Geological Society of Glasgow Excursion Itineraries

A GEOLOGICAL EXCURSION GUIDE TO THE ABERFOYLE AREA

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REVISED BY MIKE KEEN

Crags of Ben Ledi Grit Formation, Locality 3, Duke's Pass

Geological Society of Glasgow

Registered Scottish Charity SC007013

Dedicated to the memory of Brian Bluck and Jim Lawson, friends and colleagues.

Frontispiece. View looking westwards from the bridge over the River Forth at Manse Road, Aberfoyle. In the far distance on the left-hand side of the view is Ben Lomond, while the crags of Craigmore can be seen on the right-hand side towering above the flat Forth valley.

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Introduction

This is an extensively modified version of the excursion itinerary of Bluck and Lawson published in the Geological Society of Glasgow guide to the geology of the Glasgow area, edited by Lawson and Weedon (1992). This version contains photographs and extra maps and diagrams and the structure and stratigraphy have been revised in the light of the updated information in the British Geological Survey map of the Aberfoyle area (2005).

The Aberfoyle area has had an important role in the development of ideas on the structure and stratigraphy of the Dalradian, while the rocks of the Highland Border Complex have proven to be some of the most controversial in Scottish geology. There are two strongly conflicting interpretations of the stratigraphy of the area, which are summarised in Fig. 2. The first of these (A in Fig. 2) regards the Highland Border Complex as allochthonous (a rock or series of rocks which have been moved a considerable distance from their origins), a fragment, or terrane, of Laurentian affinities; the second (B in Fig. 2) holds that most of the Highland Border Complex is autochthonous (rocks in their original position or which have only been moved a short distance) and in stratigraphical continuity with the Southern Highland Group and is therefore part of the Dalradian Supergroup, with the exception of the Highland Border Ophiolite which is obducted Midland Valley terrane. These ideas are discussed more fully in the section below on the Highland Border Complex. Terranes are fault-bounded portions of the crust that differ markedly in their geology from neighbouring areas. They represent areas with different geological histories brought together by plate movement.

Purpose. To visit the Highland Boundary Fault and study some details of the structure and stratigraphy of the Highland Border Complex, with serpentinites, serpentinite breccias, (ophicarbonates*)* fossiliferous Ordovician limestones, Old Red Sandstone conglomerates. Secondly to traverse the Aberfoyle Anticline observing the Ben Ledi Grit Formation and Aberfoyle Slates, observing graded bedding, bedding-cleavage relationships, and evidence for the recumbent Tay Nappe.

Logistics. Note that many of the localities listed for the Duke's Pass are covered in bracken and are virtually inaccessible during the summer and early autumn. Access is unrestricted, but stay on the forestry paths as much as possible and leave vehicles at car parks provided, many of which **require parking fees** (make sure you have some pound coins with you). There are no trains to Aberfoyle, and bus timetables are subject to frequent changes; at the moment (2020), the direct bus service X10A from Buchanan Street Bus Station in Glasgow takes about 1½ hours. Although much of this excursion would be difficult without private transport, it is possible to undertake the excursion from the Visitor Centre (formerly the David Marshall Lodge) to the Highland Boundary Fault on foot from Aberfoyle.

Distance and time. Realistically, it is impossible to visit all of the localities in the original excursion in a single day. Some of the distances recorded in the original guide understate both the distances and time involved. There are three distinct excursions and each could take up a whole day; however, the itinerary described below can be completed in about 8 hours and involves some 7 km of walking together with several short walks from car parks.

The area to the north of Aberfoyle now forms part of a GCR (Geological Conservation Review) site:

GCR Number	2919
Name	Duke's Pass
Unitary Authority	Perth and Kinross and Stirling
Country	Scotland
Grid Ref	NN 513035

Geology of the Aberfoyle area

The geology of the Aberfoyle area is illustrated in Fig. 1 and the stratigraphy in Fig. 3. There are four main strands to the excursions described below: the Dalradian of the Duke's Pass, the Highland Boundary Fault, the Highland Border Complex, and finally the Devonian Old Red Sandstone.

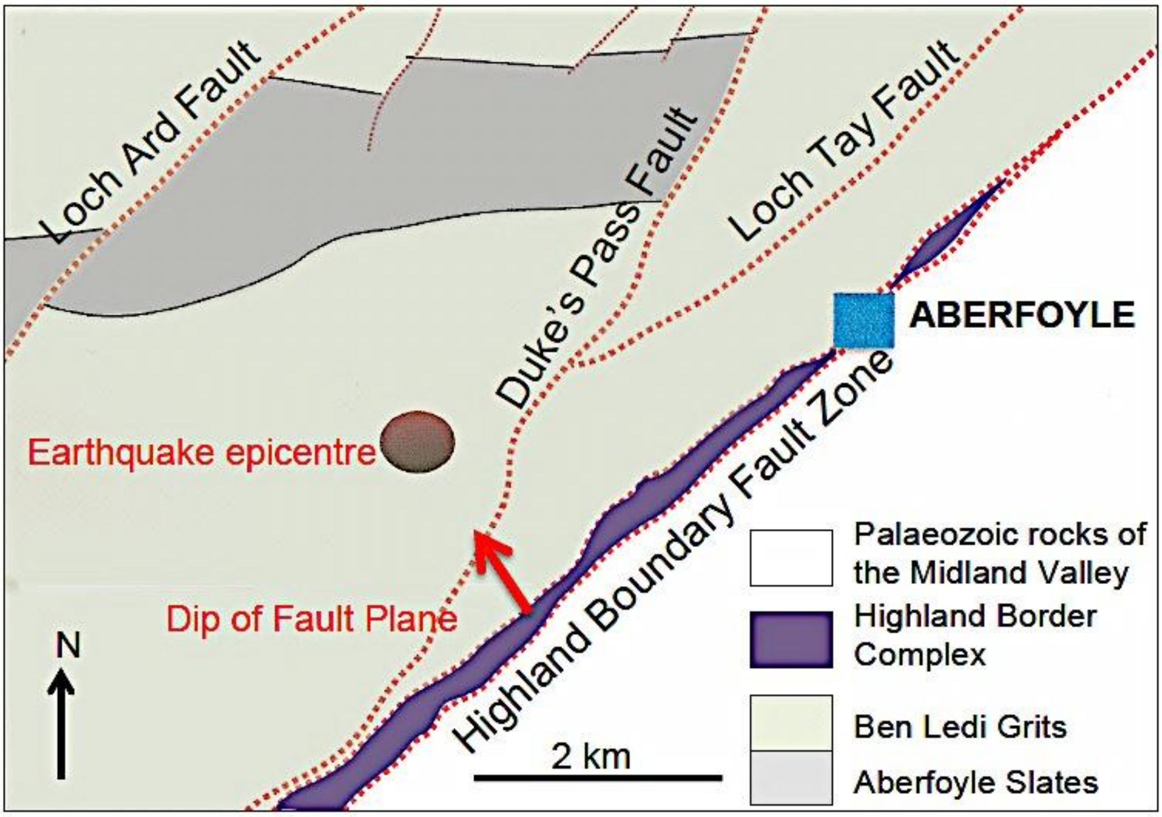

Figure 1. Geology of the Aberfoyle area. The map also shows the epicentre of the 2003 Aberfoyle Earthquake (Ottemöller and Thomas (2007)), with the estimated direction of the dip the HBF.

The **Highland Boundary Fault (HBF)** runs for 240 km across Scotland, dividing the mostly Precambrian metamorphic rocks of the Highlands to the north from the unmetamorphosed Upper Palaeozoic rocks of the Lowlands to the south (Fig. 2). This striking geological feature has been recognised for over 150 years, and is generally interpreted as the boundary between the Midland Valley and Highland terranes which docked during the Silurian, (443-417 Ma, Haughton et al. (1990); 460-420 Ma, Tanner (2007)) (Fig. 4). The terranes converged obliquely, resulting in a sinistral strike-slip transpressional regime. The location and orientation of the present-day HBF may have been controlled by rejuvenation of this strike-slip terrane boundary during the mid-Devonian Acadian Orogeny. Whatever its origin, the HBF as we know it today is a reverse fault steeply dipping to the north-west, of mid Devonian age, with vertical displacement of at least 4500m. Although there is limited evidence for lateral displacement (Hartly and Leleu (2015)), Ottemöller and Thomas (2007) indicated sinistral strike-slip movement of some 40 km during the mid Devonian. A study of the Aberfoyle earthquake of 2003 (Fig. 1) (Ottemöller and Thomas (2007)) indicated a fault plane striking WSW-ENE with a high angle of dip (65°) to the northwest, with oblique sinistral strike-slip and normal movement, i.e. indicating a tensional stress regime. The epicentre of the earthquake lay 4 km west of Aberfoyle, and 2 km north along the dip of the HBF, and the cause of the earthquake was

Figure 2. The Highland Boundary Fault.

believed to be related to post-glacial rebound. However it has to be acknowledged that it is not always easy to locate the precise position of the HBF in the Aberfoyle district.

The **Gualann Fault** is a splay of the Highland Boundary Fault, and is seen at the Lime Craig locality described below. Another large fault in the area is the **Duke's Pass Fault**, a part of the Loch Tay-Duke's Pass-Loch Ard fault system, all of which have a sinistral strike-slip displacement of several kilometres (Fig. 1).

The rocks outcropping along the Duke's Pass belong to the **Southern Highland Group**, the youngest of the Dalradian rocks in this area. They are of late Precambrian and early Cambrian age, some 600-520 Ma, and are about 2000 m thick. They can be divided into two main formations, the older Aberfoyle Slates and the younger Ben Ledi Grit Formation. The latter contains local developments of slates (Figs 8, 14). All of the rocks were metamorphosed during the mid Ordovician Grampian Event, but this metamorphism is low grade in the Aberfoyle area, with increasing metamorphic grade northwards. The Ben Ledi Grits are metagreywackes, formed by turbidity currents and debris flows within major channels

