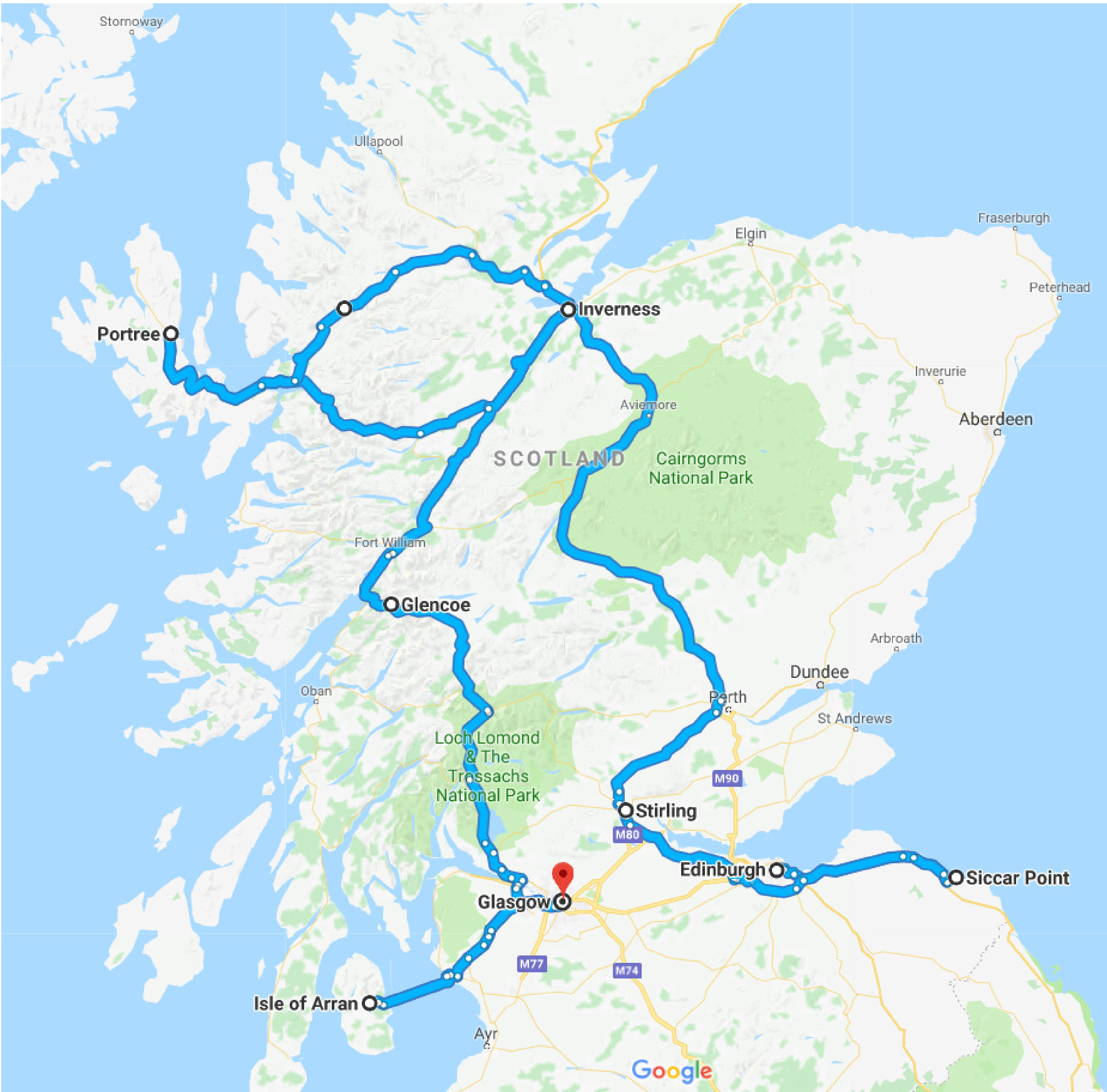
# SPRING BREAK TRIP 2018

UNIVERSITY OF PITTSBURGH AT JOHNSTOWN
DEPARTMENT OF ENERGY AND EARTH RESOURCES

# SCOTLAND!!


Stornoway
Ullapool
Fraserburgh
Elgin
Peterhead
Portree
Inverness
Inverurie
Aviemore
Aberdeen
SCOTLAND
Cairngorms National Park
Fort William
Glencoe
Arbroath
Dundee
Oban
Perth
St Andrews
Loch Lomond & The Trossachs National Park
M90
Stirling
M80
Edinburgh
Siccar Point
Glasgow
M77
M74
Isle of Arran
Ayr
Google

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# LOGISTICS AND BASICS

## Flight

| Flight | Departs | Arrives |
|---|---|---|
| British Airways BA0292 | Washington, DC-Dulles (IAD)<br>**10:30 pm** Sat, Mar 3rd | London Heathrow (LHR)<br>**10:40 am** Sun, Mar 4 |
| British Airways BA1484 | London Heathrow (LHR)<br>**1:05 pm** Sun, Mar 4 | Glasgow (GLA)<br>**2:30 pm** Sun, Mar 4 |
| Duration: 11 hours 00 minutes | | |
| British Airways BA1477 | Glasgow (GLA)<br>**8:55 pm** Sun, Mar 11 | London Heathrow (LHR)<br>**10:25 pm** Sun, Mar 11 |
| British Airways BA0217 | London Heathrow (LHR)<br>**11:25 am** Sun, Mar 11 | Washington, DC-Dulles (IAD)<br>**3:50 pm** Sun, Mar 11 |
| Duration: 10 hours 55 minutes | | |

## Scotland Basics

**Emergency Number: 112 or 999**

- *Currency:* Pounds sterling (£) – 'Quid' is often slang for pound
  - 100 pence (p) = 1£
- *Exchange Rate* (as of 12/20/17): 1£ = $1.34 USD or $1 = 0.75 £
- *Tipping:* yeah, you should probably tip, just like 5% less than what you would in the US
- *Time zone:* Greenwich Mean Time (GMT) Zone, 5 hours plus Johnstown
- *Daylight:* In March sunrise occur around 7:00 AM and sunset at about 6:15 PM.
- *Greeting a Scot:* Firm handshake and eye contact (this is pretty much true everywhere)

## March weather and climate

- *Temperature:*
  - *Southern Scotland* - daily highs average around 45°F and lows around 34°F.
  - *Northern Scotland* - daily highs average around 43°F and lows around 33°F.
- *Cloud Cover:* continuous
- *Precipitation:*
  - *Southern Scotland* - 17 days of 30 generally rain in March (~5.6 inches)
  - *Northern Scotland* - 20 days of 30 generally rain in March (~6.3 inches)

### Tides and Daylight

| Day | High | Low | High | Low | High | Sunrise | Sunset |
|---|---|---|---|---|---|---|---|
| **Sun 4** | 4:05 AM GMT / 5.65 m | 9:41 AM GMT / 0.46 m | 4:18 PM GMT / 5.83 m | 10:05 PM GMT / 0.18 m | | 6:56 AM GMT | 5:52 PM GMT |
| **Mon 5** | 4:46 AM GMT / 5.47 m | 10:16 AM GMT / 0.59 m | 4:59 PM GMT / 5.61 m | 10:42 PM GMT / 0.45 m | | 6:54 AM GMT | 5:55 PM GMT |
| **Tue 6** | 5:26 AM GMT / 5.20 m | 10:52 AM GMT / 0.82 m | 5:39 PM GMT / 5.30 m | 11:18 PM GMT / 0.81 m | | 6:51 AM GMT | 5:57 PM GMT |
| **Wed 7** | 6:06 AM GMT / 4.88 m | 11:28 AM GMT / 1.12 m | 6:22 PM GMT / 4.93 m | 11:55 PM GMT / 1.21 m | | 6:49 AM GMT | 5:59 PM GMT |
| **Thu 8** | 6:48 AM GMT / 4.55 m | 12:08 PM GMT / 1.45 m | 7:09 PM GMT / 4.55 m | | | 6:46 AM GMT | 6:01 PM GMT |
| **Fri 9** | | 12:36 AM GMT / 1.62 m | 7:37 AM GMT / 4.26 m | 12:55 PM GMT / 1.79 m | 8:05 PM GMT / 4.23 m | 6:44 AM GMT | 6:03 PM GMT |
| **Sat 10** | | 1:29 AM GMT / 1.99 m | 8:36 AM GMT / 4.04 m | 2:06 PM GMT / 2.07 m | 9:13 PM GMT / 4.01 m | 6:41 AM GMT | 6:05 PM GMT |
| **Sun 11** | | 3:12 AM GMT / 2.23 m | 9:45 AM GMT / 3.97 m | 4:13 PM GMT / 2.10 m | 10:28 PM GMT / 3.98 m | 6:38 AM GMT | 6:07 PM GMT |

## **Scottish Food** (all of these come from Wikipedia)

**Arbroath Smokie** is a type of smoked haddock – a speciality of the town of Arbroath in Angus, Scotland.

**Bannock** is a variety of flat quick bread or any large, round article baked or cooked from grain. When a round bannock is cut into wedges, the wedges are often called scones. However, in Scotland the words bannock and scone are often used interchangeably.

**Bridie** or **Forfar Bridie** is a Scottish meat pastry that originates from Forfar, Scotland. The filling of a bridie consists of minced steak, butter, and beef suet seasoned with salt and pepper. They are similar to pasties, but because they are made without potatoes, are much lighter in texture.

**Black pudding** is a type of blood sausage commonly eaten in Great Britain, Ireland and in other parts of Europe. It is generally made from pork fat or beef suet, pork blood and a relatively high proportion of oatmeal, in some recipes mixed with oat groats and sometimes even barley groats.

**Cock-a-leekie Soup** is a Scottish soup dish consisting of leeks and peppered chicken stock, often thickened with rice, or sometimes barley. The original recipe added prunes during cooking, and traditionalists still garnish with a julienne of prunes. It is called "Scotland's National Soup."

**Clootie Dumpling** a traditional dessert pudding made with flour, breadcrumbs, dried fruit (sultanas and currants), suet, sugar and spice with some milk to bind it, and sometimes golden syrup. Ingredients are mixed well into a dough, then wrapped up in a floured cloth, placed in a large pan of boiling water and simmered for a couple of hours before being lifted out and dried near the fire or in an oven.

**Cranachan** is a traditional Scottish dessert. In modern times it is usually made from a mixture of whipped cream, whisky, honey and fresh raspberries, with toasted oatmeal soaked overnight in a little bit of whisky.

**Cullen Skink** is a thick Scottish soup made of smoked haddock, potatoes and onions. An authentic Cullen skink will use finnan haddie, but it may be prepared with any other undyed smoked haddock.

**Haggis** is a savory pudding containing sheep's pluck (heart, liver, and lungs); minced with onion, oatmeal, suet, spices, and salt, mixed with stock, traditionally encased in the animal's stomach though now often in an artificial casing instead. According to the 2001 English edition of the Larousse Gastronomique: "Although its description is not immediately appealing, haggis has an excellent nutty texture and delicious savoury flavour"

**Langoustine** known variously as the Norway lobster, Dublin Bay prawn, or scampi, is a slim, orange-pink lobster which grows up to 25 cm (10 in) long, and is "the most important commercial crustacean in Europe"

**Lorne Sausage**, also known as square sausage or slice sausage, is a traditional Scottish food usually made from ground meat, rusk and spices. It is commonplace in traditional Scottish breakfasts.

**Mince and tatties** is a popular Scottish dish, consisting of minced beef and mashed potato. It sometimes contains other vegetables or thickening agents. It has had a longtime connection to school dinners, while other chefs have attempted to modernize the dish.

**Oatcake** is a type of flatbread similar to a cracker or biscuit, or in some versions takes the form of a pancake. They are prepared with oatmeal as the primary ingredient, and sometimes include plain or wholemeal flour as well. Oatcakes are cooked on a griddle (girdle in Scots) or baked in an oven.

**Pastie** is a baked pastry made by placing an uncooked filling, typically meat and vegetables, on one half of a flat shortcrust pastry circle, folding the pastry in half to wrap the filling in a semicircle and crimping the curved edge to form a seal before baking.

**Porridge** (also spelled porage, porrige, parritch) is a food made by boiling ground, crushed or chopped starchy plants—typically grain—in water or milk. It is often cooked or served with flavorings such as sugar, honey, syrup, etc. to make a sweet cereal or mixed with spices, vegetables, etc. to make a savoury dish. It is usually served hot in a bowl.

**Scotch Pie** or **Mutton Pie** is a small, double-crust meat pie filled with minced mutton or other meat.

**Scotch broth** is a filling soup, originating in Scotland but now obtainable worldwide. The principal ingredients are usually barley, stewing or braising cuts of lamb, mutton or beef, root vegetables (such as carrots, swedes, or sometimes turnips), and dried pulses (most often split peas and red lentils). Cabbage and leeks are often added shortly before serving to preserve their texture, colour and flavours.

**Shortbread** is a biscuit traditionally made from one part white sugar, two parts butter, and three parts flour. Other ingredients like ground rice or corn flour are sometimes added to alter the texture. Modern recipes also often deviate from the original by splitting the sugar into equal parts granulated and icing sugar and many add a portion of salt.

**Stovies** is a Scottish dish based on potatoes and meat. Recipes and ingredients vary widely, but the dish always contains potatoes, onions, other vegetables, sausages, roast beef, minced beef or other meat. Stovies is thus a dish intended to use left-over food.

**Tablet** (taiblet in Scots) is a medium-hard, sugary confection from Scotland. Tablet is usually made from sugar, condensed milk, and butter, which is boiled to a soft-ball stage and allowed to crystallize. It is often flavored with vanilla or whisky, and sometimes has nut pieces in it. Tablet differs from fudge in that it has a brittle, grainy texture, where fudge is much softer. Well-made tablet is a medium-hard confection, not as soft as fudge, but not as hard as hard candy.

# Scotland Drink

*Non-alcoholic:*

**Irn Bru** is the brand name of a caffeinated orange soda that outsells Coca-Cola and all other competitors within the borders of Scotland. In fact, Irn Bru is so popular it's been called "Scotland's Other National Drink," and is sometimes touted as a morning cure for the hangover caused by imbibing in Scotch whisky the night before. The soft drink debuted in 1901 under the label "Iron Brew"; the phonetic spelling of the name was adopted in 1947.

*Alcoholic:*

**Beer**

*The following list is from: http://www.independent.co.uk/extras/indybest/food-drink/beer-cider-perry/best-scottish-beer-craft-bottled-a7409191.html published on 10 Nov 2016*

1. **Swannay, Old Norway, 8%:** £3 for 330ml
2. **Fyne Ales, Jarl, 3.8%:** £2.60 for 500ml
3. **Windswept, Wolf, 6%:** £3.20 for 500ml
4. **Caledonian Deuchars IPA, 4.4%:** £1.80 for 500ml
5. **BrewDog, Elvis Juice, 6.5%:** £1.65 for 330ml
6. **Harviestoun, Ola Dubh 12, 8%:** £12 for 3 x 330ml
7. **Islay Ales, Dun Hogs Head, 4.4%:** £2.95 for 500ml
8. **Tempest Brewing Co, Elemental, 5.1%:** £1.85 for 330ml,
9. **Williams Bros, Fraoch Heather Ale, 5%:** £1.99 for 500ml
10. **Stewart Brewing, Ka Pai, 5.2%:** £2.70 for 500ml

**Scotch Whisky**

*A more expansive guide for Scotch Whisky is given on page 40*

**Dambuie**

Drambuie is a golden coloured, 40% ABV liqueur made from scotch whisky, honey, herbs and spices. The brand had been owned by the MacKinnon family for a hundred years but was bought by William Grant & Sons in 2014. It has been produced under contract at the Morrison Bowmore Distillers facility at Springburn Bond, Glasgow since 2010. (*from Wikipedia)*

## THINGS YOU SHOULD BRING

You are allowed personal item, one carry one, and one checked bag (not to exceed 51 lbs), anything more than this you will pay for yourself.

*Most Important:*

- Passport
- Driver's License

*Personal Items:*

- Toiletries
- Van/Plane Entertainment (iPod, books, cards, small board games, etc.)
- UK Electrical adaptor (they use different plugs)

*Clothes:*

- Good hiking boots or walking shoes
- Rain jacket (think polyester and gore-tex)
- Rain pants
- Wool socks (good for long days of walking or hikes)
- Sneakers
- Some warm clothes (It will be wet and chilly, count on it)
- Kilts (I'm looking at you Sam…)

*Equipment:*

- Camera and batteries
- Charger(s)
- Field Notebook
- Pencils/Pens
- Water Bottles
- Hand lens

I will likely bring a couple of rock hammers for us to share, so don't worry about that.

***<u>Note:</u>* *The airline limits you to a checked bag (not to exceed 51 lbs), a carry bag, and a personal item. Anything beyond that will be at your own expense, but let's stick with that, since we are not going to have a ton of extra space in the vehicles.***

**BRIEF ITINERARY**

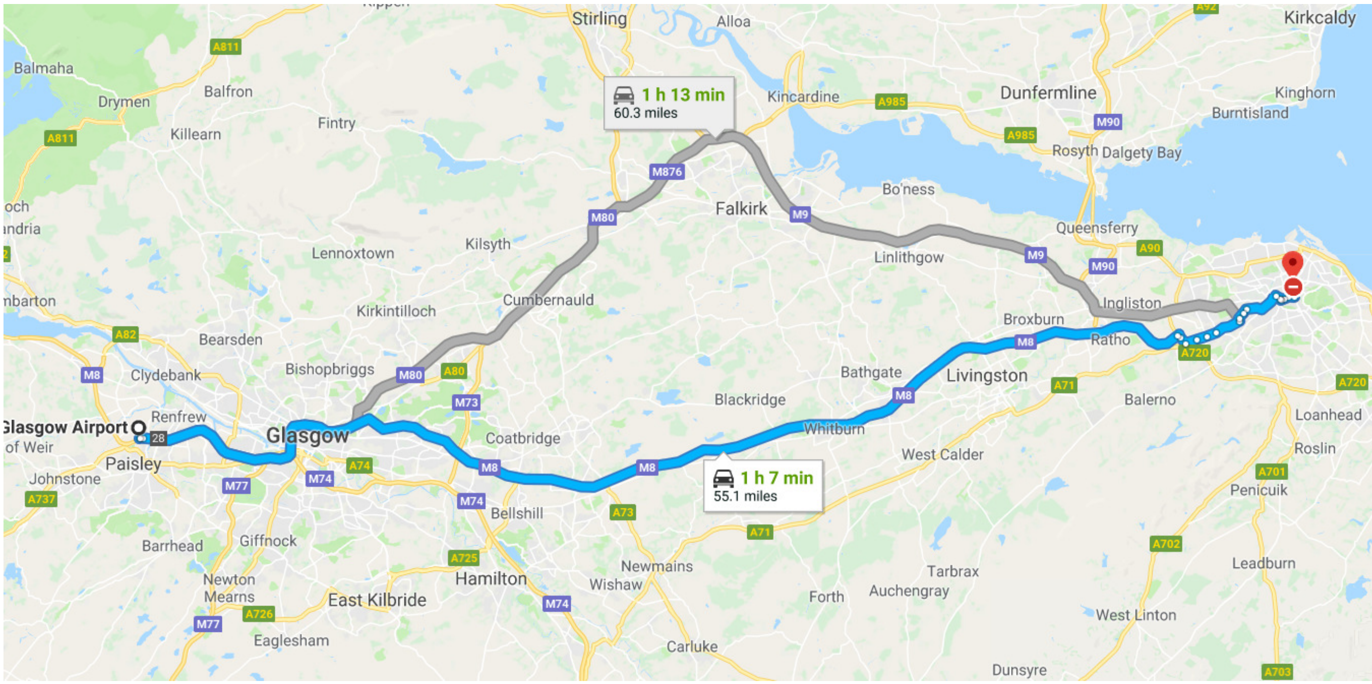
**Day -1: Saturday, March 3rd, 2018 – Board flight**

**5:00PM:** Leave Krebs Parking Lot

**8:30PM:** Arrive at Dulles Airport

**10:30PM:** Depart Washington Dulles (British Air BA0292) to London Heathrow

**Day 1: Sunday, March 4th, 2018 – Arrive in Glasgow – Get to Edinburgh**




**10:40AM:** Arrive in London Heathrow for a layover

**1:05 PM:** Depart London (British Air BA1484) to Glasgow

**2:30 PM:** Arrive in Glasgow, get rental cars, drive to Edinburgh and do some grocery shopping

**Rental Place:** Dollar Rent-a-Car

Car Rental Hall, Terminal Building,

St Andrews Drive, Paisley PA3 2ST, UK

**5:00 PM:** Grocery store

**6:00 PM:** Arrive in Edinburgh, take a nap, and then go out for a group dinner

**Hotel:** Cowgate Tourist Hostel

96 Cowgate

Edinburgh, EH1 2PW

Tel 44 808168 9610

http://www.hostelsinedinburgh.com/

**Day 2: Monday, March 5th, 2018 – Siccar Point, the Lammermuir Hills, and the Coast**

**8:00 AM:** Breakfast in the hostel

**8:30 AM:** Leave Hostel

**9:30 AM:** Arrive at St Abbs Head – Folds fault adjacent to volcanics

**10:30 AM:** Siccar Point – Hutton's Unconformity

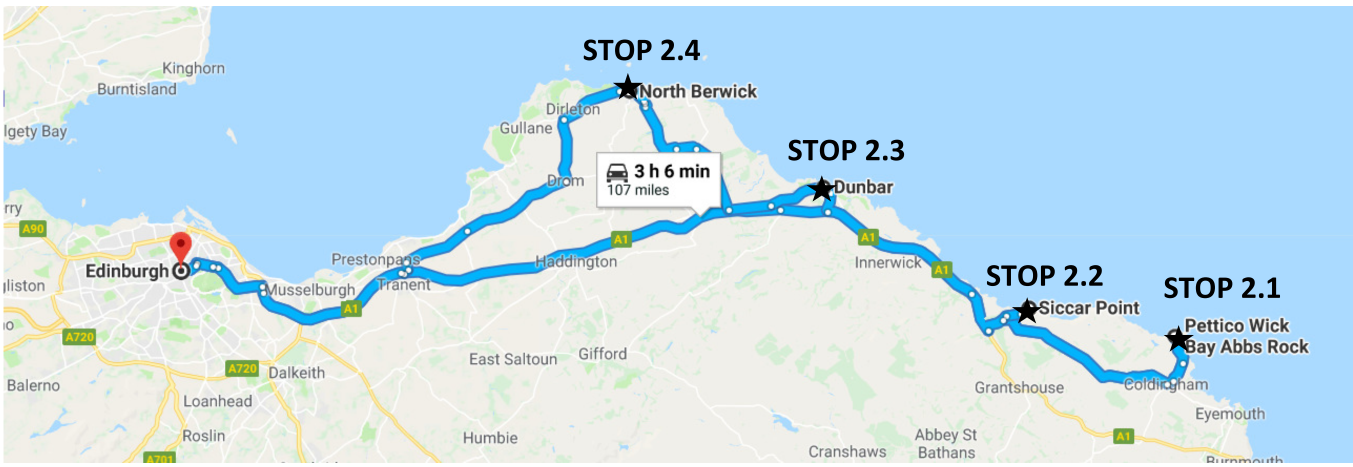
**12:00 PM:** Have lunch out of the back of the van

**1:00 PM:** Dunbar – exposed volcanic necks in the sea cliffs

**3:00 PM:** North Berwick – Carboniferous Volcanics

**5:00 PM:** Return to the hostel

**6:00 PM:** Group dinner we will cook at the hostel




**Day 3: Tuesday, March 6th, 2018 – Edinburgh Castle, Arthur's Seat/St Andrews, and Edinburgh City**

**8:00 AM:** Breakfast in the hostel

**8:30 AM:** Walk to Edinburgh Castle – Castle tour

**12:00 PM:** Lunch at the hostel

**1:00 PM:**

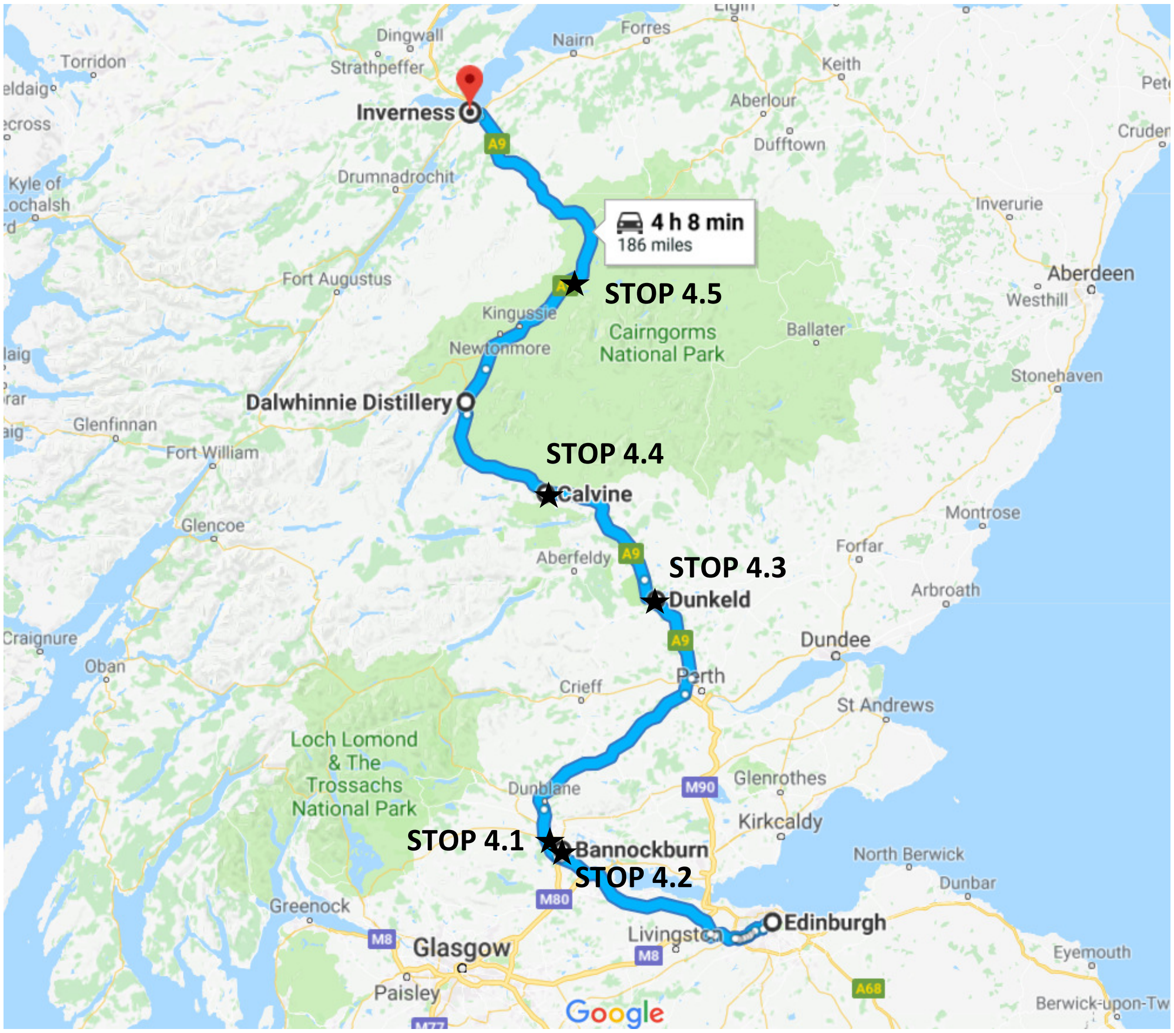
**Option #1 –** Hike around Arthur's Seat, a volcanic plug in Holyrood Park that Hutton studied (10 minute walk from the hostel)

**Option #2 –** Drive to St Andrews to see the birthplace of golf (3 hr round-trip drive from the hostel)

**Option #3 –** Explore Edinburgh (museums, shops, pubs…)

**6:00 PM:** Group dinner we will cook at the hostel

**Day 4: Wednesday, March 7th, 2018 – Stirling, Bannockburn, Dalradian Rocks, Distilleries, Inverness, AND Jake's 21st Birthday!**




**8:00 AM:** Depart from Edinburgh and drive to Bannockburn/Stirling (1 hr drive)

**9:00 AM:** Drive around Stirling Castle – no tour this time

**10:00 AM:** The Battle of Bannockburn Visitor Center

**12:00 PM:** Lunch out of the van

**12:30 PM:** Leave Stirling

**1:30 PM:** Dunkeld and Little Glen Shee – Folded Dalradian sediments

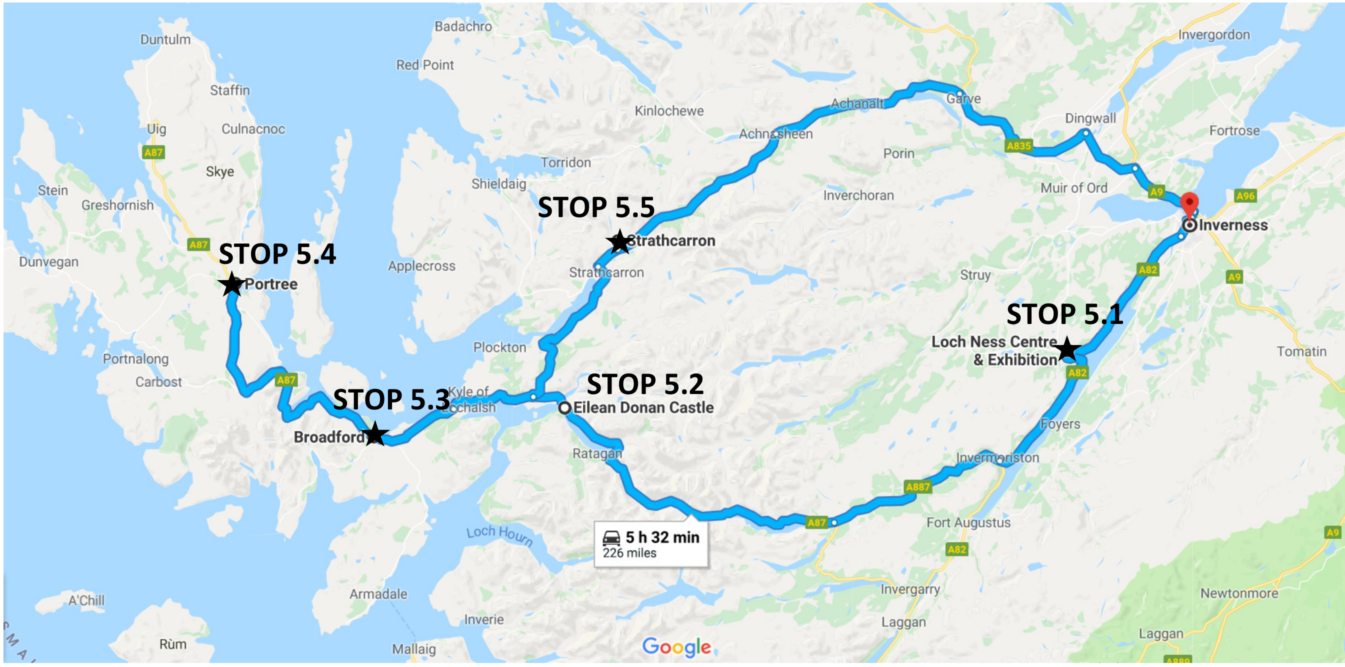
**2:15 PM:** Clunes A9 Road Cut – Folded Dalradian sediments

**3:00 PM:** Speyside Distillery (http://speysidedistillery.co.uk/), The Cairgorms Brewery (http://www.cairngormbrewery.com/), Dalwhinnie Distillery (https://www.malts.com/en-row/distilleries/dalwhinnie/), we each have to buy Jake a drink….

**6:00 PM:** Get to the hostel in Inverness

Ardconnel House
21 Ardconnel St,
Inverness, IV2 3EU
Telephone: +44 01463 240455
http://www.ardconnel-inverness.co.uk/

**Day 5: Thursday, March 8th, 2018 – Loch Ness and Isle of Skye**




**7:00 AM:** Breakfast is included at this Hostel!

**8:00 AM:** Depart from the Ardconnel House

**9:00 AM:** The Loch Ness Centre & Exhibition
http://www.lochness.com/

**11:00 AM:** Lunch at the museum

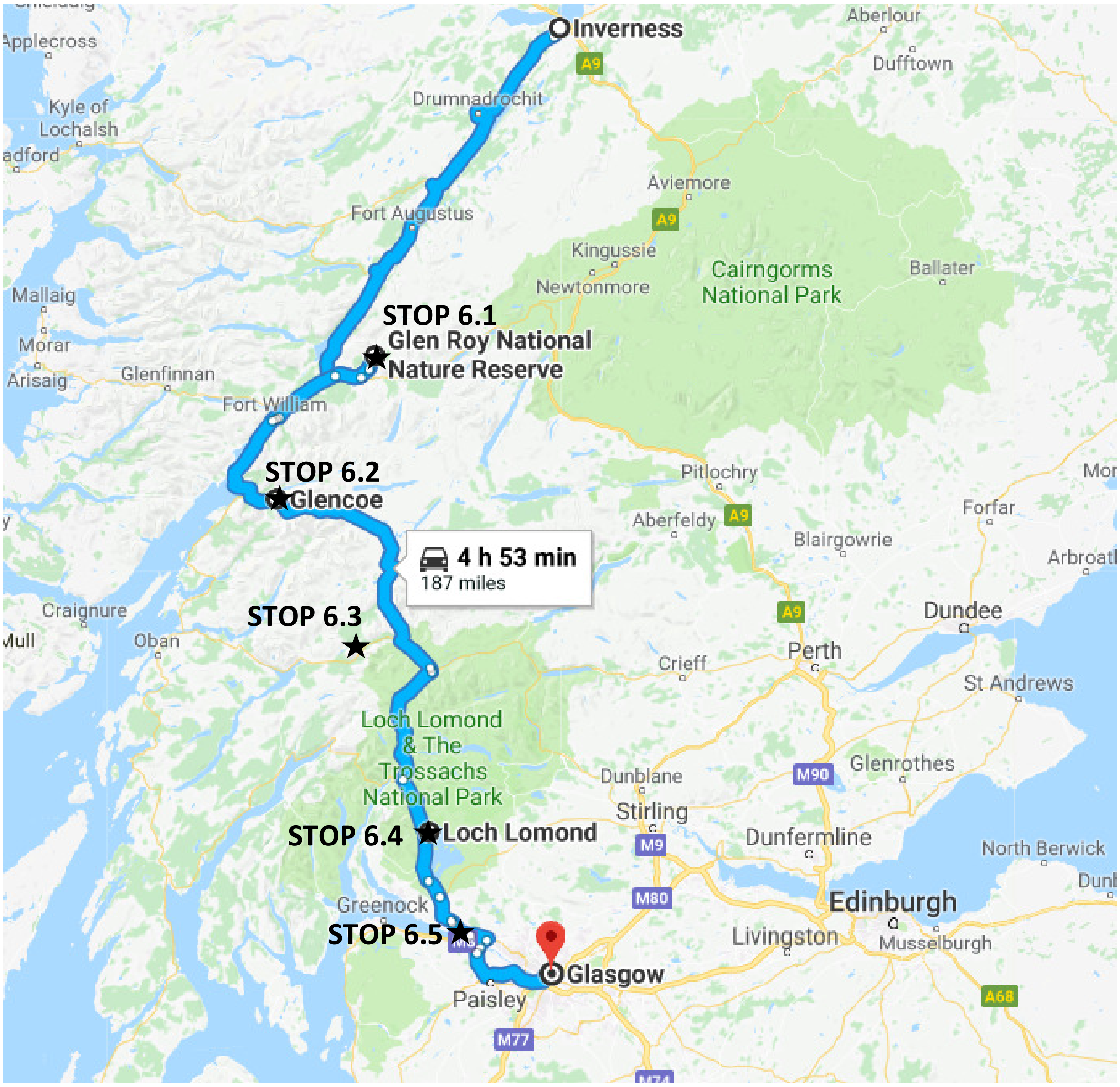
**1:00 PM:** Carr Brae above Loch Duich – Forsteritic Marbles with diopside, garnet-biotite gneisses, and possibly eclogites!!!!!!!!! But this might just be a view of Eilean Donan Castle….

**2:00 PM:** Rubha' an Eireannaich, Broadford, Isle of Skye – mafic and felsic magma mingling

**3:30 PM:** Portree, Isle of Skye

**6:30 PM:** Arrive back to the Hostel

**Day 6: Friday, March 9th, 2018 – Glen Roy, Glencoe, Loch Lomond, and Glasgow**




**7:00 AM:** Breakfast
**8:00 AM:** Pack up and depart from Inverness
**10:00 AM:** Glen Roy National Nature Reserve and the Darwin's Parallel Roads
**12:00 PM:** Lunch in Glen Roy
**1:00 PM:** Glencoe and the Ballachulish Igneous Complex
- Quarry Centre Ballachulish Visitor Centre
http://discoverglencoe.scot/listing/the-quarry-centre/

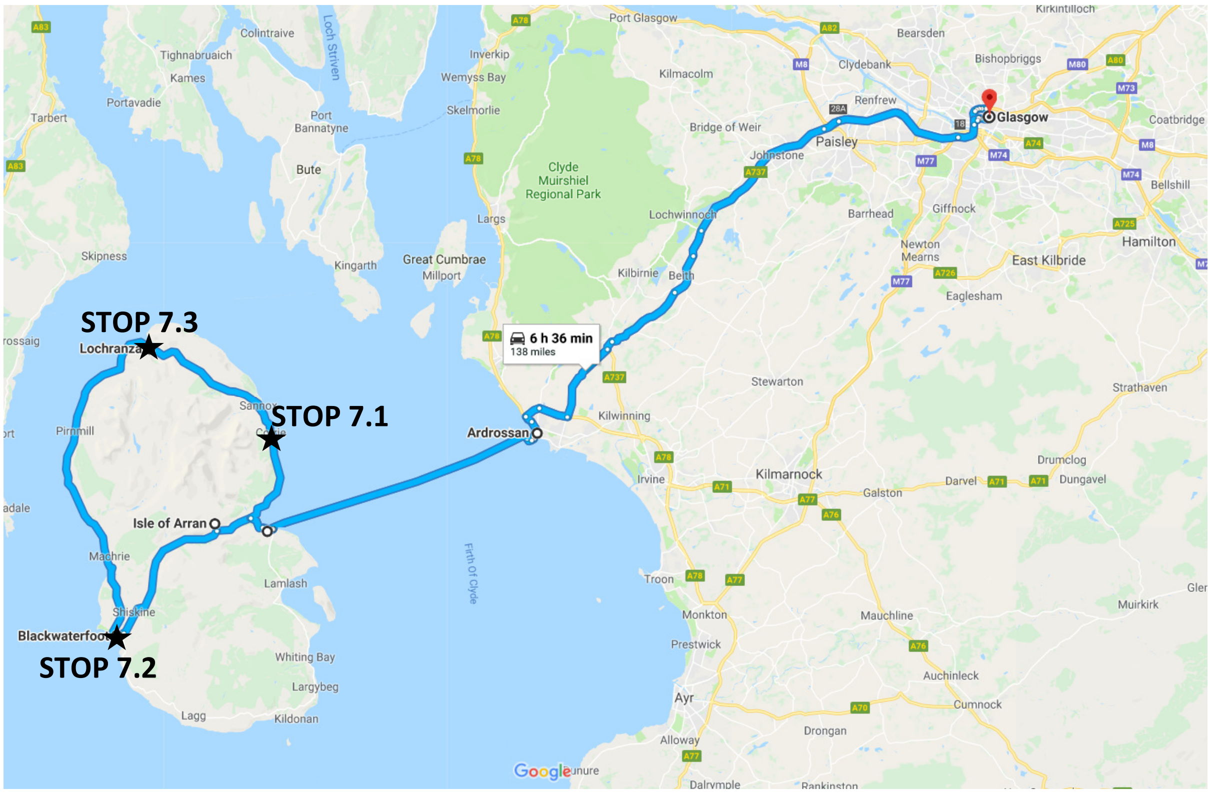
**2:30 PM:** River Orchy – Various fold structure associated with the Udlaidh Syncline
**3:30 PM:** Loch Lomond – Tay Nappe of the Southern Highland Complex
**4:30 PM:** Dumbarton Rock – Basaltic Intrusions
**5:30 PM:** Get to the Hostel in Glasgow
Euro Hostel Glasgow, 318 Clyde Street, Glasgow, G1 4NR
Telephone: +44 141 222 2828
http://www.eurohostels.co.uk/glasgow/

**Day 7: Saturday, March 10th, 2018 – Isle of Arran or Hang out in Glasgow**

***Here we have some options –***

1. *Isle of Arran – Hutton's unconformity and igneous rock features.*
2. *Back up to Loch Lomond and The Trossachs*
3. *Hang out in Glasgow – museums, shops, pubs…*

**I am writing it up for the Isle of Arran but we will see how we feel.**




**8:00 AM:** Leave the hostel

**9:00 AM:** Board the Ferry (Ferry leaves at 9:45 AM)

**10:30 AM:** Corrie Shore – tilted strata and fossils

**12:00 PM:** Lunch in Brodick

**2:00 PM:** Dumadoon – igneous intrustions

**3:00 PM:** Lochranza – Hutton's Unconformity

**4:30 PM:** Board the Ferry (Ferry leaves at 4:40 PM)

**Day 8: Sunday, March 11th, 2018 – Fly back to DC**

**6:00 AM:** Leave hostel to return the cars and for the airport

**8:55 AM:** Depart from Glasgow (British Air BA1447) to London Heathrow

**10:25 AM:** Arrive in London

**11:25 AM:** Depart for Washington Dulles (British Air BA0217)

**3:50 PM:** Arrive in Washington, DC-Dulles (IAD)

# INTRODUCTION

## Basic Geologic Background

*The following are notes from a short lecture Dr Kerrigan gave about the geology of Scotland. Additionally, portions were taken from online guide (www.geowiss.uni-mainz.de/685_ENG_HTML.php)*

**General Notes:**

- It is country part of the UK
- Cover the northern 1/3 of the island of Great Britain (30, 090 mi$^2$) same size as South Carolina or 2/3rds of PA.
- highest point is Ben Nevis, Lochaber (4,413 ft)


**Physiographic Units:**

*Outer Hebrides and Northwest Highlands:*

- Ancient rocks - Precambrian granites (Lewisian granites) and sandstones (Torridonian)
- Far north Shetland Islands (Unst) has an ophiolite sequence from the Iapetus Ocean that is one of the type examples of a "black-wall zone"

*Northern Highlands:*

- The Moine Group, the Old Red Stone and some intrusions
- Laurentain terranes

*Grampian Highlands:*

- Lots of igneous rocks intruding the Dalradian formation
- Laurentian terranes

*Midland Valley:*

- Intermediate accreted terranes

*Southern Uplands*

- Intermediate accreted terranes

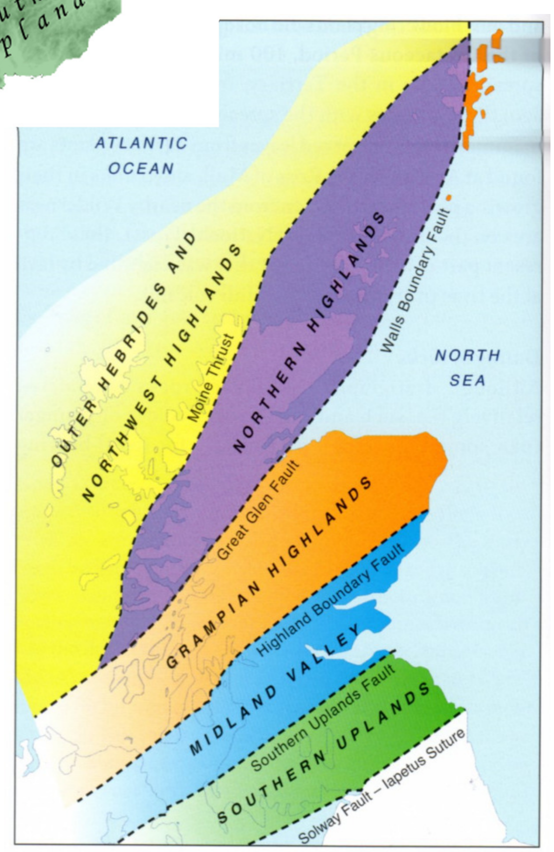



**Figure 2.1** Sketch map of geological regions of Scotland.

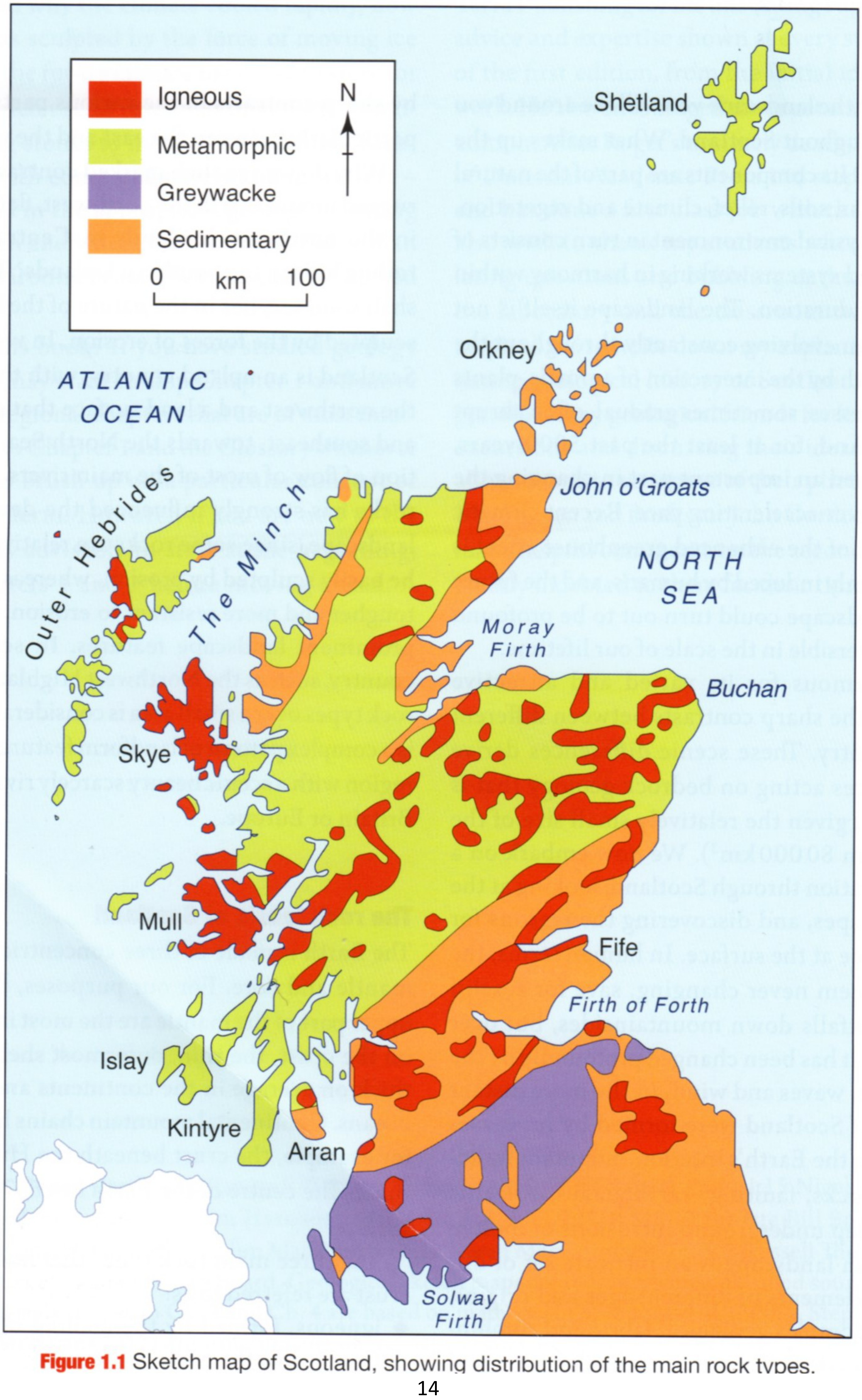
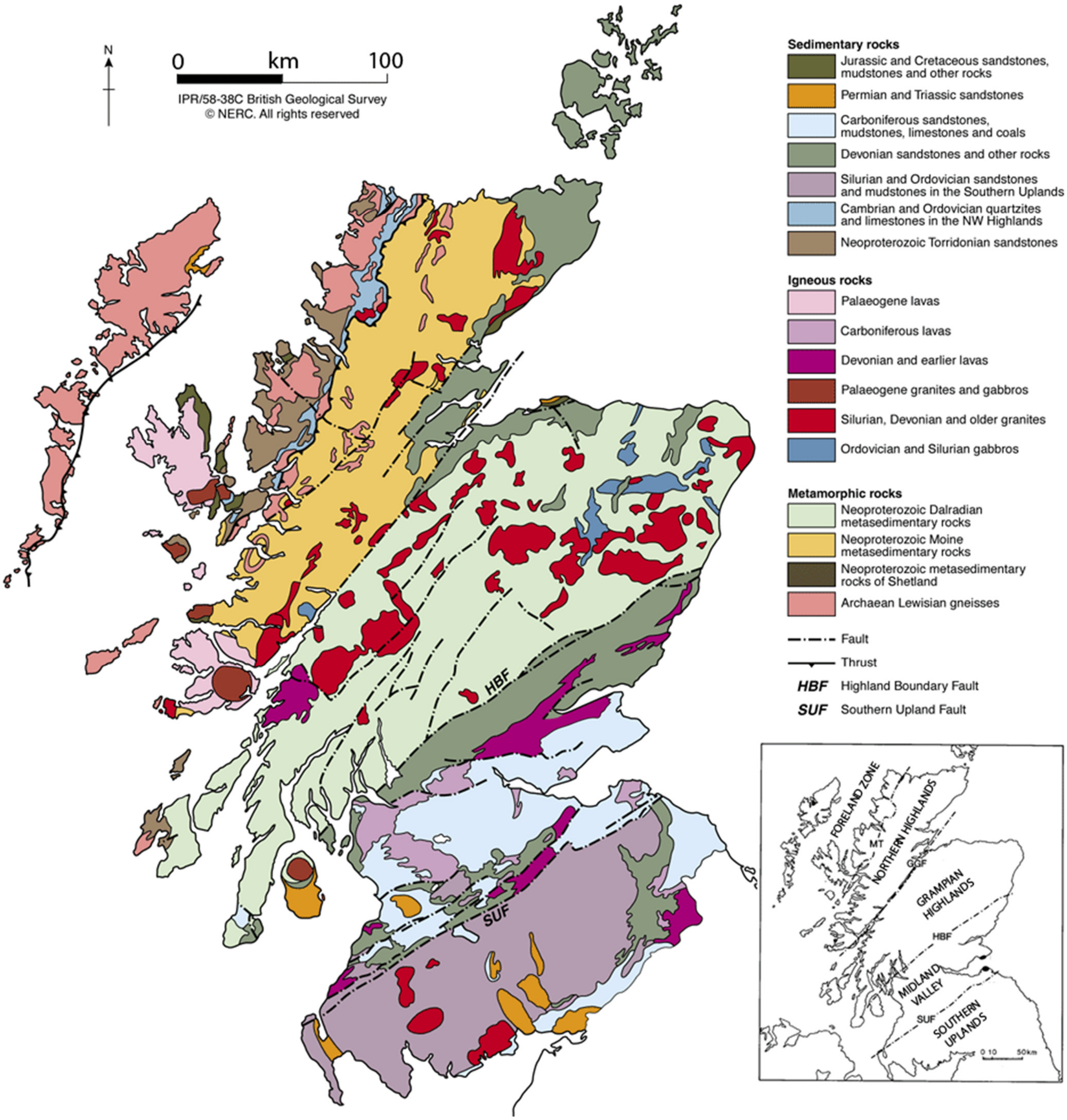



**Figure 1.1** Sketch map of Scotland, showing distribution of the main rock types.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0 km 100
IPR/58-38C British Geological Survey
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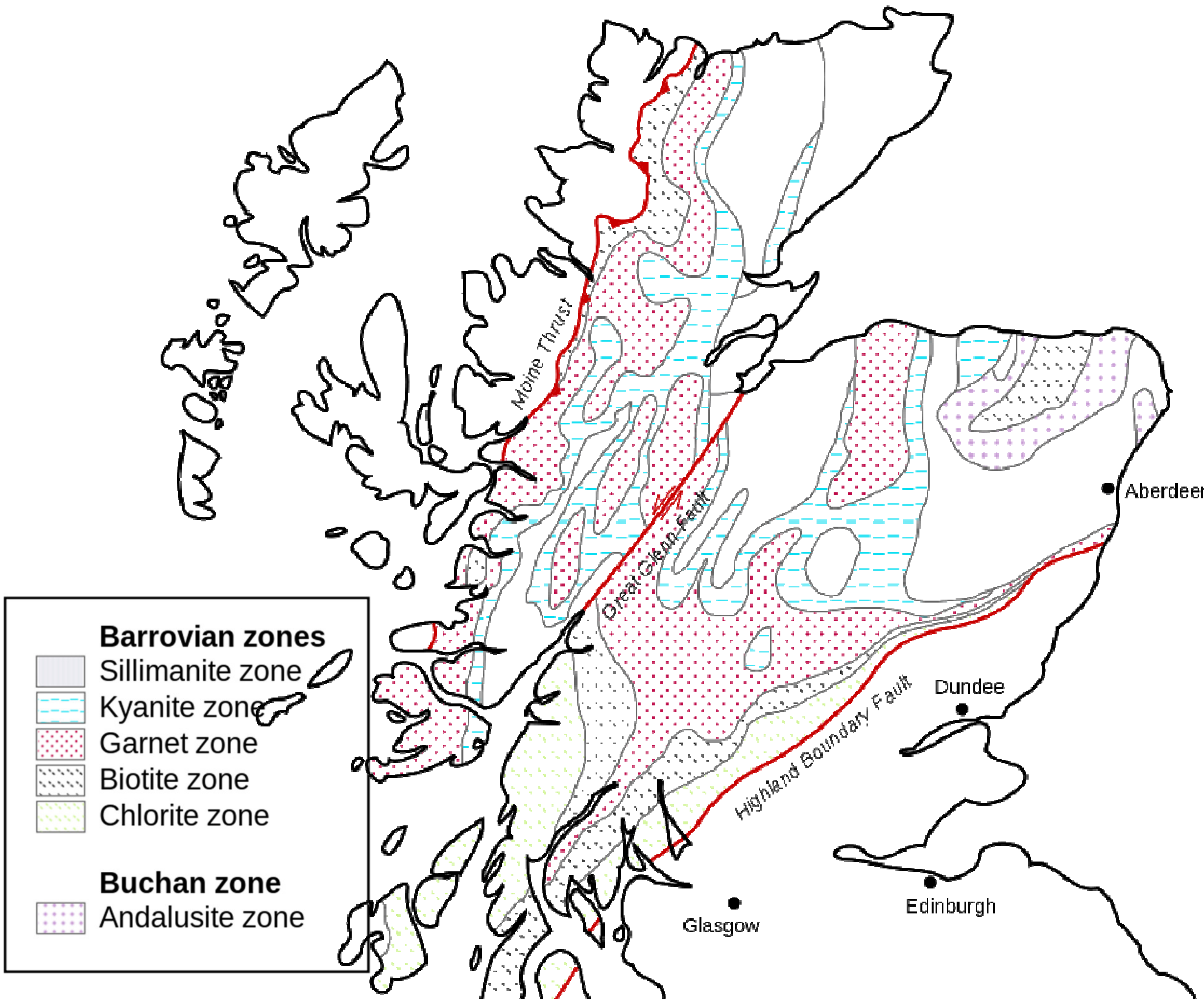
Sedimentary rocks
Jurassic and Cretaceous sandstones, mudstones and other rocks
Permian and Triassic sandstones
Carboniferous sandstones, mudstones, limestones and coals
Devonian sandstones and other rocks
Silurian and Ordovician sandstones and mudstones in the Southern Uplands
Cambrian and Ordovician quartzites and limestones in the NW Highlands
Neoproterozoic Torridonian sandstones
Igneous rocks
Palaeogene lavas
Carboniferous lavas
Devonian and earlier lavas
Palaeogene granites and gabbros
Silurian, Devonian and older granites
Ordovician and Silurian gabbros
Metamorphic rocks
Neoproterozoic Dalradian metasedimentary rocks
Neoproterozoic Moine metasedimentary rocks
Neoproterozoic metasedimentary rocks of Shetland
Archaean Lewisian gneisses
Fault
Thrust
HBF Highland Boundary Fault
SUF Southern Upland Fault
HBF
SUF
FORELAND ZONE
NORTHERN HIGHLANDS
MT
GGF
GRAMPIAN HIGHLANDS
HBF
MIDLAND VALLEY
SUF
SOUTHERN UPLANDS
0 10 50km




The map shows the distribution of regional metamorphic zones in Scotland.

