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GRAND GEOLOGIC TOUR OF SCOTLAND

June 21—July 1, 2016

Kathleen S. Goodman, Principal Hydrologist, AMEC Foster Wheeler, Editor

Chris Darmon and Colin Schofield, Geosupplies Ltd., UK, Trip Leaders

Contributing Authors:

Eric and Ingrid Cheney
Kirk Deal
Marcia Knadle and Sheri Silverman
Steve and Linda Grupp
Jim and Jill Miller
Kathleen and Rick Goodman
Steve Evans
Amy Knudson
Donn Charnley and Corinne Waters
Karen Spaulding and Rik Sandri

NWGS Field Trip Guidebook Series

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***Cover photo**: A view of the Scottish highlands (location and photo author unknown).*

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GRAND GEOLOGIC TOUR OF SCOTLAND

Kathleen S. Goodman, Principal Hydrologist, AMEC Foster Wheeler, Editor

I. FORWARD

By Kathleen Goodman

The NWGS conducted a very successful field trip to Scotland from 21 June to 1 July 2016. The trip was led by Chris Darmon and Colin Schofield of Geosupplies Ltd. of Sheffield, England. Kathleen Goodman coordinated the planning and logistics of the trip for NWGS.

Previous NWGS field trips beyond the Pacific Northwest were to the Big Island of Hawaii (2009) led by NWGS member Tom Bush, and Iceland (August, 2012). The Iceland tour was led by Kristinn Guđjónsson of Nattours, Reykjavik, Iceland. Mathew von de Ahe and Kathy Troost planned the Icelandic trip.

The Scottish field trip began near Glasgow and ended in Edinburgh. However, it concentrated on the scenic western coast of the Highlands, which have many hallowed geologic features, especially the Moine thrust. Nonetheless, the trip included a bit of the north coast and the geologically famous Siccar Point southeast of Edinburgh. And, we can't forget the wee bit of whisky tasting we did at the wonderful Glen Ord distillery outside of Inverness.

A significant problem for the Scottish trip was the lack of a guidebook. Due to copyright issues involving previous field guides published by others, Darmon and Schofield could not create a field guide for the Scottish trip. Nonetheless, during the trip they did provide numerous maps and illustrations. Tom Bush, the editor of NWGS guidebooks and archivist for the NWGS did not attend the trip; he suggested that the participants of the trip compile their own guidebook.

Bush and Goodman hit upon the idea of selecting a different pair of participants to describe each day of the trip. The format of their description was unconstrained, except that the location and geologic purpose of each stop should be recorded. The resultant description (or log) of the day was not to exceed one to three pages. Each day Goodman selected a geologist and a non-geologist to craft the log. The role of the latter was to determine the geographic location of each stop, select at least one photograph for the day, and to otherwise assist the geologist.

To provide context for the daily logs, Eric Cheney contributed the brief introduction on the geology of Scotland. Goodman volunteered to prod the authors and to compile the daily logs (with a minimum of editing).

Thanks to all of the field trip participants who contributed to this field guide. We are most grateful to Chris Darmon and Colin Schofield for a superb trip that appealed to both geologists and non-geologists, featured quaint family-owned hotels, 3 to 5 miles of hiking on most days, and, mercifully, no rain. They were, however, commonly unable to abate the vicious Highland midges.

II. A WEE DISCOURSE O'ER THE GEOLOGIE OF BONNIE SCOTLAND

By Eric S. Cheney

Abstract
The geology of Scotland records two openings of the Atlantic Ocean. The oldest rocks are > 3.1 Ga and are of North American origin. Scotland has four northeasterly striking terranes bounded by strike-slip faults (**Fig. 1**). The terranes were juxtaposed during the middle to late Silurian Caledonian orogeny.

A major focus of this trip is the Moine thrust along the west coast. The Moine was the first thrust to be recognized in the world (1882), and mylonites associated with it were the first recognized in the world. Zones of duplexes along the thrust are up to 10 km thick and 10 km long.

Devonian and younger unconformity-bounded sequences overlie the terranes. An example is the unconformity described by James Hutton at Siccar Point. Carboniferous coal was the foundation of Scotland's industrialization (1820s to 1950s). Permian and younger sequences are the source of Scotland's North Sea oil; production peaked in 1999.

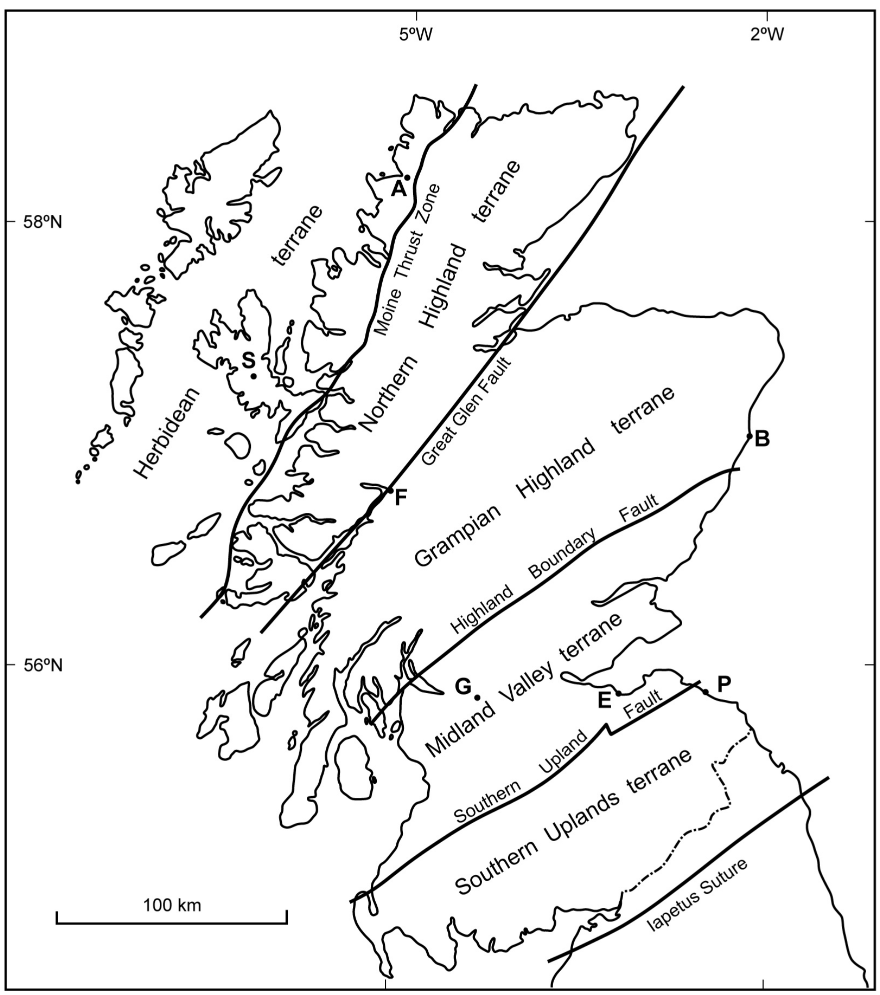


Figure 1. *Major terranes and faults of Scotland (after Trewin amd Rollin, 2002, fig. 1.3). Abbreviations: A. Assynt; B, Aberdeen; E Edinburgh; F,Fort William; G, Glasgow; P, Siccar Point, and S. Isle of Skye.*

Introduction

Purpose

The purpose of this summary of the geology of Scotland is to provide context for the NWGS field trip of 21 June to 1July, 2016. This summary also, provides context for the daily field guides in this guidebook and provides a number of references. For the sake of members of the NWGS, this guide also notes similarities between the geology of Scotland and the northwestern United States.

Geologically, the major building blocks or Scotland are terranes and unconformity-bounded sequences (UBSs). This summary gives a brief description of each major building block. Granitic intrusions of the Highlands and mafic intrusions of the west coast (**Figs. A16 and A17**) are largely omitted here. This summary also stresses that although the geology and tectonics of Scotland and the Pacific Northwest of North America differ in age and orientation, they are remarkably similar in style and sequence of events.

This summary includes an appendix of 18 PowerPoint slides, labeled A1 to A18, noted in the following text.

Background

Scotland occurs in the North Atlantic and includes three outlying groups of islands shown in **Fig. A1** (O, Orkney; S, Shetland; SK, Saint Kilda). The > 3 Ga geological history of Scotland records two openings of the Atlantic Ocean. The ancestral Atlantic Ocean (Iapetus) opened in the late Proterozoic and closed by the end of Silurian (the Caledonian orogeny). The present Atlantic Ocean began with the break-up of Pangea in the early Jurassic. As a result of shuffling of crustal fragments (terranes) after the first of these openings, some of Scotland is of North American ancestry.

James Hutton (1726 – 1797) and others began exploring the geology of Scotland at the end of the 18th century; the complexities of the crystalline rocks (and their remoteness) sorely challenged these early explorers. In contrast, William Smith (1769 – 1839) had an easier time mapping the UBSs underlying Merrie Olde England; he produced his famous map of England in 1815. The giant of English geology in the 19th Century, Charles Lyell (1797 – 1875) also concentrated on England.

For the past nine score years and more, Scotland has been mapped (and remapped in ever increasing detail). Structures were not understood in the metamorphic rocks until criteria were developed to determine the stratigraphic "way-up". Thrust faults and mylonites were first recognized here (Goodenough and Krabbendam, 2011). Other concepts developed in Scotland are those of contact and regional metamorphism and mylonites (the latter are foliated rocks formed in ductile fault zones). Of course, since the 1960s, radiometric dating has been important. Too many modern field geologists use these tools without knowing where and when they originated (**Fig. A18**).

Unattributed aspects of Scottish geology in this summary are from Oldroyd and Hamilton (2002), Trewin and Rollin (2002, and Goodenough and Krabbendam, 2011). Rather than generate a long list of references, the other chapters in Trewin Rollin (2002) that yielded minor information are noted by parentheses: 2002(3). A particularly good a guidebook for the area of the Moine thrust (with detailed geologic maps) is Goodenough and Krabbendam (2011); hereafter this reference is abbreviated as GK2011.

Geography and History

The Scottish Highlands, southern Norway, southeastern Alaska, and southernmost Chile are at latitudes between 53 and 60 degrees, are sparsely populated, have extensive archipelagoes that are laced by fjords, are mountainous, and have high rainfalls (due to westerly winds from adjacent oceans). The mountains and high rainfall provide hydropower. In Scotland hydropower is used for aluminum smelters at Fort William and Kinlochleven (from 1907 to 2001). The tree line in the Scottish Highlands is near sea level (or just a few hundred meters above it).

The remoteness and harsh conditions in the Scottish Highlands generated a turbulent and colorful political history. The British did not "subdue" the Highlands until the 1750s (**Fig. A3**, Harvie, 2014).

Geology

Caledonian Terranes

Scotland consists of five northeasterly striking, pre-Devonian terranes. Figures 1, A2, A3, and A5 outline the terranes and their bounding faults. The terranes are 50 to 100km wide and 200 to 400 km long. These terranes were amalgamated during the Caledonian Orogeny (late Silurian to early Devonian). Incidentally, Caledonia was the Roman name for Scotland.

Caledonian terranes (collectively known as the Caledonides) occur on both sides of the Atlantic Ocean. Localities include southeastern USA, New England (USA), the Maritime Provinces of Canada, Newfoundland (Canada), northeastern Greenland, England, Ireland, Scotland, and Norway (Figure A13, Waldron et al., 2014, Fig. 1).

Hebridean Terrane(s)

The Hebridean terrane (**Figs. A2 and A6**) consists of Archean rocks similar to those in Greenland (and possibly Norway) (**Fig. A9**). They are mostly gray granitic gneisses, called the Lewisian gneisses. Their maximum age currently is 3.12 Ga (GK2011). Future research, backed by geochronology, may indicate that petrologically distinct granitic domains of batholithic dimensions are terranes (**Fig. A6**). Unlike some Archean provinces elsewhere in the world, no greenstone belts occur with these gneisses. Polyphase deformation, caused by Caledonian and other overprinting, is common in Lewisian and other rocks.

Three cover sequences (UBSs) overlie the gneisses (Gk2011). The Stoer and Torrodon groups are Proterozoic red beds. The Stoer Group has a maximum thickness of < 1km and detrital zircons > 1200 Ma. The Torrodon Group has a maximum thickness pf < 1.7 km and is about 1000 Ma. The youngest Hebridean UBS consists of Cambrian to Ordovician clastic rocks and limestones (**Figs. A6 and A8**). These are correlative with the Sauk and Tippecanoe UBSs of North America, portions of which also occur in northeastern Washington (Cheney and Zieg, 2016).

Northern Highland Terrane

In the Northern Highland Terrane the only stratigraphic unit is the Moine Supergroup, which is mostly fine-grained sandstone in greenschist faces. Detrital zircons in the Moine Supergroup range from 1900 to 1000 Ga, and the supergroup is intruded by an 870 Ma pluton (GK2011). The supergroup is in the hanging wall of the 400 km long, imbricate Moine thrust zone (**Fig. A6**).

If some part of the Moine Supergroup were to be shown to be equivalent to some part of the two Proterozoic UBS of the Hebridean terrane, the Northern Highland terrane would not be a separate entity (and would be part of the same terrane as the Hebridean terrane).

