Geological processes

2

In the previous chapter we briefly examined the variety of rocks which can be found in North and Mid-Wales, and outlined a plate tectonic model which explains their origin. We now consider in more detail some of the processes occurring near plate boundaries, and the rocks which they produce.

Oceanic plate stratigraphy and subduction

Most of the rocks of the Monian terrane in Anglesey and the Lleyn peninsula were deposited against the margin of the Avalonian microcontinent where subduction of oceanic crust was taking place during the late Precambrian and Cambrian periods. This created an **accretionary complex.**

The typical depositional sequence which develops across an oceanic plate is illustrated in fig.25. New oceanic crust is produced at the mid-ocean ridge spreading centre, where upwelling mantle generates basaltic magma. Oceanic crust has a layered structure: a coarser grained **gabbro** layer is overlain by a layer of vertical sheets of **dolerite** dyke intrusions, with an upper layer of basalt pillow lava erupted onto the sea floor.

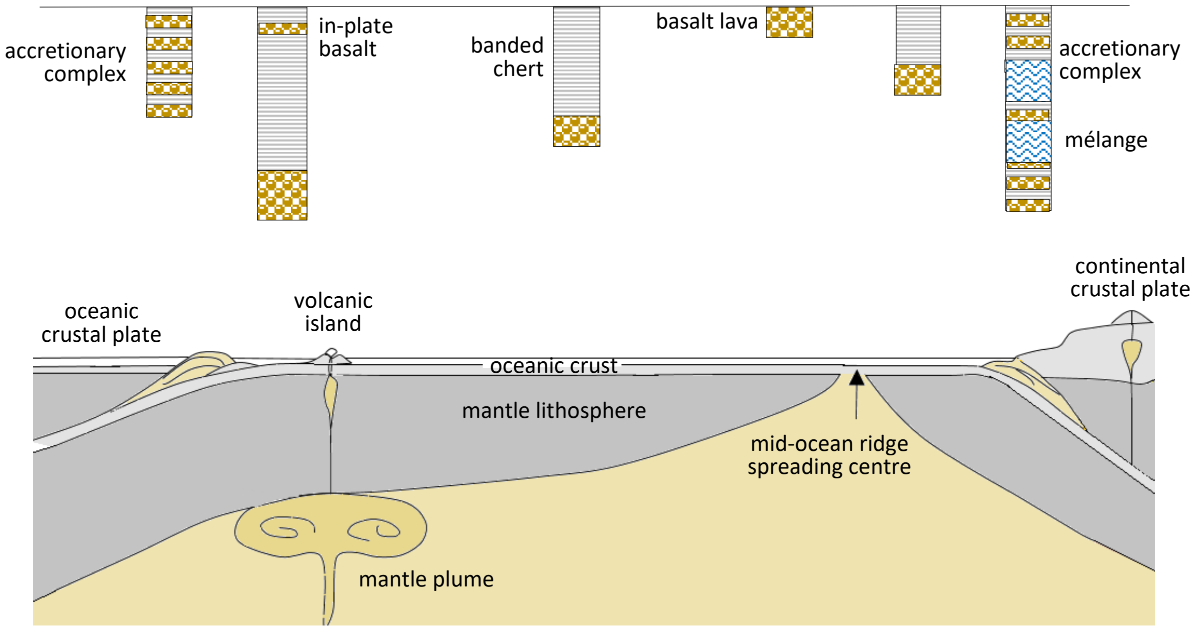

Figure 25: Ocean plate stratigraphy and accretionary complexes

Mid-ocean spreading centres are far from the sources of mud and sand provided by continents, so the accumulation of sediment on the sea bed is very slow. The only significant sediment source in the deep ocean may be silica from the skeletons of planktonic organisms. This material accumulates as bedded **chert**. Closer to land, mud may be present in suspension in sea water, perhaps due to disturbance of the sea bed during storms. Mud may be carried into the deeper ocean and settle out slowly on the sea floor.

Occasionally, volcanic islands develop within oceanic plates as they pass over hot-spots where magma is upwelling in the mantle. Eruptions can add layers of basalt pillow lavas to the sediment sequence, along with more extensive deposits of volcanic ash.

The ocean plate may eventually reach a subduction zone where the plate begins its descent into the mantle. The dense and heavy gabbro and dolerite layers of the plate, along with some basalt pillow lavas, are subducted. However, the surface layers of the plate are more buoyant and can be scraped-off to create an accretionary complex above the trench zone. This will be built up from shallow slices of pillow lavas, ocean cherts and muds.

Figure 26: Monian ocean plate stratigraphy, Porth Oer, Lleyn: (left) Pillow lavas,. (right) Bedded chert.

Progressive sheets of material detached from the descending oceanic plate are underthrust, gradually pushing the accretionary complex upwards along a sequence of fault planes. Sediment layers may still be in a soft unlithified state and can be easily folded during emplacement, as in fig.26 above.

When subduction takes place at a continental margin, rather than in open ocean, additional sediments derived from the land area may enter the subduction trench. Material will first accumulate as a layered sequence of sediments on a shallow-water shelf near the shore. The beds of sediment may then slump into the trench, perhaps as a result of earthquake activity.

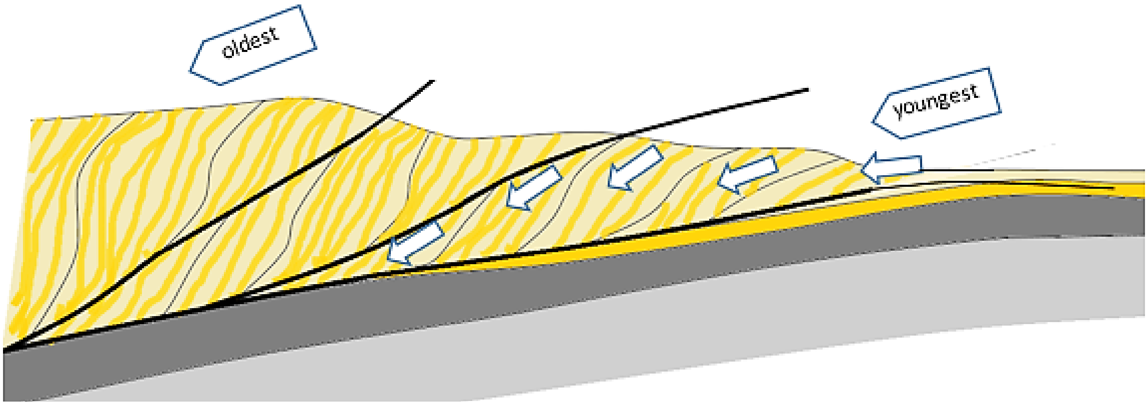

Figure 27: Development of an accretional complex

Figure 28: Mélange deposits of the Gwna formation, Uwchmynydd, Lleyn, produced by tectonic slumping into the trench zone.

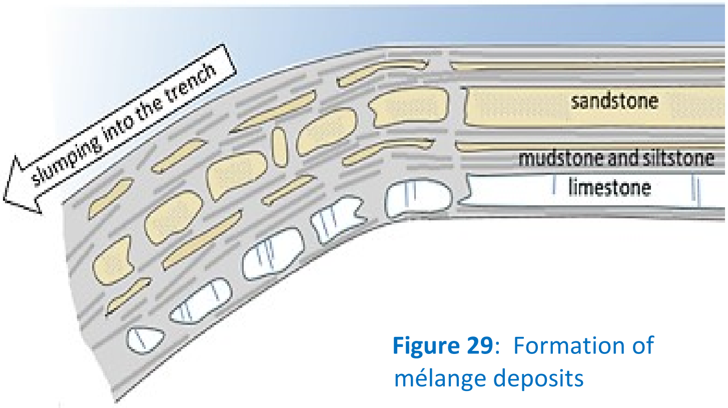

Figure 29: Formation of mélange deposits

Slump deposits known as the ***Gwna mélange*** are found along much of the north-west coast of the Lleyn peninsula. Typically the mélange consists of large blocks of limestone and quartzite sandstone in a fine mudstone matrix. A ghost stratigraphy can often be traced through the outcrop, with individual beds broken and streaked out during slumping. It is likely that the original sediment layers were at different stages of conversion to solid rock, or **lithification**. Limestone and sandstone would have formed solid layers before slumping, whilst the muds were still plastic and able to flow into the cavities between the large blocks.

Whilst most of the subduction trench deposits in Anglesey and Lleyn can be explained as ocean plate stratigraphy or sediments slumped from a continental shelf, one particular rock unit has a more unusual origin. This is a schist which occurs between relatively unmetamorphosed sheets of sediment.

Figure 30: Schist occurring within the Monian accretionary complex, Morfa Nefyn, Lleyn.

The mineral assemblage of the schist indicates that it has been subjected to the extremely high pressures normally found only at mantle depths. Geologists have found similar schists embedded in the younger subduction zones around the Pacific Ocean at the present day. It is believed that the schists originate as a slab of the accretionary complex which temporarily adheres to the descending oceanic plate and is dragged downwards.

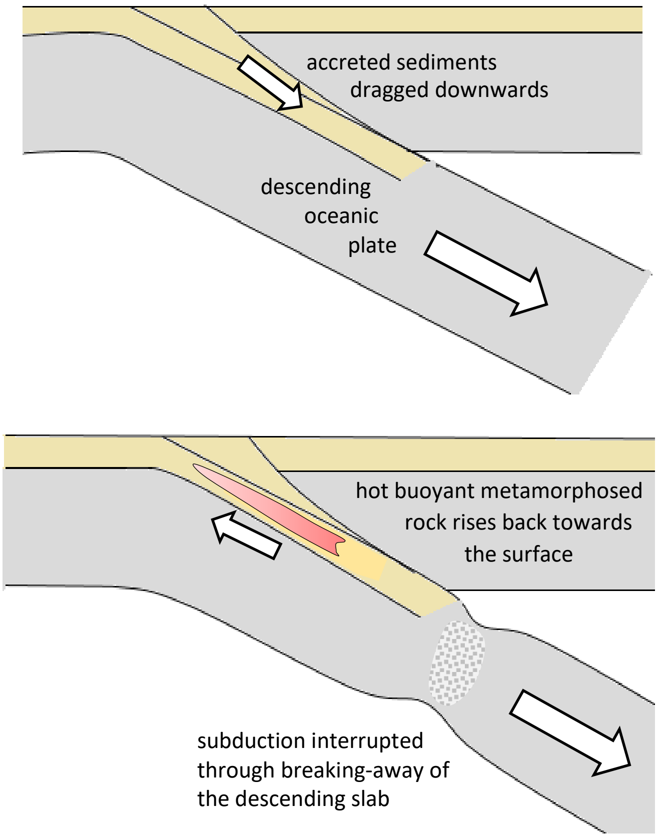

Figure 31: Development of a schist slab within the accretionary complex

At depths equivalent to the base of the crust, the subducted material is subjected to the high pressures and temperatures necessary for schist formation. The hot metamorphosed rock becomes plastic and buoyant, and a slice may break free and rise back to its original position within the accretionary complex, though now at a much higher metamorphic grade than the surrounding rocks. This process might be triggered by a temporary interruption in the plate subduction.

Igneous processes on a continental margin

As discussed in the previous chapter, various terranes were assembled into their current positions by sideways movements along **transverse faults** as Avalonia broke free of from Gondwana at the end of Cambrian times. Avalonia then moved into the Iapetus Ocean as a single microcontinent.

During Ordovician times, a subduction zone became active along the margin of Avalonia with oceanic crust of Iapetus descending below southern Britain.

By late Ordovician times, subduction also began at another trench zone off the east coast of England, as Avalonia converged with the continent of Baltica.

The Welsh basin had came to lie some distance from the margin of the Avalonian microcontinent by early Ordovician times due to the accumulation of terrane blocks to the north, in the areas of the Irish Sea, Leinster and the Lake District. A broad belt of volcanic activity associated with subduction extended across southern Britain from a subduction trench beyond the Isle of Man.

