An Essay on the Geology of NW Scotland

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The NW Highlands of Scotland contain a spectacular diversity of rocks. These chart nearly three billion years of earth history. But they also offer insights on ancient environments, the processes that formed ancient mountain ranges and the wearing away of these landscapes. In more recent times the landscape has been sculpted by ice-sheets which speak of climate changes during human existence.

This account is designed to provide a guide to some of this story. Although complicated enough, has been simplified somewhat. But it is still difficult to follow – in part because some of the more obscure parts are by no means generally agreed. There may be whole episodes of ancient mountain building that are only weakly recorded – nearly obliterated by the effects of later orogeny.

Introduction

One of the key features of the geology of NW Scotland are features that relate to an ancient period of mountain building – called the Caledonian. This ancient chain once included most of northern Britain (although its weak effects can be seen as far south as Pembrokeshire in south Wales). The most striking effects of the Caledonian system are shown by rocks in the Scottish Highlands. Rocks are tightly contorted and strongly recrystallised by the heat and pressure to which they were once subjected deep under the ancient mountain range. In places they even seem to have melted. But not all of Scotland was caught up in the Caledonian mountain belt. Rather like the village in the Asterix cartoons, one small enclave held out. We call this the Caledonian "foreland", a tract of geology that preserves a history of geological events much older than the Caledonian. The edge of the Caledonian mountain belt (the so-called "Caledonian front" that limits the foreland) runs from Durness – on the Scottish north coast, down to Lochalsh, opposite Skye. The front itself includes famous geological structures (including the Moine Thrust) that give important clues as to how mountain building happens. But more of that later. Our story starts in the foreland.

The Lewisian gneisses

The oldest rocks in the British Isles are the Lewisian gneisses. These ancient rocks show evidence for a long history of shearing and recrystallisation punctuated by periods of igneous activity. All this points to episodes of old mountain building – one of the chief ways the continental crust becomes sheared separated by periods of quiescence or rifting. Lewisian rocks can be found in the Outer Hebrides and along parts of the NW Scottish mainland. The oldest material is termed "Scourian" – named after the village of Scourie in Sutherland. Most of this material (all the obviously banded stuff for example) probably started "life" as various types of igneous rock - most likely the roots of old volcanoes. These probably formed below an arc of volcanic islands (perhaps like modern Japan). It is in this environment that the modern Earth's crust is largely formed. So the continental crust that forms the underpinnings of northern Scotland formed as the roots of old volcanoes. What's happened is that the old magma chambers, once solidified, have been squashed about and sheared. It's this process that reorganises the once igneous rock into a gneiss - and in the process the old igneous minerals are recrystallised to make new "metamorphic" minerals. The bulk chemistry doesn't change but the material changes its organisation - or mineralogy.

In the Lewisian the oldest crust formed about 3000 to 2700 million years ago. It sounds a long time ago, but the world's oldest surviving continental crust is about 4000 million years old! The shearing that reshaped the crust happened about 2450 million years ago, in an event called the "Badcallian". Perhaps this happened when ancient mountain ranges formed – the Lewisian occupying the old roots of these mountains. It's rather like what might happen if Japan was to collide with the main Asian landmass – or what happened about ten million years ago when New Guinea (volcanic island) collided with Australia (old, large continent).

After the Badcallian, the gneisses were split and intruded by sheets of igneous rocks (about 2400 million years ago and again at about 1900 million years ago). These sheets – called dykes because they are sub-vertical – have a so-called "basic" composition (they have a relatively low silica content – unlike say granite which has a high silica content, as indicated by having lots of quartz, and is said to have an "acidic" composition). The basic sheets – collectively known as the Scourie dykes must have come from melting a proportion of the upper mantle – perhaps during a weak rifting episode. But the whole lot, gneisses and dykes, were sheared some more. Old crust like the Lewisian has seen a lot of old mountain building events. Again, we're looking at the roots of the old mountain ranges. The last serious activity in the Lewisian happened at about 1800 million years ago, during the so-called Laxfordian orogeny. In places the shearing associated with this has smeared all the old Lewisian constituents (like dykes and gneissic banding) to be parallel. This was associated with local melting with granitic magma invading parts of the crust. Because this magma at least in part came from melting of continental crust, rather than simply mantle, it has a different composition to the Scourie dykes. Excellent examples can be found in the road cutting between Laxford Bridge and Rhiconich in Sutherland.