Moine thrust

A major topic of the field trip is the Moine thrust. The onshore portion of the thrust, from the north coast through Assynt to the southern tip of the Isle of Skye, is 175 km. This thrust is world famous for two reasons. In 1882/83 it was the first thrust in the world to be recognized and in 1884 it was the first area in which mylonites were described (GK2001). Charles Lapworth (1842 – 1920 discovered the thrust. By 1884 detailed geologic mapping by Benjamin Peach (1842 – 1921) and John Horne (1848 – 1928) had confirmed Lapworth's remarkable discovery (**Fig. A18**) and had also described the mylonites. With the Moine specifically in mind, in 1884 Archibald Geike coined the term "thrust" for low-angle reverse faults.

The Moine is the roof thrust of a zone that varies from a few to meters to 10 km thick. The greater thicknesses are due to the imbrication of duplexes (repetition due to multiple thrusts (**Fig. A7**)). The duplex zones in the thrust are up to 10 km thick and 10 km long (GK20112). Duplexes in the thrust zone involve Lewisian granitic rocks, the Torrodon Group, and the Cambrian to Ordovician UBSs. Lineations indicate that the direction of transport was WNW (GK2011). Maximum horizontal displacement on the thrust zone is about 85 km (GK2011).

Most mylonites are derived from the Lewisian gneiss and the Torrodon Group, but protoliths are difficult to identify. Mylonites returned to geologic popularity in the 1970s and 1980s as a result of studies of Tertiary metamorphic core complexes of the America Cordillera. Mylonites in the mid-Eocene complexes of Washington State have such features as reduction of grain size, lineations, two foliations (S/C fabric), porphroclasts, microscopic "fish", and sheath folds (like those in the Moine, as illustrated in 2002 (4, fig. 4.39).

Prior to the work of Peach and Horne, the euphemism for the Moine thrust zone was "the belt of complication" (Peach et al., 1907, p. 464).

Peach and Horne were able to decipher the thrust belt for three reasons. 1) Accurate topographic maps already existed. 2) Peach and Horne knew the stratigraphy (especially of the Cambro-Ordovician rocks. 3) Extensive outcrops on steeper slopes of ridges expose the stratigraphy and structure in three dimensions. Their final report (Peach et al., 1907) is quite impressive.

Ever since Peach and Horne, the type area of the Moine thrust (with multiple duplexes) has been around Loch Assynt. The geology of that area is beautifully illustrated by the Geological Survey of Great Britain (2007).

Grampian Highland Terrane

The Grampian Highland Terrane is mostly underlain by the Neoproterozoic Dalradian Supergroup. This supergroup consists of sandstone, siltstone, mudstone limestone, and dolomite in greenschist and higher faces (Pattison and Harte (2001). Pelites in the group host the world-famous (1693 to 1955 Ballachulish slate quarries. The metamorphic grade increases northeastward from greenschist to upper amphibolite (Figure A4) (2002(4), fig. 4.31). Tillites (2002, fig. 16.1 and plate 6) indicate that at least some of these strata are latest Neoproterozoic (and correlative with the Windermere Supergroup of northeastern Washington and adjacent British Columbia). However, some limestone may be Cambrian. Regionally most of the

Dalradian rocks are overturned and deformed by younger upright antiforms.

Late Silurian, post metamorphic felsic plutons in this terrane occur at Fort Williat, Ballachulish, Glen Coe, and Ben Nevis (**Fig. A10**). Andesite, felsic pyroclastic rocks in the Glen Coe caldera, and porphyry copper-type mineralization at Ballachulish (Pattison and Harte, 2001) indicate that these are subduction- related plutons. Ben Nevis, at 4406 feet (1324 meters) is the highest mountain in Great Britain.

Midland Valley Terrane

The Midland Valley Terrane is mostly underlain by the Old Red Sandstone and Carboniferous strata (both are described below). Hutton's famous unconformity at Siccar Point (**Fig. A11**), with Devonian Old Red Sandstone overlying Silurian greywackes and shales (**Fig. A12**; Trewin and Rollin, 2002, plate 16), is in this terrane.

Carboniferous coals (**Fig. A15**) made this terrane Scotland's industrial heartland from the 1820s to the 1950s. The heartland, extending from Glasgow to Edinburgh, bred rampant capitalism, environmental excesses (including some coal mines), Engels and Marx, and the British welfare state (Harvie, 2014).

Southern Uplands Terrane

The southern margin of the Southern Uplands Terrane is the poorly exposed Iapetus suture zone, which records the closing of, Iapetus, the ancestral Atlantic Ocean. The terrane consists of northeasterly trending fault panels of Ordovician and Silurian greywackes, plus fragments of ophiolite complexes. Sedimentary structures in beds in the panels suggest that the beds young to the NW, but the youngest graptolites are in the SE. The succession might be in a vertically rotated thrust belt on the former margin of Laurentia.

The Old Red Sandstone

The Old Red Sandstone (ORS) encompasses a variety of lithologies that are unconformable on Silurian (as at Siccar Point) and older rocks. Units in the ORS range from middle Silurian to earliest Carboniferous. Andesite and felsic volcanic rocks occur in the Silurian portion, but the majority of ORS rocks are clastic. Some marine rocks occur but most strata in the ORS are fluvial, eolian, or lacustrine. The successions in some areas contain unconformities. The ORS occurs in many areas of various extents across the breadth and length of Scotland. Most areas are generally considered to be individual depositional basins.

The ORS is like the Middle Eocene clastic and volcanic rocks of the Challis sequence in the State of Washington. Like the ORS, individual areas of the Challis rocks have long been considered to be individual depositional basins with somewhat different stratigraphies. However, the Challis sequence contains eight UBS of regional extent. In any given area, differential erosion on one or more of the regional unconformities generated seeming distinct stratigraphic successions from originally continuous units (Cheney, 2016).

In my opinion, the OPRS should be split into two distinctly different UBS. The andesites and felsic rocks in the Southern Uplands are not extensive. However, they are older and compositionally distinct from the rest of the ORS. In contrast to present usage I would limit the ORS to the mostly Devonian clastic strata. For convenience in the discussion below I label the older volcanic rocks PORSV (pre-ORS volcanic rocks).

Other UBS

Carboniferous rocks crop out mainly in the Midland Valley Terrane (**Fig. A16**). The succession consists of carbonate rocks, red beds, minor oil shale, and coal. Upward coarsening cyclothems are capped by coal. The New Red Sandstone is Permian.

Permian to Tertiary UBSs underlie the North Sea in a synformal pattern. Permian, Jurassic, and Eocene strata contain oil. Jurassic strata also occur along the west coast of Scotland, at Elgol on the southwest coast of the Isle of Skye, the northeastern coast of Skye at Tartan Rock, and elsewhere.

Off-shore drilling in the North Sea began in 1965. The production of oil greatly changed the economies (and politics) of England, Scotland, and Norway. The center of the oil industry in Scotland is Aberdeen. Peak production of oil was in 1999. The declining price of oil since 2014 has accelerated the decline in oil production and adversely affected the economy of Scotland.

Tertiary Anticlinorium

In my (E. Cheney) perspective, Scotland is a large northward trending regional antiform (or anticlinorium). It is cored by the pre-Devonian crystalline (basement) rocks. Most of the areas of ORS are near or below sea level; thus, they partially outline the antiformal pattern. Jurassic strata on the west coast of Scotland, rather than being separate depositional basins distant from the North Sea, mark the western limb of the anticlinorium.

The anticlinorium rises above the post-Devonian UBSs of the North Sea (on the east) and Merrie England (on the south). The anticlinorium is very gentle (or broad). At the latitude of the Isle of Skye, Scotland is about 250 km wide; in contrast, the highest pre-Devonian rocks on land (at Ben Nevis) have an altitude less than 1.4 km.

Comparison with the North American Cordillera

Table 1 and **Fig. A15** show the similarity of the Caledonian tectonics of Scotland and the late Cretaceous to Paleocene tectonics of the northwestern United States and adjacent Canada. The leading edge of the latter is that part of the Sevier fold and thrust belt in the northern Rocky Mountains. The age and orientation of structures of the two areas are different, but their style and the sequence of events are quite similar.

The cause of the deformation in the United States and Canada was accretion of terranes to the west. This suggests that northwest-directed accretion in Scotland was more important than commonly realized. Eocene and later accretions make the American scene somewhat more complex than the Scottish one.

Tectonic Model for Scotland

Scotland is dominated by the strike-slip faults that bound the northeasterly striking terranes. The volume edited by Trewin (2002) suggests that Scottish geologists have focused the terranes and faults and have underestimated the effects of collisional tectonics. The model favored here is that collisional tectonics were northwest-directed and were later cut by the northeast striking strike-slip faults.

The evidence for northwest-directed subduction and tectonic transport is as follows:

1) The Iapetus suture zone, which bounds the Southern Uplands Terrane, strikes northeast.

	Scotland	Northwestern United States
Post-Orogenic Sequence	Old Red Sandstone many separate areas generally regarded as separate basins mostly non-marine	Challis Sequence many separate areas generally regarded as separate basins mostly non–marine E of Interstate 5
Strike Slip Faults	Sinistral, NE striking, from NW to SE Great Glen Highland Boundary Southern Uplands Iapetus Suture	Dextral, mostly N to NW striking, from W to E: Straight Creek Entiat Lake Pasayten Sherman Purcell Trench
Syn-post orogenic plutons	Ben Nevis, Glen Coe, Ballachullish	Boulder, many in WA
Syn-post orogenic volcanics	Andesite and felsic in Southern Uplands	Elkhorn Mountain, MT
Foreland Basin	Absent, may have been rifted away by opening of the Atlantic Ocean, or exposed basement implies was eroded	Present: strata are Jurassic to Paleocene
Metamorphic Facies	Greenschist to amphibolite in Grampian	Greenschist to amphibolite, WA to MT
Thrust faults	NE striking Moine, has duplexes	NW striking Lewis et al., has duplexes
Orogeny (and age)	Caledonian (middle to late Silurian	Sevier (late Cretaceous to Paleocene)

Table 1. *Comparison of the geology of Scotland with that of the northwestern United States.*

2) Andesite and felsic volcanic rocks, which are common products of subduction, occur in the Southern Uplands Terrane. They are middle to late Silurian (older than clastic portion of the Old Red Sandstone). The volcanic rocks are a separate UBS, here labeled PORSV.

3) Felsic plutons are normal products of subduction. Those in the Grampian Highland Terrane (**Fig. A10**) appear to be the same age as PORSV in the Southern Uplands Terrane. Furthermore, these plutons have characteristics commonly associated with subduction: andesite, felsic volcaniclastic rocks, and porphyry copper mineralization.

4) The direction of transport of the Moine thrust is WNW.

Conclusions

The Caledonian orogeny in Scotland produced four northeasterly striking terranes bounded by sinistral strike slip faults. Correlations between the terranes are speculative and offsets on the faults are unknown. Thus, reconstruction of the original plate (or plates) is not yet possible. Perhaps all of the terranes formed during northwest-directed subduction on the Iapetus suture or its predecessor.

Acknowledgements

I thank David and Helen Twist of North Ballachulish hospitality and geologic library. I thank D. Twist, K. D. Goodman, and D. S. Cowan for encouraging me to write this discourse.

III. ADDITIONAL THOUGHTS ON UNCONFORMITY BOUNDED SEQUENCES (UBS) AND THE NORTH AMERICAN-SCOTIAN CONNECTION

By Kirk Deal

Briefly, UBSs are packages of sedimentary formations contained between major unconformities reflecting tectonic movements (structural displacements by faulting or folding) and/or worldwide sea level (eustatic) conditions. Resulting depositional conditions can stand high and cause widespread epeiric deposition, upon continental masses, or cause restricted deposition in oceanic plateau/slope and trench/arc environments.

The current preserved extent of UBSs reflects the original depositional extent modified by subsequent eons of erosion. Partial to complete removal of pre-existing sediments results from alternating erosion and deposition, leaving the formations bounded below by the previous major unconformity on which they were deposited and above by the subsequent major unconformity which was imposed by subareal erosion (i.e., tectonic uplift or sea level lowering). The sedimentary basins of the world contain their geologic history within these UBSs which may remain in one basin and yet be lost to erosion in another.

Quite explicably the sedimentary rock within time equivalent UBS can show worldwide similarities. Global weather conditions have at times produced the same age depositional systems of similar characteristics at great distances of separation evidencing arid continental or marine conditions. Examples abound in the geologic record as mentioned elsewhere: Devonian age sandstones of eastern North American and equivalents in Great Britain; Carboniferous age coals from east North America and equivalents in the Midland Valley of Scotland; Cretaceous age chalks from Austin, TX to Dover's White Cliffs on the English Channel; Permian age Red Beds from the Rocky Mountains, western USA to Great Britain and as far as South Africa.

At times these lithologic (rock) similarities between distant areas of the same age rock merely reflect tectonic separation of adjacent rocks across faults of great displacement as evidenced by the opening of the Atlantic Ocean. In other cases time correlative UBS sediment similarities reflect the same worldwide climactic conditions across great distance resulting in widespread sedimentary rock product similarities.

Torridonian and Cambro-Ordovician UBS Examples

Within our study area in Scotland, the Torridonian and overlying Cambrian through Ordovician sections comprise two separate UBS systems that have a mirror image in distant western No. America preserved in the depths of the Grand Canyon.

