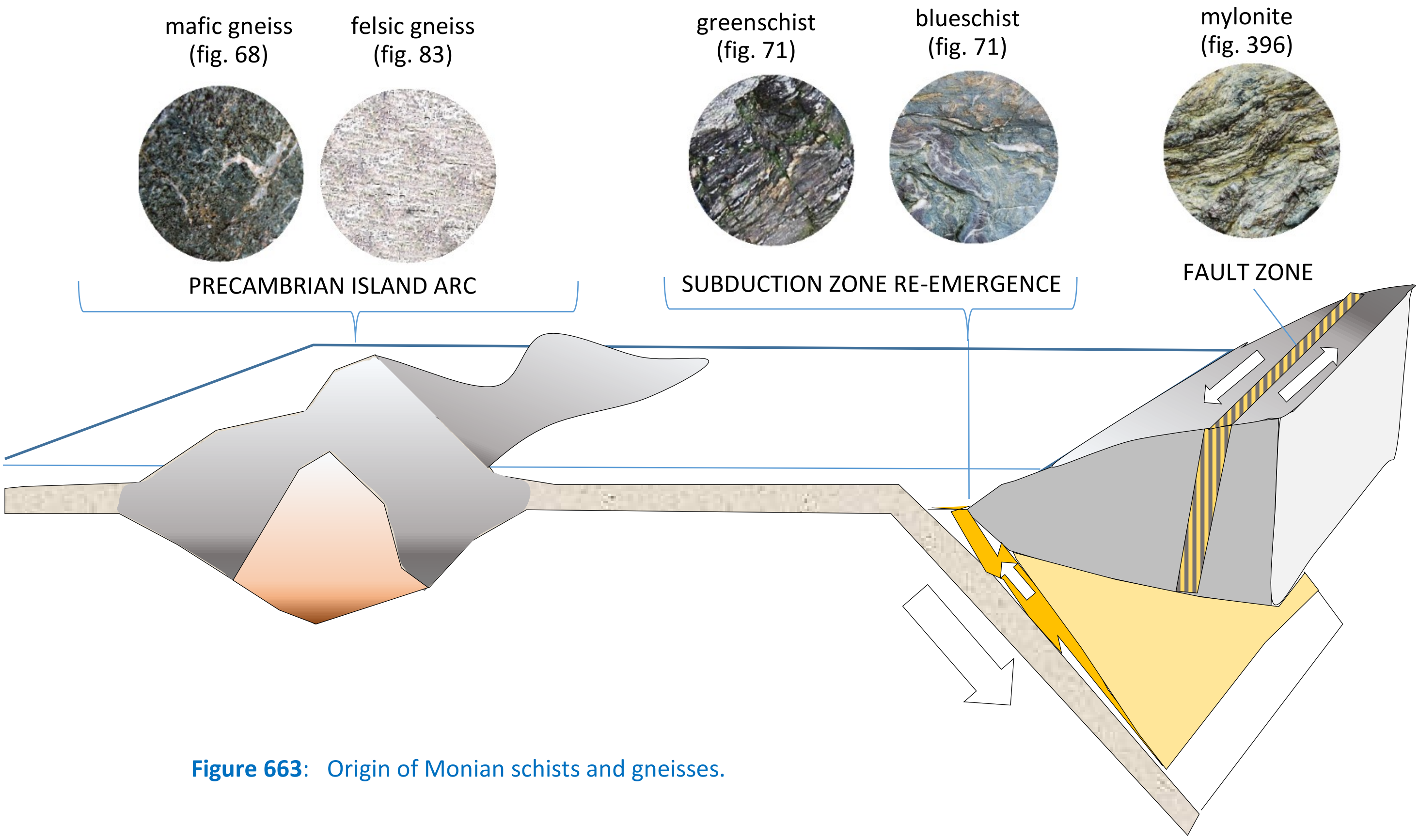


Figure 663: Origin of Monian schists and gneisses.

We have gathered evidence that subduction took place on the margin of the Avalonian microcontinent in the area of the present-day Lleyn peninsula. In **Chapter 1**, we proposed a plate tectonic model in which the Avalonian island arc converged with the continent of Gondwana in late Precambrian times, then broke away again in the late Cambrian to begin a journey northwards across the Iapetus Ocean.

Two alternative models have been proposed for the approach of Avalonia to the coast of Gondwana. In the first, the compass orientation of Avalonia was the same as at the present day, so south Wales lay adjacent to the Gondwana margin with Anglesey further away towards the ocean. The alternative model sees the orientation of Avalonia reversed, so that Anglesey lay adjacent to the Gondwana margin with south Wales further away.

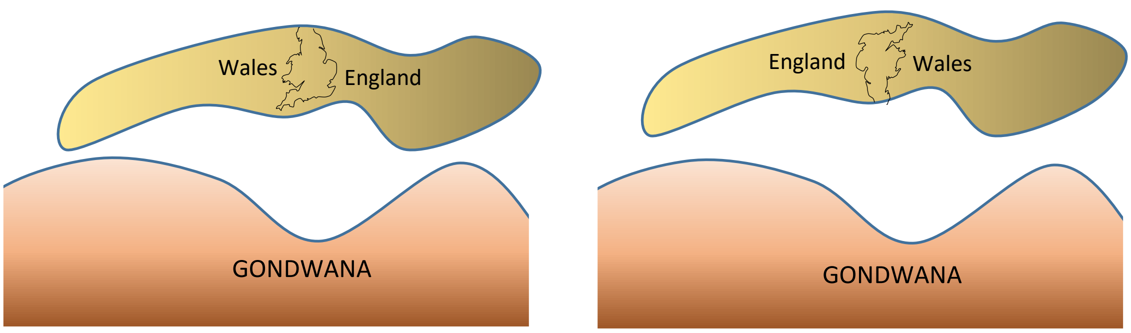


Figure 664: Possible orientations of Avalonia in relation to Gondwana during the Cambrian period.