The Torridonian rocks

We next pick up the story when the gneisses got to the earth's surface - about 1000 million years ago. The uplift and erosion had worn away any manifestation of the older mountain ranges. But 800 million years ago out to the west of mainland Scotland there were mountains of Lewisian gneiss and these shed debris eastwards. The material piled up and is now the Torridonian sandstone (bit of a misnomer because lots of the Torridonian is made up of pebbles - not just sand grains). This material blanketed the Lewisian - geologists call this type of junction (here between old Lewisian gneiss and younger - but still rather ancient, Torridonian sandstone) an “unconformity”. For time, it represents a big break in the record of geological events. But it also represents an ancient landscape, the Earth's surface at the time the Torridonian sandstone was laid down. The detritus probably piled up to over 8 km thick but much of this has since been worn away. Remnants are preserved and form the mountain masses of Ben More Coigach, Cul Mor, Suilven and Quinag. The detritus that formed the Torridonian sandstone was carried by rivers and some of these ancient valleys are still preserved. The most dramatic of these is preserved under the mountain, Slioch. The ancient valley has been filled in by the Torridonian sandstone which banks against the sides of Lewisian gneiss. This is the unconformity. In Assynt the unconformity at the base of the Torridonian can be found, for example on the slopes of Beinn Garbh, where it also picks out old valleys and hills.

The Cambrian sediments

After the Torridonian the next rocks to be preserved are of Early Palaeozoic a period of dramatic explosion in complexity of life on Earth. But the rock sequence in NW Scotland also has rich variety – useful for when we try to unfathom the complexities of mountain building. The oldest of these rocks are the Cambrian quartzites. They are seen forming the eastern slopes of Canisp and Quinag. Further south these same quartzites cap the Torridonian on Beinn Eighe. Elsewhere the quartzites lie direct on the Lewisian, such as beneath the mountain of Arkle.

The quartzites are almost pure quartz (hence the name) - essentially a very clean sandstone. Quartz is the most inert common mineral and is very hard. So it survives after all other sorts of grains have been dissolved or abraded away. In the modern world the type of environment which is this harsh - always turning the grains over and over, is found in very shallow seas - the sandy sea bed continuously on the move due to tides and waves. So the quartzites were most probably deposited in a shallow sea. You can see the evidence for the current activity in this shallow sea as cross-bedding in the quartzites. The junction with the Torridonian below is almost planar, inclined gently to the east. It's another unconformity but the old landscape it represents was flat, but is now tilted. This planation happens best by erosion at a coast line. Putting it together the quartzites deposited in a shallow sea and as the sea came in (so-called "transgression") it planed down the landscape, creating the flat surface onto which the quartz sand accumulated.

The top part of the quartzites (the Pipe Rock) contains burrows - the oldest expressions of life in NW Scotland. These pipes are thought to have been formed by worms - burrowing into the sand (before it was cemented together to make the quartzite) - perhaps escaping from predators like trilobites. The sea action has destroyed all other evidence of life - there are no body fossils preserved - so it's only the burrows, an example of a trace fossil (called Skolithos) that remain. The effect of burrowing was to destroy much of the depositional structure in the quartzites – so cross-bedding is only rarely preserved in the Pipe Rock.