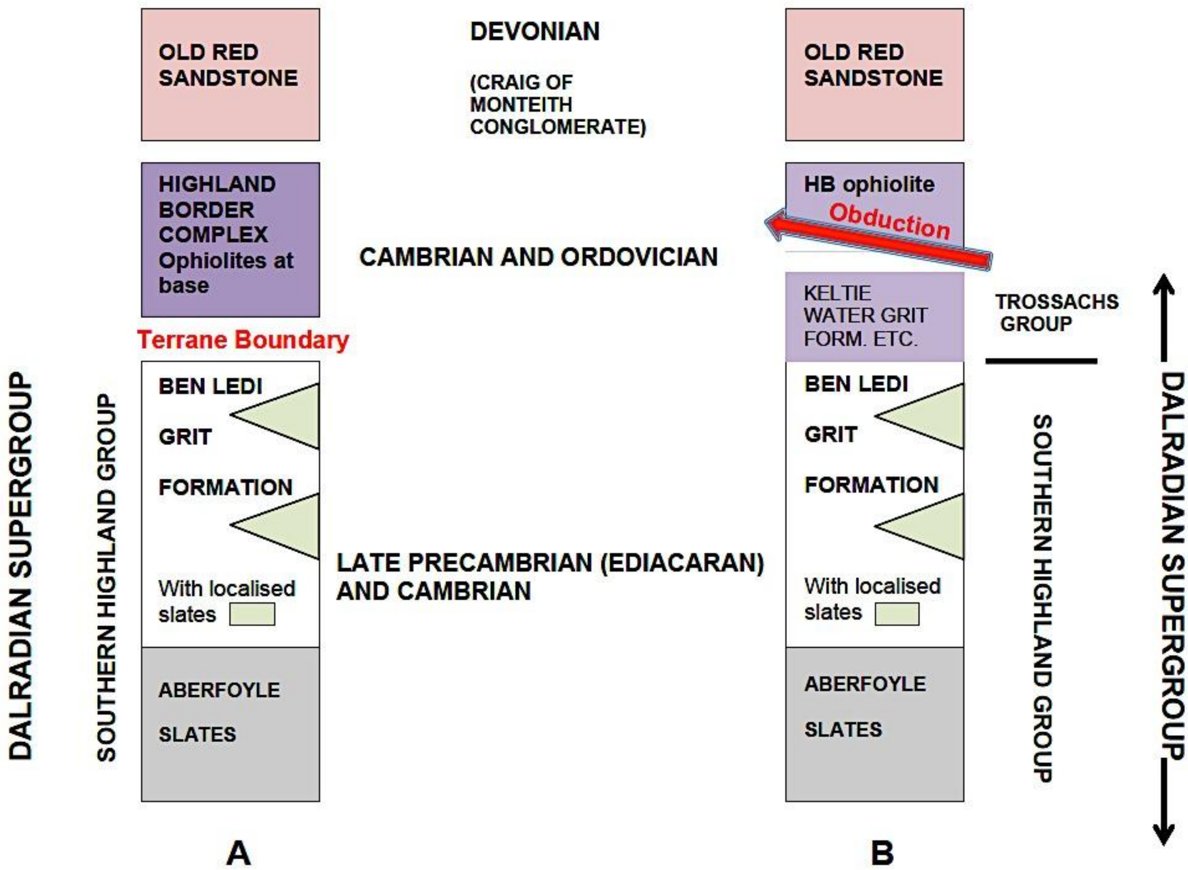

Figure 3. The stratigraphical succession around Aberfoyle. A shows the Southern Highland Group as the youngest part of the Dalradian, with the Highland Border Complex interpreted as being a separate terrane from the Dalradian; B is the model of Tanner and Sutherland (2007) where the HBC is regarded as being in continuity with the Dalradian (the Trossachs Group) apart from the obducted Highland Border Ophiolite.

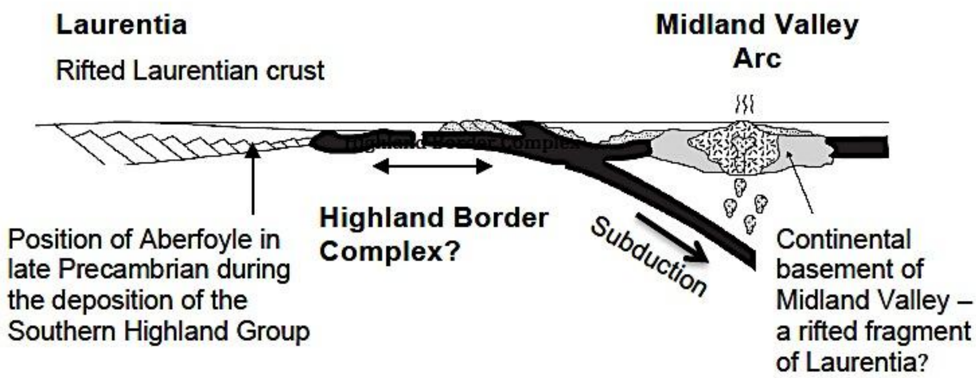

Figure 4. A possible plate tectonic setting for the late Dalradian and Cambro-Ordovician of the Aberfoyle area. (Adapted from Tanner et al. (2013).)

(submarine canyons) of a submarine fan delta complex along the rifted eastern continental margin of Laurentia (Figs 4, 6). Laurentia was essentially North America, and this area of Scotland lay on its eastern border. During deposition of the early Dalradian rocks, Laurentia was part of a supercontinent named Pannotia and was adjacent to Baltica and Gondwana (Fig. 6); sediments from this early period indicate deposition in shallow marine environments associated with rifting of the supercontinent. As the rifting developed, the new ocean of Iapteus formed and sea-floor spreading led to the breakup of the supercontinent. By the time that the Dalradian rocks around Aberfoyle were deposited, Iapetus was a wide ocean (Figs 4, 6), and the sediments are a thick deep-water turbidite sequence (Fig. 5). The slates would originally have been mudrocks deposited in deep basins along this continental margin. Recent work by the Geological Survey (2005) has indicated that the slates to the east of the Duke's Pass Fault (see below) occur within the Ben Ledi Grit Formation and are therefore younger than the Aberfoyle Slates exposed to the west of the fault.

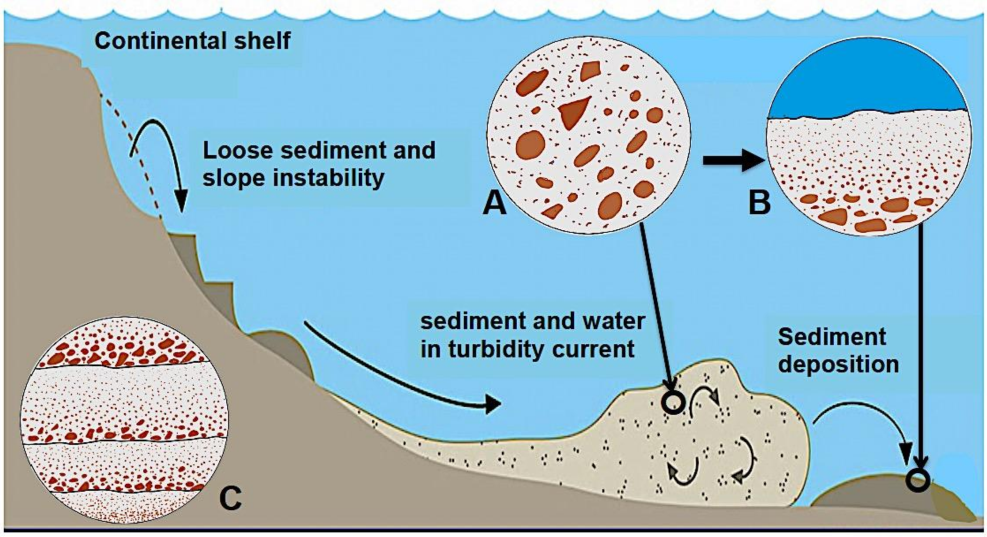

Figure 5. Turbidite sequence and graded bedding. A turbidite bed forms when a turbidity current of sediment-laden water (triggered by an event such as an earthquake) flows down the continental slope and deposits the sediment at the foot of the slope. The insets show (A) the unsorted nature of the sedimentary clasts within the turbidity current; (B) settling of clasts to form graded bedding; and (C) a succession of graded beds which form within the area of deposition. Graded bedding is useful in determining the "way up" of sedimentary successions; when it is well developed the base is easily recognised by the presence of the coarser material, but in the field the sharp base of the bed, with coarse grains overlying much finer grains, is more easily observed. A turbidite sequence consists of a succession of beds formed by turbidity currents, not all of which will show grading. (Base diagram modified from NOAA.)

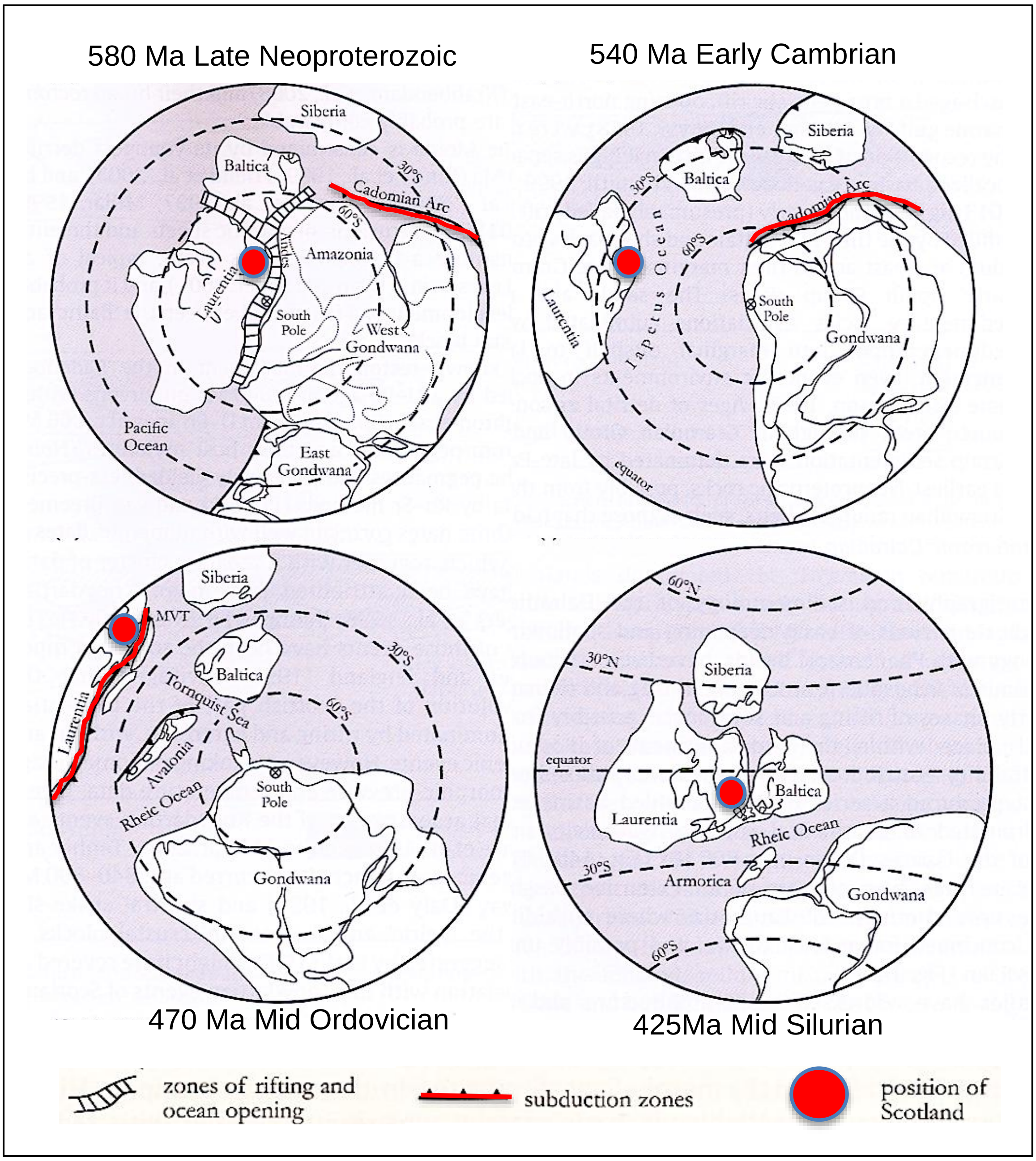

Figure 6. Global palaeogeographical reconstructions showing the position of Scotland from the late Precambrian (580 Ma), when the Southern Highland Group was deposited, to the mid-Silurian. The late Precambrian reconstruction shows rifting within the supercontinent of Pannotia which led to the formation of the Iapetus Ocean during the latest Precambrian and Cambrian, the period during which the Southern Highland Group was deposited. During these periods Scotland was a part of Laurentia, i.e. North America. By the mid-Ordovican, Iapetus was closing, and collision of oceanic arcs created the Grampian Orogeny – part of the larger Taconic Orogeny that affected most of the eastern side of Laurentia. Iapetus had closed by the mid-Silurian, and Avalonia and Baltica were now joined with Laurentia. (Adapted from Tanner et al. (2013).)