We chose to follow the model of Pothier et al. (2015) which places Avalonia in the inverted position. The microcontinent then rotated by 180° during its transit across the Iapetus Ocean, to reach the northern hemisphere with the correct present-day orientation for Wales (**Chapter 1 figs 21-23**).

Other geologists have also suggested models in which the Avalonian continent rotates during its transit across Iapetus, although the proposed mechanisms vary. Keppie & Keppie (2014) have developed a model in which the Avalonian island arc approaches Gondwana, rotates in contact with the continent during the Cambrian period, and is then released (fig. 665).

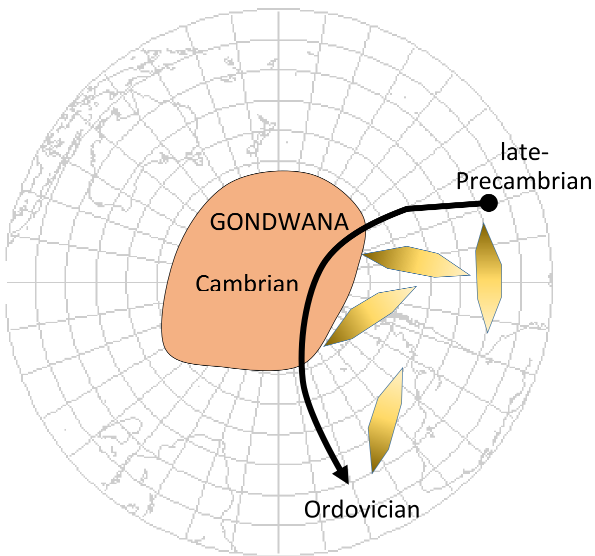


Figure 665: Rotation model for the transit of Avalonia.

A key feature of several of the plate tectonic models is that transverse faulting occurred during the break-away of Avalonia from Gondwana. This is necessary to account for the present-day distribution of very similar Precambrian and Cambrian rock formations in Britain and the Canadian provinces of Newfoundland and Nova Scotia. We discussed the model by Pothier et al. (2015) which identifies a series of terranes separated by branches of the Menai Strait fracture zone in North Wales (**Chapter 1 fig. 20**). Murphy et al. (2006) go a step further in suggesting that transverse fault movement was the main mechanism which transferred the Avalonian microcontinent from the coast of Gondwana to the coast of Lawrentia during Ordovician times (fig. 666).

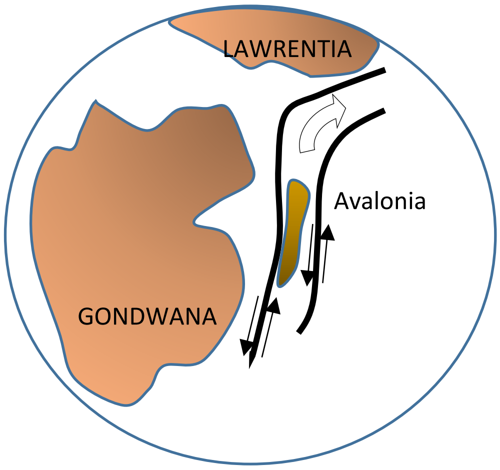


Figure 666: Transverse fault model for the transit of Avalonia.

Whilst detailed evidence for Precambrian and early Cambrian events is lacking due to the great age of the rock formations involved, it would be reasonable to draw some tentative conclusions:

- The area now forming North West Wales originated as an island arc in the southern ocean during the late Precambrian.
- The island arc, known as Avalonia, reached the coast of Gondwana during the early Cambrian period, before breaking away again in the middle to late Cambrian.
- It is reasonable to suggest that the orientation of Avalonia placed Anglesey closest to the coast of Gondwana, with South Wales further away.
- The break away of Avalonia from Gondwana involved the operation of constructive and destructive plate margins , combined with large scale transverse faulting.

A problematic rock type for geologists in Lleyn and Anglesey has been the **basalt pillow lavas** within the Gwna Group. For many years these lavas were considered to be Precambrian, as they outcrop close to heavily deformed schists and may themselves show evidence of metamorphism. More recently however, Cambrian fossils have been found in sediments interbedded with Gwna pillow lavas in Anglesey, indicating a Cambrian age. It seems that both age assessments may be correct. We should treat pillow lava as a rock type, in a similar way to sandstones or granites, which can be repeatedly formed at widely different times within the geological time scale. It is probable that pillow lavas were preserved from both the closure period when Avalonia converged with Gondwana in the late Precambrian, and also from the period of fracturing and breaking-away of Avalonia in Cambrian times.

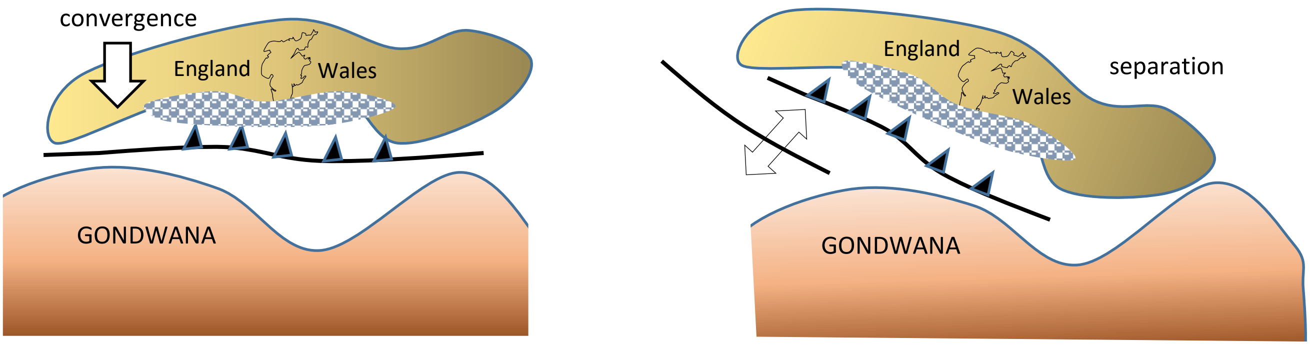


Figure 667: Accumulation of ocean floor pillow lavas at trench zones during late-Precambrian convergence and mid-Cambrian break-away of Avalonia in relation to Gondwana.