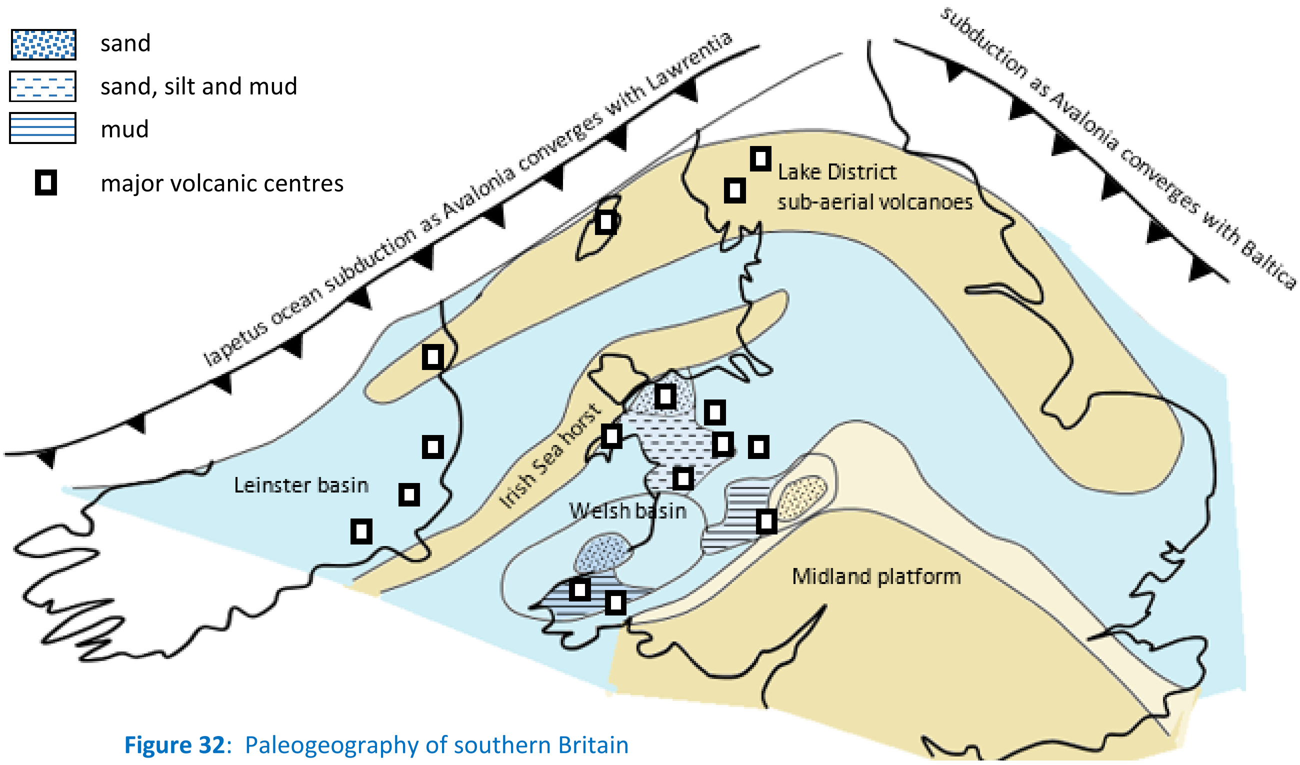

Figure 32: Paleogeography of southern Britain in late Ordovician times.

The Avalonian microcontinent would have been underlain by thin continental crust, broken by deep faults produced during terrane movement. This created a series of up-faulted blocks, known as **horsts**, separated by down-faulted basins termed **grabens**. The Welsh area was a basin covered by shallow sea (fig.32).

Subduction was accompanied by extensive igneous activity. Molten magma is generated at subduction zones by a more complex process than simple melting, and involves a series of stages:

> Metamorphic reactions take place in the descending crustal plate as the temperature and pressure increase with depth. Sedimentary minerals such as clay contain hydroxyl groups, the constituents of water, locked into their crystal lattices. These minerals are converted during metamorphism to anhydrous silicates such as **amphibole** and **pyroxene**, with the release of water molecules as superheated steam.
>
> The superheated steam escapes upwards into the mantle wedge above the subducting slab, where it reduces the density and viscosity of the semi-plastic mantle **peridotite**. This generates diapirs**,** zones of mantle material which can flow more easily and move upwards through positive buoyancy.

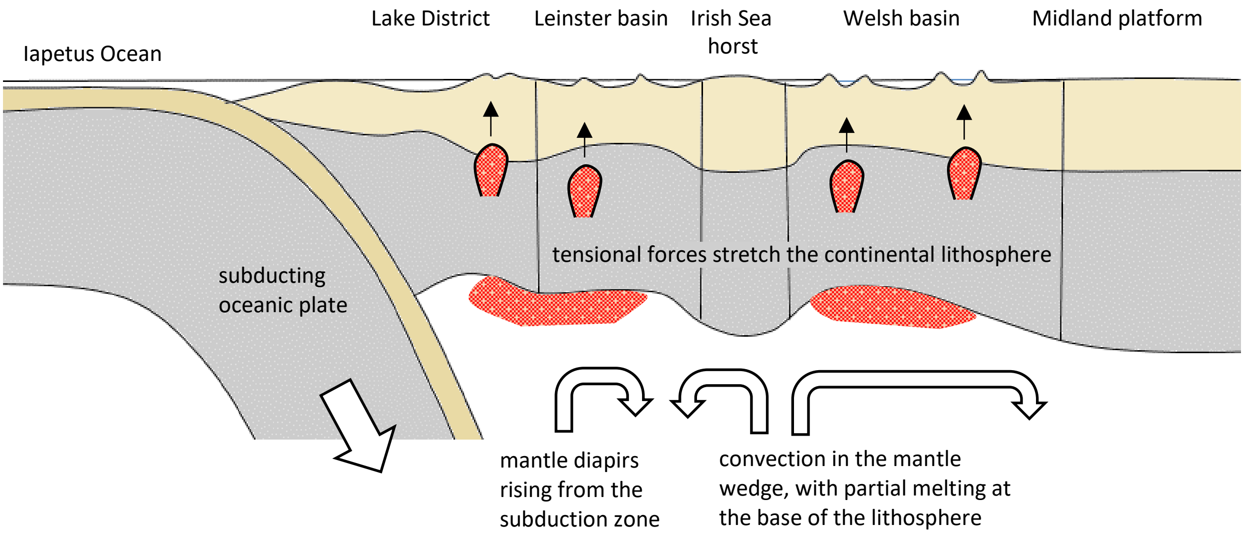

Figure 33: Cross section of southern Britain during Ordovician subduction.

The confining pressure on the rising mantle diapir reduces as it approaches the base of the lithosphere, and partial melting begins. This process will generate magma which can rise through the crust and produce volcanic eruptions .

An important feature of igneous rocks is their silica content. Where the amount of silica is low, the rocks have a high iron and magnesium content and are dense and dark in colour. Typical rock types are gabbro, dolerite and basalt. By contrast where the amount of silica is high, the rocks are composed mainly of quartz and feldspar minerals and are light in density and colour. Granites and rhyolites are formed.

The Ordovician volcanic rocks found in Wales have a strongly bimodal distribution. High silica rhyolites and low silica basalts are common, but few volcanics have an intermediate silica content. We need to consider the reasons for this contrast in the chemistry of the magma types, and its effect on volcanic activity.

The magma generated by partial melting of mantle diapirs at the base of the crust will be of low-silica basaltic composition. When subduction takes place at a oblique angle to the continental margin, this can cause tension and allows crustal fractures to open intermittently as fluid pathways. The basaltic magma can then easily reach the sea bed and be erupted as lava flows (fig. 34a). Magma remaining within the crust at the end of the eruption will form vertical dykes or horizontal sills of dolerite.

Direct movement of magma to the surface is not always possible, either because fractures are temporarily closed by compressional forces, or because magma has reached the base of a solid unfaulted section of crust. In this case, an alternative method of magma ascent known as **stoping** can occur. Heat and pressure in the fluid magma causes blocks of overlying crustal rock to fall into the melt and be assimilated, providing an upwards pathway for the magma. Rocks such as sandstone and mudstone have a high silica content, so their assimilation can produce a magma of rhyolitic composition. In contrast to the gentle outpouring of basalt lavas, rhyolitic magma has a high visocosity and is often erupted explosively to produce a volcanic ash cone (fig. 34b).

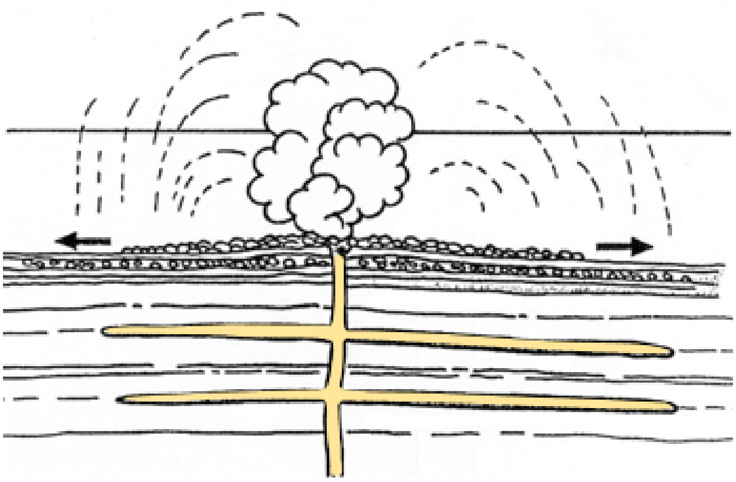

Figure 34(a): Basic volcanic phase

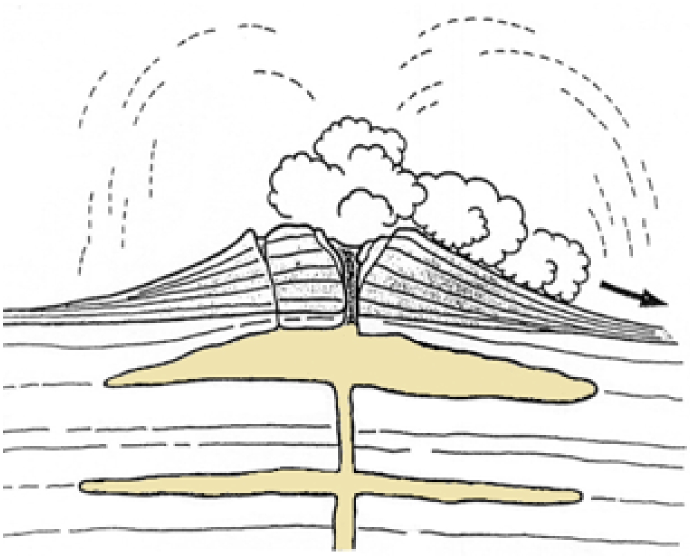

Figure 34(b): Rhyolitic volcanic phase

The types of eruptive deposits depend on both the viscosity of the magma and its water content. Water can dissolve under pressure in a deep magma chamber, and escapes from solution as bubbles of superheated steam as the magma rises and pressure is reduced. This process of **vesiculation** produces a light froth of magma which is then expelled rapidly upwards, expanding as the pressure is released.

If very little water is present in the magma, this remains in solution up to a shallow depth. Vesiculation occurs close to the volcanic vent, and the magma froth flows under gravity down the sides of the volcano as a dense cloud which settles to form an ignimbrite.

When a larger amount of water is present, vesiculation begins at greater depth. The effect is to produce magma froth which increases in velocity as it rises. The magma froth is projected explosively upwards from the vent to produce ash particles which rain down through the air or sea water around the volcano (fig.35).

During the culmination of Ordovician volcanic activity in Snowdonia, a caldera structure developed. This was initiated by rise of magma along the Beddgelert and Nant Gwynant fault zones, followed by the development of an extensive high level rhyolitic magma chamber beneath central Snowdonia. Subsidence of the overlying crust eventually led to the formation of a ring fracture (fig.36).

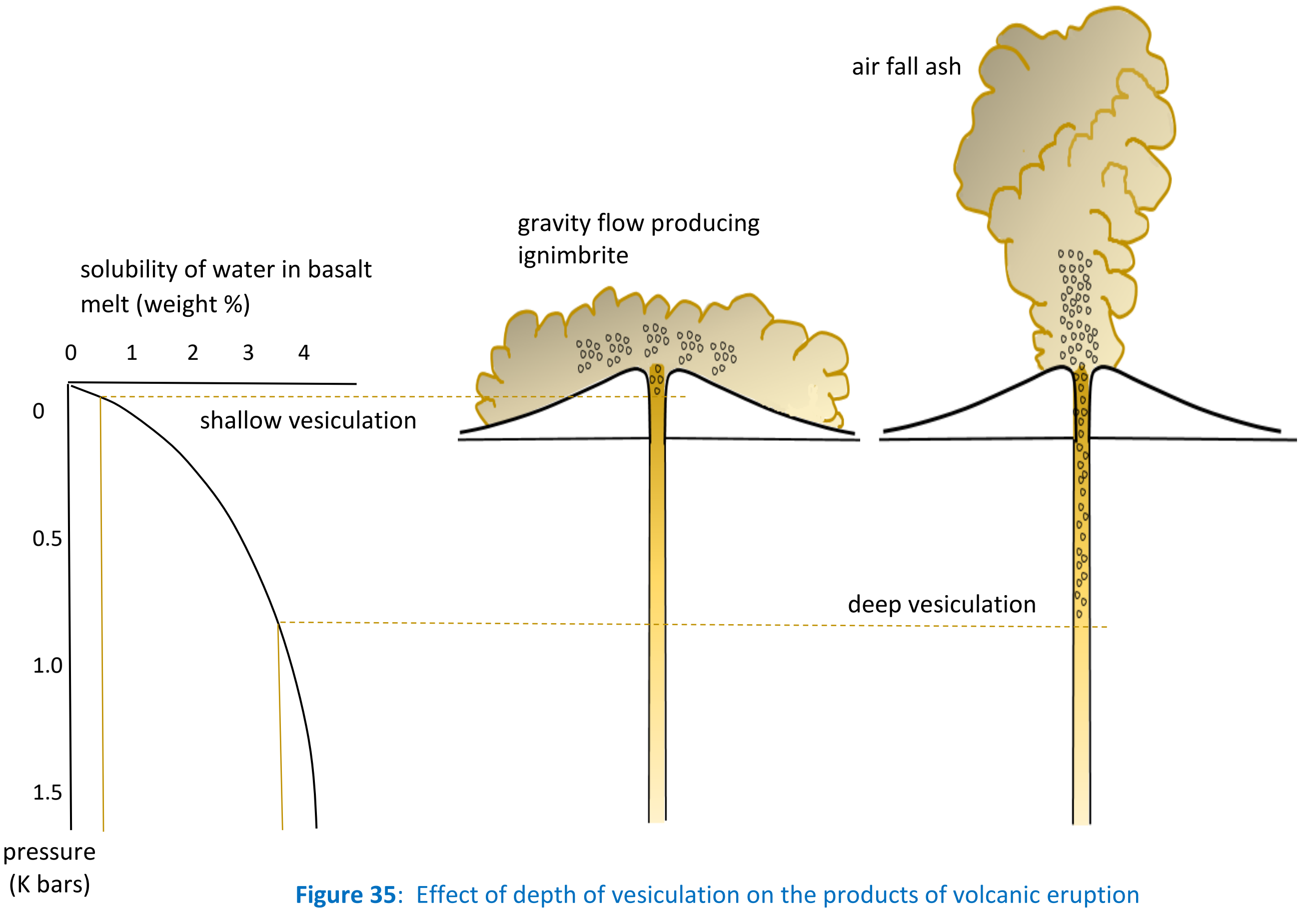

Figure 35: Effect of depth of vesiculation on the products of volcanic eruption

Erosion of the Snowdon volcanic centre at the present day has exposed many interesting features of its internal structure. We get a glimpse of the magma chamber itself in the Tan y Grisiau microgranite to the south of the caldera. Heat from the magma has recrystallized the overlying rocks to produce a metamorphic aureole.