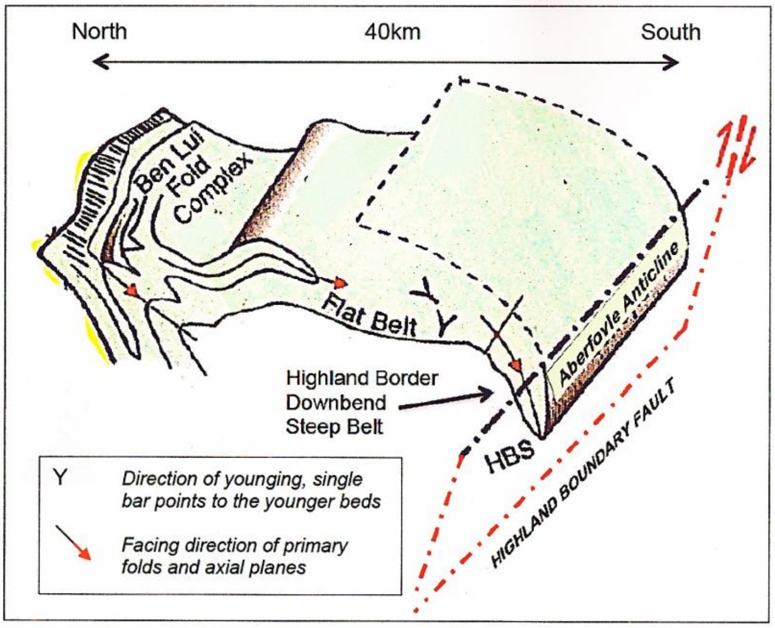

Figure 7. The Tay Nappe. (Adapted from Stephenson and Gould (1995).)

Dalradian structures are conventionally explained in terms of four phases of deformation, referred to as D1-D4, where D1 is the oldest, and which occurred during the mid-Ordovician Grampian Event of the Caledonian Orogeny (474-464 Ma). In the Aberfoyle area we can see several Grampian structures. The major structure is the **Tay Nappe**, with the **Aberfoyle Anticline** as its nose or closure (Fig. 7). The rocks are steeply dipping in the vicinity of the Highland Boundary Fault, and so are referred to as the Steep Belt. Further north the lower limb of the Tay Nappe is exposed where the rocks are sub-horizontal, and referred to as the Flat Belt. The rocks of the Steep Belt form the Aberfoyle Anticline, part of the Highland Border Downbend. D1 saw the folding of rocks to form the Aberfoyle Anticline, while peak deformation occurred during D2, when the large recumbent fold of the Tay Nappe formed. Metamorphism of the rocks occurred during the D2 and D3 phases (474-464 Ma), i.e. after the nappe formation, although the rocks exposed near Aberfoyle were at structurally high levels and so underwent only low grade metamorphism. The Highland Border Downbend formed during D3 or D4.

Sedimentary structures within these Dalradian grits and slates led Shackleton (1957) to conclude that the Aberfoyle Slates occupy the core of a major fold of which grits form the limbs. Shackleton (1957) has also shown that the axial planar slaty cleavage of the Aberfoyle "Anticline" has a downward-facing relationship to bedding (i.e. the axial plane of folds on all scales encounters successively *younger* rocks when traced *downwards*). Consequently, he concluded that the Aberfoyle Anticline is a synform - the downbent nose of a major gravity nappe, the Tay Nappe, which has its roots far to the north across the Cowal Anticline (Fig. 7).

Some structural terms are illustrated in appendices at the end of this guide.

The **Highland Border Complex (HBC)** lies between the Midland Valley and Grampian terranes, and consists of a set of highly faulted rocks that include some fossiliferous limestones and shales. Its age and affinities have been debated for a long time. Some workers (e.g. Henderson and Robertson (1982), Tanner and Sutherland (2007)) maintain that these beds were folded together with the Dalradian and are therefore either part of the Dalradian sequence, or lay on top of the Dalradian at the time of folding (B in Fig. 2). Others (e.g. Longman et al (1979), Bluck (2002, 2010)) took the view that the Highland Border Complex was younger than the rocks of the Dalradian and represented an entirely different rock assemblage formed in a totally different tectonic setting (A in Fig. 2). Curry et al (1984) and Bluck (e.g. 2002) divided the HBC into four units of early Cambrian to late Ordovician age (Fig. 9). In this scenario, the oldest rocks (1) are the ophiolites, represented here by the serpentinite (an ophiolite is a piece of oceanic crust plus part of the underlying mantle, obducted (emplaced) onto continental crust), overlain by the Dounans Conglomerate and limestone (2), overlain in turn by black shales and pillow lavas (3), and finally the Achray Sandstone (4) – i.e. the rocks become younger as the Dalradian outcrop is approached (Fig. 9). Palaeontological evidence suggests that the HBC was contemporary with at least the early stages of the Grampian Orogeny (474-464 Ma for the orogeny, fossils dated to 470 Ma and younger). This interpretation is supported by stratigraphical evidence and way-up criteria (Bluck (2010)). In this model, the Highland Border Complex came into contact with the Dalradian during the mid to late Silurian, well after the Dalradian had been deformed during the Grampian Orogeny. Tanner and Sutherland (2007) however believed that most of the rocks of the HBC were in stratigraphical and structural continuity with the Dalradian, and proposed the term **Trossachs Group** for rocks in sequence with the Dalradian, and considered the Highland Border Ophiolite to have been obducted onto the Grampian terrane during the Ordovician. This model is supported by the presence of Grampian-age structures in both the Trossachs Group and the ophiolite. The evidence for either model indicates a strong Laurentian affinity for the rocks and fossils of the Highland Border Complex, so their origin must lie along the Laurentian margin. The ophiolite is usually interpreted nowadays as forearc oceanic/sub-continental mantle rocks.

Devonian rocks present in the area are the **Old Red Sandstone** Craig of Monievreckie Conglomerate Formation of the Arbuthnot Group, belonging to the lower two stages of the Devonian, the Lochkovian-Pragian (419-407 Ma). They are alluvial fan conglomerates and are seen at Lime Craig quarry. The conglomerates disappear south eastwards but dramatically thicken to the north east where they form the Monteith Hills, They are part of the steeply dipping northern limb of the Strathmore Syncline. The axial plane of this structure runs parallel to the Highland Boundary fault, and is also inclined at a similar angle and direction to the Highland Boundary Fault, a point made by Tanner (2010), who suggested that the two formed at the same time during the mid Devonian.

The youngest solid rock seen is a Carboniferous dolerite dyke intruded along the Gualann Fault.

The Landscape around Aberfoyle

Aberfoyle is the gateway to the Trossachs and the southern Highlands, standing more or less on the border between the Lowlands to the southeast and the Highlands to the north. Driving through the Duke’s Pass gives magnificent views of some of the highest peaks of the southern Highlands and at the northern end of the area, at Loch Achray, Ben Venue is a short distance to the west, rising to 727 m.

Aberfoyle lies in the valley of the River Forth and the drive from Aberfoyle up the steep hill to the Duke’s Pass is through Dalradian rocks forming the eastern side of the Forth valley; the pass itself is at a height of about 200 m, with higher ground rising to 300 m or so. For much of the Lime Craig Trail (Excursion 1), the steep topography that is encountered is the valley side of the Forth.

The River Forth at Aberfoyle flows straight across the strike of both the Dalradian and the Devonian rocks, as well as the Highland Boundary Fault, apparently completely disregarding the geology and geological structure of the area. This leads us to assume that the course of the river is a relict of an older drainage system, older even than the present-day mountains. It is believed to relate to a drainage pattern dating back to the Miocene epoch, some 20 million years ago, while the mountains we see today, although related to the old Caledonian mountains, were uplifted only some 1-3 million years ago. Ice sheets covered most of Scotland during the **Devensian Glaciation**, which is the most recent glacial epoch; this reached its peak about 18,000 years ago when the ice was at least 1000 m thick, meaning that the whole area covered by this guide would have been buried under the ice sheet. The climate warmed and the ice retreated so that between 13,000 and 12,000 years ago Scotland was mostly ice free. However, the climate cooled and glaciers reappeared in the western Highlands between 11,000 and 10,000 years ago, leading to a final glacial event referred to as **The Loch Lomond Readvance (or Stadial)**. In our area a lobe of this ice cap is known as the **Monteith Glacier** and was in the form of a piedmont glacier, a type formed when glaciers from upland areas fan out onto relatively flat plains. The Monteith Glacier stretched eastwards as far as the Lake of Monteith, where a prominent arcuate terminal moraine marks its end. This end moraine is 30 m high and some 20 km long and is composed of ridges and mounds of sand and gravel stretching from Port of Monteith southwards towards Buchlyvie. Aberfoyle lay towards the northern margin of this glacier, with ice stretching southwards for some 10 km to higher ground seen south of Loch Ard Forest. The glacier deepened the Forth Valley around Aberfoyle, with ice around 200 m thick. The prominent crags of Craigmore, overlooking the western part of town, formed during this period by the intense cold near the top of the glacier, while ice covered the lower areas up to and beyond the Visitor Center. Loch Ard occupies a rock basin deepened by glacial scouring, with a water depth of 32 m.

Glacial features seen during the excursion, include roches moutonnées, glacially smoothed surfaces with striations, till (boulder clay), and post-glacial features such as knickpoints.

One final feature is worth mentioning. Sea level rose after the melting of the ice at the end of the Ice Age, and in our area, the sea spread into the Forth valley as far as Aberfoyle some 6,500 years ago; the land sub subsequently rose due to glacial rebound and the sea retreated, but it left behind the clay and peat lands of the Carse of Stirling.

A major topographic feature is formed by beds of vertically dipping and very hard conglomerates of the Monievreckie Conglomerate, forming a very prominent physical feature known as a “hog back”, a ridge parallel to the Highland Boundary Fault, most noticeably forming the Monteith Hills. In many places, and including our area, these actually form the highest points of the landscape, rather than, as you might expect, the Highland rocks of the Dalradian.

Excursion 1. The Lime Craig and Highland Boundary Fault Trail (Figs 8-13)

This excursion (Fig. 8) follows the Lime Craig Trail (formerly named the Highland Boundary Trail), which is **sign-posted by red markers,** from the lodge visitor centre at Aberfoyle, where parking (park and pay) and refreshments are available, and which is now the entry point for “Go Ape” tripwire excursions. The whole trail has a circuit of 3¾ miles (6 km), and takes 2 - 3 hours, depending upon how long you take to examine the rocks. It is approximately 2 miles of a strenuous sustained uphill trek to Dounans Quarry along a well maintained forestry road, with a rise of about 150 m; the return route is downhill via the old tramway which is a very steep path and best avoided if you have trouble with your knees or hip! – you can return by the same route as you came up. If you have used public transport to reach Aberfoyle, after the downhill walk along the tramway you can walk through the Dounans field centre to reach the main road at Aberfoyle rather than trekking back to the visitor centre.

The visitor centre has a small display of rocks with an introduction to the geology of the area, organised by members of the Strathclyde Geoconservation Group and the Geological Society of Glasgow. An excellent striated glacial surface can be seen close to the main entrance to the visitor centre building (Fig.10A). The view to the south reveals ridges of conglomerate within the Old Red Sandstone that are steeply dipping on the northern side of the Strathmore Syncline. The Carboniferous volcanic rocks of the Campsie Fells can be seen in the distance.