Collectively the quartzites attain a thickness of about 160 metres – a remarkably constant value through the NW Highlands. The next rocks up the sequence are called the Fucoid Beds. These sediments are characteristically brown-coloured in outcrop and often have rather luxuriant mosses covering them so that they can appear to look rather like bits of rotten tree when seen in small outcrops. They get there name from the mis-interpretation of small features seen on bedding planes as the cast of sea-weed (fucoides). In fact these features are another form of trace fossil – probably a grazing trail of a small beast on the old sea bed. The Fucoid Beds contain lots of different types of trace fossil but they are most important for containing rare, preserved body fossils – particularly of the Cambrian predators – trilobites. These rocks are important, not only because they point to a flourishing ecosystem at the time but also because they have species that are found only in sediments of earliest Cambrian age. Elsewhere rocks of this age have been dated using radio-isotope geochronology (effectively the only way of getting absolute, rather than just relative, ages from rocks) as being about 520 million years old. The palaeo-environment for the Fucoid Beds is harder to deduce than for the quartzites. Because it has fossils it must be marine (land-animals did not evolve until after the Cambrian period). Further it passes up directly from the Pipe Rock without a discordance. Indeed burrows from the bedding plane covered by the Fucoid Beds pass down into the top Pipe Rock unit. This means that the Pipe Rock environment changed directly into the environment represented by the Fucoid

Beds. In some places the Fucoid Beds contain polygonal cracks indicative of desiccation. So we can deduce that they were deposited under very shallow-water (even temporarily subaerial) conditions. However, the range of grain sizes present in the Fucoid Beds strongly suggests that their environment was not subjected to winnowing currents – it must have been rather calmer than for the quartzites. One option is that the Fucoids were deposited in a system of shallow lagoons. Taken together then perhaps we have a history of gradual sea level fall (so-called regression) through the quartzites and up into the Fucoid Beds. But this is reversed by the next sequences up.

The Fucoids are overlain by another package of very clean, coarse gritty quartzites, again with vertical burrows. The unit contains very small (2mm) spiral shells which gives the unit its name – the Salterella Grit. Collectively the Fucoids and Salterella are only about 25m thick but their distinct appearance can be exceptionally useful for picking out structures. Depositionally, the same palaeo-environmental deductions can be made for the Salterella Grit unit as were reached for the Pipe Rock. This suggests a return to a shallow water, open shelf environment. We might presume then that the sea-level has risen again (transgression). However, the grits pass up into limestones and dolomites of the Durness group. The carbonates have a cumulative thickness of over 1 km but in general it is only the lower few tens of metres that are preserved. Although much of the Durness has been recrystallised it is still possible to recognise traces of feeding burrows, algal mats and filaments together with small scours and carbonate grains called ooids. All these features are indicative of deposition in a shallow sea. A critical aspect however is the absence of a sandy input. So a key deduction is that although the Durness was deposited in a shallow sea there was no adjacent landmass that shed significant detritus. Presumably the landmass that provided the detritus for the quartzites had been planed down by the time carbonate deposition began. Fossil evidence suggests that the carbonates began to accumulate towards the end of the early Cambrian but it continued on, albeit with breaks, for a further 50 million years, into the Ordovician period.

The Moine

Overlying the Durness carbonates in southern Assynt is a sequence of rocks that are now called the Moine. The clearest contact is found at Knockan Crag. Some nineteenth century researchers, notably Murchison, considered the Moine to represent rocks younger than the Durness carbonates and that the boundary between them was simply depositional. But the Moine, although locally showing sedimentary features, has been metamorphosed (hence they are meta-sediments). It does not lie with depositional continuity upon the carbonates.

Rather it has been carried on by a fault – the Moine Thrust. This structure and its relations are described later. It represents the front of the Caledonian mountain belt. Let's cross into the old mountain range to try and see back to the state of the rocks before the mountains were formed. This is not easy because of strong deformation and metamorphism. But there are some things we do know.

First, the Moine sediments were deposited on continental crust very much like the Lewisian. They are underlain by rocks that have the same features as the Lewisian – and which show a much older and complex history than the Moine on top. This contact is an unconformity, rather like exists between the Torridonian and Lewisian on the foreland. Indeed some people consider the Moine and Torridonian to be equivalents. Support for this comes from the bracket on the age of deposition. Dating of detrital grains of zircon shows the sediments to be derived from rocks older than about 1000 million years – so the Moine is younger than this. But the oldest igneous rocks that intrude the Moine are dated at about 875 million years, so the Moine must be older than that.