The majority of Scotland enjoyed Barrovian metamorphism that reflects a 'normal' crustal geotherm (moderate d*P*/d*T*), characterized by the kyanite to sillimanite transition in metapelitic rocks. Metamorphism in the Buchan area in the NE was at lower *P*, and is characterized by the andalusite to sillimanite transition in metapelitic rocks.

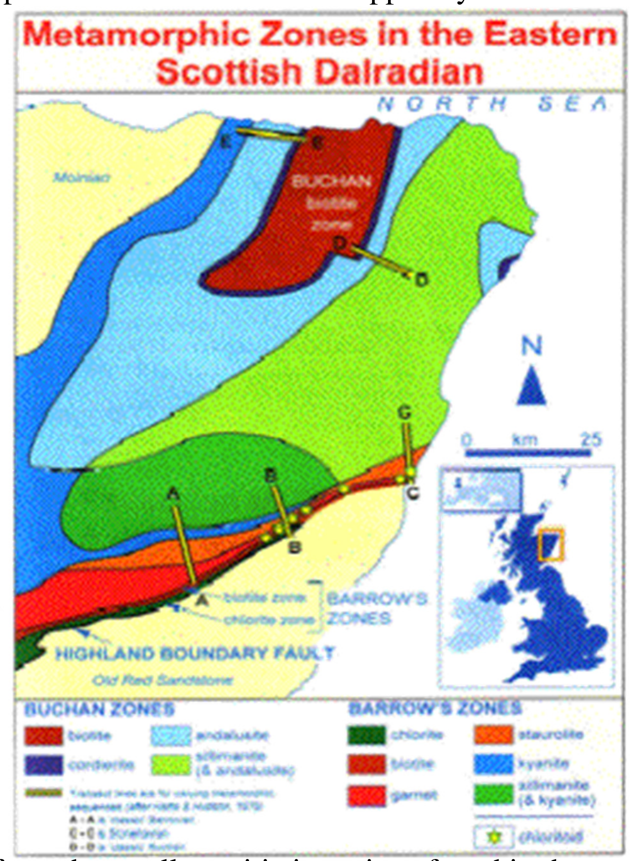
| Unmetamorphosed Rock | Facies A | Facies B | Facies C | Facies D | Facies E |
|---|---|---|---|---|---|
| **Shale - Mudstone** | *chlorite*<br>muscovite<br>*albite*<br>quartz | *biotite*<br>chlorite<br>muscovite<br>albite<br>quartz | *garnet*<br>biotite<br>muscovite<br>albite*<br>quartz | *staurolite*<br>garnet<br>biotite<br>*plagioclase**<br>quartz | *sillimanite*<br>garnet<br>biotite<br>plagioclase<br>quartz |
| | Slate or phyllite | Phyllite | or Schist | Schist or | Gneiss |
| **Andesitic Volcanic Tuff** | *actinolite*<br>albite<br>epidote<br>chlorite<br>quartz | actinolite<br>albite<br>epidote<br>chlorite<br>quartz | *hornblende*<br>albite<br>epidote<br>quartz | hornblende<br>*plagioclase*<br>quartz | hornblende<br>plagioclase<br>quartz |
| | Chlorite or | Actinolite Schist | | Amphibolite | |
| **Sandy Limestone or Siliceous Dolomite** | *dolomite*<br>calcite<br>quartz | *tremolite*<br>calcite<br>quartz | tremolite<br>calcite<br>quartz | *diopside*<br>calcite<br>quartz | diopside<br>calcite<br>quartz |
| | Marble | Tremolite | Marble | Diopside | Marble |

## Scottish Regional Metamorphism - Barrovian

The Dalradian Supergroup of the Grampian Highlands is a thick sequence of deformed and metamorphosed sediments (mainly marine) and volcanics deposited between approximately 800 Ma and 500 Ma. The Dalradian block is structurally bounded to the north by the Great Glen Fault and to the south by the Highland Boundary Fault (Fig. 1). The rocks were affected by the complex Grampian Orogeny, the result of the early stages of closure of the Iapetus Ocean during the early to mid- Ordovician.

George Barrow (1853 - 1932) was a British geologist and is one of the all-time superstars of metamorphic geology. In one of the most important metamorphic studies in history (published in 1893), he was the first to map a metamorphic field gradient by determining a sequence of metamorphic zones in the Scottish Highlands (see Fig. 2). Every first appearance of an index mineral was taken by Barrow as the beginning of a new metamorphic zone. The lines connecting the first appearance of a mineral and separating the zones are isograds. The age of peak metamorphism is now constrained to 465-470 Ma (i.e., Ordovician).

The underlying principles of metamorphic zones were later clarified by the Finnish geologist Pentti Eskola, who introduced the concept of the metamorphic facies. The zones as mapped by Barrow with increasing grade:




**Zone of digested clastic mica (now the Chlorite Zone)**
quartz-chlorite-muscovite-plagioclase

**Biotite Zone**
quartz-chlorite-biotite-muscovite-plagioclase

**Garnet Zone**
quartz-muscovite-biotite-garnet-plagioclase

**Staurolite Zone**
quartz-muscovite-biotite-garnet-staurolite-plagioclase

**Kyanite Zone**
quartz-biotite-muscovite-garnet-kyanite-plagioclase

**Sillimanite Zone**
quartz-biotite-muscovite-garnet-sillimanite-plagioclase

Barrow believed the zones resulted from the heat from the small granitic intrusions found in the high-grade zones. Another geologist, C.E. Tilley, working on the same rocks in a different area suggested that the temperature of each zone was largely determined by the depth of burial. Tilley (1924) suggested that the isograds mark rocks originating under closely similar P-T conditions, essentially what we believe today.

**Scottish Regional Metamorphism - Buchan**

The Buchan Facies Series of regional metamorphism is characterized by the widespread development of andalusite and cordierite in metapelitic rocks, indicating that the conditions of metamorphism were at lower *P* than those of the Barrovian Facies Series. Once again, the type locality of Buchan metamorphism is the Dalradian of Scotland.

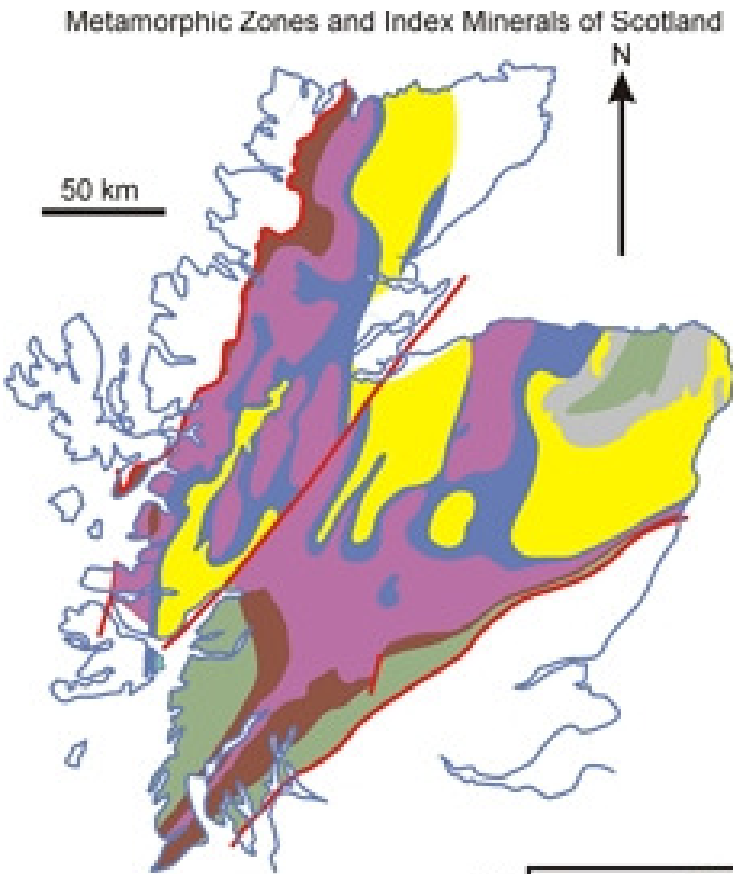
The Buchan is characterized by the following metamorphic zones:

**Biotite Zone (Greenschist Facies)**

**Cordierite Zone (Amphibolite Facies)**

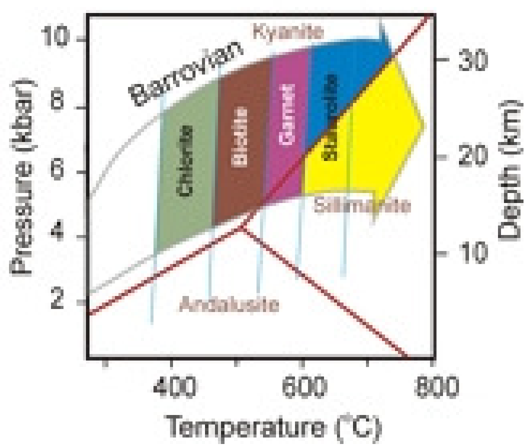
**Andalusite Zone (Amphibolite Facies)**

**Sillimanite Zone (Amphibolite to Granulite Facies)**




We will not be able to make to the Buchan zone on this trip but maybe some future trip where we could look at these classic rocks, examining the classic low-*P* metamorphic zones and associated assemblages developed in metapelitic and calc-silicate rocks. We will see partially melted rocks (migmatites), meta-gabbros and associated contact metamorphic rocks, amphibolite-facies shear-zones, sedimentary structures and much else.

Perhaps the world's best-exposed regional isograds occur within the coastal section around Banff.

**Geologic History:**

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

One of the key features of the geology of NW Scotland relate to an ancient period of mountain building – the Caledonian. This ancient chain once included most of northern Britain. The most striking effects of the Caledonian system are shown by rocks in the Scottish Highlands. Rocks are tightly contorted and strongly recrystallised by the heat and pressure to which they were once subjected. But not all of Scotland was caught up in the Caledonian mountain belt. The Caledonian "Foreland zone" (Fig. 1 inset) is a tract of geology that preserves a history of geological events much older than the Caledonian. The edge of the Caledonian mountain belt (the so-called "Caledonian front" that limits the foreland) runs from Durness – on the Scottish north coast, down to Skye

*<u>Archean and Proterozoic</u> – Part of Laurentia*

**Lewisian gneisses (Northwest Highlands)**

- some of the oldest rocks in Europe (3 Ga)
- Mainly metamorphosed Anorthosites in the northwestern portion

The oldest rocks in the British Isles are the Lewisian gneisses. These ancient rocks show evidence for a long history of shearing, recrystallisation and igneous activity. All this points to episodes of ancient mountain building. Lewisian rocks are found in the Outer Hebrides and along parts of the NW Scottish mainland (Fig. 1). The oldest material is termed "Scourian" – named after the village of Scourie in Sutherland. Most of this material probably started as various types of igneous rock - most likely the roots of old volcanoes such as in modern Japan. The old magma chambers have been highly deformed and metamorphosed forming orthogneiss.

In the Lewisian the oldest crust formed about 3000 to 2700 million years ago. The shearing that reshaped the crust happened about 2450 million years ago, in an event called the "Badcallian". After the Badcallian, the gneisses were split and intruded by sheets (dykes) of igneous rocks about 2400 million years ago and again at about 1900 million years ago. These intrusions, collectively known as the Scourie dykes, have a basic composition and must have come from melting part of the upper mantle – perhaps during a weak rifting episode. The gneisses and dykes were then sheared and metamorphosed again. The last serious activity in the Lewisian happened about 1800 million years ago, during the so-called Laxfordian orogeny. In places the shearing associated with this has smeared all the old Lewisian constituents (like dykes and gneissic banding) into parallel and is associated with local melting (migmatisation), with granitic dykes invading parts of the crust.

**Torridonian sandstones (Northwest Highlands)**

- Proterozoic (1.2-0.85 Ga) sandstone laid down on top of the gneisses

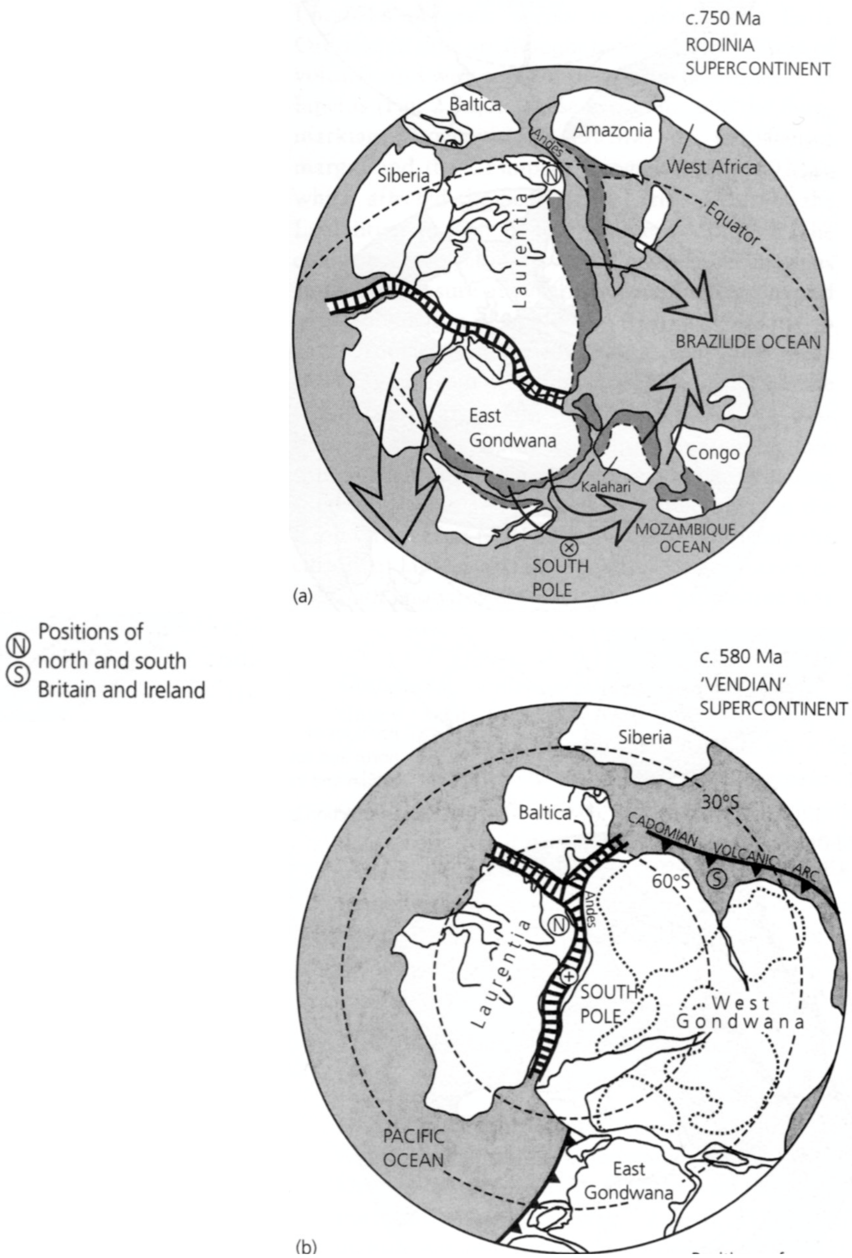
When the Lewisian gneisses got to the earth's surface - about 1000 million years ago - the uplift and erosion had worn away much of the older mountain ranges. However, out to the west of mainland Scotland there were mountains of Lewisian gneiss and these shed debris eastwards. The material piled up and as the Torridonian succession, which is mainly red (i.e., oxidised) sandstone. This material covered the Lewisian preserved as an "unconformity", representing the Earth's surface at the time the Torridonian was deposited. The detritus probably piled up to over 8 km thick but much of this has since been eroded. The detritus that formed the Torridonian sandstone was carried by rivers and, the channels of which are still preserved in places

**Moine (Northern Highlands)**

- Shallow water sediments deposited (980-870 Ma), birth of Iapetus Ocean
- Folded in 780 and 480 Ma thrusted 430 Ma

**Dalradian (Grampian Highlands)**

- All types (800-500 Ma) – from shallow then deeper seds but also lavas
- Folded and metamorphosed at 470




Woodcock and Strachan, 2000

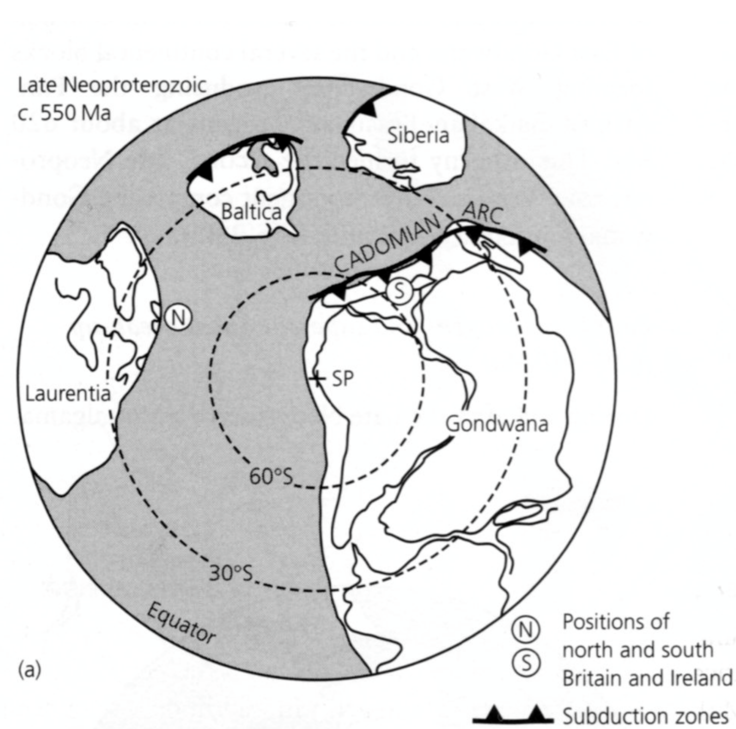
<u>Cambrian</u> – *Part of Laurentia*

Sed rocks deposited in Northwestern Highlands

After the Torridonian, the next preserved rocks are of Early Palaeozoic, a period of dramatic explosion in life on Earth. The oldest of these rocks are the Cambrian basal quartzites. The quartzites are almost pure quartz probably representing deposition in very shallow seas in which the activity of tides and currents are recorded as cross-bedding. The unconformable junction with the Torridonian below is almost flat, suggesting the Torridonian had been nearly completely eroded following a marine transgression. The top part of the quartzites (the Pipe Rock) contains burrows - the oldest expressions of life in NW Scotland. These pipes, a type of trace fossil called Skolithos, were probably formed by worms burrowing into the sand. The effect of burrowing was to destroy much of the depositional structure in the quartzites and cross-bedding is only rarely preserved in the Pipe Rock. Collectively the quartzites attain a thickness of about 160 metres.

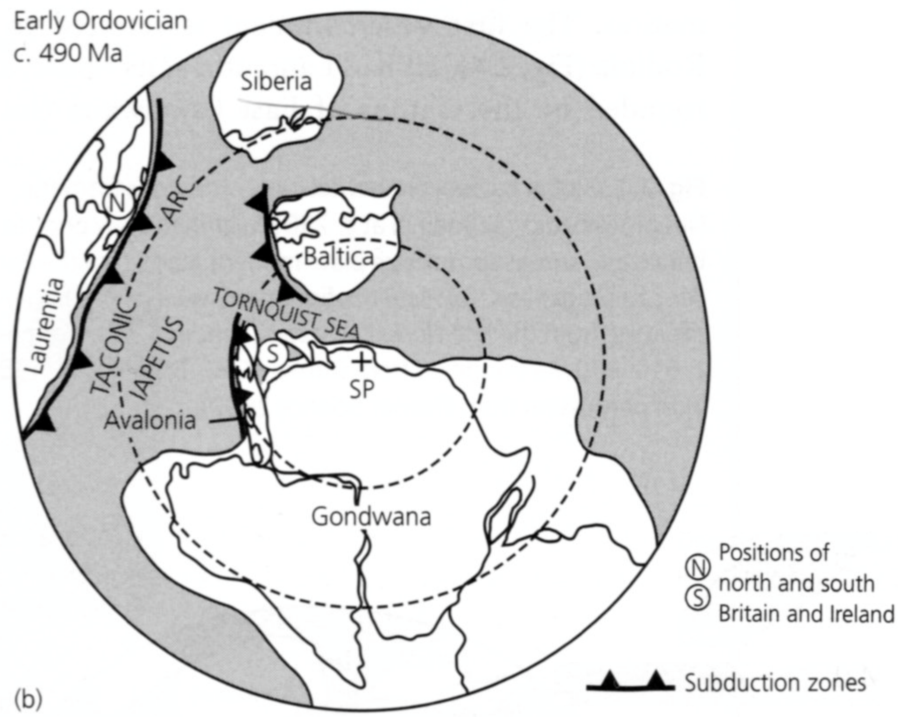
The next rocks are called the Fucoid Beds. These sediments are brown-coloured in outcrop and often have mosses covering them and may look like bits of rotten tree in small outcrops. Irregular features in these rocks are another form of trace fossil – probably a grazing trail of a small beast on the old sea bed. The Fucoid Beds contain lots of different types of trace fossil but are most important for containing rare body fossils – particularly of the Cambrian predators, trilobites. These rocks are about 520 million years old and again record a shallow marine (maybe lagoonal) environment. The Fucoid beds are overlain by clean, coarse-grained quartzites with vertical burrows. The unit contains small (2mm) spiral shells which gives the unit its name – the Salterella Grit. Collectively the Fucoid Beds and Salterella Grit are only about 25m thick.

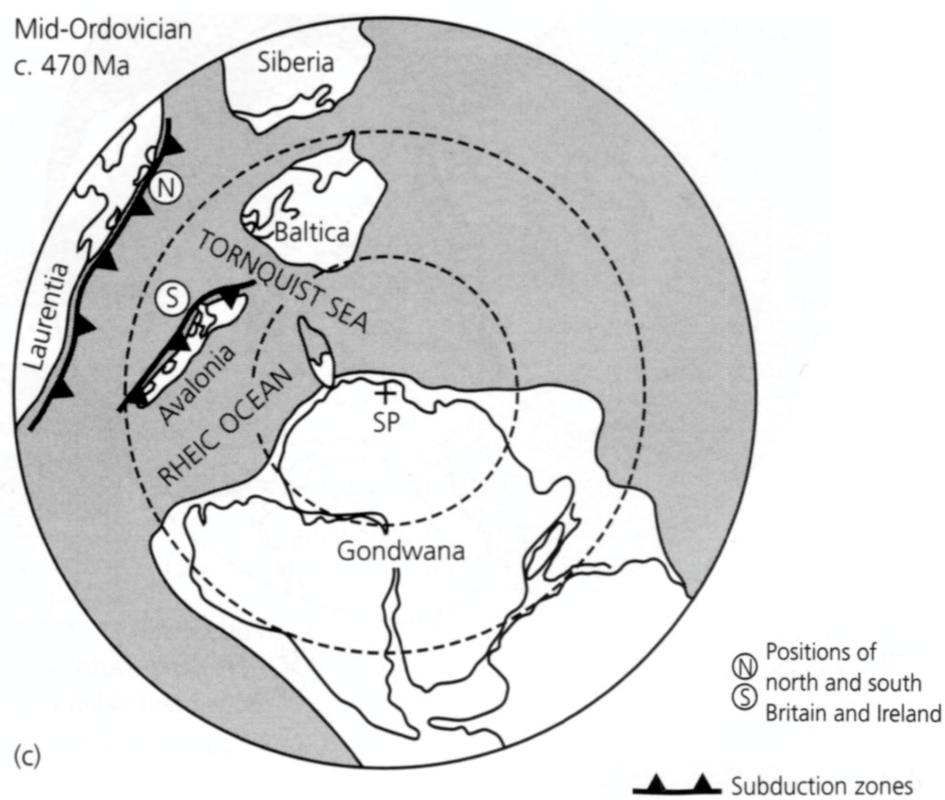
The grits pass up into limestones and dolomites of the Durness group. The carbonates have a cumulative thickness of over 1 km but in general only the lower few tens of metres are preserved. Although much of the Durness has been recrystallised it is still possible to recognise traces of feeding burrows, algal mats and filaments together with small scours and carbonate grains called ooids. All these features are indicative of deposition in a shallow sea. Fossil evidence suggests that the carbonates began to accumulate towards the end of the early Cambrian but it continued on, with breaks, for a further 50 million years, into the Ordovician period.



*<u>Ordovician</u> – Part of Laurentia*

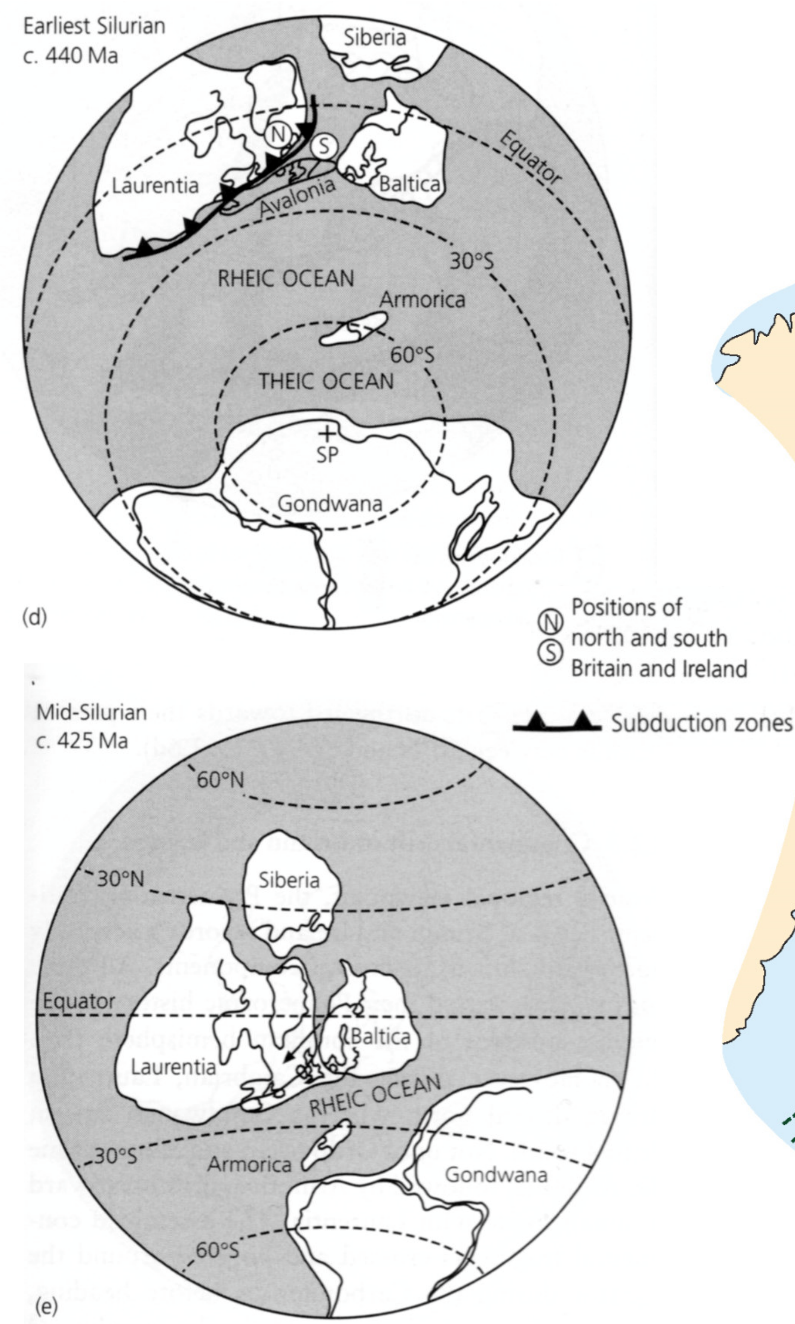
- Limestones/deep water rocks deposited in Southern Uplands
- Laurentian coastal margin on the Iapetus

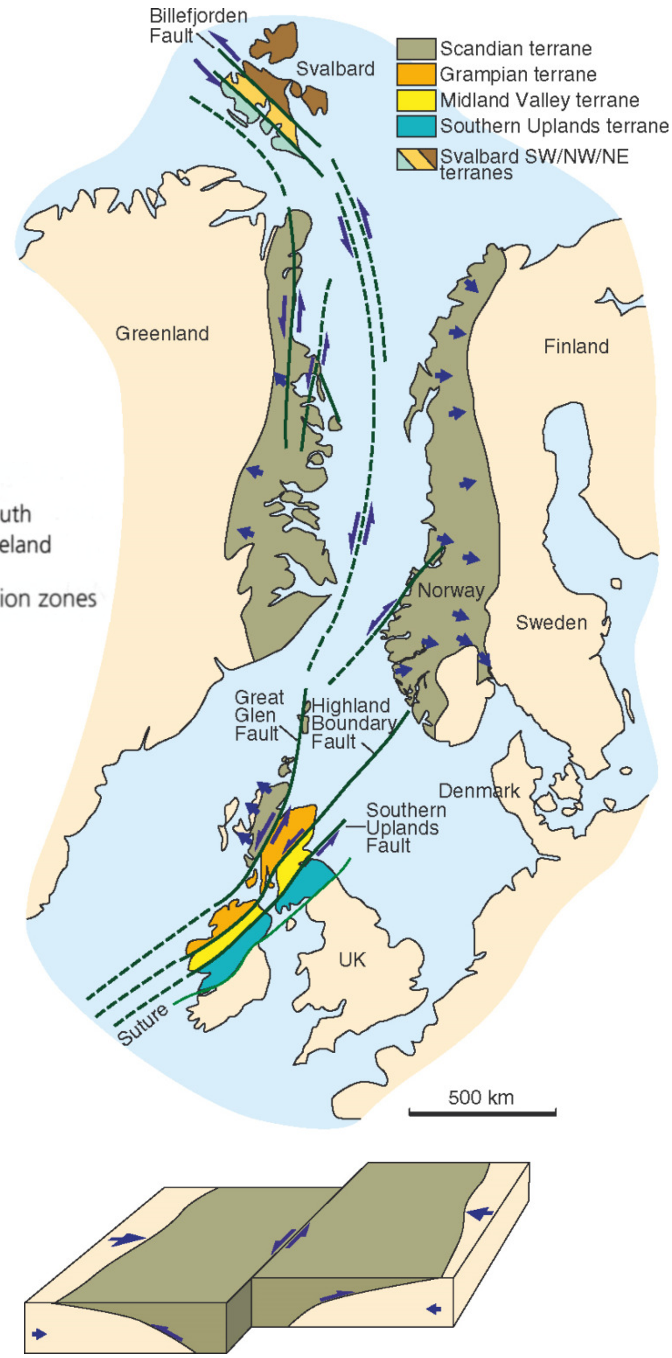


*<u>Silurian</u> – Part of Laurentia*

- Collision of Avalonia and growth of the Caledonides
- Greywackes scraped off trench area in Southern Uplands
- Igneous activity in the Midland Valley
- By the end of the Silurian Great Britain is fully connected



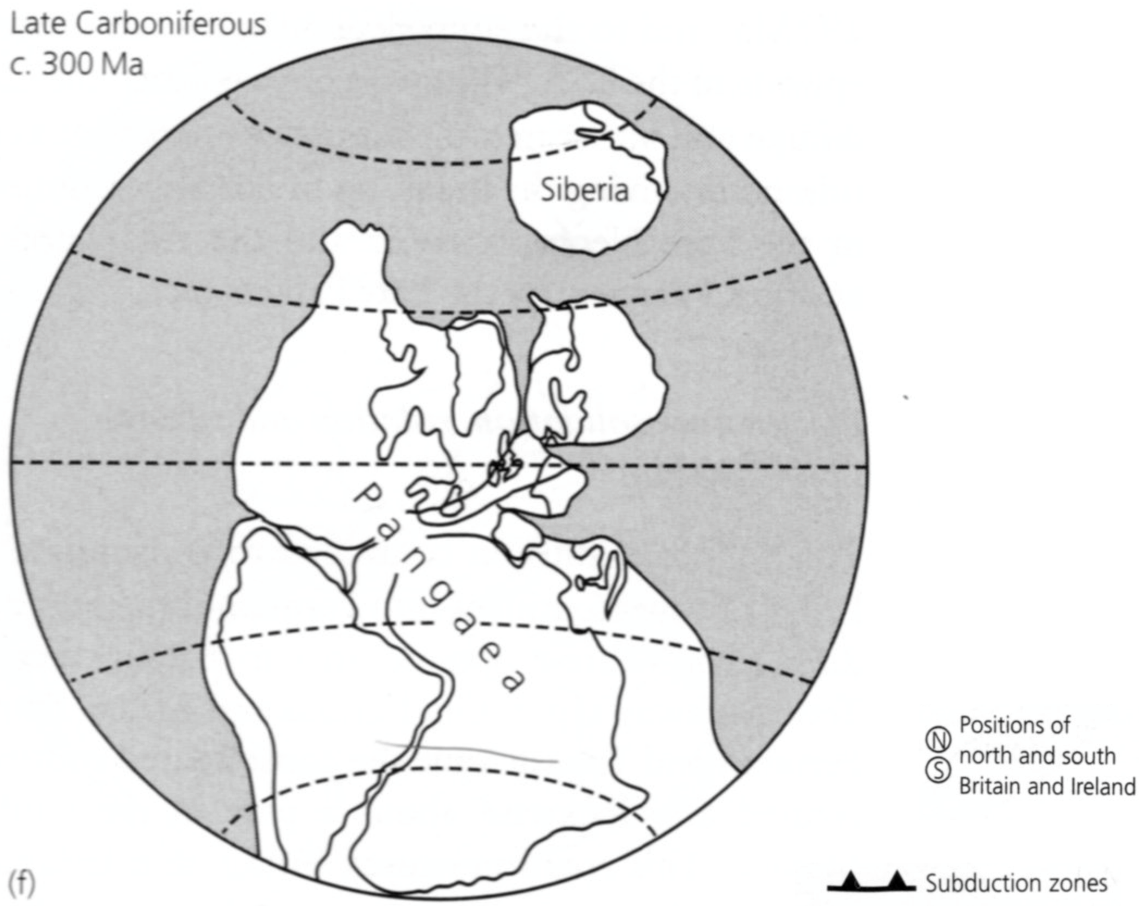

Fossen, 2010

*Devonian*

- Scotland is in the interior of a continent
- Desert Redbeds deposit – the Old Red Sandstone – contemporaneous with the Catskill Red Beds in NY and New England
- Lavas and Granites ~400 Ma

*Carboniferous*

- Volcanoes in the Midland Valley and the Southern Uplands
- Variscan mountains form in the south – last orogeny completing Pangea
- Desert Redbeds deposit – the Old Red Sandstone – contemporaneous with the Catskill Red Beds in NY and New England
- Lavas and Granites ~400 Ma




*Permian*

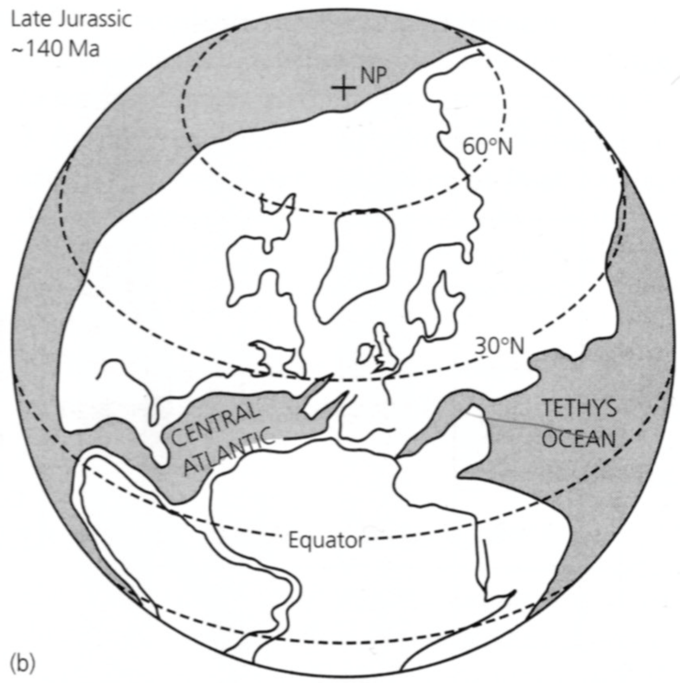
- Volcanoes in the Midland Valley, Erosion in the uplands

*Triassic*

- Desert conditions persist - stable

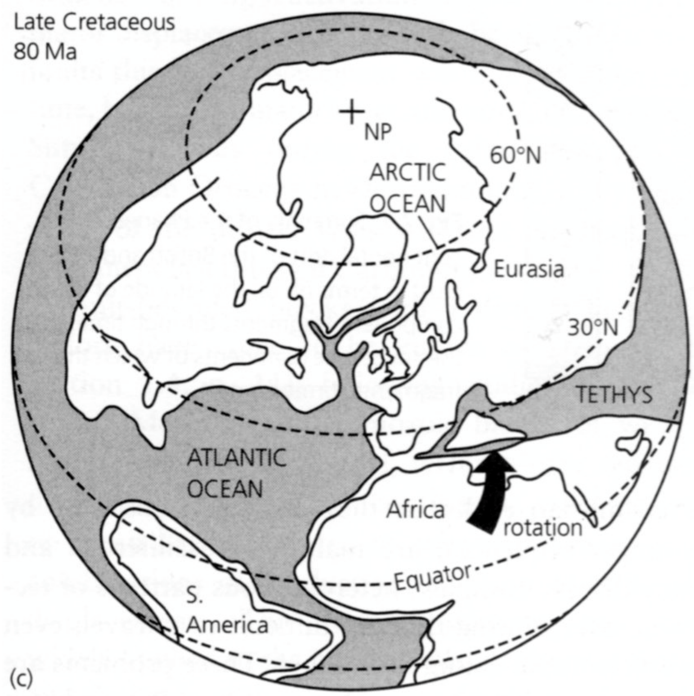
*Jurassic*

- Break up of Pangea - marking the beginning of Scotland's separation with Laurentia
- shallow water limestones deposited (oil shales too)



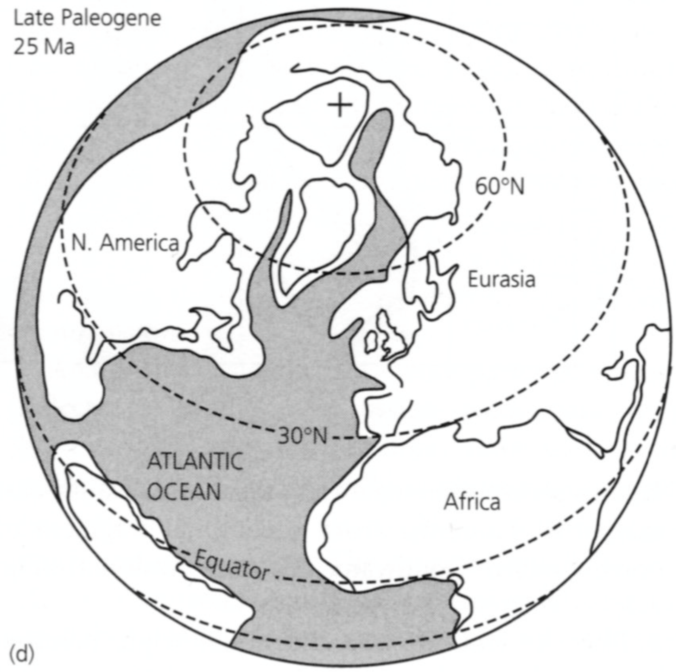

*Cretaceous*

- Continued splitting and drifting

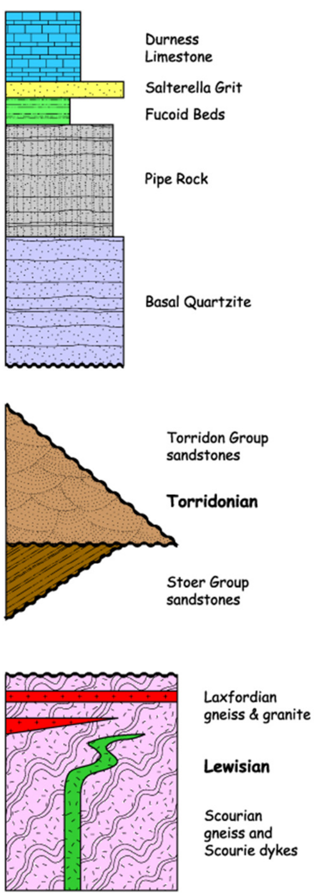


*Paleogene*

- Volcanism in the west




## Stratigraphy of NW Scotland




**Cambo-Ordovician (500-540 Ma)** - mainly marine

Durness: dolomitic limestone

Salterella Grit: impure sandstone with small spiral shelly fossils
Fucoid Beds: dolomitic siltstone, earliest body fossils (trilobites)

Pipe Rock: quartz sandstone with vertical burrows (Skolithos)

Basal Quartzite: quartz sandstone with cross bedding
*Thickness of Basal Quartzite plus Pipe Rock is about 160 metres*

**Torridonian succession (800-1200 Ma)** - mainly alluvial

Torridon Group: mostly red-brown sandstones
*Thickness up to 6 kilometres*

Stoer Group: Red-brown sandstone, conglomerate, mudstone
*Thickness up to 2 kilometres*

**Lewisian Complex** - basement gneisses

Laxfordian (c.1750 Ma)
Gneiss (pink) with granite sheets (red)

Scourian (c.2700 Ma)
Gneiss (pink) with mafic dykes (green)

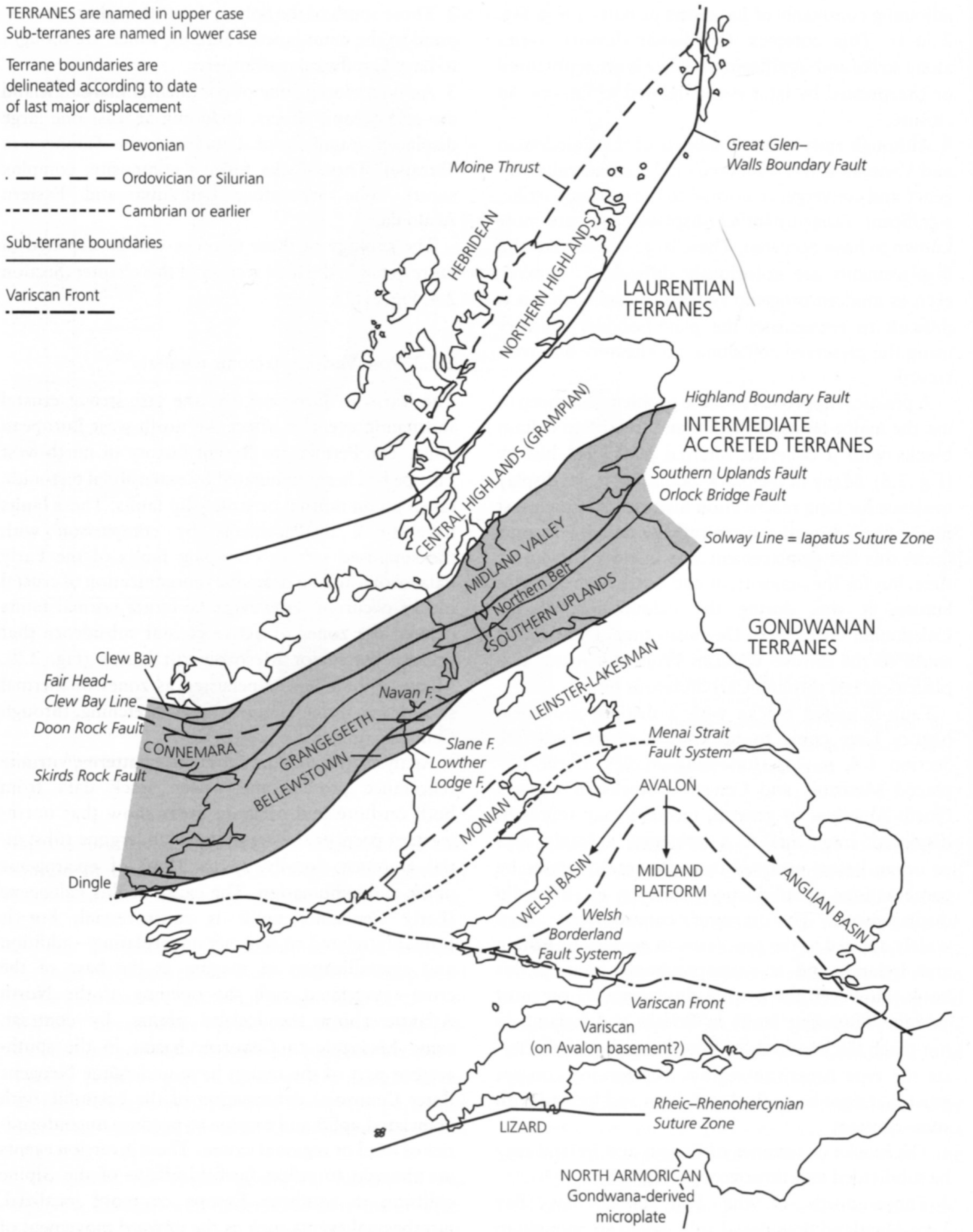
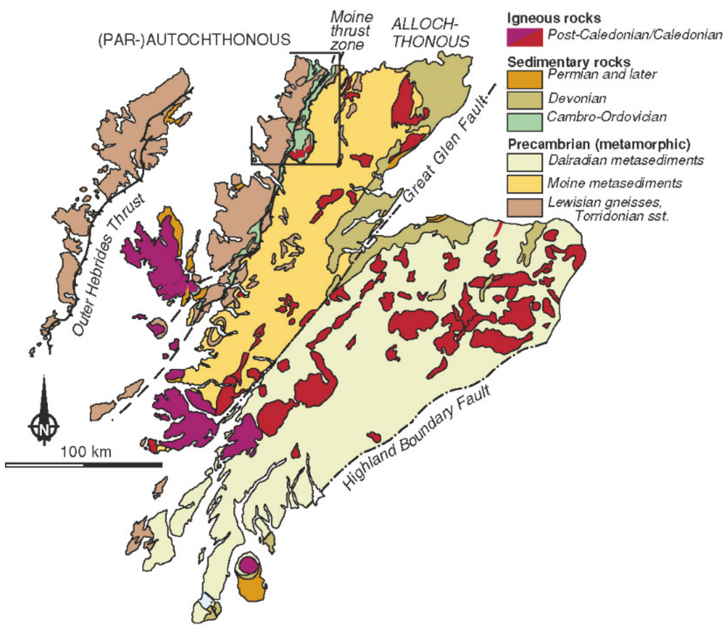


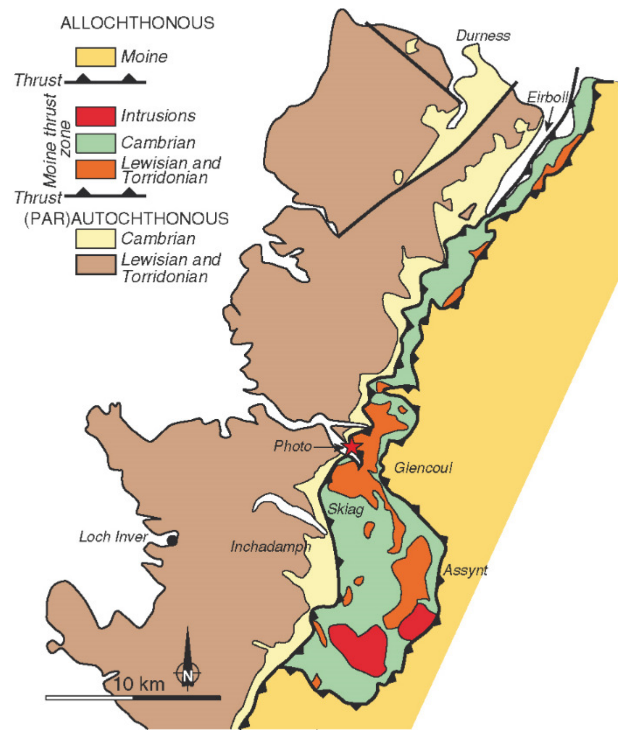

**Fig. 2.8** Simplified Palaeozoic terrane map of Britain and Ireland (after Bluck *et al.* 1992, with permission of the Geological Society, London 1999).

**Major Faults:**

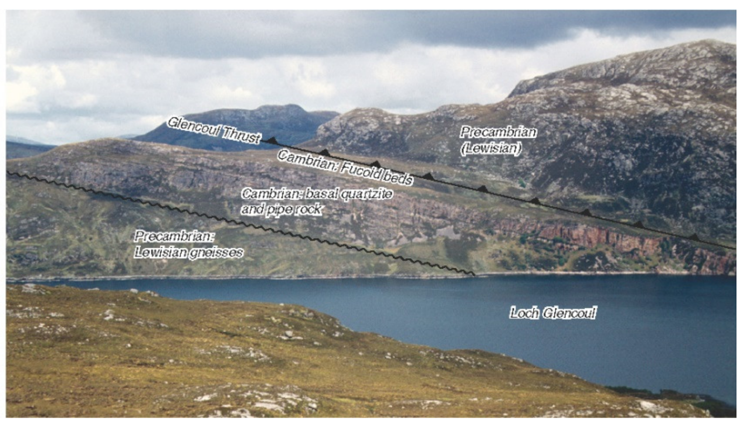
*Moine Thrust*

- Separates the NW Highlands/Islands from the Northern Highlands
- Precambrain but reactivated during Caledonian (Devonian)
- Classic thrust fault ~100 km of motion (NW) moving Moine and Dalradian rocks on top of Lewisian basement and younger sed rocks
- Imbricate structures, duplexes, mylonites, etc.
- First true description of a thrust fault




Sharp thrust contact between Precambrian gneisses and underlying Cambrian quartzite in the Moine thrust zone.




Sliver of Lewisian basement thrust above Cambrian sedimentary layers. Older rocks resting on younger ones, as seen here, are a classic feature in thrust and nappe regions.

Fossen, 2010

*<u>Great Glen Fault</u>*

- Separates the Northern Highlands from the Grampian Highlands

*<u>Highlands Boundary Fault</u>*

- Separates the Grampian Highlands from the Midland Valley – truly the highlands from the lowlands
- Transpressive and sinestral with little movement
- Associated with the Acadian Orogeny - Devonian

*<u>Southern Uplands Fault</u>*

- Separates the Midland Valley from the Southern Uplands

*<u>Solway Line</u>*

- Separates the Southern Uplands from the Leinster-Lakesman (England)
- Break off from interterrains and Avalonian/Gondwanan terrains
- Site of the former Iapetus – suture line

**Orogenies:**

*Acadian*

- Microcontinent breaks off of Gondwana and collides with Baltica (slightly) and then docks on Laurentia

*Caledonian*

- Assembly of Pangea – contiguous with the Appalachian/Alleghenian orogeny
- Closure of Iapetus

*Grampian*

- Main phase of the Caledonian Orogeny and specifically refers to the collision of Baltica and Laurentia - Devonian

*Variscan (or Hercynian)*

- Basically one of the last orogenies to form Pangea
- Euramerica (Laurussia) and Gondwana

**Physiographic Units:**

*Outer Hebrides and Northwest Highlands:*

- Ancient rocks (Precambrian)
- Far north Shetland Islands (Unst) has an ophiolite sequence from the Iapetus Ocean that is one of the type examples of a "black-wall zone"

*Northern Highlands:*

- The Moine Group, the Old Red Stone and some intrusions
- Laurentain terranes

*Grampian Highlands:*

- Lots of igneous rocks intruding the Dalradian formation
- Laurentian terranes

*Midland Valley:*

- Intermediate accreted terranes

*Southern Uplands*

- Intermediate accreted terranes

# GENERAL INFORMATION

## Scientific Value of Scotland's Geodiversity

*The following is an excerpt from:*

*Gordon, J.E. & Barron, H.F (2011). Scotland's geodiversity: development of the basis for a national framework. Scottish Natural Heritage Commissioned Report No. 417.*

Scotland's rocks and landforms are a key asset of national and international importance for a number of reasons:

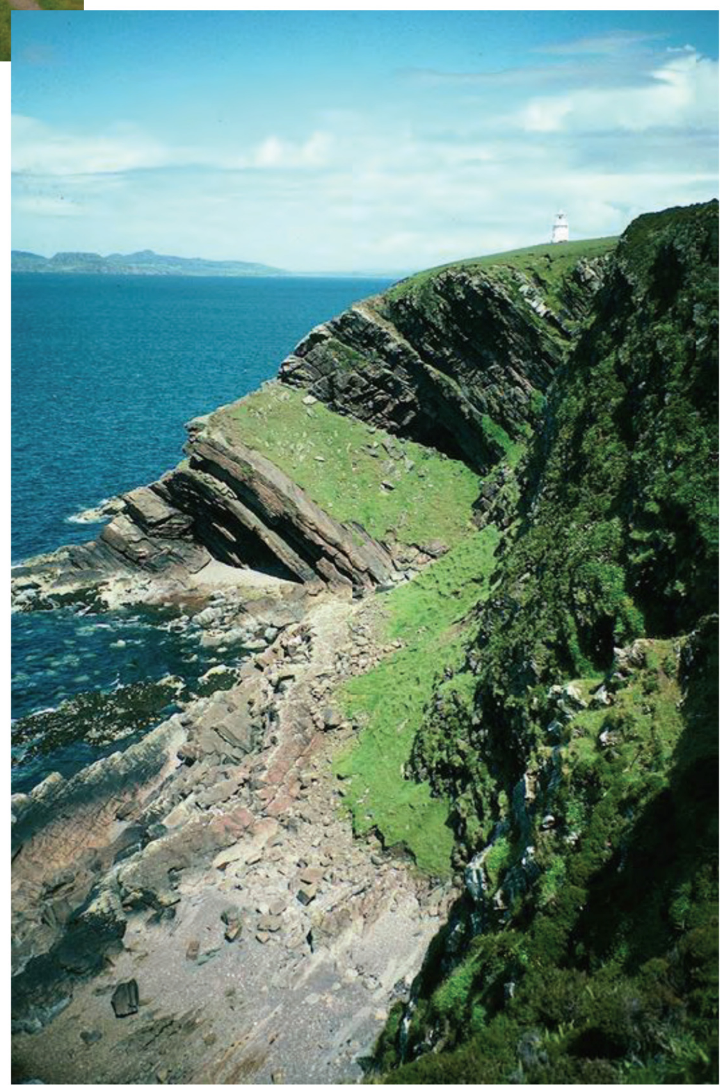
- geological diversity - reflecting the length of the preserved geological record, plate tectonic history and diversity of palaeogeographies, palaeoenvironments and geological processes and the extent to which these phenomena are exposed at surface and so accessible for observation and study;
- Scotland's role in the history of geology;
- understanding past geological processes (e.g. volcanism, crustal deformation) and their modern counterparts;
- records of palaeoenvironmental conditions, palaeogeography, and structural and metamorphic evolution now preserved in sedimentary, igneous and metamorphic rock units covering the last billion years;
- rich and diverse fossil record that spans critical moments in evolution;
- ice age environmental change and landscape modification;
- postglacial and contemporary geomorphological processes, including soil formation.