Free trail guides are available in the lodge visitor centre. The actual Lime Craig Trail can be followed from the visitor centre, but a short cut is recommended here for the geologist. Take an unmarked trail at the north eastern end of the parking area – park at the far side of the pond. This trail leads downhill to the 16 m high **Waterfall of the Little Fawn** (NN 5215 0170, Fig. 10B) where it joins the official trail. The waterfalls have formed a short gorge creating a

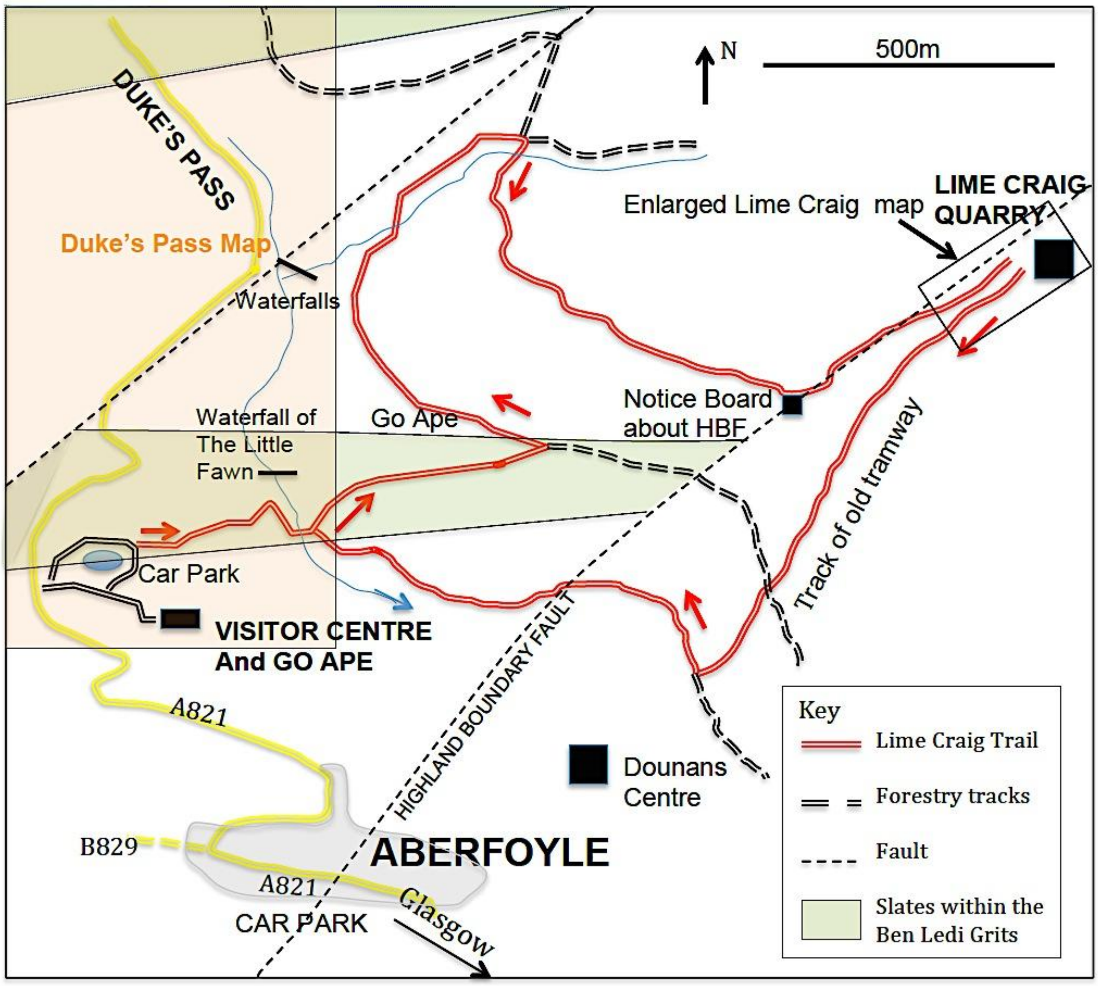

Figure 8. The Lime Craig and Highland Boundary Fault Trail.

knickpoint – a feature marked by a sudden change in slope along a river profile such as a waterfall. Such features form in response to a sudden change in base level of the river, in this case the melting of the Monteith Glacier. Further waterfalls can be seen en route to Lime Craig Quarry (Fig. 8). Glacial boulder clay can be seen in ditches and streams by the track on the way up to Lime Craig Quarry.

The first rock exposures are seen at these waterfalls – Dalradian grits with slates. The route crosses the stream by a footbridge – turn left when you reach the forestry road. At this point there is also a sign-posted path to hides to view wildlife – red squirrels are usually seen at the hide. The next uphill walk reveals exposures of green and purple slates in the left hand roadside ditch – do not confuse these *in situ* exposures with the Aberfoyle Slates used in the construction of the road, which come from the old slate quarries seen later in the excursion.

After five minutes or so uphill walking, bear left at junction with another forestry track (follow the red sign posts). This takes you past the "Go Ape" area on the left. Follow the track which bends to the right for a further kilometer or so to a cross roads where you take the right hand track; the track to the left is the Wayfarer's Path which leads to the forestry track with exposures of slate at Locality 2, Duke's Pass.

A short distance along this track are good exposures of the Ben Ledi Grit. Further along there is a display board describing the Highland Boundary Fault. Although this is not actually on the fault, it does give a good indication of the boundary between the Highlands to the north and the Midland Valley below to the south. At this locality there is a splendid view looking towards the Campsies; in the foreground the ridges are of Old Red Sandstone conglomerates, the intervening lower ground indicating outcrops of sandstones of the Old Red Sandstone.

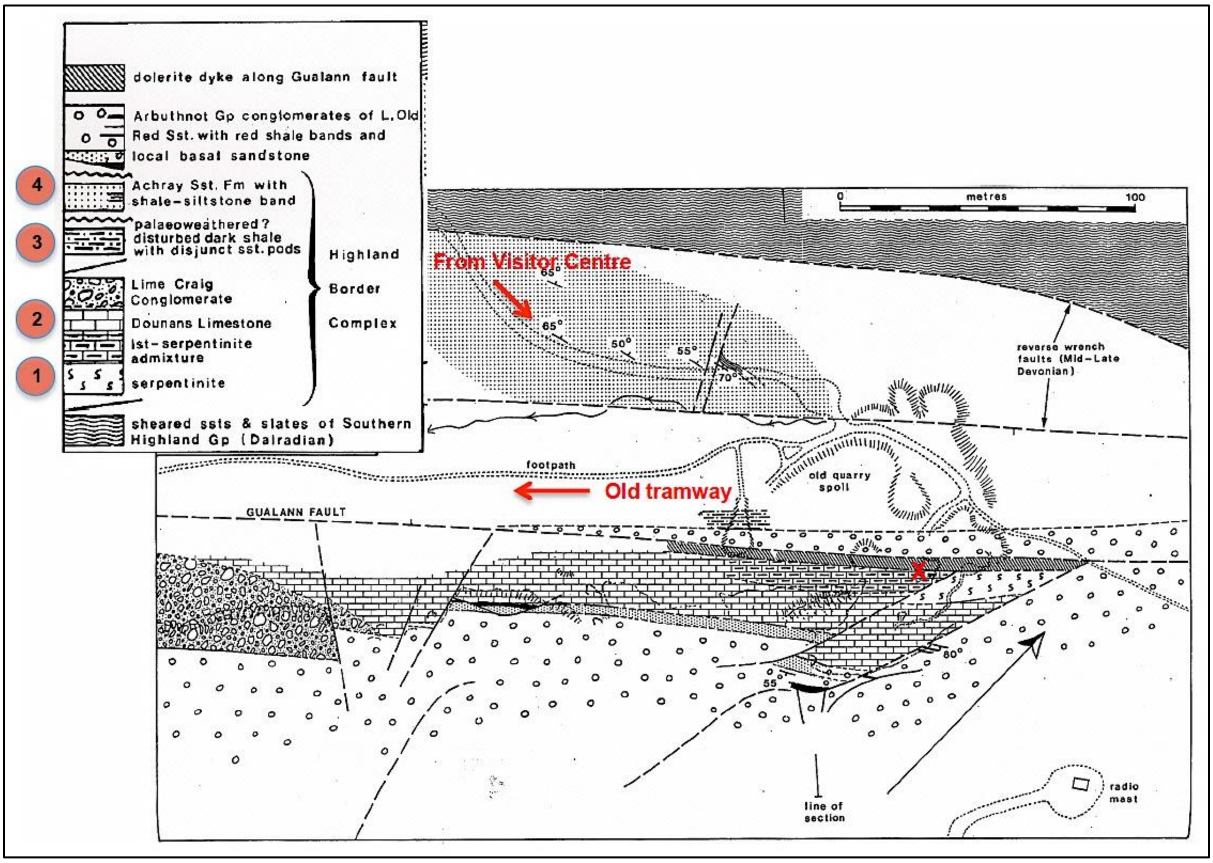

Figure 9. Geological map of the Limecraig Quarry and environs, with locality numbers from Bluck et al (1984); the numbers in red circles refer to the four units described by Curry et al. (1984) and Bluck (2002).

About one hundred metres further up the track you cross the Highland Boundary Fault – but no exposures or even physical features! A little further on are inclined beds of the Achray Sandstone, and you are now on the map of Fig. 9 of this guide – and within the Highland Border Complex.

(a) Before reaching the quarry, there are exposures in steeply dipping sandstones and shales on the north side of the track. These sandstones belong to the Achray Sandstones and the interbedded shales have yielded pale yellow (unheated) chitinozoa of middle Ordovician age (Burton and Curry 1984). The same shale has also yielded black chitinozoa of lower Ordovician age that have probably been derived from an older formation which had experienced elevated temperatures after deposition.

Lime Craig Quarry (NN 533 018; Fig. 10C) lies c l00 m south of the Highland Boundary Fault (Figs 9 and 11) and east of the high quarry spoil. Walk up the track past the tip heaps to where the ground levels out for a few feet and turn right to access the exposures of Lower Old Red Sandstone conglomerates, Ordovician limestones, serpentinite-limestone mixtures, serpentinite and the trace of the Gualann Fault along which there is now a Carboniferous dyke. Mechanical excavation here exposed the rocks and clarified their relationships for Curry et al. (1982) (Fig. 9), but the exposures have since become overgrown.

(b) Stand on a small mound to view the rocks to your left as you face the high near-vertical conglomerate face ('X' in Fig. 9). The dolerite dyke is seen as a vertical intrusion about a metre across, to the east of which is the serpentinite and to the west a thin sliver of Old Red Sandstone conglomerate (this latter rock is now very overgrown and difficult to find) (Fig. 10D).