Subsidence allowed magma to rise as a **ring dyke**, producing eruptions from a series of centres around the caldera margin. Greatest thicknesses of ashes accumulated in the central area of the caldera, but ash deposits also extend outwards beyond the caldera margins.

Periodic refilling of the magma chamber caused an uplift of the overlying crust along circular, outwards directed fractures which were infilled by magma to form **cone sheets**. Examples are seen today in the crags overlooking the village of Tremadog.

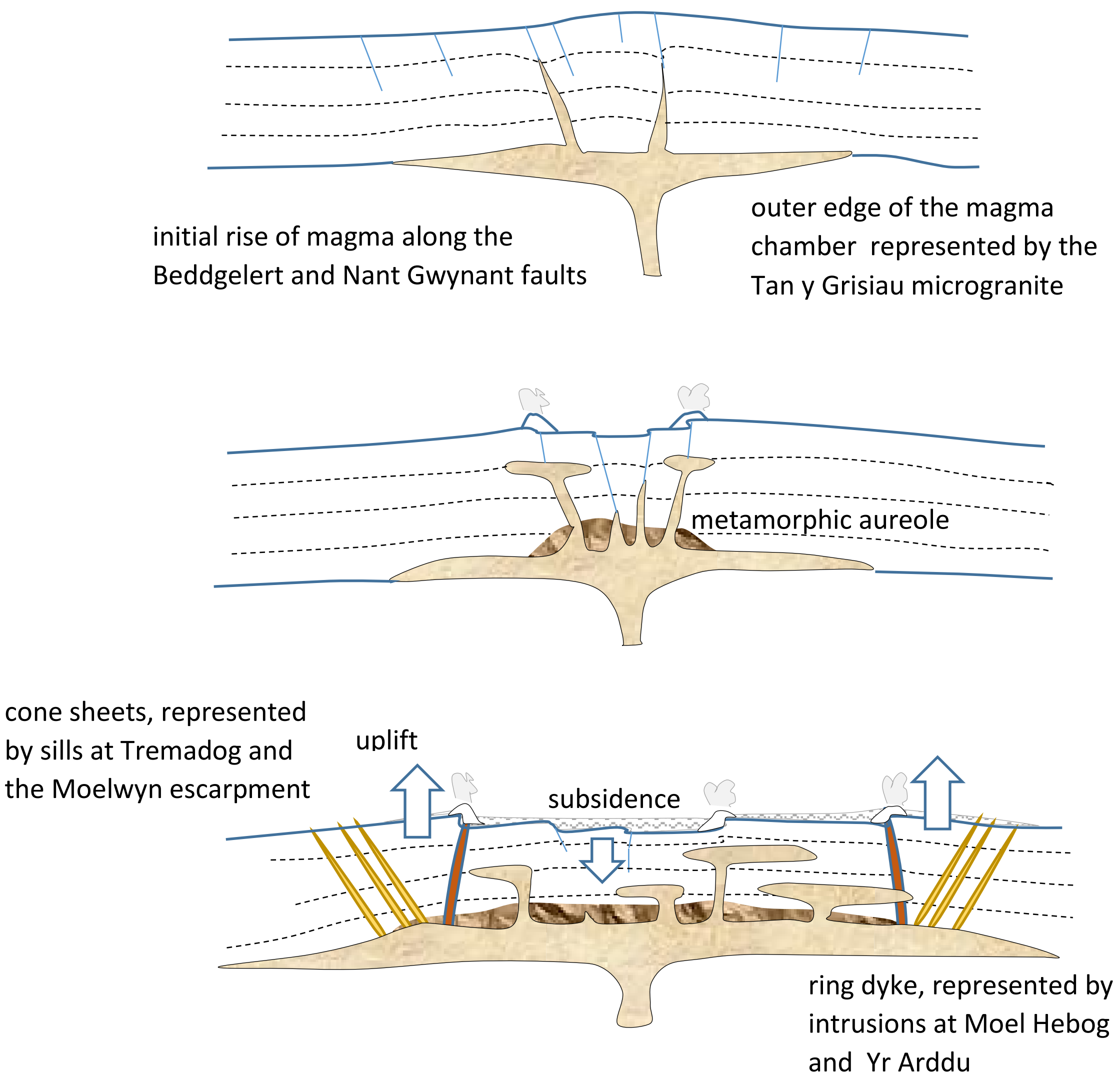

Figure 36: Development of caldera structures above the magma chamber

An important feature of igneous rocks is their crystal size. Almost all Ordovician intrusions in north Wales have a fine or very fine grain size, and it is interesting to consider why this is the case.

Textbooks may suggest that crystal size is determined simply by the rate of cooling of the magma, with slow cooling of a major intrusion producing large crystal size whilst fast cooling of a thin dyke or sill produces a fine grained rock.

This, however, is probably an over- simplification. Water content of the melt can play a crucial role in determining crystal size.

Considering first a magma with very little dissolved water present, the rate of cooling does indeed affect crystal growth. As the temperature of the melt falls, a point is reached where crystal nuclei begin to form. At first there will be few nuclei, and ions can move from the surrounding melt to build the crystals. As the temperature continues to fall,

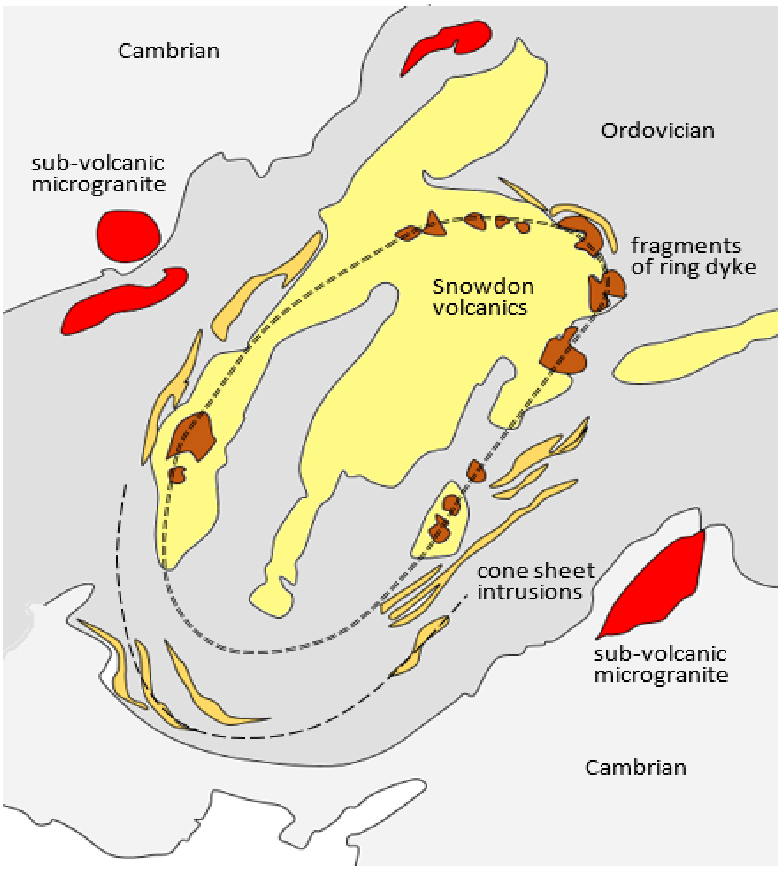

Figure 37: Features of the Snowdon caldera.

however, more nuclei rapidly appear and form foci for the growth of many small crystals.

If we now consider a situation where a significant amount of water is dissolved under high temperature and pressure in the melt. This has the effect of inhibiting the formation of crystal nuclei, whilst increasing the mobility of ions to move through the melt to the points where crystals are growing (Nabelek et al., 2010). Large crystals are able to form, as seen in granites in areas of Britain such as Dartmoor and Aberdeen. The important feature of these coarse granites is that they formed deep underground in developing mountain chains, where high confining pressures prevented the escape of superheated steam from the magma.

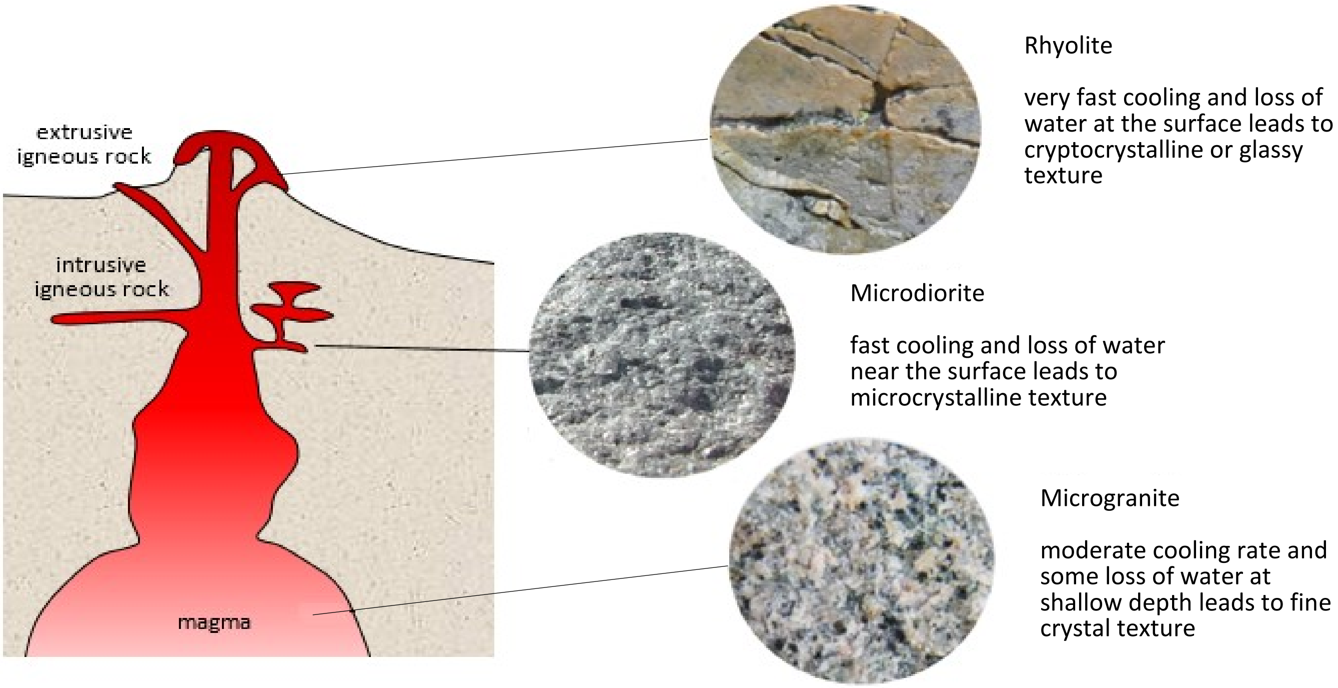

Figure 38: Crystal size in igneous rocks.

Let us return now to our discussion of Ordovician igneous rocks in north Wales. We find that some bodies of granite, such as the Tan y Grisiau and Trefor intrusions, are many kilometres in extent and will have cooled very slowly; at least in their central regions. We might expect a large crystal size, but these rocks are uniformly fine grained microgranites. The explanation seems to lie in their shallow depth of emplacement beneath volcanic centres, with tensional stresses in the overlying crust allowing open fractures to develop. Water dissolved under pressure in the magma at depth was quickly vented off, leaving the melt dry and promoting the nucleation of many small crystals.

Where rhyolitic magma reaches the surface, any remaining water will be lost and the rapid rate of cooling can lead to solidification directly to a glass. However, over geological time, originally glassy rhyolites will usually undergo devitrification and develop a microscopic crystal structure.