Areas such as the NW Highlands, Glen Coe, Rum and Arthur's Seat in Edinburgh have all provided crucial evidence for interpreting past geological processes of global significance. In the NW Highlands, the work of Sutton & Watson (1951) on the Lewisian Gneiss Complex laid much of the groundwork for unravelling the geological history of poly-deformed gneissic terrains. Following Lapworth's recognition that thrusting could occur on a crustal scale in the Loch Eriboll area, Peach & Horne (Peach at al., 1907) mapped and described the Moine Thrust Belt, probably, the most famous of the major Caledonian structures. Geological mapping of the Glen Coe area, early in the 20$^{th}$ century, revealed volcanic rocks of Devonian age attributable to cauldron subsidence, the first example of this volcanic feature to be identified and described in the older geological record (Clough et al., 1909). The Tertiary volcanic geology of Rum has yielded much information on the processes taking place in the environment of the magma chamber, with the development of theories relating to the origin of layering in igneous rocks (e.g. Wager & Brown, 1968). The Arthur's Seat volcanic complex (Figure 2.3) provided key evidence supporting the theories of James Hutton, who demonstrated that igneous rocks were emplaced as a hot fluid magma, rather than being formed as sedimentary deposits. Such evidence laid the foundations for the development of modern geology. Arthur's Seat is still regarded as an excellent example of a dissected ancient volcano (Upton, 2003) and one which attracts geologists from around the world; as do the other examples cited above and many others.

Scotland's rocks also provide outstanding records of palaeoenvironmental conditions and palaeogeography preserved in sedimentary rock formations covering the last billion years. For example, at Cailleach Head in Sutherland (Figure 2.4*),* a section through the youngest sediments of the 'Torridonian' succession represents the best example of cyclothemic sedimentation in Britain (Stewart, 2002). These c. 1000 million year old sedimentary rocks comprise around 20 units of lakebed shales and silts, interspersed with alluvial fan deposits.

Figure 2.4 Hutton's section at Salisbury Crags, Edinburgh. (Photo: Colin MacFadyen).

Figure 2.5 Cailleach Head, Sutherland. (Photo: Colin MacFadyen).



The Highlands and Islands and the Southern Uplands form the type area of the Caledonide orogeny and provide evidence of their complex structural and metamorphic evolution between 1000 and 400 million years ago. This occurred when Scotland lay near to, or on, the margin of a large continental mass called Laurentia, which included Greenland and North America.

Equally, Scotland's fossil heritage has had a crucial role in studies of the evolution of the plant and animal kingdoms. Although metamorphic and igneous rocks underlie more than half of Scotland's area, the remaining sedimentary rocks, especially the Palaeozoic and Jurassic sequences, contain rich fossil assemblages of immense diversity, some of which are unique. These have yielded the world's oldest known vertebrate (Dineley & Metcalf, 1999), a rich diversity of early amphibian remains (Milner & Sequeira, 1994), one of the earliest known reptilians – *Westlothiana lizziae (*Smithson et al., 1994), the oldest known example of an *in situ* fossilized terrestrial ecosystem (hot spring), in the form of the Rhynie Chert (Cleal & Thomas, 1995), and some of the earliest mammal remains (Waldman & Savage, 1972). Scotland is also of great importance in the history and development of palaeontology through the work and publications, for example, of Louis Agassiz and Hugh Miller on the fossil fishes of the Old Red Sandstone (Agassiz, 1835; Miller, 1840) (Figure 2.5).

Evidence from Scotland is crucial for studies of Quaternary glaciation (the Ice Age of the last 2.6 million years). Scotland lies at the maritime fringe of NW Europe, in a region that is climatically sensitive due to its proximity to the atmospheric and marine polar fronts and the North Atlantic Drift. The diverse landform and depositional records of Scotland and the adjacent continental shelves are potentially of great value for understanding the coupling of the atmosphere, oceans, ice sheets and biosphere during periods of rapid climate change in this region (Gordon & Sutherland, 1993; Bradwell et al., 2008; Stoker et al., 2009). In particular, there is the opportunity to link terrestrial and offshore evidence with the high resolution Greenland ice core and deep-sea records (e.g. Scourse et al., 2009). The wealth of information relating to the period following the Last Glacial Maximum and the termination of the last glacial cycle, a time of remarkably rapid environmental change, now provides unprecedented opportunities to reconstruct climate change and to assess the sensitivity of geomorphological and biological systems, as reflected in glacier dynamics, sea-level fluctuations and changes in terrestrial and marine biota (Lowe & Walker, 1997).

Figure 2.6 Achanarras Quarry, Caithness, is a world-class locality for Devonian (Old Red Sandstone) fossil fish. (Photo: R. Davidson).

Quaternary palaeoenvironmental records preserved in loch sediments, peat bogs and coastal and estuarine sediments are important in setting current environmental changes into a longer-term context, particularly the effects of climate variability on the landscape, sea level and ecosystems, and in assessing scenarios of future change (e.g. Edwards & Whittington, 2003; Walker & Lowe, 2007). From these records it is possible to understand how climate, physical processes, sea level and habitats have changed in the past and hence evaluate current observed or anticipated changes in both geomorphological and ecological systems in that context (cf. Birks, 1997; Werritty & Leys, 2001; Willis & Birks, 2006; Willis et al., 2007, 2010a, b; Froyd & Willis, 2008; Davies & Bunting, 2010; Geherls, 2010). In turn, this may help inform conservation management and the potential for recovery from human impacts. For example, such records should allow an assessment of the extent to which projected changes arising from global warming and sea-level rise are likely to lie within the range of natural changes that have occurred within the Holocene, or to what extent significant thresholds are likely to be crossed, which may have economic and social costs as well as environmental implications through increased frequency of storm events or flooding.

Table 2.1 Geodiversity features and localities of exceptional value on a world scale and contributions of Scottish geology and geologists to the development of geoscience. (See also Box 2.1)

| Field | Exceptional features | Key localities | Major Scottish contributions and features |
|---|---|---|---|
| Stratigraphy and structural geology | Unconformity (historical significance) | Siccar Point, Jedburgh | **James Hutton** (1726 - 1797): 'The father of modern geology'. Recognition of the immensity of geological time. His 'Theory of the Earth' (1788) proposed the idea of a rock cycle in which weathered rocks form new sediments and that granites were of volcanic origin.<br><br>**John Playfair** (1748 - 1819): His book 'Illustrations of the Huttonian Theory of the Earth' (1802) summarized Hutton's work and brought Hutton's principle of uniformitarianism to a wide audience.<br><br>**Sir Charles Lyell** (1797 - 1875): His 'Principles of Geology' (1830) built on Hutton's ideas, developing further the theory of uniformitarianism, where the Earth's history can be explained by gradual change over time. He also proposed the idea that different periods of geologic time could be established by reference fossils. Lyell was a powerful influence on the young Charles Darwin. |
| | Moine Thrust<br><br>Moffat Shale sequence (historical significance) | NW Highlands<br><br>Dob's Linn: the global Ordovician – Silurian boundary stratotype | **Sir Roderick Murchison** (1792 - 1871): Second Director General of the Geological Survey. Wrongly thought Moine schists were not older than Silurian as they were above the Durness Limestone.<br><br>**James Nicol** (1810 - 1879): The first clear account of the succession of the fossiliferous Lower Palaeozoic rocks of the Southern Uplands.<br><br>**Charles Lapworth** (1842 - 1920): Unravelled the structural complexity of the Southern Uplands using graptolite assemblages. In the NW Highlands he was the first to propose the controversial theory that here older rocks were found lying above younger, suggesting complex folding or faulting as a cause. Later **Peach** and **Horne** surveyed the area and their monumental memoir proved Lapworth correct.<br><br>**Benjamin Peach** (1842 - 1926) and **John Horne** (1848 - 1928): Provided the first major synthesis of thrust belt structure and the basis for descriptions of fault and shear zone processes and deductive methods for unravelling tectonic histories. Wrote the classic memoir 'The Geological Structure of the North-West Highlands of Scotland' (Peach et al., 1907). |
| | | | **John MacCulloch** (1773 - 1835): Surveyed and compiled the first large-scale geological map of Scotland, published posthumously in 1836. |
| Mineralogy | | | **William Nicol** (1771 - 1851): Inventor of the Nicol prism and the thin section. |
| | Many mineral species first identified in Scotland | Leadhills, Strontian, Tyndrum | **Matthew Heddle** (1828 - 1897): Published 'Mineralogy of Scotland', helped create the Mineralogical Society, and as President of the Edinburgh Geological Society he helped to convince the government to set up the Geological Survey of Scotland in 1855. |
| Metamorphic geology | Lewisian and Torridonian rocks | Western Isles, NW Highlands | **John Sutton** (1919 - 1992) and **Janet Watson** (1923 - 1985): Unravelled the geological history of a polydeformed high-grade gneiss complex, which was a world first (Sutton & Watson, 1951). |
| | Barrovian metamorphic | Glen Clova, Glen Esk | **George Barrow** (1853 - 1932): Discovery of metamorphic zones. |

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| | zones | | |
| Igneous geology | Palaeogene layered intrusions | Cuillin of Skye and Rum | **Alfred Harker** (1859 - 1939): Pioneered the use of the petrological microscope and the thin section in interpretive petrology; ground-breaking work on layered intrusions in Skye and Rum.<br>**Lawrence Wager** (1904 - 1965) and **Sir Malcolm Brown** (1925–1997): The first to study layered intrusions in detail and understand magma chamber processes (Wager & Brown, 1968). |
| | Cauldron subsidence | Glen Coe, Rum | **Sir Edward Bailey** (1881 - 1965): Recognition of cauldron subsidence in Glencoe (Clough et al. 1909). |
| | Igneous intrusion relationships | Salisbury Crags, Glen Tilt | Recognition that igneous rocks formed from magma – end of the Neptunian doctrine. At Glen Tilt, **James Hutton** showed that granite formed from the cooling of molten rock, not precipitation out of water as the Neptunists of the time believed. |
| Geochronology | | | **William Thomson** (Lord Kelvin) (1824 - 1907): The first to calculate the age of the earth and contributed to the understanding of the internal structure of the Earth. |
| | | | **Arthur Holmes** (1890 - 1965): A pioneer of geochronology – performed the first uranium-lead radiometric dating of a rock. |
| Quaternary geology and geomorphology | Glacial landforms and processes | Glen Roy, Cairngorms, the Cuillin, Carstairs Kames, NW Highlands | **James Forbes** (1809 - 1868): Made a major contribution to the emerging science of glaciology through his work in the Alps. Published one of the first detailed studies of glacier landforms in Scotland in his classic paper 'Notes on the topography and geology of the Cuchullin Hills in Skye, and on the traces of ancient glaciers which they present' (1846).<br>**Sir Andrew Ramsay** (1814 - 1891): Played a key part in developing ideas on landscape modification by glacial erosion.<br>**Sir Archibald Geikie** (1835 - 1924): In his 1863 paper 'On the phenomena of the glacial drift of Scotland', the effects of ice action in Scotland were for the first time clearly and systematically demonstrated.<br>**James Geikie** (1839 - 1915): Contribution to the advancement of glaciation, and was described as one of "the most eminent glacialists of his day". During his geological survey activities, he found evidence of warmer, inter-glacial periods. He suggested that the existence of river terraces at different levels might indicate climatic cycles during the Pleistocene, as opposed to Agassiz's theory of a single great Ice Age. |
| | Land- and sea-level changes | Forth Valley, Islay, Jura | **Charles Maclaren** (1782 - 1866): Development of the concept of eustasy.<br>**Thomas Jamieson** (1829 - 1913): Development of the concept of isostasy.<br>**Brian Sissons** (1926 - ): Demonstrated the isostatic tilting of shorelines in Scotland and published numerous classic papers on the patterns of former relative sea-level changes in an isostatically uplifted area. |
| | Machair | Outer Hebrides | Landform and habitat assemblage unique to Scotland and Ireland. |
| | Dynamic coastal landforms | West coasts of Shetland and Orkney, Spey Bay, Sands of Forvie, Morrich More | Features associated with high-energy, exposed environments; blown-sand features; extensive areas of sand coast progradation; features associated with glaciated coasts. |
| Palaeontology | Devonian fossil fish faunas | Moray Firth, Cromarty, Caithness | **Hugh Miller** (1802 - 1856): Stonemason and self-taught geologist, writer, theologian and palaeontologist. His study of the fossil fishes of the Old Red Sandstone (Devonian), led to his writing of three best-selling books: 'The Old Red Sandstone'; 'Footprints of the Creator'; and |

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| | | | ‘Testimony of the Rocks’. |
| | | | **Rev David Ure** (1750-1798): The ‘Father of Scottish Palaeontology’, published ‘The History of Rutherglen and East-Kilbride’, with the first images and description of ostracods and rhizodont fish. |
| | | | **John Young** (1823-1900): Immense contribution to the understanding of Carboniferous fossils of the West of Scotland. |
| | | | **Elizabeth Anderson Gray** (1831-1924): Extensive and meticulous collector of Ordovician and Silurian fossils of the Girvan area of Ayrshire. |
| | | | **Robert Kidston** (1852-1924): The most influential palaeobotanist of his day; published more than 180 papers on the taxonomy and distribution of floras of the Carboniferous, Permo-Carboniferous and Devonian. The first to use a microscope to study fossil spores. |
| | Early Devonian plants and animals | Rhynie | The Rhynie chert is an Early Devonian Lagerstätte containing exceptionally preserved plant, fungus, lichen and animal material, study of which is important in the understanding the development of some of the earliest terrestrial life on Earth. |
| | Carboniferous shark fauna | Bearsden | Discovery of specimens that have led to advances in shark evolution (S.P. Wood). |
| | Middle Jurassic dinosaur footprints | Skye | Discovery and study of globally rare trackways (N. Clark). |
| | Conodont animals (*Clydagnathus windsorensis)* | Granton foreshore, Edinburgh | The world’s first specimen of a conodont animal (Briggs et al., 1983; Aldridge et al., 1993). |
| | *Westlothiana lizziae* | East Kirkton Quarry, Bathgate | One of the oldest reptile-like animals ever discovered (Smithson et al., 1994). |
| Continental drift | | | **Arthur Holmes (**1890–1965): Championed the theory of continental drift, proposing that the Earth's mantle contained convection cells that dissipated radioactive heat and moved the crust at the surface. His famous book ‘Principles of Physical Geology’ (1944), ended with a chapter on continental drift; part of this model was the origin of the seafloor spreading concept (Vine, 1966). |
| Climate change | | | **James Croll** (1821–1890): Self-educated scientist who developed a theory of climate change based on changes in the Earth's orbit. His work was widely discussed but his theory was generally disbelieved. However, the basic idea of orbitally-forced insolation variations influencing terrestrial temperatures was further developed by Milutin Milankovitch in the 1920s and 1930s. |
| Geoconservation | | | **John Muir** (1838–1914): ‘The Father of National Parks’. |

## James Hutton: A man ahead of his time

*The following is taken from:*
*Lothian and Borders RIGS Group, (date unknown) James Hutton: A man ahead of his time. Lothian and Borders RIGS Group Leaflet, 4 pgs.*

### Introduction

Scotland between the years of 1730 and 1790 enjoyed a spell of intense intellectual activity known as the Scottish Enlightenment - a unique period in history, one of optimism, improvement and discoveries in industry, commerce, agriculture, science and the arts.

James Hutton grew up during this period and made a considerable contribution to our understanding of Earth processes and of the immensity of Time. He was a landowner, farmer, agriculturalist, physician, and an outstanding natural philosopher who was elected to the Royal Society of Edinburgh. Hutton, of course pre-dated photography so the only clues we have as to his appearance come from painting and sculpture, not all of which can be considered life-like.

From the portrait by Sir Henry Raeburn
**Founder of Modern Geology**
(1726 – 1797)

Hutton is depicted with a hammer in his right hand and rock specimen in his left (sculptor David Watson Stevenson). On his left is John Hunter the renowned surgeon and anatomist. The building stone is red, wind-blown, desert sandstone of Permian Age (286-248 million years old) from Dumfriesshire.

### James Hutton's Theory

The surface of the Earth is constantly being eroded and the products deposited in the sea. Hutton believed the sediments were then compressed, folded and uplifted, sometimes with volcanic activity, for the cycle of erosion to resume. He also said that earth processes of the past were similar to those acting at present (a prevalent idea - Comte de Buffon 1790), and that the slow cycle was capable of repeating itself. He put it succinctly: " the result, therefore, of our present enquiry is that we find no vestige of a beginning - no prospect of an end."

**James Hutton Memorial Garden**

This marks the site of James Hutton's Edinburgh home on St John's Hill in the Pleasance above Holyrood Road.

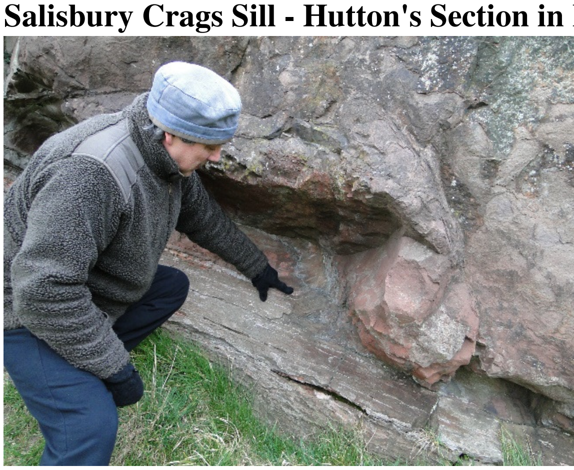

A plaque at the entrance from the car park at Edinburgh University Centre for Sport and Exercise reads:- This memorial garden was constructed in 2001 for the University of Edinburgh and marks the site of the house and garden of James Hutton (1726 - 1797) at St. John's Hill. The garden contains a memorial plaque and five boulders (indicated on the key below) which illustrate two main themes of Hutton's geological work.

Hutton used the presence of granite veins in metamorphosed sedimentary schist in Glen Tilt near Blair Atholl to demonstrate that granite is an igneous rock and that it must have been younger than rocks it penetrated. The granite veins can be seen in the two boulders from Glen Tilt. The three other boulders are conglomerate from Barbush near Dunblane and are full of fragments of older rocks, demonstrating the continuity and cyclic nature of geological processes.

**Memorial garden boulders.**

The two lower boulders from Glen Tilt came from close to the actual spot investigated by Hutton. They show granite veins penetrating the country rock. The upper boulder is full of fragments of pre-existing rocks from a previous cycle of erosion.

**Salisbury Crags Sill - Hutton's Section in Holyrood Park, Edinburgh**



A key site in his new understanding of geology is at the south end of this escarpment formed by the intrusive dolerite sill that is over 300 million years old. Hutton associated 'extreme heat' as the agent of folding and uplift of strata. The question as to what produced the heat could not be answered at that time. In Hutton's own words “We know that the land is raised by a power which has for its principle subterraneous heat, but how that land is preserved in its elevated station, is a subject which we have not even the means to form a conjecture.” He believed that molten rock (magma) under pressure could be 'intruded' between or across layers of sedimentary rocks, sometimes reaching the surface as lava flows. He found evidence to support this in Holyrood Park. The photograph shows a section of the Salisbury Crags sill where igneous rock (called whinstone locally) has been intruded between sedimentary layers. Here at the base of the sill magma has forced its way into the underlying sedimentary strata. Such a dynamic contact feature is incompatible with the then contemporaneous view that igneous rocks 'crystallised like salt from sea water'.

**North Newton shore, Arran 1787**

Hutton discovered his first unconformity site in the summer of 1787. This site displays an angular unconformity between steeply inclined metasedimentary rocks of the Precambrian Dalradian Supergroup (600my. old) and the much younger sedimentary rocks of the latest Devonian / earliest
Carboniferous Kinnesswood Formation (360my. old). The exposure is unusual in having a calcreted 'surface' in both series of rocks suggesting a long period of exposure of the unconformity surface in a hot semi-arid climate when the younger rocks started to be laid down.

**Inchbonny, Jedburgh (photographed in 2001)**

Here, at the second of his unconformity sites, at Inchbonny, Hutton found nearly vertical sedimentary strata with horizontal Upper Old Red Sandstone red beds on top. He concluded that the vertical beds must have been raised above the surface of the ocean , subjected to the levelling effect of weathering and erosion before sinking below sea level when a new set of sediments mainly sandstones and mudstones were deposited on top. Hutton was wrong in one detail. At none of his sites of unconformity are the directly overlying rocks of marine origin but they are in fact fluvial.

**Siccar Point near Cockburnspath 1788**

Hutton believed that cyclic processes (similar to orbits in astronomy, and blood circulation in the body) operated in the Earth. He saw weathering and erosion denuding the land and producing sediments under the sea which then consolidated into rock. The cycle was continued through uplift with the necessary energy supplied by internal heat. He thought of the Earth as a dynamic heat engine capable of helping to drive the cycle. The most convincing proof of his cyclic theory was obtained on the Berwickshire coast at Siccar Point, the third of his unconformity sites which he visited with Sir James Hall and John Playfair.

Silurian sediments were laid down and consolidated into poorly sorted sandstones (greywackes). These rocks were uplifted, folded and eventually eroded. Deposition of fresh red Upper Old Red Sandstone sediments took place during the following geological period of the Upper Devonian. The rock cycle continued, resulting in the present day picture. In this spectacular exposure, the gap in time represented by the unconformity is about 55 million years!

**Hutton's farmhouse at Slighhouses near Duns, Berwickshire.**

At the start of the 18th century agriculture was still rather primitive in Scotland with heavy wooden ploughs, no hedges or fences, and a 'runrig' system of scattered strips of cultivation. Between 1697 and 1703 there were periods of famine in the land, and harvest failures. This farm and that at Nether Monynut, eight miles away were inherited by Hutton. From 1754 to 1767 he chose to live at Slighhouses. He set about enclosing and draining the land. He introduced new methods of crop rotation and ploughing, with modern ideas he had seen in practice in Norfolk and Flanders. During this time he never lost his enthusiasm for solving geological problems. Slighhouses Farm is on Upper Old Red Sandstone sedimentary rocks (370my. old) with a superficial cover of glacial till deposited during the last ice age about 27000 -13000 years ago.

**Hutton's Marl Pit.**
Hutton used Slighhouses as a living laboratory to investigate agriculture and other natural history phenomena. The marl pit he created is still in evidence, and he wrote of using marl (limey mud) on his fields to improve crop yield. He was not always successful as some of the marl was not limey**.**

**Collegiate Church. (15th century Gothic)**
This is the resting place of Sir James Hall of Dunglass, geologist and chemist, (1761 - 1832). He admired Hutton, while not accepting the enormous periods of time required for Hutton's Uniformitarian view that geological history is a matter of ordinary forces and unlimited time. In 1798 Sir James Hall investigated the action of heat and pressure on rocks. The Wernerians had pointed out that basalt, when heated and cooled in experiments, turned to glass not crystalline rock, therefore basalt must be a precipitate from a universal ocean.

Hall allowed molten basalt to cool very slowly, and it reformed as crystals not as a glass. By experiment, he showed the igneous nature of basalt and granite. In 1785, the Church held that the age of the Earth was nearly 6000 years. Bibles published in 1793 were annotated to that effect.

**Hutton roof, National Museum of Scotland.**
Andy Goldsworthy's four sandstone blocks invite us to look down through the layers of time and think of their formation from desert sands 270 million years ago, and yet again to the origin of the sand grains from erosion in periods even farther back in time**.**

**Hutton's grave in Greyfriars Churchyard Edinburgh.**
His grave in the Balfour family vault in the section known as the Covenanters' Prison was unmarked until November 1947 when a simple plaque was erected marking the 150$^{th}$ anniversary of Hutton's death. In 1997 a Bicentennary International Conference was held in Edinburgh, a wreath laid, and a eulogy spoken by Professor Donald McIntyre which finished with these words:- " Today we have come to know that living creatures evolve, that continents drift, that stars and galaxies are born, mature, grow old and die. We salute the memory of James Hutton, who opened our minds to these wondrous possibilities."

# The Scotch Whisky Guide

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## The History of Scotch Whisky

The first written mention of Scotch was found scribed on June 1st, 1495 in Volume X on page 487 of the Exchequer Rolls of Scotland where it reads "To Friar John Cor, by order of the King, to make aqua vitae VIII bolls of malt". The Exchequer Rolls were records of all royal income and expenses. In this particular entry, it documents that Cor was given eight bolls of malt to make aqua vitae throughout the months of 1494. What this shows is that despite being the earliest written reference, distillation was well under way come the fifteenth century. If we only take into account the eight bolls given to Cor in 1494, we can estimate that 1500 bottles of whisky were produced that year. Evolving from a Scottish drink called uisge beatha (meaning "water of life"), whisky began to circulate throughout the country, causing policymakers to begin taxing it come the year 1644. Unfortunately, despite the government's attempt to regulate and draw income from such a popular drink, distillers began to sell it illegally and sales flourished across Scotland. By 1780 there were eight legal distilleries in all of Scotland competing against more than four hundred bootleg operations. By 1823 Parliament realized that in order for the legal producers to be able to compete with the pirates, they would have to ease restrictions and this decision is what gave birth to the famous 'excise act'.

The popularity of whisky swelled again in 1831 with the invention of the column still. Now, thanks to new technology, distilleries were able to mass produce a smoother spirit at a significantly lesser cost.

Then in 1880, Scotch whisky became a global phenomenon thanks to a new microscopic insect that preyed on the grape vines in France. Since wine and brandy were considered two of the most popular drinks of the day, when the phylloxera bug began to destroy vineyards across France, wine and brandy production came to an almost immediate halt. With alcoholics around the world craving a substitute, the doors to the global marketplace opened wide for Scotland's distillers and Scotch whisky became the world's new popular drink.

## Types of Scotch Whisky

There are two main types of Scotch whisky; single malt and single grain. From those two types, three sub categories are formed. Those categories are blended Scotch, blended malt Scotch and blended grain Scotch.

### Single Malt

Single malt Scotch whisky is today, the most popular choice in North American homes. This is an aged whisky made by a single distillery using only malted barley and water. It contains no other cereals and must be distilled, produced and bottled in Scotland.
Single Grain

### Single grain

Scotch whisky is less commonly found on the shelves of your local liquor store. It starts out with water and a malted barley but then has additional whole grains or cereals added to it which prevents it from complying with the laws that would permit it to be called single malt. Just like with single malt Scotch, it too, has to be bottled in Scotland in order for it to be able to use the "Scotch" name. It is this type of Scotch that most blended Scotch whisky is made from.

**Blended Scotch**

A blended Scotch whisky is made from at least one or more single malt Scotch whiskies that is blended together with a single grain Scotch whisky.

**Blended Malt Scotch**

A blended malt Scotch is actually one of the most uncommon types of Scotch that can be found today. Previously called a "vatted malt" or a "pure malt" it is when the blender takes two or more single malt Scotch whiskies from at least two separate distilleries and blends them together to create one batch of whisky.

**Blended Grain Scotch**

A blended grain Scotch is similar to that of a blended malt, except it utilizes two or more single grain Scotch whiskies from at least two separate distilleries. They are then blended together to create a single batch of whisky.

**Double Malt Scotch**

Many people have heard of a whisky referred to as a "double malt" Scotch. It should be noted that these do not actually exist. Whenever a bottle of single malt Scotch is referred to as "double malt" or "triple malt" it simply means that it was aged in two or more types of casks. The true term for this is double wood or triple wood. This is very common in the whisky world and despite being aged in multiple casks, it still remains in the single malt category.

**The Name**

While most consumers have a general understanding that Scotch whisky must always be from Scotland, few actually know the legal requirements behind naming a bottle of whisky "Scotch". The title of "Scotch" is defined and regulated by a document created on November 23, 2009 called the "Scotch Whisky Regulations 2009" or SWR. Not only regulating production, the act also governs the labeling, packaging and the advertising of Scotch whisky within the United Kingdom. The SWR is a complete replacement of the previous regulations which focused exclusively on the production process. While the SWR is technically only valid within its jurisdiction, international trade agreements have been put in place which effectively makes some provisions of the SWR apply in countries outside the United Kingdom.

The document defines Scotch whisky in the following manner:

**1:** Must be produced at a distillery in Scotland from water and malted barley (to which only whole grains of other cereals may be added) all of which have been:
- Processed at that distillery into a mash
- Converted at that distillery to a fermentable substrate only by endogenous enzyme systems
- Fermented at that distillery only by adding yeast
- Distilled at an alcoholic strength by volume of less than 94.8% (190 US proof)
- Wholly matured in an excise warehouse in Scotland in oak casks of a capacity not exceeding 700 litres (185 US gal; 154 imp gal) for at least three years

**2.** Scotch whisky must retain the color, aroma and taste of the raw materials used in, and the method of, its production and maturation.

**3.** It may not contain any added substances, aside from water and plain (E150A) caramel coloring.

**4.** It must comprise a minimum alcoholic strength by volume of 40% (80 US proof).

## The Production Process

The production of Scotch whisky begins with water. It is for this reason that many of the distilleries still found today are located adjacent to pure water sources such as a river or even a borehole. While transportation is far more effective today, when the vast majority of Scottish distilleries were erected, having to transport large quantities of fresh water proved to be difficult, thereby requiring the distilleries to be built near a plentiful source.

One of the things that separates Scotch whisky from other whiskies is that the water in Scotland tends to be much softer with significantly lower mineral and calcium contents. For the distilleries located on the west coast of Scotland, particularly on the islands, the water has a much higher peat content due the water running through peat bogs, which cause it to have a slightly brown tinge. While there is no direct evidence to suggest this natural peat effects the flavor of the whisky, many distilleries believe it to be special, and for that reason they are very protective of their water supply.

While there is no legal obligation to use Scottish barley to produce Scotch whisky, the vast majority of barley used to make whisky around the world is from Scotland, therefore making it cost effective to utilize local barley.

Once the water is collected it's used in a variety of ways, the first of which is often to malt the barley. In order to successfully malt barley, the grains are soaked in the water which causes the starch to convert into a type of sugar called maltose which feeds a process known as *Germination*.

Over the next six days little shoots begin to grow all over the grains which lets the producer know the barley is ready to be dried. To do this, the distillery will elect to use hot air or peat smoke to dry out the grains which stops further growth of the shoots and prevents it from rotting. While the majority of distilleries now purchase their barley pre-malted, there are still a small handful of producers that choose to malt the barley from scratch. Despite the process being painstaking and lengthy, distilleries such as *The Balvenie* and *Highland Park* view it as a tradition and pride themselves on their malting floors.

Now that the barley is properly malted, it gets ground until it resembles something like flour. The water source is again introduced and the mixture is poured into a vessel called the Mash Tun. As the barley mixture steeps in the hot water, the mashing tun separates the solids from the sugars and the process is repeated at least twice more. By the time this part of the production process is completed, the hot sugary liquid, called the Wort is ready to continue being turned into whisky.

The next step in whisky making is called the Fermentation Process. The wort is pumped into a wooden or stainless steel receptacle called the Washback and dried or creamed yeast is added to the mix. Once the yeast is added to liquid, it begins to rapidly multiply using up the oxygen in the washback and creating carbon dioxide. As blades mix the yeast into the wort, over the next 48 hours, the yeast begins to devour the sugars turning the wort into alcohol. The distiller now chooses whether or not to remove the liquid or let it sit for up to another 70 hours which produces a fruitier flavor.

The next step is the actual distillation of the whisky. This is when the alcohol is poured into a copper pot still to undergo a series of two distillations, or in some cases, three. The first distillation, called the Wash Still is where the alcohol is heated until it boils and its vapor is condensed into liquid and carried through the coiled pipes. The new liquid is then dumped into cooling vats and is now typically around 28% alcohol. Then, the process is repeated and the spirit is re-distilled until it reaches approximately 70% alcohol. As it distills, the vapor is pumped into a rectifying column, making its way through a water-cooled condenser to the spirit safe. The spirit safe then captures the purest cuts that will eventually mature into Scotch whisky.

What's interesting to note is that the stills used are often a variety of shapes and sizes. What this does is changes the style of the whisky based on the type of flavor profiles the producer wants in its stock. Next, the best cuts of the spirit are slightly diluted with more water and poured into wooden oak casks (usually from bourbon whiskey or spanish sherry) where the whisky will sit and mature for at least three years, developing a complex range of flavors and aromas as it soaks up the hidden spirits still buried deep in the wooden casks. After it's sat for the minimum required length of three years, it is now ready to be bottled or stored longer, increasing its age and complexity.

**The Regions of Scotland**

Divided into five distinct regions, Scotland produces a variety of whiskies that take on certain flavor profiles based on the region they're distilled in.


**The Highlands**

Known as medium bodied whiskies, they are typically lighter and more luxurious than their brothers Islay, but stronger than the ones in the Lowlands. Today there are many highland distilleries, some of which include Aberfeldy, Balblair, Ben Nevis, Clynelish, The Dalmore, Dalwhinnie, Glen Ord, Glenmorangie, Oban and Old Pulteney. On the islands, you can find Arran, Jura, Tobermory, Highland Park and Scapa, as well as Talisker still operating today. While many whisky connoisseurs believe the islands should have their own region, they are still technically classified as a part of the highlands.

**The Lowlands**

Generally considered the lighter and most delicate whiskies, the Lowland distilleries often produce spirits with very little to no peat. Today the only distilleries still in operation are Auchentoshan, Bladnoch and Glenkinchie. However, a fourth distillery has recently opened called Daftmill, but its first release is still in production and is not expected to be released to the public until sometime in 2015.

**Speyside**

Home to the most elegant and inspired whiskies in Scotland, Speyside is also home to the most distilleries in the Country, some of which include Aberlour, The Balvenie, Cardhu, Cragganmore, Glenfarclas, Glenfiddich, Glenglassaugh, The Glenlivet, Glen Moray and The Macallan.

**Campbeltown**

With the majority of its bottles aged at the 10 year mark, the region is home to just three active distilleries which include Glen Scotia, Glengyle and Springbank.

**Islay**

Considered the heavy-hitters of Scotch whisky, these spirits are usually heavily peated, often oily and even sometimes compared to iodine. Islay is home to a current eight distilleries which include Ardbeg, Bowmore, Bruichladdich, Bunnahabhain, Caol Ila, Kilchoman, Lagavulin and Laphroaig.

**Recommended Whiskies**

Scotch whisky has long been my favorite spirit. On any given evening you can usually find me in my living room enjoying a dram or two as I listen to my records or watch an old movie. This list, while partial, are a few of my favorite whiskies, all of which I highly recommend.

**The Highlands**

The Dalmore King Alexander III *(one of my favorite bottles in the world)*
The Dalmore Cigar Malt Reserve *(this Scotch pairs perfectly with a medium to full-bodied cigar)*
Jura Superstition *(press your palm against the logo for good luck)*
Highland Park 12 Year
Scapa 16 Year
Talisker 18 Year

**The Lowlands**

Auchentoshan Three Wood (no peat, very delicate and quite inexpensive. A perfect introduction to Scotch whisky)
Glenkinchie 12 Year
Rosebank 12 Year

**Speyside**

The Macallan Fine Oak
The Macallan 12 Year (while there are many incredible, older bottles, the 12 year is my nightly dram)
The Macallan 25 Year
Aberlour 12 Year (probably the best bottle in its low price point)
Aberlour A'bunadh
The Balvenie Doublewood

**Islay**

Bowmore 18 Year
Lagavulin 16 Year
Caol Ila Moch
Laphroaig 12 Year

**Campbeltown**

Glen Scotia 12 Year
Springbank 10 Year

**Conclusion**

Scotch has and I presume will always be a spirit that one either loves or hates. While a taste for it can be developed over time, typically the most common palate development occurs amongst gentlemen who already enjoy the taste and simply grow to appreciate the varieties.

I would highly recommend that if you've never tried Scotch whisky before, that you begin with a gentler, more subtle bottle such as the Auchentoshan 12 year or the Dalwhinnie 15 year , and not with a dram of Lagavulin or Laphroaig.

One final tip for the Scotch connoisseur is to always keep a few basics on hand. This way should you have company over, if they are inclined to try a dram of Scotch but don't have the appreciation for it, rather than wasting a remarkable whisky on a plebeian's palate, I always keep a bottle of 12 year old Glenlivet and Glenfiddich in my bar. That way you can save the premium whisky for those who will truly enjoy it.

# Geology and Whisky

*The following is take from:*

Cribb, S. and Cribb, J., 1998, Whisky on the Rocks. British Geological Survey, Keyworth, Nottingham, United Kingdom, 73 pgs.

## *Whisky on the Rocks*

*'I will give unto him that is athirst of the fountain of the water of life freely.'* Revelation, 21.6.

The presence of water has always controlled the siting of distilleries, because not only is there a requirement for reliable supplies of clean, fresh, process water but also large volumes are needed for cooling purposes. Most distilleries are sited on the banks of streams or rivers. In the past these were the source of the process waters, but nowadays, particularly in areas where population and land usage has increased, it is not unusual for the water to be collected higher up in the hills and then piped to the distillery, sometimes over a distance of several kilometres. The original streams can still provide waters for cooling. In areas that are intensively farmed, or are close to large centres of population, many of the shallow or surface water sources are no longer usable at all and deeper boreholes or the public water supply have to be used. Such a change in supply can mean water of a different chemistry has to be used and this can have a significant effect on the whisky produced.

The primary source of water is rain, but what happens to rainwater before its arrival at the distillery affects its *chemistry* and thus the uniqueness of the resulting malt whisky. The rain may end up as a stream or river, in a loch or a reservoir, coming from the rock as deep or shallow boreholes (5), or as a spring high on a hillside (1, 2).

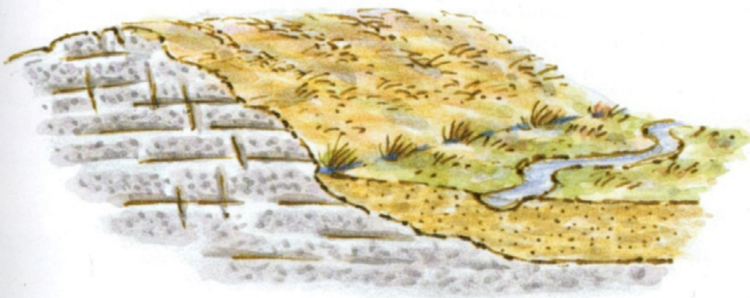
If it falls on bare mountains made of crystalline rocks it will flow rapidly downhill as streams. This water has little chance to interact with the underlying rocks and often has a low mineral content. It will be acid and soft.

**1** A spring line forms where the water table intersects the land surface.

**2** Water is forced to the surface because it cannot pass through an impermeable layer.

On the other hand if the strata are more permeable, or have many joints and fractures (4), the rain will percolate into and through the rock (3), dissolving it and increasing the water's *mineral* content. Limestones and sandstones, for example, yield waters rich in carbonates or sulphates; such waters will be neutral or slightly alkaline and hard.

*'Soft water, through peat, over granite'* was the traditional and still oft-quoted view of the best water for distilling. Remarkably, out of the 100 or so single malt whiskies, less than 20 use water that fits this description. What is certain is that the water must be crystal clear; it must be pure, and the source must be reliable.

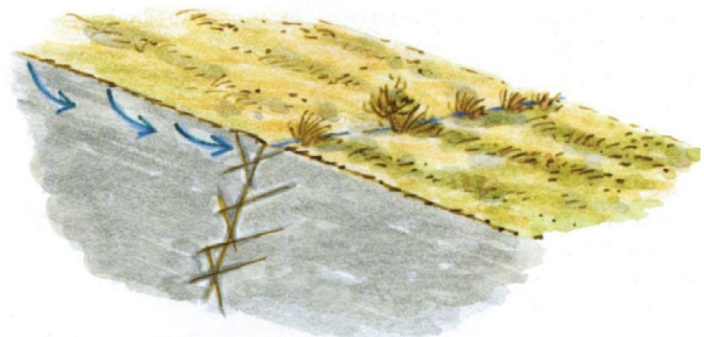


**3** Water flows through joints and cracks in rocks and appears at the edge of a valley filled with impermeable clay.

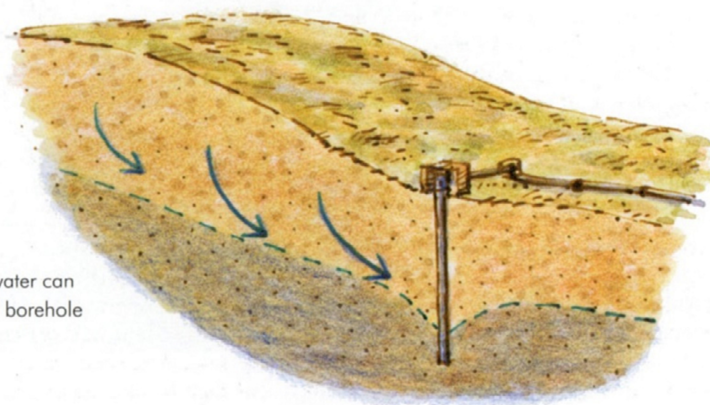
There is no prescribed way to appreciate fully the flavour of the whisky, but it is generally agreed by the experts that the addition of a little water releases the aromatics and increases the perception of both taste and smell. The ideal is to be able to use the water from which the whisky was made.

Several distilleries have taken the lead from Glen Grant, which in Victorian days kept spirits by the distillery dam and allowed a special tasting for favoured clients. If you are ever lucky enough to get such an opportunity, seize it with both hands, but if not, try to use a pure, unsparkling Scottish mineral water to dilute your whisky.

Your tour is about to begin, but first let us look at Scotland's geology, famed throughout the world for its variety and the pioneering spirits of its geologists, beginning with James Hutton, the *founder of modern geology*. Scottish localities have given their names to a chemical element *(strontium)*, minerals *(cairngorm, leadhill*ite, *mull*ite, *tobermor* ite) and rocks *(appin*ite, *kentallen*ite, *mugear*ite*)*: exports of significance, if not as famous as the whiskies!



**4** A fault breaks the rocks and creates a channel of easy flow to the surface.



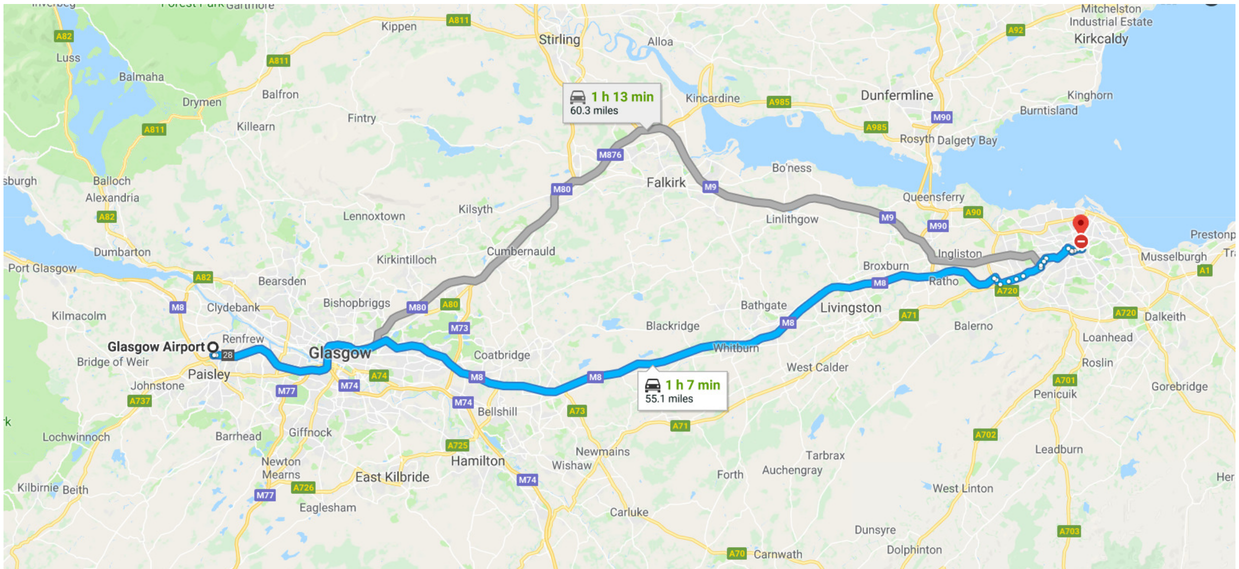
**5** Underground water can be tapped by a borehole or well.

# DETAILED ITINERARY

**Day -1: Saturday, March 3rd, 2018 – Board flight**

**5:00PM:** Leave Krebs Parking Lot
**8:30PM:** Arrive at Dulles Airport
**10:30PM:** Depart Washington Dulles (British Air BA0292) to London Heathrow

**Day 1: Sunday, March 4th, 2018 – Arrive in Glasgow – Get to Edinburgh**




**10:40 AM:** Arrive in London Heathrow for a layover
**1:05 PM:** Depart London (British Air BA1484) to Glasgow
**2:30 PM:** Arrive in Glasgow, get rental cars, drive to Edinburgh and do some grocery shopping

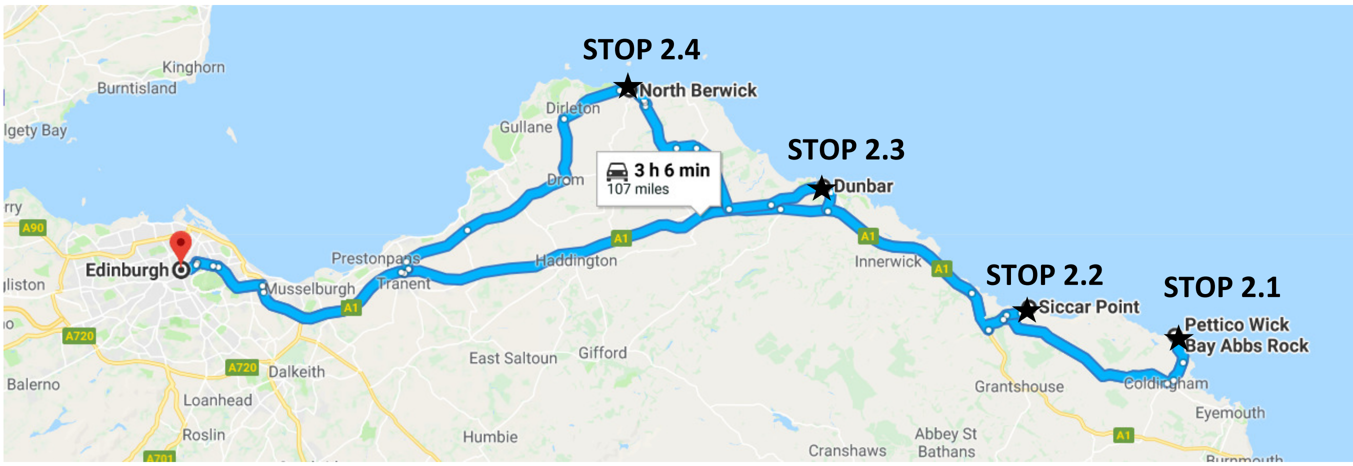
**Rental Place:** Dollar Rent-a-Car
Car Rental Hall, Terminal Building,
St Andrews Drive, Paisley PA3 2ST, UK

**5:00 PM:** Grocery store
**6:00 PM:** Arrive in Edinburgh, take a nap, and then go out for a group dinner

**Hotel:** Cowgate Tourist Hostel
96 Cowgate
Edinburgh, EH1 2PW
Tel 44 808168 9610
http://www.hostelsinedinburgh.com/

**Day 2: Monday, March 5th, 2018 – Siccar Point, the Garleton Hills, and the Coast Edinburgh**

**8:00 AM:** Breakfast in the hostel
**8:30 AM:** Leave Hostel
**9:30 AM:** Arrive at St Abbs Head – Folds fault adjacent to volcanics
**10:30 AM:** Siccar Point – Hutton's Unconformity
**12:00 PM:** Have lunch out of the back of the van
**1:00 PM:** Dunbar – exposed volcanic necks in the sea cliffs
**3:00 PM:** North Berwick – Carboniferous Volcanics
**5:00 PM:** Return to the hostel
**6:00 PM:** Group dinner we will cook at the hostel




**STOP 2.1:** *Pettico Wick, St Abbs Bay*

*The following is taken from:*

Holdsworth, R.E., Tavarnelli, E., and Clegg, P., 2002, The nature and regional significance of structures in the Gala Group of the Southern Uplands terrane, Berwickshire coast, southeastern Scotland. Geological Magazine, v. 139, n. 6, 707-717.


**Abstract** – Structures deforming Llandovery turbidites of the Gala Group in the Southern Uplands terrane are spectacularly exposed in the Berwickshire coastal section, southeastern Scotland. The upward-facing, upright to NW-vergent folds and associated structures appear to record a single regional phase of subhorizontal NW–SE contractional deformation, with a steeply dipping direction of bulk finite extension. These structures are markedly different from those developed in rocks correlated with the Upper Llandovery Hawick Group exposed some 5 km to the south in the Eyemouth–Burnmouth coastal section. Here a highly domainal system of sinistral transpressional strain occurs, with zones of steeply plunging curvilinear folds, clockwise cleavage transection and bedding-parallel sinistral detachment faults. The markedly different bulk strain patterns in the Berwickshire coastal sections are thought to reflect the regionally diachronous nature of transpressional deformation in the Southern Uplands terrane. There are striking similarities in the structures recognized in the Berwickshire coastal sections and those developed in stratigraphically equivalent units along strike in southwestern Scotland and Northern Ireland. This confirms the lateral structural continuity and correlation of tracts and tract boundaries along the entire length of the Southern Uplands terrane. The regional structure suggests that a phase of top-to-the-NW backthrusting and backfolding associated with the southern margin of the Gala Group outcrop marks the transition from orthogonal contraction to sinistral transpression in the Southern Upland thrust wedge during late Llandovery times.

## 1. Introduction

The widely studied Southern Uplands terrane in the Caledonian orogen of Scotland (Fig. 1a) forms part of a broad belt of Palaeozoic deformation that resulted from the sinistral oblique closure of the Iapetus Ocean (Dewey & Shackleton, 1984; Soper & Hutton, 1984; Soper *et al.* 1992). Numerous studies have documented the structures present in this terrane in some detail, notably in Northern Ireland (e.g. Anderson & Cameron, 1979; Anderson & Oliver, 1986; Anderson, 1987), southwestern Scotland (e.g. Stringer & Treagus, 1980, 1981; Anderson & Oliver, 1986; Kemp, 1986, 1987; Barnes, Anderson & McCurry, 1987; Stone, 1995, 1996; Lintern & Floyd, 2000) and inland regions of the Southern Uplands (e.g. Barnes, Phillips & Boland, 1995; Phillips *et al.* 1995; Stone, 1996). However, with the exception of the detailed BGS memoir (Greig, 1988), there are few modern published accounts of the well-exposed section of deformed Silurian rocks exposed along the Berwickshire coastline in southeastern Scotland (Fig. 1b). Holdsworth *et al.* (2002) have recently published a detailed description of the structural geology of the Eyemouth to Burnmouth section (Fig. 1b) where they document evidence for strain partitioning during bulk sinistral transpression leading to a complex and highly domainal style of deformation. The present paper gives an account of the structures in the northernmost coastal section of Berwickshire between Fast Castle & Pettico Wick. The relatively simple pattern of neutral- to slightly NW-verging, cylindroidal folding contrasts sharply with the more complex transpressional deformation seen in the Eyemouth–Burnmouth section that lies only 5 km to the south. These findings have implications concerning the structural and tectonostratigraphic continuity of the Southern Uplands terrane and shed further light on the regional significance of NW-directed movements in this otherwise SE-directed zone of overthrusting.