A major feature of the geology of North West Wales is the presence of a series of **terranes**, each composed of a contrasting sequence of rock formations. The terranes are separated by major transform faults, and appear to have formed in widely different locations before moving to their current positions. The plate tectonic model of Pothier et al. (2015) suggests that these movements occurred in late Cambrian times during the break away of Avalonia from Gondwana.

Our fieldwork has provided convincing evidence for the existence of separate pre-Ordovician terranes in the Harlech Dome, north-west Lleyn, and Arfon regions. Work further afield in Newfoundland and Nova Scotia has allowed the model to be further developed (**Chapter 1 fig. 19**).

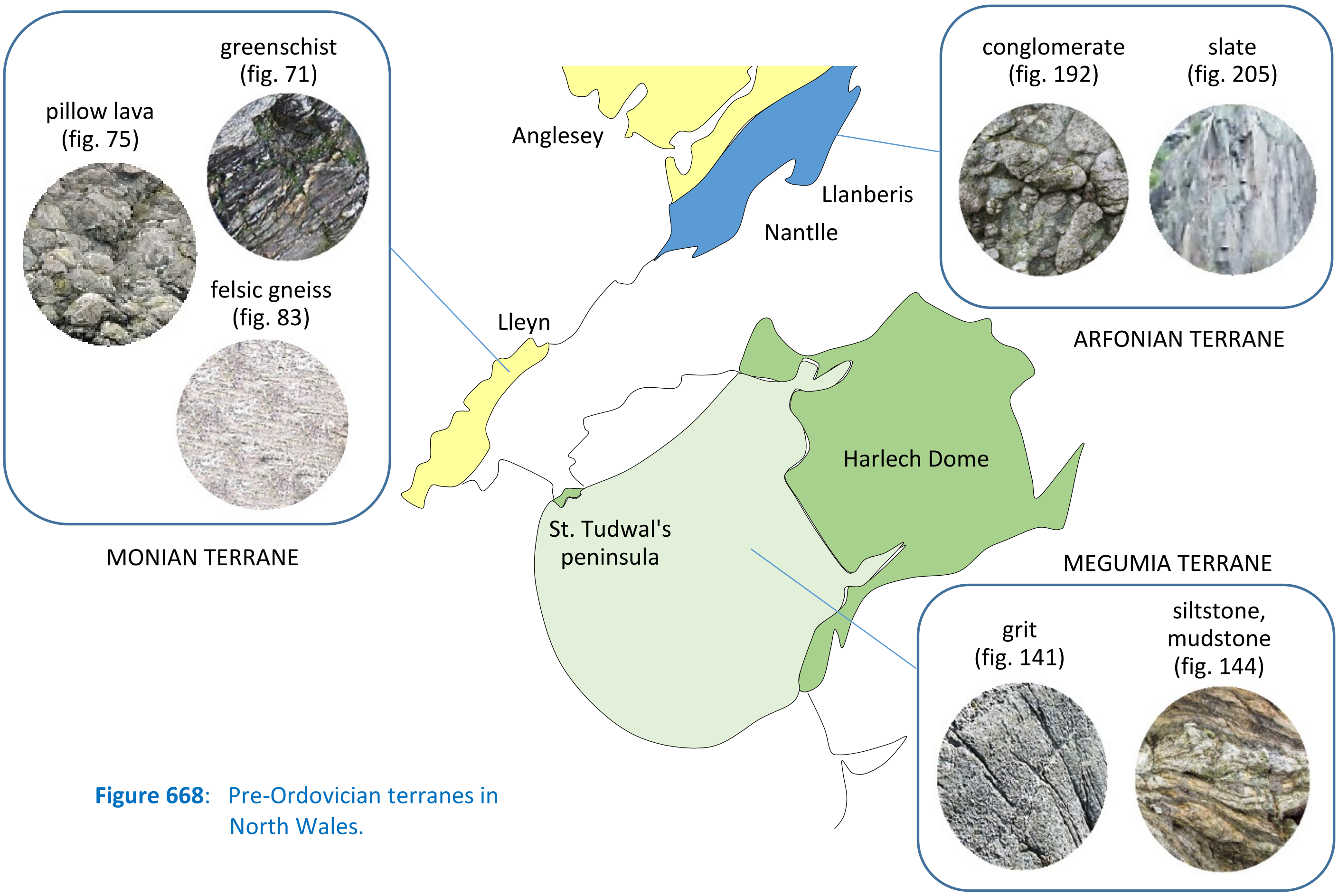


Figure 668: Pre-Ordovician terranes in North Wales.

We have identified major northeast-southwest transverse **fracture zones** across Wales which were initiated in the Cambrian period. These faults were accompanied by a series of major north-south fractures, which together allowed the readjustment of rigid basement blocks during the break away of Avalonia from Gondwana.

It is difficult to over-emphasise the importance of the deep crustal fractures, which were reactivated on a number of occasions during Lower Palaeozoic times. Vertical movements along the major faults controlled the depth of the marine basin, and consequently the patterns of sediment deposition. The fracture zones provided pathways for magma during the Ordovician period, producing eruptive volcanic centres and emplacing dykes, sills and larger intrusive bodies. The fracture zones also provided pathways for the hydrothermal fluids which later emplaced heavy metal mineral lodes.

In fig. 669 we summarise some of the evidence for important geological processes associated with the north-south Rhobell fracture zone.