A final feature of interest involving igneous activity in Snowdonia is the thermal effect of large intrusions on the surrounding country rocks to produce **metamorphic aureoles**. The Tan y Grisiau microgranite intrusion has a particularly well developed aureole of spotted and banded **hornfels** around its margins (fig.39). Similar hornfels occurs a number of miles away in the area of Migneint, suggesting a continuation of the microgranite at shallow depth below the ground. During the development of hornfels, the rock takes on a hard crystalline texture similar to an igneous intrusion. This is due to recrystallization of clay minerals in the original mudstones to produce the silicate minerals **chlorite** and **sericite**. The recrystallization is likely to have been catalysed by superheated steam escaping from the hot microgranite below.

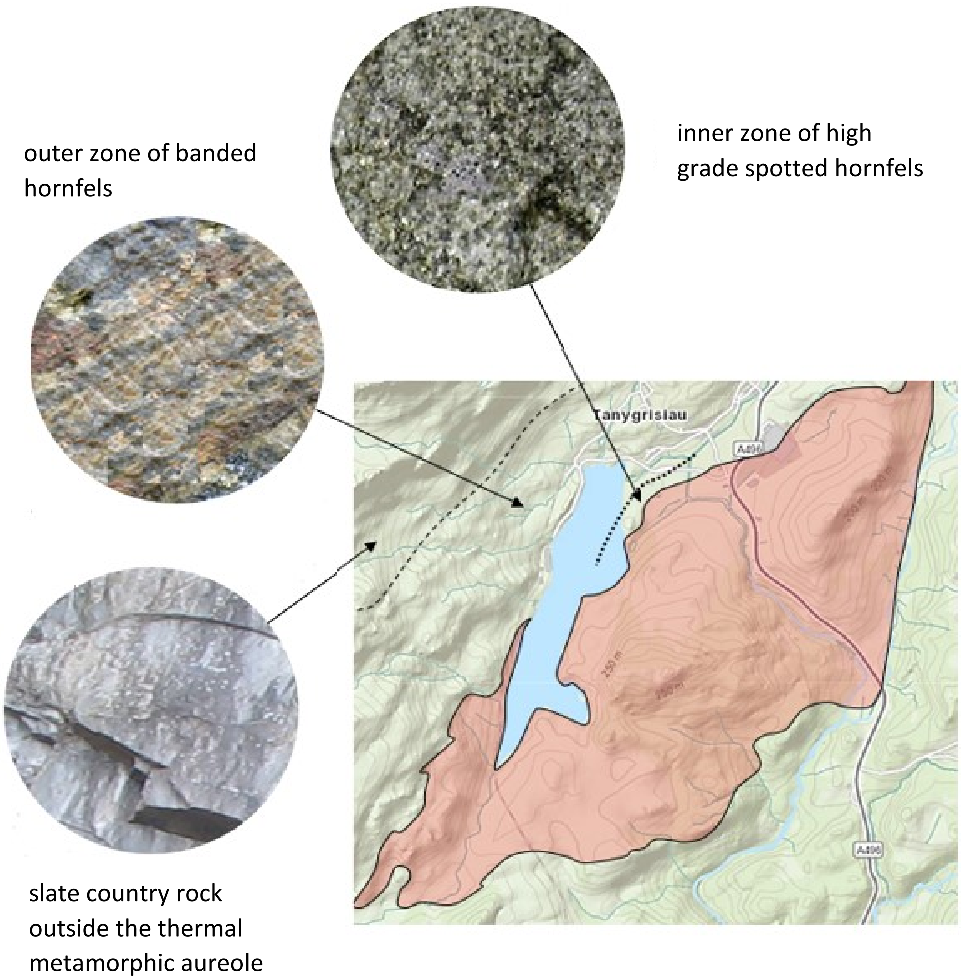

Figure 39: Metamorphic aureole of the Tan y Grisiau microgranite intrusion.

Sedimentary environments

The majority of Cambrian, Ordovician and Silurian sediments in North and Mid-Wales were deposited under water in a marine basin.

Over this long period of time, the depth of the water varied as fault movements affected the basin floor, and changes took place to the position of the coastline. However, the environments and mechanisms of sediment deposition remained remarkably consistent throughout the period.

Along the shoreline, sands and pebble conglomerates were deposited in the intertidal **littoral zone** where wave energy is high. Layers of sand may exhibit ripple marks of the type commonly seen on present day beaches.

A little further from the shore, but still in the shallow water of a shelf environment, storm deposits could be preserved (Nichols, 2009). These sands show a characteristic hummock and swale pattern within the bedding, as in figure 40.

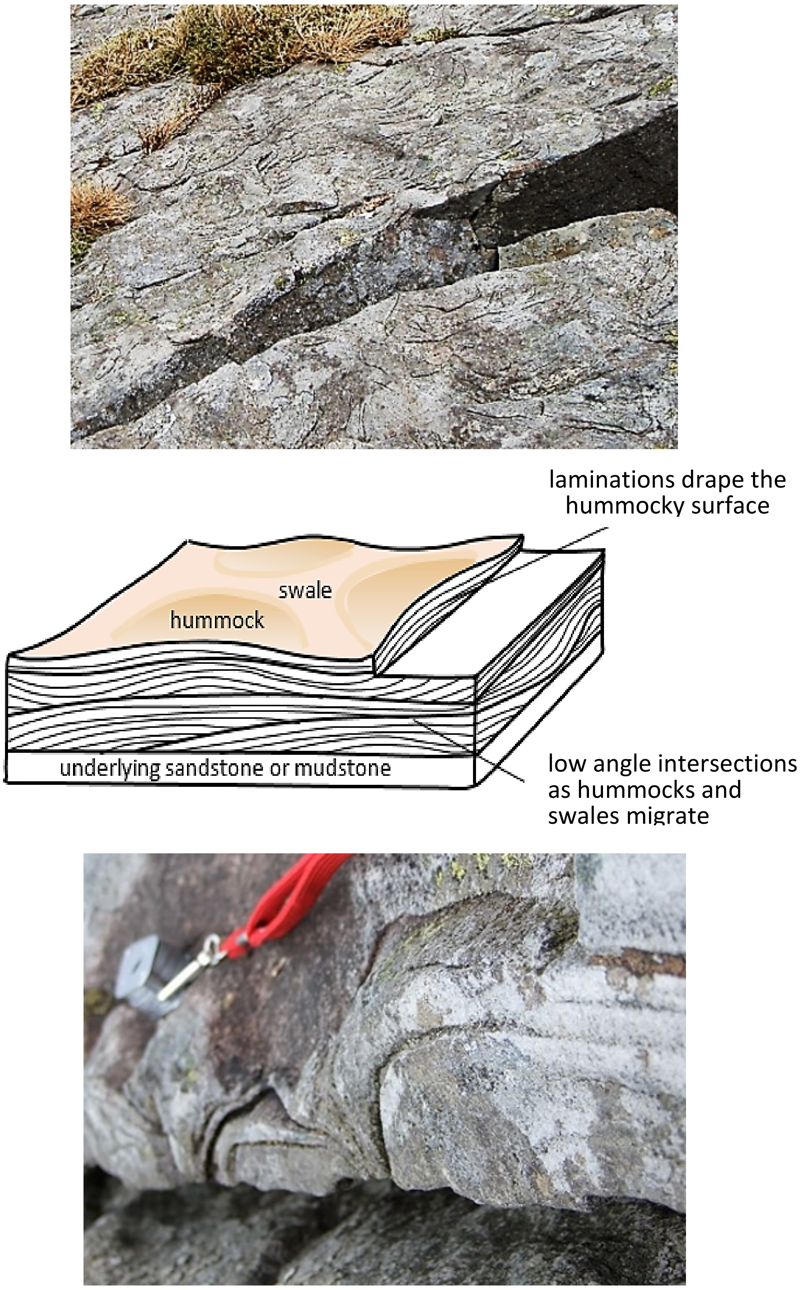

Figure 40: Storm deposits of Silurian age, Plynlimon, illustrating hummock and swale structure

Further away from the shore, sediments were commonly deposited on the floor of the deeper Welsh basin by turbidity currents. Sand, pebbles, silt and mud carried to the coast by large rivers would accumulate on the shallow marine shelf at a river mouth. At intervals, perhaps triggered by earthquakes or storms, an unstable mass of mixed sediment may break away and slump into the deeper water as a turbidite flow.

On reaching the basin floor, the largest pebbles and coarse sand would be quickly deposited. Finer sand, silt and mud would continue to be carried across the basin floor before settling out. In some cases, the turbidite flow may change direction to follow the axis of the basin, particularly if the basin floor is deepening along its axis.

Turbidite deposits can be classified according to their location relative to the source of the turbidity current (Walker, 1984). Sediments laid down close to the source are described as **proximal** turbidites, whilst those deposited further away are **distal** turbidites. It has been found that a characteristic sequence of sediment layers are deposited during and after the passage of each turbidite flow. The most complete sequence is observed in proximal turbidites where up to five layers, named A to E, may be present (figure 42).

A is a thick layer, perhaps several metres in thickness, of sediment grading upwards from pebbles and granules to coarse sand. Typically, bedding is absent. This layer represents rapid deposition from the fast moving head of the turbidite flow.

B is a further deposit of coarse sand, but now exhibiting parallel bedding. This material is deposited from fast flowing bottom currents below the turbidite cloud.

C represents a change from parallel bedding to inclined **cross-bedding**, produced as sand is deposited, then moved by the fast flowing water to produce a sequence of bed ripples.

D represents the introduction of finer **silt** grade material, interbedded with lenses of mud, as the turbidite cloud passes and the energy of the flow declines.

E is the final mud layer, produced by gentle sedimentation from the cloudy water in the wake of the turbidite flow.

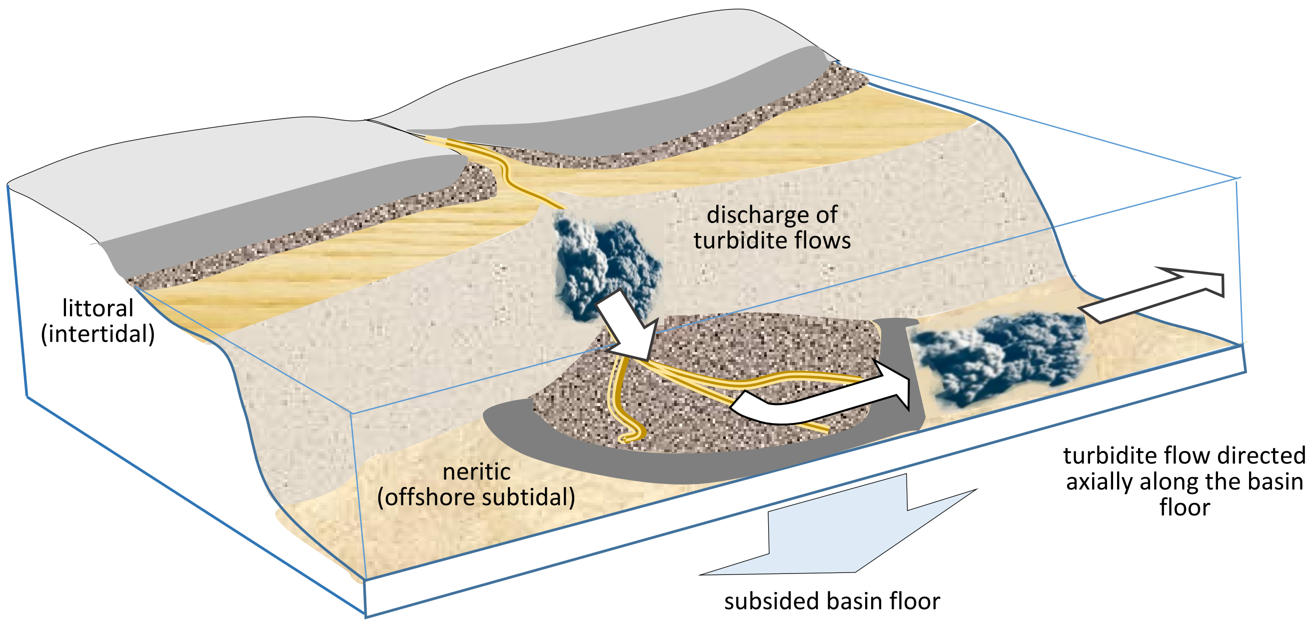

Figure 41: Turbidite deposition in the Welsh basin.

This sequence may be repeated as each turbidite deposits its sediment. Further away from the source in the distal environment, the coarser material will already have been lost, so only the upper layers may be laid down as each flow passes. The A layer and perhaps the B layer will be missing, with only the lower energy finer horizons represented.

The characteristics of turbidite sediments can sometimes be used to identify and examine in detail the depositional fan which develops on the basin floor at the base of a coastal shelf. A series of fan lobes may be developed, with each showing channel features similar to a sub-aerial delta. The density contrast between the turbidite flow and normal sea water causes the dense cloud of sediment to stay close to the bottom, scouring out a channel across the fan which may be followed by subsequent flows.