Comparing the Cambro-Ordivician sections of western North America and Scotland, they both begin with deposition on a Cambrian unconformity into continental sandstones. In the Grand Canyon the Sauk UBS of N.A. begins with the deposition of the well known basal Tapeats Sandstone on to the unconformity into the Proterozoic Chuar Group. The Tapeats Sandstone is followed upward by the Bright Angel Shale which in turn is covered by the Muav Limestone.

In Scotland we see the time correlative Cambro-Ordivician UBS is deposited on the unconformity cut into the Proterozoic continental sandstones of the Torridonian Group. The mirror image Cambro-Ord. Scottish UBS begins with deposition of mid Cambrian Basal Quartzite Formation plus the Pipe Rock Fm. (also a quartzite), followed upward with the Fucoid Bed shale which in turn is covered by the Durness Limestone.

In these time correlative UBSs in western North America and northwestern Scotland the classic trilogy of formations: basal quartzite overlain by shales (pelites) culminating with limestone deposition is evidence of the progressive flooding of a continent, the onlap of an ocean and it's sediments on to a continent. Although the Scottish sequence is relatively thin compared to the Sauk UBS of the Grand Canyon, all lithologies are present and in the proper sequence to reflect the time correlative same characteristic formation types deposited at great distances of separation, on a scale of global proportions.

To flesh out the UBSs below the Cambrian requires more work. The Proterozoic rocks below the Cam.-Ord. UBS, in a rough sense could be considered a single UBS down to the Archean unconformity, depending on the scale and purpose of analogy. More realistically however, given the great expanse of time represented, there is more than one UBS within the Proterozoic rocks of the NW Highlands of Scotland and the Grand Canyon. This is to say that there is at least one more unconformity in the section between the unconformity on the top of the Torridon Group (Scotland) /Chuar Group (Grand Canyon) and the unconformity above the Archean basement on Lewisian Gneiss in Scotland and the Vishnu Schist in the Grand Canyon.

This field trip has demonstrated how observing field geology in one area is enhanced by observations from other correlative rocks. By observing field relations in several localities perspective can be gained regarding similarities and differences, learning what is important to retain for a larger view and what are unique details to the locale.

IV. ROAD LOG

DAY 1—JUNE 21, 2016
DUMBARTON TO PLOCKTON

By Eric and Ingrid Cheney

Purpose
The primary purpose of today's field trip was to examine the lithologies in the Dalradian Supergroup of the Grampian Highlands terrane. This portion of the Dalradian is composed predominantly of fine-grained clastic rocks (pelites) that have been metamorphosed to slates, phyllites, and schists (metapelites). Specifically, we noted the change in the regional metamorphic facies from lower greenschist to possibly amphibolite (from slate to schist).

Route
We drove Highway A82 from Dumbarton (north of Glasgow) to northeast of Fort William. Stops 1-1 to 1-6 are alongside A82. About 20 miles NE of Fort William, we turned west on A87 and followed it to the vicinity of Lockton, Stop 1-7 is on A87.

Fort William is on a northeasterly trending fjord, Loch Linnhe, which marks the Great Glen fault. From the bus we could see the penstocks for the aluminum smelter at Fort William. Northwest of the Great Glen fault is the Northern Highland terrane. A87 follows the valley of Glen Shiel to saltwater; this scenic valley was deeply glaciated into sandstones of the Moine Supergroup. Very low water levels in reservoirs in the valley attest to the present severe drought. At Kyle of Lochaish we turned north for Plockton.

STOP 1-1: Luss
Luss is on Loch Lomond just north of the Highland Boundary fault. Small outcrops along the highway south of Luss are slaty (C. Darmon, 22 June 2016, personal communication). According to Darmon, ultramafic rocks have recently been found along the fault, as befits a major crustal fault.

STOP 1-2: Inverberg
A large new roadcut displays lustrous gray phyllite with folded quartz veins. Although probably in greenschist facies, the phyllite is higher in metamorphic grade than the slates in the Luss area. This type of Barrovian facies series is common in the Dalradian rocks of the Grampian Highlands terrane.

STOP 1-3: Inveruglas
This stop is across the river from a hydroelectric powerhouse. Schist with folded foliation probably represents a higher metamorphic grade that Stop 1-2. Blocks (erratics) of fine-grained metasandstone (termed "psammite" by some British geologists) may indicate a somewhat higher metamorphic grade upstream (to the north).

STOP 1-4: Loch Tulla (Ranoch Moor)
This and Stop 1-5 are typical of the treeless, rainy, and wind-swept nature of the highlands. A few plots of reforestation do exist. Reforestation is more abundant along highway A9 in the eastern part of the terrane.

The rock here is tan weathering, very fine-grained quartzite. It contains epidote, a trace of magnetite, and numerous folded quartz veins. Quartzites like this one outline map-scale folds in this portion of the otherwise pelitic Dalradian Supergroup.

STOP 1-5: Glen Coe
The Glen Coe igneous complex consist of andesitic sills (406 Ma), felsic volcaniclastic rocks, and granite intruded along ring faults. The andesite and felsic volcanic rocks are late Silurian (part of the PORSV mentioned in the section II). This stop is at new road construction along the river.

The rock here is porphyritic, medium-grained granite with a preferred orientation (foliation) of the feldspars. The following characteristics suggest that the rock is somewhat hydrothermally altered: 1) some of the feldspars are irregularly pink; 2) biotite (< 3mm) is not fresh and some is composed of < 0.5 mm aggregates, and 3) disseminated magnetite and very fine-grained pyrite occur in trace amounts. This kind or alteration is common in porphyry copper deposits.

STOP 1-6: Ballachulish Slate Quarry
This large quarry operated from 1693 to 1955. Slate from this and surrounding quarries was used throughout Great Britain and was shipped at least as far Iceland.

The quarry is dominated by black slate with a steeply dipping cleavage. Quartzite (Stop 1-4) and limestone occur nearby, but not in the quarry. One pod of tan weathering dolomite < 0.5 m thick occurs. Bedding is discontinuously outlined by sparse relict graded beds and by white minerals subparallel to the cleavage (**Fig. 2**). If the white minerals were abundant, the rock would have been worthless). Kink bands (a second cleavage) are minor, and quartz veins (**Fig. 2**) are rare. A meter-thick uncleaved greenstone (metabasalt) dike and rare quartz veins cut the slate (Figure 1); they would have been discarded as waste.

STOP 1-7: Eilean Donan Castle

On A67 a few hundred meters east of the Eilean Donan Castle (**Fig. 3**) are moderately dipping serpentinized pyroxenite and a coarse-grained quartz and feldspar gneiss (metaalaskite). The pyroxenite is several meters thick and poorly foliated. The alaskite is well foliat4ed and folded. Presumably these are Lewisian (Archean) rocks. The pyroxenite may mark a fault or be a tectonic slice in the alaskitic gneiss.

Figure 2. *Left: quartz vein cutting slate in the Ballachulish quarry, Stop 1-6. Right: Greenstone dike cutting slate in the Ballachulish quarry, Stop 1-6. Note that the slate is cleaved, but the dike is not. White minerals in the slate mark original bedding. The circular black objects in groups of four are drill holes about 2.5 cm in diameter. Ray Redd photos.*

Figure 3. *Eilean Donan Castle at Stop 1-7.*

DAY 2—JUNE 22: ISLE OF SKYE— NORTH SKYE LOOP

By Marcia Knadle and Shari Silverman

This day started out with a trip over the Skye Bridge from Kyle of Lochalsh to Kyleakin on the Isle of Skye. First, we were introduced to the Skye Cuillin, featuring a gabbroic intrusion, the core of a large basaltic volcano (the "Black Cuillin"), and large granitic intrusions (the "Red Cuillin") both if which formed around 56-60 ma. Our guide told us that the granites were emplaced first and that the basalts erupted about 2 or 3 million years later. Other sources (Peter Toghill's *The Geology of Britain* and the Bell and Williamson article in *The Geology of Scotland*, edited by Nigel Trewin, as well as Kathryn Goodenough's field guide from the AWG trip in 2008) say that the basalts erupted first, starting around 59 ma, and that the granites intruded the basalt flow pile and underlying Jurassic, Paleozoic and Proterozoic (Torridonian) sediments and Archaean Lewisian basement 3 to 4 million years later. The Black Cuillin was one of a line of volcanic centers running north-south through Britain from the north end of the Hebrides to the east coast of Northern Ireland. Collectively, these volcanoes spread large quantities of basaltic sills and plateau lavas across the Hebrides and Northern Ireland, collectively forming a Large Igneous Province (LIP), thought to originally comprise a volume of basaltic lavas on par with the Deccan Traps. The volcanos and intrusions were associated with the crustal thinning and eventual rifting leading to the opening of the Atlantic Ocean at around 55 ma, which occurred some 200 miles to the west. The granites presumably formed through melting of the underlying Lewisian Gneiss and Torredonian sandstones. The rest of the day, we drove a northern loop around the Trottenish Peninsula of Skye, looking at large sills and lava flows, which were deposited on Jurassic shallow marine and fluvial sediments, typically observable along the strandline. We also observed the Quiraing, large mass wasting formations of the basalts near the north end of Skye, which have been sliding in large rotational blocks along the underlying Jurassic mudstones since the Quaternary.

STOP 2-1: Road Cut above Loch Ainort
Location: This stop is located on the A87 NW of the head of Loch Ainort, and north of the waterfall that descends from Brusch nam Bo. To view it, park on the SE side of the road in a pullout, ascend a short hill on the SE side of the throughcut, then face the NE side of the throughcut. That is the road cut. Beinn Dearg Mhor is the peak that is behind the cut to the NE.

<u>Road Cut</u>: This features examples of both the gabbroic intrusions ("Black Cuillin") and large granitic intrusions ("Red Cuillin")

Light Rocks: Granitic "Red Cuillin".
Dark Rock: Basalt diabase: "Black Cuillin".

<u>Additional Features</u>: ***Glacial Landscape*** to the SW and upslope from the road cut is a cirque. It flows from a "Red Cuillin" formation.

STOP 2-2: Sligachan Quarry
<u>Location:</u> Further north along A87, the Sligachan Quarry is located on the SE side of both A87 and Loch Sligachan. It is downslope and N-NW of Sgurr Mhair.

<u>Quarry:</u> Within the "Black Cuillin", basalt dikes cut into other basalt dikes and gabbros, and possibly diorite. Some dikes are porphyritic (rocks with large crystals [phenocrysts]). Very large feldspar phenocrysts are visible in some of these rocks. Some are vesicular (with holes formed from gas bubbles) or amygdaloidal (vesicular with secondary minerals within vugs [holes]). Secondary minerals observed at the quarry include calcites and quartz, but zeolites may also be present. Glassy inclusions caused by rapid cooling were also noted.

STOP 2-3: Old Man of Storr
Location: Upslope from Bearreraig Bay and Loch Leathan. Visible from a distance from both north and south. We pulled off on the side of the A855 to the south by Loch Leathan for a photograph.

Landform: As the land rose, the slope failed and slid rotationally, tilting the basalt backwards. The rotating blocks included Jurassic slates, diabase sills, and claystone. The numerous failure surfaces resulted in multiple landslides. These caused the hummocky nature of the slope.

STOP 2-4: Lealt
Location: North of the Old Man of Storr (which is visible to the south) is Lealt and Inver Tote. On the north side of the Lealt River along A855 is a large parking area to the east. Pull into that lot. A short trail leads east to the cliffs above Inver Tote. This stop has three areas of interest along the trail.

1). ***Diabase pillars***: see stop 5.

2). ***Diabase Sill Quarry:*** On the left (north) about halfway down the trail is a diabase sill quarry. The rock was used for building stone. In general, this sill's thickness varies between 10 and 40 meters thick.

3). ***Diatomite:*** This location is an overlook with an interpretative sign explaining diatomite. Diatomite is a white, clay-like deposit formed from microscopic siliceous skeletons of diatoms (single-celled aquatic algae). Diatoms live in shallow water. This species was indicative of the warm climate of their environment during the Tertiary.

Diatomite is used for numerous purposes. Mined three miles away at Loch Cuithir, this diatomite was processed in the structures on the shores of Inver Tote below the interpretative sign. It was calcined and ground to be used as stabilizer for dynamite, then shipped to South Africa.

STOP 2-5: Kilt Rock
Location: On the east side of the A855, east of both Loch Mealt and the village of Elishader, is Kilt Rock. Turn into the parking lot for Mealt Falls, which flows off of Kilt Rock and park.

Kilt Rock: Columnar diabase pillars overlie Jurassic sandstone. The diabase shrank while it cooled forming the pillars. The village of Staffin and Staffin Bay are nearby. The word Stafainn comes from the Old Norse for pillars.

From Coach: Quiraing
Location: Landscape around the village of Glashvin and nearby towns: road A855.

Quiraing: The road traverses the contour of an active, massive multiple landslide, like that of the Old Man of Storr stop. The A855 frequently needs repair. The slide is rotational. Jurassic shale is located at its toe and the base of the active failures. Dinosaur tracks were found on the Jurassic sedimentary rocks.

STOP 2-6: Duntulm Castle
Location: Continue along the A855 to its northwestern-most position near Duntulm. There is no parking area. Pull off on a wide side of the road to the closest point of the

castle. Duntulm Castle's remains stand upon a cliff and is visible from the road.

Duntulm Castle:

1. Along the trail to Duntulm Castle is an igneous dike which snakes its way through the Jurassic sediments to the south.