Unlike the Torridonian, the Moine sediments are widely believed to be marine deposits, that probably accumulated on an ancient continental shelf. They preserve cross-bedding and ripples that generally imply current flow towards the north and north-east. It might be tempting to suggest that the Moine then were the offshore equivalents to the Torridonian. But countering this idea is the evidence that the Moine was not derived from erosion of the Lewisian. It's detrital minerals all yield much younger ages (1800 to 1000 million years). Possible sources for these minerals are found in Ireland.

The Moine rocks of NW Scotland have all been strongly deformed and metamorphosed. It is tempting to relate these effects to the Caledonian mountain building that brought the Moine against the Cambrian rocks (more about which follows shortly). But the story is more complicated than that. The Moine outcrop includes granitic gneisses that, together with basic igneous rocks, intrude parts of the metasedimentary succession. These have been dated at about 870 million years. Further, some intrusions cut early folds. Metamorphic garnets in the Moine have also yielded ages of around 800 million years. Some geologists have suggested that the history of magmatism, metamorphism and deformation records a period of mountain building. They give this episode the name "Knoydartian" after its type area in western Scotland. But other geologists suggest that the history charts quite the opposite style of tectonics – rifting.

The main mountain building events in Scotland.

Regardless of the status of the "Knoydartian" orogeny, geologists generally agree that the main event to effect the Moine after its deposition was a main period of mountain building that happened about 470 to 450 million years ago. In places the effect on the Moine is remarkable. Once-bedded sediments have been sheared out, in places very tightly folded and smeared so that an entirely new layering is imposed on the rocks. Mineral grains can be strung out like needles. All this happened in response to thickening the old crust, essentially by two different mechanisms. One involves that stacking of sheet upon sheet of crust, a process known as thrusting. Another involves large-scale folding, in effect forming a giant concertina of the layers. The thickened crust warmed up, rocks near the surface became buried and the combined effect was to metamorphose the Moine again. No wonder it is hard to see through all this to the pre-existing state of the rocks.

The deformation and metamorphism that hit the Moine at this time form part of a very much larger belt – the Caledonian orogen. This mountain building period was complex and drawn out. On a large scale it culminated in the collision between a southern continent (called Avalonia) and a northern one (called Laurentia), broadly along the modern England-Scotland border. The collision came about through the closure of an intervening ocean called Iapetus, in much the same way as the modern Himalayas and Tibet have formed in response to the collision between Eurasia and the Indian subcontinent with the closure of the Tethys ocean. And like for Tethys, the closure of Iapetus was long and drawn out, with final collision preceded by periods of mountain building as small terranes and island arcs were swept up. There remains much controversy within the geological community as to how much of the framework of the British Isles is made up of a collage of distinct terranes, stitched together by the protracted Caledonian orogeny, or whether it consists of episodic collision events.

To go into the whole Caledonian story would take another website! However, it is pertinent to discuss the timing of the main phases of orogeny and how they impact on NW Scottish geology. The main deformation in the Scottish Highlands SE of the Great Glen (called the Grampian) is about 470 million years old. Some researchers have thought that the deformation and metamorphism in the Moine (NW of the Great Glen) is also of this age. However, recent age-dating suggests that the Moine deformation (associated with the Caledonian) is about 430 million years old - a phase in the Caledonian known as the Scandian.

The Moine Thrust Belt

Although the timing of deformation in the Moine is yet to be fully resolved, the whole lot has been shunted westwards. The Moine has been carried onto rocks of the foreland during the late stages of Caledonian mountain building along a major fault – called the Moine Thrust. Current best estimates suggest that this movement exceeded 100km. We can use small scale features along the thrust to deduce the direction and sense of movement. Where the Cambrian Pipe Rock lies beneath the thrust, such as at the Stack of Glencoul in northern Assynt, the fossil worm burrows have been smeared out, swept over by the shearing. Mineral grains have also been streaked by the movement. These indicators show that the Moine moved towards the WNW. But the structure is more complex than that. The Cambrian sediments, the Torridonian and even thin slices of Lewisian gneiss have all been shunted up forming fantastically complex mounds of strata. Subsequent erosion has exposed these from beneath the sheet of Moine metasediments. We call this the Moine Thrust Belt: the early geologists, somewhat perplexed by the structural shenanigans, termed it the "zone of complication". In some places thin strips of Cambrian strata, for example just the Fucoid Beds and Salterella Grit, have been stacked up dozens of times. Walking across these structures you can encounter rhythmically repeated units. In other places single units like the Pipe Rock are stacked up internally. In this way an original stack of Pipe Rock, about 75m thick, has been piled up to make ranges like Arkle and Foinaven, 7 km across and over 800m deep. But perhaps the most startling features are the thin sheets of Lewisian caught up in the Moine Thrust Belt. These sheets, in places a few hundred metres thick, have been carried for many tens of kilometres. The old Lewisian structures are preserved intact within the sheet despite these movements.