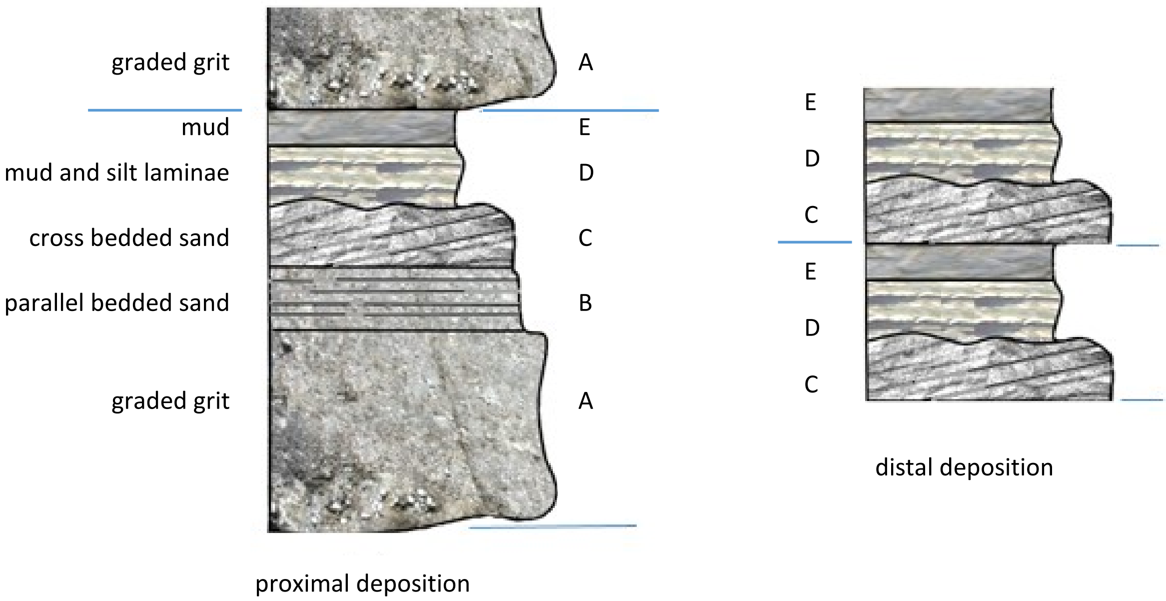

Figure 42: Sediment layers within turbidite deposits.

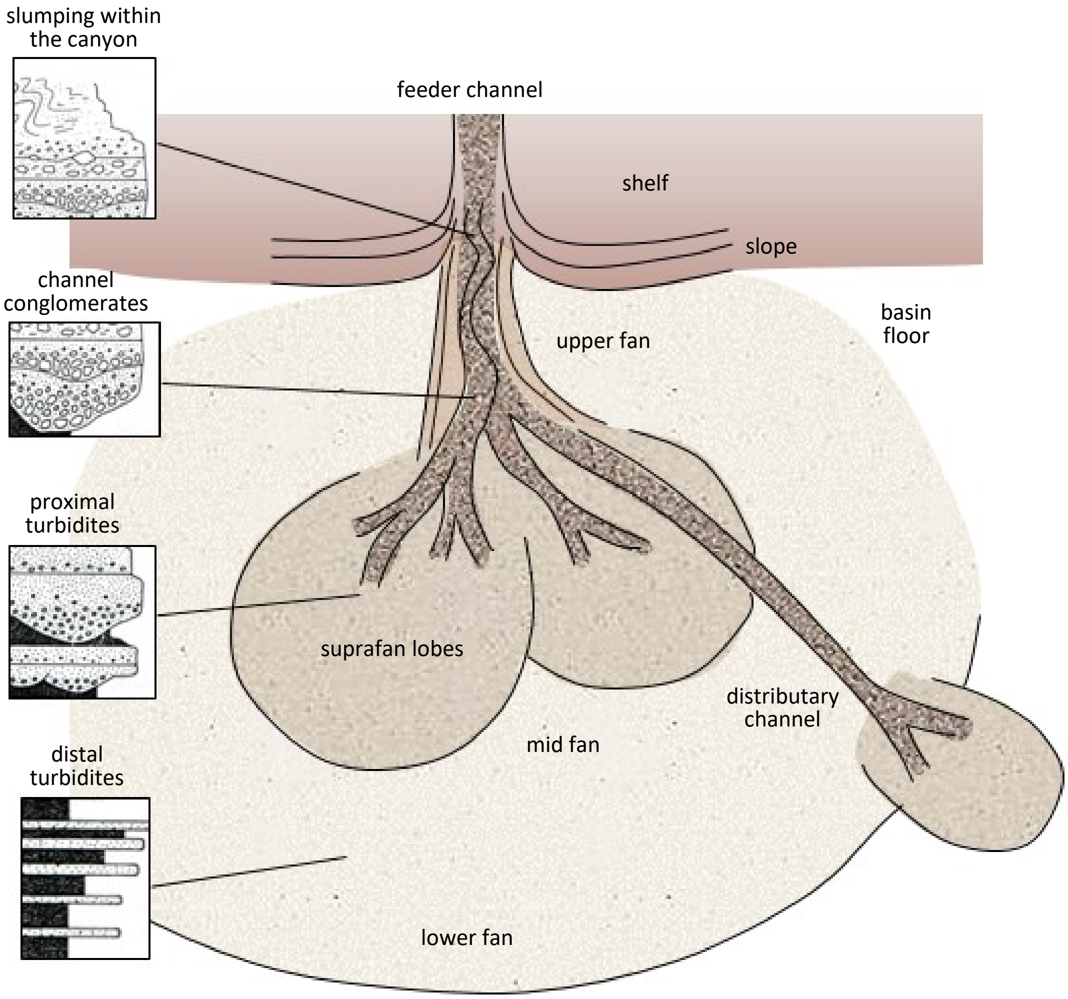

Figure 43: The structure of a turbidite fan complex

Within the channels of the fan complex, the flow will have high energy and only the coarsest material may be deposited. Channel deposits may be made up only from a sequence of graded grit A units. In steeper parts of the channel, the rapidly deposited sediment may slump under gravity when the flow has passed, producing soft sediment folds.

On reaching the flatter areas of the fan complex, the turbidite cloud can escape from the channel and dissipate across the fan lobes. The first influx of coarse sediment may scour grooves in the soft mud surface left after previous deposition. Where these **sole marks** are preserved, they can provide useful information of the flow direction of turbidity currents.

Figure 44: Soft sediment slump folds in a turbidite sandstone. Rhinog Grits, Cwm Bychan.

Figure 45: Sole marks on the base of a turbidite sandstone. Aberystwyth Grits.

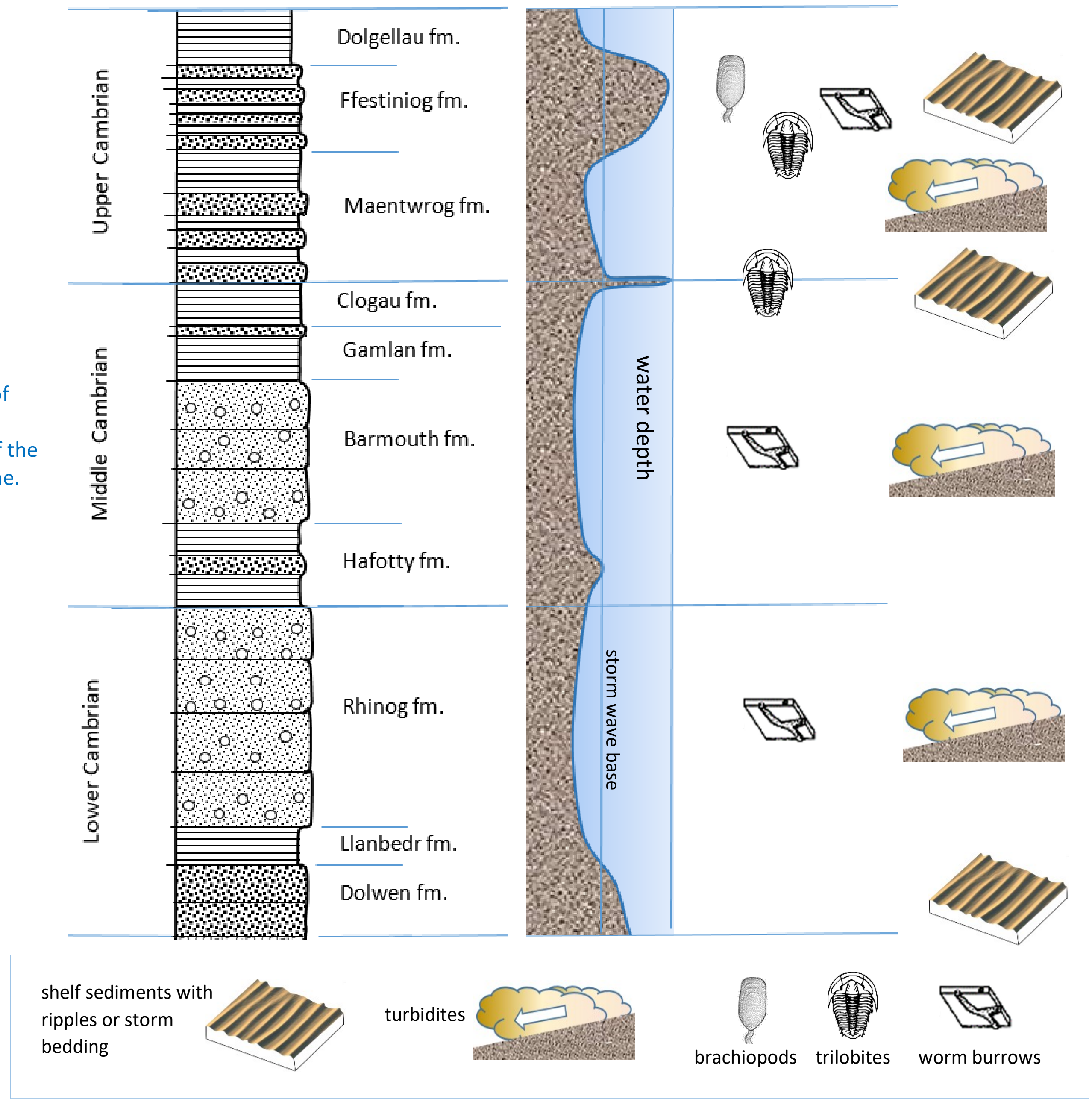

Figure 46:

An analysis of Cambrian sediments of the Harlech Dome.

By analysing the textures of a sequence of sedimentary strata, and identifying depositional features similar to those described above, it may be possible to reconstruct the geological history of an area. Results are shown in figure 46 for an analysis of Cambrian strata in the Harlech Dome (Crimes, 1970).

We see that for much of the Cambrian period in the Harlech Dome area, the basin floor lay below the base of storm waves. Sediments were deposited mainly by turbidity currents. Many of the coarse grits seen in lower and middle Cambrian ***Rhinog*** and ***Barmouth*** formations are channelled fan complexes. By contrast, the thinner bedded turbidites of the upper proximal turbidites which accumulated in Cambrian ***Maentwrog*** formation are distal deposits laid down across the flat basin floor.

At the beginning of the Cambrian during deposition of the ***Dolwen*** formation, and again at several times during the upper Cambrian, the basin became shallower. This may have been due to fault movements affecting the basin floor, or a change in the position of the coastline. We can identify the periods of shallow water from shelf sediments showing tidal ripples or storm bedding. Additional evidence is provided by preserved fossils, which we will consider next.

Paleoecology

Remains of organisms found in sedimentary rocks can be of value to scientists in several ways. Most fundamental is the evidence provided to biologists about the evolution of plants and animals over geological time, culminating in our present day flora and fauna. Geologists have traditionally used fossils as a means of identifying the ages of sedimentary formations, since particular species may only exist for a short period of the geological time scale.

A further, very important, use of fossils is in determining the environmental conditions under which particular sediments were deposited. As at the present day, an ancient marine animal species may have a preference for particular ecological conditions. These might be determined by the depth of the sea bed, type of bed sediment, or strength of water currents. Each of these factors can affect the opportunities provided to the animal for shelter, feeding, and protection from predators. We will examine some typical marine organisms preserved in Welsh basin sedimentary rocks.

In the deeper waters of the Welsh basin, the most commonly found fossils are **graptolites**. These structures are not single organisms, but colonies of tiny filter feeding polyps. Each polyp lives within a cup called a **theca** attached to one of the branches or **stipes** of the graptolite. The whole structure can drift freely in deep water, and may eventually sink to the basin floor and be preserved in muddy sediments.

Figure 47: Ordovician graptolite *Didymograptus*

The graptolites evolved rapidly and underwent many morphological changes, so are valuable for accurate dating and correlation of Ordovician and Silurian sediments in Wales.

The majority of fossils preserved from intertidal beach environments in the Cambrian of north Wales are **brachiopods**. These bivalve creatures often lived in burrows in the sand, emerging at high tide to feed on passing food particles then retreating into their burrows as the tide receded.

Figure 48: Brachiopods on upper Cambrian mudstone. Coed y Brenin.

Lower down the shelf, in the shallow subtidal region of the sea bed, a common marine animal was the **trilobite**. These creatures occupied a similar ecological niche to present day lobsters or crabs, moving over the sea bed as predators or scavengers, or swimming to feed on plankton.

Figure 49: Trilobite, upper Cambrian. Coed y Brenin.

Apart from the preservation of trilobite body fossils, it is particularly interesting that **trace fossils** of trilobites can also be found. Trace fossils are marks made in the sea bed sediment by the activity of a creature, then preserved when the sediment is lithified to produce a solid rock. Examples of trilobite trace fossils are shown in figure 50.