2. Also, in the bay near Duntulm Castle, dinosaur tracks were found in 2015.

3. ***Primary Attraction (Layers in Sill):*** Leave the trail and walk downslope in field to the west side of the castle so that the cliff it upon which it stands is visible.

From other locations, it is known that this diabase sill measures approximately 25 meters thick. The bands of each layer result from olivine (darker mineral) grading up in mass to pyroxene (lighter mineral). Clinopyroxene phenocrysts up to 30 cm thick have been observed.

Layers in such a thin sill are unusual, and suggest multiple intrusive phases from a magma chamber where heavier minerals were settling out and getting re-entrained with each intrusive event. The location is fairly distant from the Black Cuillin, probably over 25 miles, so it's unclear where the magma source was located.

From Coach: Uig (Top of Quiraing)
Uig provides good views of the Quiraing's multiple landslides discussed in between Stops 5 and 6.

DAY 3—JUNE 23: SOUTH ISLE OF SKYE TOUR

By Steve and Linda Grupp

Description
Plockton to Broadford (So. Skye), Torrin, Elgol, Kilchroist, return to Plockton.

Depart Plockton at 09:15, where group stayed prior evening; located near lower elevations of Moine Thrust; shortly after leaving pass through a Scottish croft village; no extensive outcrops due to thick vegetation. Passed Kyle Railway Station, over Skye Bridge onto Isle of Skye and through Broadford toward Elgol.

STOP # / Location / Arrival and Departure Time

STOP 3-1 / North of Teangue along A851 / 10:00/12:00
Stop and walk about 1 mile uphill toward the northwest on a dirt path. Moine Thrust exposed in river bottom. Cambro-Ordivician sediments thrust over Lewisian. Broadford Noteworthy mylonite from Lewisian at contact. Region described as a "Belt of Complexity" or "Garden of Skye." Approx. 2.5 mile hike; interesting note: some of road fill composed of crushed marble quarried near here. Excellent photo of Moine Thrust contact contained in Chris' power point.

Travel to next location passed a working marble quarry near Torrin about 12:20. Also passed Red and Black Cullins to the west. Parts of an igneous complex active between 60-65 mya. The Cullins show definite geomorphological features indicative of glaciation formed during the ice age.

STOP 3-2 / Town of Elgol / 13:45/14:45
Black shale outcrop just at the upper outcrops above the beach are representative of the hydrocarbon "source rock" of Jurassic Age. The bottom of the sequence on the beach is Cambro-Ordivician limestone with the Jurassic sediments sitting above an

unconformity. Also, a Tertiary sill is easily observable on the beach. Excellent photo at Elgol contained in Chris' powerpoint.

STOP 3-3 / Red Cullin / 14:50/14:55
Quick picture stop of Red Cullin and associated glacial features such as sealoch, cirque and arêtes. Red Cullin represents the early silicic igneous activity around 60 mya.

STOP 3-4 / Black Cullin / 15:05/15:10
Another quick photo stop of the Jagged Black Cullin. This represents the later massive mafic eruptions and intrusions up until 65mya. Excellent photo of Black Cullin contained in Chris' power point.

STOP 3-5 / Cill Chroisd / 15:30/17:00
Hike to marble quarry crossed what Chris' described as "the best karstic stuff in Scotland."

Marble quarry--Many 'clints" and "grykes" are readily observable. These carbonate rocks are dolomitic and don't easily effervesce with HCl acid. The rock was used as building stone, headstones and decorative rock. Some ruins of two distinct ages along the hike demonstrate the building applications. Entering the quarry one also enters a zone of "metasomatism", where the typical suite of skarn minerals may be found like marble, wollastonite, olivine, serpentinite and brucite.

This quarry was active for about 30 years around 1900.

Returned to Plockton.

DAY 4—JUNE 24, 2016: PLOCKTON TO INCHNADAMPH

By Jim and Jill Miller

Depart Plockton for Inchnadamph
Take Highway A890 from Balmarcara to Garve

STOP 4-1

- Photo stop at viewpoint above Loch Carron (**Fig. 4**)
- West side of Loch is Torridonian

Figure 4. *Loch Carron looking north. Loch is underlain by Moine Thrust belt.*

sandstone

- Moine Thrust zone occupies the Loch
- East side of Loch (from viewpoint) is formed by Moinian rocks

Drive to north end of highway A890 and turn left (northwest) on highway A835 near Garve, toward Inchnadamph.

Lunch at Ullapool

STOP 4-2

- Photo stop at crest of hill about one mile north of Ullapool
- Fjord at Ullapool is named Loch Broom
- Torridonian sandstone on south side of Loch, dipping at about 30 degrees
- Cross-cutting rills on slope may be a result of Tertiary dikes that weather more rapidly than siliceous sandstone (**Fig. 5**).

STOP 4-3

- Photo stop with view toward the northwest of mountains formed almost entirely by Torridonian sandstone
- Last ice advance did not cover the highest peaks in this area (unlike the Skye region)
- Light-colored capping of Skac Pollaich mountain marks the presence of a basal quartzite of Cambrian age

STOP 4-4

- Knochan Crag interpretive trail (**Fig. 6**)
- This location shows most of the rock units exposed in the Assynt region
  - Cambrian-Ordovician sedimentary rocks
  - Torridonian sandstone

Figure 5. *Torridonian sandstone on south side of Loch Broom, with cross-cutting rills.*

Figure 6. *View toward the west from the summit of the interpretive loop trail. The mountains are formed almost entirely in Torridonian and Cambrian-Ordovician sedimentary rocks. The lake (loch) formed from differential erosion by glacial ice.*

- Base of Moine Thrust is exposed well (**Fig. 7**), with Moinian rocks (1 billion years old) now overlying limestone of Cambrian-Ordovician age on the interpretive loop trail

STOP 4-5

- Arrive at historic Inchnadamph Hotel in Assynt (**Fig. 8**)
- Famous location for geologic mapping of complex geologic terrains and the development of modern geology (**Fig. 9**)

DAY 5—JUNE 25, 2016
INCHNADAMPH AREA

By Kathleen and Rick Goodman

Start walking from the parking lot at Inchnadamph Hotel in the Loch Assynt area, N 58°8’55.32” W 4°58’24”.

Figure 7. *The Moine Thrust surface clearly exposed on the interpretive trail, with Moine rocks overlying Cambrian limestone. Genevieve Kralis for scale.*

Figure 8. *The historic Inchnadamph Hotel in Assynt.*

Figure 9. *Terrain of the Assynt region.*

STOP 5-1: Traligill Cave

Traligill cave walk in the valley of the trolls is about a 4-mile walking trip.

Location of the best karstic scenery in Scotland. Walk up the dolomitic limestone of the Upper Cambrian Eilean Dubh Fm. (Durness Group) passing through several thrust imbricates within the limestone traversing the undistinguishable sole thrust (**Fig. 10**). The dolomite exhibits clints (blocks) and grykes (solution-enhanced fractures) weathering.

About 0.6 miles from the start, there is a shepherd's cottage (Glenbain cottage) where we stand on moraine deposits from the last glaciation. The deposits are kame deposits. Looking northwest across the valley at a recently built mansion that used Cambrian fucoid Ardvreck Fm for the floors in the house but they didn't allow for expansion and the floor cracked and so the house has not received a permit for habitation.

Walk uphill on the Ceum path to the creek bed of the River Traligill. The creek along this path for the next 0.5 mile follows the thrust fault; the creek disappears and emerges via sinkholes.

Spring where creek emerges from the limestone at the thrust plane (a minor thrust) with the dark Cambrian limestone (Ghrudaidh Fm.) in the hanging wall and the light limestone (Eilean Dubh Fm.) in the footwall. Karst sinkholes developed at the fault contact and could have started developing in the early Tertiary. Later the fault contact was covered by till during glaciation but when uncovered later by erosion, it is likely that karstic activity reactivated.

Continue walking up hill about 0.6 mile to the Upper Traligill cave where water flows down into a sinkhole about until it comes out at the Lower Traligill cave. Walk back down to Inchnadamph Hotel for lunch.

Board bus to drive on A837 toward the

Figure 10: *Lower Traligill cave developed at the thrust contact of the limestone and dolomite, where the creek water enters the underground system.*

southeast to where the road crosses the Allt a'Mhuillin stream. Park at the roadside and walk about 100 yards.

STOP 5-2: Allt a'Mhuillan quarry

Borolanite quarry: Borolanite type locality—the rock quarried from this location was only used sometime in 1940s to build a stone bridge about 2 miles away (Seen in Stop 5-3). Excursion 10.6 of the Goodenough & Krabbendam (2011) book describes the borolanite as medium-grained, purple-grey melanite-biotite-pyroxene nepheline-syenites, which are cut by pegmatitic veins with an unusual mineral assemblage of feldspar, nepheline, biotite, melanite, magnetite, titanite, allanite, zeolite, and blue cancrinite. Later shear zones cut all the rock types. The quarry is the type-locality for borolanite (see Wikipedia description at the end of this day's log). Board bus and drive approximately 2 miles to southeast on A837.

STOP 5-3: Stone Bridge

Picture of a rock of borolanite from a stone bridge that was built in the 1940s (**Fig. 11**). The bridge was built over a creek cut into the Moinean schist. Figure 10 shows foliation of phenocrysts of pseudoleucites that are compositionally nepheline-alkali feldspar.

Borolanite is a coarse-grained nepheline syenite containing alkali feldspar, nepheline, melanite and biotite (Mindat, 2017). The term is used locally at the Loch Borralan intrusion in Scotland (using an earlier

Figure 11. *Borolanite used as building stone in bridge. Note white pseudoleucite.*

spelling of the locality), the only silica-undersaturated, ultra-potassic plutonic complex in Britain, and among the most K_2O-rich rocks on Earth (Parsons, 2007).

Drive about 4 miles north northwest on A837 past Ledmore and the intersection of A835.

STOP 5-4: Loch Awe quarry

Quarry in the Cambrian Ardvreck group fucoid beds. Rare trilobites up to 10mm have been found. Field trippers found evidence of burrows, soft sediment deformation, ripple marks, etc. but no trilobites on this day. According to Excursion 16.5 of Goodenough and Krabbendam (2011), the rock is locally metamorphosed.

Drive north on A837 toward Inchnadamph. About 1.5 miles south of Inchnadamph park at the parking area at the side of the road and look up at the cliffs to the northeast.

STOP 5-5: Stronchrubie Cliffs

Near the road the Pipe Rock member and Fucoid Beds crop out. In the cliffs (**Fig. 12**) to the northeast are the dolostones of the Ghrudaidh Formation cut by light grey sills of vogesite. The structural geology is complicated here. According to Excursion 16.6 of Goodenough and Krabbendam (2011) the upper cliffs are Stronchrubie imbricate thrust slices which root into a floor thrust, called the Stronchrubie Thrust. Below the Stronchrubie Thrust lies the Sole thrust at the base of the cliffs.

DAY 6—JUNE 26, 2016
ASSYNT TO CLACHTOLL BEACH

By Steve Evans

Loch Assynt and the Stoer Peninsula South

STOP 6-1: The Little Assynt Estate Nature Reserve

First stop of the day was the Little Assynt Estate, also known as the Leitir Easaidh

Figure 12. *Stronchrubie Cliffs.*

Path. We walked along a graveled path to a small loch with an outhouse powered by the sun and wind. From there we walked to the highest point on the estate, then on to another view point before returning to the bus. The estate consists of 3,000 acres managed by the Assynt Community. The rock consists of Lewisian Gneiss Complex rocks, a well foliated, high grade Archaean metamorphic material originally formed roughly 3,000 Ma. The main purpose of the stop was to introduce the typical topography and landscape formed by the Lewisian rock, one of thin soil, and hummocky topography with a relief of several tens of feet. Also characteristic of the topography was the presence of numerous small lochs, or lochans, which dotted the landscape. Since the area had been over-ridden by glaciation, but was not planed smooth, it was postulated that the landscape was an exhumed topography, originally buried by Torridonian sandstone, which erosion had stripped away. It was said that pockets of sandstone could be found in places.

STOP 6-2: Town of Lochinver

The second stop of the day was in the town of Lochinver. The main purpose of this stop was coffee, and to visit the informational center in the town. The center contained numerous interesting displays, including one showing the extent of glaciation during the last ice advance. According to this display, the ice did not cover the entire area of the Stoer Peninsula.

STOP 6-3: Town of Achmelvich

At Achmelvich we encountered a white sand beach formed of broken shell debris rather than quartz material (**Fig. 13**). Following a break for lunch, we walked up the old Crofters' road to the north. We were told that in the 1980s, a recent resident to the area with a legal background realized that the Crofters had no real rights to the land they occupied. He led a movement that established the right of the Crofters to their land, and regulated the use to which the land could be put by requiring that the land be worked as a Croft by whoever owned the plot. The area contained variations of the Lewisian gneiss separated by major fractures. Research has established that the original rock of the gneiss consisted of Tonalite intrusives. Recent research has suggested that the Lewisian consists of several terranes that have amalgamated, and that the contact zones are zones of weakness. The Lewisian has been intruded by basaltic dikes of the Scourie Dike swarm. The Lewiston package contains a full suite of rocks, parts of which also occur in Greenland and Norway. We climbed the Crofters' road to a high ridge, crossing pockets of fertile land formed by Crofters bringing seaweed up to a sheltered area where they could grow crops. From the ridge top we could get views of the

Figure 13. *Achmelvich beach.*

Torridonian Mountains between passing rain squalls.