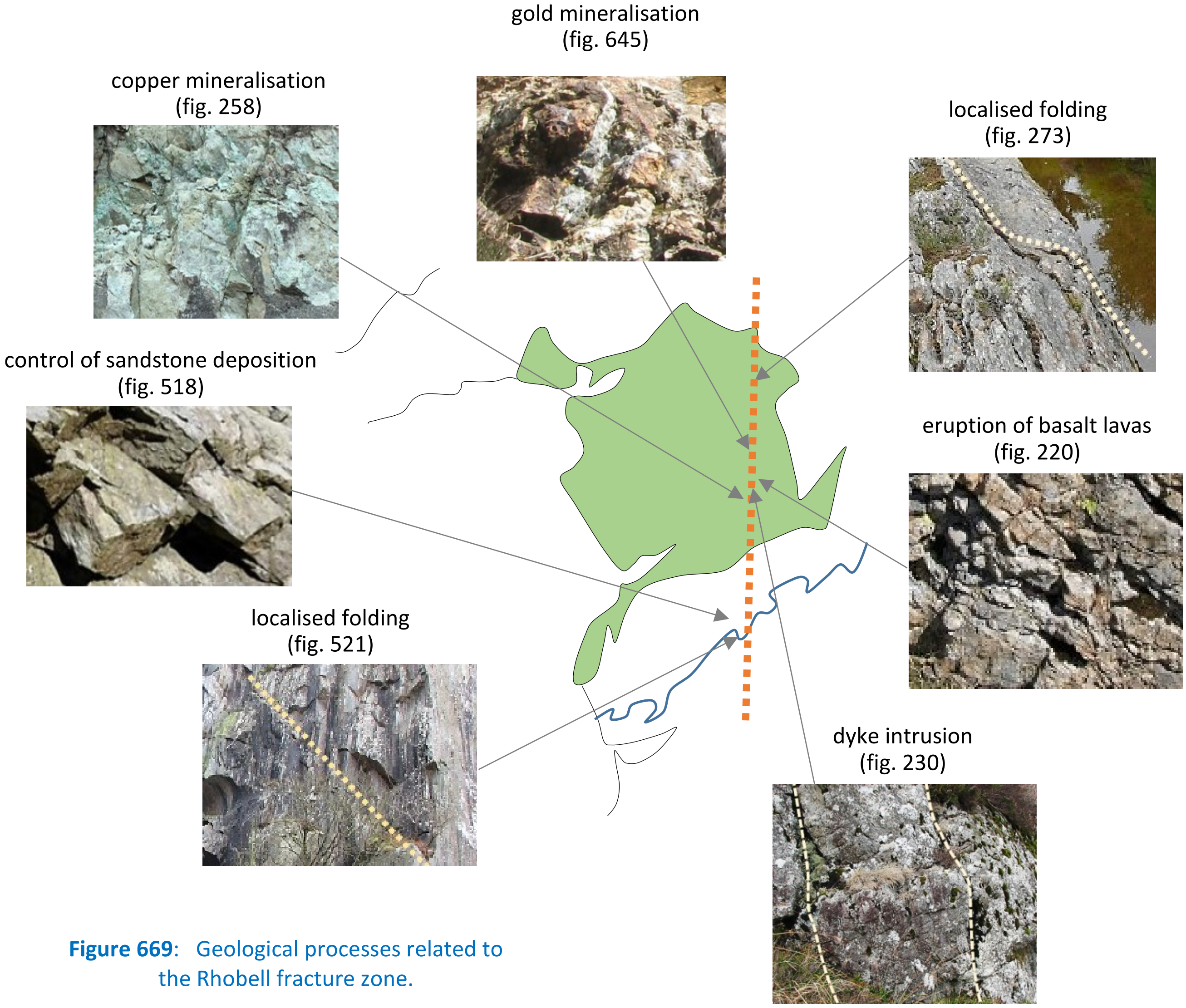


Figure 669: Geological processes related to the Rhobell fracture zone.

The Vale of Ffestiniog appears to be the location of another deep crustal fracture zone, though this is not represented as a simple fault line on the surface at the present-day. In fig. 670 we summarise the evidence that important geological processes were related to this fracture.