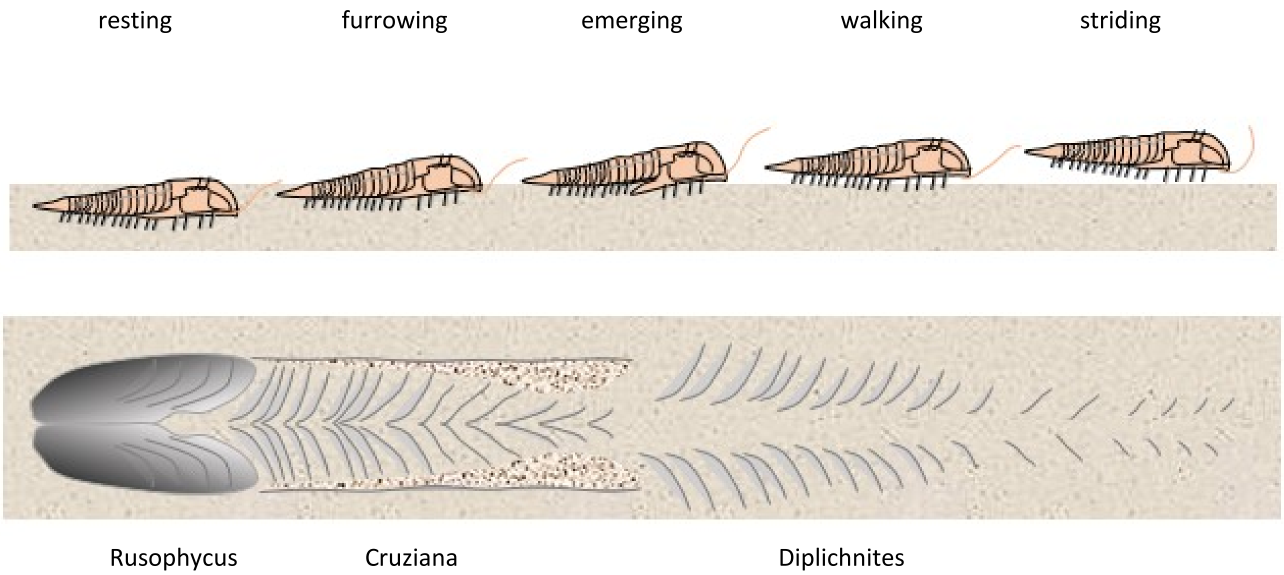

Figure 50: Trilobite trace fossils.

In resting mode, the trilobite excavates a shallow depression in the sand in which it can conceal itself whilst waiting for food particles or prey to pass by. These resting impressions may be preserved, and are given the identification name ***Rusophycus***. When the trilobite emerges onto the sea bed, a characteristic series of grooves are produced by its multiple pairs of legs. Initially the grooves are continuous (***Cruziana***), but split into two parallel tracks as the creature rises from the sandy sea bed (***Diplochnites***).

Figure 51: *Rusophycus* trilobite resting impression. Cambrian

Trace fossils can be used to develop detailed paleo-ecological models for particular sedimentary rock formations. In addition to trilobite tracks, various mollusc and worm burrows may be preserved, along with traces made by worms moving across the sediment surface. Both vertical and branching horizontal networks of burrows may be present.

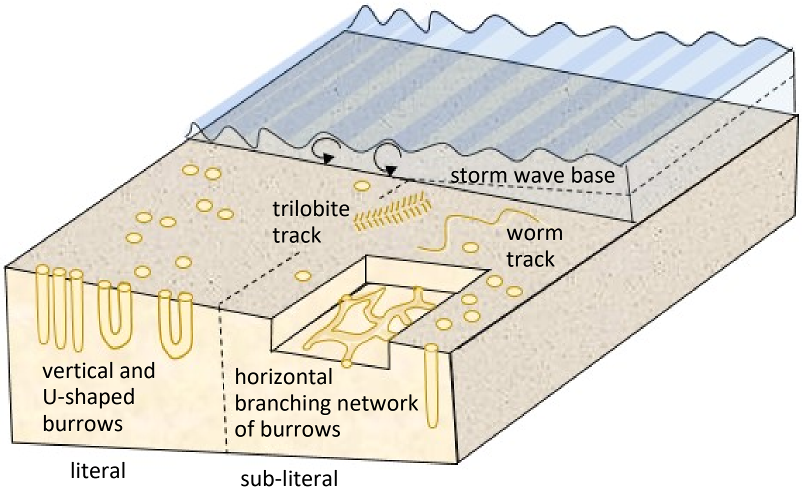

Figure 52: Variety of trace fossils found in a shallow water marine environment.

Some mudstones have lost their clear bedding in places due to the action of burrowing animals redistributing the sediment. This is a process known as **bioturbation**.

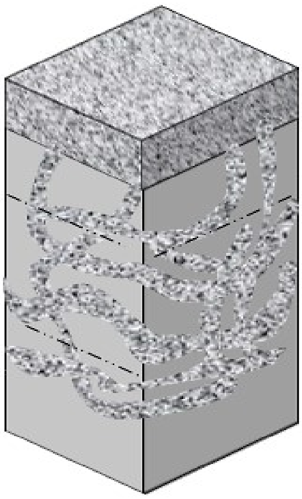

Figure 53: Bioturbation: downwards transfer of sediment through a burrow system.

Basin tectonics

An important aspect of the geology of north and mid-Wales is the presence of a series of major fractures which extend to the base of the crust. These fractures have allowed both horizontal and vertical movements of overlying crustal blocks to take place. The earliest identified fault movements in north Wales took place along the Menai fracture zone, as terranes were assembled into their current relative positions during the Cambrian period.

During Ordovician times, volcanic centres developed as an Iapetus ocean plate descended into the subduction zone below Wales. The distribution of volcanic centres across Wales is not random, but appears to follow lines linked to deep fractures in the crust which provided easy pathways for magma to rise to the surface.

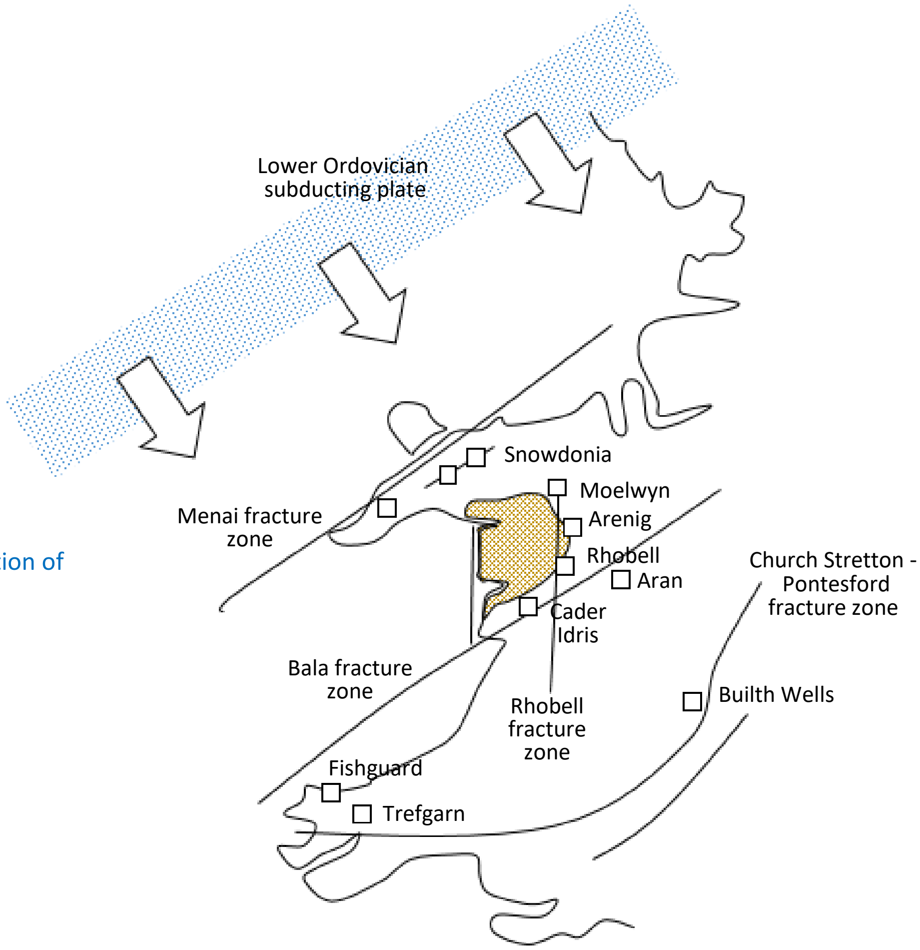

Figure 54: Distribution of Ordovician volcanic centres in Wales.

We see that a series of volcanic centres in Snowdonia and the Lleyn peninsula follow the NE-SW trend of the Menai fracture zone, with the Cader Idris and Aran centres lying on the similarly oriented Bala-Mawddach fracture zone. Volcanic centres along the eastern side of the Harlech Dome in the Moelwyn mountains, and at Arenig and Rhobell Fawr, lie along the N-S oriented Rhobell-Corris fracture. Volcanic centres at Builth Wells in mid-Wales and at Trefgarn in Pembrokeshire can be related to the system of faults which formed the south eastern margins of the Welsh basin.

In addition to a control on volcanic activity, the deep crustal fractures within and around the Welsh basin had a crucial effect on water depths, and consequently on sedimentary processes. Several types of block movement took place.

Where fractures exist at depth in the crust, horizontal strike-slip movement or vertical dip-slip movement could take place between adjacent crustal segments. These fault movements might be triggered by compression or tension in the crust during plate movements. It is often the case that a single major fracture at depth can diverge into a series of sub-parallel faults near the surface, termed a **flower structure**. Subsidence within the fault zone can produce a localised downfaulted trough known as a graben, whilst crustal blocks on either side remain as uplifted horsts.

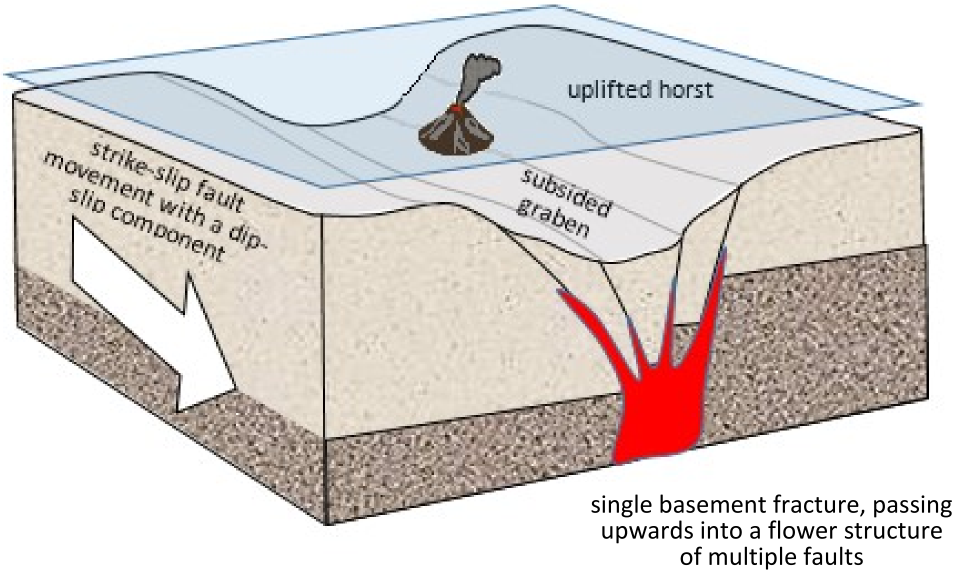

Figure 55: Development of a subsided trough above a deep fracture.

A major graben existed in early Ordovician times along the eastern side of the Harlech Dome block. The fractures were the sites of multiple dyke intrusions oriented in a north-south direction, providing feeder vents for the Rhobell volcanic centre.

Throughout the Cambrian, Ordovician and Silurian periods, the Welsh basin was an area of overall crustal subsidence within the continental crust of the Avalonian microcontinent. Uplifted areas of crust persisted in the Midlands of England, the Irish Sea, and between Leinster in Ireland and the English Lake District. In area between these land masses, crustal blocks intermittently subsided along major crustal faults to produce areas of shallow or deeper water.