STOP 6-4: Town of Clachtoll

Another coastal town on the Stoer Peninsula, with white calcareous sand, covered in excursion 3 of north-west highlands of Scotland guide. The road there passed through typical hummocky topography of the Lewisian, with even more pronounced relief than stop 6.1. Also, a site where the basal unconformity between the Lewisian gneiss and the Torridonian sandstone. After hopping a fence by means of a stair intended for that purpose, we went down to the beach in a cove south of the main town beach. On the way we passed an outcrop of basal Torridonian sandstone with 12 to 18 inch, angular blocks of Lewisian gneiss embedded in it. On the beach was Torridonian unit is termed the Diadaig Formation, and basically buried the Lewisian landscape. The Torridonian was deposited by short, powerful rivers draining mountains in Canada, about 1,000 My ago, for an unconformity spanning roughly 2,000 My. At this stop we also touched on recent discoveries of possible bacteria fossils in rocks around Enard Bay, associated with shocked quartz and ring structures suggestive of an impact crater. The idea is that this may be one of the places life on earth started. On the way back to the bus, we passed a thickly bedded sandstone, one of the other units within the Torridonian Group.

STOP 6-5: Loch Assynt (Pine Island)

Locality 1.1 in excursion 1 of the guide. This stop also shows the contact between the Lewisian and the Torridonian, and the unconformity. We were told that recent geochemical research has suggested the source area in modern western Canada, not eastern Canada as previously believed.

STOP 6-6: Loch Assynt

This stop was to observed the basal Torridonian Sandstone above the unconformity. Leaving the stop, we crossed the Cambrian unconformity.

STOP 6-7: Loch Assynt, Skiag Bridge and intersection with A894

Here we observed the Pipe Rock Member of the Cambrian Ardvreck Formation outcrop at locality 1.10 of the guide. We walked east along the roadside some 500 meters to the next pull-out, and saw the overlying Fucoid Bed Member of the same formation, followed by the Salterella Grit Member, all conformably overlying each other, and all below the thrust belt faults in the stable foreland. Following this stop we returned to the hotel.

DAY 7—JUNE 27, 2016
NORTHERN COAST

By Amy Knudson

STOP 7-1: Double Unconformity

Parking: Lay-by on left with view of Aardvrek Castle

Location: 58.169971, -4.998504

Notes: Look south across the Loch at the large hill with units dipping gently (~10°) to the east (**Fig. 14**). In the foreground along the base of the hill lies the hummocky Lewisian Gneiss basement (3.1-2.8 Ga). On the west end, the arkosic Stoer Group (1.7-1.2 Ga), part of the Torridonian succession, and sometimes referred to as Torridonian sandstone, lie unconformably on the Lewisian. There is a dip slope defining the ridgeline and at a break in slope along this profile another layered unit appears, the Cambrian basal unit of Aardvreck quartzite, also dipping to the east. The quartzite is lying disconformably on top of the Stoer Group. Follow, with your eye, the contact

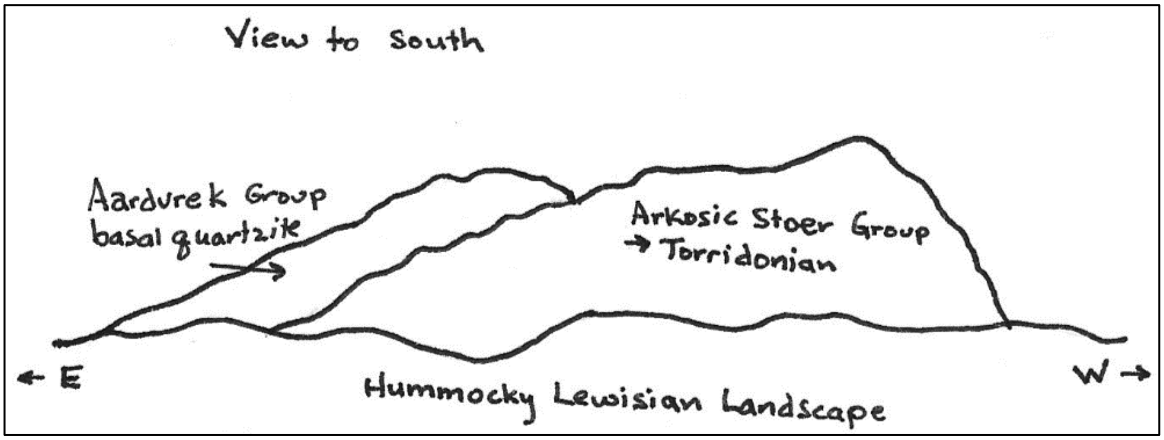


Figure 14. *Sketch of the view across the Loch to the south.*

between the two sedimentary units starting from the subtle V at the top of the ridge along the dip to the east (left) and you will find where the Stoer Group pinches out and Cambrian quartzite lies directly on top of the Lewisian. The protolith for the quartzite is likely a great thickness of eroded Torridonian group, likely measured in kilometers. The Lewisian was likely irregular when these units were emplaced and the hummocks may reflect ancient topography.

STOP 7-2: Cambrian Aardvrek quartzite
Parking: Lay-by with view of Quinag to west and Loch Glencoul to north.
Location: 58.216416, -4.998499
Notes: Looking west towards the peak of Quinag you can observe that it is comprised of a multitude of Torridonian layers. However, where you are standing there is Cambrian Aardvrek Quartzite directly on Lewisian basement with no Torridonian intervening (similar to Stop 1). Walk back up the road about 70 m (230 ft), around the corner for access to the Aardvrek Quartzite underfoot and a view of hummocky Lewisian basement directly below the Quartzite to the east. This is the stable foreland and the thrust(s) have not affected these contacts.

STOP 7-3: Loch Glencoul
Parking: Lay-by at Unapool signpost with view of Loch Glencoul and Informational sign

Location: 58.241459, -5.008033
Notes: View to east and north up the Loch towards the Stack of Glencoul (**Fig. 14**). Here is a view of the Sole Thrust contained wholly within the Lewisian, the Ben More/Glencoul Thrust in Aardvrek Quartzite and Lewisian, and the Moine Thrust between the Lewisian and the Moine at the Stack of Glencoul (see diagram). On the opposite side of the road (dangerous crossing) is fault gouge that is not quite mylonite. The road follows the Sole thrust at this location, which places Lewisian against Lewisian.

STOP 7-4: Multicolored Rock Stop
Parking: Lay-by on left
Location: 58.389975, -5.025301
Notes: View of the complexity of the basement terrain is revealed in a relatively new road-cut. The oldest rock is granulite facies gneiss (no longer Lewisian, but in the Rhiconic Terrrane) at ~ 3 Ga. This is cut by the black, foliated Scourie amphibolite dikes at 2.3 Ga, pink granites in pegmatite dikes (showing some boudinage) intruded around

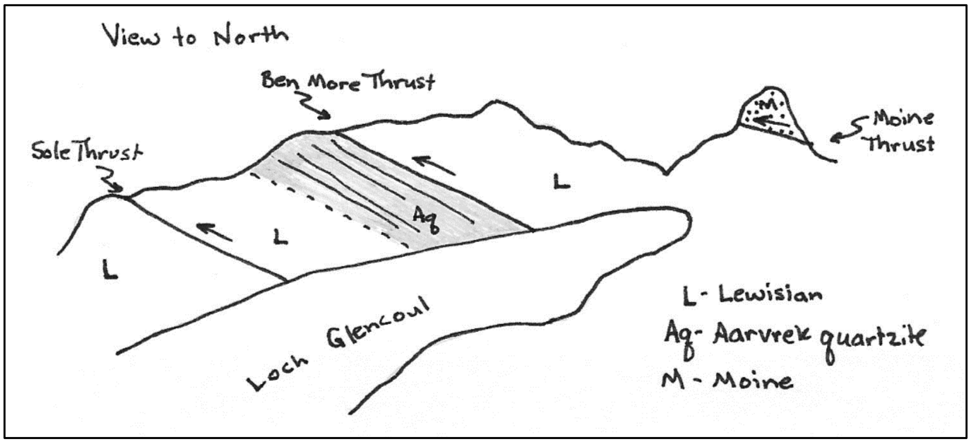


Figure 14. View to the north up the Loch towards Stack of Glencoul.

1.8 Ga, and white Quartz veins (no signs of boudinage), are younger than the last metamorphic event which occurred at 1.74 Ga.

Driving notes
Between stops 4 and 5 the road follows a long, flat-bottomed valley toward the north coast. This glacially formed valley becomes the Kyle of Durness in the northern reaches. Marine sediments have filled in the bottom of the valley well above current sea level due to prior inundation, and further flattened the bottom of the valley.

STOP 7-5: Smoo Cave
Parking: Parking lot specifically for access to Smoo Cave on left side.
Location: 58.56346, -4.721262
Notes: Massive cavern in the Durness limestone of Cambrian-Ordovician times. This limestone occurs in a thin band along the coast, surrounded by impermeable quartzite and gneiss. The river disappears into a hole, which is viewable from a walkway on the opposite side of the road. The river waterfall can be viewed from within the cave. The cave was created as both a fresh water karst feature as well as being enlarged and eroded from the ocean inlet. If you complete the walk along the path to the east, there is a lovely viewpoint near the northernmost point of Scotland off the main access path through a gate into pastureland.

STOP 7-6: Scourie Dikes
Parking: At end of side road near cemetery.
Location: 58.351721, -5.16496
Notes: Type locality for Scourie Dikes from 2.3 Ga. Some of these amphibolite dikes can be seen across the loch as dark islands, if the tide is low you can access the dikes in this location.

STOP 7-7: Unapool Rock Stop - Museum
Parking: along the road
Location: 54.248015, -5.005408
Notes: A museum with gift shop and café has some interesting video showing a GIS model of the landscape and a fly-through animation of some local landscape features you should recognize from your travels. Rocks and information on the local area are available for viewing.

DAY 8—JUNE 28, 2016
ASSYNT TO DUNBAR

By Donn Charnley and Corinne Waters

This day was one mainly devoted to travel. Route 835 from Assynt to Dunbar through Elphin, Inverness and Edinburgh.

Much of the bedrock we traveled over in the morning is Upper Cambrian sheared limestones. We crossed the Moine Thrust belt (once more) last seen at Knockin Rock. Lush vegetation here due to the limestone bedrock.

STOP 8-1: Ullapool
Small hydropower facility here. Loch Broom on right, Loch Glascaarnoch on left. Small exposed granitic plutons form a couple of hills here. Drove by Loch Lomaod and Loch Ness.

Inverness
We visited the Glen Ord distillery here. Rich fields of barley abound here.

Now on Route A-9. Cairngorn Mountains, with a ski area. Occasional exposed Devonian granitic plutons, intruded into the Moine Belt rocks, form the higher hills here.

Tea break at Pitlochry
We have passed over the (buried) Highland Boundary fault. We are in Devonian and Carboniferous sediments here, with occasional exposed Pennsylvanian Basalt sill forming the low ridges in the area. These have been eroded by the Quaternary Ice Sheets, which have also left some small drumlins north-south in the area.

STOP 8-2: Perth
Bedrock here is gray sandstones (graywackes?) and oil shales. Coal has been mined here in the past.

Firth of Forth
M-8 Motorway around Edinburgh to Dunbar.

DAY 9—JUNE 29, 2016
DUNBAR TO EDINBURGH
TO SICCAR POINT TO DUNBAR

By Karen Spaulding, Ric Sandri, and Kathleen Goodman

STOP 9-1: Arthur's Seat Volcano in Edinburgh
On our last day, we saw two outcrops used by James Hutton when he developed his Theory of the Earth, as well as the volcanoes and sills that dominate Edinburgh. Hutton, as part of the Enlightenment movement, used these and other sites for his argument for deep time, the rock cycle, and other ideas. This was in conflict with the Neptunists who believed that rocks formed from the crystallization of minerals in the Earth's oceans.

On the drive from Dunbar to Edinburgh, there were various volcanic hills in the distance, the largest being Arthur's Seat in Holyrood Park. The current landscape of the area has been formed by glaciation. The valleys are filled with dry, glacial outwash as the glaciers moved first north to south then west to east to the sea. The small lochs are probably where the glaciers eroded the softer rocks and left depressions.

Arthur's Seat, a Carboniferous volcano, and other Devonian volcanics are located in a valley bounded by faults that trend NE-SW, the Colinton Fault to the west and the Pentland Fault to the east. To the south of Arthur's Seat are Blackford Hill, the Braid Hills, and the Pentland Hills, all Devonian.

Prior to the Carboniferous volcanism, the area was covered by the Cementstone Group sediments, formed in the Lower Carboniferous. The rocks include a marine limestone, freshwater sandstones, shales and a soil layer and coal seam, indicating vegetation and a shallow water environment.

There are 13 lava flows in the area. Holyrood Castle sits on the remnants of Lava 1 (Castle Rock), which is to the northwest of the volcano. Lavas 2 and 4 were erupted from the Lion's Head and Lava 3 from an area between the Haunch and Castle Rock. The remaining flows erupted from the Lion's Haunch Vent. After the end of the eruptions, the volcano was buried by sediments and the Salisbury Craig sills were intruded. The entire area was tilted to the east and later erosion and glaciation exposed the rocks.