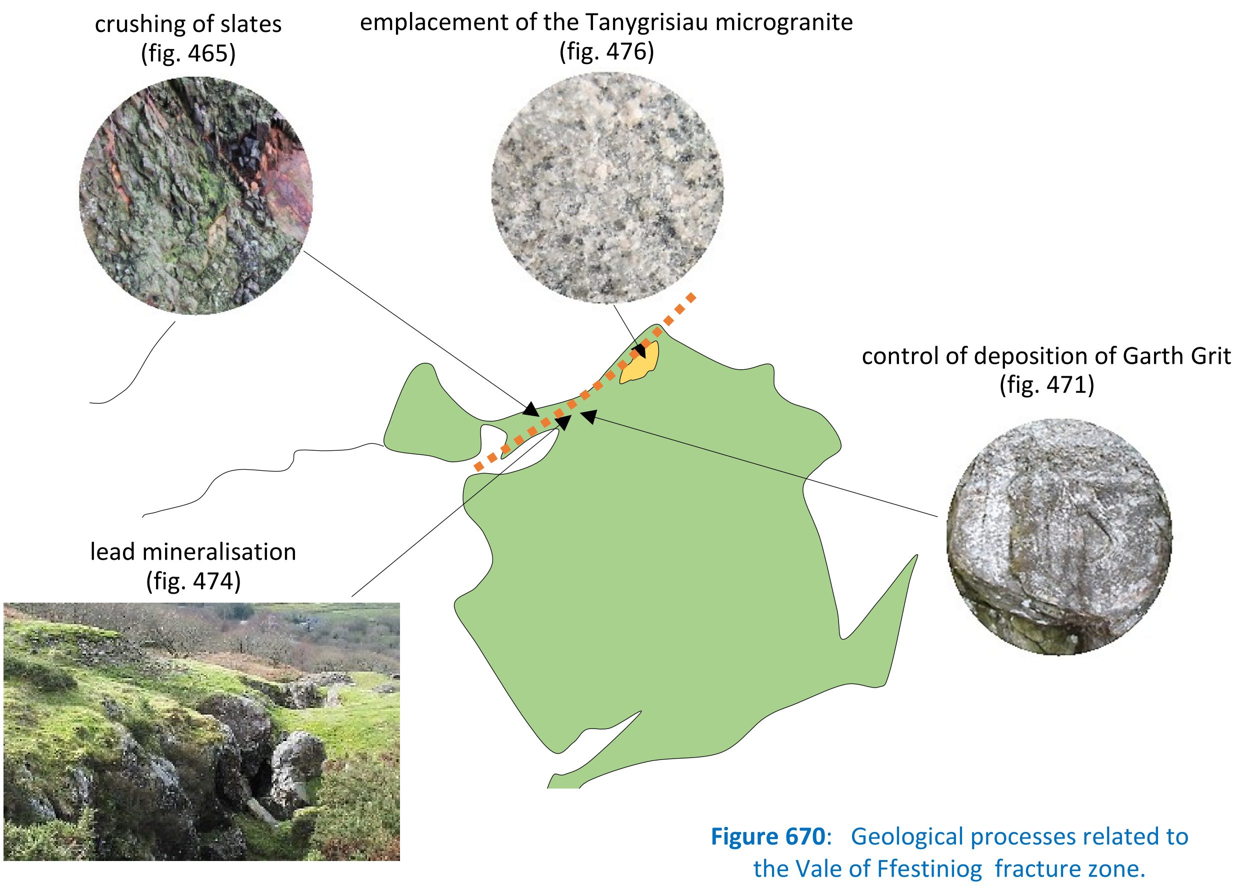


Figure 670: Geological processes related to the Vale of Ffestiniog fracture zone.

Much of our knowledge of sediment deposition in the Welsh Basin comes from a study of sedimentary structures and fossil evidence. At different times and in different locations we have found a range of indicators of water depth, allowing palaeogeographical maps to be constructed (fig. 671). Directions of sediment transport can be determined from structures such as: current bedding (**Chapter 9 fig.268**; **Chapter 14 fig.403 and fig.423**), and flute and grove casts on the bases of turbidite beds (**Chapter 21 fig.596**).

Sediment deposition in the Welsh marine basin has been strongly controlled by faulting in the underlying basement. Vertical movement on north-south fractures created shelves which stepped down into the deep north-south oriented central trough, as in **Chapter 20 fig. 556** and **Chapter 22 fig. 602**. Within this general pattern, vertical movements on the northeast-southwest faults produced localised deep sub-basins into which coarse sediments could be deposited as turbidite fans (see **Chapter 5 fig. 135** and **Chapter 11 fig. 307**).

Palaeocurrent measurements for the lower Cambrian grits of the Harlech Dome (Crimes, 1970) indicate transport of sediment from the north. Detrital zircon ages suggest that lower Cambrian sediments were derived by weathering of Archaean metamorphic rocks of Gondwana. These lines of evidence taken together are consistent with the Avalonian microcontinent lying next to the coast of Gondwana in lower Cambrian times. Sediment was carried by rivers to the coast of Gondwana, then discharged into the Welsh basin which occupied the downfaulted central section of the Avalonian microcontinent, as in **Chapter 1 fig. 20(b)**.

By upper Cambrian times, palaeocurrent data indicates that sediment supply direction is now predominantly from the south, and the dominant grain size of the sediment has been reduced from sand to silt and mud. A possible explanation is that the break-away of Avalonia from Gondwana began at this time, cutting off the supply of coarse sediment from the major continent. Finer grained material entering the Welsh basin came from the weathering of uplifted areas of the Avalonian microcontinent to the south of Wales and the Bristol Channel.