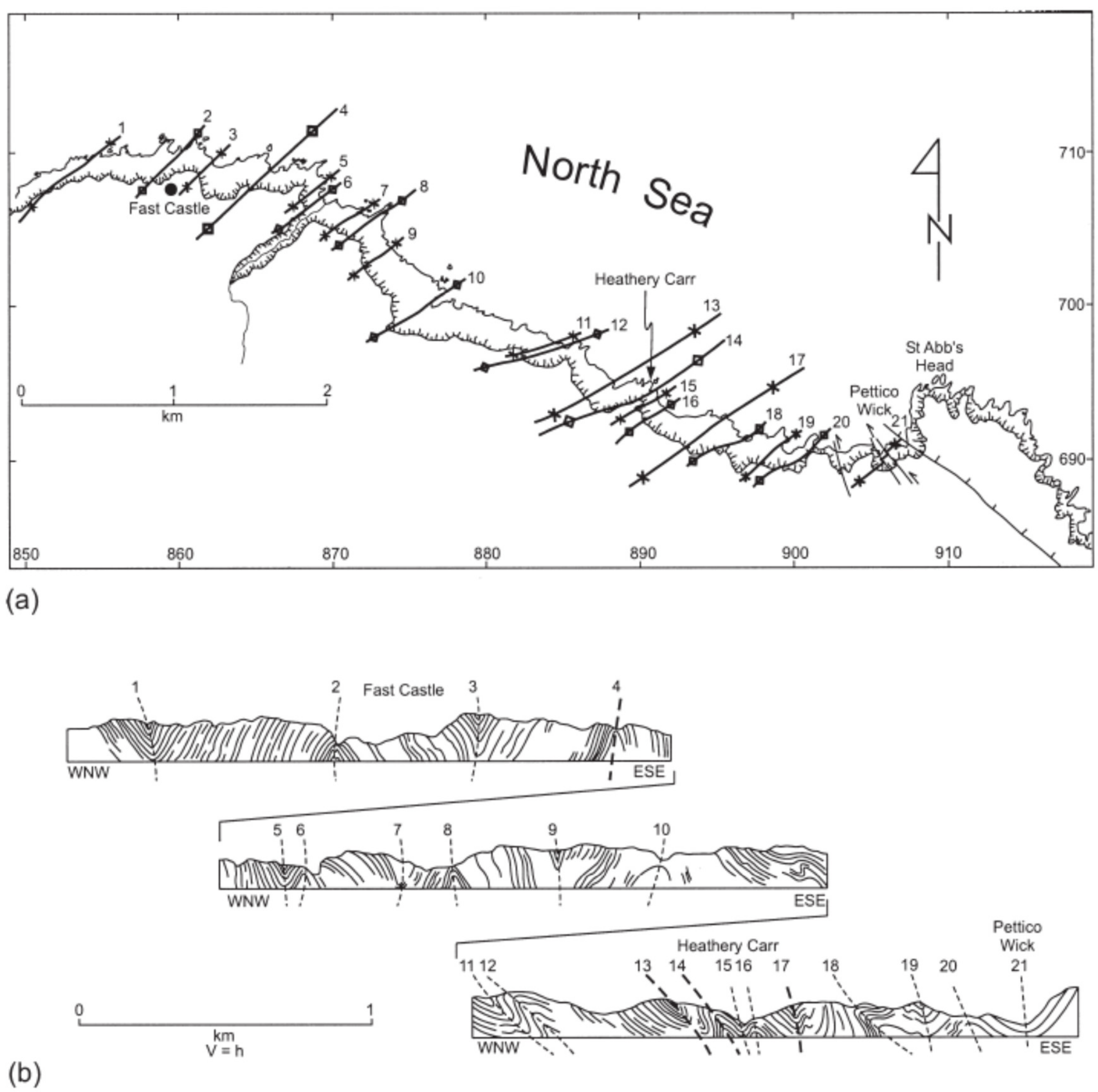
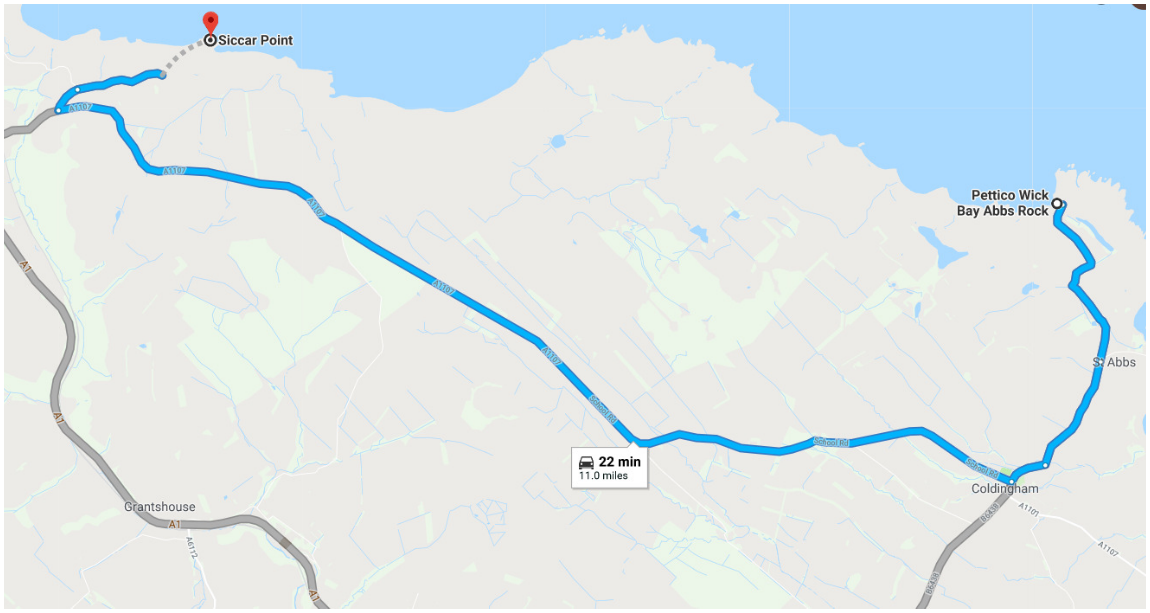
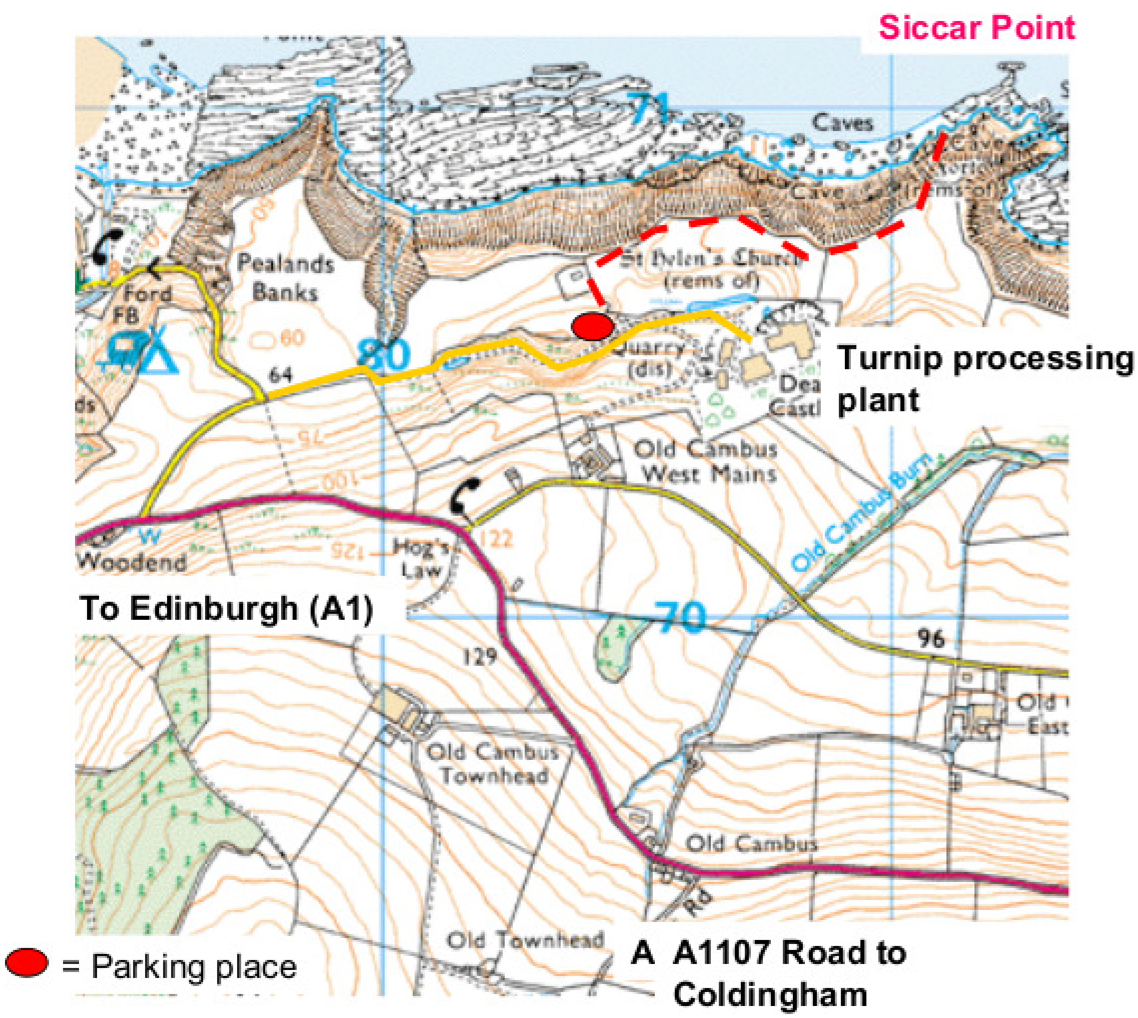



Figure 2. (a) Simplified structural map and (b) cross-section of the Fast Castle–Pettico Wick coastal section, with axial traces of major folds indicated.

**STOP 2.2:** *Siccar Point*



# Siccar Point,
## the world's most important geological site

James Hutton, father of modern geology, visited Siccar Point by boat in 1788, an event which led to a profound change in the way the history of the Earth was understood. A man ahead of his time, James Hutton used the evidence from Siccar Point to decode Earth processes and to argue for a much greater length of geological time than was popularly accepted.

As John Playfair later recorded of their visit *"The mind seemed to grow giddy by looking so far into the abyss of time".* A concept of 'deep time' emerged with the recognition that the geological processes occurring around us today have operated over a long period and will continue to do so into the future.

You can visit Siccar Point today, and see the spectacular junction between two distinctive types of rock, just as Hutton himself found it.

The two sets of rocks at Siccar Point are dark grey steeply tilted rocks formed in an ancient ocean, and the much younger, almost horizontal red rocks formed on land. The deposition of the two different types of rock was not continuous, but separated by a gap of 65 million years during which time the older rocks were changed and eroded.

Walk in James Hutton's footsteps and explore the story of this remarkable man and our modern understanding of his geology, representing millions of years of erosion, deposition, folding, faulting and uplift.

# How to get to Siccar Point


*© OpenStreetMap contributors*

Location 40 miles east of Edinburgh, close to the A1. From the A1 head towards Coldingham on the A1107. After crossing the narrow Pease Dean Bridge, take first left, signposted Pease Bay. Then proceed straight on, ignoring the next left turn to Pease Bay. Park in the large lay-by on the left-hand side of the road, before the gates into the Drysdales' site. From here two information boards guide you along the cliff top path to Siccar Point. Nearest toilets and shop are at Cockburnspath village (see map).

**SAFETY WARNING** Visit Siccar Point at your own risk. The grassy slope down to the rocks is steep, may be slippery and there is no path. Sturdy footwear is recommended. The safest option is to view the rocks from the top of the grassy slope; binoculars may be useful. Hammering and rock specimen collection is prohibited.


**Acknowledgements**

We are grateful to Drysdales for a donation towards printing costs for this leaflet.

Text: Based on an original project by Alex Crabtree; taken forward by Angus Miller and other members of the Lothian and Borders GeoConservation Group.

Images: Andrew McMillan, Angus Miller, Mike Browne

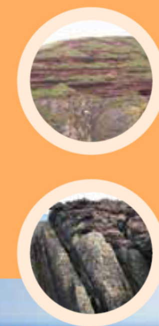
Designed by Derek Munn

Produced by the Lothian and Borders GeoConservation Group of the Edinburgh Geological Society, a charity registered in Scotland Charity No: SC008011.

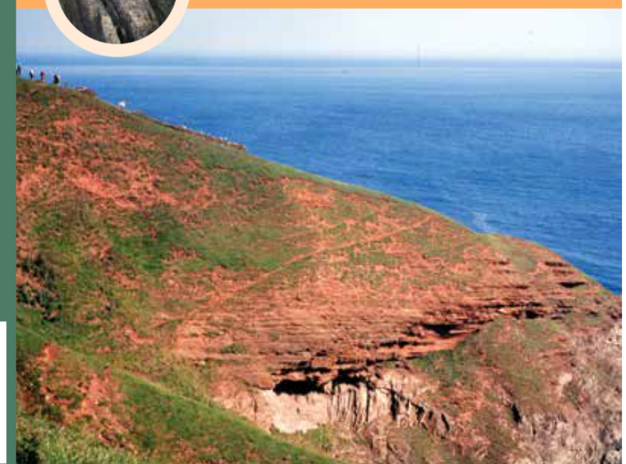




lbgeoconservation@edinburghgeolsoc.org

# Siccar Point



## Hutton's Unconformity
*Travel through the "abyss of time"*

Lothian and Borders GeoConservation

# James Hutton 1726 -1797

James Hutton was born in Edinburgh on 3rd June 1726. At the age of 14 he went to Edinburgh University to study humanities and medicine. Later he studied chemistry and anatomy in Paris, before obtaining his MD in 1749 from Leyden in the Netherlands.

In 1750, he inherited and worked two farms in the Scottish Borders. He travelled to Norfolk and Flanders to learn new farming methods and employed them on his own lands. After witnessing first-hand the processes of erosion and sediment deposition on his farms, he became interested in geology.

Hutton returned to Edinburgh in 1767, where he developed and finally published his geological theories. He was an important contributor to the Scottish Enlightenment, a period when Edinburgh, described by Tobias Smollett as "a hotbed of genius", saw the rise of revolutionary ideas in sciences and humanities. Hutton enjoyed the company of prominent Enlightenment figures including Sir James Hall of Dunglass (also a natural philosopher), James Watt, Adam Smith and Joseph Black.

Hutton's Theory of the Earth was presented in 1785 in front of the Royal Society of Edinburgh, then published in 1788 and enlarged to two volumes in 1795. Field visits to his three famous unconformity sites in North Arran, Jedburgh and Siccar Point took place in 1787-88. All provided evidence in support of his theory. He died on 26th March 1797, and is buried in Greyfriars Kirkyard, Edinburgh.

**Hutton at Siccar Point**

Hutton realised that the processes of erosion, deposition and uplift were connected and operated continuously, driven by the earth's internal heat, in a way not understood at the time. At Siccar Point in 1788, he finally found the clear evidence he needed to demonstrate his understanding of the processes and cycles that shaped the Earth.

Hutton arrived at Siccar Point by boat, accompanied by Sir James Hall of Dunglass and John Playfair.

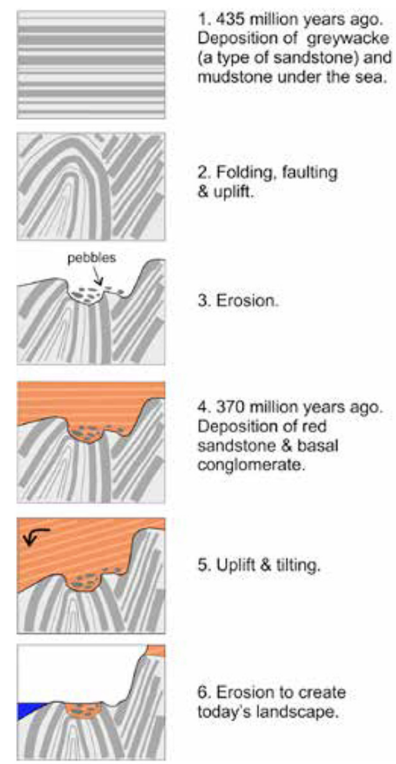
Playfair wrote: *"Dr Hutton was highly pleased with appearances that set in so clear a light the different formations, and where all the circumstances were combined that could render the observation satisfactory and precise … We felt necessarily carried back to a time when the schistus on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited, in the shape of sand or mud, from the waters of the supercontinent ocean... The mind seemed to grow giddy by looking so far into the abyss of time; and whilst we listened with earnestness and admiration to the philosopher who was now unfolding to us the order and series of these wonderful events, we became sensible how much further reason may sometimes go than imagination may venture to follow."*

Hutton inferred from the sharp junction between the two sets of rocks that an enormous interval of time was required for the underlying strata to be folded and eroded before the overlying sandstones were deposited. The fundamental geological principle of deep time was thus established and Hutton famously concluded his work Theory of the Earth with: *"We find no vestige of a beginning – no prospect of an end".* Since then different geological eras have been recognised and dated, and we now know that the Earth is around 4.5 billion years old.

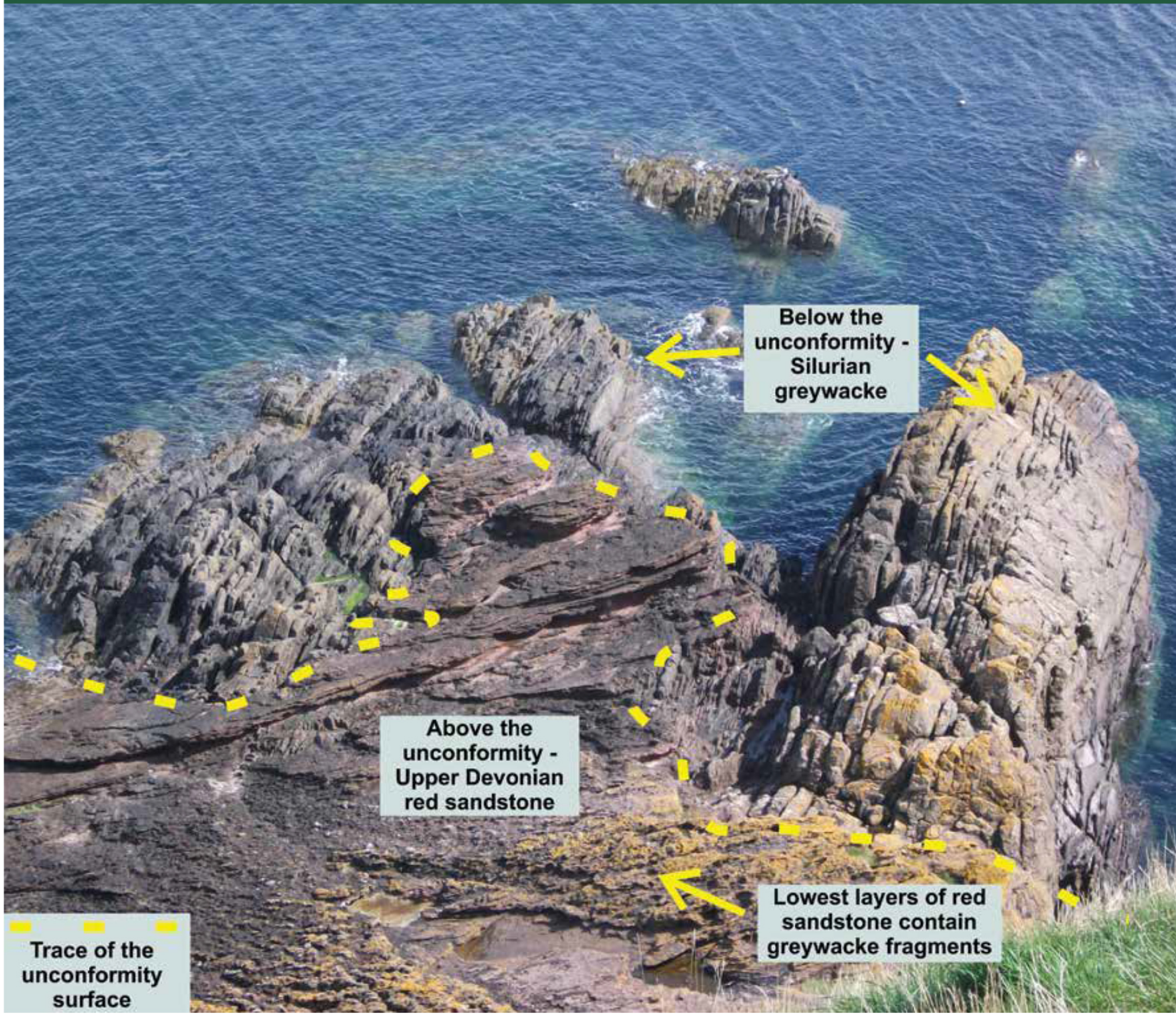
Hutton's discoveries fulfilled a tremendous mission: placing geology in a much wider time frame than the popular belief that the Earth was created in 4004 BC (as calculated by Bishop Ussher in 1650). This enabled geology to become a science in its own right with Hutton as its founding father.

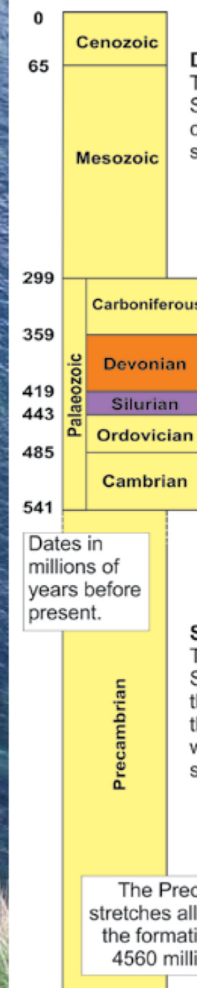
# The Siccar Point Unconformity

The two sets of rocks at Siccar Point are separated by an unconformity: an ancient land surface representing a time gap in the normal geological sequence. The Siccar Point unconformity is clearly visible as an etched junction with the dark grey vertical rocks underneath and the much younger, almost horizontal red rocks on top.

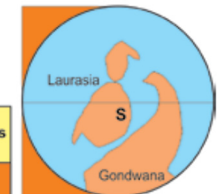


# Hutton's Unconformity - the view from above




**Devonian Period**
The upper rocks at Siccar Point formed in a continental setting just south of the equator.




S - position of Scotland


**Silurian Period**
The lower rocks at Siccar Point formed on the northern margin of the Iapetus Ocean, which was closing slowly.

## BELOW THE UNCONFORMITY

**Silurian greywacke sandstone and mudstone**

These rocks formed as flat-lying layers in deep water during the Silurian period, about 435 million years ago. Greywacke is a type of hard sandstone containing a mixture of rock fragments in a fine matrix of clay. The greywacke layers are separated by thin layers of mudstone, and together the rocks tell an interesting story of the conditions on the ocean floor. Most of the time, gentle ocean currents brought fine-grained mud into the deep sea, allowing the slow build up of layers that would eventually form mudstone. But every so often, dramatic, fast-moving torrents of sediment would be swept down the continental slope, forming layers of unsorted sandstone – the greywacke. These turbidity currents have been observed in modern oceans, and the greywacke layers at Siccar Point demonstrate that the same process happened here.

The Silurian strata at Siccar Point formed in the Iapetus Ocean, a long-lost ocean that separated two continents. As the Iapetus Ocean closed, the sea floor was subducted beneath the northern continent and some of the sea floor sedimentary rocks were buckled and compressed. The layers you can see at Siccar Point are now nearly vertical because of this tectonic movement.

After the ocean had closed, the ocean-floor rocks spent 65 million years at the surface, gradually being eroded. The softer mudstone layers wore away more easily, leaving the edges of the greywacke layers protruding dramatically and giving a corrugated land surface with many metres of visible relief.

Recent erosion by the sea follows the same pattern, so that the Silurian rocks exposed at Siccar Point and along the coast to the east have a distinctive character with strong ribs of greywacke separated by narrow clefts where mudstone has worn away.

James Hutton thought these rocks were laid down under the sea, and this was confirmed in 1792 when Sir James Hall found recognisable marine shells in associated rocks not far from Siccar Point.

**THE UNCONFORMITY** Intricate, three-dimensional surface representing a 65-million year gap in deposition.

## ABOVE THE UNCONFORMITY

**Upper Devonian red sandstones**

These rocks occur widely across Scotland. They formed on land in a low-lying area experiencing a tropical climate with wet and dry seasons. Rivers deposited sand and silt as the wet season declined. In the dry season this material was blown about by the wind, sometimes into dunes. Soils were poorly developed and vegetation sparse, consequently the erosive power of the rivers was even greater than it is today. The red colour of the rocks results from the presence of iron oxide. The sands and silts were deeply buried and gradually converted into rocks.

**Upper Devonian basal conglomerate**

Angular slab-like fragments of the underlying greywacke sandstone are common in the lowest layers of the red sandstones. These fragments were created from erosion of the older rocks, dumped on the land surface as talus (scree) and moved on by highly energetic, seasonal rivers flowing in desert wadis (valleys). The alignment of these fragments shows that the current flow in the wadis was from the northeast.

## What was Hutton looking for?

Hutton and his companions were well aware of the surrounding geology, and the landscape contrast between the older grey rocks - forming the hills of the Southern Uplands - and the younger rocks to the north and west that underlie more fertile farming areas.

In making their boat journey along the coast, they were hoping to find a clear example of the unconformity exposed in a sea cliff. The cliff on the south side of Siccar Point does show the unconformity very well, but Hutton was delighted to find that at the Point itself he could actually walk on the unconformity, *"a beautiful picture of this junction washed bare by the sea"* (Playfair).

*From:* McAdam & Clarkson, 1996, pgs. 146-151

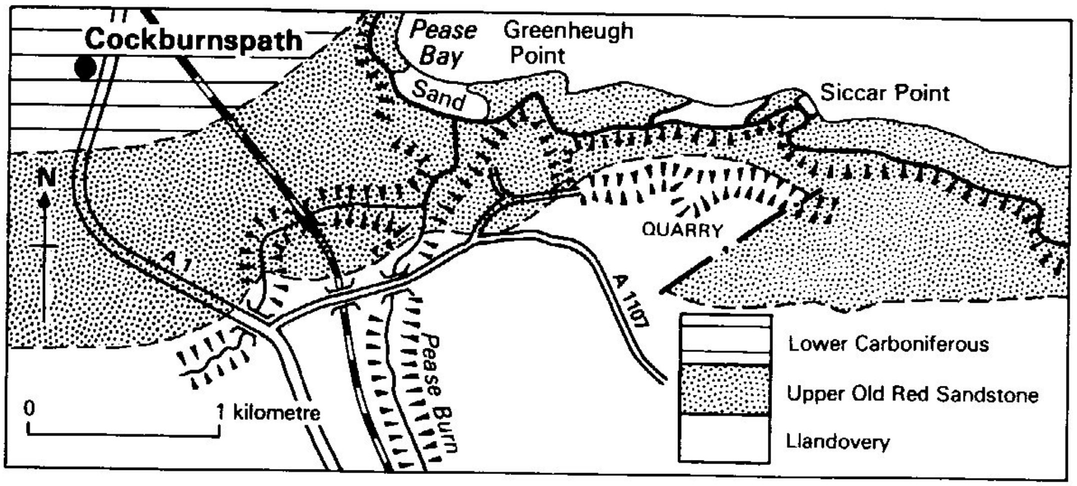
# SICCAR POINT: HUTTON'S CLASSIC UNCONFORMITY

**O.S. 1:50000 Sheet 67 Duns and Dunbar**
**B.G.S. 1:50000 Sheet 34 Eyemouth**
**Route: Map 18**

HISTORICALLY the Siccar Point unconformity is world-famous because its discoverer, James Hutton, was the first geologist to grasp the true significance of such a structure. Although this was not the first unconformity that Hutton had observed—the others were in Arran in 1786 and Jedburgh in 1787—it is certainly the most spectacular. His view of the rocks of the Earth as being the products of an essentially cyclical, oft-repeated process was triumphantly demonstrated at Siccar Point in 1788.

Siccar Point (NT 813 710) lies on the coast 4 km east of Cockburnspath. Turn east off the A1, a little over 2 km south of Cockburnspath on to the A1107. This road crosses the post-glacial gorge of the Pease Burn almost at once and the quarry road to Siccar Point turns off 450 m on the left after the narrow bridge over the gorge. Keep to the right fork of the quarry road, cross the grid bridge and continue along an extremely fine glacial drainage channel into Old Cambus Quarry. Continue through the north-east gate in the quarry and strike obliquely left up the hillside towards the far corner of the field, 60 m below which lies Siccar Point and Hutton's unconformity. From the cliffs a fine panorama can be seen to the north-west of the Upper Old Red Sandstone grading up into the grey sandstones of the Lower Carboniferous (Cove Excursion). The lighthouse in the middle distance at Barns Ness lies on the Lower Limestone Group (Catcraig Excursion) and in the far distance the Bass Rock juts out from the sea with North Berwick Law lying inland slightly to the west. Both are plugs of phonolitic trachyte (North Berwick Excursion).

Siccar Point speaks eloquently for itself and needs little description. It is spectacular at any stage of the tide. An inclined uneven basement of vertical greywackes and shales of Llandovery, Silurian, age youngs to the WNW and is covered unconformably by gently dipping dull-red breccia and sandstone of Upper Devonian or Lower Dinantian age. The breccia is composed of greywacke fragments. The breccia and sandstones were formed under flood conditions. The strong imbricate structure of the clasts in the breccia shows that the direction of derivation of the material was from the NNE and not from the cliffs above.




MAP 18. Siccar Point

Both Hutton and Playfair deserve to be quoted. Hutton described it (1795, I, 458) as follows:

"Having taken boat at Dunglass burn, we set out to explore the coast; and, we observed the horizontal sandstone turn up near the Pease burn, rising towards the schistus. We found the junction of that schistus with the red sandstone and marly strata on the shore and sea bank, at St. Helens, corresponding in general with what we had observed in the burns to the westward. But, at Siccar Point, we found a beautiful picture of this junction washed bare by the sea. The sandstone strata are partly washed away, and partly remaining upon the ends of the vertical schistus; and, in many places, points of the schistus strata are seen standing up through among the sandstone, the greatest part of which is worn away. Behind this again we have a natural section of those sandstone strata, containing fragments of the schistus.

After this nothing appears but the schistus rocks, until sandstone and marl again are found at Red-heugh above the vertical strata. From that bay to Fast Castle we had nothing to observe but the schistus, which is continued without interruption to St. Abb's Head. Beyond this, indeed, there appears to be something above the schistus; and great blocks of a red whin-stone or basaltes come down from the height and lie upon the shore; but we could not perceive distinctly how the upper mass is connected with the vertical schistus which is continued below.

Our attention was now directed to what we could observe with respect to the schisti, of which we had most beautiful views and most perfect sections. Here are two objects to be held in view, in making those observations; the original formation or stratification of the schisti, and the posterior operations by which the present state of things has been procured. We had remarkable examples for the illustration of both those subjects (Figure 19).

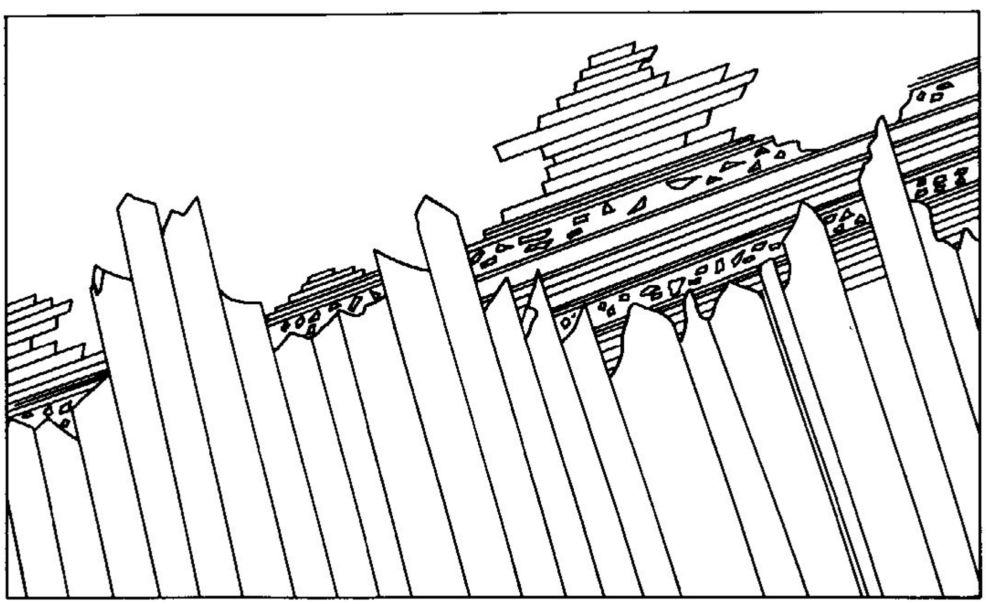


FIG 19. Siccar Point

With regard to the first, we have every where among the rocks many surfaces of the erected strata laid bare, in being separated. Here we found the most distinct marks of strata of sand modified by moving water. It is no other than that which we every day observe upon the sands of our own shore, when the sea has ebbed and left them in a waved figure, which cannot be mistaken. Such figures as these are extremely common in our sandstone strata; but this is an object which I never had distinctly observed in the alpine schisti; although, considering that the original of those schisti was strata of sand, and formed in water, there was no reason to doubt of such a thing being found. But here the examples are so many and so distinct, that it could not fail to give us great satisfaction.

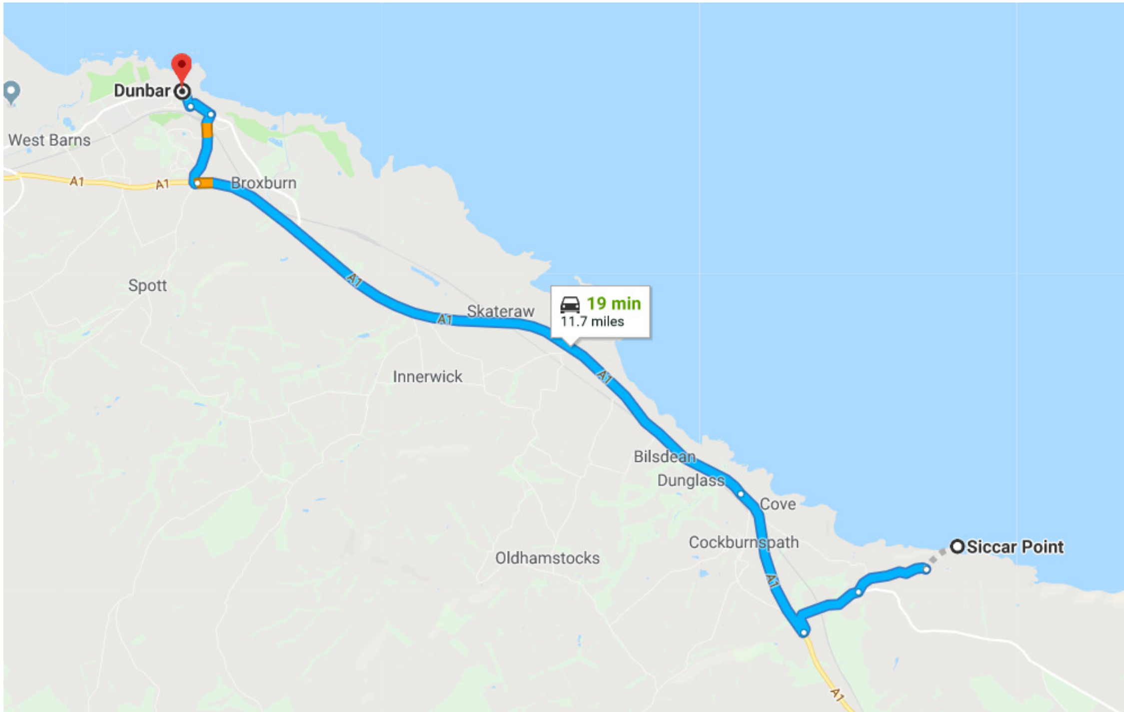
We were no less gratified in our view with respect to the other object, the mineral operations by which soft strata, regularly formed in horizontal planes at the bottom of the sea had been hardened and displaced. Fig. 4 represents one of those examples; it was drawn by Sir James Hall from a perfect section in the perpendicular cliff at Lumesden burn. Here is not only a fine example of the bendings of the strata, but also of a horizontal shift or hitch of those erected strata."

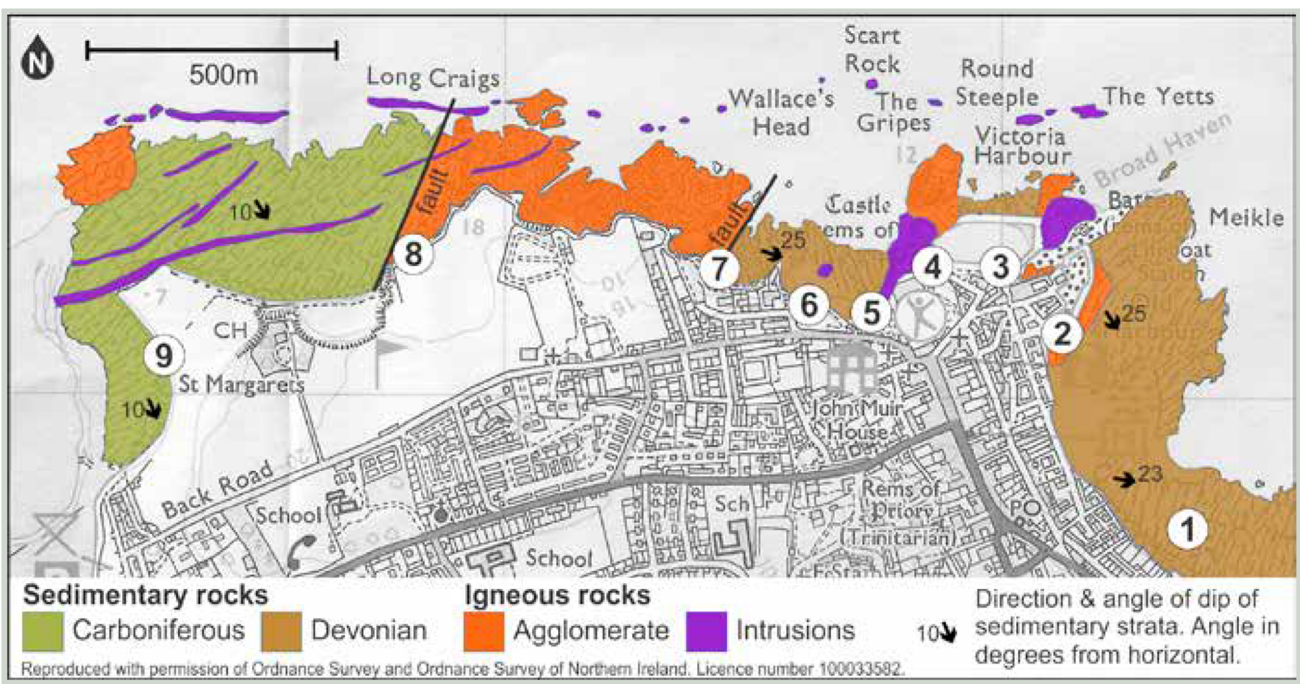
Hutton's clinical description is in marked contrast to that of the eloquent prose of Playfair (1805, 71–72).

"The ridge of the Lammer-muir Hills in the south of Scotland, consists of primary micaceous schistus, and extends from St Abb's-head westward, till it joins the metalliferous mountains above the source of the Clyde. The sea-coast affords a transverse section of this alpine tract at its eastern extremity, and exhibits the change from the primary to the secondary strata, both on the south and on the north. Dr Hutton wished particularly to examine the latter of these, and on this occasion Sir James Hall and I had the pleasure to accompany him. We sailed in a boat from Dunglass, on a day when the fineness of the weather permitted us to keep close to the foot of the rocks which line the shore in that quarter, directing our course southwards, in search of the termination of the secondary strata. We made a high rocky point or headland, the Siccar, near which, from our observations on the shore, we knew that the object we were in search of was likely to be discovered. On landing at this point, we found that we actually trode on the primeval rock, which forms alternately the base and the summit of the present land. It is here a micaceous schistus, in beds nearly vertical, highly indurated, and stretching from south-east to north-west. The surface of this rock runs with a moderate ascent from the level of low-water, at which we landed, nearly to that of high-water, where the schistus has a thin covering of red horizontal sandstone laid over it; and this sandstone, at the distance of a few yards farther back, rises into a very high perpendicular cliff. Here, therefore, the immediate contact of the two rocks is not only visible, but is curiously dissected and laid open by the action of waves. The rugged tops of the schistus are seen penetrating into the horizontal beds of sandstone, and the lowest of these last form a breccia containing fragments of schistus, some round and others angular, united by an arenaceous cement.

Dr Hutton was highly pleased with appearances that set in so clear a light the different formations of the parts which compose the exterior crust of the earth, and where all the circumstances were combined that could render the observation satisfactory and precise. On us who saw these phenomena for the first time, the impression made will not easily be forgotten. The palpable evidence presented to us, of one of the most extraordinary and important facts in the natural history of the earth, gave a reality and substance to those theoretical speculations, which, however probable, had never till now been directly authenticated by the testimony of the senses. We often said to ourselves, What clearer evidence could we have had of the different formation of these rocks, and of the long interval which separated their formation, had we actually seen them emerging from the bosom the deep? We felt ourselves necessarily carried back to the time when the schistus on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited in the shape of sand or mud, from the waters of a superincumbent ocean. An epocha still more remote presented itself, when even the most ancient of these rocks instead of standing upright in vertical beds, lay in horizontal planes at the bottom of the sea, and was not yet disturbed by that immeasurable force which has burst asunder the solid pavement of the globe. Revolutions still more remote appeared in the distance of this extraordinary perspective. The mind seemed to grow giddy by looking so far into the abyss of time; and while we listened with earnestness and admiration to the philosopher who was now unfolding to us the order and series of these wonderful events, we became sensible how much farther reason may sometimes go

**STOP 2.3:** *Dunbar*



*From:* McAdam & Clarkson, 1996, pgs. 119-132 - There is also a leaflet

# *DUNBAR*

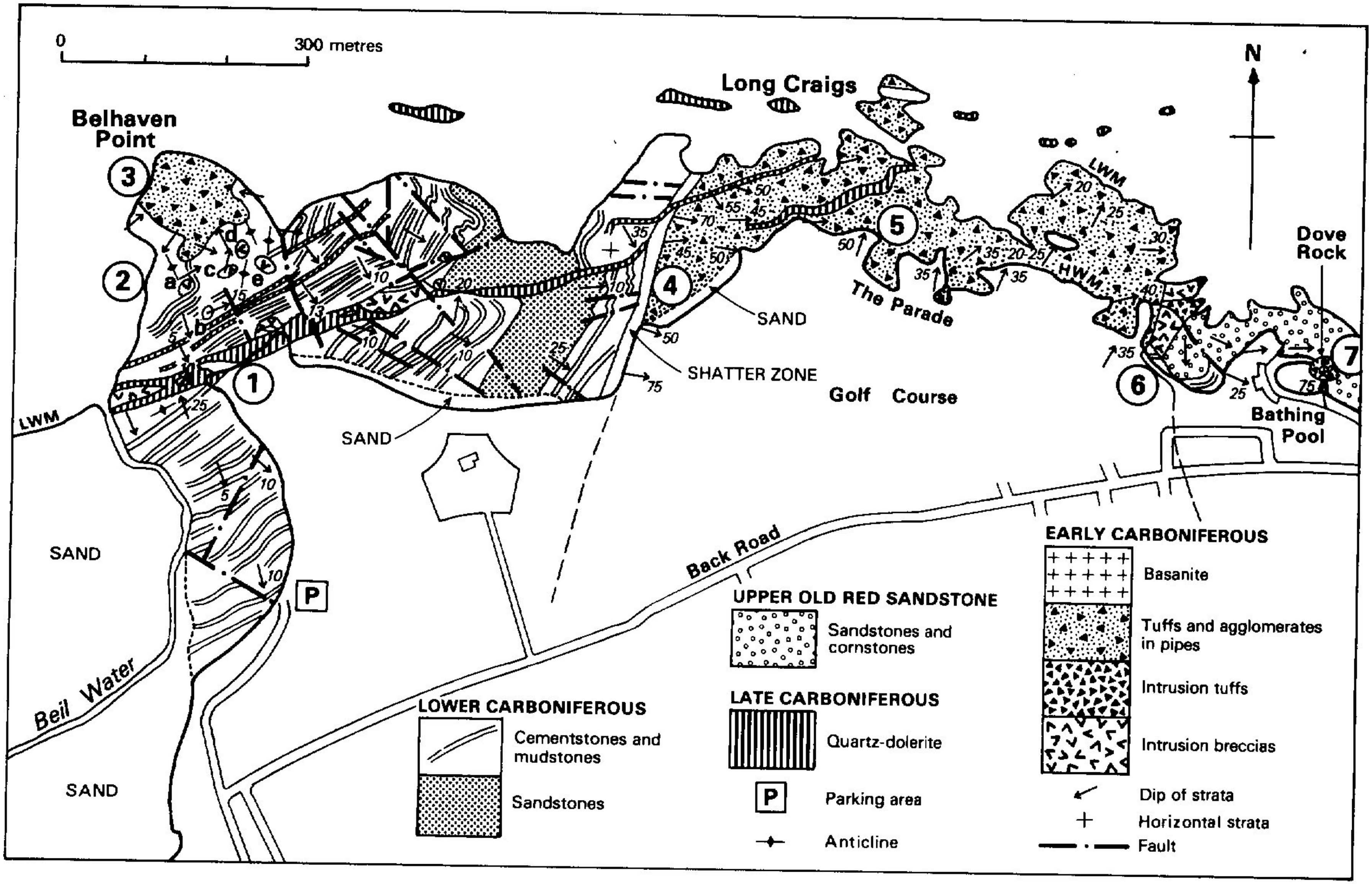
**O.S. 1:50000 Sheet 67 Duns & Dunbar**
**B.G.S. 1:50000 Sheet 33E Dunbar**
**Route: Maps 14 and 15**

THE main object of the excursions is to study volcanic necks (pipes) exposed in the cliffs and on the intertidal wavecut platform. These structures mark the sites of former underground channels which fed early Carboniferous (Dinantian) volcanoes. Erosion has since removed the volcanoes and some thickness of the rocks beneath them so that the pipes are now seen at various levels below the original surface of eruption. The rocks in them consist mainly of lithified volcanic ash (tuffs), with subordinate agglomerates and alkali-basaltic intrusions, and they are surrounded by the sediments of Upper Old Red Sandstone and Lower Carboniferous age through which the original feeder channels penetrated. At the time of the volcanism, these sediments were probably so young that they still contained water. Moreover, the volcanoes were erupted on a surface covered by shallow sea or lagoon, so that water from surface or sediments gained access to the ascending molten magma column and gave rise to violently explosive (phreatomagmatic) activity. Modern comparison is thus with maars or ash-rings like early Surtsey (Walker and Croasdale 1972) rather than with Strombolian basaltic cinder cones found in inland areas.

Two processes have been recognized in the emplacement of the pipes at Dunbar (Francis 1962). In the first eruptive phase the pipes are assumed to have been drilled through the sediments by a gas-propelled stream advancing above the molten magma column and containing fragments of ragged-edged, chilled basalt and of sediments broken by the stream from the walls of the channels. Remnants of the process are now to be seen at pipe margins where adjacent sediments are shattered and intimately penetrated by the gas-driven ash and where blocks and fragments show flow-orientation. The process is also seen in small ring-structures (cryptovolcanic) representing upward drillings which were arrested before reaching the surface. In the second phase, which followed when eruption ceased, bedded ash (now tuff) at or near the contemporaneous surface subsided into the feeding channels, sometimes to depths of hundreds of metres. The bedding structures provide evidence not only of ash-fall at the surface, but also of flow ranging from lateral base-surge engendered by violent eruption to mass debris flows down inner flanks of the original sub-aerial ash-rings. The eventual preservation of the layering ranges from relatively intact to wholly collapsed, depending partly on how loose the ash was at the time and partly on the depth to which it subsided. Because of the subsidence the margins of such pipes are commonly ring-faults, and the process of down-drag is also reflected in the attitude of the sediments adjacent to those faulted margins. Thus, two different kinds of ash from the same volcanoes are brought together at one level—the material subsided from the surface at the centre of the pipes—and the deeper-seated intrusional material still in place at the margins.

The sediments and pipes are traversed by a group of ENE quartz-dolerite dykes of Stephanian age, best seen at Belhaven and forming offshore skerries farther east. The dykes and the earlier tuffs are reddened to greater or lesser degree, reflecting the colouration of the surrounding sediments. This feature at Dunbar, and elsewhere, has been attributed by Lorenz (1972) to circulation of ground-water from the sediments, leading to oxidation of the iron content in the volcanic rocks.

The itinerary below is designed for two excursions, one from Belhaven to the Parade (p. 122) and the other around Dunbar itself (p. 127). However, if only one day is available it is suggested that they can be combined by starting at Belhaven Point (locs. 1, 2), traversing the Parade Neck at the foot of the cliffs (locs. 4, 5, 6), ascending by steps to the road, walking from there to the harbour area (locs. 7, 8, 9) and thence south-eastward near high water mark (H.W.M.) (locs. 11, 12, 13). The total walking distance is about 6 km, ending a similar distance by road from the starting point. In a race against the tide, this sequence might be varied in the




MAP 14. Belhaven and the Parade

knowledge that some of the harbour exposures (7, 8) can be seen when most others are covered by the sea.

There are frequent train and Lowland Scottish service buses from Edinburgh to Dunbar. For excursions by road, the main parking area for cars and buses is near the Barracks, in Dunbar, though limited car parking can also be found near the beach at Belhaven and at Victoria Harbour in Dunbar.

### *Excursion A—Belhaven and the Parade (Route: Map 14)*

Starting from the car-parking area at Belhaven Beach (NT 662 787) the walking distance is about 2 km ending in a steep flight of steps up from the beach behind the Bathing Pool. It is a similar distance returning to the car park along Back Road or, preferably, along the Parade itself, which offers fine vantage points down to the foreshore.

#### *1. Linear Breccia and Quartz-dolerite Dyke*

The sediments at Belhaven consist mainly of rhythmic alternations of Lower Carboniferous cementstones and mudstones with one thick bed of sandstone. They dip generally south-eastwards. They are traversed at H.W.M. by an ENE linear volcanic breccia which is irregularly intruded by the widest of the local quartz-dolerite dykes. Its margins are defined by faults inclined towards one another and locally flanked inside by blocks which are aligned parallel to the margins. Eastwards the faults diverge, the southern having a displacement of about 30 m. At its western extremity the breccia includes large blebs of 'white trap'. The breccia, which has two small cryptovolcanic ring structures emplaced along the northern bounding fracture, is assumed to belong to the early Carboniferous volcanism.

#### *2. Cryptovolcanic Ring Structures*

Five small areas of breccia (a-e, Map 14) are referred to as ring structures, though they tend to be oval rather than circular in plan. In some places their contacts with the surrounding sedimentary rocks are vertical or steeply inclined inwards; in other places an impression is gained of high-angled outward dip though this is nowhere capable of demonstration. The breccias consist mainly of local cementstones and marls. Peripherally the flat surfaces and longer axes of the blocks become orientated with the margins. At the centre, however, the blocks are usually completely jumbled, though in one ring (e) the centre consists of relatively undisturbed cementstones and marls. Two rings (b, d) contain red tuffs which appear to penetrate the breccias; they are most prominent at the margins, but also (c) form dykes and pods associated with veins and blebs of decomposed chilled basalt ('white trap').

Maufe (in Clough *et al.* 1910, p. 90) thought that they were necks which pierced low domes and were contemporaneous with, and overlapped by the sediments. However, they are now believed to be incipient pipes which never reached the surface. Those margins which show apparent overlap merely reflect the upwards pressure of the gas-tuff stream, while the inwardly-inclined fractured margins represent a slightly lower erosional level in funnel-shaped fractures, with the marginally orientated blocks evidencing a variety of flow-banding.

### 3. Belhaven Point Neck

The margin of the neck is irregular in outline. To east and west, where the irregularity is least prominent, the adjacent sediments are turned down towards the margin, but where the neck extends southward the sediments are either horizontal or dip away from the contact. The neck filling ranges in grade from fine-grained tuffs to lapilli-tuffs and has a red colour mottled by yellow and green juvenile basaltic material. Near the margin the tuffs also contain blocks of cementstone and sandstone similar to the country rocks outside. The tuffs have an unbedded appearance except for what seems to be a vertically stratified discrete raft, measuring $2{\cdot}5 \times 7{\cdot}5$ m, near the centre of the neck. Two small bosses, measuring $3{\cdot}5 \times 6$ m and $7{\cdot}5 \times 7{\cdot}5$ m, to south and centre respectively, are of basanite similar to the other vent intrusions of the district, though they are partially carbonated.

### 4. Parade Neck: West Margin

The largest neck in the area, nearly 1 km in diameter, takes its name from the promenade along the top of the cliffs in which it is well exposed. The cementstones immediately outside the neck are nearly flat at L.W.M., but at H.W.M. they dip in towards the margin at progressively higher angles until they pass into a zone 9 to 15 m wide in which the sediments are highly inclined or vertical and show signs of shattering and squeezing out. Inside the neck also, the easterly dip of the bedded tuffs becomes steepest adjacent to this zone, though in places the bedded tuffs appear to pass into massive tuffs containing blocks of sedimentary rock. In the cliff about 15 m inside the margin is a spectacular intrusion of sandstone within the tuffs. It is partly sill, partly dyke, arranged in 'step-and-stair', but the internal layering, which resembles bedding, remains parallel to the enclosing walls. This, together with off-shoots of sandstone which peter out at various angles into the tuffs, shows the body to be intrusive.

Still nearer to the western margin of the neck a 2 m dyke of mottled grey and purple sandstone can be traced northwards, first thinning out for a short distance, then forming pods inside a line of crush and later reappearing as a sill which seems in ground plan to change horizon through the bedded tuffs. An offshoot dyke, 25 to 40 cm thick, is intruded westwards to cut the vent-marginal zone of crushed and inwardly down-turned sediments. The main dyke contains some magmatic debris and two separate elements of vertical flow-banding, one of which crosses the other obliquely in much the same way as current bedding in sedimentary rocks. At H.W.M. the main dyke pinches out more abruptly, though its course is continued into the cliff by a line of disturbance. On the western side of the dyke there is another 3 m intrusion, consisting of a purple sandy siltstone banded with streaky, purple and yellow tuff. At first sight this seems to be a large xenolith of bedded tuffaceous sediment dipping westward at 65°–85° and crumpled and faulted on a small scale. On closer examination, however, the streaky yellow layers in the tuff are seen to be flow-banded and intrusive into the siltstone and the adjacent dyke of sandstone. The flow-banding of yellow basaltic lapilli and the 'bedding' of the siltstone, moreover, remain orientated parallel to the margins of the mass as it pinches out southwards. It is suggestive of two, if not three, successive pulses of intrusion hereabouts.

### 5. Parade Neck: Bedded Tuffs and Sandstone Dykes

Along the shore and in the cliffs the vent-filling consists of bedded reddish and brown tuffs ranging from fine-grained to lapilli-tuffs. They consist of variable proportions of two main components. One is a sandstone suite seen in thin section to consist mainly of quartz grains with subordinate amounts of orthoclase, microcline, plagioclase and mica: the other is basaltic and consists partly of crystalline material, but more abundantly of yellow vesicular glass (refractive index exceeding 1·54 and usually replaced by carbonate, kaolinite or turbid decomposition products). Some of the glassy fragments appear to have enclosed grains of quartz. In some of the fine layers the glass is elongated parallel to the bedding, giving rise to a macroscopic vitroclastic texture. Blocks of basalt, tuff, indurated cementstone, cornstone, sandstone and shale ranging in diameter up to 1·2 m, but averaging about 12 cm, are scattered throughout. Local disruption of the subjacent layering and sagging in the beds a little farther below testify to their emplacement as bombs: some of the basaltic bombs, moreover, are grouped in a manner suggesting spatter. However, although the tuffs near the western margin appear to be of similar ash-fall origin, the cross-bedding throughout the remainder of the neck is on a scale which is entirely consistent with deposition from a series of base-surges driven from an eruptive source or sources located to north-east, east or south-east (Leys 1982).

The tuffs are crossed by a roughly rectilinear pattern of master joints trending north-east and north-west. The younger quartz-dolerite dykes have been emplaced along the fractures, as have many further sandstone dykes laminated parallel to their high-angled enclosing walls. This lamination—an alignment of micas—is less pronounced at the centres of the dykes than at the margins. Some dykes are cemented by, or pass laterally into carbonate. The joint system and the sandstone intrusions are believed to date from the subsidence stage of the Parade Neck.

### 6. Parade Neck: Eastern Margin

The eastern margin is outlined by a boulder-strewn trench, narrowing northwards and containing a partially exposed band of green and purple streaky rock which is up to 1 m thick and is inclined westwards into the neck at 60°. This appears to be fault-gouge rather than flow-banding. Inside the margin the tuffs display an intricate pattern of small-scale faulting, but there is no local breakdown of bedding as there is in the west. In further contrast the dip continues unchanged up to the edge of the neck where the tuffs are laced with anastomosing veins of carbonate and/or hematite which have a sub-parallel alignment with the neck margin. Such veining is characteristic of the inner linings of pipes which have undergone subsidence and is presumed to have formed during that process. At high water mark the relationship of the neck to the sediments is obscured by sand and shingle, but to the south-east a junction is exposed in the cliff alongside the path, where it is marked by a block of false-bedded sandstone 1 m wide, narrowing downwards and tilted at 70° away from the hematite-veined tuffs.

Outside the margin the massive sandstone is diced by small-scale fractures, and the blocks so formed are dislocated and recemented by sand apparently derived from the breakdown of the same beds. The bulk composition of the rock is thus unchanged, but the large constituent blocks can be picked out on weathered surfaces by slight differences in coarseness, colour and orientation. An irregular fracture plane separates this slightly brecciated zone from the undisturbed massive sandstone to the east. The sandstones inside and immediately outside the brecciated zone have rough carious surfaces showing anastomosing patterns of grooves and ridges. They result from fracture during the volcanism and from the filtering and forcing of fine sand along the fractures by gas action.

The brecciated zone is traversed by a dyke of intruded tuff, about 60 m long, tapering from 15 m to 9 m in width as it is followed north-eastwards to low water mark. It is cut off to the west by the gouge at the east margin of the neck and traversed by a north-westerly fault which has a landward down-throw. The outcrop of the tuff dyke is shifted by this fault in a direction which indicates that the dyke is inclined south-eastwards. The tuff is a green, or patchily red, well-mixed rock full of basaltic lapilli. Against the north-western wall of the mass the lapilli are orientated to display flow-banding. The tuff may represent an apophysis, intruded into

Upper Old Red Sandstone, of the material which filled the vent at its pre-subsidence level.

### *Excursion B—Dunbar (Route: Map 15)*

From the car parking areas at the Barracks (677 791) or Victoria Harbour (679 793), the walking distance is about 4 km (3 km if the Dove Rock is excluded), with 2 km to walk back through the town to the starting point.

#### *7. Dove Rock*

Dove Rock is a small plug of basanite surrounded by a narrow inner zone of tuff and an outer zone of partly brecciated inwardly dipping sandstone bounded by a ring fracture. Further incipient ring fractures are seen beyond it. As similar rocks and structures can be seen elsewhere, and as the bathing pool makes access difficult, it is suggested that if time is short both this locality and the seaward side of Castle Rocks could be omitted.