We walked trails on two large features, Arthur's Seat volcano (with the Lion's Head area and the Lion's Haunch) and the Salisbury Craigs. Our first stop was at Samson's Ribs, on the south side of the Lion's Haunch. There are columnar basaltic ash and tuffs, some with E-W glacial striations. Below the columns are vent agglomerates. We then walked west to the Salisbury Craigs. Along the way Chris pointed out Duddington Loch and North Barrick (???) a volcanic plug to the east in the sea.

The Salisbury Craigs are doleritic intrusions. At one site, Hutton's Section, late basalt flows overlay Carboniferous sandstones. Hutton used this site to illustrate that there are 2 kinds of rocks, sedimentary and igneous, and that intrusions are younger than the surrounding rock. Further along the walk we passed a quarry which supplied building stones and curb rocks for the city, and Hutton's Rock, a piece of rock with a hematite vein that was left unquarried.
Looking down from the walk is St. Leonards Craig, a sill that is now a low line of hills south of the Salisbury Craigs. Before heading down to street level, we passed the Cat Nick, another site showing relative age with sandstones cut by the Salisbury Craig and both cut by the Cat Nick intrusion.

The group crossed to the Scottish Parliament building which is faced with marble from the Ledaig borolanite quarry near Inchnadamph (see Day 5).

STOP 9-2: Siccar Point
Drive east on A199 out of Edinburgh until it connects with highway A1. Go past Cocksburnpath to the junction with A1107 (about 35 miles east of Edinburgh). From the junction, follow the road about 0.5 mile to a parking area on the north side of the road where you will find a marker sign for Siccar Point. Follow the walking path depicted on the sign to the northeast about 0.5 mile to a second information sign in the upper headlands overlooking Siccar Point.

Siccar Point is the iconic outcrop that gave James Hutton in 1788 the final proof that geologic history was much longer than the few thousand years accepted at the time (**Fig. 15**). His friend, John Playfair, who accompanied him to the site wrote later, "The mind seemed to grow giddy by looking so far into the abyss of time." The outcrop is a textbook example of an angular unconformity with Lower Silurian graywacke at a nearly vertical angle overlain by the low dipping Upper Devonian or Lower Carboniferous Old Red Sandstone. The angular unconformity represents 55 million years of uplift and erosion. It is considered by many to be the most significant geological site in the world.