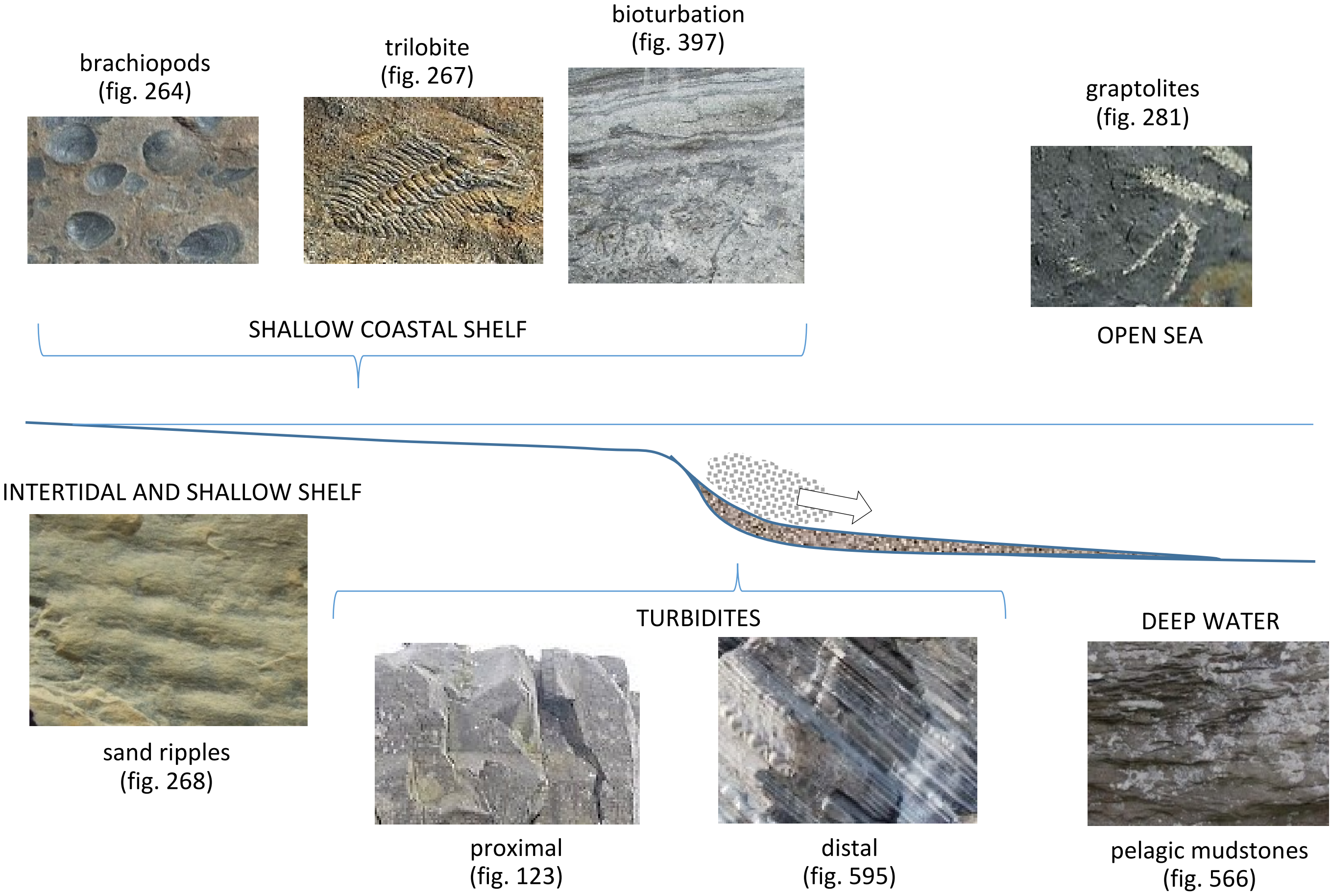


Figure 671: Indicators of water depth and depositional environment.

An unusual rock type found within the middle Cambrian succession of the Harlech Dome is the manganese ore of the Hafotty formation (**Chapter 5 fig.139**). This is thought to have formed as a chemical precipitate from sea water which was highly enriched in manganese. The very high concentration of manganese necessary would suggest the chemical weathering of large areas of mafic igneous rocks such as basalt. It is possible that the initial break away of Avalonia was accompanied by transverse faulting and the uplift of large volumes of basalt pillow lavas along the continental margin, exposing these rocks to rapid subaerial erosion.

Following the break away of Avalonia, the Ordovician period in Wales was marked by extensive volcanic activity. This was related to plate subduction as Avalonia transited across the Iapetus Ocean, eventually docking with the continents of Baltica and Lawrentia.

From our examination of outcrops around the Harlech Dome, in central Snowdonia, and in the Lleyn peninsula, we can reach some general conclusions about the nature of the Ordovician volcanic events:

- The earliest volcanic centre to develop in the area was at Rhobell Fawr, emerging from the Welsh basin as a volcanic island. Eruptions were almost entirely of basalt, although rocks with a range of silica content can be found within the sub-volcanic intrusion complex now exposed beneath the volcano.
- Volcanic activity spread during lower Ordovician times to centres around the Harlech Dome located on or close to major deep crustal fractures. Both basaltic and rhyolitic magmas were erupted. Variations in silica content may be the result of changes in the stress holding the deep crustal blocks together or allowing them to move apart.

Figure 672: Ordovician igneous rocks from the areas investigated.

During periods of crustal relaxation, basic magma could easily and rapidly rise to the surface without modification. During periods of compression, uprise of magma was inhibited: silica content could be increased by processes of fractional crystallisation and crustal assimilation within high level magma chambers before eruption.

- The volume of volcanic material erupted in lower and middle Ordovician times was relatively limited. However, Ordovician volcanic activity greatly increased in the upper Ordovician across the whole region, with huge volumes of rhyolitic ignimbrites erupted in Carodoc times. These eruptions were linked to large high level magma reservoirs in the form of bosses, as at Manod and Aran, or extensive thick sills as at Cader Idris, Arenig and Moelwyn. In central Snowdonia, eruptions culminated in the subsidence of a large volcanic caldera. It appears that magma had been accumulating over a long period of the Ordovician in a magma reservoir in the lower crust, supplied by mantle diapirs released above a subducting plate. During this time, fractional crystallisation and crustal assimilation allowed a large volume of felsic magma to be formed. In upper Ordovician times, the reservoir became unstable, releasing huge volumes of the felsic magma upwards towards the surface through the major fracture zones below the Welsh basin.

- Large microgranite intrusions of upper Ordovician age are found in the Trefor area of Lleyn, and at Tan y Grisiau near Blaenau Ffestiniog. These intrusions have a considerably coarser grain size than the rhyolitic intrusions found at other volcanic centres. It is likely that the Trefor and Tanygrisiau intrusions never ascended high enough to connect to the surface through faults and joints in the overlying rock. The superheated steam dissolved in the melt at depth could not escape, and water molecules catalysed the growth of larger crystals in comparison to a similar body of dry melt.

- A unique mafic to ultramafic intrusion complex occurs on the Lleyn peninsula at Mynydd Penarfynydd. The rocks are again coarser grained than the typical microgabbros seen at other volcanic centres. It appears that a deep crustal fracture at this point was able to repeatedly tap a source of mafic magma in a deep crustal reservoir.

- Volcanic activity abruptly ended during the upper Ordovician. Great thicknesses of sediment, mainly fine grained silt and mud, were laid down in a subsiding Welsh marine basin during the Silurian period.

We now review evidence related to the **structural geology** of the region. It is clear that the rock succession was affected by folding and faulting on a series of different occasions.

The earliest structures we see are due to convergence of the Avalonian microcontinent with Gondwana in late Precambrian times. Examples are folds and faults within the Gwna mélange (**Chapter 3 fig.101**), folding of the ocean plate stratigraphy (**Chapter 3 fig.93**), and contorted foliation in schists (**Chapter 13 fig.396**).

The next major phase of earth movements affecting the area was related to the break-away of Avalonia from Gondwana. At the very end of Cambrian times, uplift and erosion created an unconformity in the sedimentary succession (fig.673 below). During this break in sedimentation, eruptions of basalt occurred from a localised volcanic centre at Rhobell Fawr. It is likely that the major structure of the Harlech Dome was created at this time. A section of the underlying Precambrian basement was uplifted, producing drape folds in the Cambrian strata at the edges of the raised block (**Chapter 4 fig.109**). Examples of folding which occurred at this time can be found in Coed y Brenin (**Chapter 9 fig.273**).

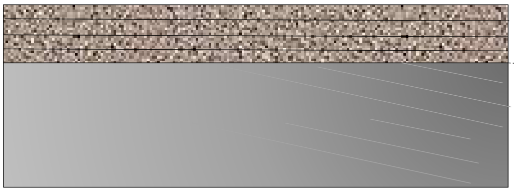
By Silurian times, subduction beneath Wales from the Iapetus Ocean to the north had ceased (**Chapter 1 fig. 23**), and final convergence was completed by subduction from the Rheic Ocean to the south (**Chapter 1 fig. 24**).