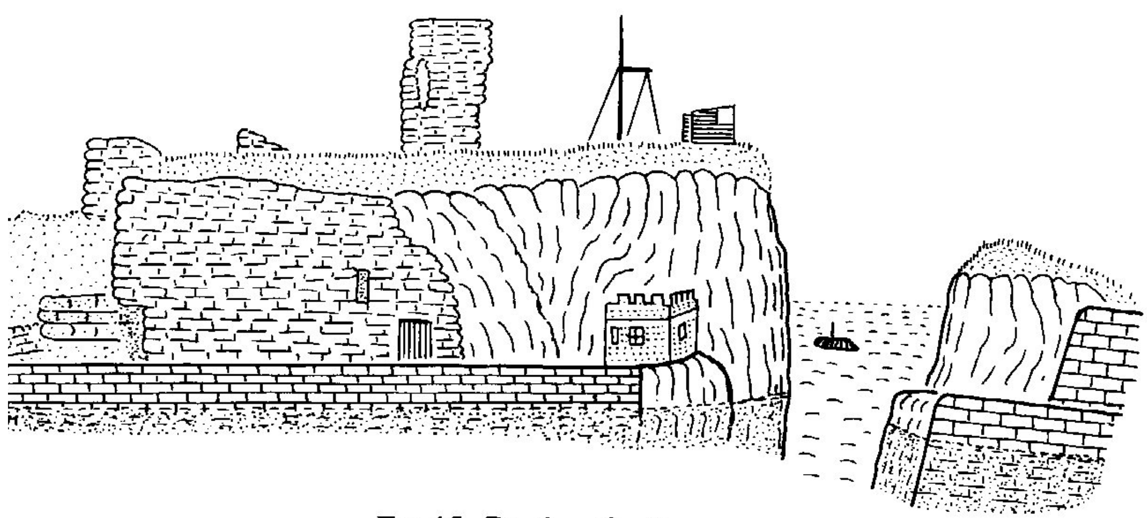


FIG 15. Dunbar Castle

#### *8. Castle Rocks*

The neck at Castle Rocks straddles the entrance to the New (Victoria) Harbour (Figure 15), but the margin is accessible at only one locality, just south of the entrance. Even here it is partially obscured by the wall of the old castle, where shattered indurated sandstones dip westward towards the neck. The tuff, which can be examined north of the harbour is red and green and contains evenly distributed lapilli of basalt and older tuffs up to 2 or 3 cm in diameter. It is coarsest to the south-east where there are blocks of fine-grained basalt, up to 30 cm across. The tuffs are indurated by basanite dykes and traversed by red veins containing a central portion of calcite and chalcedony and an outer lining of hematite.

### *9. The Battery*

The Battery is built on a columnar, reddened, decomposed porphyritic basalt (Figure 16) which appears to be conformably underlain by bedded tuffs. It resembles early Carboniferous lavas cropping out 1·5 km to the east (Clough *et al.* 1910, pp. 91, 105–6) rather than the basanites of the minor intrusions associated with the necks. Neither the basalt nor the underlying tuff appears to lie within the Old Harbour Neck (see below) and their stratigraphical position is obscure within a faulted sequence of both Old Red Sandstone and Carboniferous sediments.

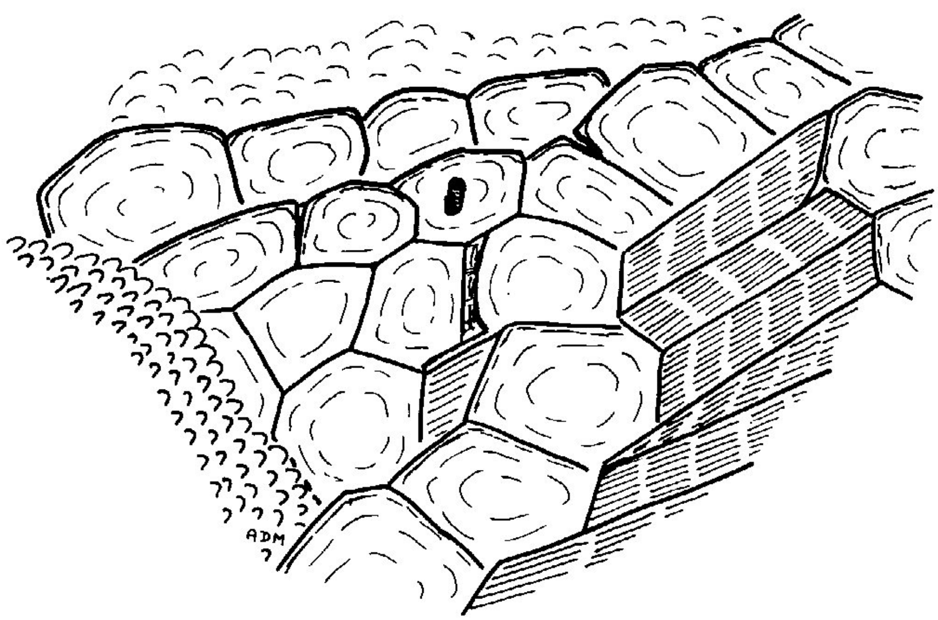
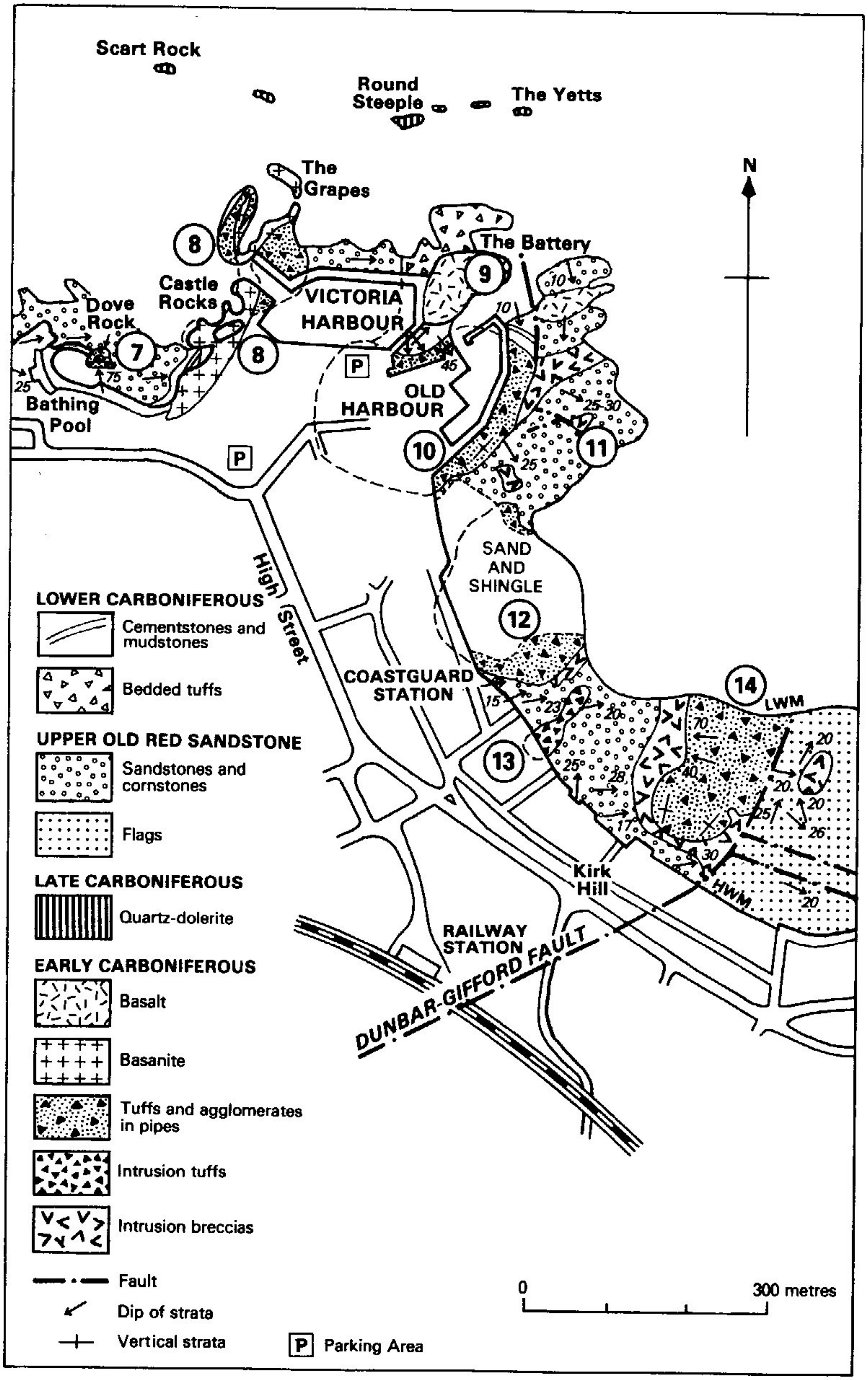



FIG 16. Columnar basalt, The Battery, Dunbar

### *10. Old Harbour Neck*

The neck underlying the Old Harbour is most clearly delineated on its eastern side where the flanking sandstones




Map 15. Dunbar

form a wall rising above the volcanic rocks. This wall, which inclines in towards the neck at between 50° and 60°, is vertically fluted and polished and represents a plane of movement cutting off the bedding. Veins of intrusion tuff can be seen in the sandstone. Followed seawards, the margin swings west beneath the Old Harbour wall and reappears between the two harbours where it has a south-westerly trend. Beneath the drawbridge on the east wall of Victoria Harbour the outer flanking sediments comprise red marls and cementstones with interbedded yellow and green tuffs. They are crumpled and tilted steeply towards the neck, swinging round from there to dip conformably northward beneath a basalt underlying the Battery. South of the inter-harbour area the neck margin is built over, but a few exposures of tuff can still be seen west and south of the Old and Victoria harbours respectively.

The neck filling consists of red or, locally, green lapilli-tuffs which are bedded in the north and west, where they strike parallel to the walls and dip inwards at angles ranging from 45° to vertical. East of the Old Harbour wall, however, they have a heterogeneous aspect. This derives partly from the presence, close to the margin, of basaltic blocks and masses of country rock up to 2·5 m in diameter, and partly from the breakdown of original bedding. The bedded relics—some of them intensely crumpled—do not form discrete blocks, but merge instead into an apparently structureless rock. The peripheral tuffs are laced by anastomosing veinlets of hematite and there are, in addition, sills and dykes of similar material up to 60 cm thick. A linear breccia lies to the east of the neck. It has a north-easterly alignment decreasing in width as it is traced from the margin towards low water mark. Like the linear breccia at Belhaven it is derived from the local sediments (sandstones in this instance); it occupies a faulted trough and in places contains marginally orientated blocks. By way of contrast, however, it appears to be related to the adjacent neck, for there is no well defined margin between the two, and the western part of the breccia is penetrated by red tuffs which are similar to the unbedded variety in the neck. The sandstones in the breccia and along the neck margin show typical carious weathering as described from the eastern margin of the Parade Neck.

### *11. Cryptovolcanic Ring Structures*

Two ring structures are exposed to the east of the Old Harbour Neck. The northern is emplaced along a fracture radial to the neck and consists of blocks of local sandstone penetrated by veins of red tuff. Here and in the southern structure the margins are outlined in part by vertically aligned blocks of sandstone.

### *12. Coastguard Station Neck*

This neck, like that of the Old Harbour, rimmed by massive sandstone. Where the margin is continuously exposed on the south it has a regular curving outline and is inclined inwards at 70–80°. Long slices of sandstone, apparently detached from the walls, are now separated from the parent mass of country rock by a narrow zone of unbedded red tuff. The neck filling also resembles that at the Old Harbour in its patchy red and green colour, random scatter of bombs, marginal plexus of red hematitic veins and nearly vertical bedding which strikes parallel to the walls in some places, but in others breaks down to a chaotic arrangement of fragments.

### *13. Tuff Dyke*

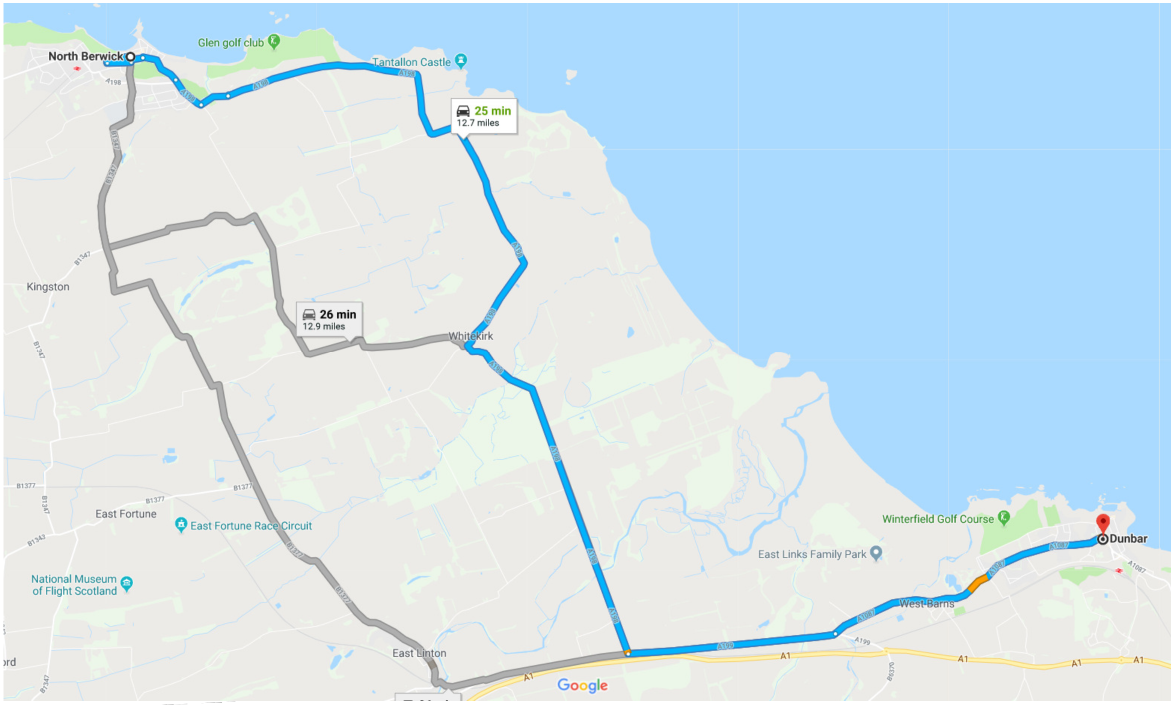
This intrusion has a north-easterly trend. Its extent at H.W.M. is obscured by sand, but where first seen it is about 12 m wide narrowing seawards to between 2 and 4 m, finally wedging out in an easterly direction among beds of massive sandstone. The tuff is red with patches of green and yellow basalt and a few bombs of crystalline material. Near the margins it is enriched with fragments of local sandstone up to 30 cm long, and arranged with their long axes parallel to the sides of the dyke. Hair fractures, picked out by red hematite, traverse the steep irregular sandstone walls and the finer constituents of the tuff penetrate raggedly for short distances along these. It is supposed that although the intrusion is not continuous with the Coastguard Station Neck and its filling is differently constituted, the two bodies may have been connected at a lower level before the subsidence of the neck.

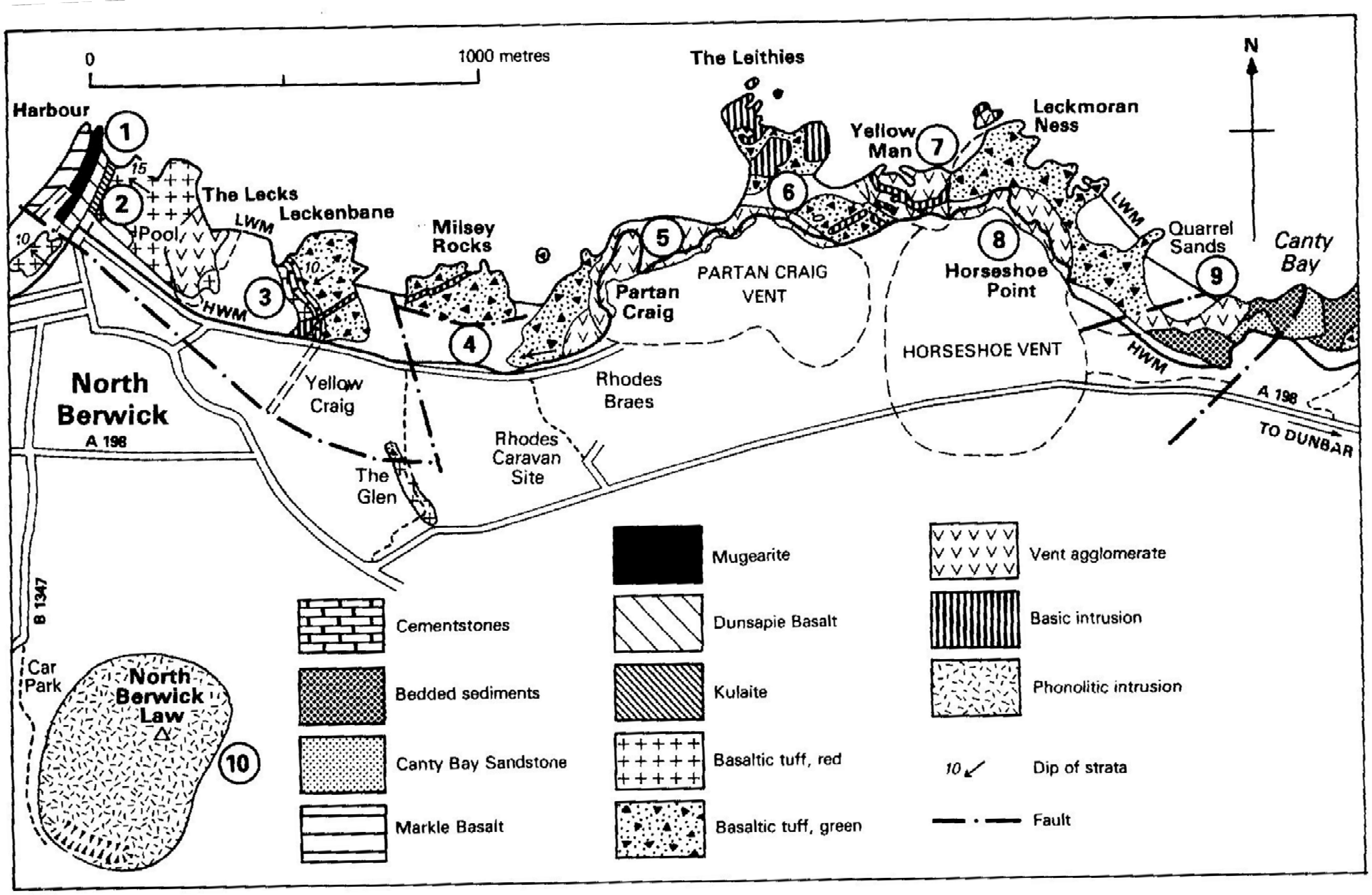
### *14. Kirk Hill Neck*

The Kirk Hill Neck is cut off to the east by the Dunbar-Gifford Fault, but to west and south the margin is vertical and has an irregular outline. The neck filling is again similar to the tuffs of the Old Harbour and bedding is more apparent towards the margins than at the centre. The strike of the bedding is approximately parallel to the neck margin to east and west, but adjacent to the southern margin the strike is variable. The bedding is vertical in the east, but dips westwards away from the centre of the neck at 40–70° in the west. In the north-western part of the neck there is a raft of sandstone measuring 2·5 × 6 m and south-west of the raft there is a 30 cm dyke of sandstone. The latter does not contain flow-banding like the dykes of the Parade Neck. At the indented south margin, tongues of red tuff penetrate the brecciated sandstone wall-rock and the yellow lapilli in this tuff are clearly aligned in flow structure against the sandstone.

E. H. FRANCIS

**STOP 2.4:** *North Berwick*

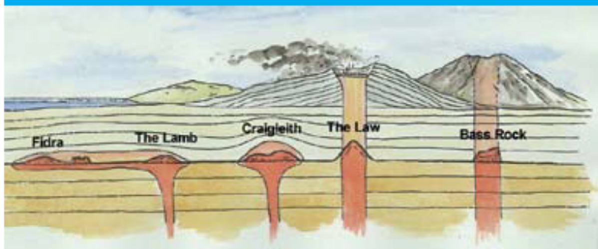



MAP 9. North Berwick to Canty Bay

*From:* McAdam & Clarkson, 1996, pgs. 88-108

## Islands visible from the shore




The offshore islands are all composed of igneous rocks formed as molten rock (magma) cools and hardens underground. They are called intrusions, unlike most of the rocks seen on the shore which were formed at the surface as volcanic extrusions. There's been lots of erosion to allow us to see these rocks that formed beneath the surface. Intrusive rocks forming under volcanoes today might not be seen for millions of years.

Bass Rock and Berwick Law are made of an unusual rock called phonolite, a "sounding stone", so called because it makes a metallic noise if hit with a hammer. If you get up close to the rock, it appears lighter in colour and has larger crystals which cooled more slowly than the basalt. These big masses of rock are ancient plugs, bodies of magma that solidified in the neck of a volcano.

Craigleith is lower with sloping sides, and is an example of a laccolith, a mushroom-shaped body of magma that has intruded into surrounding layers of rock and cooled.

Fidra and Lamb can be seen farther to the west. They are part of another intrusion forming a sheet of basalt rock called a sill.

## How to get there

North Berwick, 25 miles east of Edinburgh, is easily accessible by train, bus or car. For details of public transport contact Traveline on 0800 608 2 608 or visit www.traveline.org.uk. This leaflet describes a walk eastwards along the shore from the Scottish Seabird Centre at North Berwick harbour, close to the town centre. The Seabird Centre is well sign-posted. There's plenty of free parking nearby, both along the beach and at car parks in the town. There are public toilets at the Seabird Centre (inside and out) and at the Melbourne Place car park.

**Safety and conservation**

The beach is accessible at all states of the tide but some of the features are covered at high tide. You should be aware that the shore is slippery and has loose materials, with the risk of tripping, slipping and falling. North Berwick shore is part of a Site of Special Scientific Interest because of its geology and hammering of the rocks is not encouraged.

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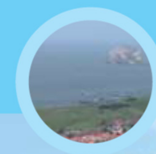
# North Berwick

# Volcanoes



## Geological Walk

**Local Geodiversity Site**

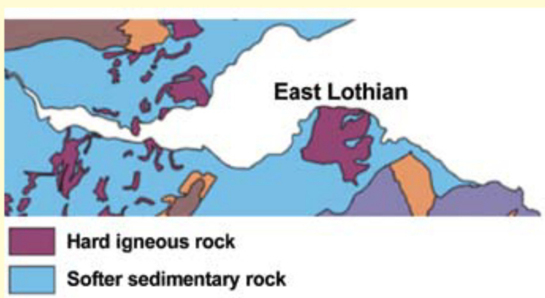
Lothian and Borders RIGS Group

# Introduction

North Berwick is known for its seabirds, offshore islands and its prominent hill, Berwick Law. What you may not know is that this was once an area of intense volcanic activity. This leaflet takes you on a walk along the shore, exploring different parts of these ancient volcanoes and finding out why what happened in the past is important today – helping to create the local scenery, giving a safe anchorage and safe homes for seabirds.

So where are these volcanoes? If you stand outside the Seabird Centre and take a look around, you'll see plenty of evidence for volcanoes in the shape of the land. Berwick Law rises steeply above the town, and is the remains of an extinct volcano. Volcanoes create hard rock, called igneous rock, made of tiny crystals that lock together and are difficult to break apart. All igneous rocks start out as magma, hot molten liquid rising from inside the Earth. If the magma reaches the surface it cools quickly and erupts from a volcano as lava or ash. If magma gets trapped underground it will cool more slowly, resulting in larger crystals and a tougher rock – the islands offshore formed like this.

The Scottish Seabird Centre sits on top of lava flows that erupted around 345 million years ago. These lava flows make a headland jutting out to sea. A great site for the Seabird Centre, and also for a sheltered harbour.




On a larger scale, North Berwick lies at the northern edge of East Lothian, which juts out into the Firth of Forth. The coast is shaped this way because of the local igneous rocks, formed by the volcanoes that erupted here in the past.

# Rocks as clues to the past

In studying rocks, geologists are trying to unravel the stories of the past – detectives working with limited information. There are many different kinds of rock, made of different chemicals and with varying minerals and texture. How can we work out how they formed? By using knowledge of what's happening around the world now to understand North Berwick's rocks, and work out what happened in the past in Scotland.

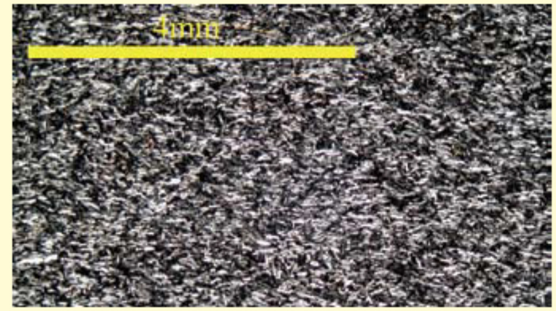
When a volcano erupts in places such as Iceland and Hawaii, the lava often cools to create a smooth, dark rock called basalt. The basalt layers under the Seabird Centre formed in the same way - the present provides a key to understanding the distant past.

*Above: recent lava flow at Krafla in Iceland.*

# Rocks under the microscope

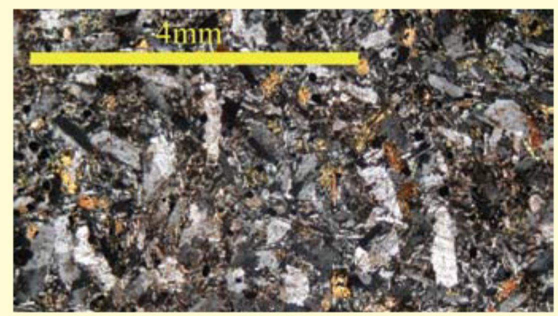
Geologists often take rocks back to the lab and cut them into slices, called thin sections. Under the microscope and with light shone through them, the rock's minerals and their shapes can be seen more easily.

These photos of thin sections from North Berwick are all taken at the same scale to show different sizes of grains. Each individual patch of colour is a single mineral grain.

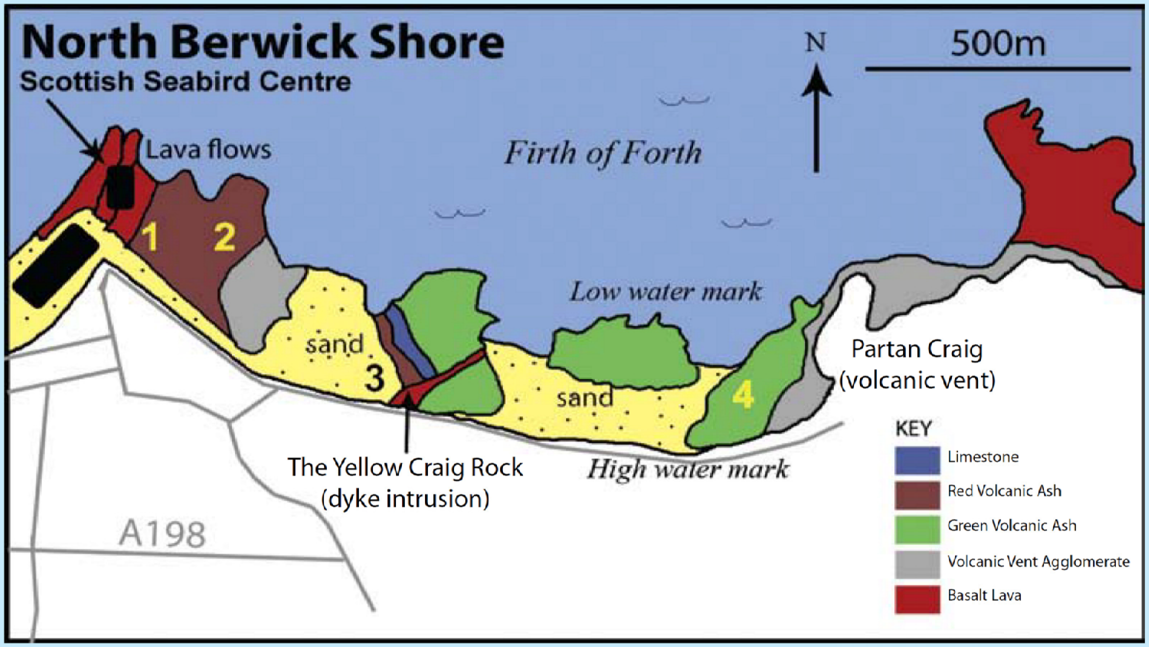



*Above: Basalt from lava flow at North Berwick pier. Out of the three rocks shown here, this one cooled the fastest, giving small crystals.*


*Above: Basalt from Lamb Island. The few larger crystals formed first and cooled more slowly than the many smaller crystals that formed later.*



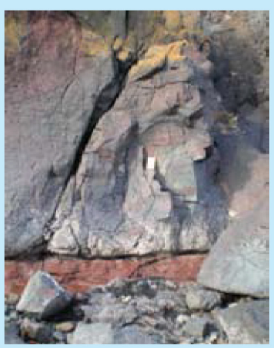

*Above: Bass Rock phonolite, which cooled relatively slowly and so has larger crystals than the basalt.*




The walk along the shore takes you through the different parts of ancient volcanoes. We'll walk back through time, down through the layers that used to be inside the volcano, and end up in an ancient crater. You don't have to worry about flying lava bombs or red hot lava flows. These volcanoes have been extinct for 340 million years! But do watch out for slippery rocks underfoot.

## Stop 1: Lava flows

The Seabird Centre was built on a layer of rock which can be seen from the beach next to the Centre.



Look closely and you might see small shiny crystals within the rock; a sign that it has crystallised from magma. Most of the crystals are tiny and best seen using a microscope (see pictures overleaf).

This rock is called basalt, and it formed as part of a lava flow, which spread out over the landscape while molten and cooled quite quickly, forming small crystals.

Basalt is very different from sedimentary rocks such as sandstone, which are formed from grains of eroded rock cemented together.

As you stand looking at the lava, you can imagine the scene around 340 million years ago, when a fast-moving lava flow came out of a nearby crater and spread across the landscape. North Berwick used to be even more exciting than it is today!

## Stop 2: Layers of volcanic ash

Look at the flat red rocks next to the lava flow of stop 1, on the foreshore near the paddling pool (they are covered when the tide is in). These rocks are softer than the basalt cliffs.

The red rocks formed in a very different way than the basalt, when volcanic ash was erupted and settled into layers that were slowly turned to rock. It is known as tuff.

The red layers lie underneath the lava, and they tell us that before the lava flows erupted, the volcano was very active.

Time after time, showers of ash and rock fragments were blasted into the sky. This probably happened because there was lots of water around: magma and water make an explosive mix.

## Stop 3: The Yellow Craig Rock

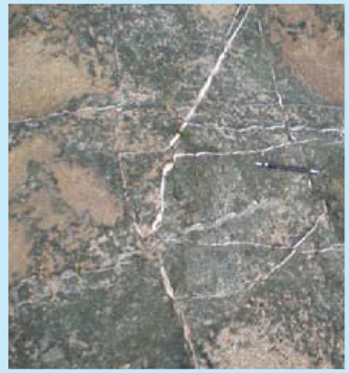
A short walk along the beach to the east will take you to the Yellow Craig Rock, a lone cliff that protrudes out of the sand like a ship's keel.

Named because of the colour of the lichen, it is another resistant igneous rock feature. Up close, the rock looks similar to the cliff at stop 1 – it is basalt. This rock has a different shape, though, and is an example of a dyke intrusion (illustrated in section below).

# The Yellow Craig Rock *(stop 3 continued)*

The Yellow Craig Rock shows us what happens underground when a volcano erupts – not all the magma makes it to the surface, and it doesn't all come up in the main crater of the volcano. Here we can see what happens when magma forces its way along a vertical crack through older rocks underground.

There used to be older, softer layers of volcanic ash around the Yellow Craig Rock, but this has now mostly been worn away, leaving the hard rock behind. You can still see some of these layers by walking towards the sea and looking back inland. The low ridges of rock are the edges of beds that tilt towards the road. The rocks are red and green volcanic ash with one thin band of limestone between them, which is quite tricky to pick out. Look out for a rounded, knobbly appearance, which is typical of this limestone.



Around 20 metres to the east of the Yellow Craig Rock you can find flat exposures of green volcanic ash. White lines that cut the rock in different directions are veins of the mineral calcite that have formed when hot fluids moved along cracks. Here, there are a range of sizes of rocks embedded in the ash.

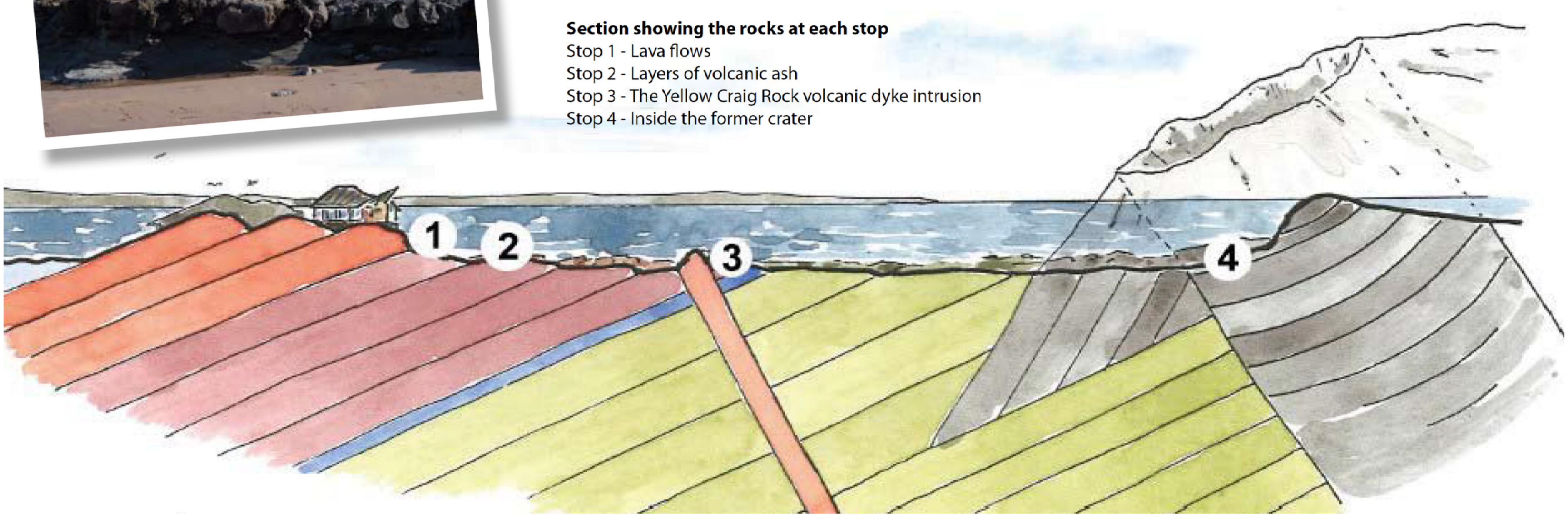
## Stop 4: Partan Craig volcanic vent

At the far end of the shore, facing west, lies a green-grey cliff. The layers in this cliff are mostly made of green volcanic ash, and form a broad bowl shape, with a steeper right hand side.

On closer inspection, it is possible to see large blocks of material embedded in the volcanic ash. The curved layers and enclosed lumps of rock are the main clues that tell geologists that this rock is a vent agglomerate – a jumbled mass of rock fragments and ash that have fallen back into the vent of a volcano.

So you are now standing inside an ancient volcano's crater – something we can't do in a modern volcano! Imagine the scene as this volcano erupted, with all these blocks on the move, being thrown up into the air by violent explosions. Later, as the volcano came to the end of its life all this material slumped down into the volcanic vent, where we see it today.

**Section showing the rocks at each stop**
Stop 1 - Lava flows
Stop 2 - Layers of volcanic ash
Stop 3 - The Yellow Craig Rock volcanic dyke intrusion
Stop 4 - Inside the former crater



**Day 3: Tuesday, March 6th, 2018 – Edinburgh Castle, Arthur's Seat, and Edinburgh City**

**8:00 AM:** Breakfast in the hostel

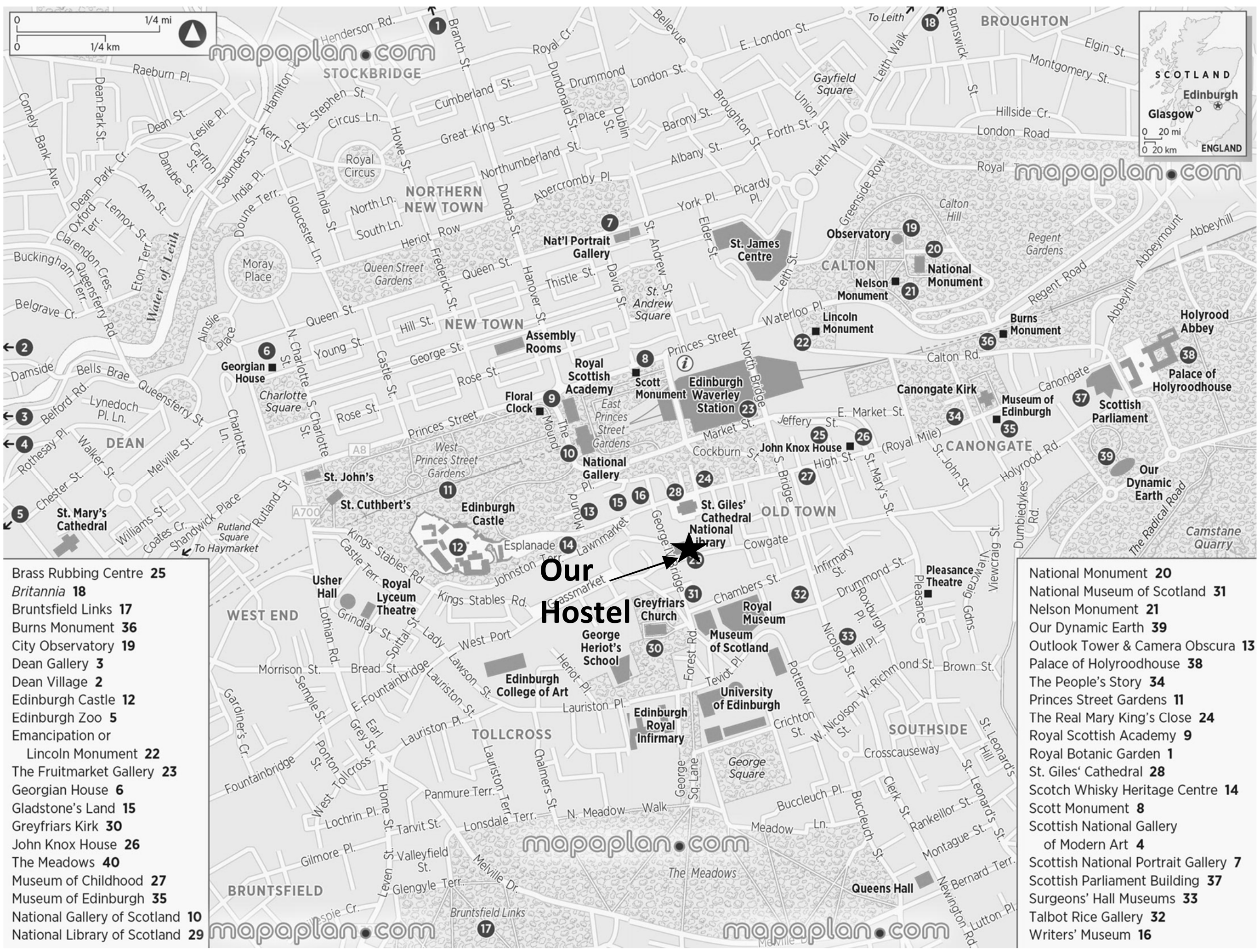
**8:30 AM:** Walk to Edinburgh Castle – Castle tour

**12:00 PM:** Lunch at the hostel

**1:00 PM:**

- **Option #1 –** Hike around Arthur's Seat, a volcanic plug in Holyrood Park that Hutton studied (10 minute walk from the hostel)
- **Option #2 –** Drive to St Andrews to see the birthplace of golf (3 hr round-trip drive from the hostel)
- **Option #3 –** Explore Edinburgh (museums, shops, pubs…)

**6:00 PM:** Group dinner we will cook at the hostel



**STOP 3.1:** *Edinburgh Castle*

*From Wikipedia:*

Edinburgh Castle is a historic fortress which dominates the skyline of the city of Edinburgh, Scotland, from its position on the Castle Rock. Archaeologists have established human occupation of the rock since at least the Iron Age (2nd century AD), although the nature of the early settlement is unclear. There has been a royal castle on the rock since at least the reign of David I in the 12th century, and the site continued to be a royal residence until 1633. From the 15th century the castle's residential role declined, and by the 17th century it was principally used as military barracks with a large garrison. Its importance as a part of Scotland's national heritage was recognised increasingly from the early 19th century onwards, and various restoration programmes have been carried out over the past century and a half. As one of the most important strongholds in the Kingdom of Scotland, Edinburgh Castle was involved in many historical conflicts from the Wars of Scottish Independence in the 14th century to the Jacobite rising of 1745. Research undertaken in 2014 identified 26 sieges in its 1100-year-old history, giving it a claim to having been "the most besieged place in Great Britain and one of the most attacked in the world".

Few of the present buildings pre-date the Lang Siege of the 16th century, when the medieval defences were largely destroyed by artillery bombardment. The most notable exceptions are St Margaret's Chapel from the early 12th century, which is regarded as the oldest building in Edinburgh, the Royal Palace and the early-16th-century Great Hall, although the interiors have been much altered from the mid-Victorian period onwards. The castle also houses the Scottish regalia, known as the Honours of Scotland and is the site of the Scottish National War Memorial and the National War Museum of Scotland. The British Army is still responsible for some parts of the castle, although its presence is now largely ceremonial and administrative. Some of the castle buildings house regimental museums which contribute to its presentation as a tourist attraction.

The castle, in the care of Historic Scotland, is Scotland's most-visited paid tourist attraction, with over 1.4 million visitors in 2013, and over 70% of leisure visitors to Edinburgh visiting the castle. As the backdrop to the Edinburgh Military Tattoo during the annual Edinburgh International Festival the castle has become a recognisable symbol of Edinburgh and of Scotland.

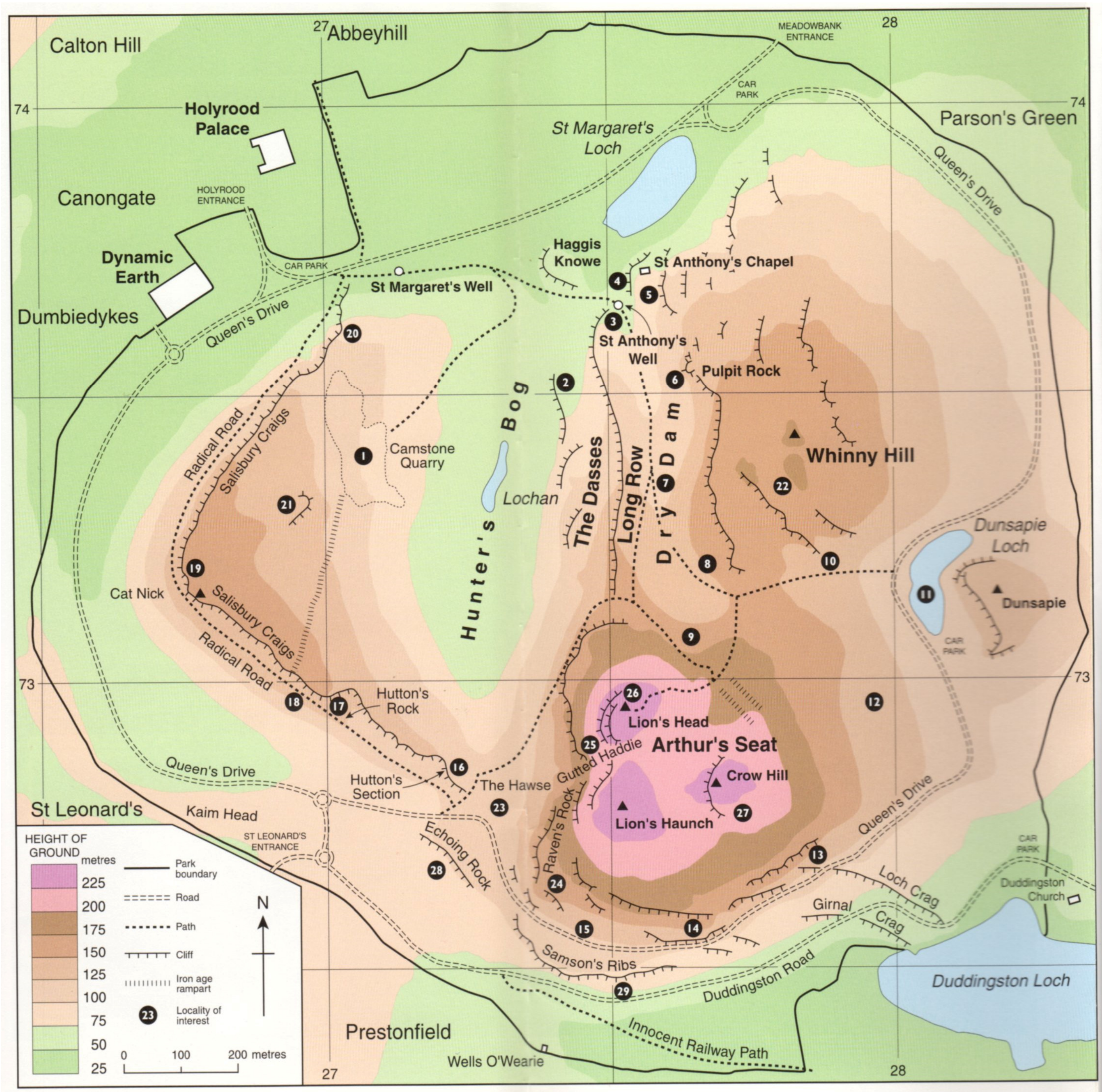
*Geology*

Diagram of a crag and tail feature, such as the Castle Rock: A is the crag formed from the volcanic plug, B is the tail of softer rock, and C shows the direction of ice movement. In the case of Edinburgh, the castle stands on the crag (A) with the Royal Mile extending along the tail (B)

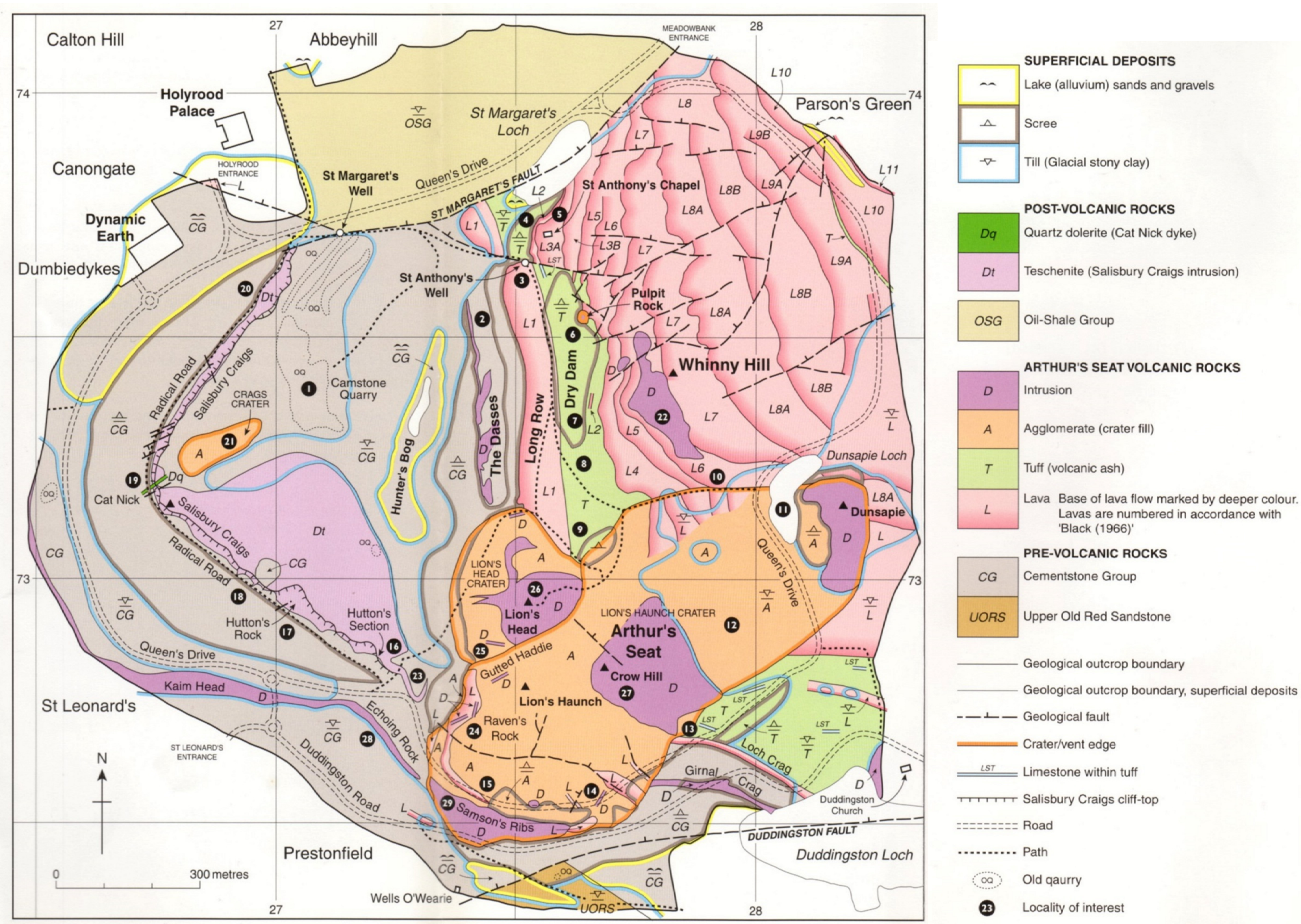
The castle stands upon the plug of an extinct volcano, which is estimated to have risen about 350 million years ago during the lower Carboniferous period. The Castle Rock is the remains of a volcanic pipe, which cut through the surrounding sedimentary rock before cooling to form very hard dolerite, a type of basalt. Subsequent glacial erosion was resisted by the dolerite, which protected the softer rock to the east, leaving a crag and tail formation.

The summit of the Castle Rock is 130 metres (430 ft) above sea level, with rocky cliffs to the south, west and north, rising to a height of 80 metres (260 ft) above the surrounding landscape. This means that the only readily accessible route to the castle lies to the east, where the ridge slopes more gently. The defensive advantage of such a site is self-evident, but the geology of the rock also presents difficulties, since basalt is extremely impermeable. Providing water to the Upper Ward of the castle was problematic, and despite the sinking of a 28-metre (92 ft) deep well, the water supply often ran out during drought or siege, for example during the Lang Siege in 1573.

**STOP 3.2:** *Arthur's Seat*




MAIN FEATURES OF HOLYROOD PARK

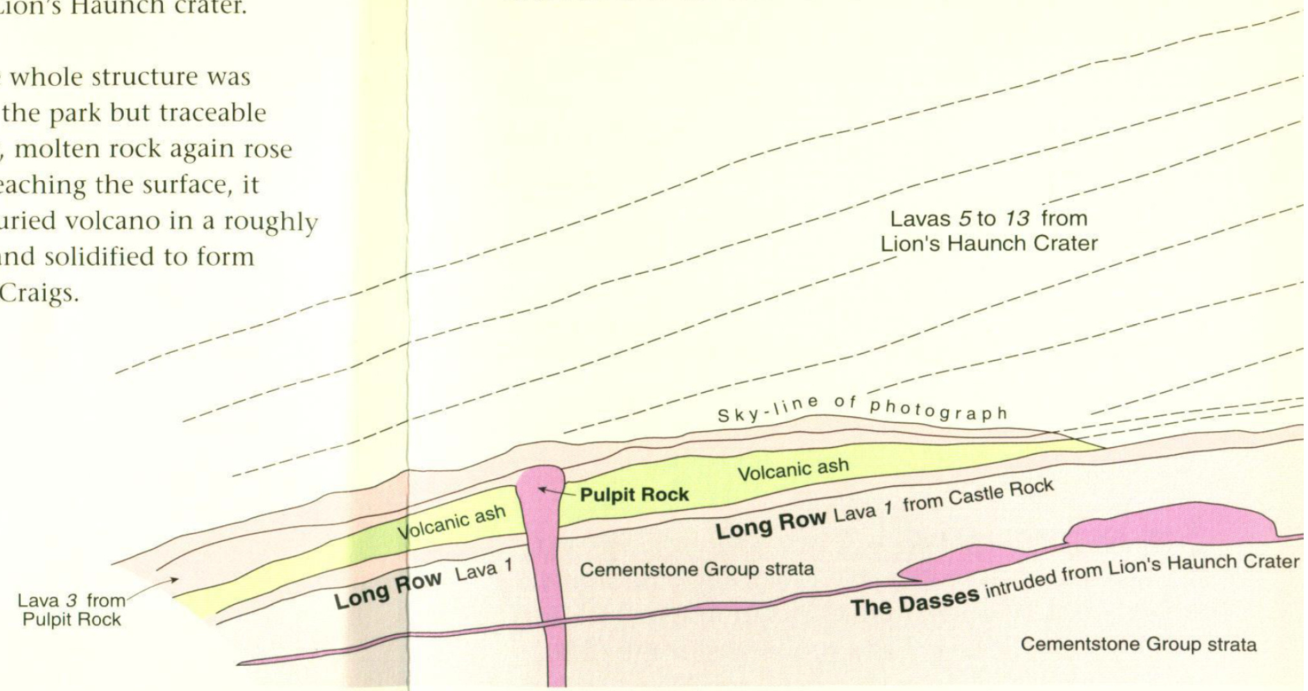



GEOLOGICAL MAP OF HOLYROOD PARK

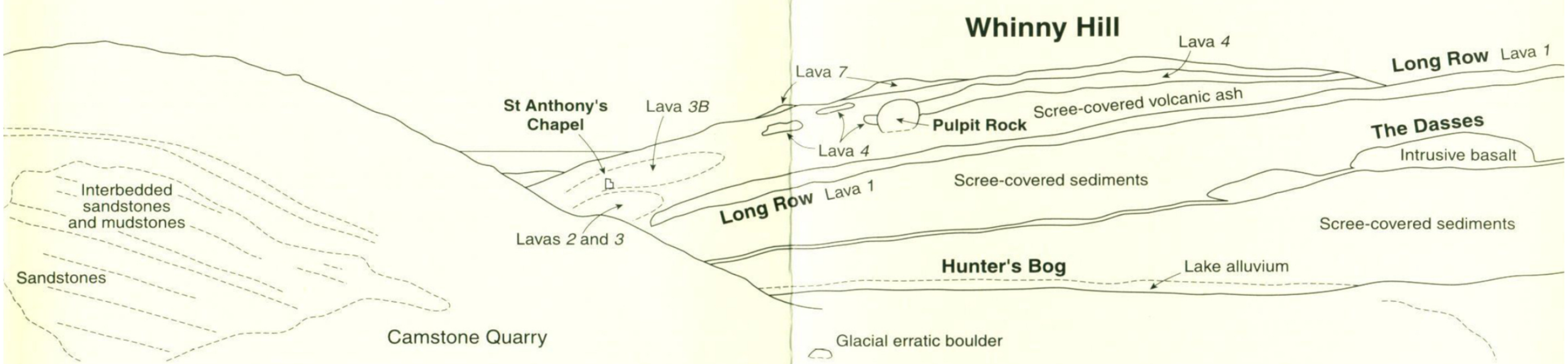
came from a small side crater now marked by the Pulpit Rock. Later lavas came from the Lion's Haunch crater.