Figure 15. *The angular unconformity and Siccar Point. Photo by Donn Charnley.*

APPENDIX A:
ADDITIONAL FIGURES

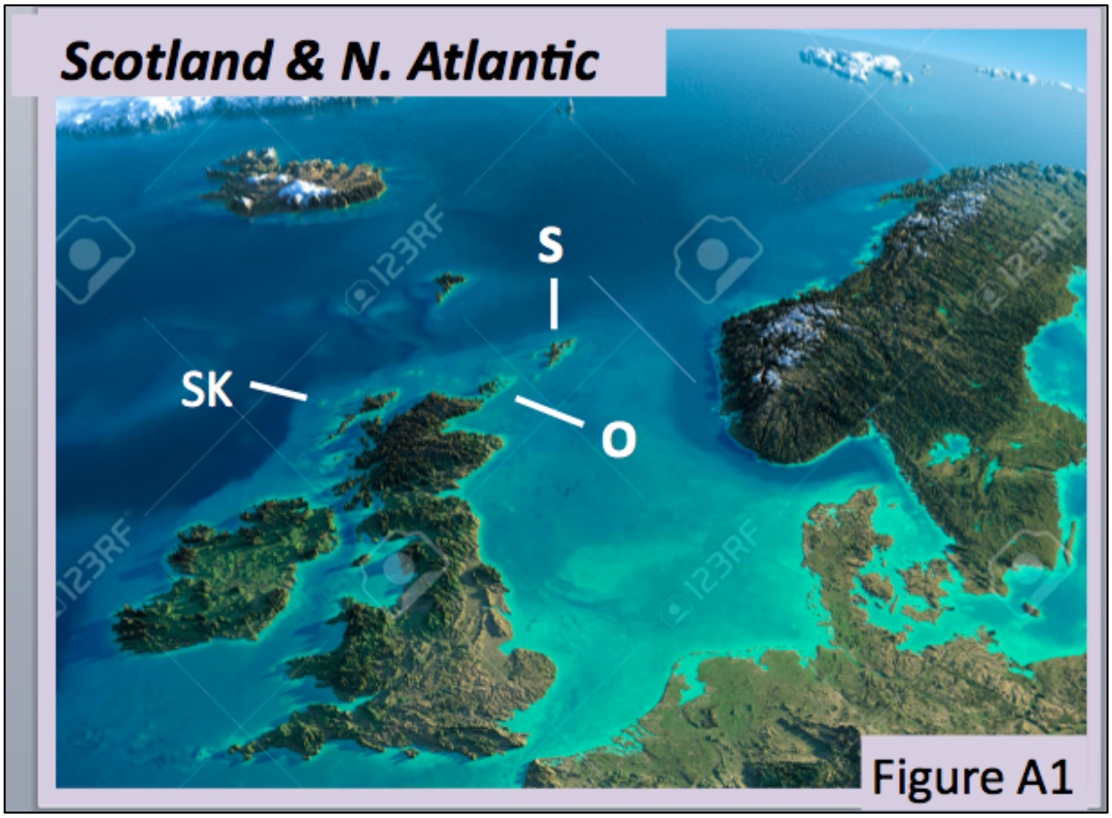


Figure A1

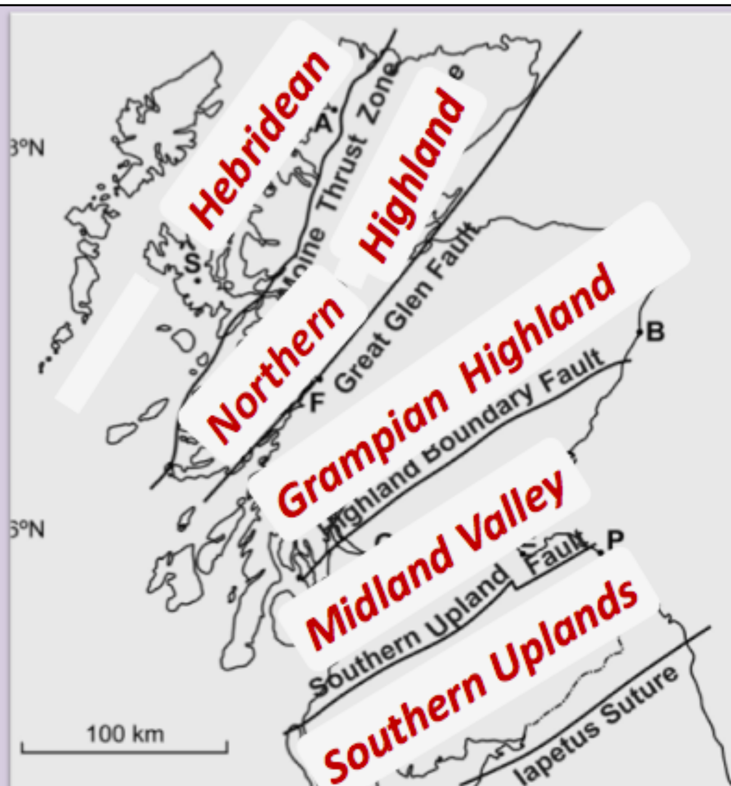


Figure A2
5
Terranes
of
Scotland
after Trewin and Rollin, 2002, Fig. 1-3

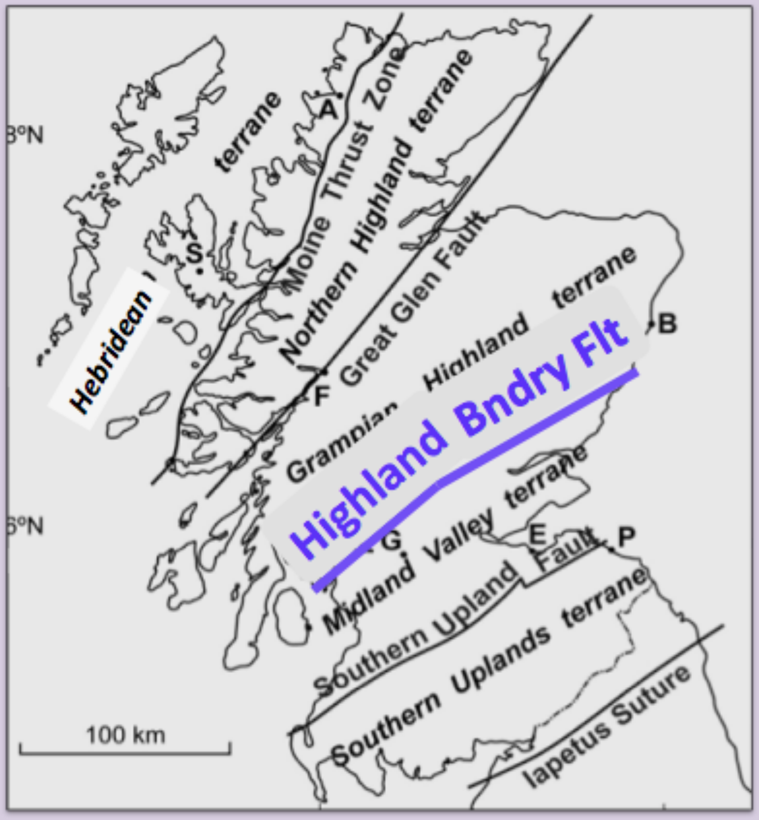


Figure A3

Highlands

Sil. to Archean
Rugged
1749 English
agrarian
tourism

Lowlands

Perm. to Sil.
hilly to flat
industrial
commercial

Metamorphic Zones & Index Minerals Of Scotland

Source: Google via Imperial College London

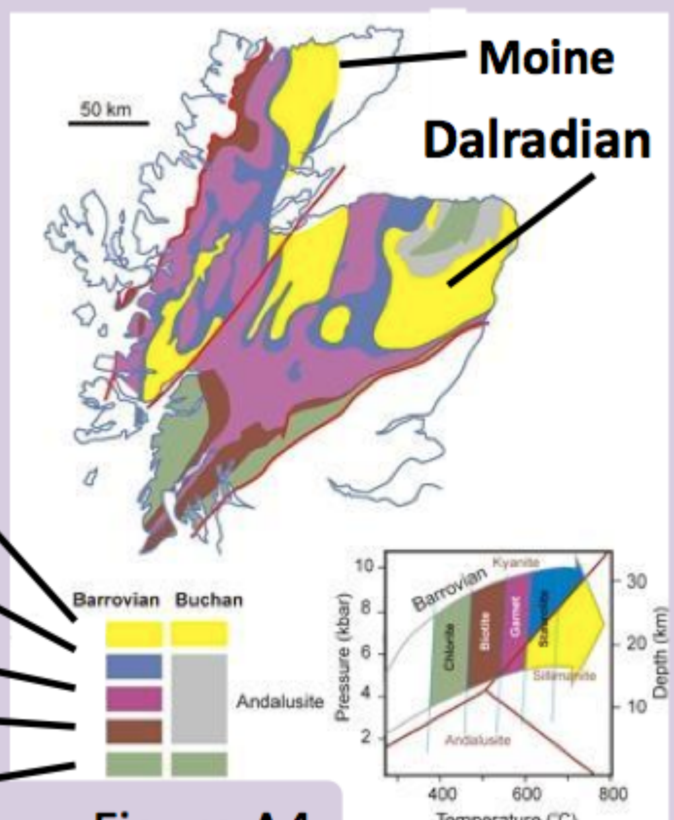


Figure A4

Figure A5

Moine Thrust

after Trewin and Rollin, 2002, Fig. 1-3

area of Fig. A6

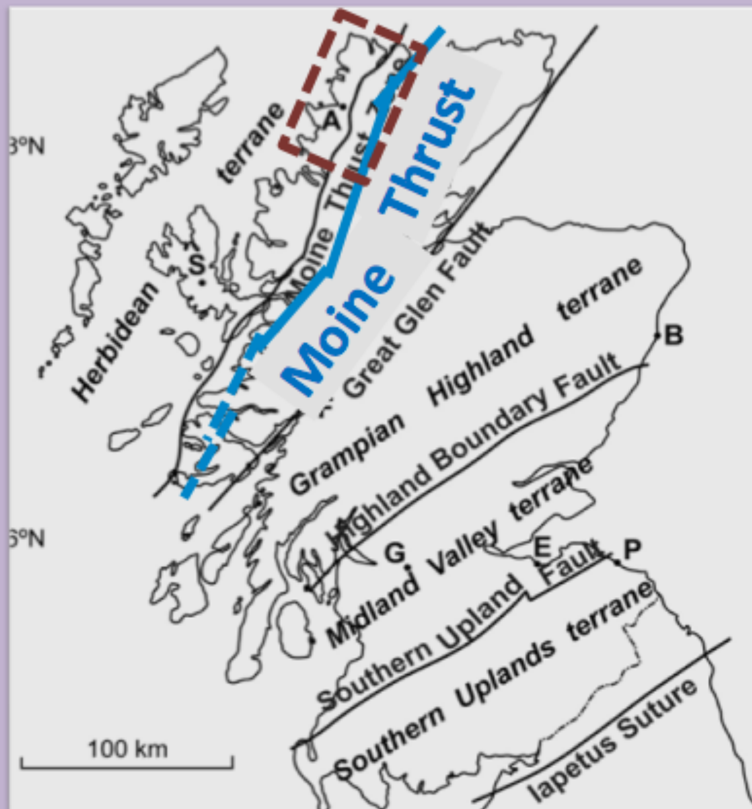


Figure A6

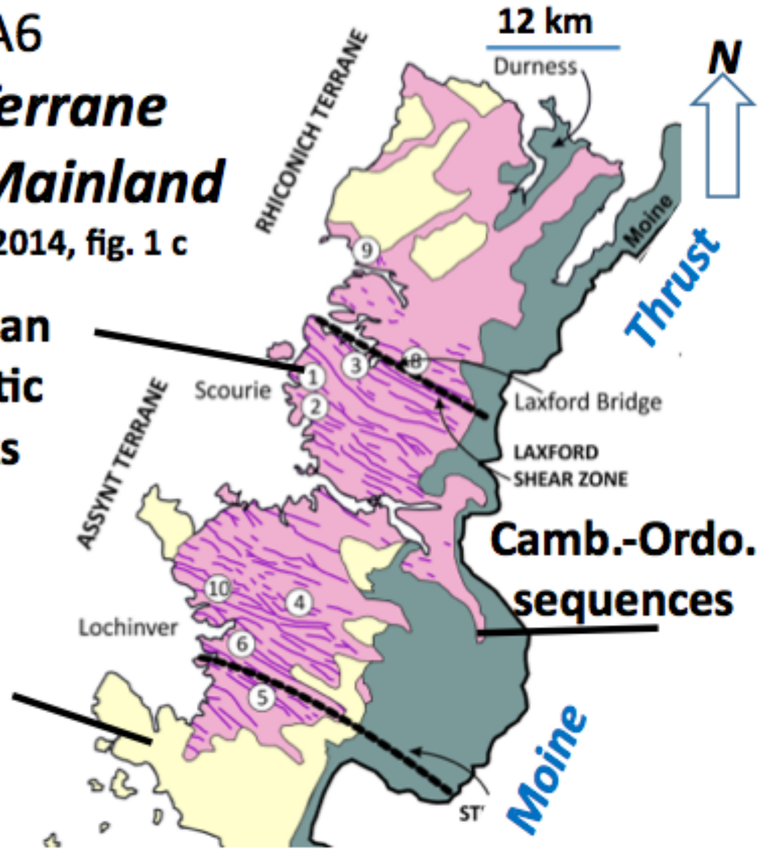
Hebridian Terrane

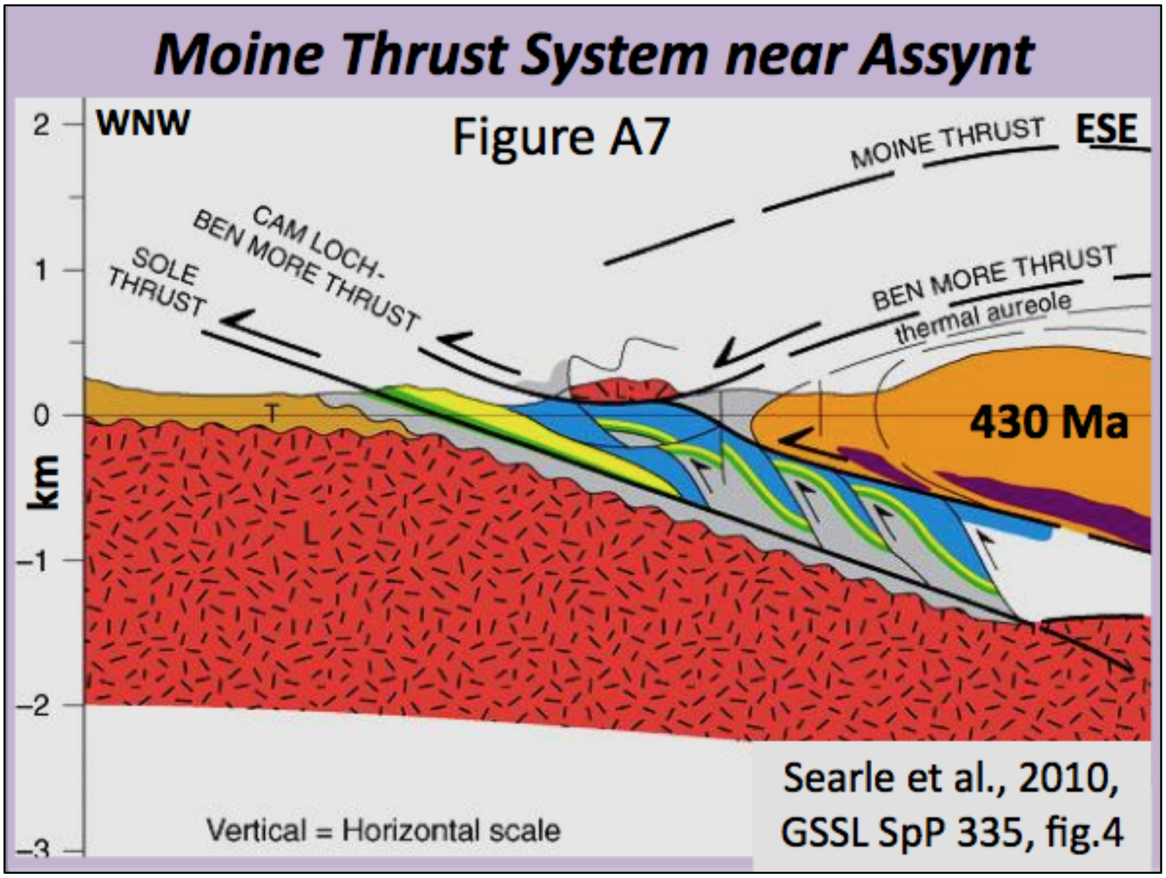
NW Scottish Mainland

after Hughes et al., 2014, fig. 1 c

Archean granitic rocks

2 Proterozoic red sequences




Moine Thrust System near Assynt
WNW
Figure A7
MOINE THRUST
ESE
CAM LOCH-
BEN MORE THRUST
SOLE
THRUST
BEN MORE THRUST
thermal aureole
430 Ma
km
2
1
0
−1
−2
−3
Vertical = Horizontal scale
Searle et al., 2010,
GSSL SpP 335, fig.4

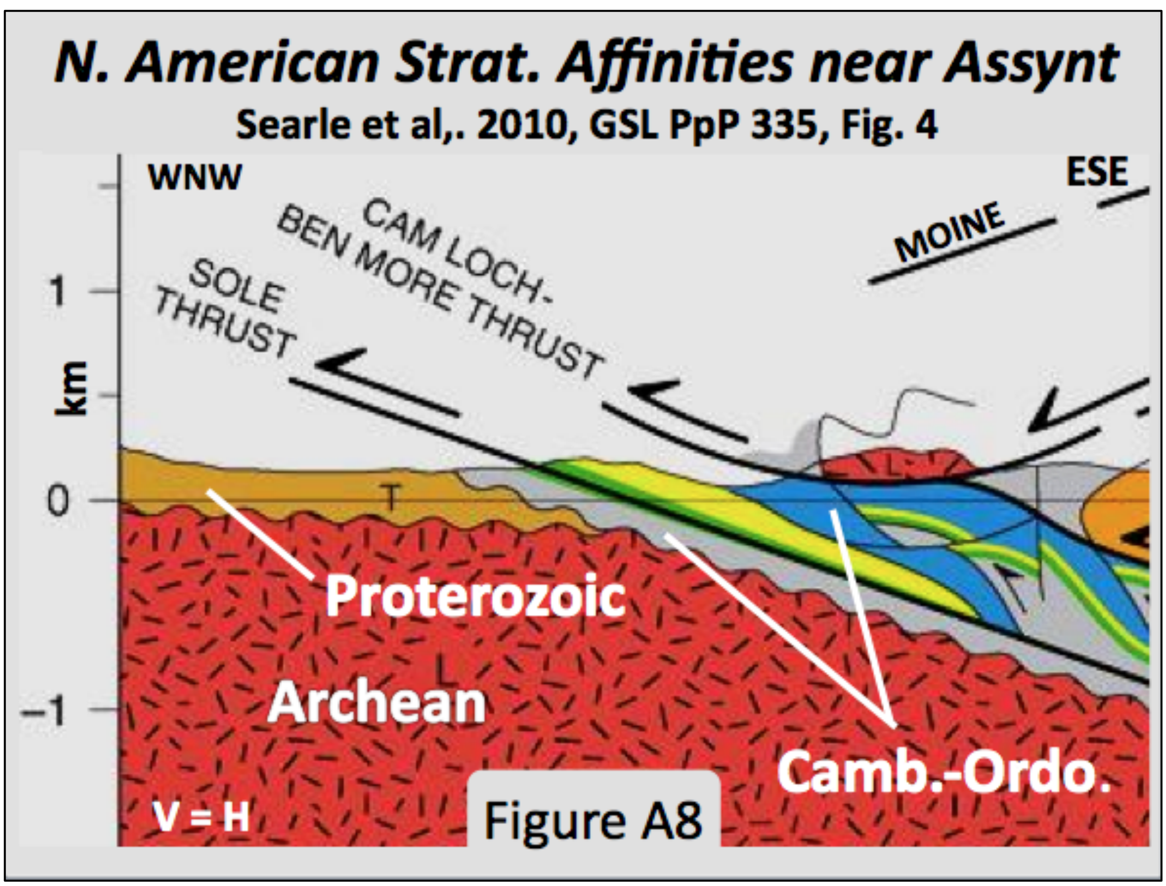

N. American Strat. Affinities near Assynt
Searle et al,. 2010, GSL PpP 335, Fig. 4
WNW
ESE
CAM LOCH-
BEN MORE THRUST
SOLE
THRUST
MOINE
km
1
0
−1
Proterozoic
Archean
Camb.-Ordo.
V = H
Figure A8