The convergence of Avalonia with Lawrentia culminated in earth movements in Wales during the Acadian orogeny in the early Devonian.

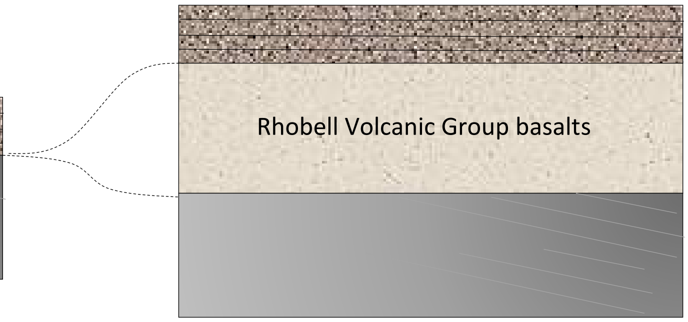
ST. TUDWAL'S PENINSULA

RHOBELL FAWR

Lower Ordovician sandstone



Upper Cambrian mudstone



unconformity

Lower Ordovician sandstone overlying
Upper Cambrian mudstone
(fig.175)

Lower Ordovician sandstone
(fig.221)

Rhobell basalt
(fig.220)

Figure 673: Formation of an unconformity at the base of the Ordovician.

unconformity

Rhobell basalt overlying
Upper Cambrian mudstone
(fig.175)

Acadian folding and faulting affected the Ordovician and Silurian sediments of Plynlimon (**Chapter 20 fig.568 and fig.569**), and the mid-Wales coast (**Chapter 21 fig.592**). Many major structures were formed by these earth movements: the Snowdonia syncline, Dolwen pericline and Caerdeon syncline of the Harlech Dome, and the Llyfnant, Plynlimon and Van Domes.

Another important effect of the Acadian orogeny was the formation of slate. Pure mudstones from a variety of geological formations were converted to economically valuable slate deposits at this time. During the field excursions we saw outcrops of Cambrian slate in the Harlech Dome (**Chapter 4 fig.131, Chapter 5 fig.158 and fig.163**). We then visited quarries which worked Ordovician slates in the Blaenau Ffestiniog area (**Chapter 17 fig.490, fig.501**) and around Corris (**Chapter 18 fig.524**) . The majority of slate deposits developed with a near-vertical cleavage which is parallel to the axial planes of folds. The exception is in the Blaenau Ffestiniog quarries where the mass of the Tanygrisiau microgranite intrusion has deflected stresses to produce a gently dipping cleavage.

Woodcock (2012b) has suggested that the Acadian orogeny in Wales was due to subduction of oceanic crust beneath Britain from the Rheic ocean to the south (**Chapter 1 fig.24**). The solid crustal block of the Midland Platform was forced northwards as a wedge, which caused sideways compression of the thick sequence of sediments infilling the Welsh Basin (fig.674). Folds were produced which run almost north-south, as we observed around Plynlimon and along the mid-Wales coast.

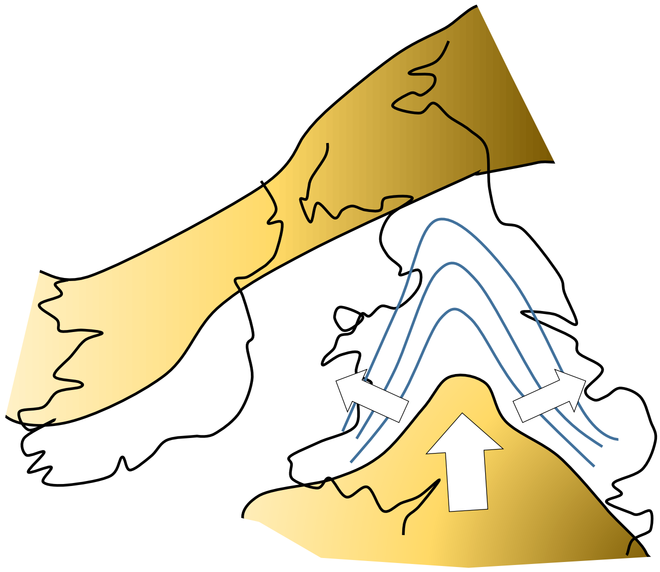


Figure 674:
Midland platform compressed into the sedimentary succession of the Welsh basin.

In addition to folding, the Acadian orogeny reactivated major faults in the Precambrian basement below Wales. Transverse movement took place on the Bala fault at this time, causing sideways displacement of Ordovician and Silurian strata by about 1 mile.

The Bala fracture zone had previously formed a pathway for the rise of magma beneath Cader Idris during the Ordovician volcanic episode. However, the solidified mass of igneous rocks now presented an obstruction and it appears that the Bala fault became re-aligned to the south of the volcanic centre through softer sedimentary rocks.