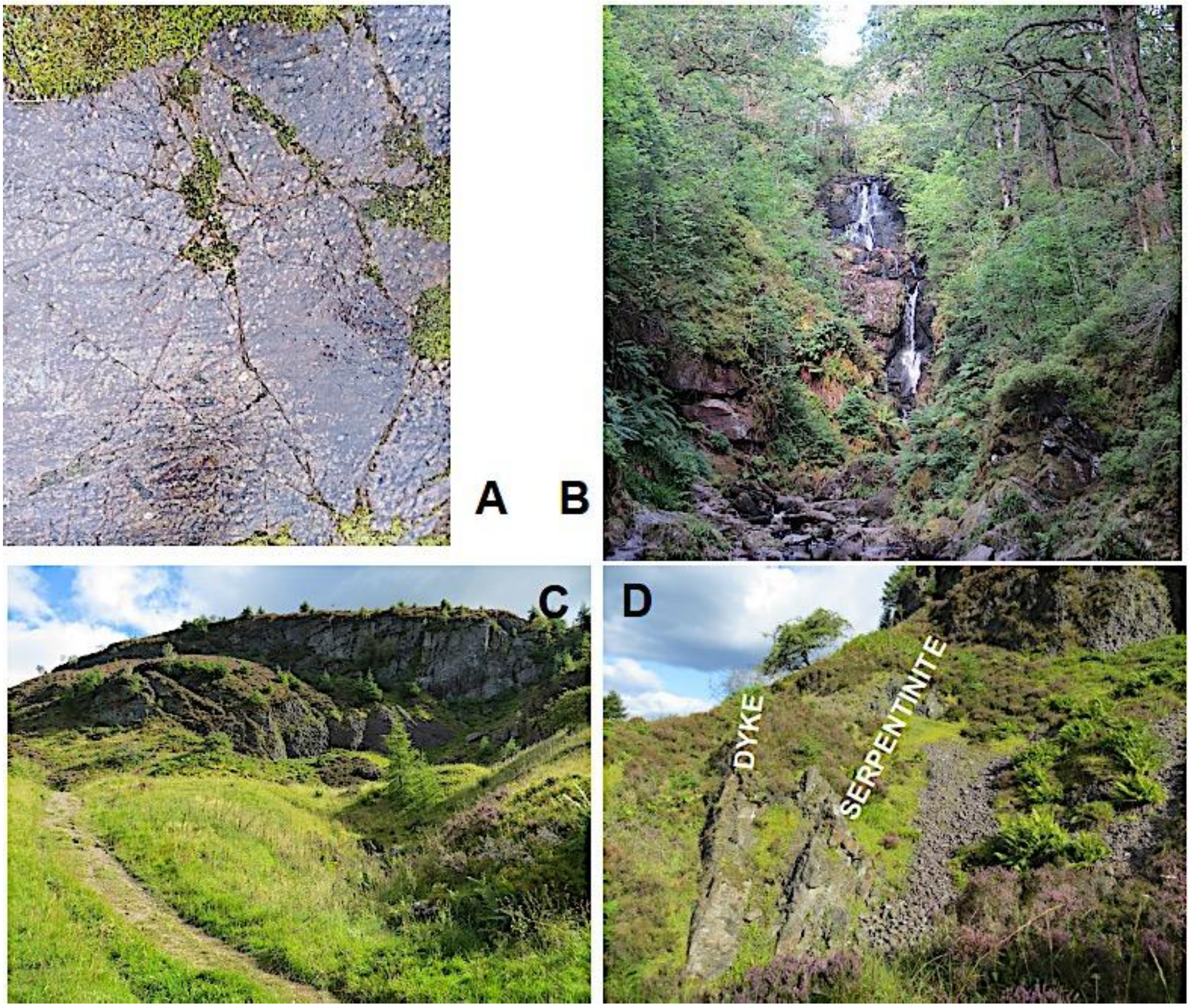

Figure 10. A. glacial smoothened surface at the visitor centre. B. Waterfall of the Little Fawn. C: Lime Craig Quarry. D. view from the small mound.

Conglomerates are also visible in the very high east face of the quarry, so the thin outcrop at (b) is a downfaulted part of this thicker conglomerate sequence to the NE. The fault responsible for this displacement is the Gualann Fault, a splay of the Highland Boundary Fault, which can be traced as far as the west side of Loch Lomond. The Gualann Fault is now more or less vertical, but Bluck (2015) believed it to have been originally a subhorizontal thrust, with movement from the northwest.

On the east side of the dyke (i.e. to the right hand side as you view it from the small mound) lies an outcrop of soft dark serpentinite (Fig. 12A). This rock differs in colour and texture from the brown weathering carbonate-serpentinite which is associated with the limestone; this latter rock is probably a sheared breccia and conglomerate made up of serpentinite clasts.

(c) The high ground to the SW of the quarry (to your right from the small mound) is partly formed of brown weathering, pale grey limestone from which an abundant fauna has been collected (Curry et al. (1982); Ingham et al. (1986)) (Fig.12B). The limestone contains sand-gravel sized clasts of serpentinite, gabbro, dolerite, spilite and other clasts of basic igneous rock. It was probably deposited in shallow water and was partly sourced in a pre-existing mass of oceanic crust (Bluck et al. (1984)). Pillow lavas are present at this level at Balmaha on Loch Lomond, but not here. The discovery in the Isle of Bute of a metamorphic sequence which resembles one produced beneath obducted ocean crust provided further evidence for the existence of an ophiolite along the Highland Border. Furthermore, the age of 540 Ma for the cooling of this metamorphic assemblage indicated that the ophiolite was older than the

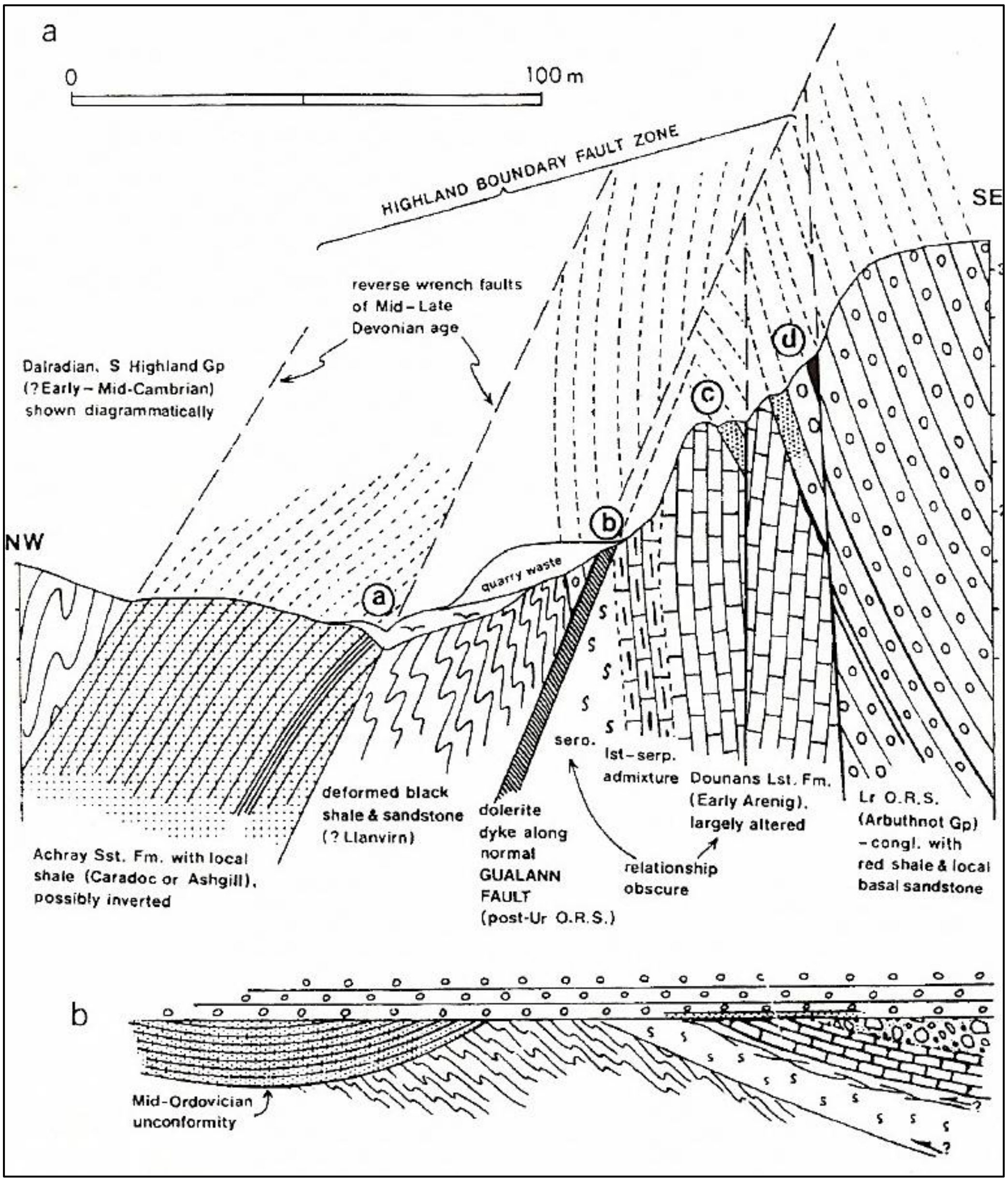

Figure 11. (a) geological cross section (as indicated on Fig. 9); (b) the attitude of the Highland Border Complex at the time of Lower Old Red Sandstone deposition. (From Curry et al. (1984).)

limestone found at this locality and could therefore be the source of the ophiolitic detritus found within it. The term **ophicarbonate** is sometimes used for rocks consisting of serpentinite and carbonate, where the serpentinite is commonly fragmented or brecciated, and veined and impregnated by the carbonate material.

Although a large silicified fauna has been obtained from this limestone, the fossils are not abundant and are small and difficult to find and see. The faunas include the trilobites: *Distazeris*, *Punka, Ischyrotoma*, *Illaenus;* brachiopods: *Archaeorthis*, *Orthidium*, *Orthambonites;* conodonts, gastropods, bryozoans, crinoids and ostracods. These and many others are figured in Ingham et al. (1986) and indicate a mid-Arenig age (Floian (early Ordovician) in terms of the international stages of the Ordovician, *c*. 478-470 Ma), of Laurentian affinity. The carbonates are interpreted as carbonate banks situated on uplifted and eroded oceanic crust.

(d) Steeply dipping and poorly sorted **Lower Old Red Sandstone** conglomerate with clasts up to cobble and small boulder size interstratified with thin red sandstones (Fig. 12C).

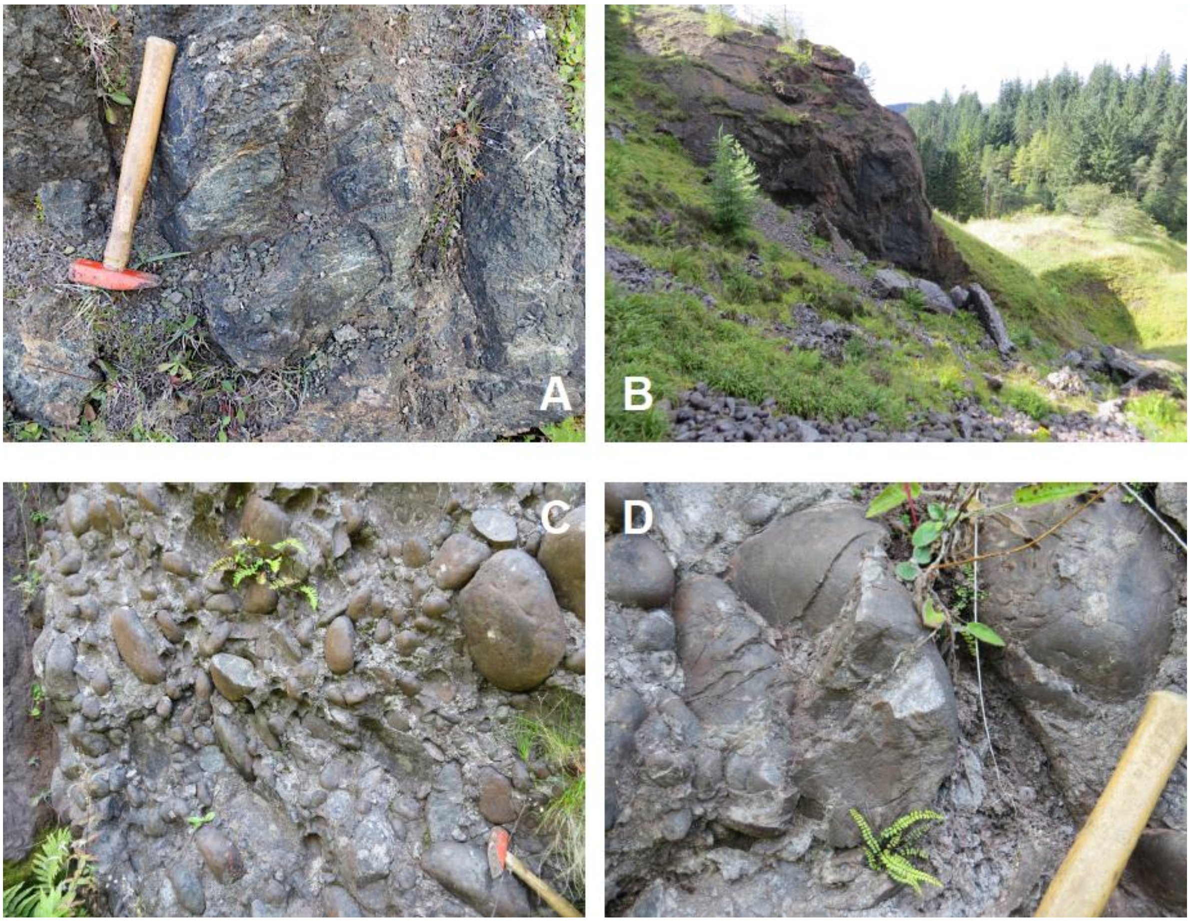

Figure 12. A. serpentinite; B. serpentinite-limestone; C. Old Red Sandstone conglomerate; D. sheared clasts within the conglomerate.