Figure A9
Pre-Iapetus Configuration

but note omission of Cambrian & Ordovician UBS

after Hughes et al., 2014, Precam. Res., v. 250, fig. 1c

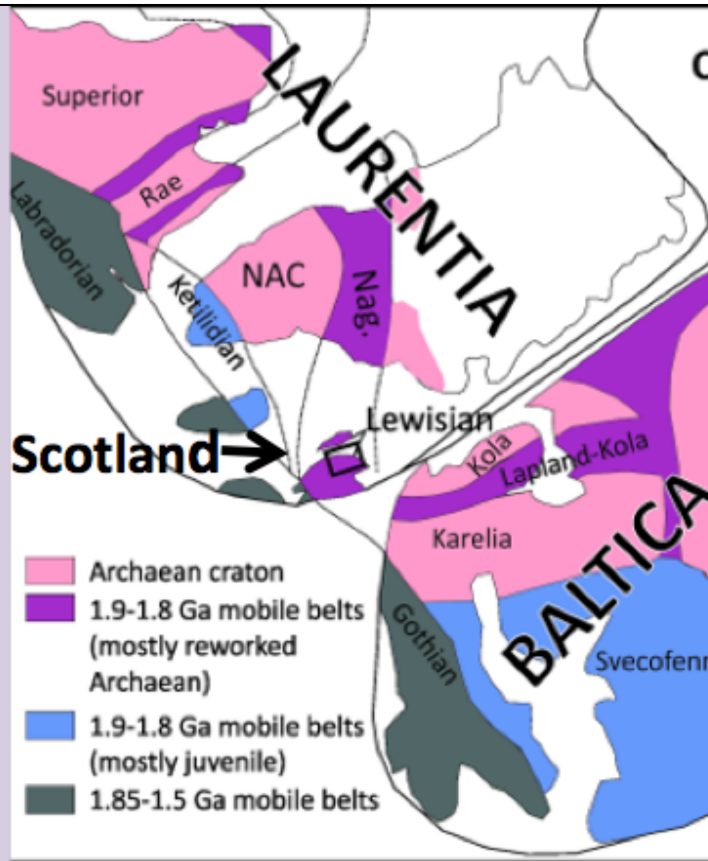


Figure A10
Silurian Granitic Plutons

B = Balla-chulish
BN = Ben Nevis
GC = Glencoe

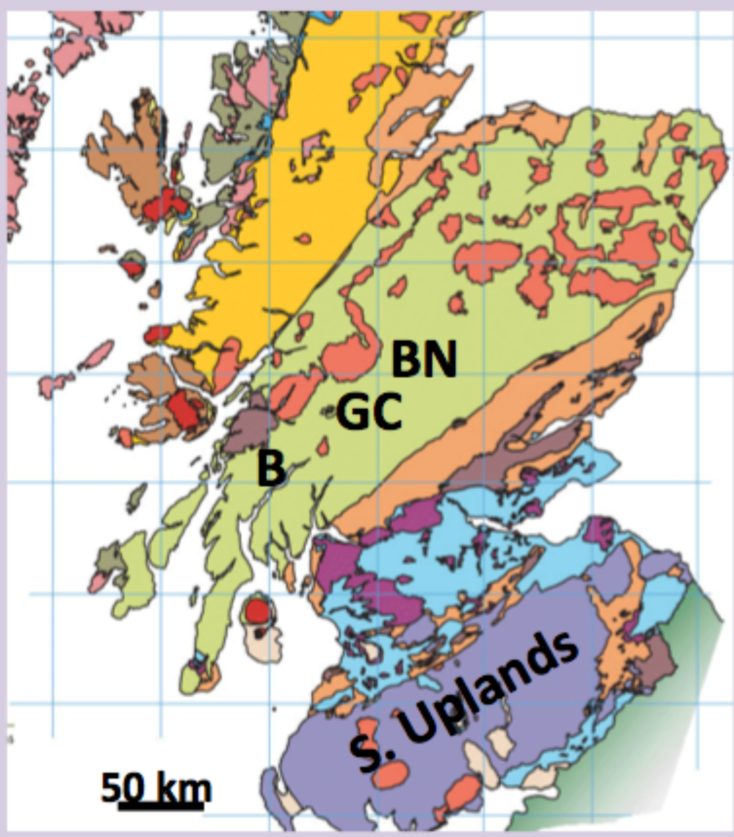


Figure A11

Siccar Point

&

5

Terranes of Scotland

after Trewin and Rollin, 2002, Fig. 1-3

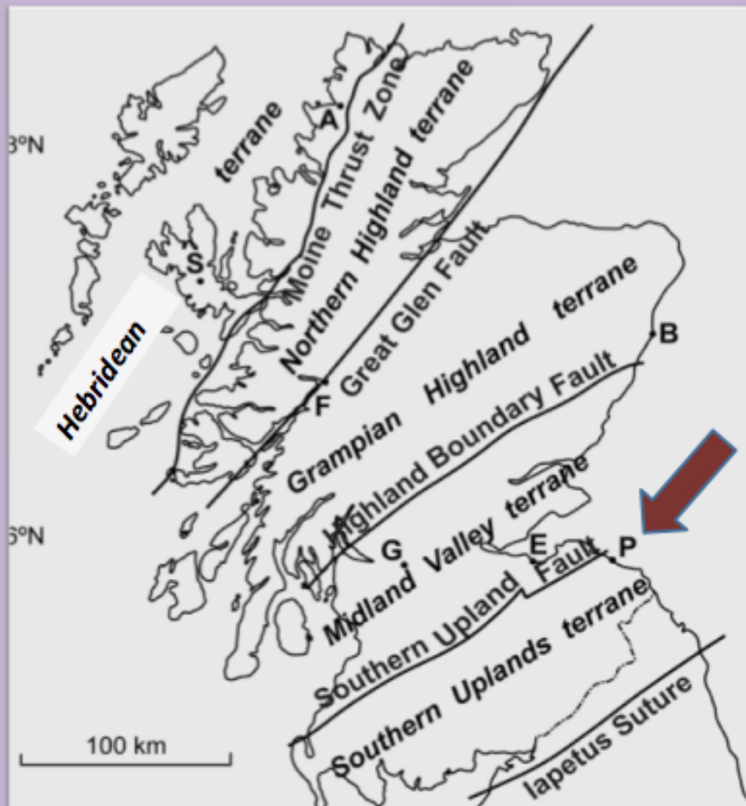
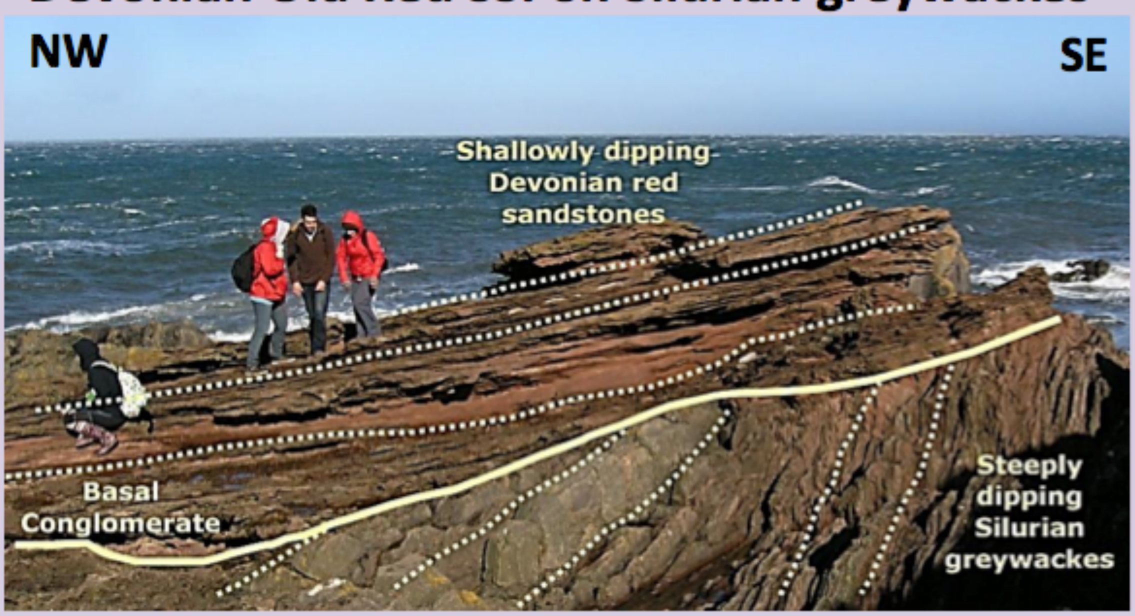


Figure A12

Siccar Pt, the Caledonian Unconformity

Devonian Old Red SS. on Silurian greywackes



Source: Google

Figure A13

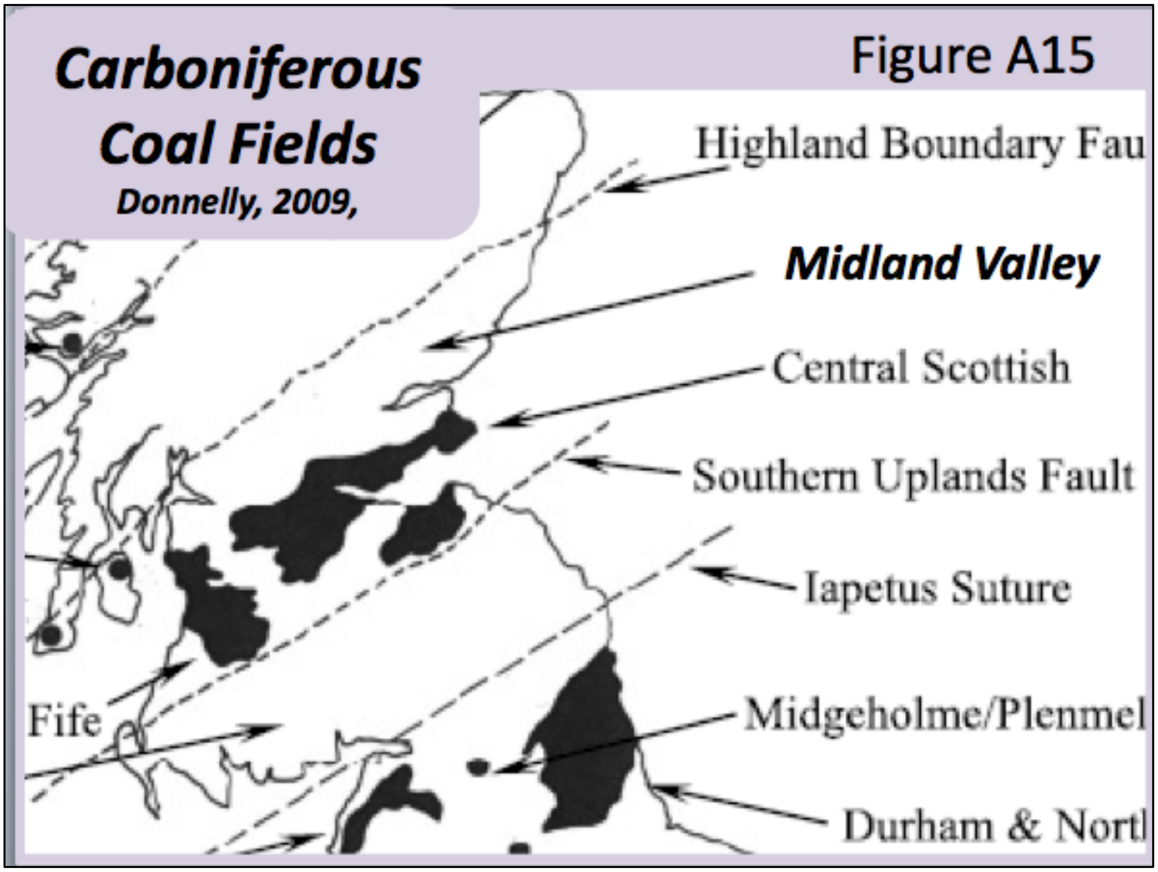
Caledonides

Sources:
Google &
Waldron, et al., 2014, JGSL, v. 171, p. 555-569, fig . 1A

Caledonian of Scotland vs. Sevier NW USA

	Scotland	NW USA
Later "basins"	Old Red Ss.	Challis UBS
Strike-slip faults	NE, sinistral,	N & NW, dextral
Late plutons	Ben Nevis, et al.	Boulder, & in WA
Late volcanics	South. Uplands	Elkhorn Mtn., MT
Foreland basin	removed ?	Jur. to Paleocene
Meta. facies	grn. to amphb.	grn. to amphb
Thrust duplexes	Mcine, to NW	Lewis, to NE
Miogeocline	Neoproto.- Sil.	Mesoproto.-Cret.

Figure A14


Carboniferous
Coal Fields
Donnelly, 2009,
Figure A15
Highland Boundary Fau
Midland Valley
Central Scottish
Southern Uplands Fault
Iapetus Suture
Fife
Midgeholme/Plenmel
Durham & Nortl

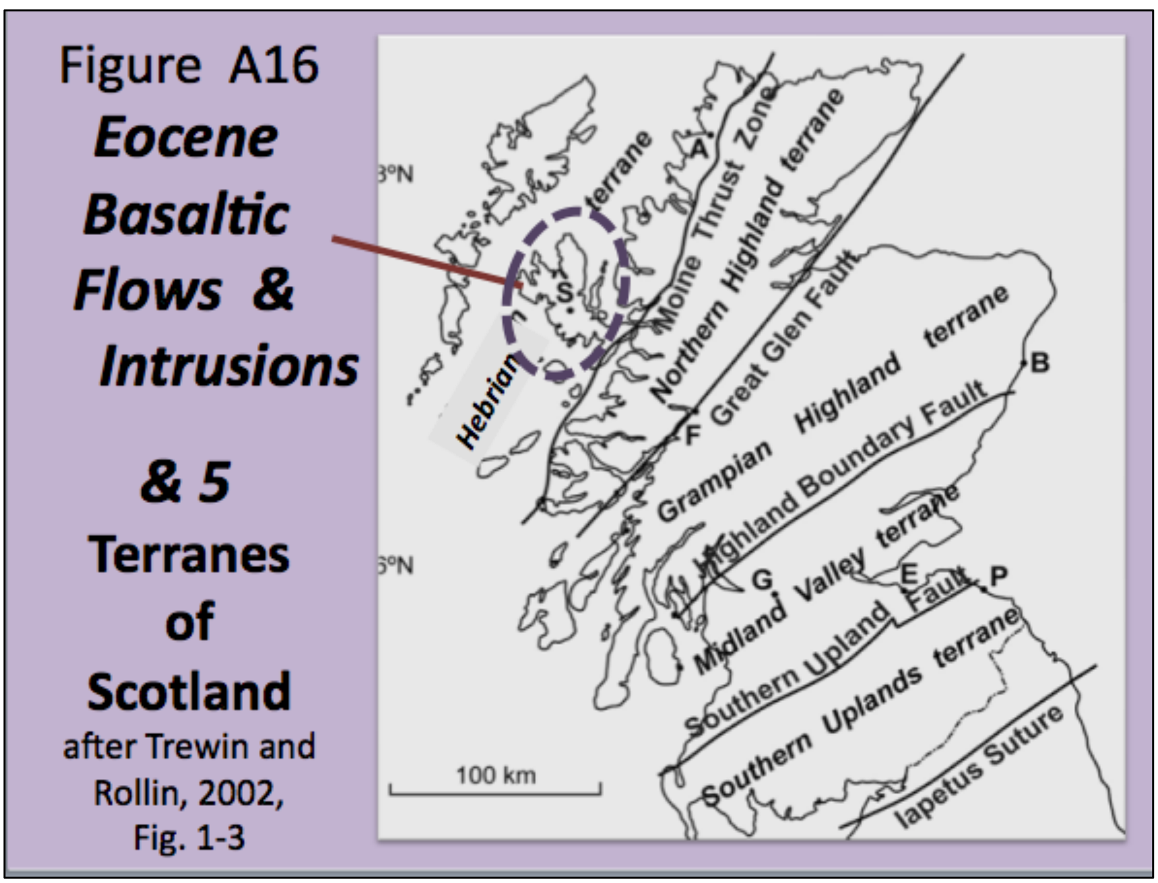


Figure A16
Eocene
Basaltic
Flows &
Intrusions
& 5
Terranes
of
Scotland
after Trewin and
Rollin, 2002,
Fig. 1-3
Hebrian
terrane
S
A
Moine Thrust Zone
Northern Highland terrane
Great Glen Fault
F
Grampian Highland terrane
B
Highland Boundary Fault
Midland Valley terrane
G
E
P
Southern Upland Fault
Southern Uplands terrane
Iapetus Suture
100 km

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