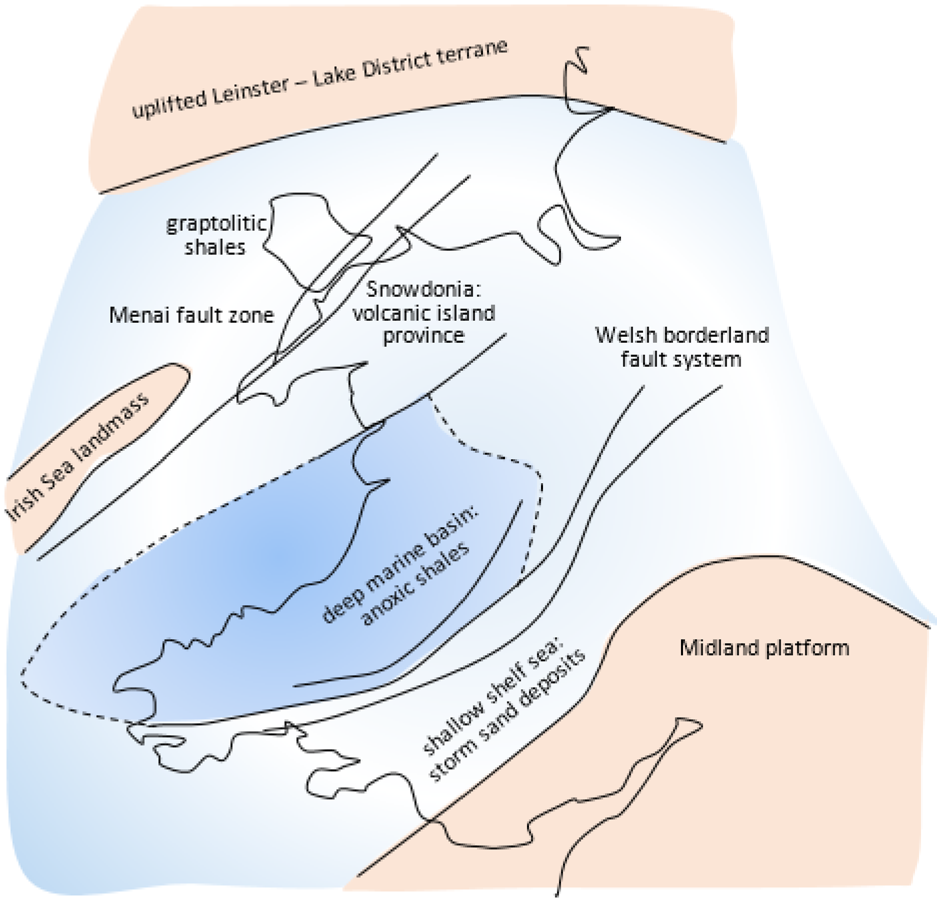

Figure 56: The Welsh basin during the mid-Ordovician period

Downwards movement of the blocks between the fault zones may have been more rapid on one margin than the other, leading to a tilting of the crustal block in a **half-graben** structure.

During the late Ordovician to end Silurian period of sedimentation in the Welsh basin, deeper water conditions were found in the central area where subsidence was greatest, with a series of half graben structures allowing the basin floor to step downwards from the shallow shelf of the Midland platform (figure 35). It is possible to reconstruct the paleogeography of these periods by identifying areas of coarser and thicker sediment which were laid down as turbidite fans at the base of each of the subsiding faults. Finer muddy sediment was deposited in the stable areas away from the sea bed fault lines.

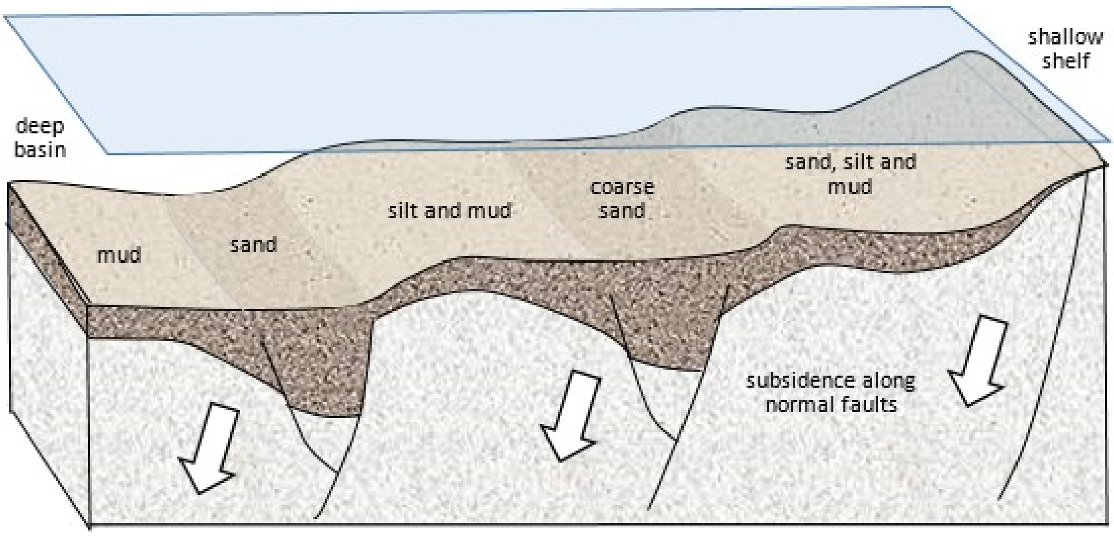

Figure 57: Development of a series of half-graben structures.

At the end of the long phase of basin sedimentation in central Wales, the Devonian period was marked by brief but widespread folding, faulting and low grade regional metamorphism known as the Acadian Orogeny. At this time, the thick succession of muds, silts and sands in the Welsh Basin may not have been fully lithified. Tilting of the basement blocks caused slump folding as sediments slipped down-slope. Minor fold structures in the Silurian of mid-Wales can often be attributed to **soft sediment deformation** in unlithified sediments.

The cause of the Acadian orogeny was the closure of the ***Rheic ocean***, bordered to the south by continental fragments which now make up parts of France and Spain. Subduction began beneath southern Britain, with associated volcanic activity in Pembrokeshire and southern Ireland.

The descent of oceanic crust was sufficiently rapid for the mid-ocean plate boundary to be carried into the subduction zone. Hot oceanic crust alongside the former spreading centre provided buoyancy, so that the Rheic ocean plate remained at shallow depth beneath the Welsh region.

In Wales, an important feature of the Acadian orogeny was the formation of economically important slate deposits. Clay particles in the original sea-floor muds were recrystallized to form flakes of flat mica minerals such as **sericite**. The mica flakes became oriented according to the stress field in the rock, producing the slatey cleavage which allows the rock to be easily split into thin sheets. The orientation of the cleavage in the slate deposits of north and mid-Wales affects the way in which the rock is quarried in surface and underground workings. In the Blaenau Ffestiniog area, the cleavage dips at a relatively gentle angle, whilst in the Corris area the cleavage is close to vertical. Large igneous intrusions in central Snowdonia such as the Tan y Grisiau Granite resisted deformation forces during the Acadian orogeny, so that folds and cleavage wrap around these solid masses and flatten off above them. Elsewhere, cleavage developed parallel to the axial planes of large folds.

Subduction caused northwards thrusting of the wedge-shaped Precambrian mass of the Midland platform in England. The strong, massive block was compressed into the Wesh Basin sedimentary succession, causing alignment of many fold and cleavage structures parallel to the basin margin (fig. 58) .

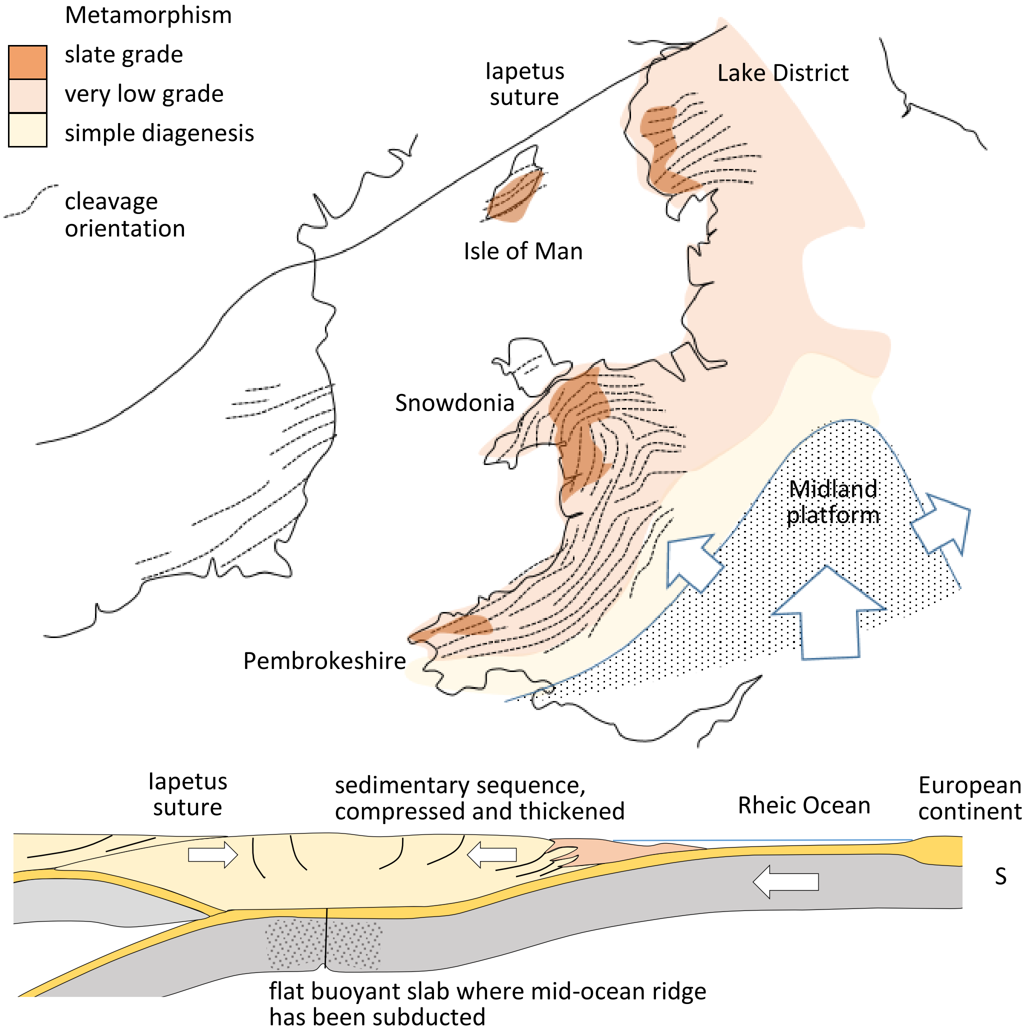

Figure 58: The Acadian orogeny in southern Britain.

Whilst Acadian metamorphism converted mudstones into slate at a higher metamorphic grade, a reverse process affected many of the igneous intrusions in north and mid-Wales.

Figure 59: Microdiorite metamorphosed to 'greenstone' Coed y Brenin

Mafic minerals originally formed at high igneous temperatures, such as olivine and pyroxene, became unstable during the Acadian orogeny and regressed to lower temperature mica-type minerals, particularly chlorite and sericite. The overall effect has been to give many intrusions a grey-green colouration; indeed, early geologists often described the igneous intrusions of the region as 'greenstone'.

Mineralisation

Two principal types of heavy metal mineralisation occur in the region. The first type is closely related to Ordovician volcanic activity, whilst the second type is associated with regional metamorphism in the Acadian orogeny during the Devonian period.

Copper ore deposits of volcanic origin were formed during the late stages of the Rhobell volcanic event. Hot mineralising fluids were released from the crystallising magma below the volcano, and were joined by flows of groundwater in convection cells driven by heat from the magma chamber (fig.60).

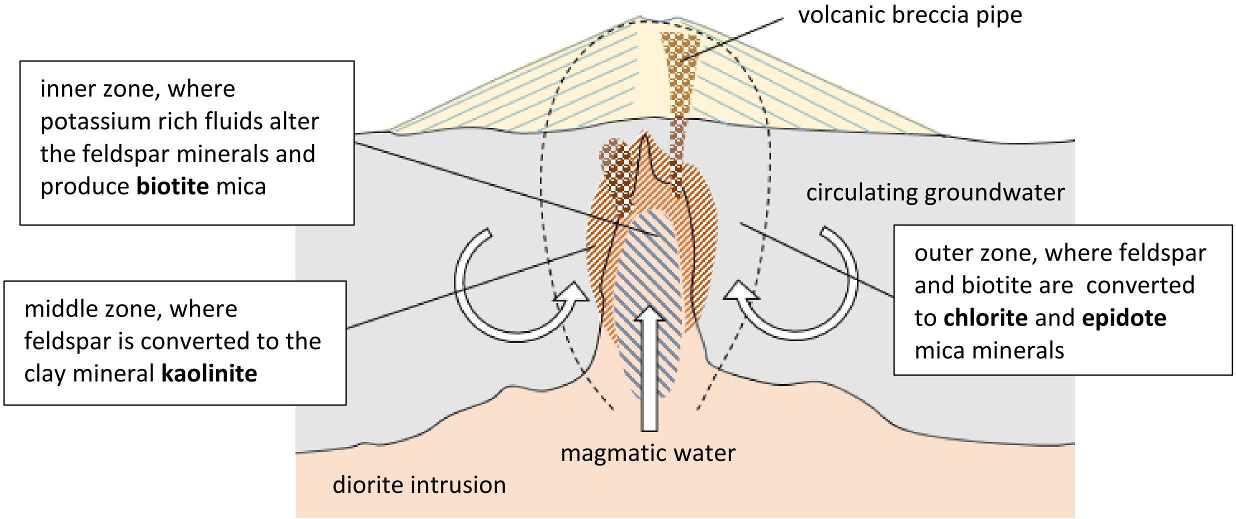

Figure 60: Model for a porphyry copper mineral deposit.

As the hydrothermal fluids moved through the overlying rocks, they caused a series of chemical reactions. Feldspar, amphiboles and other mafic minerals were progressively converted to micas and clay minerals. At the same time, the hot fluids were able to transport copper and iron in solution. As the temperature of the fluid decreased, metal sulphides were deposited as widely disseminated crystals along the many tiny fractures in the rock, or in more concentrated ore bodies in volcanic breccia pipes below the volcanic cone.