These rocks are on the steeply dipping northern limb of the inclined Strathmore Syncline. The cobbles are mainly quartzite of unknown origin and some andesite, and both are very well rounded. The brittle quartzite clasts are often fractured (Fig. 12D). The significance of these fractures was recognised by Ramsay (1964) as indicating shear, as well as reverse movement along the Highland Boundary and related faults; the fractures are oriented at right angles to the trend of the HBF (Fig. 13). More recent studies by Baron and Parnell (2004) on fluid inclusion planes within the healed microfractures, indicated that these microfractures are oriented perpendicular to the trend of the HBF, and probably formed during the mid Devonian Acadian (the time of initiation of the present-day HBF) with moderate temperature (102-238°C) fluids. They describe a second set oriented parallel to the HBF and formed during extension associated with the intrusion of late Carboniferous dolerite dykes. Shear zones are prominent in the high face of the quarry, with obliquely oriented slickensides but little evidence of fault movement. The conglomerates were deposited in large alluvial fans, probably 8-12 km in length, and derived from either the southwest or east. The source of the clasts is not clear, but they may have been derived from the now buried Midland Valley basement; there are no Dalradian clasts in these conglomerates, and it is believed that at this time in the early Devonian the Dalradian had already been eroded to a flat peneplain. Harley and Lelieu (2015) suggested derivation from Baltica to the east (for palaeogeographic units see Fig. 6).

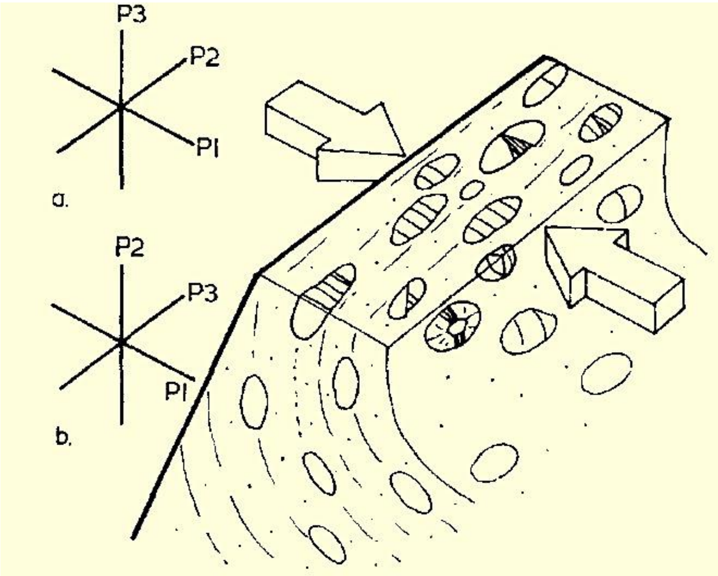

Figure 13. The relationship of the fractured pebbles within the Old Red Sandstone conglomerates, and the Highland Boundary Fault. a and b show the possible orientations of the principal stresses. The orientation of the fractures suggests strike-slip shear movement, indicating that the intermediate stress (P2) is vertical (b); in the case of compression and reverse movement the minimum stress (P3) would be vertical (a). (After Ramsay (1964).)

It is suggested that you finish the Highland Boundary Fault excursion at this point. The remaining localities described in the original guide are difficult to access and are very overgrown – however they are listed below. An alternative route, if you feel fit, is to walk back to the path by the spoil tips and ascend to the top of the hill – for a magnificent view, but only if the weather is clear. Return to the visitor centre, either via the old tramway or back along the route you came up.

Remaining localities at Lime Craig

(e) This locality, and to a lesser extent (f), are difficult to find, particularly in the summer when there is much vegetation. (e) is also fairly inaccessible so only the agile and enthusiastic should attempt this part of the excursion. Follow the cliff made by the limestone along the path for c. 100 metres, then scramble and climb to the limestone-Old Red Sandstone boundary. Here the Old Red Sandstone is seen to rest on the limestones of the Highland Border Complex. The contact is an unconformable one but with some minor movement along the plane of the unconformity. The formerly held view that this is the Highland Boundary Fault is now discarded.

(f) Conglomerates with abundant quartzite and psammitic clasts up to small boulder size. This is a conglomerate which is considered by Bluck et al 1984 to be part of the Highland Border Complex and probably younger than the Lower Arenig Dounans Limestone. Some of the psammitic clasts have yielded ages of 1800 Ma (Dempster and Bluck 1988) suggesting a source in a metamorphic terrane far older than the Moine and Dalradian.

Excursion 2. Localities along the Duke’s Pass (Figs 14-19)

This excursion is based on localities shown in Fig. 11, which is modified from Fig. 15 of Lawson and Lawson (1976). The geology has been updated with reference to the recently published geological survey map (BGS 2005). The sequence consists of two main lithologies, “grit” (metagreywackes) and slate.

Recent mapping by the Geological Survey (2005) in the Duke’s Pass area has revealed many faults and some minor folding within the major Aberfoyle synformal anticline. It is also evident that the **Duke’s Pass Fault** shows major oblique sinistral strike-slip displacement and that the slates to the west of the fault (as seen in the Aberfoyle slate quarries) are unrelated to those to the east. The latter are pelite and semipelite formations within the main Ben Ledi Grit Formation and are therefore younger than the Aberfoyle Slates. However this does not distract

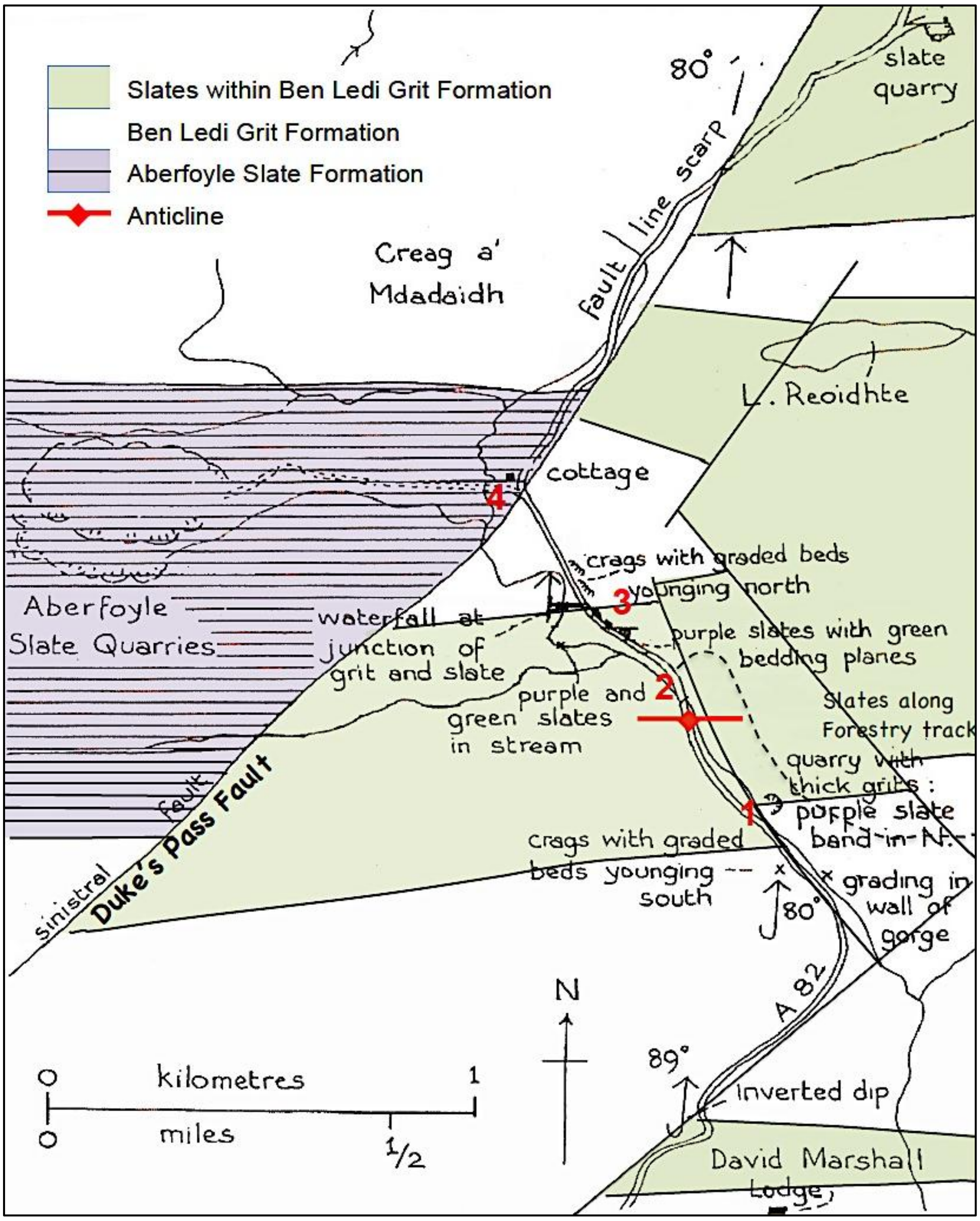

Figure 14. Simplified geology of the Duke's Pass. The numbers refer to the localities described in the text. (After the map of Lawson and Lawson (1976), updated with information from the BGS map (2005).)

from the main purpose of the excursion, which is to study easily accessed localities to the east of the Duke's Pass Fault. Evidence of way-up criteria help in the recognition of a synformal anticline and the presence of a major recumbent fold with a downturned nose.

The geology of this area has been described in some detail by Tanner et al. (2013).

Locality 1 (NN 5200 0225)

Take the A821 northwards from the visitor centre and traverse the Duke's Pass. This road was constructed in 1810 by the Duke of Montrose – hence the "duke"- in response to the large influx of tourists coming to the area following its popularisation in the writings of Sir Walter Scott. There are superb views of the Trossachs and the Highlands along this winding road, with plenty of laybys and pull-ins.

There are many roches moutonnees in the grits along the winding part of the road between Aberfoyle and the Visitor Centre, some with glacial striations, but parking here is difficult. It is suggested that you park in a layby on the right hand side of the road (Locality 1 in Fig. 14); if it is occupied (fairly often in good weather) there is another and larger layby a hundred metres further on.

Figure 15. Graded bedding in stream section at Duke's Pass. The base of the unit is on the left; the beds dip to the NE at 80°, but young to the SW.

From this layby it is possible to visit the features shown on the map. As the road straightens out just before the layby, the stream on the right displays good water worn surfaces of a steeply dipping graded grit with load casts indicating that the beds are inverted, as **they dip northeastwards but young to the southwest (Fig. 15)**. The best exposures can be difficult to find depending upon the water level in the stream; as a guide, bedding is the major lineation seen, but there is also prominent jointing. This stream eventually forms the waterfall of the Little Fawn, already seen on the Lime Craig excursion.