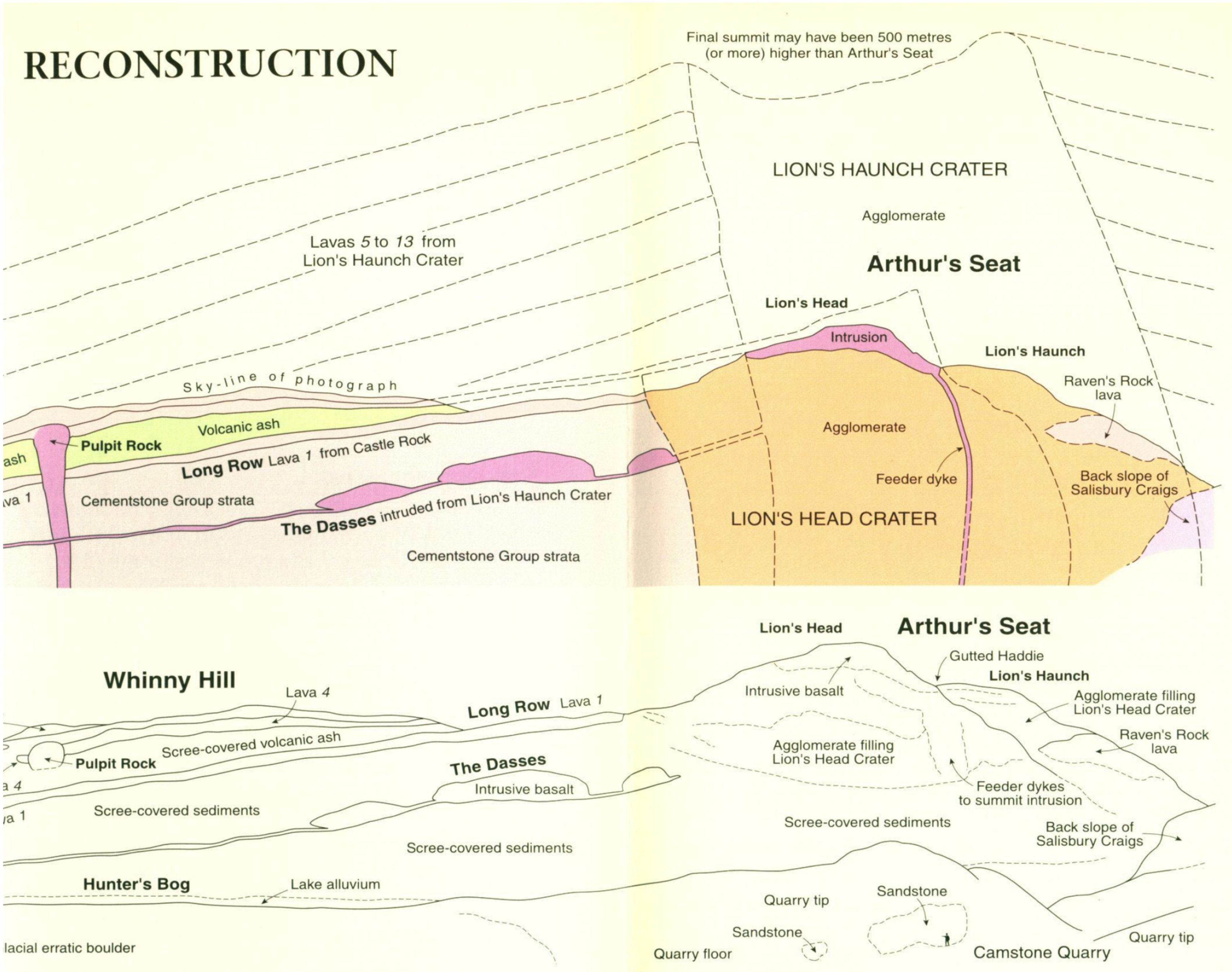
After volcanic activity ceased, the whole structure was buried by sediments (not seen in the park but traceable elsewhere). Millions of years later, molten rock again rose from the depths, but instead of reaching the surface, it intruded the rocks beneath the buried volcano in a roughly horizontal layer where it cooled and solidified to form the rock we now see as Salisbury Craigs.

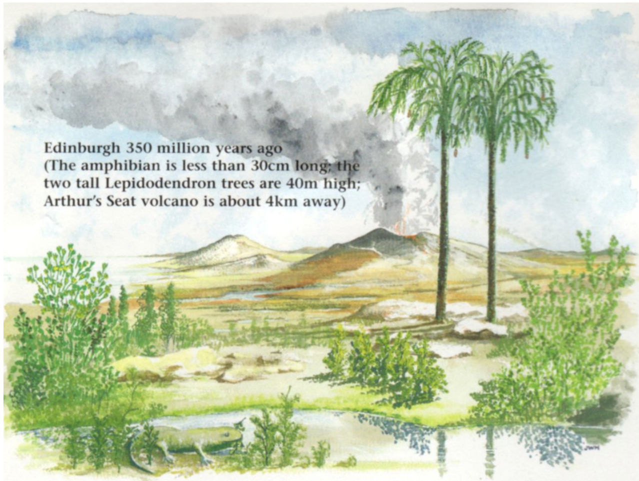
## RECONSTRUCTION




## *PANORAMA*



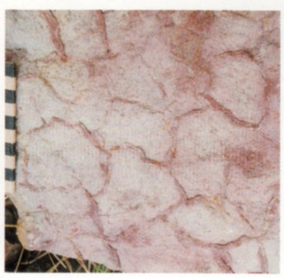

RECONSTRUCTION
Final summit may have been 500 metres (or more) higher than Arthur's Seat
LION'S HAUNCH CRATER
Agglomerate
Lavas 5 to 13 from Lion's Haunch Crater
Arthur's Seat
Lion's Head
Intrusion
Lion's Haunch
Raven's Rock lava
Sky-line of photograph
Volcanic ash
ash
Pulpit Rock
Long Row Lava 1 from Castle Rock
Agglomerate
Feeder dyke
Back slope of Salisbury Craigs
va 1
Cementstone Group strata
The Dasses intruded from Lion's Haunch Crater
LION'S HEAD CRATER
Cementstone Group strata
Lion's Head
Arthur's Seat
Gutted Haddie
Lion's Haunch
Whinny Hill
Lava 4
Long Row Lava 1
Intrusive basalt
Agglomerate filling Lion's Head Crater
Raven's Rock lava
Pulpit Rock
Scree-covered volcanic ash
Agglomerate filling Lion's Head Crater
The Dasses
Intrusive basalt
Feeder dykes to summit intrusion
a 4
a 1
Scree-covered sediments
Scree-covered sediments
Back slope of Salisbury Craigs
Scree-covered sediments
Hunter's Bog
Lake alluvium
Quarry tip
Sandstone
Sandstone
Quarry tip
lacial erratic boulder
Quarry floor
Camstone Quarry




# THE WALK STARTS HERE

Arthur's Seat volcano erupted about 350 million years ago when what is now Scotland was near the equator: a region of volcanoes, low hills, coastal plains and shallow seas enjoying a warm climate, something like the East or West Indies today.

*Camstone Quarry*

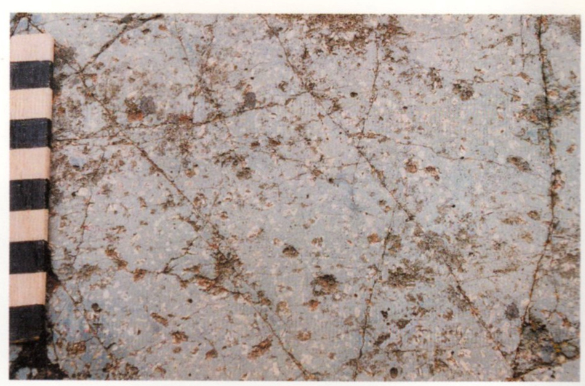


*Drying-out cracks (cm scale)*

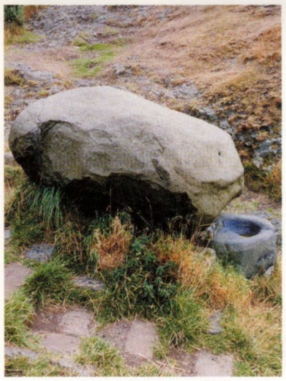
1 **CAMSTONE QUARRY.** Here we see rocks formed from mud and sand washed down by rivers, before the volcano erupted. We are standing on a low coastline by a shallow sea under a hot sun, as shown by ripple marks and drying-out cracks preserved in some of the rocks. Notice also that the rock layers (along with all the rocks in the park, including those of the volcano) slope down eastwards, going deeper underground in that direction. This is due to earth movements, long after the rocks were formed, tilting them down towards the east. From the quarry we can admire the view shown in the panorama: see the other side of the leaflet.

*Dasses: flow lines on top surface*

2 **THE DASSES** (NORTH END). These crags, like all those in the park, are made of volcanic rock called basalt, which was once hot enough to be molten. Here, the rock cooled and solidified deep underground, forming an intrusion. (Lava, on the other hand, flowed from the crater down the side of the volcano, and solidified there with a rough 'crusty top', as may be seen at locality 13.)
Look at the top surface of the Dasses (i.e. the east side, facing Long Row) and note that it is not crusty and rough, showing it to be an intrusion.
The flow lines on the top surface show that the basalt was intruded in a north-westerly direction.
Throughout the park, different varieties of basalt can be recognised and their distribution reveals the structure and history of the volcano. A close look at the Dasses rock shows tiny oblong off-white crystals of a mineral called feldspar. Compare this with a block fallen from the Long Row: here no individual crystals can be made out with the naked eye, showing it to be a different sort of basalt.



*White feldspar crystals in dark matrix (cm scale)*

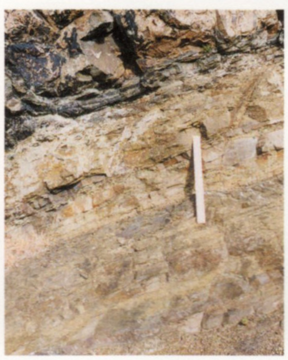


St Anthony's Well, capped by a boulder carried by the ice-sheet

Limestone (stick 30cm)

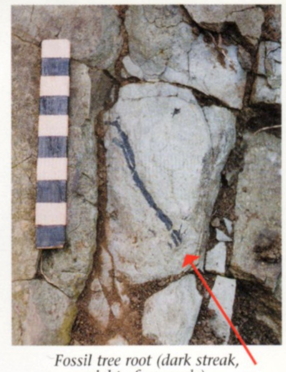
**3 ST ANTHONY'S WELL.** This is a spring (the water now piped away) rising on a geological fault, which is a near-vertical fracture formed by earthquakes breaking the rock layers. The fault runs east-west under the path approaching the spring. Haggis Knowe and Long Row are both formed from the same lava flow (number L1 on the map): note how the fault has displaced the Haggis Knowe crag west of the line of the Long Row crag, and that the fault therefore downthrows to the north (i.e. the north side has subsided relative to the south side). About 30 metres east of the well, and south of the fault, a limestone crops out. It is a chemically precipitated rock but also contains small sand grains: it gives a picture of a lagoon drying out with sand blown in by the wind.

Columnar lava on layers of ash and mudstone



Lava on ash and mudstone (stick 30cm)

**4 BELOW AND WEST OF ST ANTHONY'S CHAPEL.** Here, columnar lava (number L3A on the map) rests on volcanic ash. The lava columns, like the better but much later ones on Staffa, formed as the rock shrank as it cooled. Volcanic ash is a rock made of basalt fragments (looks like ash but is not burnt). When molten basalt comes to the surface the pressure on it is released and bubbles of gas form, just as happens with a fizzy drink when the bottle is opened. If the pressure release is sudden, the molten rock blows into little fragments. Compare this ash, which you can break with your fingers, with the hard lava above. Notice a layer with fossil roots of plants (irregular dark streaks): we are standing in a forest that was overwhelmed by the volcano.



Fossil tree root (dark streak, right of cm scale)

Chapel: stones mostly basalt with some ash (greenish); and pale freestone sandstone for carved work

**5 ST ANTHONY'S CHAPEL** was built as a hermitage around 1450. Note that most of the stone in the building is of basalt quarried on site, but the carved work is of freestone, probably from Camstone Quarry. Freestone is a sandstone which can be cut in any direction without splitting. The chapel stands on the lower, columnar part of the basalt lava 3, the upper part of which makes the cliff east of the chapel. Note that the basalt includes irregular rough slaggy-looking pieces of solidified lava crust which became incorporated into the still-flowing lava.

*Pulpit Rock*

**6 PULPIT ROCK.** This marks a little side volcano from which flowed the lava which makes the cliff above the chapel. This lava (number L3) does not appear (at the present level of erosion) south of the St Anthony's Fault. Lava 4 which wraps round the Pulpit Rock and makes the eastern crest of the Dry Dam valley, does not extend north of the fault. Probably the fault moved during volcanic activity and so controlled the flow of the lavas.

**7 DRY DAM.** Walking up Dry Dam, note that this valley has been formed by the erosion of the relatively soft ash which crops out (i.e. comes to surface) here, whereas the harder more resistant lavas stand up as hills on either side.

*Lumps of lava in ash (stick is 80cm long)*

**8 HILLSIDE EXPOSURE ABOVE THE PATH.** The ash here contains large lumps of lava which have rolled down from the crater which was only 150 metres away.

*Corrie at head of Dry Dam*

**9 TOP OF DRY DAM.** This is a corrie (a semicircular steep-sided hollow), gouged out by ice some 15,000 years ago - not so spectacular as Highland corries but formed in the same way.

*Whinny Hill: scarp and dip topography*

**10 SOUTHERN END OF WHINNY HILL.** Walking down to Dunsapie Loch we follow the edge of the crater which is to the right (south). To the left note how successive lava flows form ridges which are steep and craggy on the west but gentler and grass covered on the east. This is 'scarp and dip' topography formed by erosion of the easterly sloping (dipping) layers of lavas. This topography extends right across the north-eastern part of the park. We can trace out the lavas by following the ridges.

*Dunsapie, from Crow Hill*

**11 DUNSAPIE LOCH.** Note the hill of Dunsapie which is a basalt intrusion resisting erosion because it is a solid mass.

*Cultivation terraces on Crow Hill*

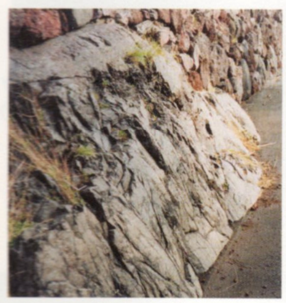
**12 CROW HILL TERRACES.** Ice Age ice-sheets, crossing Arthur's Seat from west to east, severely eroded west-facing slopes but deposited stony clay on eastern lee slopes. Here, therefore, prehistoric men found enough depth of soil to make these terraces for growing crops. The ice sheet melted away about 15,000 years ago.

*Ashes and mudstones on lava 1*

**13 LOCH CRAG** is the continuation of the Long Row lava on the other side of the crater. Note the rough top of the lava overlain by layers of ash and mudstone. If the crag is followed uphill, it is seen to be abruptly cut off, about halfway up the steep slope above the road, by the crater edge, showing that this crater is younger than the lava.

Agglomerate

**14 CLIFF ABOVE QUEEN'S DRIVE.** Beyond locality 13 for about 300 metres the cliff above the road is mainly made of agglomerate. This is simply debris of all sizes that fell into the crater when volcanic activity ceased. The rock is best appreciated opposite a recess in the wall. Here jumbled pieces of grey basalt lie in a matrix stained red by iron oxides.



*Ice-smoothed rock*

*Scratched and polished face of fault*

**15 TWO HUMPS OF ROCK** at the edge of the road and below the retaining wall. The eastern one shows the face of a geological fault or fracture where two rock masses have ground past each other, mutually polishing and scratching. Run your fingers across the face of the rock to appreciate this effect. (Beware of traffic when crossing the road.) The western lump of rock has been smoothed into rounded shapes by the ice sheet grinding over it. Stones held in the base of the ice have scratched the bedrock making near-horizontal striations. Again, feel the surface to appreciate its character and difference from the fault-affected rock.

*Hutton's Section: basalt (red at base) on sandstones*

*Detail of Hutton's Section (stick 80cm)*

**16 HUTTON'S SECTION.** Salisbury Craigs, which dominate the rest of this walk, are formed by a huge layer of basalt intruded many millions of years after the volcano became extinct. When it formed, the basalt layer was roughly horizontal, but now it slopes eastwards (as do all the rocks in the park). Its westwards extent has been eroded away, and eastwards it passes underground. We do not know its original complete extent. The base of the basalt, resting on sandstones, is exposed in the first quarry. This exposure is Hutton's Section, so-called because it was one used by him to demonstrate his ***Theory of the Earth*** (1788) which laid the foundation of geological science (see panel overleaf). Notice how the basalt has disrupted the sandstone layers by its forcible intrusion. Note also that the basalt is finer-grained near the contact with the sandstones because here it cooled and crystallised more quickly.

*Hutton's Rock, with vein of iron ore (stick 30cm)*

**17 HUTTON'S ROCK** is a knob of basalt cut by a vein of iron ore, reputedly left unquarried at Hutton's request, and is thus an early example of environmental conservation.

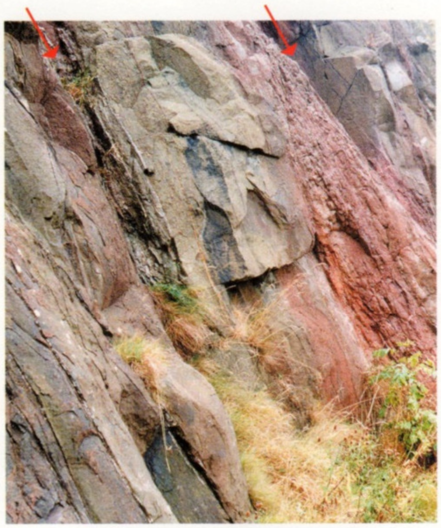
*Crumpled sandstone layers are cut off (left and right of stick) by overlying basalt*

**18 CRUMPLING** at the base of the basalt intrusion. Looking at the way the basalt distorts and cuts across the sandstone and mudstone layers we can try to imagine the tremendous force exerted by the intrusion.

**19 CAT NICK.** A small geological fault has broken the rock, making it weaker and so enabling the weather to erode it into this cleft. Ten metres north of the Cat Nick is a vertical wall-like intrusion about two metres wide. It may be recognised by its greenish tinge, compared with the reddish colour of the Craigs. Notice how the Cat Nick intrusion cuts both the Salisbury Craigs intrusion and the underlying sandstones. The cross-cutting relations thus show relative ages: sandstones, then Craigs intrusion, then Cat Nick intrusion.

*Vertical intrusion cutting basalt and sandstone*

# ADDITIONAL LOCALITIES

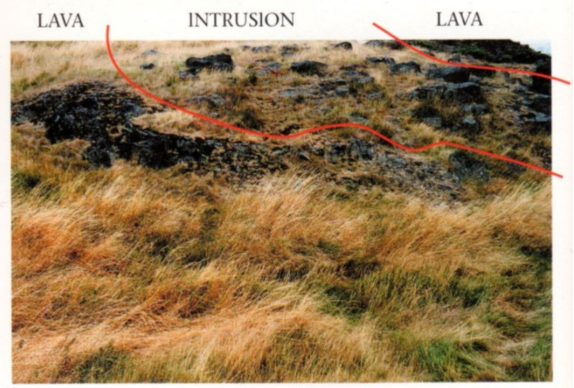


*Veins of iron ore and calcite spar cutting basalt*

**20 NORTH END OF SALISBURY CRAIGS.** Here the basalt and the overlying sandstones were quarried nearly 200 years ago for road paving stones. Notice that cracks in the rocks have in places been infilled with calcite spar (the white mineral) and iron ore (reddish coloured).

*Crags Crater: the V-shaped rocky slope marks its margin*

**21 CRAGS CRATER** forms a low oval hill southwest of Camstone Quarry and consists of the agglomerate crater-fill of a small side volcano.




*Whinny Hill intrusion (rounded blocks) between lavas (skyline and irregular foreground crag)*

**22 WHINNY HILL INTRUSION.** This, like The Dasses, affords an opportunity to appreciate different types of basalt. The intrusion is black and coarse-grained and is exposed as rounded lumps, whereas the lava flows into which it was intruded are dark purplish-grey and fine grained and form irregular crags. Feel with your fingers the difference between the rough intrusive basalt and the smooth lava basalt.

**23 THE HAWSE.** Where the path crosses the end of Salisbury Craigs, a vein of iron ore and calcite spar cuts the basalt. The extreme south-eastern end of the intrusion is seen some 40 metres east of The Hawse where it dies out in a north-pointing outcrop. The large blocks on the slope below Raven's Rock have fallen from above and are not part of the Salisbury Craigs intrusion.

## 24 RAVEN'S ROCK

and the crag south of it running down to the road is a lava flow just within the crater and now dipping eastwards at a very steep angle. The rough path up the slope crosses Raven's Rock where a gully has been eroded along a geological fault running NW-SE. Another gully, running down south-westwards to the first one, exposes the top of the lava and the base of the overlying agglomerate. Here this is finely grained and ashy: farther east it is very coarse, as exposures all along the hillside show.

*Coarse agglomerate with steep NE dip (into the crater)*

*Raven's Rock: near-vertical lava (dark) overlain by red ash and agglomerate.*

*Top of Gutted Haddie: columnar basalt of Lion's Head intrusion against Lion's Haunch agglomerate*

## 25 GUTTED HADDIE

is a gully eroded along the contact between the Lion's Head and Lion's Haunch infilled craters. The latter cuts the former and so was formed after activity ceased at the Lion's Head. Exposures in the Gutted Haddie show the Lion's Haunch agglomerate in contact with the Lion's Head agglomerate and with the columnar basalt intrusion which makes the Lion's Head summit of Arthur's Seat.

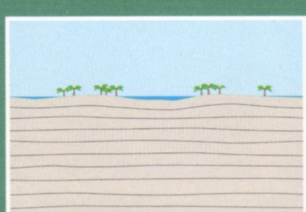
## 26 SUMMIT OF ARTHUR'S SEAT.

From here may be seen magnificent views of most of the Midland Valley and farther Highland mountains up to 110km away.

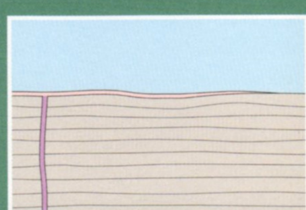
## 27 CROW HILL

Summit is formed of basalt (probably an intrusion but perhaps a lava: evidence is lacking) which shows excellent columnar structure. The depression north of Crow Hill is defended by an Iron Age double rampart.

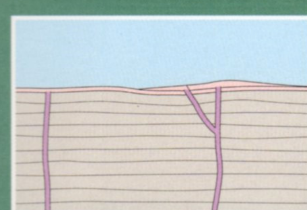
# STAGES IN THE GEOLOGICAL HISTORY OF THE VOLCANO



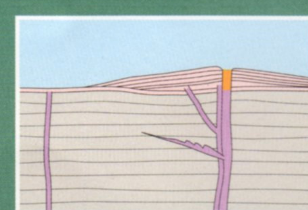
*1. Cementstone Group: sand and mud in shallow lagoons*



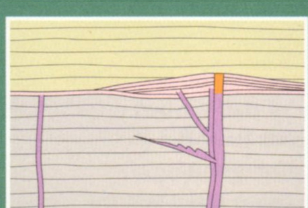
*2. First eruption at Castle Rock of lava 1*



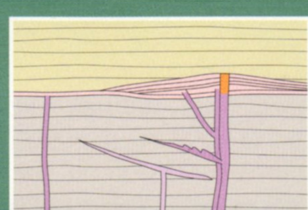
*3. Second eruption, at Lion's Head of ashes and lavas 2 to 4; lava 3 from side volcano at Pulpit Rock*



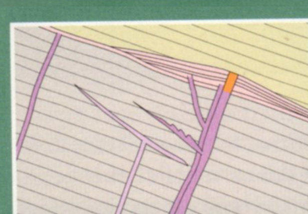
*4. Third period of eruption, at Lion's Haunch: lavas 5 to 13, some ashes; intrusion of The Dasses*



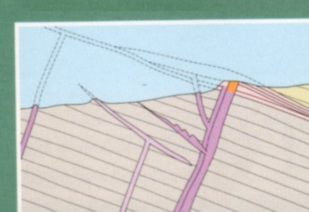
*5. After volcano became extinct, sands and muds deposited burying the volcano*



*6. Intrusion of Salisbury Craigs*



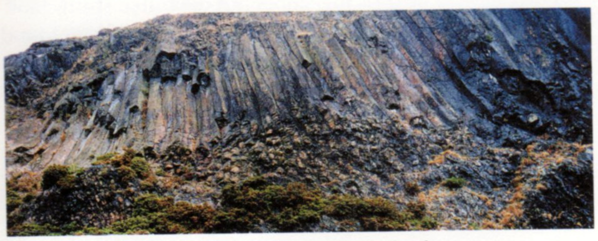
*7. Earth movements tilt all the rocks to the east at 25°*



*8. Erosion lays bare the volcanic rocks*

*Platy jointing in mugearite (stick 30cm)*

28 **ECHOING ROCK** is a ridge formed by the outcrop of the St Leonard's intrusion which forms a layer roughly parallel with the rock layers into which it was forced. The outcrop continues to the west along Kaim Head and the park boundary to Dumbiedykes and beyond. The basalt of this intrusion is a mugearite, containing more sodium than usual and distinguished in the field by close spaced 'platy' jointing.



*Samson's Ribs columnar intrusive basalt*

29 **SAMSON'S RIBS** is a wide vertical intrusion along the edge of the crater-fill. It shows magnificent columnar jointing.

## TECHNICAL NOTE FOR PROFESSIONAL GEOLOGISTS

The Arthur's Seat volcanic formation, about 300m thick, lies at the base of the Lower Oil-Shale Group, low in the Visean in the early Carboniferous. At that time, about 350Ma ago, what is now Scotland was near the equator in a cratonic region on the southern margin of a North Atlantic continent.

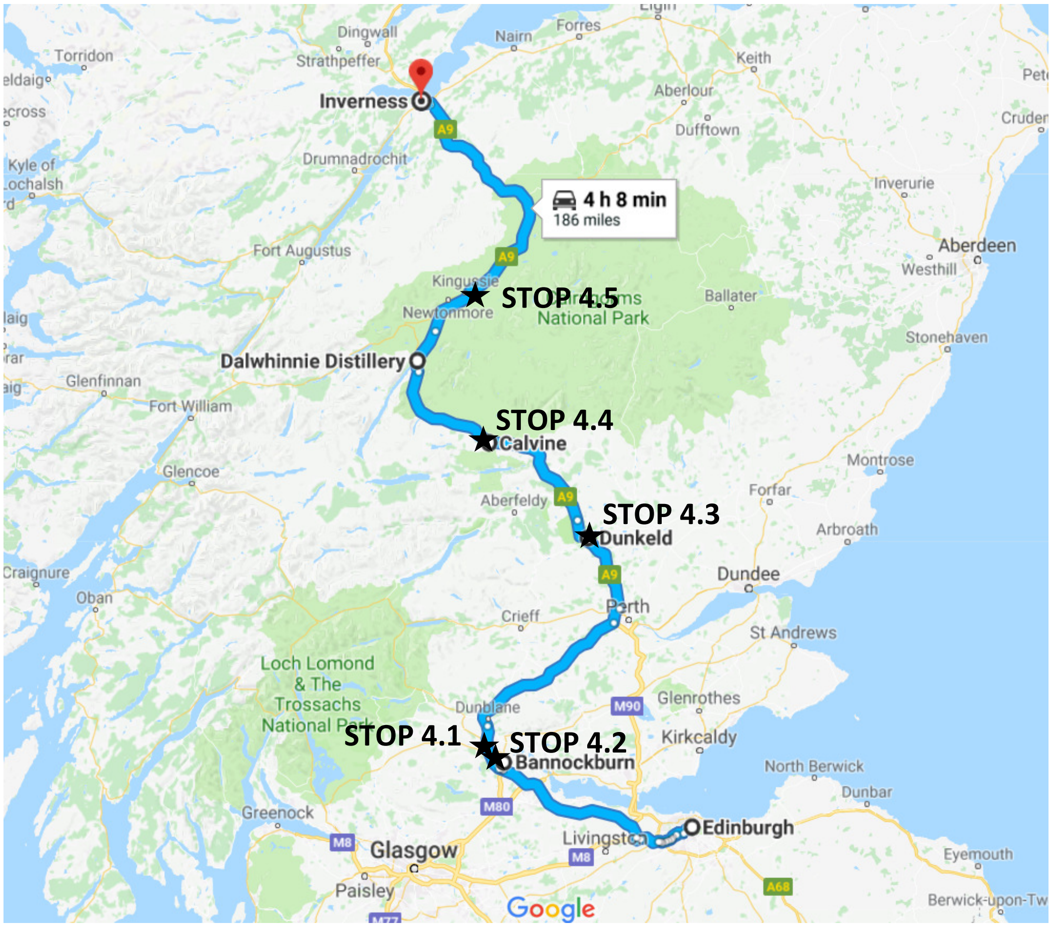
A generally tensional stress regime pertained, allowing intra-plate, mildly alkaline volcanism to be widespread in space and time through the Scottish Carboniferous.
The small Arthur's Seat volcano happens to be at the right level of erosion for its structure to be displayed to advantage.

Strata below the volcanic formation crop out in the western part of the park and belong to the Cementstone Group. They consist of grey, red and green sandstones and mudstones with thin cementstones (chemically precipitated dolomites). There is a restricted fauna of spirorbis, naiaditid bivalves, estheriids, ostracods and fish.
Cross-bedding, ripple marks, desiccation features and some root horizons indicate cyclic, shallow water, fluvial and lagoonal sedimentation.

The volcanic rocks are porphyritic olivine basalts with titaniferous augite, labradorite, iron ore and minor analcite. No petrogenetical trend can be observed in the Arthur's Seat basalts, but variations in phenocryst sizes and proportions coupled with detailed mapping enable the history and structure to be worked out.
Lava 1 (Long Row) and the Castle Rock, Crow Hill, Dunsapie and Samson's Ribs intrusions are Dunsapie-type basalt (olivine-plagioclase-augite-phyric basalt). Lavas 2 and 3 and the Pulpit Rock and Whinny Hill intrusions are Craiglockhart-type basalt (ankaramite; olivine-augite-phyric). Lava 4 and Lion's Head intrusions are Dalmeny-type (olivine microphyric).
Lavas 5, 6 and 7 are Jedburgh-type (hawaiite; labradorite-olivine-microphyric). Lavas 8, 9 and 10 and the Dasses, Girnal and part of St Leonard's sills are Markle-type (hawaiite; labradorite-phyric). Lava 11 and most of St Leonard's sill are mugearite (with oligoclase instead of labradorite; purplish colour and close platy jointing). Partial deuteric albitization affects several lavas and intrusions.

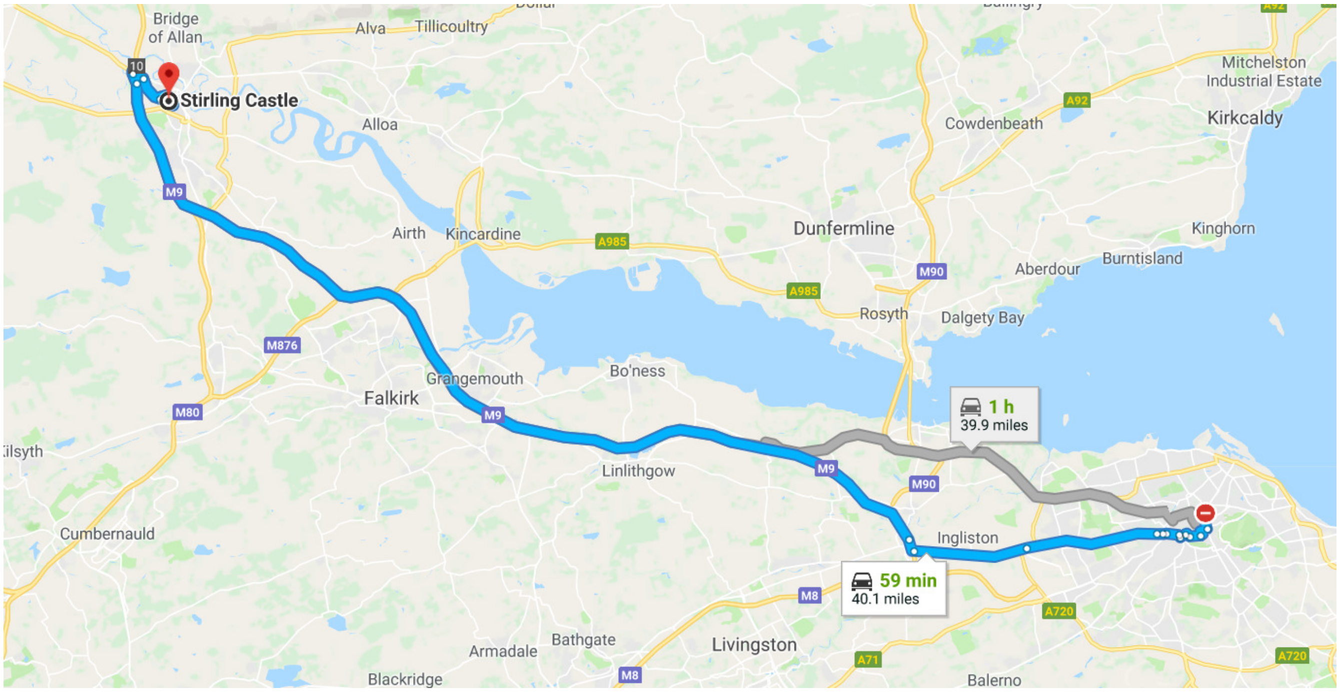
Salisbury Craigs sill is a teschenitic dolerite (labradorite, augite, olivine, analcite and iron ore) of early Namurian (325Ma) age. The Cat Nick dyke is a later quartz-dolerite.

**Day 4: Wednesday, March 7th, 2018 – Stirling, Bannockburn, Dalradian Rocks, Distilleries, Inverness, AND Jake's 21st Birthday!**




**8:00 AM:** Depart from Edinburgh and drive to Bannockburn/Stirling (1 hr drive)
**9:00 AM:** Drive around Stirling Castle – no tour this time
**10:00 AM:** The Battle of Bannockburn Visitor Center
http://battleofbannockburn.com/
**12:00 PM:** Lunch out of the van
**12:30 PM:** Leave Stirling
**1:30 PM:** Dunkeld and Little Glen Shee – Folded Dalradian sediments
**2:15 PM:** Clunes A9 Road Cut – Folded Dalradian sediments
**3:00 PM:** Speyside Distillery (http://speysidedistillery.co.uk/), The Cairgorms Brewery (http://www.cairngormbrewery.com/), Dalwhinnie Distillery (https://www.malts.com/en-row/distilleries/dalwhinnie/), we each have to buy Jake a drink….
**6:00 PM:** Get to the hostel in Inverness
Ardconnel House
21 Ardconnel St
Inverness, IV2 3EU
Telephone: +44 01463 240455
http://www.ardconnel-inverness.co.uk/

**STOP 4.1:** *Stirling Castle*




*From Wikipedia:*

Stirling Castle, located in Stirling, is one of the largest and most important castles in Scotland, both historically and architecturally. The castle sits atop Castle Hill, an intrusive crag, which forms part of the Stirling Sill geological formation. It is surrounded on three sides by steep cliffs, giving it a strong defensive position. Its strategic location, guarding what was, until the 1890s, the farthest downstream crossing of the River Forth, has made it an important fortification from the earliest times.

Most of the principal buildings of the castle date from the fifteenth and sixteenth centuries. A few structures of the fourteenth century remain, while the outer defences fronting the town date from the early eighteenth century.

Before the union with England, Stirling Castle was also one of the most used of the many Scottish royal residences, very much a palace as well as a fortress. Several Scottish Kings and Queens have been crowned at Stirling, including Mary, Queen of Scots, in 1542, and others were born or died there.

There have been at least eight sieges of Stirling Castle, including several during the Wars of Scottish Independence, with the last being in 1746, when Bonnie Prince Charlie unsuccessfully tried to take the castle. Stirling Castle is a Scheduled Ancient Monument, and is now a tourist attraction managed by Historic Environment Scotland.

*From:* Brown and Gillen, 2015, pgs. 37-38

## Locality 1.22 [NS 7910 9400]

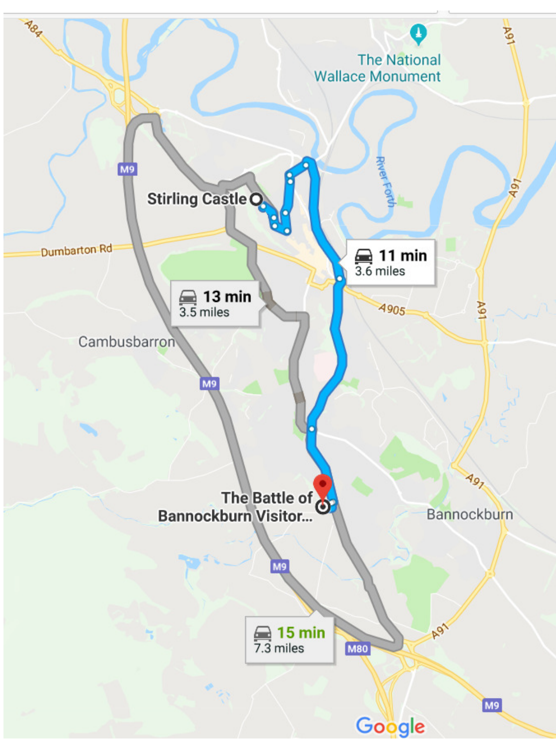
Stirling Castle Esplanade viewpoint.

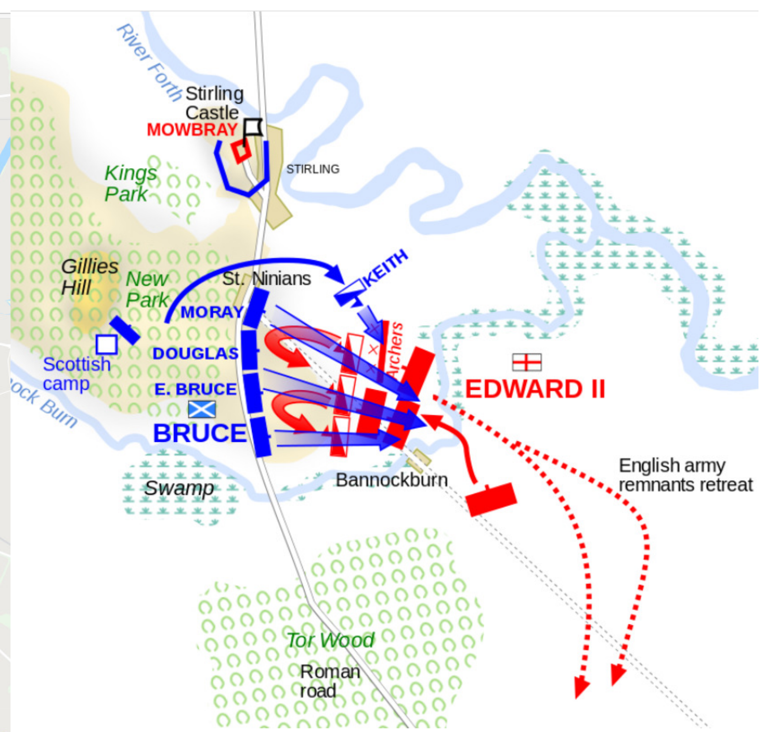
Continue north to the castle esplanade. The castle was built in many different stages of different stones, including rocks from Ballengeich, Cat Craig and Longannet [NS 9500 8567] quarries. The esplanade is a superb vantage point to see the geology of the Forth valley, and to understand the relationship between geology and scenery. From the esplanade, looking westwards up the Forth valley, the distant Grampian Highlands can be seen. The prominent mountains on the horizon are all composed of 600 million year-old metasedimentary rocks belonging to the Southern Highland Group of the Dalradian Supergroup. Situated on part of the overturned limb of the huge recumbent structure known as the Tay Nappe, Ben Lomond is formed of relatively flat-lying cleaved wacke sandstones, pelitic (mudstone) rocks and metavolcaniclastic 'green beds' of the Ben Ledi Grit Formation. Other mountains composed of rocks of this formation, including Ben Venue, Ben Ledi, Stuc a' Chroin and Ben Vorlich, lie within the down-turned hinge-zone of the Tay Nappe. The core of the nappe includes rocks of the Aberfoyle Slate Formation. The Highland Boundary Fault that extends through the southern end of Loch Lomond, behind the Menteith Hills, through Callander to Stonehaven on the east coast, divides the Grampian Highland metamorphic rocks from the younger sedimentary and volcanic rocks of the Midland Valley. Immediately south of the Highland Boundary Fault the Menteith Hills are composed of steeply dipping conglomerates and sandstones of Early Devonian age (410 million years old).

Rocks of Early Devonian age underlie all the ground between the Menteith and Ochil hills. Looking north from the esplanade, the Ochil Hills with Dumyat at the SW end consist of a sequence of lavas and volcaniclastic sedimentary rocks (Ochil Volcanic Formation). Westwards, towards Dunblane and beyond, the volcanic rocks pass up into a sequence of sedimentary strata including fluvial sandstones and finer grained sedimentary rocks laid down in lakes and extensive alluvial plains. The West Ochil Fault separates the volcanic sequence exposed in the Ochil Hills from younger coal-bearing Carboniferous rocks underlying the flat valley floors of the Forth and Devon. The fault effectively forms the spectacular scarp face of the Ochils, through the south side of Stirling University campus, and eastwards past Menstrie, Alva and Dollar. The fault has had the effect of downthrowing the Carboniferous strata to the south by a maximum of about 3000 m at Tillicoultry.

Most of the Carboniferous rocks in the vicinity of Stirling are hidden by a thick succession of Late Devensian and Holocene marine and estuarine sediments formed at various stages following deglaciation of the Forth valley about 13,500 years ago (Figure 5.2). These sediments infill a glacially overdeepened depression that locally is greater than 180 m deep. The principal upstanding hills in the valley floor are composed of rock types that were more resistant to glacial erosion. The main one is quartz-dolerite that in the Stirling district forms a transgressive sill, intruded during late Carboniferous times into Carboniferous sedimentary rocks and displaced locally by faulting and stepping. The Midland Valley Sill-complex extends under Stirling, Falkirk, West Lothian and Fife. Prominent is the Castle Rock, a crag-and-tail shaped by the action of eastward-moving ice which plucked bare the western faces and deposited debris to the east. The brown-ochre weathering and blocky jointing of the dolerite can be easily seen. To the north, Abbey Craig with the Wallace Monument (built in 1869) is also part of the sill, displaced slightly to the east by a small fault.

**STOP 4.2:** *The Battle of Bannockburn*



*From Wikipedia:*

The Battle of Bannockburn 24 June 1314 was a significant Scottish victory in the First War of Scottish Independence, and a landmark in Scottish history. Stirling Castle, a Scots royal fortress, occupied by the English, was under siege by the Scottish army. The English king, Edward II, assembled a formidable force to relieve it. This attempt failed, and his army was defeated in a pitched battle by a smaller army commanded by the King of Scots, Robert the Bruce.

The Wars of Scottish Independence between England and Scotland began in 1296 and initially the English were successful under the command of Edward I, having won victories at the Battle of Dunbar (1296) and at the Capture of Berwick (1296). The removal of John Balliol from the Scottish throne also contributed to the English success. The Scots had been victorious in defeating the English at the Battle of Stirling Bridge in 1297. This was countered, however, by Edward I's victory at the Battle of Falkirk (1298). By 1304 Scotland had been conquered, but in 1306 Robert the Bruce seized the Scottish throne and the war was reopened.

Edward II of England came to the throne in 1307 but was incapable of providing the determined leadership that had been shown by his father, Edward I, and the English position soon became more difficult. Stirling Castle was one of the most important castles that was held by the English as it commanded the route north into the Scottish Highlands. It was besieged in 1314 by Robert the Bruce's brother, Edward Bruce, and an agreement was made that if the castle was not relieved by mid-summer then it would be surrendered to the Scots. The English could not ignore this challenge and military preparations were made for a substantial campaign in which the English army probably numbered 2,000 cavalry and 15,000 infantry, many of whom would have been longbowmen. The Scottish army probably numbered between 7,000 and 10,000 men, of whom no more than 500 would have been mounted. Unlike the heavily armoured English cavalry, the Scottish cavalry would have been light horsemen who were good for skirmishing and reconnaissance but were not suitable for charging the enemy lines. The Scottish infantry would have had axes, swords and pikes, with few bowmen among them.

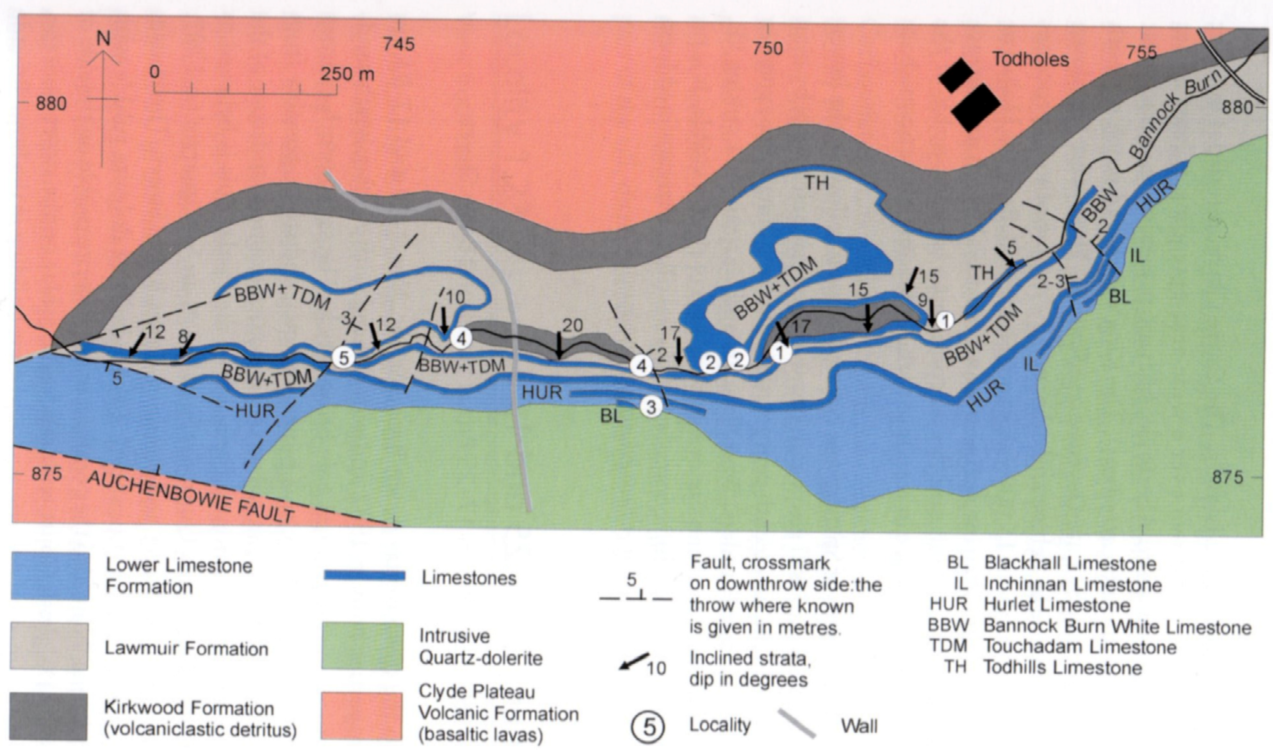



**Figure 2.1** Map of late Viséan rocks exposed in the upper Bannock Burn near Todholes, showing localities for Excursion 2. Adapted from Francis *et al.* (1970, fig. 13).

*From:* Brown and Gillen, 2015, pgs. 40-51

Excursion 2

# Bannock Burn

Bill Read

*Purpose:* To view the deeply weathered top of the basaltic lava pile of the Clyde Plateau Volcanic Formation (Strathclyde Group); to examine the overlying Kirkwood Formation derived from the reworking of weathered lava, and its relationship to the marine sedimentary rocks in the cyclically deposited Lawmuir Formation above; to inspect the Lower Limestone Formation (Clackmannan Group) including the Hurlet, Inchinnan and Blackhall limestone cycles.

*Logistics:* This excursion is on land belonging to Sauchie Estates Ltd, Cultenhove Farm, Sauchieburn Estate, Stirlingshire and Todholes Farm. Care should be taken whilst traversing round the numerous small waterfalls in the burn and whilst crossing fences. ***A 3-tonne maximum load limit applies to the local access roads, so that this excursion is not suitable for coach parties***. Leave the centre of Stirling, drive south to the Bannockburn Heritage Centre and turn right at [NS 798 905] onto the road to Howietoun Fishery. Turn right at the junction at [NS 7862 8790] and then at the junction with the Carronbridge road at [NS 7694 8744]. The car park is at [NS 7600 8782].

*Maps:* OS 1:50,000 Sheet 57 Stirling & the Trossachs; OS 1:25,000 Stirling & Ochil Hills West; BGS 1:50,000 Sheet 39W Stirling; locality map Figure 2.1.

Figure 2.1 is a geological map of the Bannock Burn near Todholes Farm. The stream section displays the deeply weathered top of the basaltic lava pile of the Clyde Plateau Volcanic Formation overlain by the diachronous Kirkwood Formation. This consists of bedded and cross-stratified volcaniclastic detritus derived from the lavas, which were progressively buried by younger deltaic and marine sediments during the late Viséan. Repeated marine transgressions gradually deposited sediments that covered the old lava landmass.

The overlying cyclically deposited Lawmuir Formation (Paterson & Hall, 1986) also has a diachronous base, but this formation contains marine limestones and broadly resembles the overlying Lower Limestone Formation (Clackmannan Group). In the thicker basinal sequences of the Clackmannan Syncline to the east, quartzose fluviodeltaic sands represent regressive intervals with lowered sea levels, which alternated with the transgressive intervals represented by the marine limestones. However, these sandstones are absent from the basin-margin Todholes and Touchadam sections. Figure 2.2 illustrates two vertical sections down from the Hurlet Limestone through the Lawmuir and Kirkwood formations at Todholes (A) and farther downstream around Touchadam Quarry (B) [NS 7600 9055], 4 km NNE along strike. The two basin-margin sections show considerable changes in thickness and lithology.

Limestones in the Lawmuir Formation, formerly designated alphabetically in downward order (Dinham & Haldane, 1932, pp. 14–16), have been renamed the Bannock Burn White (E), the Touchadam (F) and the Todholes (G) limestones. The Hurlet Limestone (formerly Murrayshall Limestone or D) marks the base of the Lower Limestone Formation. It was deposited during a major marine transgression that finally submerged almost all of the old subaerial lava pile. Both it and the overlying Inchinnan Limestone (C) were extensively quarried locally for lime and are generally seen only as loose blocks.

## Locality 2.1 [NS 7532 8779 to 7501 8768]

Kirkwood Formation and lateral attenuation of the Todholes Limestone.

From the car park, walk NW to the ford at [NS 7574 8810], 700 m east of Todholes Farm, where the minor road to North Third Reservoir crosses the Bannock Burn. Pass through the gate immediately south of the ford on the left (SW) side of the road and walk south-westwards, parallel to the burn, keeping on the south side of a high drystone wall, to join the stream at [NS 7542 8778]. Walk upstream, noting on the way a landslip on the path

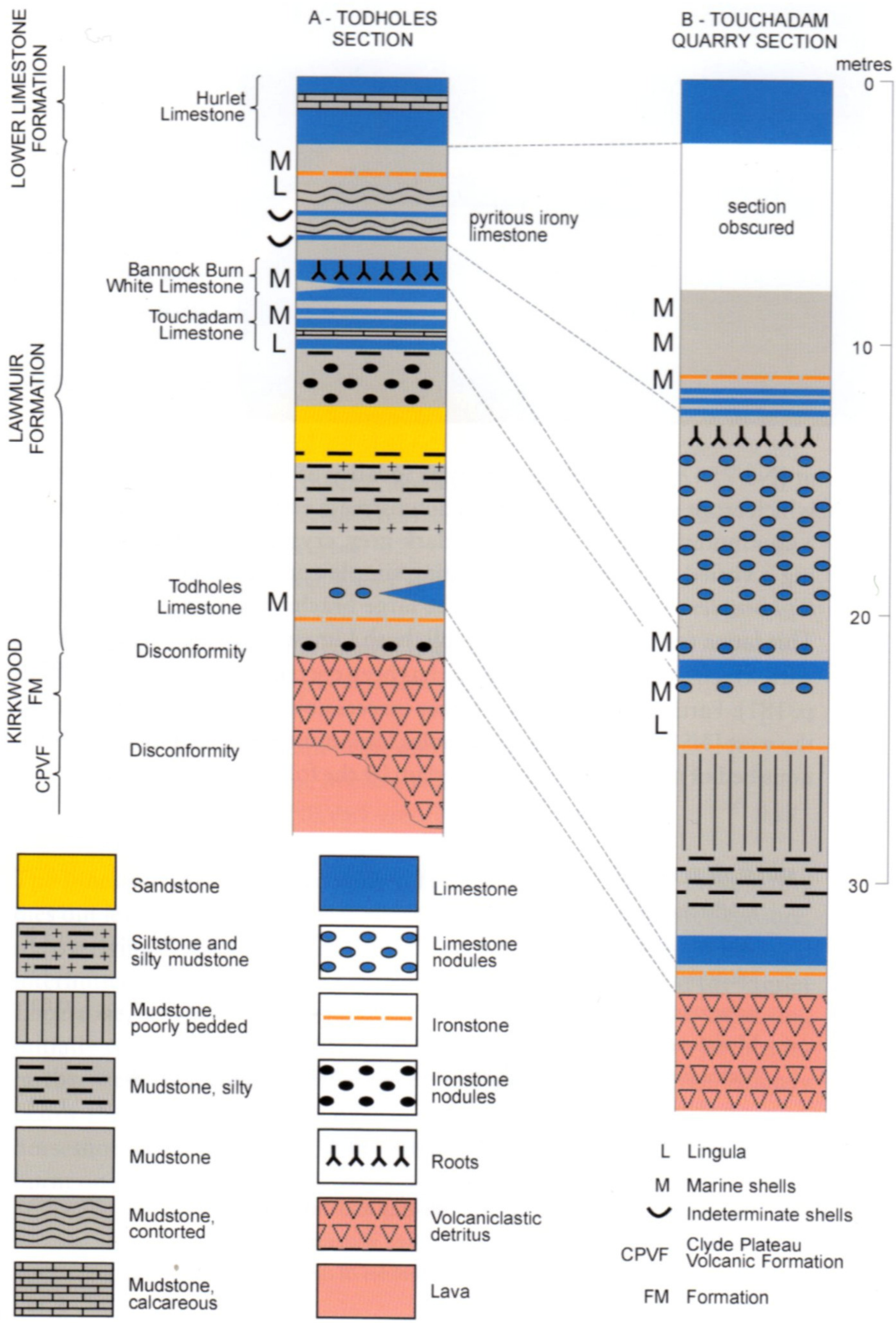



**Figure 2.2 (opposite page)**
Vertical sections of late Viséan rocks exposed in the Bannock Burn, (A) near Todholes and (B) near Touchadam Quarry. Adapted from Francis *et al.* (1970, fig. 15).