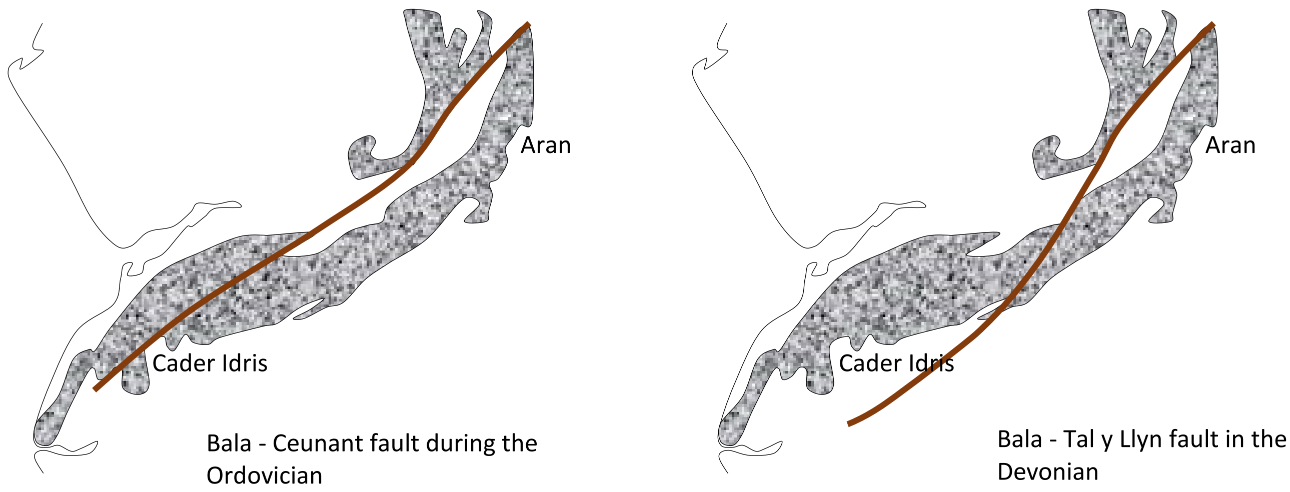


Figure 675:
Re-routing of the Bala-Mawddach fracture zone around the igneous centre of Cader Idris.

The Acadian orogeny led to compression and thickening of the sedimentary succession of the Welsh basin. This forced strata down to depths of over 5km, where pressures and temperatures were sufficient to initiate low grade metamorphism. Recrystallization of clay minerals in mudstones and mafic minerals in igneous rocks could occur, often producing mica-type minerals such as sericite and chlorite. Mudstones were converted to slates, whilst igneous rocks developed the metamorphic mineral assemblages described by early geologists as 'greenstones'.

During regional metamorphism, hydrothermal fluids were released. These high temperature and high pressure aqueous fluids had great solvent power and could dissolve silica and heavy metals. Travelling upwards through the crust, a reduction in temperature and pressure led to the deposition of ore deposits. We are able to summarise information about heavy metal deposits in the region:

- Lead and zinc occurs principally in the North Cardiganshire ore field, though lead mines are also found in the Vale of Ffestiniog. It is likely that the source of these metals is from metamorphism of large thicknesses of mudstones.
- Copper vein deposits occur principally in central Snowdonia. It is likely that large thicknesses of felsic ashes provided the metal source.
- Gold deposits occur around the Harlech Dome. A likely source of the metal is a large thickness of Precambrian mafic igneous rocks beneath the area.
- Disseminated copper ores occur in Coed y Brenin in conjunction with the Ordovician volcanic centre of Rhobell Fawr. Copper was either released directly from the solidifying igneous intrusions dissolved in a hydrothermal fluid, or was deposited by convecting groundwater systems driven by heat from the igneous centre.

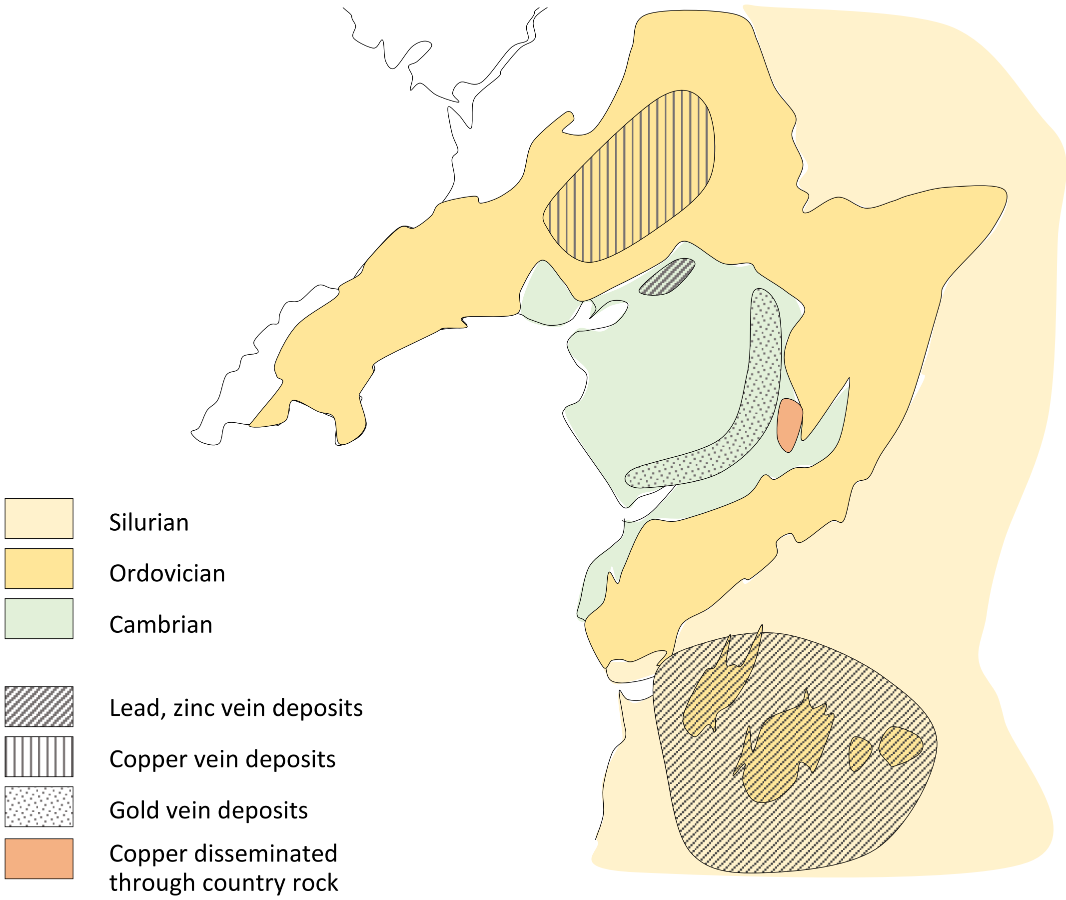


Figure 676: Distribution of heavy metal deposits.