A disseminated copper ore body is now exposed at the surface at Hermon in Coed y Brenin in the core of the Rhobell volcano, and a large volcanic breccia pipe containing copper ore was worked at the nearby Glasdir mine.

Copper deposits are found across much of central Snowdonia in the area between Porthmadog, Ffestiniog, Beddgelert and Llanberis. The ores are again associated with volcanic activity, but less directly than in the case of the Rhobell volcanic centre (fig.61).

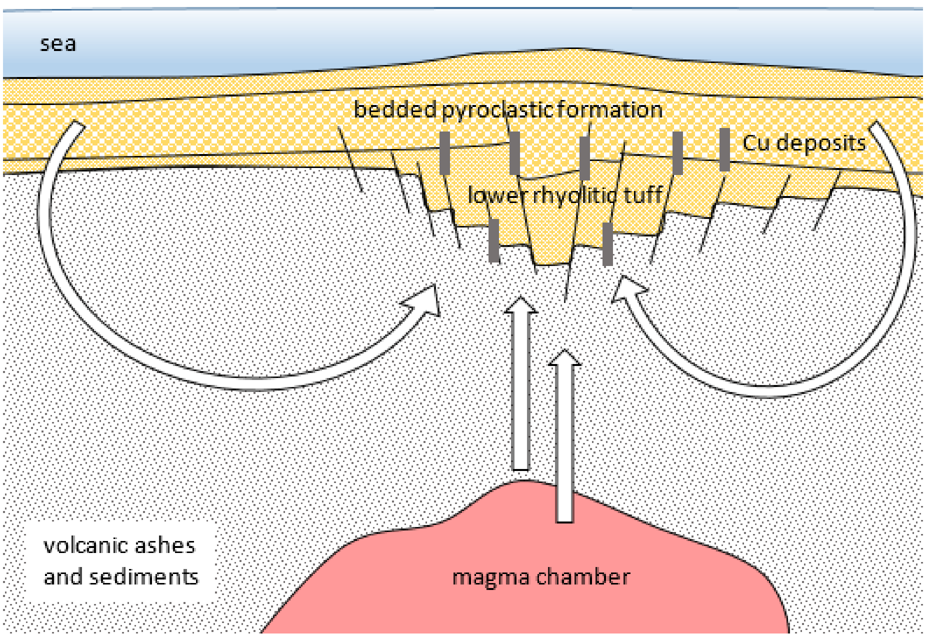

Figure 61: Copper mineralisation in Snowdonia

After eruptions from the Snowdon caldera ended, the deep magma chamber below the region would have retained its heat for millions of years. Hydrothermal fluids were released in the late stages of crystallisation, and were joined by water moving in convection cells driven by the heat of the intrusion. In late Ordovician times, North Wales was covered by shallow sea, providing a source of water for the convection cells.

Hot circulating water was able to dissolve copper and iron from the thick sequence of volcanic ashes and sediments which had accumulated in the region during earlier volcanic activity. The minerals were carried upwards and channelled along faults in the overlying strata, where a reduction in temperature and pressure could initiate the deposition of ore minerals.

Copper is present in quartz veins, with ore richest around the base of the ***bedded pyroclastic formation***, and to a lesser extent at the base of the ***lower rhyolitic tuff formation***. This localisation of the ore may be the result of a combination of factors: temperature and pressure conditions were right for crystallisation at these depths, the strength of the rock allowed open fractures to form, and the chemical composition of particular strata promoted the deposition of heavy metals.

The second major group of heavy metal deposits are those emplaced during the Acadian orogeny (James, 2011). Compression of the Ordovician and Silurian sedimentary strata of mid-Welsh during mountain building led to the thickening of the rock sequence with intense folding. As sediments were pushed down to greater depth, pressures and temperatures increased and low grade regional metamorphism began.

Recrystallisation of clay minerals released saline hydrothermal fluids which were able to dissolve substantial quantities of lead and zinc as they moved upwards through the thick sedimentary sequence. As the hydrothermal fluids reached higher levels, a fall in temperature and pressure allowed the deposition of mineral veins along **normal faults** which had formed at a late stage of the Acadian earth movements (fig. 62).

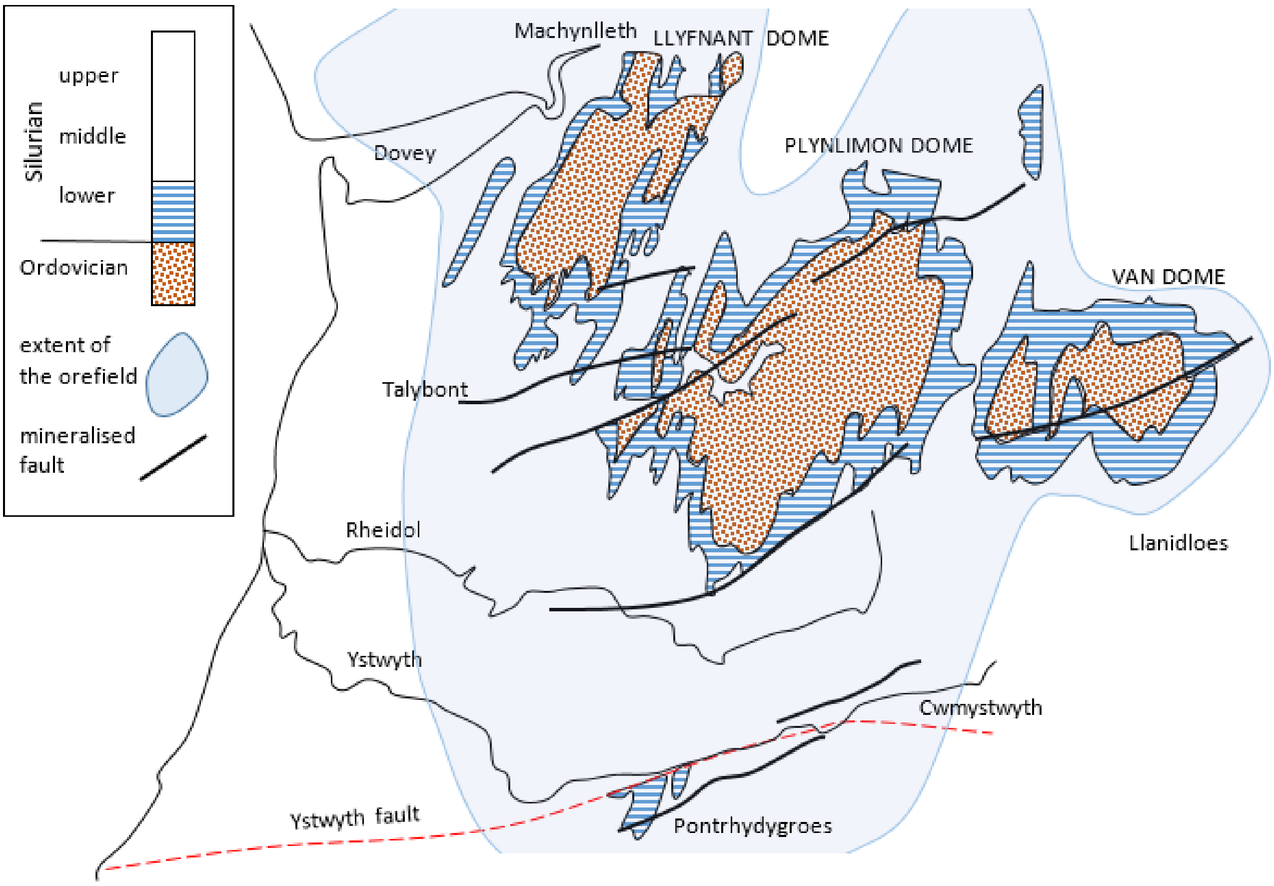

Figure 62: The central Wales lead-zinc ore field.

The ore field is centred on the up-folded central region of the basin to the north and south of the ***Plynlimon Dome***. Temperatures and pressures would have been greatest in the thickened sedimentary succession along this axis.

We find that major ore bodies are located where the faults pass through zones of coarser sandstone within the Ordovician and Silurian marine sediments. These sand layers played an important role in initiating crystal formation in the hydrothermal fluid.

Another area of mineral deposits emplaced during the Acadian earth movements lies further to the north around the Harlech Dome; this is the Dolgellau gold belt. Hydrothermal fluids were again produced at depth by metamorphic processes, but in this case the source of the fluids may have been a large thickness of late Precambrian volcanic ashes buried beneth the Harlech Dome area.

Mineral deposits of the Dolgellau gold belt are largely localised along two axes; a north to south group which follows the ***Rhobell-Corris*** fracture zone, and a north-east to south-west group which follows the ***Bala-Mawddach*** fracture zone. It is likely that these deep fractures chanelled the mineralising fluids upwards towards the surface, where crystalisation took place along normal faults as the fluid temperatures and pressures were reduced (fig.63).

As in the case of the mid Wales deposits, the nature of the sedimentary rocks has affected the localisation of gold ore deposits. Mine sites are closely linked to the outcrop of the ***Clogau shale*** formation of middle Cambrian age. Clogau shale was orginally deposited as mud on the sea bed under anoxic conditions, and contain grains of carbon and iron pyrite. At the later time when hydrothermal fluids passed through the rocks, these chemically active substances could promote the formation of heavy metal minerals.

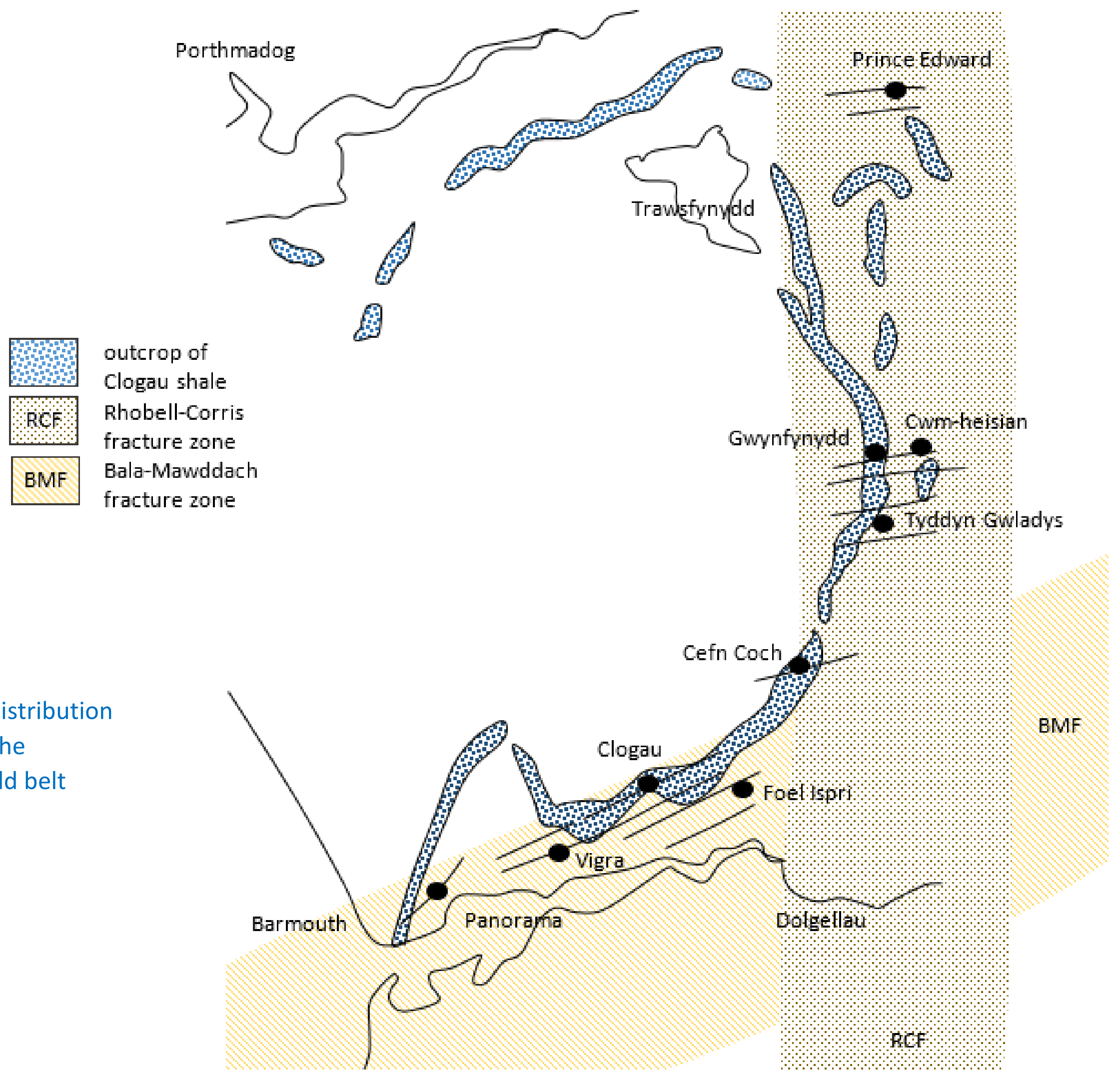

Figure 63: Distribution of mines in the Dolgellau gold belt