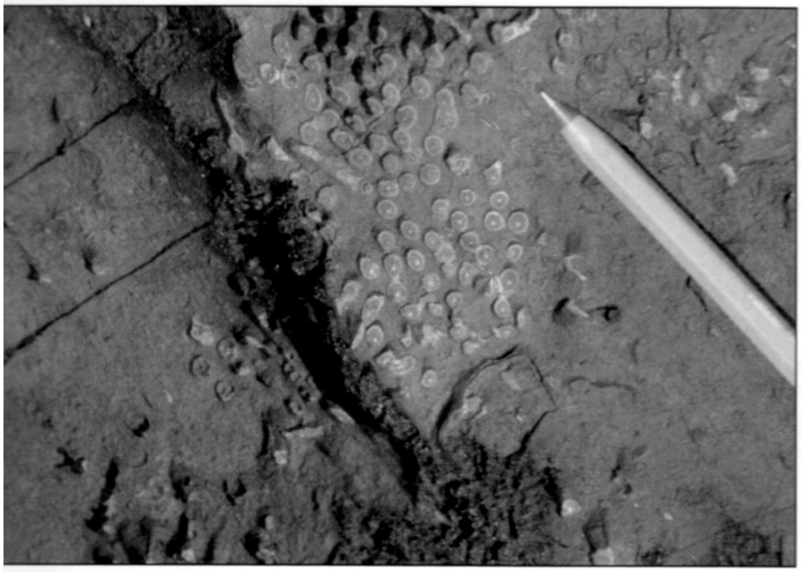


**Plate 2.1**
Locality 2.1.
Colonial coral
(*Siphonodendron sp.*)
in Todholes Limestone,
Lawmuir Formation.

at [NS 7542 8781]. This is the type locality of the Todholes Limestone, which crops out in the burn at the downstream end of the locality. Here it is a continuous bed, 0.7 m thick, of dark-grey, crystalline limestone containing a varied marine fauna, including simple corals, the compound coral *Siphonodendron* (Plate 2.1) and the large brachiopod *Gigantoproductus*. This fauna resembles that of the Hollybush Limestone of the Paisley district, with which the Todholes Limestone has been correlated (Francis *et al.*, 1970, p. 181). Farther upstream, in a rather inaccessible exposure about 300 m to the west [NS 7503 8773], the Todholes Limestone is reduced to a discontinuous bed of nodules, which is underlain by the following succession:

| | Thickness (m) |
|---|---|
| LAWMUIR FORMATION | |
| Mudstone, dark-grey, poorly bedded at top; articulate brachiopods | 0.15 |
| Siltstone, dark-grey, ferruginous | 0.15 |
| Ironstone, sideritic, silty | 0.01 |
| Mudstone, pale-grey, grading down into greenish-grey volcaniclastic detritus of silt and sand grade, which contains a nodular, sideritic bed 0.4 m thick | 1.58 |
| (Erosional unconformity, truncating beds below) | |
| KIRKWOOD FORMATION | |
| Volcaniclastic detritus, grey, greenish-grey and dull purple, generally upward-fining, cross-stratified with easterly-dipping foresets; contains rounded pebbles of decomposed basalt in lenses and towards base | 5.50 |

The unconformity between these two formations is well seen between [NS 7505 8772 and 7503 8773] (Plate S.6). The Todholes Limestone, 45–55 cm thick, crops out in the burn and rises above the volcaniclastic beds at [NS 7521 8771]. Its surface is slightly karstified and weathers black. Mudstone can be seen above and below. The basal bed is definitely not an ash-fall tuff but a water-sorted deposit derived from the reworking of decomposed bole-like material on top of the lava pile. The beds in the Lawmuir Formation above the now-discontinuous nodular Todholes Limestone are more accessible in the south bank at [NS 7501 8768], where the following section is exposed:

| | Thickness (m) |
|---|---|
| Sandstone, greenish-grey, chloritic, mostly fine-grained, upward-coarsening, with argillaceous siltstone laminae towards base; root traces at top | 0.84 |
| Siltstone, greenish-grey, argillaceous, with sandy laminae towards top | 1.40 |
| Mudstone, olive-green with grains of volcaniclastic detritus, grading down into dark-grey mudstone with silty, micaceous laminae | 1.75 |
| Mudstone, dark-grey, mostly fissile, with harder silty and sideritic beds towards top; articulate brachiopods at base | 1.02 |
| TODHOLES LIMESTONE, dark-grey, fine-grained, in nodules | 0.15 |

The limestone cannot be recognised farther upstream and it presumably dies out less than 200 m to the west. On the south side of the last exposure, the overlying Touchadam and Bannock Burn White limestones are exposed intermittently. Above them lie extensive opencast workings in the Hurlet Limestone, which continue upstream for the rest of the section, appearing initially on the south side of the stream and then extending to both sides farther west. Talus from these old workings obscures the beds immediately below the Hurlet Limestone over most of the section. Several primitive, horseshoe-shaped clamp kilns show that at least some of the limestone was burnt on site.

## Locality 2.2 [NS 7495 8765 to 7493 8766]

Bannock Burn White and Touchadam limestones.

The two limestones lie very close together, but are of markedly different lithology (see below). They crop out in, and immediately upstream from, a waterfall [NS 7494 8765], which is the type section of the former limestone. Here the following section is exposed:

| | Thickness (m) |
|---|---|
| Mudstone, blackish-grey, locally carbonaceous, fissile, silty towards top, with thin beds and nodules of pyritous, sideritic, ironstone | 2.62 |
| Limestone, dark-grey, fine-grained, pyritous | 0.10 |
| Mudstone, dark-grey | 0.15 |
| BANNOCK BURN WHITE LIMESTONE, mottled pale- and dark-grey yellowish-weathering and dolomitised at the top, which locally contains carbonaceous root traces; pale-grey and crystalline below, locally pseudobrecciated; abundant crinoid columnals, articulate brachiopods, bryozoa, etc. | 1.03 |
| (junction at [NS 7492 8764], above small waterfall) | |
| TOUCHADAM LIMESTONE, dark-grey, fine-grained, argillaceous, flaggy; divided into five layers by thin beds of dark-grey, calcareous mudstone; crinoid ossicles and abundant articulate brachiopods. (Cut by small NW–SE fault) | 1.88 |
| Mudstone, mostly dark-grey, fissile; paler and more silty towards base, which contains a thin sideritic limestone up to 0.07 m thick, with shell fragments | 1.01 |
| Sandstone, grey, mostly fine-grained, sideritic | 0.10 |
| Mudstone, pale-grey, silty and sandy, poorly bedded, with sideritic concretions | 1.83 |

The Touchadam Limestone contains fragments of goniatites in exposures farther west and probably correlates with the lower part of the Blackbyre Limestone of the Paisley district. The overlying Bannock Burn White Limestone almost certainly correlates with the upper part of the Blackbyre Limestone (Wilson, 1989) and with the combined White Nodular Limestone and Coral Limestone of the Corrie Burn section some 11 km to the SW

(Robertson & Haldane, 1937, p. 18). The non-marine Baldernock Limestone lies at this stratigraphical horizon on the south side of the Campsie Fells (Dinham & Haldane, 1932, pp. 14–16). A widespread fall in sea level took place shortly after the Bannock Burn White Limestone had been deposited, so that its top was exposed, dolomitised and locally colonised by vegetation. The roots at the top of this limestone mark the horizon of the Hurlet Coal of the Central Coalfield. Walk upstream, noting in passing the excellent exposures of Touchadam Limestone and its capping of dark-grey, fissile mudstone.

## Locality 2.3 [NS 7483 8761]

Lower Limestone Formation and Midland Valley Sill-complex.

Cross the burn and the old opencast workings in the Hurlet Limestone to the south and climb to the foot of the cliff. This locality lies on the SW (upthrow) side of a small NW–SE fault, which also truncates a broad platform of the Touchadam Limestone at water level. The exposure detailed below shows strata in the lower part of the Lower Limestone Formation, between the Hurlet Limestone and the ochreous bed that marks the horizon of the Blackhall Limestone, immediately below the quartz-dolerite sill. This limestone has been metamorphosed locally. The strata between the Hurlet and Blackhall limestones are much thinner in this section than they are farther east in the Clackmannan Syncline (Francis *et al.*, 1970, figs. 15 & 16), indicating that the area above the old lava pile continued to be an area of reduced subsidence (basin margin), even towards the end of the Viséan Epoch.

| | Thickness (m) |
|---|---|
| Dolerite, medium-grained and columnar-jointed at top, but finer grained, platy and amygdaloidal at chilled base | 3.20 |
| Horizon of BLACKHALL LIMESTONE. Soft, yellowish-brown, ochreous bed containing a thin intercalation of hard-baked, pale-grey mudstone with shell fragments | 1.12 |
| Wedge of fine-grained dolerite (basalt), which thins to west | 0.76 |
| Mudstone, pale-grey, baked hard and bleached | 0.30 |

| | |
|---|---|
| Alternating beds of pale whitish-grey and brownish-grey sandstone, mostly fine-grained and ripple-laminated, in upward-coarsening sequences, and dark-grey, micaceous siltstone and silty mudstone, containing drifted plant scraps | 8.66 |
| Mudstone, dark-grey, silty, micaceous | 0.15 |
| Gap, obscured by talus. Trenching revealed collapsed workings in the INCHINNAN LIMESTONE (which was originally about 1 m thick) underlain by a 0.10 m-thick coal and 0.25 m of seatclay (mudstone reworked by roots) | 1.65 |
| Sandstone, whitish-grey and brownish-grey, mostly fine-grained, with silty micaceous laminae; roots at top | 0.69 |
| Gap, obscured by talus, down to approximate level of the worked-out HURLET LIMESTONE. (Outcrops about 12 m to the west along the strike suggest that most of this gap is occupied by alternating beds of sandstone and siltstone, similar to those seen above the Inchinnan Limestone) | 10.00 |

The limestone beds in the above section represent widespread marine transgressions, which may be traced over the greater part of the Midland Valley of Scotland and into the north of England. The repeated upward-coarsening sequences of sandy strata between the limestone beds probably represent minor, local delta-lobes that were built out during periods of lowered sea level and occasionally colonised by vegetation. These sandy beds die out south-westwards, towards Glasgow. Return downhill and cross the burn to Locality 2.4, just beyond a substantial fence at [NS 7482 8765].

## Locality 2.4 [NS 7481 8766 to 7458 8769]

Kirkwood Formation and shoreward facies of basal Lawmuir Formation.

Within this locality the deeply weathered top of the Clyde Plateau Volcanic Formation is exposed, together with the overlying Kirkwood Formation and the basal Lawmuir Formation, in a small inlier. At the east end of the inlier, strata just below the horizon of the Todholes Limestone are exposed dipping SSE at 14°, but there is no trace of that limestone anywhere within the inlier and it has probably died out. The cross-stratified, decomposed, reworked, volcaniclastic detritus of the Kirkwood Formation is well

**Plate 2.2**
Locality 2.4. Coarse-grained volcaniclastic detritus in Kirkwood Formation.

exposed in the stream bed and in both banks (Plate 2.2). It is mostly yellowish-green in colour and tends to become coarser towards the base, ranging from a silty mudstone to a conglomerate containing rounded pebbles of weathered lava. The basal Kirkwood Formation is difficult to distinguish in some places from the in-situ bole-like material produced by the deep tropical weathering of the topmost lavas. However, the Kirkwood Formation is here obviously much thinner than in the exposures farther downstream. Tuff, containing blocks, may be seen above the lava at [NS 7465 8768], where another fence crosses the stream. The following section in the Bannock Burn White and Touchadam limestones can be seen at [NS 7457 8766]:

| | Thickness (m) |
|---|---|
| Mudstone | 2.40 |
| Limestone | 0.15 |
| Mudstone | 0.10 |
| Limestone, fossiliferous, nodular | 1.10 |
| Nodular limestone, shelly | 0.10 |
| Limestone | 0.65 |
| Calcareous mudstone | 0.35 |
| Mudstone | 0.50 |
| Limestone | 0.30 |
| Mudstone | 0.50 |
| Limestone | 0.10 |
| Mudstone | 0.30 |

Continue upstream, past a good exposure of the Bannock Burn White and Touchadam limestones in the north bank where fossils may be collected from loose material, and cross a small NNE–SSW fault with an easterly downthrow which brings up strata close to the horizon of the Todholes Limestone, to reach Locality 2.5 at a prominent waterfall at [NS 7448 8767].

## Locality 2.5 [NS 7447 8763 to 7443 8767]

Hurlet Limestone and shoreward facies of the Bannock Burn White and Touchadam limestones.

The Bannock Burn White and Touchadam limestones form the prominent waterfall at this locality (Plate 2.3). Here the Touchadam Limestone has thinned to 0.49 m and is separated from the overlying Bannock Burn White Limestone by some 0.75 m of calcareous mudstone containing abundant brachiopods. The Bannock Burn White Limestone has not thinned perceptibly and remains more than 1 m thick. Its weathered, decalcified and dolomitised top contrasts with its unweathered, highly fossiliferous, lower portion. The beds below the Touchadam Limestone are exposed below the waterfall and are similar to those already described in Localities 2.1 and 2.2. The chief interest lies in the beds above the Bannock Burn White Limestone, which are better exposed upstream from the waterfall than anywhere else in the Todholes section. The following section through these beds is exposed in the north bank, between [NS 7445 8766 and 7443 8763]:

**Plate 2.3**
Locality 2.5. Waterfalls in the Bannock Burn, formed by the Bannock Burn White and Touchadam limestones, Lawmuir Formation.

| | Thickness (m) |
|---|---|
| HURLET LIMESTONE, dark-grey, crinoidal; argillaceous towards base, which is decomposed locally to an ochreous bed | 0.37 |
| Mudstone, dark-grey, fissile; top calcareous with abundant articulate brachiopods, but base ferruginous with *Lingula* | 0.61 |
| Mudstone, dark-grey, fissile and ferruginous with silty, sideritic ironstone beds up to 0.03 m thick; decomposed pyrite concretions and selenite crystals; basal 0.10 m is contorted, whereas the beds immediately above and below are unaffected | 1.58 |
| Mudstone, dark-grey, fissile, with sideritic nodules and beds of dark-grey, argillaceous limestone up to 0.10 m thick; fragmental marine shells at base | 1.83 |
| (Irregular top of BANNOCK BURN WHITE LIMESTONE) | |

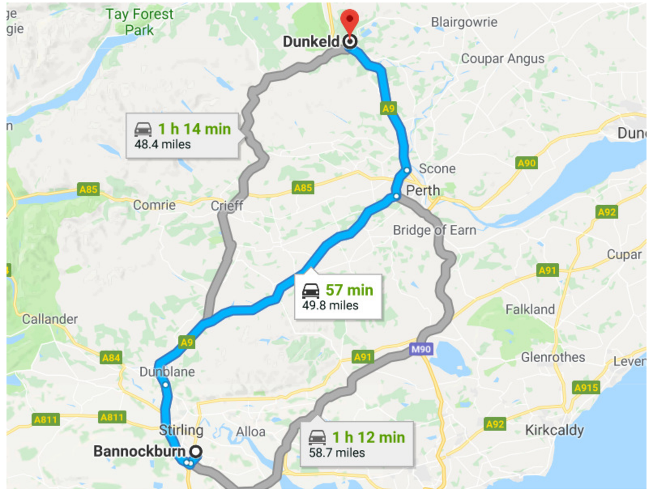
Only the base of the Hurlet Limestone is preserved at the top of this section, but a loose block of similar limestone that lies in the stream indicates that the Hurlet Limestone was at least 1 m thick. There is no trace of the Hurlet Coal. Upstream the section is truncated by a NE–SW fault with a throw of about 3 m down to the SE.

If time is still available, visitors have two choices. They may either examine a set of faulted exposures, mostly in the Bannock Burn White and Touchadam limestones, farther upstream, or they may return to their cars, drive north past the North Third Reservoir, and visit the Touchadam section, illustrated in Figure 2.2. In the Touchadam section, the Bannock Burn White Limestone has been almost entirely replaced by a pale-grey mudstone, locally derived from volcaniclastic detritus (Figure 2.2; Francis *et al.*, 1970, pp. 170–2, fig. 14). Before leaving the west end of the Todholes section, the visitor should climb out of the immediate valley of the upper Bannock Burn in order to see the view to the NE. Here a component of the Midland Valley Sill-complex (intruded into the marine mudstones above the Blackhall Limestone) is seen forming the impressive cliffs of Sauchie Craig. North of the prominent gap in these cliffs at Windy Yet, the sill transgresses down into sedimentary rocks below the Inchinnan Limestone, before rising upwards in a dyke-like body along the plane of the Wallstale Fault. This proves that the fault was formed before the dolerite was intruded.

**STOP 4.3:** *Dunkeld – River Braan at The Hermitage*

*The Following is from:*

Browne, M.A.E., and Gillen, C. (editors), 2015, A Geological Excursion Guide to the Stirling and Perth Area. Edinburgh Geological Society, pgs. 213-226.




Excursion 18

## Dunkeld and Little Glen Shee

Philip Rose

*Purpose:* To examine a cross-section through the Tay Nappe; to see evidence for three phases of deformation, which produced large- to small-scale folds; to examine Dalradian metamorphosed sedimentary rocks of the Birnam Slate and Grit Formation and the Dunkeld Grit Formation (Southern Highland Group).

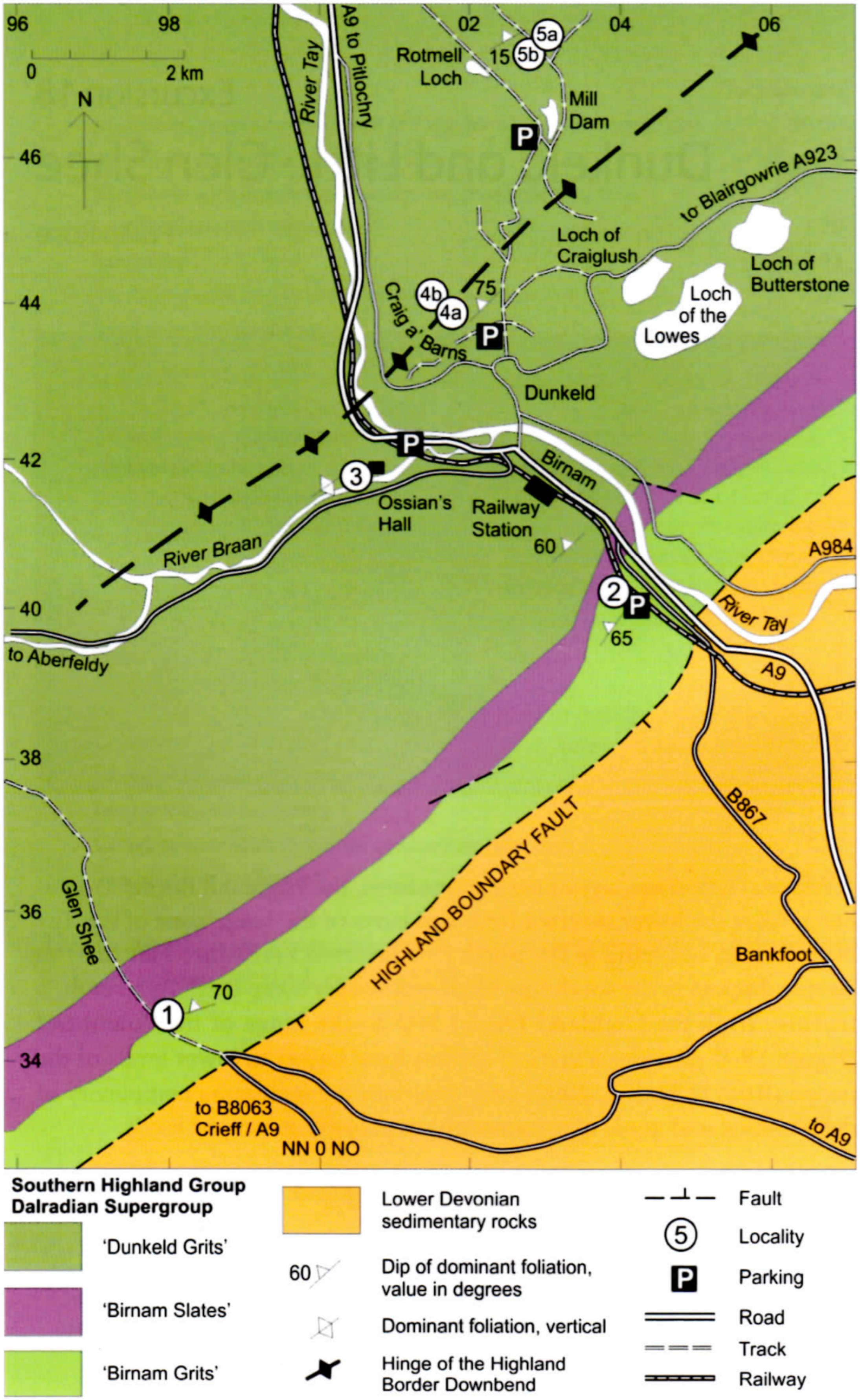
*Logistics:* This is a one day excursion. For advice on shooting and forestry activities, contact the Factor, Murthley and Strath Braan Estate, Murthley near Dunkeld for Birnam Hill, contact Landsdown Estates for Little Glen Shee and the Factor at Atholl Estate Office, Blair Atholl for Craig a' Barns area.

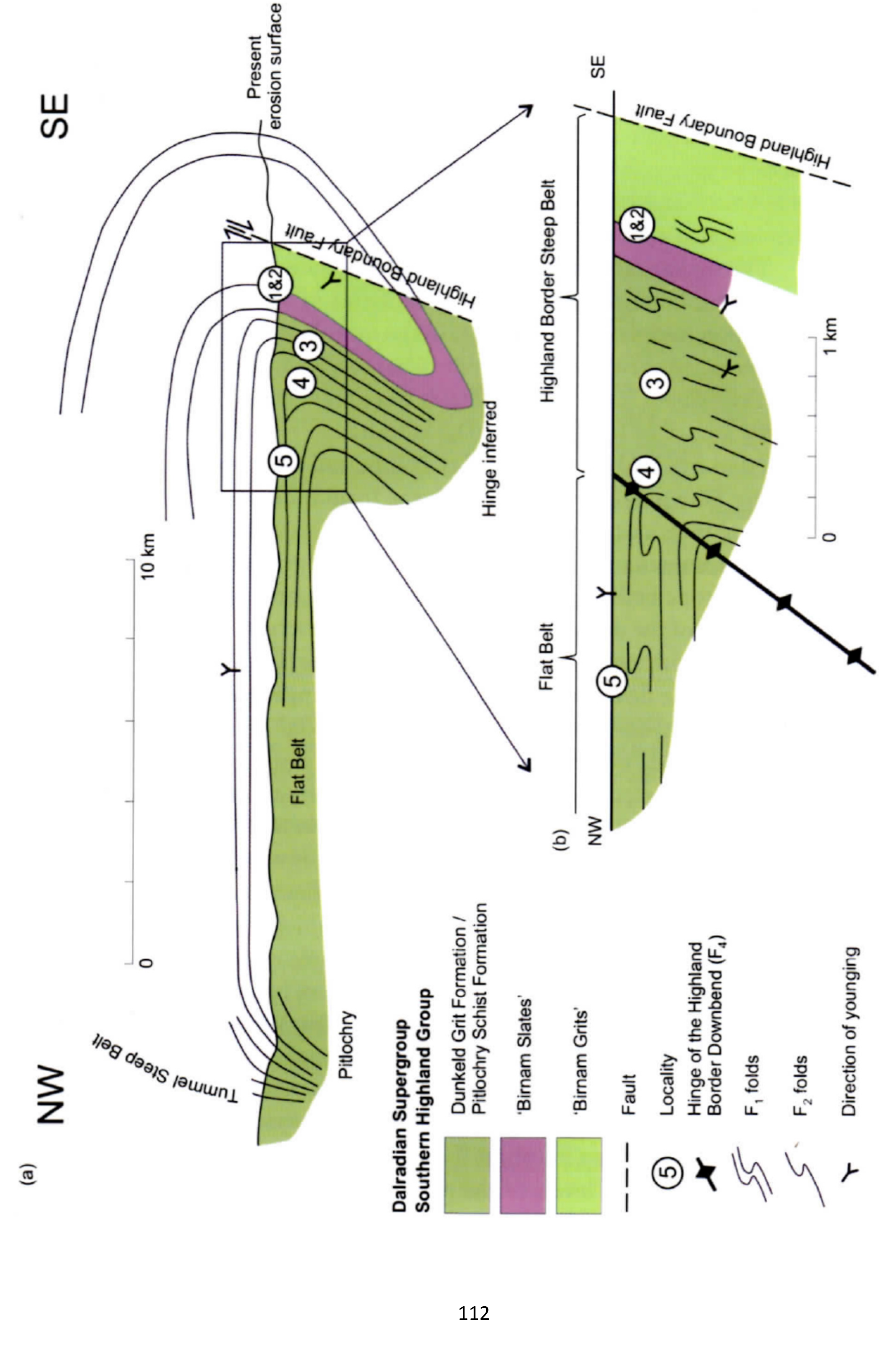
*Maps:* OS 1:50,000 Sheet 52 Pitlochry to Crieff; OS 1:25,000 Sheet 379 Dunkeld, Aberfeldy & Glen Almond; BGS 1:50,000 Sheet 55E Pitlochry; locality map Figure 18.1.

A regional late-stage, asymmetric monoform, the Highland Border Downbend, folds the lower inverted limb and parts of the hinge zone of the Tay Nappe from flat lying in the north (the inverted Perthshire Flat Belt) to steeply dipping in the south (the Highland Border Steep Belt). As a result, a traverse from the Highland Border NW to the hinge of the downbend (Figure 18.2) provides a vertical section from higher to lower levels of the nappe (Rose & Harris, 2000) and illustrates the increasing complexity of deformation and grade of metamorphism at lower structural levels.

**Figure 18.1 (next page)** Geological map of the Highland Border area around Dunkeld and Little Glen Shee, showing localities for Excursion 18.

**Figure 18.2 (page 215)** (a) Schematic cross-section through the Tay Nappe from Pitlochry to Dunkeld, showing relative positions of localities for Excursion 18; (b) Detailed geology in relation to major features of the structure. Adapted from a drawing by Philip Rose in Tanner *et al.* (2013, fig. 24).


96
98
02
04
06
0
2 km
N
46
44
42
40
38
36
34
A9 to Pitlochry
River Tay
Rotmell Loch
5a
5b
15
Mill Dam
to Blairgowrie A923
Loch of Craiglush
Loch of Butterstone
Loch of the Lowes
4b
4a
75
Craig a' Barns
Dunkeld
3
Ossian's Hall
Birnam
Railway Station
60
River Braan
to Aberfeldy
2
65
A984
River Tay
A9
B867
HIGHLAND BOUNDARY FAULT
Glen Shee
1
70
Bankfoot
to B8063 Crieff / A9
NN 0 NO
to A9
Southern Highland Group
Dalradian Supergroup
'Dunkeld Grits'
'Birnam Slates'
'Birnam Grits'
Lower Devonian sedimentary rocks
60 Dip of dominant foliation, value in degrees
Dominant foliation, vertical
Hinge of the Highland Border Downbend
Fault
5 Locality
P Parking
Road
Track
Railway


(a)
NW
SE
Tummel Steep Belt
Pitlochry
0
10 km
Flat Belt
Present erosion surface
Highland Boundary Fault
Hinge inferred
1&2
3
4
5
(b)
NW
SE
Flat Belt
Highland Border Steep Belt
Highland Boundary Fault
0
1 km
Dalradian Supergroup
Southern Highland Group
Dunkeld Grit Formation / Pitlochry Schist Formation
'Birnam Slates'
'Birnam Grits'
Fault
Locality
Hinge of the Highland Border Downbend ($F_4$)
$F_1$ folds
$F_2$ folds
Direction of younging

The metamorphosed sedimentary rocks (Birnam Slate and Grit Formation and Dunkeld Grit Formation) in this part of the Tay Nappe were originally interbedded grit, sand and mud and are part of the Southern Highland Group, the second youngest group in the Dalradian Supergroup. The thickest slate unit, formerly the 'Birnam Slates', separates the 'Dunkeld Grits' to the north from the older 'Birnam Grits' to the south. The commonly gritty metasandstones show normal grading and are interpreted as turbidite deposits that accumulated as part of an extensive submarine fan system.

The structural history of this part of the Grampian Highlands can be considered in terms of three principal phases of deformation and cleavage formation (termed $D_1$, $D_2$ and $D_4$ in the overall regional scheme). The first two were associated with prograde metamorphism and the emplacement of the Tay Nappe. A third phase ($D_3$) is recognised farther to the NW but not in this area. The fourth phase ($D_4$) is related to retrograde metamorphism linked to regional uplift of the Tay Nappe and formation of the Highland Border Downbend. $D_1$ resulted in the formation of large-scale folds of bedding ($F_1$), associated with a spaced pressure-solution cleavage in the metasandstones and a slaty cleavage in the finer grained metamudstone and metasiltstone beds ($S_1$). At high levels of the nappe, now seen only on the steep limb of the downbend, these folds are preserved as downward-facing structures with steeply NW-dipping axial planes (Localities 18.1 and 18.2). Unrolling the downbend by 120° about its hinge restores the $F_1$ folds to recumbent structures with gently dipping axial planes. Detailed fabric studies provide evidence for modification of the $F_1$ folds in a rotational strain field, related to the more-intense $D_2$ deformation seen at deeper levels of the nappe (see Locality 18.3 and Rose & Harris, 2000).

In the Dunkeld area there is no major downward-facing synform comparable with the Aberfoyle Antiform of Shackleton (1957) to the SW; the overall succession youngs to the NW from the Highland Boundary Fault to the downbend hinge. However, there is ample evidence for the development of a complex series of large-scale $F_1$ folds of bedding in the Sma' Glen–Glen Almond area north of Crieff, and in the Ben Vane–Ben Ledi area. They possibly lie in a wide hinge zone of the Tay Nappe. $D_2$ deformation resulted in intense small-scale folding ($F_2$) and attenuation of $S_1$ and more rarely of bedding. $D_2$ is also associated with a strong horizontal planar fabric ($S_2$) and a N–S stretching lineation ($L_2$), but is developed only at intermediate and low structural levels of the nappe (Locality 18.3). Curved inclusion

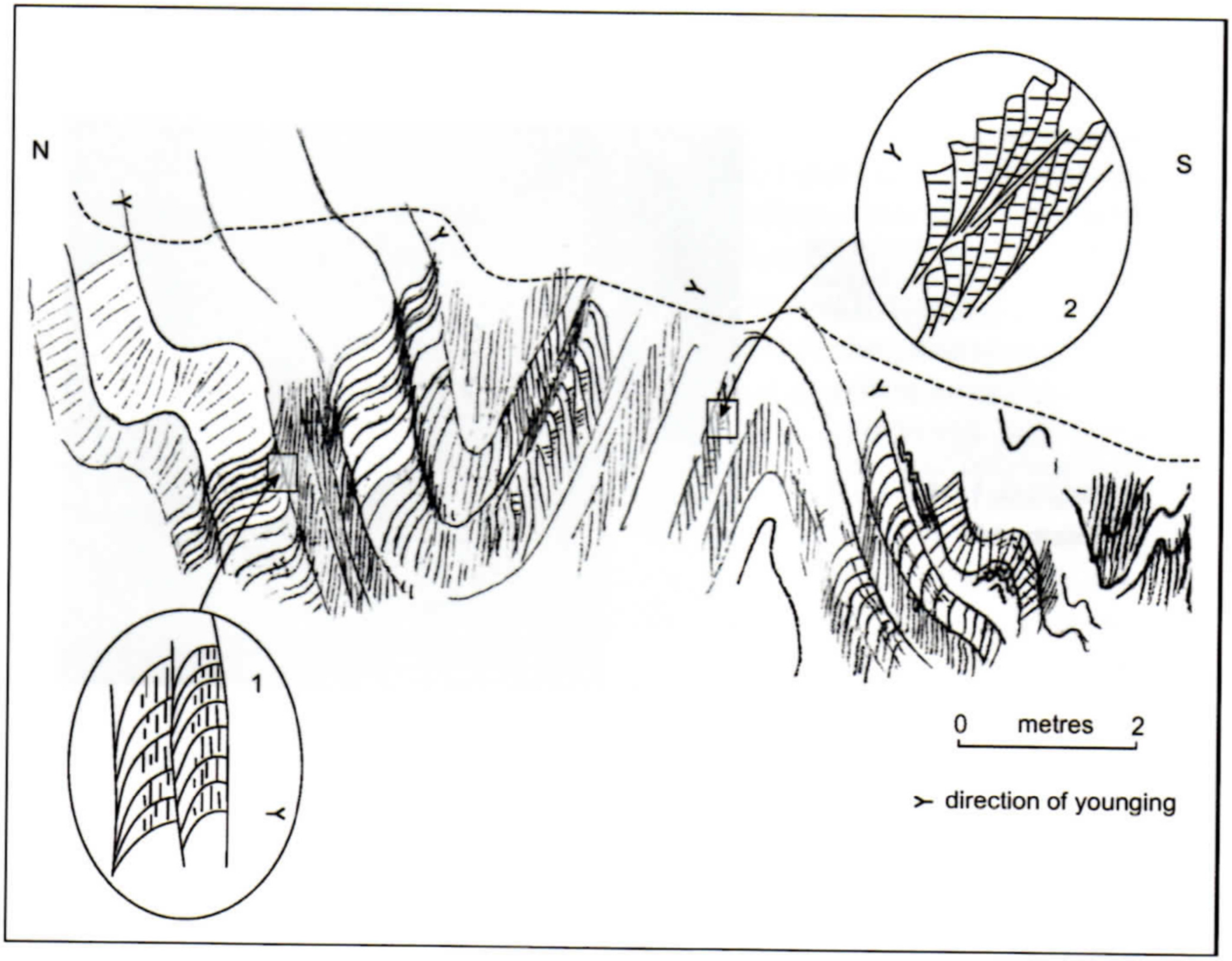



**Figure 18.3** Details of downward-facing $F_1$ folds close to the downbent hinge zone of the Tay Nappe at Little Glen Shee, Locality 18.1, Plate S.1. Fanning of the $S_1$ cleavage around minor folds and its refraction reflecting the original grain size are clearly shown. Insets show generalised detail of relations between gross bedding, the $S_1$ spaced cleavage and re-orientated bedding lamination. Adapted from Tanner *et al.* (2013, fig. 25).

trails in garnet show that $D_2$ deformation was coeval with the main metamorphism. Shear criteria (see Locality 18.5) have been interpreted to show that $D_2$ involved a component of SE-directed simple shear. However, the models of Harris *et al.* (1976) and Bradbury *et al.* (1979), which invoke bedding-parallel, south-directed simple shear to generate the $F_2$ folds, are an oversimplification, as $F_2$ refolds of bedding are also seen.

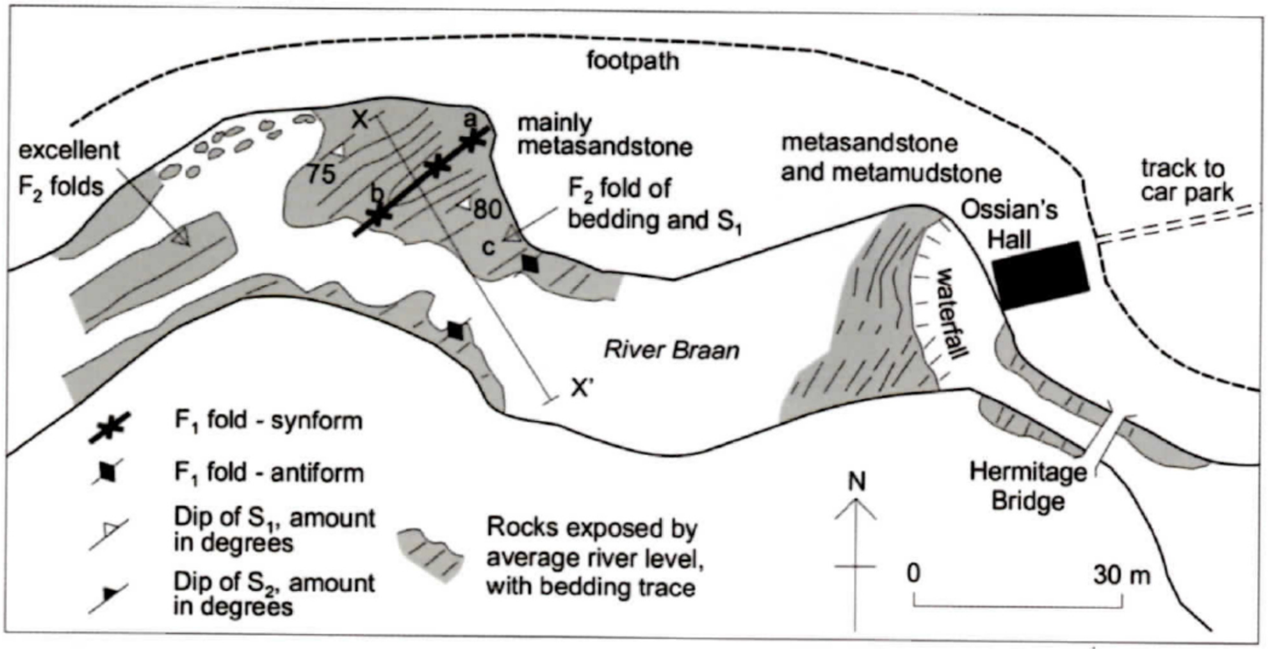
An alternative version of this excursion has been published by Treagus (2009). Some localities are also described in the Geological Conservation Review (GCR) of the Dalradian of Scotland (Tanner *et al.*, 2013).

## Locality 18.3 [NO 0078 4178]

River Braan at The Hermitage: intense $F_2$ folding at intermediate levels.

From Birnam Hill drive north and join the A9. Pass Little Dunkeld and take the turning on the left [NO 0138 4230], signposted to The Hermitage, and park in one of the two large car parks. Take the path south-westwards by the river to Ossian's Hall (National Trust), and at the first right-angle bend upstream from Ossian's Hall examine the large flat exposure in the Dunkeld Grit Formation [NO 0078 4178] on the north bank. **These rocks become dangerously slippery in wet weather**, and flood conditions can severely restrict the area of exposure. This locality is also situated on the steep limb of the Highland Border Downbend, now only 800 m SE of its hinge. The metamorphic grade is higher than at Birnam Hill – cleaved metasiltstones are phyllitic with a high percentage of muscovite. $D_2$ deformation is well developed locally and tight folding of the first pressure-solution cleavage ($S_1$) can be seen. Thick composite sandy (psammitic) units are interbedded with mixed sandy and muddy (pelitic) units but convincing graded bedding has not been found, so that the structural facing cannot be demonstrated. A traverse across the flat surface illustrates the relationship between $F_1$ and $F_2$ (Figure 18.4). In parts bedding is difficult to discern.

Locality 18.3a lies at the NE end of the rock pavement below a low vertical face. $S_1$, a 0.5–1.0 cm-spaced striping in metasandstone, changes its orientation relative to bedding across the exposure, indicating the presence of an $F_1$ synform. $F_2$ folds of $S_1$ consistently verge towards the NW and have steep axial planes, generally orientated close to bedding (Plate 18.2). Bedding is rather obscure but can be detected by the absence of $S_1$ striping in more-pelitic beds. The pelitic beds also carry a crenulation cleavage that dips at around 45° to the



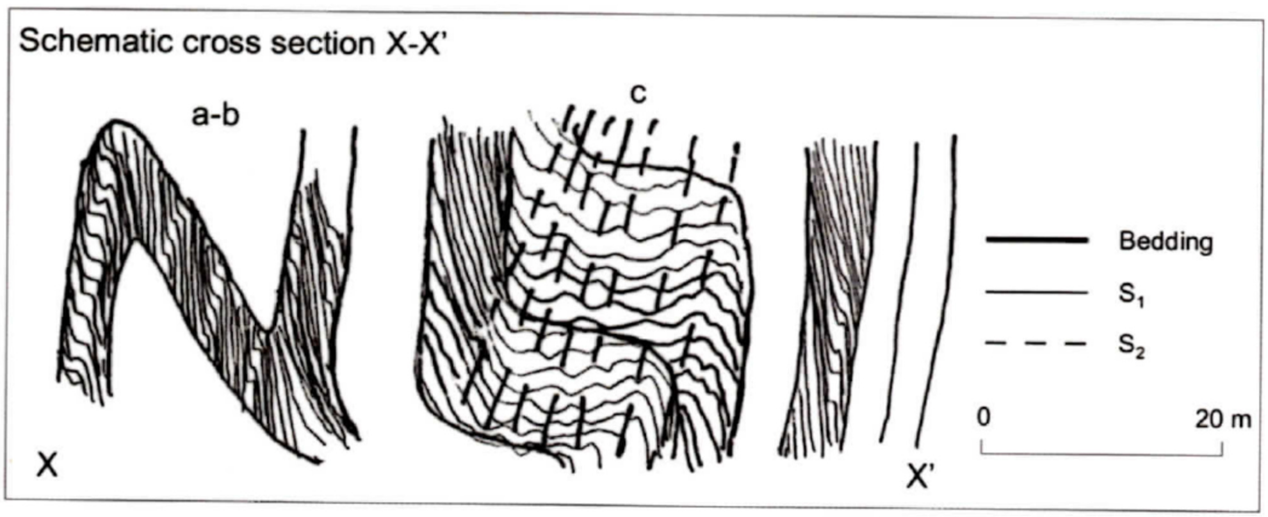




**Figure 18.4** Detailed geological map and cross-section, showing relationships between $D_1$ and $D_2$ structures at The Hermitage, Locality 18.3.

**Plate 18.2 (above)**
Locality 18.3a. Characteristic $F_2$ folds of spaced $S_1$ cleavage in metasandstone at The Hermitage

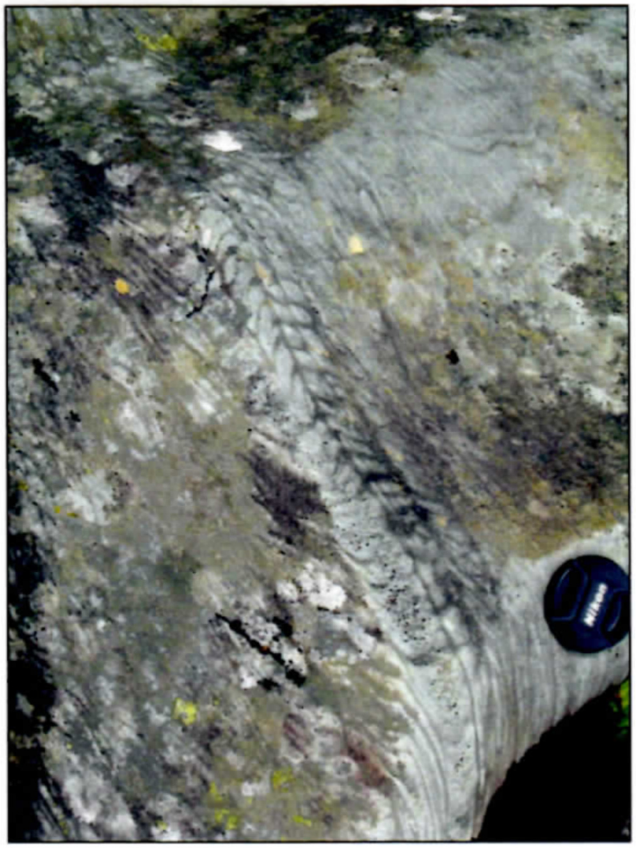
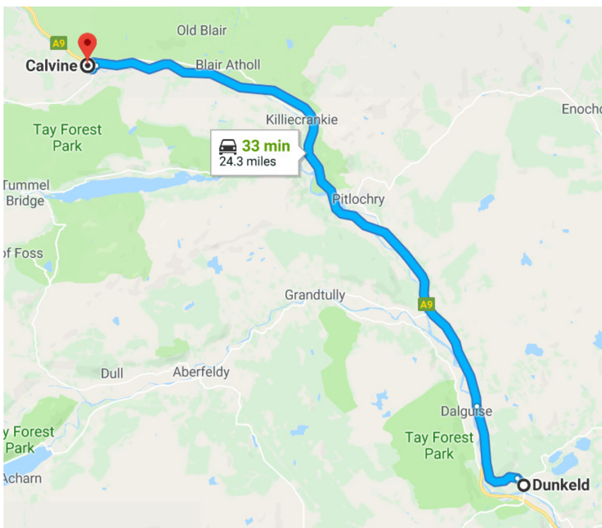


**Plate 18.3 (right)**
Locality 18.3c. Lozenge-shaped microlithons' formed by $S_2$ spaced pressure-solution cleavage (top left to bottom right) cutting a folded earlier, $S_1$ spaced cleavage in metasandstone, The Hermitage.

NW and is probably related to the downbend here. Locality 18.3b is along the strike of the $F_1$ fold axial plane from Locality 18.3a. The $F_1$ synformal closure can be seen but here it has a core of metasiltstone. In this area there are several examples of $F_2$ folds that show strong attenuation of $F_1$ fold limbs and the development of a second pressure-solution striping ($S_2$ cleavage) in their hinge regions. Between Localities 18.3b and 18.3c the bedding and $S_1$ cleavage are generally steep and their relative orientations are consistent with an $F_1$ synformal closure to the NW. At Locality 18.3c, $S_1$ has a shallow dip and is cut by a steep second pressure-solution cleavage ($S_2$), giving the rock a 'lozenge' appearance (Plate 18.3). In the centre of the lozenge zone, bedding also has a shallower dip, suggesting the presence of an $F_2$ fold of bedding and cleavage (Figure 18.3). This suggests that locally the $F_1$ fold stack was refolded by $F_2$. If time is available, it is possible to walk westwards up the river for just over a kilometre to the local beauty spot of the Rumbling Bridge waterfall; good examples of lozenge-shaped 'microlithons' between the $S_1$ and $S_2$ cleavage planes (as in Plate 18.3), refolded folds and rodding lineation can be seen here at the top of the falls [NN 9963 4120]. Alternatively, a short drive from Little Dunkeld along the A822 leads to the same place.

**STOP 4.4:** *Clunes in Calvine*

*The following is from:*
Treagus, J.E., Tanner, P.W.G., Thomas, P.R., Scott, R.A., Stephenson, D. 2013, The Dalradian rocks of the central Grampian Highlands of Scotland. Proceedings of the Geologists' Association, v. 124, pgs. 148-214.




## 14. A9 Road Cuttings and River Garry Gorge (NN 686 717–NN 804 656) (P.R. Thomas)

### *14.1. Introduction*

The rock exposures in the 20 km-long section of Glen Garry between the Drumochter Pass and Blair Atholl are of national, if not international, importance since they form an almost continuous section through the Grampian Group rocks in the central Grampian Highlands. Not only does the bed of the River Garry itself have 75% exposure, most of it above water level for much of the year, but the parallel A9 road also provides a series of long clean rock cuts. Hence, the exposures are frequently visited by student parties and professional geologists. The GCR site is noteworthy for its wealth of minor folds and sedimentary structures, which can be used to demonstrate the position and geometry of some of the major folds that make up the central part of the Grampian fold belt.

The site lies on the inverted limb of the recumbent, SE-facing Tay Nappe and provides a unique section through D1 and D2 minor and major folds, related to that regionally important structure. It also provides an essential link between two later major upright folds, the Drumochter Dome to the north-west (see Fig. 32) and the Ben Lawers Synform to the south-east (see the *Ben Lawers* GCR site report); those are the folds that control the outcrop pattern of the Dalradian in much of the central Grampian Highlands, as illustrated and discussed by Treagus (1987, Fig. 1b and p.12).

The rocks of Glen Garry were originally described by Barrow (1904) as Moine 'granulites' (an obsolete term for high-grade psammitic metasedimentary rocks). The paper mentions 'water-pipe' structures at Clunes and some overturned folds, but provides little other specific data. Apart from a brief description of a fold in a quarry on the A9 road by McIntyre (1950), the main work, which forms the basis for this account, is that of Thomas (1965, 1979, 1980, 1988). Further useful comments were made on the sedimentology by Glover and Winchester (1989) and Banks (2007), and on the structure by Lindsay et al. (1989).

### *14.2. Description*

The following numbered descriptions of key localities start in the north-west, near the summit of Drumochter Pass, and follow the road and river down towards Blair Atholl (Fig. 32). All of the exposures are within psammitic rocks of the Grampian Group. The dominant fold-set is named F2 and its axial plane schistosity S2. Rarely observed folds which clearly pre-date F2 or S2 are designated F1, although S1 is generally parallel to bedding.

#### *14.2.1. Stalcair Cut (NN 686 717)*

At the third lay-by on the southbound section of the A9 dual carriageway descending from the Drumochter Pass, gently dipping inverted beds face down to the south-east on the S2 axial-plane schistosity and lenses of calcsilicate rock in the schistose psammites are well seen. Roadside exposures 200 m to the east, by a pylon buttress, display schistose laminated psammites with superb trough ripple-laminations and larger dune beds as well as sediment slump structures (Banks, 2007; Fig. 33). Overturned, NW-vergent, F2 folds in the cut face plunge gently towards 070° and are clearly downward facing. A strong S2 axial-plane cleavage cuts S1, which is parallel to bedding, and dips at 30° towards 160° at this locality. The exposures are on the north-west, inverted, limb of the F2 Garry Synform, the hinge-zone of which is seen at locality 2.

*14.2.2. Wade Stone Cut (NN 694 716–NN 699 71) and River Garry (NN 697 714–NN 714 706)*

At the fourth lay-by on the southbound dual carriageway, a high rock face, on the curve of the road, cuts obliquely across the hinge-zone of a major F2 fold, the Garry Synform. The section east of the lay-by is in the gently dipping inverted limb of the synform, with NW-verging minor folds, but east from the retaining wall F2 minor folds become more neutral in vergence as the hinge is reached. The folds, plunging at 20° to 070° with an axial-plane dip of 40° to the south-east, are downward facing. Evidence is based on the many fine examples of ripple-laminated and dune-bedded schistose psammites. Lenses of calcsilicate rock are deformed by S2, but post-D2 microcline porphyroblasts in the schistose psammites could be evidence of later metasomatism.

There are both early quartz veins, which are folded, and later cross-cutting veins. NE-trending microdiorite dykes and faults can also be traced in the rock-face. The major Allt an Stalcair fault-zone, seen in the Allt Stalcair at NN 693 717 to the west, is mineralized with calcite and haematite.

The northbound lay-by, nearer to the River Garry, enables both road and river sections to be seen. Good way-up evidence is found in the river beneath the railway bridge (NN 6995 7131), and immediately upstream is the hinge of the Garry Synform. One kilometre downstream from the railway bridge, the hinge of the major F2 Creag a' Mhadaidh Antiform can be traced (NN 7090 7075), plunging at 10–14° to 070–080° with fine examples of overturned folds containing trough cross-laminations on steep limbs and an S2 crenulation schistosity dipping at 20–30° to the south. Exposures around the footbridge at NN 7120 7065 have considerably tightened and overturned minor folds involving some refolding of F1 folds. These continue downstream to a point where very regular low dips mark the commencement of the 'Dalnacardoch Banded Zone' (see locality 3b), about 200 m upstream from the confluence with the Edendon Water.

*14.2.3. Edendon Cut (NN 7108 7084–NN 7140 7075)*

The next lay-by on the A9 southbound is east of the major F2 closure of the Creag a' Mhadaidh Antiform. At the west end of the rock cut (NN 7114 7083), very tight F1 folds verge north-west and appear to face downwards to the south-east as indicated by deformed current-ripple laminations. At the burn (NN 712 708) a strike-slip fault trending 024° brings in a more-psammitic lithology and overturned, NW-vergent, F2 folds plunging at 16° to 075°. At the east end of the lay-by, above a low-dipping ductile thrust, slightly more-open F2 folds plunging at 20° to 082° with an axial-plane schistosity dipping at 35° to the south, fold thin quartz veins and are cut by a microdiorite dyke.

*14.2.4. Dalnacardoch Cut (NN 719 705)*

Half a kilometre south-east of the last locality, in the deep southbound road cut, an apparently regular sequence of flaggy to schistose psammites dipping at between 25° and 30° is far more complex when closely inspected. This is the 'Dalnacardoch Banded Zone', which envelopes very tight F1 and F2 folds as well as a later generation of reclined folds on both major and minor scales. At the north-west end of the highest section (NN 7183 7055), very tightly

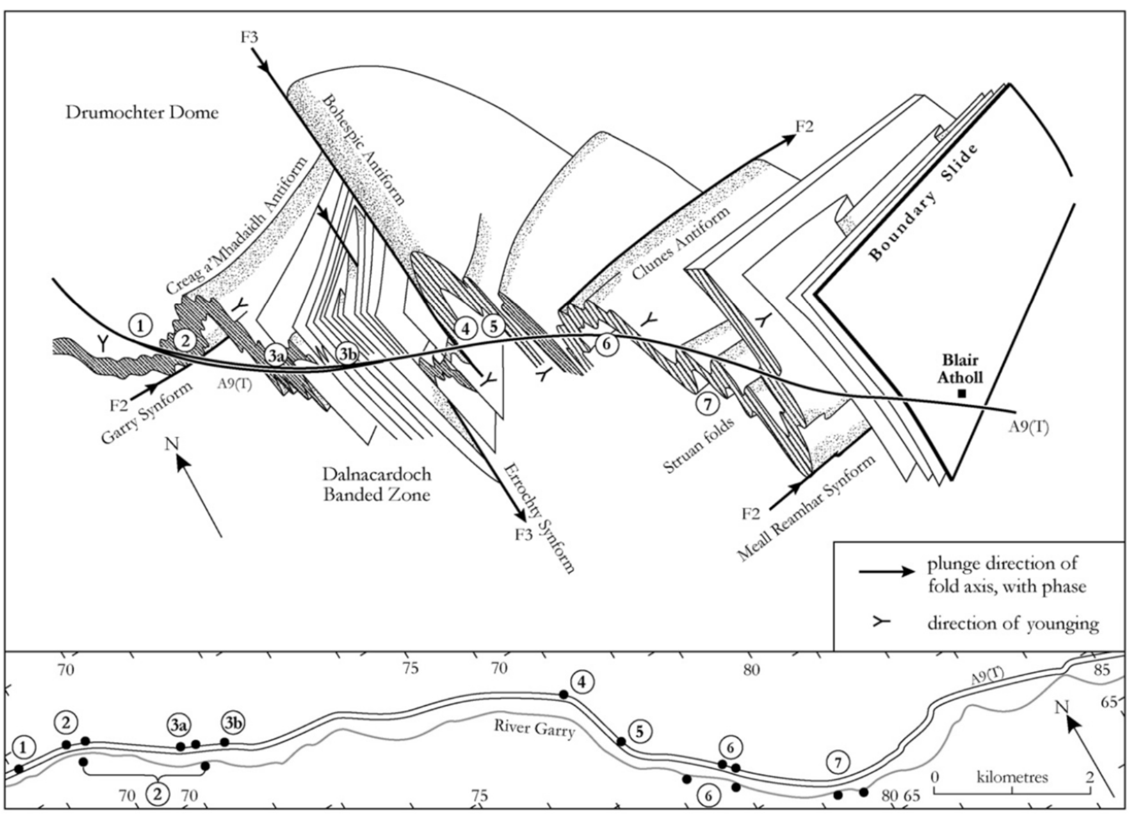



**Fig. 32.** The major structures of Glen Garry depicted in three dimensions and showing the localities 1–7 that are described in the text. Below is a map of the Glen Garry section showing the A9 road, the River Garry and the positions of the numbered localities.
Adapted from Thomas (1988, fig. 1.2).