The small quarry to the east of the layby (NN 5205 0225) has unfortunately been fenced off and much overgrown so is no longer accessible. If you wish to look into the quarry, cross the small stream, where it should be possible to appreciate that the grits are dipping steeply to the left (i.e. roughly northwards). Graded bedding with a basal erosion surface could be seen in the quarry, indicating **younging to the south, although the beds dip northwards**, i.e. a similar situation to the stream sections. The grits are coarse in their basal layers, with clasts of subangular quartz, feldspar and rock fragments especially of shale. Purple slates occur on the northern side of the quarry, which are seen to be older than the grits as the graded bedding indicates younging to the south.

Other occurrences can be seen in exposures in crags on the left of the road; all of these localities show the same structure, i.e. beds dipping to the north, but younging to the south. Therefore as you proceed northwards into exposures of slates, the rocks become older.

Locality 2 (NN 5165 0270)

There is a small pullin for just one car on the left side of the road immediately before the forestry track on the right, and there is room for one or two cars to park on the track itself before the forestry gates while still leaving the track unblocked. The track goes southwards and passes to the east of the small quarry of Locality 1. After a five minute walk, good exposures of purple and green slates can be seen in road cuttings along the track. The cleavage dips to the north at 60-70°. Bedding in the slates is rarely observed, but can be picked out by very thin silty laminae marked by colour differences and more siliceous layers. Very fine-scale graded bedding in silty laminae shows that the rocks are inverted; the cleavage dips at a lower angle than the bedding, so the fold is overturned and the fold and first cleavage face downwards. The major structure is closing downwards, i.e. it is a **synform**.

Locality 3 (NN 5158 0290)

Now drive a short distance along the road and park in a small pullin on the left and opposite a road cutting into crags of grit (see cover photograph). If there is more than one car it is necessary to go a little further on and park on the forestry track at the cottage (see below). Immediately opposite the pullin is a wide gully with crags on both sides. The crags on the left hand side as you face the gully were, until recently (2018), fenced in with deer fencing and so were not accessible. They are covered in lichen and sphagnum moss, so are unrewarding for a short visit. One feature of interest can be seen in these crags near the roadside, where coarse slickensides suggest oblique-slip faulting striking ENE-WNW, which is also the strike of the bedding here so it may represent movement along bedding planes. There is also a lot of quartz veining, suggesting that the gully may be the site of a fault. The best exposures are at the far end of the south side of the gully (the right hand side), but as the gully has become very waterlogged in recent years, it is suggested that you approach this locality by walking southwards along the road to the end of the road cutting and approach the far end of the rocks from this side, where there are excellent exposures of metre-scale graded bedding indicating **younging to the north.** These graded beds dip to the south so are overturned (Fig. 16). Quartz clasts at the base of some graded beds are a centimeter or so in size. It is worth spending a short time examining the road cutting. Note that the beds dip at a high angle to the north, which is the general direction of dip for rocks around this area; graded bedding is not as prominent, but indicates younging to the north, so not overturned. Also note some thin slate units which are highly deformed with quartz veining. Possible loadcasts have also been described from this locality, and can be seen at the southern end of the road cut. If you now walk southwards along the road, i.e. into older units, there are good exposures of purple slates in low roadside cuttings.

When these observations are taken together with those made at Locality1, it is clear that we have crossed the axis of a fold; the slates in the middle are older than the grits, and the fold can be shown from bedding-cleavage relationships to close downwards. Although the structure is **synformal,** the presence of older rocks in the centre indicates that it is an **inverted anticline**. The anticline is overturned with an axial plane inclined to the north at about 70°.

Figure16. Inverted graded beds at Locality 3. The beds dip at 65° to the south (200°). They show younging to the north. The hammer head is 16 cm long; the bed shown is 85cm thick.

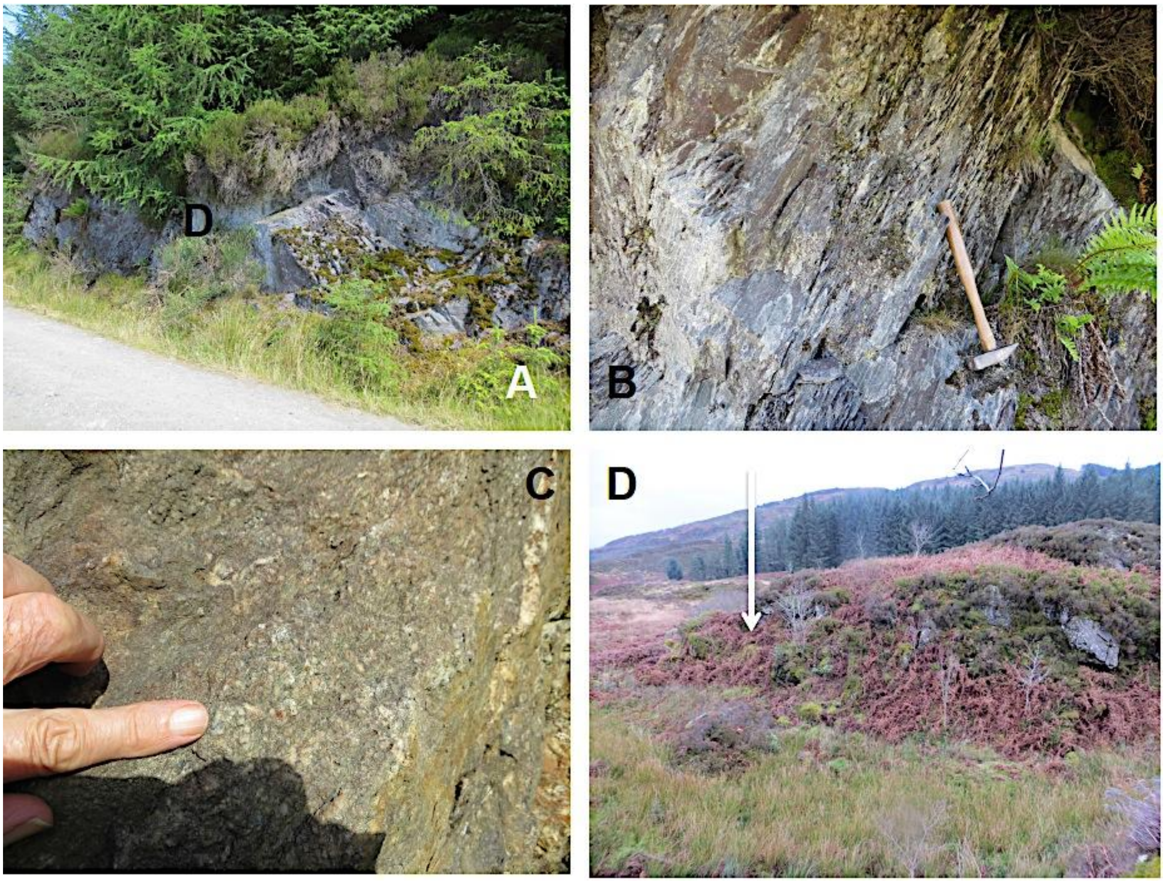

Figure 17. Exposures in Duke's Pass. A and B: slates in forestry track, Locality2. C and D: Locality 3; C shows the base of a graded bed dipping northwards (north is to the left of the photograph); D is the view across the gully, showing the position of excellent graded bedding in the crags on the southern side of the gully.

Locality 4 (NN 505 031)

The **Aberfoyle slate quarries** can be visited by parking along the forestry track which leads from the cottage – do not go beyond the parking area just beyond and almost opposite the cottage because the track is gated, and turning is very difficult at the gates which are usually closed. It takes about 5 minutes to walk to the quarries from the parking space; you first see the quarry dumps – walk a little further on for a view of the quarry face. This is mostly hidden by slips, and is also fenced off; there is a lot of loose slate to examine, so do not cross the fence! The Aberfoyle Slates have been described by Walsh (2000) in her study of the Scottish slate quarries. She noted that the slates have been worked since at least the 17th century when they were used at Stirling Castle, and that the quarries were one of the last in Scotland to cease production – in 1954. The slates vary in colour, with blue, grey, green, and purple, and these colour variations often allow the recognition of bedding. The cleavage planes dip at about 70° to the north, and sometimes show a slight sheen, suggesting an almost phyllite grade of metamorphism, supporting Thomas (in Tanner et al. (2013)) who postulated that these rocks on the western side of the Duke's Pass Fault reveal a lower structural level than those to the east. The slates have thicknesses of 5-14 mm, and it appears that only small slates were produced. Thin quartz veins are common, but unlike at Ballachulish there are no pyrite crystals. Seven main bands of slate could be distinguished with occasional thin bands of grit and limestone. The rocks in the quarry are cut by at least six northeasterly trending sinistral strike-slip faults trending sub-parallel to the Duke's Pass Fault.

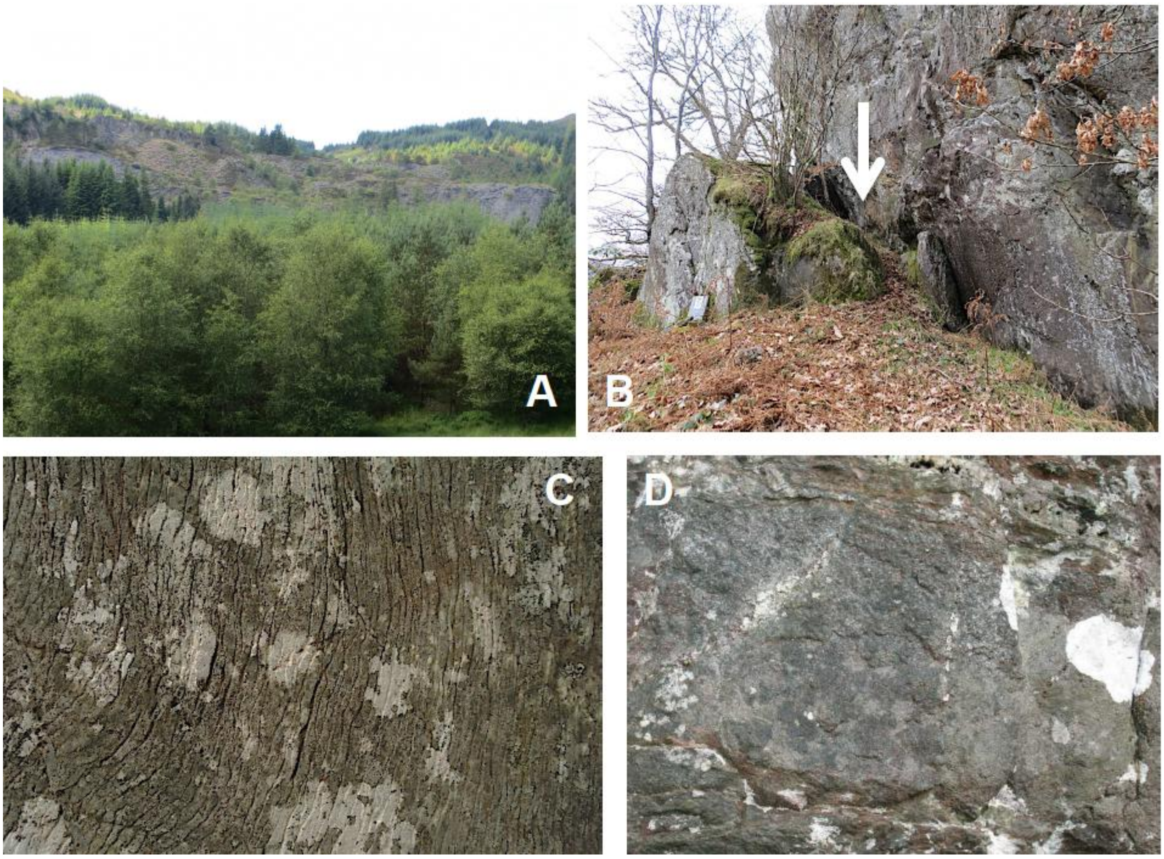

Figure 18. A. Aberfoyle slate quarries viewed from the A821. B. Creag Noran showing the locality for graded bedding (arrow). C. S1 cleavage at Creag Noran. D. inverted graded bedding at Creag Noran (thickness of bed is 25 cm).