The Moine Thrust Belt is generally taken to be the edge (or "front") of the Caledonian mountain belt. Many other, younger, mountain belts (e.g. Alps, Himalayas) have similar features at their margins where the heartland of thickened, stacked continental crust has been carried onto its stable counterpart (or "foreland"). Indeed, the discoveries of the geologists in the NW Highlands at the end of the nineteenth century gave considerable impetus to understanding the processes of mountain building in general.

Magmatism in the Moine Thrust Belt

One particularly curious feature of NW Highland geology is the presence of igneous rocks intruded within the Cambrian and other strata of the Moine Thrust Belt and the adjacent foreland. These rocks represent small volumes of melt from the mantle that were injected into the crust while it was being stacked. They are most widely found in southern Assynt where large intrusive bodies are found. But thin sheets can be traced north through Assynt. Some of the intrusions appear to be broadly contemporaneous with thrusting. Radiometric dating (at about 430 million years old) gives an age, not only for intrusion but also for thrusting.

What happened next?

The Caledonian orogeny was the last great period of mountain building in northern Britain and indeed the igneous rocks that came in while the Moine Thrust Belt was developing are the youngest rocks in Assynt. So it might be tempting to think that the modern landscape simply represents the roots of the once great Caledonian chain. One might presume these rather small mountains are the mere stumps of a once great Himalayan-style range, gradually worn down by erosion in the intervening 400 million years. But this is too simple. The landscape tells are far more interesting story.

Although there are no rocks younger than 430 million years old in Assynt, younger sediments are to be found nearby. The Devonian period that started and continued after the end of the Caledonian orogeny saw substantial erosion of the thickened continental crust. In northern Scotland detritus shed from the mountains accumulated in the so-called Orcadian basin (named after the Orkney islands) to the east. Remnants of the basin are found in mainland northern Scotland indicating that the modern erosion level was largely achieved by this time. The Caledonian mountains were formed and then eroded away almost straight away. The Scottish Highlands in general continued to act as a source of detritus right into late Carboniferous times (at least until about 300 million years ago). By this stage the giant supercontinent of Pangea was nearly fully developed, as all the world's continental crust became joined. What followed, indeed what for Britain continues pretty much to today, is a period of rifting and continental break-up. To a large degree the modern coast-line of NW Scotland reflects this rifting, with the subsidence of the Sea of Hebrides and Minches. The Great Glen Fault moved at this time, linking a basin opening in what is now the Moray Firth to others on the west coast. This happened during the late Triassic and early Jurassic time (about 200 million years ago) and sediments of this age in the inner Hebrides record that the neighbouring Scottish mainland was rather low-lying and only gently eroding. Today the mainland is mountainous. Why?

The answer to this question also lies away from Assynt but on a clear day you can see part of the evidence. The first piece is the Atlantic ocean – which formed as the great Laurentian continent broke apart forming Europe and North America. This started happening off NW Scotland about 50 million years ago. Spreading of the Atlantic ocean floor was preceded by volcanism. And the roots of the volcanoes are found today in the Hebrides, in the Cuillin hills of Skye, in Rum and on the Arnamurchan peninsula. The volcanoes were the surface expression of basaltic magmatism generated melting in the mantle triggered by rifting. But not all the magma made it up to the volcanoes. Geophysical data suggest that vast amounts were plastered on to the base of the crust. And the effect of this would have been to jack the crust up, pushing up the landscape on top. So the height of the NW Highlands does not reflect the wearing down of the Caledonian mountain belt but rather it tells of the amount of uplift created next to the rifting crust as the Atlantic opened.

Glacial landscapes.

Uplift next to rifting crust is relatively commonplace around the world. Good examples are the Ethiopian Highlands, formed broadly associated with rifting in East Africa and along the Red Sea. But the NW Highlands of Scotland are not a simple plateau as might be expected if the only process consisted on magma jacking up the crust. The key to the modern landscape of NW Scotland is glaciation. Our story now changes from one of tectonics to a tale of climate change. But the problems of deducing a history are similar. Just as the intensity of Caledonian orogeny in the Moine makes it difficult to reconstruct early mountain building episodes, so in the landscape it is difficult to see back beyond the most recent glaciations. So let us start with the present and work back.

The last major period of ice occupation within the Scottish Highlands ended at about ten thousand years ago (we're not talking millions at the moment!). This most recent glacial period is termed the Loch Lomond stadial (after the site of the moraines left by it). The thickest ice, perhaps 600m thick, lay over modern Rannoch Moor (east of Glencoe). The northern limit of the main ice cap and major valley glaciers was the Torridon area. In Assynt permanent ice was restricted to a few north facing high corries. The valley lakes were there, receiving sediment, at this time. But the oldest sediments in the lakes of Assynt are only about 12 thousand years old. The landscape has been swept clean of material, presumably by glaciers far more widespread than those of the Loch Lomond stadial. The Loch Lomond was just a short blip in the local climate that followed the end of the major glacial called, in Britain, the Dimlington stadial (sometimes called Late Devensian because of the stage within which happened).

During the Late Devensian much of northern Britain was completely ice-covered. The effects are to be seen throughout Assynt. Smooth pavements of rock, particularly the quartzites, show scoured abrasions that track the passage of ice. These flow lines deflect around mountain massifs such as Quinag. The classic hills of Suilven, Canisp and Stac Pollaidh show the streamling effects brought about by flowing glaciers. It was thought that the entire landscape of NW Scotland was buried by Late Devensian ice. But the highest, more outlying hills seem to have remained poking out of the ice, forming nunataks. On Quinag there are thick piles of frost-shattered rocks that testify to long periods of emergence. If they had been over-run by the ice all this debris would have been carried off.

Although a few nunataks may have poked out between the Late Devensian glaciers, generally the glaciation was so strong that it wiped the sedimentary record of older glaciations and the intervening interstadials away. But in Assynt there is a unique record, preserved below ground. The "Bone Caves" near Inchnadamph record fauna from mid Devensian times, including bear and deer. That there were earlier glaciations can be deduced from elsewhere. The greatest southern extent of ice in the British Isles reached nearly to the Thames. This Anglian glaciation peaked about 350 thousand years ago. But there have been many other glaciations, cycles of ice advance and retreat, which presumably have left their mark on the NW Highlands. Certainly the deep fiords and valleys owe their shape to far more than just a few thousand years of ice action. And they will doubtless continue to be shaped by glaciations when the ice returns.

Find out more

Reading the account of the geology of NW Scotland it becomes obvious that there is still much to find out, many conundrums remain. But geologists have found out a lot, particularly over the past couple of decades as techniques of radiometric dating have improved. This means that many old text books have less complete or even disregarded histories. This makes the recommendation of further reading rather dangerous. One of the better texts is:
The Geological History of Britain and Ireland (edited by Nigel Woodcock and Rob Strachan, published by Blackwell Science in 2000). It does pretty much what its title suggests and includes a useful introduction about how geological histories might be unravelled from rocks. But it can still be rather technical at times. Rather less useful, more dated but generally more widely available is **The Geology of Scotland** (3rd edition by Gordon Craig; published by the Geological Society in 1991). Other widely available publications include the British Geological Survey's Regional Geology of the **Northern Highlands of Scotland** (the 4th edition appeared in 1989, edited by Johnstone and Mykura), which is rather technical and a bit staid.