Locality 5. Creag Noran (NN 5041 0658)
The excursion continues northwards along the A812 towards the Trossachs. Just beyond the cottage an escarpment on the left marks the position of the Duke's Pass Fault. Further on, slates are seen along a forestry track on the right hand side. Continue for another two miles or so to Loch Achray. The final stop is a prominent crag just beyond the entrance to the Loch Achray Hotel; there is a small parking area on the loch side opposite the exposure, but otherwise continue along the road for another 200 metres to a large car park on the left (park and pay) and walk back to the exposure.

There is a steep embankment leading up to the cliffs of this locality, which is becoming increasingly overgrown. A view of the exposure shows sub-horizontal bedding picked out by beds of coarser sediment, with sub-vertical wavey cleavage developed in the finer sediments. An excellent exposure of inverted graded bedding, about 30cm thick, can be seen in a cleft on the left hand side of the cliff (Figs 18B, D) The metamorphic grade is higher here than along the Duke's Pass, giving quartz chlorite schists. This S1 cleavage is thus nearly normal to the bedding and is deformed by D2 deformation, resulting in widely spaced crenulation cleavage. This locality lies on the inverted lower limb of the large recumbent fold forming the Tay Nappe.

A simple interpretation of the features seen on this excursion is given below (Fig. 19).

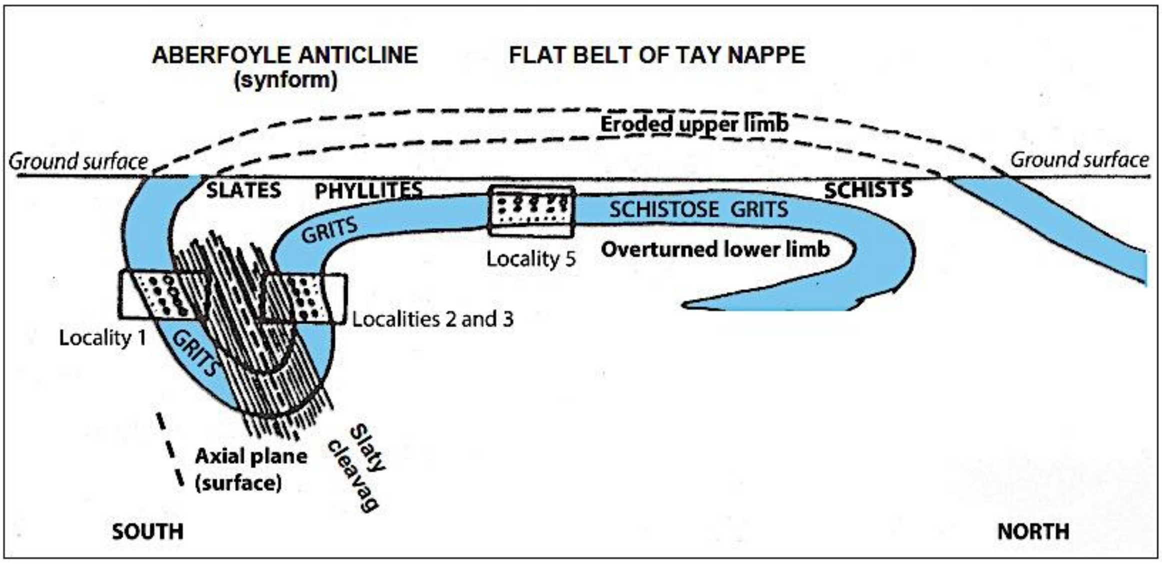

Figure 19. An interpretation of the structure seen along the Duke's Pass, showing the positions of the localities visited. The diagram shows the Steep Belt and Downbend of the Aberfoyle Anticline and the flat belt of the Tay Nappe. Metamorphic gradient increases northwards: the "Grits" of the Aberfoyle Anticline become the Schistose Grits, while the slates become phyllites and then schists.

Excursion 3. Localities to the southwest of Aberfoyle

In the original excursion guide, two localities were described to the southwest of Aberfoyle, and for the completeness of this guide are included below. At least three hours is needed to visit these exposures, which are now quite overgrown and difficult to find. From the west end of Aberfoyle take the small road south over the Forth, and head SSW to a car park at Balleich (c 1 km from Aberfoyle). Follow the forestry road west from the car park to the locality where this road crosses Bofrishlie Burn. Henderson et al. (2009) have published details of a further three localities in this area

Locality 1. Bofrishlie Burn (NS 5003 9901): Black shales and cherts. In both the stream section and along the forest road are good exposures of folded and sheared black shales and cherts. These rocks have yielded brachiopods, bivalves and radiolaria to Jehu and Campbell (1917) and chitinozoa to Downie et al. (1971). On the basis of chitinozoa these beds are probably Llanvirn-Llandeilo in age, and beds with these characteristics have been recorded in Stonehaven, where they are also assigned to that age-span.

On the NW and SE sides of the burn there are exposures of grey sandstone with interbedded siltstones and black shales. These beds make up most of the ridge lying parallel with the road on the NW side. The contact between these sandstones and the black shales is faulted, although Jehu and Campbell (1917) record an unconformable relationship between them. Some grey sandstones have black mudstone and shale clasts in them which may support the view that they rest unconformably on the shale-chert sequence.

Locality 2. (NX 4954 9861): **Unconformity between Highland Border Complex and Old Red Sandstone**. From Locality 1, continue SW along the forestry track. Take the left fork at the first road junction and the right fork at the second junction. Walk 90 m on the road over a small hill to the low lying outcrops 20 m from the road. The unconformable contact between the Old Red Sandstone and the underlying Highland Border Complex is seen in these bare rock exposures. The basal Old Red Sandstone is a breccia with clasts of shale and sandstone and forms the base to a sequence of coarse quartzite bearing conglomerates, sandstones and a thin andesitic lava which partly forms the high ridge to the south.

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Appendix 1. Folds

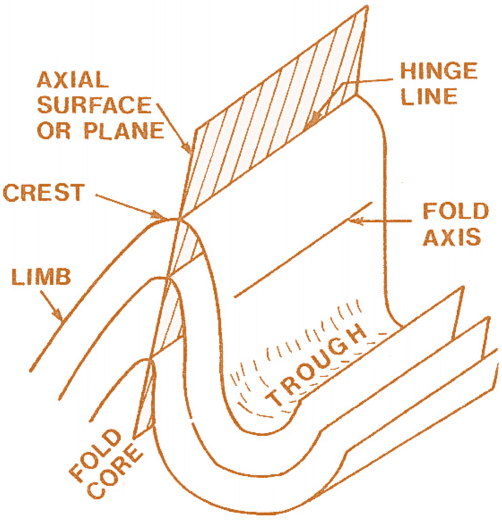
Deformation

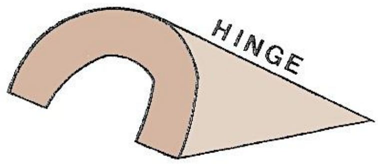
When rocks are subjected to stress they deform in a variety of ways. The type of geological structure produced depends upon the type of force being applied – compression, tension, or shear forces. Two common types of geological structures produced are **folds** and **faults**.

Folds

Folds are produced by compression. There are two principal types of fold – anticlines and synclines. The dip is the inclination of a bed of rock from the horizontal and strike is at right angles to this where dipping bed appear to be horizontal.

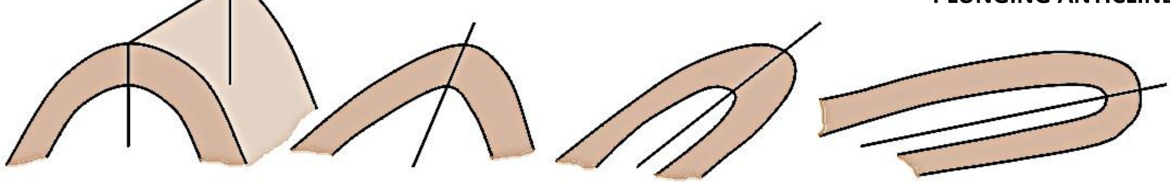
Limb: the two sides of a fold.
Hinge line: where the limbs meet.
Axial plane: the plane, or surface, on which all the hinge lines lie.
Crest: the highest point of a fold.
Trough: the lowest point of a fold.
Antiform: the limbs meet upwards.
Anticline: a fold with the oldest beds in the centre – antiforms and anticlines are usually the same structure, and most geologists use this word to describe an antiform unless there is clear evidence that the structure has been overturned.
Synform: the limbs meet downwards.
Syncline: a fold with the youngest beds in the centre – synforms and synclines are usually the same structure, and most geologists use this word to describe a synform unless there is clear evidence that the structure has been overturned.
Plunge: the hinge line is inclined.
Nappe: a large scale and complex recumbent fold, often associated with large thrusts.





PLUNGING ANTICLINE

TYPES OF FOLD

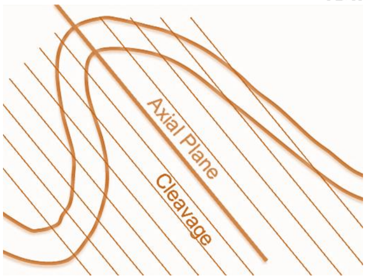


UPRIGHT ANTICLINE
The axial plane is vertical

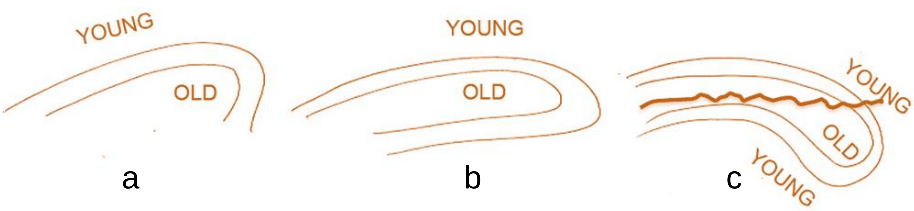
INCLINED
the axial plane is inclined

OVERTURNED
One limb underlies the other, i.e. it is inverted

RECUMBENT
The axial plane is approximately horizontal



Axial plane cleavage (slaty cleavage) – develops parallel to the axial plane



How a structure which is both an antiform and an anticline (a) can be deformed into a recumbent fold (b) and then a nappe (c). In the case of the nappe a land surface is drawn and there is now an anticline (i.e. a fold with the oldest rocks in the centre) which is also a synform (a fold where the limbs close downwards) – the situation seen along the Duke's Pass.

Appendix 2. Faults

Faults are fractures in the earth along which one side has moved relative to the other. This plane of displacement is referred to as a fault plane. There are three main types of fault: **reverse faults** where the side overlying the fault plane has moved upwards, **normal faults** where it has moved downwards, and **strike-slip faults** where the displacement is horizontal. These are usually associated with the earth's crust being subjected to compression, tension, or shearing respectively. **Thrust faults** are a special type of reverse fault where the fault plain is inclined at a low angle or may even be horizontal. Thrusts are often very large scale (many kilometres).

Transpression occurs when a region of the Earth's crust experiences strike-slip shear and a component of shortening, resulting in oblique shear. Transpression typically occurs at a regional scale along plate boundaries characterized by oblique convergence.

~60°.