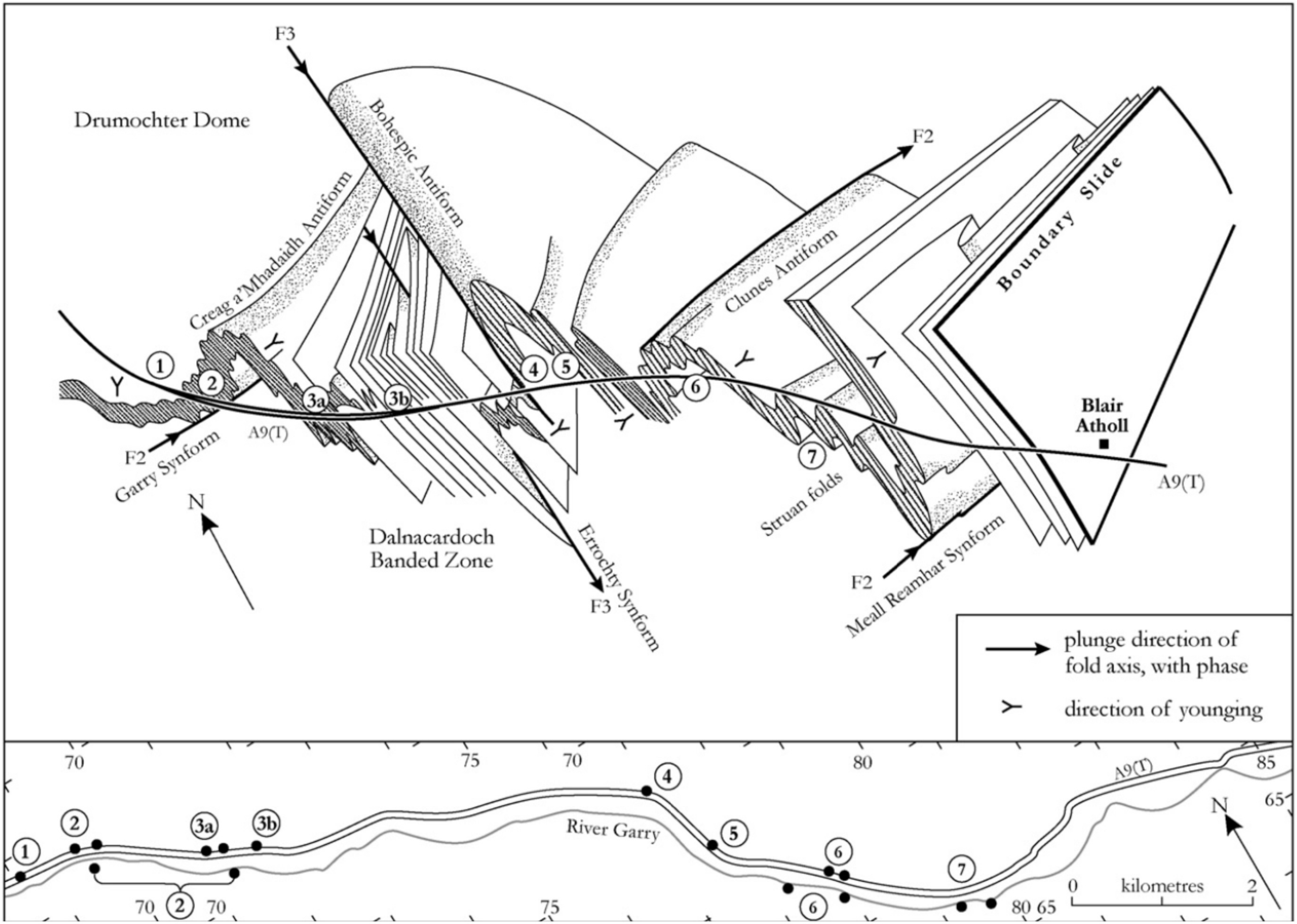



**Fig. 32.** The major structures of Glen Garry depicted in three dimensions and showing the localities 1–7 that are described in the text. Below is a map of the Glen Garry section showing the A9 road, the River Garry and the positions of the numbered localities.
Adapted from Thomas (1988, fig. 1.2).

**Fig. 33.** Cross-bedded laminated schistose psammites at the Stalcair Cut on the A9 road (locality 1). The beds young to the right (south-east), and thus the F2 fold is downward facing. The masonry buttress is *c.* 4 m high. See Thomas (1988, fig. 1.5) for an annotated sketch of this view (photo: P.R. Thomas).

refolded isoclines occur, whereas farther into the cutting isoclinal folds lie within an apparently simple banding (NN 7198 7046). The cutting also contains bands of mixed gneissose lithologies, in which post-D2 boudins are quite common. Late rotational shears in the form of large kink bands also occur at the eastern end of the cut.

In the River Garry, the Dalnacardoch Banded Zone is at least 4 km wide from NN 716 706 to NN 748 694 and contains both F1 and F2 folds, as well as folds of a later deformation. The latter are associated with the north-west limb of the major post-D2 Errochty Synform, which is thought to pass through the River Garry near Dailnafraoich (NN 7375 6983); here, exposures of F1 and F2 isoclines are refolded about reclined folds of the later generation, which plunge at 10–30° to 140–170°. The river also exposes a number of interesting crush-zones parallel to banding in which angular schistose clasts are preserved in narrow breccia bands less than a metre in thickness.

*14.2.5. Allt Crom Cut (NN 769 690)*

Just to the west of the Allt Crom bridge on the A9 road, a cutting at NN 7688 6896 exposes the hinge of a major antiformal fold in three dimensions (Fig. 34). Plunges of both major and minor folds here are in the range 16–25° towards 150–170°, but strong axial cleavage planes appear to be restricted to the hinge-zone, where they dip at 40° to 080°. The western limb dips at 35–45° towards 080° and the less-steep eastern limb dips at 20–30° towards 135°; the interlimb angle from here northwards remains at less than 40°. This undoubted major hinge can be traced for 1 km north in surface exposures and also in the Allt a' Chireachain, 3 km to the north, at NN 7752 7194, where the plunge is 20° to 140°. In the Garry Gorge immediately to the south, it is difficult to follow the precise trace of the antiform; it is seen towards Glen Errochty, though in a much more-open reclined style at this higher structural level. This fold is equated with the Bohespic Antiform, the major post-D2 fold complementary to the Errochty Synform (see below).

*14.2.6. Black Tank Cut (NN 773 680)*

This wide cutting is dominated by a major, tight, overturned F2 antiform, the hinge of which can be detected opposite the northbound lay-by in schistose psammites dipping at 38° to 116°. The plunge is unusual for the area at 8° to 218° with a cleavage dip of 30° to 136°. The high rock face is controlled by regularly dipping planar structures 1–3 m apart with a dip of 52–55° towards 270° to 290°. Some joint faces are mineralized with quartz and pyrite whilst other fault planes display slickensides, some with dip-slip and others involving strike-slip final movements. Several of these discontinuities caused wedge failures of the face during construction. At the south-east end of the cut a large red microdioritic sill, dipping to the east at 26° in very regular layers of schistose psammite, is downfaulted to the north-west.

*14.2.7. Clunes Gorge (NN 782 671–NN 789 667) and Clunes Cut (NN 785 670–NN 789 668)*

This superb river locality has now been rivalled by the new road cut only 150 m to the north (Fig. 35). Both localities demonstrate the presence of the Clunes Antiform, a major F2 structure, folding cross-bedded and ripple-laminated psammites, quartzites and semipelites, stratigraphically located near the transition between the Bruar Psammite Formation and the Tummel Quartzite and Psammite formations. Linear features seen in the river section, such as the famous 'water-pipe' mullions (NN 784 667) (Barrow et al., 1905, p. 68), plunge consistently parallel to the axes of the F2 minor folds. Minor folds, abundantly displayed in the road cut (Fig. 35), plunge consistently at about 10° to 045°, with a strong S2 axial-planar cleavage dipping at 20–30° to 120°. At both localities the SE-vergent, overturned, folds can be seen climbing towards the hinge of the major antiform, which lies near the south-east end of the cut and some distance down the Clunes gorge (NN 787 667). The sedimentary structures consistently show that the section is inverted overall and that the F2 folds face downwards to the south-east.

Several vertical and inclined microdiorite dykes cut both the river and the road sections. The widest of these is not only porphyritic but also contains xenoliths made up from a variety of metamorphic rocks, some of which are quite distinct from normal Grampian Group lithologies. Immediately west of one of the dykes, at the north-west end of the road cut, early, presumed F1, isoclinal folds can be seen to be refolded by the F2 minor folds.

Downstream around NN 790 664, major faults cut the river section and start to bring in lithologies that can be assigned more-readily to the Bruar Psammite Formation.

*14.2.8. Struan Exposures (NN 802 657–NN 808 655)*

Inverted, regularly SE-dipping, flaggy psammites and quartzites form the bed of the River Garry for 1 km below the junction with the Allt a' Chrombaidh (NN 790 664), but from 200 m above the twin bridges at Calvine (NN 802 657) and downstream almost as far as Struan church (NN 808 655), numerous overturned F2 folds have been entrenched by the river. These NW-vergent folds have consistent plunges of 20–30° to 060°, and amplitudes of 5–20 m.

At the 'Salmon Leap' (NN 8037 6565), sedimentary structures are best preserved on the steep limbs of the folds, in laminated schistose psammites with interbedded semipelitic layers. The proof that the layering is true bedding lies in the presence of a number of well-preserved sedimentary dykes, washouts and slump structures (Fig. 36), all of which consistently young to the south-east on steep limbs of folds, which thus face down to the

**Fig. 34.** The exposed hinge of the Bohespic Antiform in the A9 road cut near the Allt Chrom, looking north (locality 4). Car gives scale. See Thomas (1988, fig. 1.4) for an annotated sketch of this view (photo: P.R. Thomas).

south-east as at Clunes (locality 6). The rocks here are assigned to the topmost part of the Bruar Psammite Formation.

### 14.3. Interpretation

In essence, the sections at localities 1 and 2 and 4–7 are dominated by minor and major folds of the second generation, which fold all earlier planar structures (S0 and S1). In the more-pelitic lithologies, a strong crenulation cleavage is developed, axial-planar to the folds. Both the folds and the cleavage can be correlated, in style and geometry, with the regional D2 structures. The three-dimensional structure of the area is made more complex by the presence of a third deformation phase, described by Thomas (1980) as D3 but which is thought by others to pre-date the ENE-trending upright folds described as F3 by Treagus (1999, 2000) in the Appin and Argyll group rocks south of the Rannoch–Tummel area. Treagus (2000) gave these late structures a local designation of De, being unable to state categorically whether they pre- or post-date the regional D3 phase.

This late phase is associated with the major N-S-trending Errochty Synform and the Bohespic Antiform, described by Rast (1958) from the boundary of the Grampian Group with the Appin and Argyll groups to the south (see the Meall Dail Chealaich GCR site report). Minor structures associated with this phase become remarkably intense in the mid-part of the Glen Garry section, where the Errochty Synform produces the tight reclined structures at locality 3. This gives rise to the Dalnacardoch Banded Zone, which destroys most of the stratigraphical continuity and causes the re-orientation of all earlier folds around its hinge. Since no sedimentary structures are preserved in this high-strain zone, it is possible that bedding has been transposed and the schistosity might be composite. The presence of well-preserved sedimentary structures outside the banded zone introduces the possibility of some stratigraphical subdivision but the psammitic nature of most of the lithologies reduces the confidence of correlations north and west of the Dalnacardoch area.

In spite of the refolding by this later fold-pair, the major F2 folds described above, and the majority of the minor folds on their long limbs, are consistently overturned and vergent to the north-west, whilst being downward facing to the south-east on the second cleavage (Fig. 32). The Garry Synform and the complementary Craig a' Mhadaidh Antiform demonstrate this relationship particularly well on the north-west limb of the Errochty Synform. In the core of the Errochty Synform and on its common limb with the Bohespic Antiform, between localities 2 and 4, the facing of the D2 structures is not clear. However, on the south-east limb of the Bohespic Antiform the north-west vergence and south-east facing of the D2 structures is very clear from the exposures of the Clunes Antiform, seen in conjunction with the Meall Reamhar Synform (see the *Creag nan Caisean–Meall Reamhar* GCR site report). It is likely that the Clunes Antiform is the lateral equivalent of the Creag a' Mhadhaidh Antiform.

Fig. 35. Downwards- and SE-facing F2 folds on the rock faces of the Clunes Cut on the A9 road, looking north-east (locality 6). Height of section about 8 m (photo: J.E. Treagus).


**Fig. 36.** Sedimentary dykes of schistose semipelite in schistose psammite (top, centre), cross-lamination and slump folds in the River Garry, Struan (locality 7). Beds young to the right (south-east) on the steep overturned limb of an F2 fold. The compass is *c.* 5 cm in diameter (photo: P.R. Thomas).

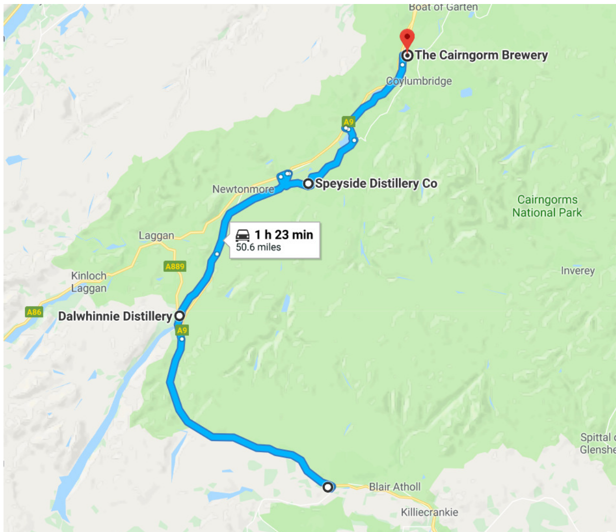
The geometry, north-west vergence and south-east facing of the D2 structures is consistent with that observed in the Appin and Argyll groups to the south (see, for example, the *Strath Fionan*, *Slatich* and *Craig an Chanaich to Frenich Burn* GCR site reports). This is consistent with their origin on the lower limb of the Tay Nappe, in its development during top-to-the-SE D2 simple shear of originally upright F1 folds (Treagus, 1987). This concept is supported by the observation, in the Clunes locality particularly, that the sedimentary structures are best preserved in the steeply dipping, short limbs of the F2 folds, where they have suffered the least rotation and deformation. The rarely observed minor first generation folds also appear to be facing down to the south-east, on the long limbs of second folds. This suggests that, on the removal of the second deformation, these folds would have been part of an upward-facing fold train (see Section 1.1), originally on the south-east limb of a major F1 anticline.

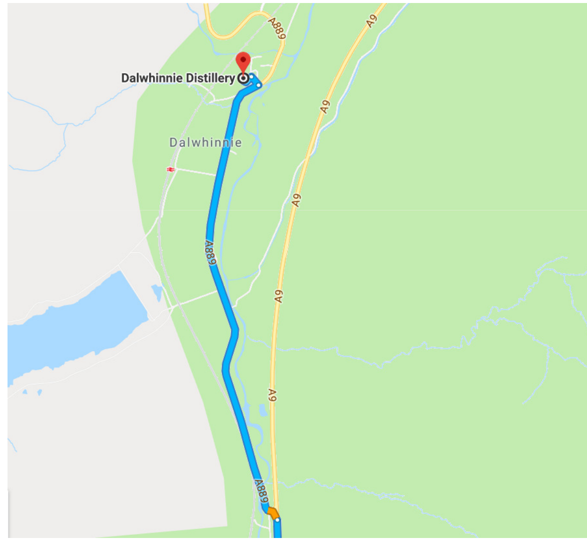
### 14.4. Conclusions

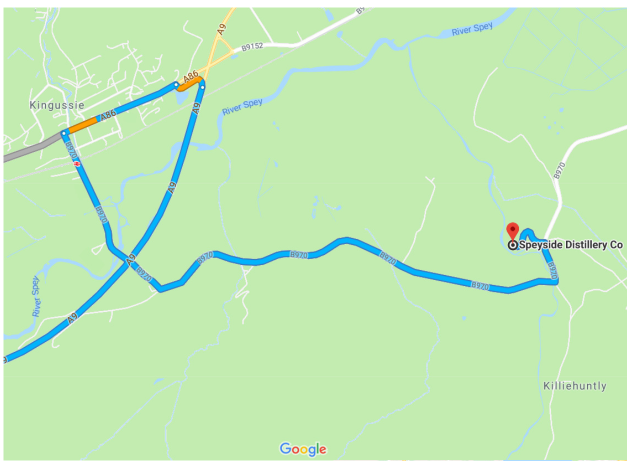
Glen Garry, from Drumochter to Calvine, is traversed by two parallel, excellently exposed ribbons of rock, one natural (the River Garry) and one man made (the A9 road). Both have been instrumental in providing vital evidence to help our understanding of the complex geological structure of the Grampian Group and without them very little three-dimensional interpretation of the structure would have been possible. Both minor and major folds, as well as sedimentary structures, are clearly and spectacularly displayed in exceptional clean and continuous exposures of rocks that are poorly exposed elsewhere. Most of the folds belong to the regional D2 phase of deformation, are north-west verging and face downwards to the south-east on the inverted lower limb of the F1 Tay Nappe. However, this site also exposes the hinges of an important pair of later folds, the Bohespic Antiform and the Errochty Synform, which exert a major influence on the overall outcrop pattern in the Schiehallion area to the south.

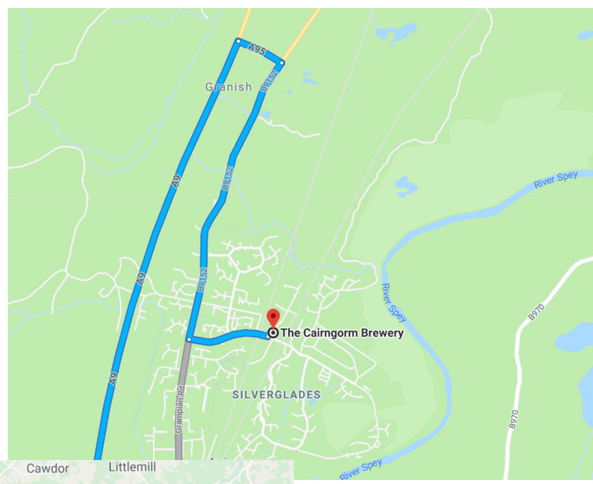
**STOP 4.5:** *Distilleries and Breweries*

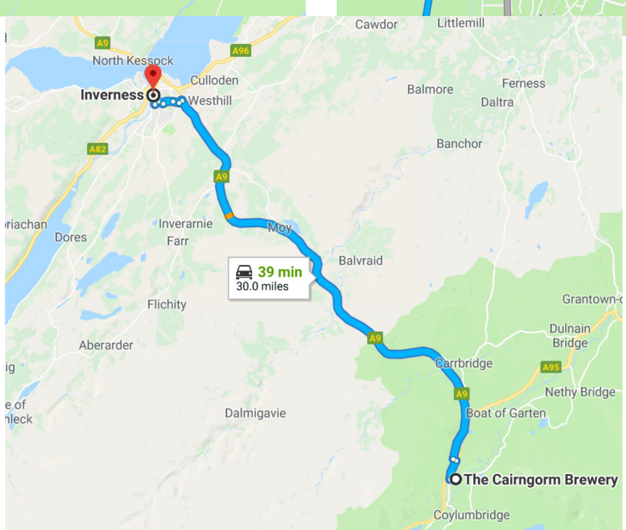
Dalwhinnie Distillery (https://www.malts.com/en-row/distilleries/dalwhinnie/), Speyside Distillery (http://speysidedistillery.co.uk/), The Cairgorms Brewery (http://www.cairngormbrewery.com/), we each have to buy Jake a drink….



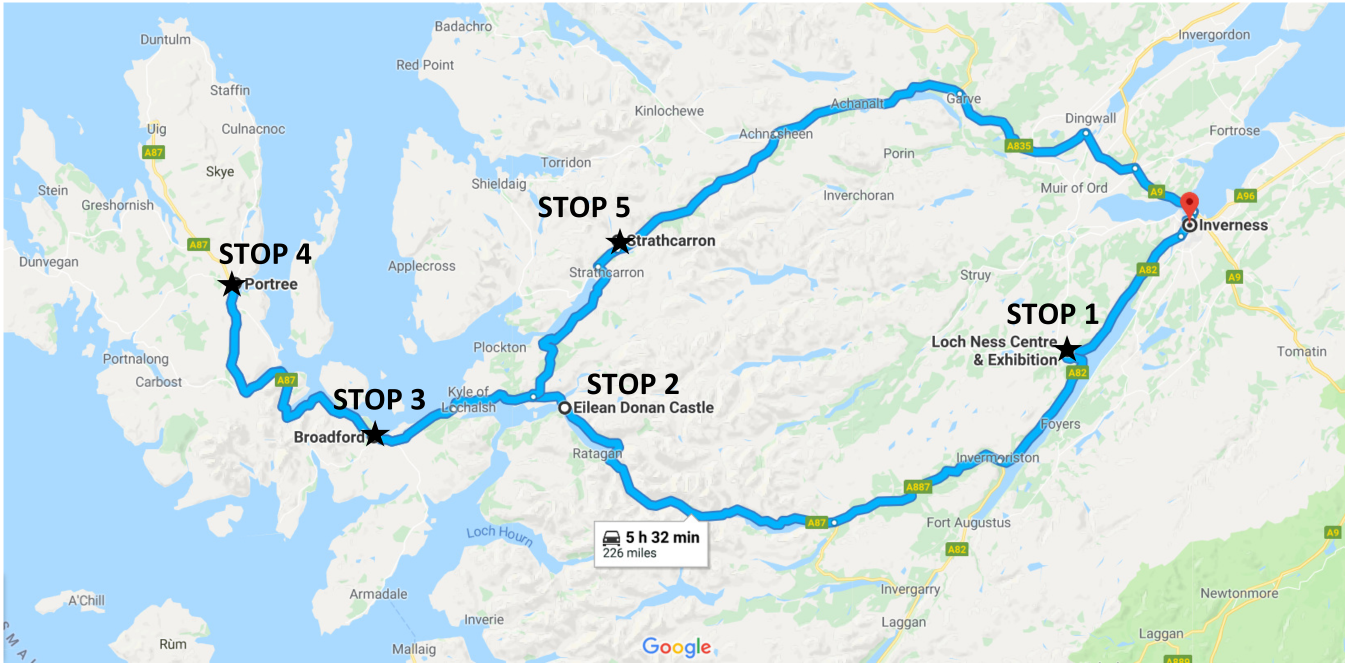



## Day 5: Thursday, March 8th, 2018 – Lock Ness and Isle of Skye




**7:00 AM:** Breakfast is included at this Hostel!

**8:00 AM:** Depart from the Ardconnel House

**9:00 AM:** The Loch Ness Centre & Exhibition

http://www.lochness.com/

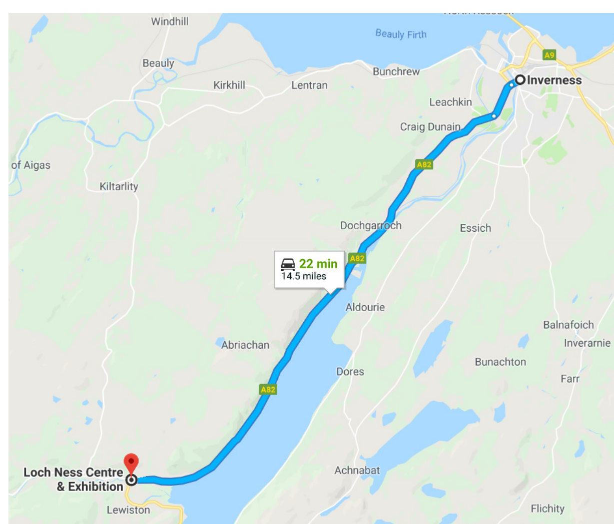
**11:00 AM:** Lunch at the museum

**1:00 PM:** Carr Brae above Loch Duich – Forsteritic Marbles with diopside, garnet-biotite gneisses, and possibly eclogites!!!!!!!!! But this might just be a view of Eilean Donan Castle….

**2:00 PM:** Rubha' an Eireannaich, Broadford, Isle of Skye – mafic and felsic magma mingling

**3:30 PM:** Portree, Isle of Skye

**6:30 PM:** Arrive back to the Hostel




**STOP 5.1:** *Loch Ness and Museums*

The Loch Ness Centre & Exhibition
Drumnadrochit, Loch Ness
Inverness-shire IV63 6TU

*The following is taken from the Wikipedia article on Loch Ness:*
*https://en.wikipedia.org/wiki/Loch_Ness*
*and*
*https://en.wikipedia.org/wiki/Loch_Ness_Monster*

Loch Ness is a large, deep, freshwater loch in the Scottish Highlands extending for approximately 37 kilometres (23 miles) southwest of Inverness. Its surface is 16 metres (52 feet) above sea level. Loch Ness is best known for alleged sightings of the cryptozoological Loch Ness Monster, also known affectionately as "Nessie". It is connected at the southern end by the River Oich and a section of the Caledonian Canal to Loch Oich. At the northern end there is the Bona Narrows which opens out into Loch Dochfour, which feeds the River Ness and a further section of canal to Inverness. It is one of a series of interconnected, murky bodies of water in Scotland; its water visibility is exceptionally low due to a high peat content in the surrounding soil.

Loch Ness is the second largest Scottish loch by surface area at 56 $km^2$ (22 sq mi) after Loch Lomond, but due to its great depth, it is the largest by volume in the British Isles. Its deepest point is 230 m (126 fathoms; 755 ft), making it the second deepest loch in Scotland after Loch Morar. A 2016 survey claimed to have discovered a crevice that pushed the depth to 271 m (889 ft) but further research determined it to be a sonar anomaly. It contains more fresh water than all the lakes in England and Wales combined, and is the largest body of water in the Great Glen, which runs from Inverness in the north to Fort William in the south.

Loch Ness with Urquhart Castle in the foreground

*Villages and places*

At Drumnadrochit is the "Loch Ness Centre and Exhibition" which examines the natural history and legend of Loch Ness. Boat cruises operate from various locations on the loch shore, giving visitors the chance to look for the "monster". Urquhart Castle is located on the western shore, 2 km (1.2 miles) east of Drumnadrochit. Lighthouses are located at Lochend (Bona Lighthouse) and Fort Augustus.

Nessie captured in the infamous 1934 'Surgeon's Photograph'

*Monster*

The Loch Ness Monster, or Nessie, is an aquatic being which reputedly inhabits Loch Ness in the Scottish Highlands. It is similar to other supposed lake monsters in Scotland and elsewhere, and is often described as being large in size, with a long neck and one or more humps protruding from the water. Popular interest and belief in the creature has varied since it was brought to worldwide attention in 1933. Evidence of its existence is anecdotal, with a few disputed photographs and sonar readings.

The creature commonly appears in Western media where it manifests in a variety of ways. The scientific community regards the Loch Ness Monster as a being from folklore without biological basis, explaining sightings as hoaxes, wishful thinking, and the misidentification of mundane objects.

*Monster Origins*

The word "monster" was reportedly applied for the first time to the creature on 2 May 1933 by Alex Campbell, water bailiff for Loch Ness and a part-time journalist, in an Inverness Courier report. On

4 August 1933 the Courier published a report by Londoner George Spicer that several weeks earlier, while they were driving around the loch, he and his wife saw "the nearest approach to a dragon or pre-historic animal that I have ever seen in my life" trundling across the road toward the loch with "an animal" in its mouth. Letters began appearing in the Courier, often anonymously, claiming land or water sightings by the writer, their family or acquaintances or remembered stories. The accounts reached the media, which described a "monster fish", "sea serpent", or "dragon" and eventually settled on "Loch Ness monster".

On 6 December 1933 the first purported photograph of the monster, taken by Hugh Gray, was published in the Daily Express; the Secretary of State for Scotland soon ordered police to prevent any attacks on it. In 1934, interest was further piqued by the "surgeon's photograph". That year, R. T. Gould published an account of the author's investigation and a record of reports predating 1933. Other authors have claimed sightings of the monster dating to the sixth century AD.

*Island*

Loch Ness has one island, Cherry Island, at the southwestern end of the loch, near Fort Augustus. It is an artificial island, known as a crannog, and was probably constructed during the Iron Age. There was formerly a second island (Dog Island) which was submerged when the water level was raised during the construction of the Caledonian Canal.

*Hydroelectricity*

Loch Ness serves as the lower storage reservoir for the Foyers pumped-storage hydroelectric scheme, which was the first of its kind in the United Kingdom. The turbines were originally used to provide power for a nearby aluminum smelting plant, but now electricity is generated and supplied to the National Grid. Another scheme, the 100 megawatt Glendoe Hydro Scheme near Fort Augustus, began generation in June 2009. It was out of service between 2009 and 2012 for repair of the tunnels connecting the reservoir to the turbines.

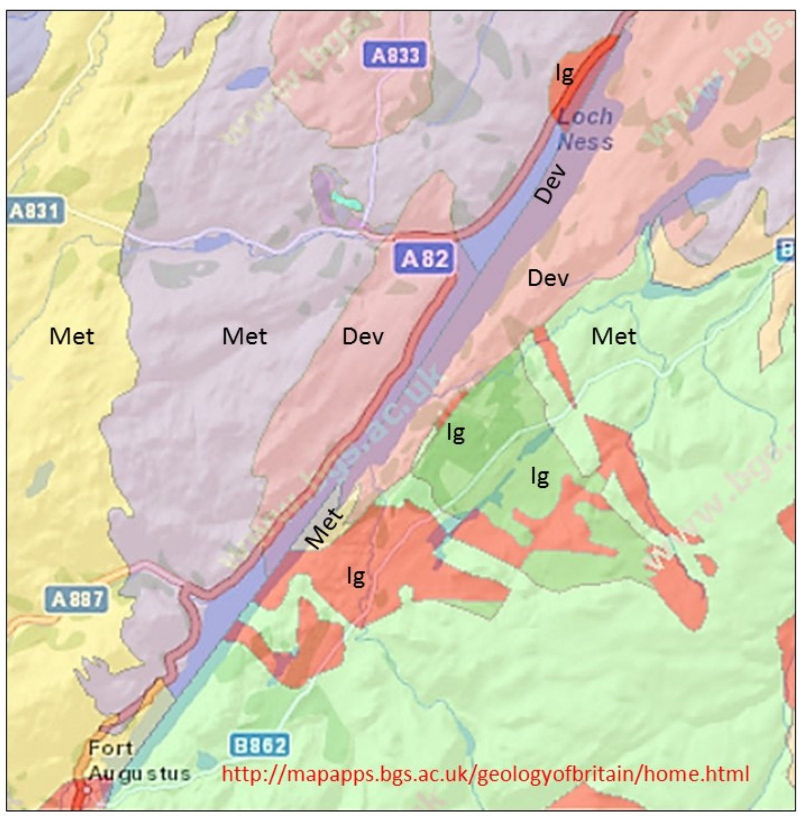
*Geology*

Loch Ness lies along the Great Glen Fault, which forms a line of weakness in the rocks which has been excavated by glacial erosion, forming the Great Glen and the basins of Loch Lochy, Loch Oich and Loch Ness.

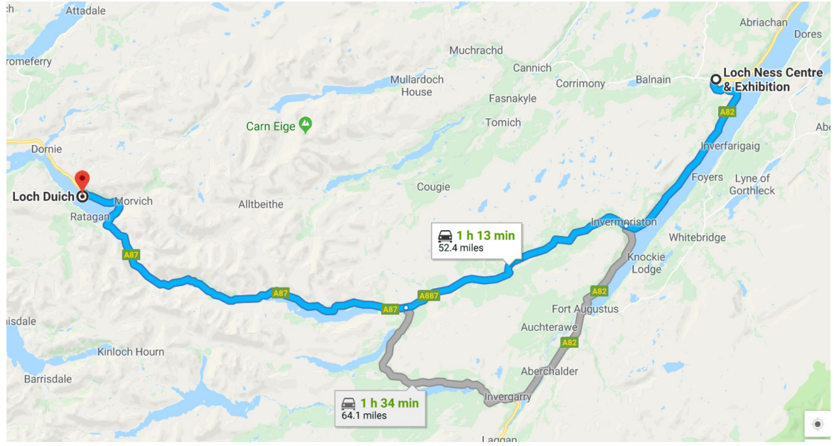
Dev = Devonian Non-marine sediments deposited in desert rivers and alluvial fans

Ig = Igneous rocks

Met = Metamorphic rocks



**STOP 5.2:** *Carr Brae above Loch Duich*




*The following is taken from:*
Storey, C., 2008, A field guide to the Glenelg-Attadate Inlier, NW Scotland, with emphasis on the Precambrian high-pressure metamorphic history and subsequent retrogression. Scottish Journal of Geology, v. 44, no. 1, pp. 17-34.

## Synopsis

The Glenelg-Attadale Inlier contains Proterozoic eclogites and Late Archaean mafic high-pressure granulites. Eclogites were formed both in the Palaeoproterozoic (around 1.75 Ga) and the Mesoproterozoic (around 1.1 Ga). The inlier is the only place in the British Isles that contains significant and unequivocal crustal eclogites and furthermore is one of the few places that retains clear evidence of having been strongly affected by the *c.* 1.1–1.0 Ga Grenvillian orogeny. The excursions provide an opportunity to study these rare rocks and gain insight into how they formed and how they were exhumed back to the surface.

### Excursion 4

This excursion presents an opportunity to visit the most accessible and best-preserved occurrence of mafic high-pressure granulite within the WU. A transect (Fig. 8) southeastward along the road allows study of the transition from relatively unstrained gneisses of the WU through to a major shear zone, the Barnhill Shear Zone (BSZ) that separates the WU from the EU. Away from the BSZ to the SE the strain gradient in the EU can be studied and contrasted with that in the WU.

The excursion is along the main A87 road on the north side of Loch Duich close to the village of Dornie and Eilean Donan Castle. Park either at the car park at Eilean Donan Castle or at a more convenient location *c.* 0.5 km south along the main A87 road where there is a conspicuous crag of green-black rock on the loch side of the road and an unofficial parking area for several vehicles [NG 885 254]. Leave the vehicle here and follow the transect by foot, taking care along this busy stretch of road. Allow 2–3 hours for this excursion.

#### Locality 1

A conspicuous outcrop of mafic high-pressure granulite occurs within a low-strain zone in the WU, close to Eilean Donan Castle [NG 885 254] on the lochward side of the road adjacent to the parking space (Fig. 8). The rock contains preserved patches of a high-pressure granulite facies assemblage with a granoblastic polygonal texture comprising garnet, diopside, plagioclase and quartz (Fig. 9a), with occasional brown hornblende (Fig. 9b) and orthopyroxene. Small patches of white trondhjemitic leucosome are present within the granulite (Fig. 9c) and locally these coalesce to form veins where melt has been able to migrate (Fig. 9d). The melting event occurred during high-pressure granulite facies metamorphism. Retrogression is evident even within the best-preserved patches, with thin symplectitic rims of amphibole and plagioclase along grain boundaries (Fig. 9e). In more extreme cases the diopside has been partially to completely replaced by calcic amphibole (Fig. 9f). The feldspar is commonly dusted with randomly orientated laths of zoisite that Rawson (2004) suggested may have resulted from later eclogite facies metamorphism under fluid- and deformation-limited conditions.

Dating of both the mafic high-pressure granulite and the trondhjemitic leucosome by the zircon U–Pb ID-TIMS method has been attempted and indicates a Late

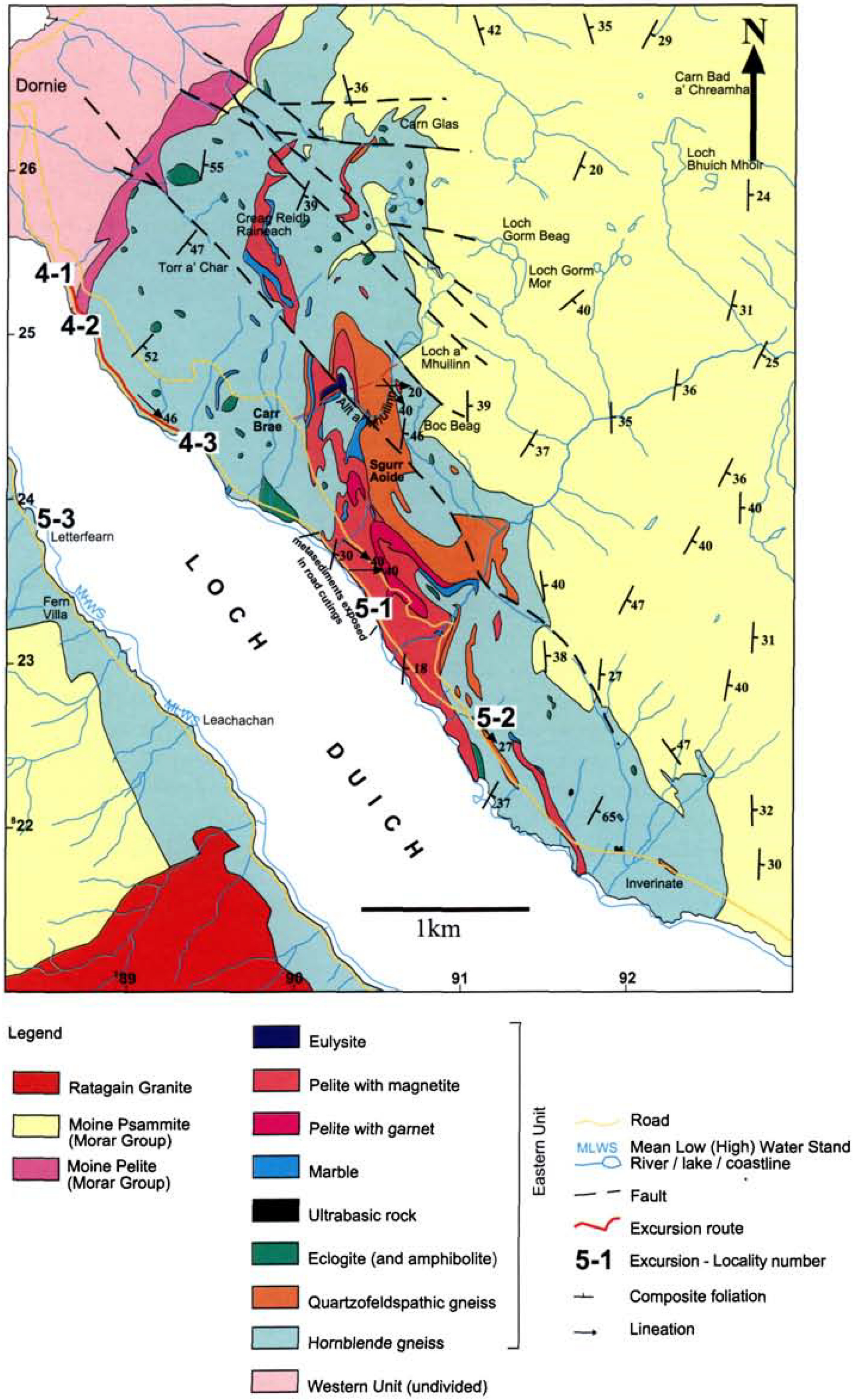



FIG. 8. Geological map north of Loch Duich covering excursions 4 and 5 (based on May *et al.* 1993, fig. 5).

Archaean (*c.* 2.7 Ga) age (Storey *et al.* unpubl. data), quite distinct from the Palaeoproterozoic eclogite facies metamorphism in the WU and late Mesoproterozoic eclogite facies metamorphism in the EU. However, the zircons have overgrowths and may have also lost radiogenic Pb, resulting in discordant analyses with a Palaeoproterozoic lower intercept around *c.* 1.7 Ga and possibly some later disturbance. Lu-Hf and Sm-Nd garnet-clinopyroxene dating from the mafic high-pressure granulite yields ages of 1718 ± 6 Ma and 1586 ± 5 Ma, respectively (Storey *et al.* unpubl. data). This indicates resetting of these systems during subsequent high-grade metamorphism in the Palaeoproterozoic and possibly later.

## Locality 2

To the SE along the road the WU gneisses are dominantly felsic and dip towards the ESE. The gneisses become highly strained in the area [NG 887 252] where the roadside outcrop has been blasted creating a sub-vertical face that has been covered with wire netting for safety reasons. At the northern end of the netting the gneisses can be traced into the WU felsic gneisses, but at the southern end (*c.* 30 m away) they are ultramylonitic and have a distinctly different character. The gneisses commonly contain thin interbanded felsic and mafic gneisses, the latter commonly containing garnet. This lithological character can be traced south-eastwards to progressively lower strain where it is clear that these gneisses correlate with those of the EU. Thus, the contact between the WU and EU is exposed behind the netting. Interestingly, and in contrast with all other exposed localities of the BSZ throughout the GAI, no Moine metasediments are present within the BSZ here.

The EU ultramylonites have an extremely small grain size, of the order of 5 μm diameter, composed of amphibole, plagioclase and quartz, and the phases are thoroughly admixed, suggesting a diffusion creep deformation mechanism. Within the groundmass, porphyroclasts of garnet and dark green to brown amphibole have been rounded during deformation. A mineral stretching lineation is present on the ultramylonitic foliation surface that plunges steeply down dip towards the ESE. The strain has been sufficiently high that no kinematic indicators have formed and been preserved, but elsewhere along the BSZ there is evidence for a top-to-the-west (*sensu lato*) sense of shear. Synkinematic titanite within felsic mylonites from the BSZ south of Glen More have been dated to 669 ± 31 Ma (Storey *et al.* 2004), which is considered a minimum age for $D_2$ shearing.

Southwards along the road the $D_2$, steeply ESE-dipping high-strain fabric persists for up to 1 km. Along this section the $S_2$ mylonitic fabric commonly contains rootless isoclinal fold hinges within the foliation and a dominant ESE-plunging mineral stretching lineation. These folds and the high-strain $S_2$ fabric are commonly refolded and the axes of the new folds are subparallel to the transport direction, although they are locally curvilinear. It is likely that these folds are $F_2$ and formed during incremental shearing. The thickness of the zone of ultramylonites within the hanging wall of the BSZ (i.e. the EU) is in stark contrast to that within the footwall (the WU) and demonstrates that the majority of the strain was partitioned into the EU.

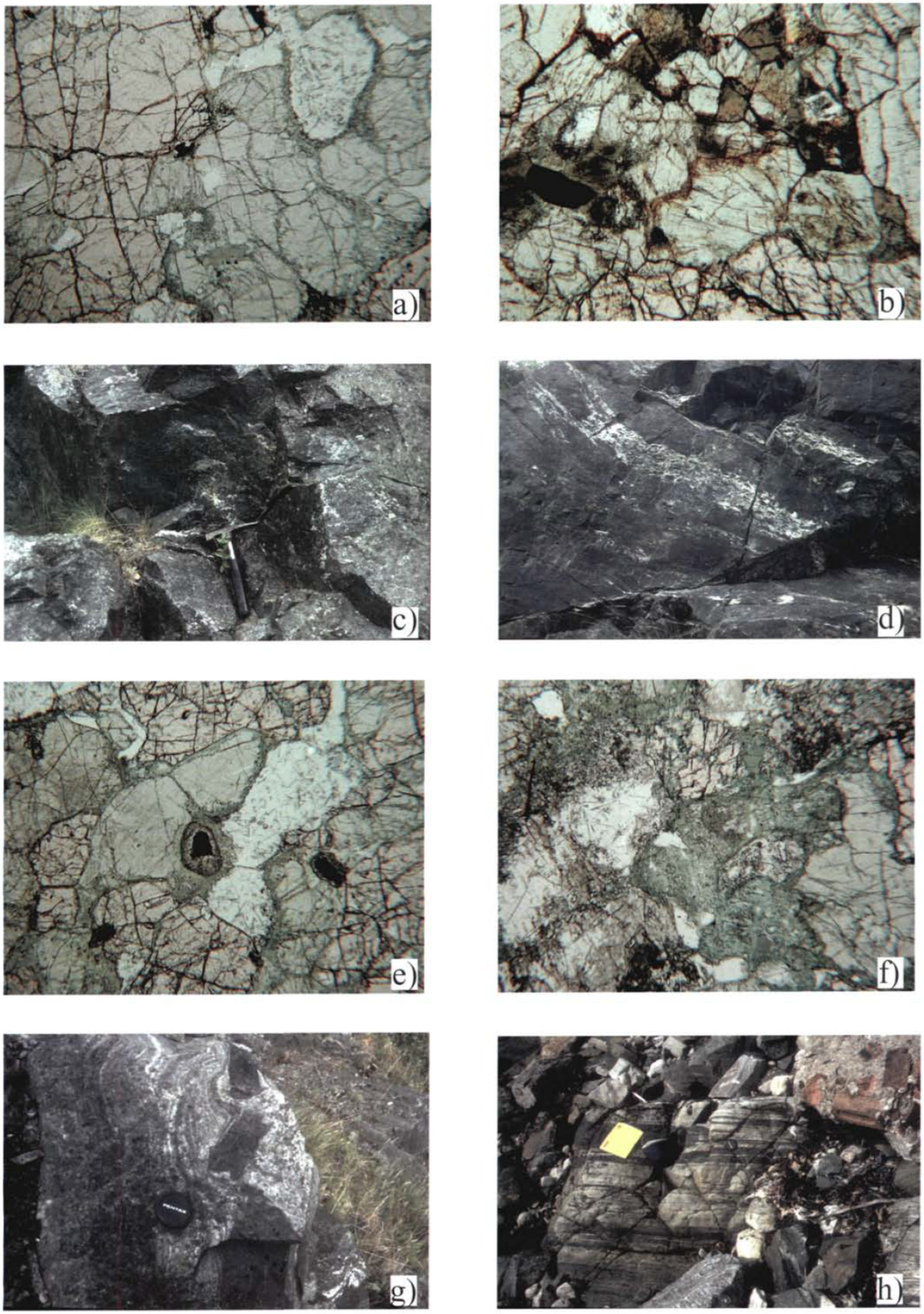
## Locality 3

Further south, low outcrops on the landward side of the main A87 road [NG 8930 2445] are demonstrably lower strain as migmatitic textures are preserved within grey trondhjemitic gneisses and mafic gneiss inclusions retain sharp contacts with the surrounding gneiss (Fig. 9g) and locally partially melt at their contacts. The gneiss is typical of trondhjemitic gneisses elsewhere within the EU where the strain is sufficiently low and has a Late Archaean protolith age (Storey *et al.* unpubl. data). On the opposite side of the road, outcrops along the shore of Loch Duich illustrate how similar gneiss is transformed into the high-strain banded grey/mafic gneiss (Fig. 9h) typical of the dominant EU lithology.

## Discussion and interpretation

Mafic sheets within the northern part of the WU locally contain relict high-pressure granulite facies assemblages associated with in-situ partial melt patches and veins producing trondhjemitic leucosome, reflecting a Late Archaean melting event. For the most part the granulite facies assemblage is retrogressed to amphibolite facies. In many mafic sheets within the WU the only evidence of a granulite facies event is the ubiquitous presence of trondhjemitic melt veins. The WU underwent eclogite facies metamorphism in the Palaeoproterozoic around 1.75–1.7 Ga that resulted in the partial resetting of U–Pb systematics in zircon and

FIG. 9. (**a**) WU mafic high-pressure granulite displaying coarse granoblastic polygonal texture of diopside, garnet and plagioclase. Note partial replacement along rim contacts of diopside by symplectites of amphibole and plagioclase. Randomly orientated laths within plagioclase are zoisite. Field of view 3 mm. (**b**) WU mafic high-pressure granulite displaying coarse granoblastic polygonal texture of diopside, garnet and brown hornblende. Field of view 3 mm. (**c**) WU mafic high-pressure granulite with trondhjemitic melt veins and patches. (**d**) WU mafic high-pressure granulite with trondhjemitic melt veins coalescing to form a mobilized sheet. (**e**) WU mafic high-pressure granulite displaying relict coarse granoblastic polygonal texture of diopside, garnet and plagioclase. Note symplectites of amphibole and plagioclase along diopside grain boundaries and ilmenite rimmed by framboidal titanite in these areas. Randomly orientated laths within the plagioclase are zoisite. Field of view 3 mm. (**f**) WU mafic high-pressure granulite displaying evidence of strong retroression with much of the diopside replaced by amphibole. Field of view 3 mm. (**g**) EU trondhjemitic gneiss with inclusions of partially melted mafic rock retaining mostly sharp contacts. Low strain zone within the EU at the margin of the BSZ high strain zone. (**h**) Typical aspect of EU banded trondhjemitic/mafic gneisses. Moderate strain area at the margin of the BSZ high strain zone.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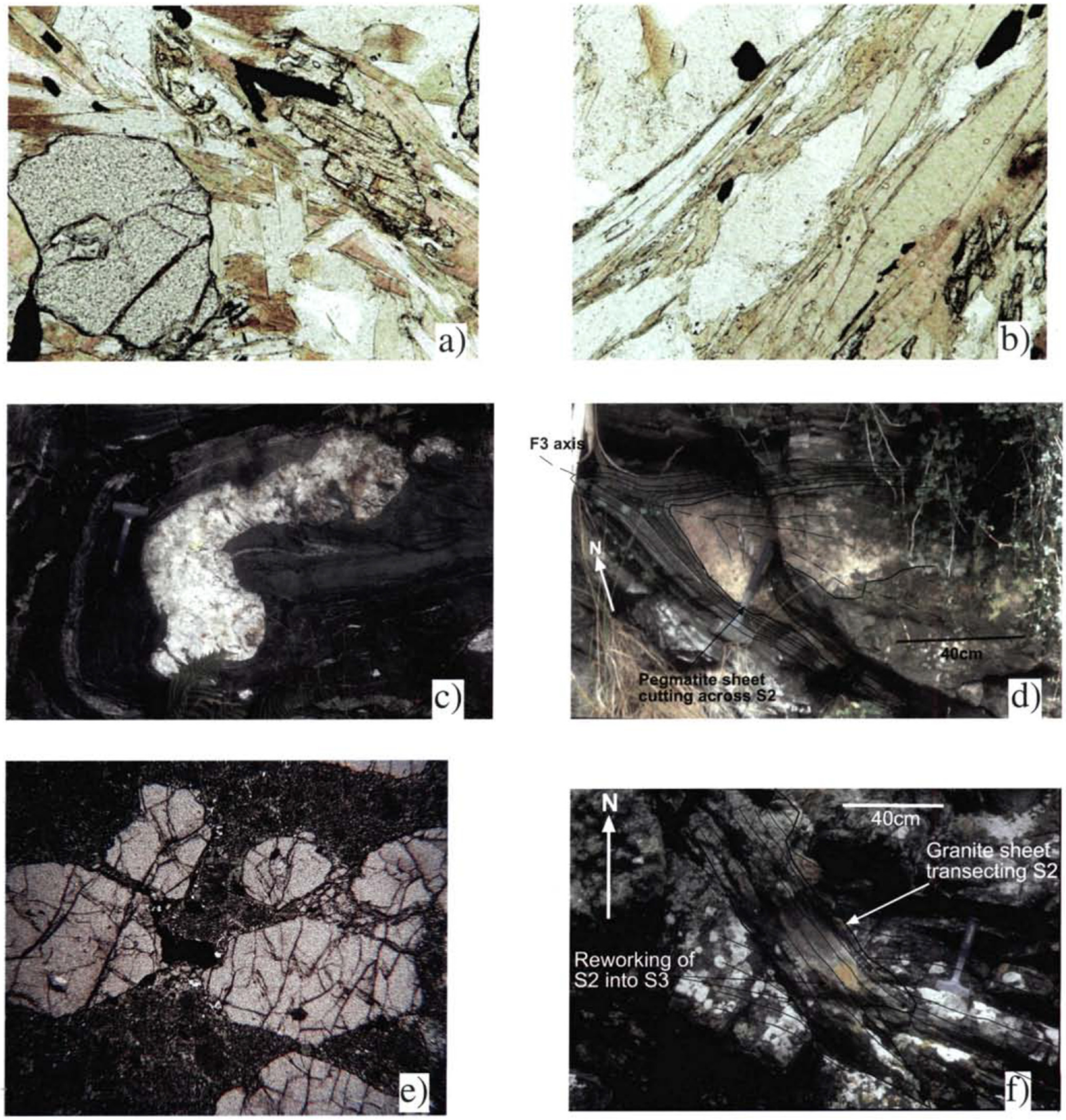



FIG. 10. (**a**) EU garnet, kyanite mica schist. Relict garnet in micaceous foliation. Field of view 4 mm. (**b**) EU garnet, kyanite mica schist. Biotite and phengitic mica intergrown in foliation. Field of view 4 mm. (**c**) EU calc-pelites containing leucosome vein that cuts across $S_2$ and note the $F_2$ rootless isoclinal fold within $S_2$. Vein and $S_2$ refolded around $F_3$ fold hinge. Note the boudinage of small leucosome veinlet on the left-hand side of the photo around the fold hinge. (**d**) Granitic pegmatite cutting high-strain $S_2$ fabric at low angle. Both pegmatite and $S_2$ are refolded around $F_3$ fold hinge. (**e**) EU streaky eclogite with relict garnet and omphacite aligned L-S shape fabric. Note elongate tabular nature of garnet. Relict omphacite grains are totally replaced by symplectites of amphibole and plagioclase. Field of view 2 mm. (**f**) EU amphibolites with strong $S_2$ fabric intruded by granite sheet. Granite sheet and $S_2$ fabric are reworked by later $D_3$ deformation, producing a new $S_3$ fabric.

complete resetting of Lu-Hf and Sm-Nd systematics in garnet and clinopyroxene. Apart from this, the presence of zoisite inclusions in granulite facies plagioclase may be the only petrologic manifestation of the later eclogite facies overprint. This is most likely due to the lack of fluid during the eclogite facies event resulting in metastability of the dry residual mafic granulites.

The protoliths to the EU grey trondhjemitic gneisses are of Late Archaean age but mafic xenoliths do not retain any evidence of having undergone a Late Archaean granulite facies event. Thus they may be broadly equivalent in terms of age and lithology to their counterparts in the WU but not necessarily part of the same tectonic unit.

The WU and EU are separated by a major, *c.* 1 km wide, $D_2$ shear zone with a dominant top-to-the-west (contractional) sense of displacement, with most of the strain focused into the EU in the hanging wall, implying that it travelled from greater depth. The shear zone was responsible for juxtaposition of the WU and EU and operated some time in the period *c.* 980–670 Ma.

### Excursion 5

This excursion presents an opportunity to visit easily accessible roadside localities (Fig. 8) that have a strong bearing on the evidence for timing and the nature of Neoproterozoic to Lower Palaeozoic tectonic events responsible for decompression of the EU eclogites. The relationship between $D_2$ and $D_3$ fabrics is critical in terms of timing and their bearing on the retrograde exhumation path. An opportunity to visit EU metasediments that have undergone eclogite facies metamorphism is also presented.

The localities are based on roadside exposures on the northern (A87) and southern (Ratagan to Totaig road) side of Loch Duich (Fig. 8). Parking and access issues are described for each locality. Allow 3–4 hours for this excursion.

#### Locality 1

Along the main A87 road on the northern side of Loch Duich, road cuttings expose metasedimentary rocks belonging to the EU behind crash barriers [NG 905 233 to NG 900 239]. Park in a lay-by just to the south of the termination of the crash barriers where there is ample room for several cars or minibuses. Walk back along the road to the crash barriers and access the cliff exposures behind the barriers. The area can become overgrown but is usually cleared on an annual basis. Ticks are common at this locality so take care to minimize flesh exposure and check yourself afterwards.

At the southern end of the exposure metapelites show a strong $S_2$ schistosity. These contain biotite, plagioclase, garnet, kyanite, quartz, white mica and chlorite together with conspicuous mauve garnet porphyroblasts up to 10 mm diameter. Kyanite is less obvious in the field, but relicts are commonly present in thin section (Fig. 10a). Rawson (2004) identified phengitic white mica (>3.2-3.6 Si a.p.f.u.) intergrown with biotite in the matrix (Fig. 10b), also implying relicts of eclogite facies metamorphism.

Further northwards along the exposures the pelites become dominantly calcareous with increasing proportions of epidote. Marble used to be exposed at the northern end of the section but has since become overgrown. It is likely that this progression from aluminous to increasingly calcareous sediments is primary and formed part of an original subaqueous (sea floor?) succession subducted along with basalts and trondhjemitic gneisses to eclogite facies.

Within these exposures there is widespread evidence of partial melting of the metapelites, with leucosome development in veins (Fig. 10c). The leucosome development is also a time-marker as it demonstrably cuts across the dominant $S_2$ fabric but, along with $S_2$, is folded around $F_3$ fold hinges, resulting in boudinage of the leucosome around hinge zones (Fig. 10c). Unfortunately the leucosome does not contain U- or Th-bearing accessory minerals or other minerals that can be radiometrically dated. The area is dominated by M and W folds and occupies the hinge of a major $F_3$ fold that can be traced southwestwards throughout the GAI and the Moine.

#### Locality 2

Drive south along the A87 road for *c.* 800 m until you reach a left turn towards Carr Brae. Opposite this junction on the right-hand side of the road is off-road parking for several cars or minibuses. Walk south along the road and examine the low exposures on the landward side of the road, taking great care of traffic.

Approximately 50 m south of the Carr Brae junction [NG 9115 2260], low roadside exposures on the landward side of the road contain banded EU felsic gneisses with a strong $S_2$ fabric intruded by granitic pegmatite cutting $S_2$. Both the $S_2$ fabric and the pegmatite are locally folded around $F_3$ folds (Fig. 10d). The pegmatite contains euhedral igneous titanite that has been dated by U–Pb ID-TIMS methods to $437 \pm 6$ Ma (Storey *et al.* 2004). This date indicates that $D_2$ is older than this and $D_3$ younger.

#### Locality 3

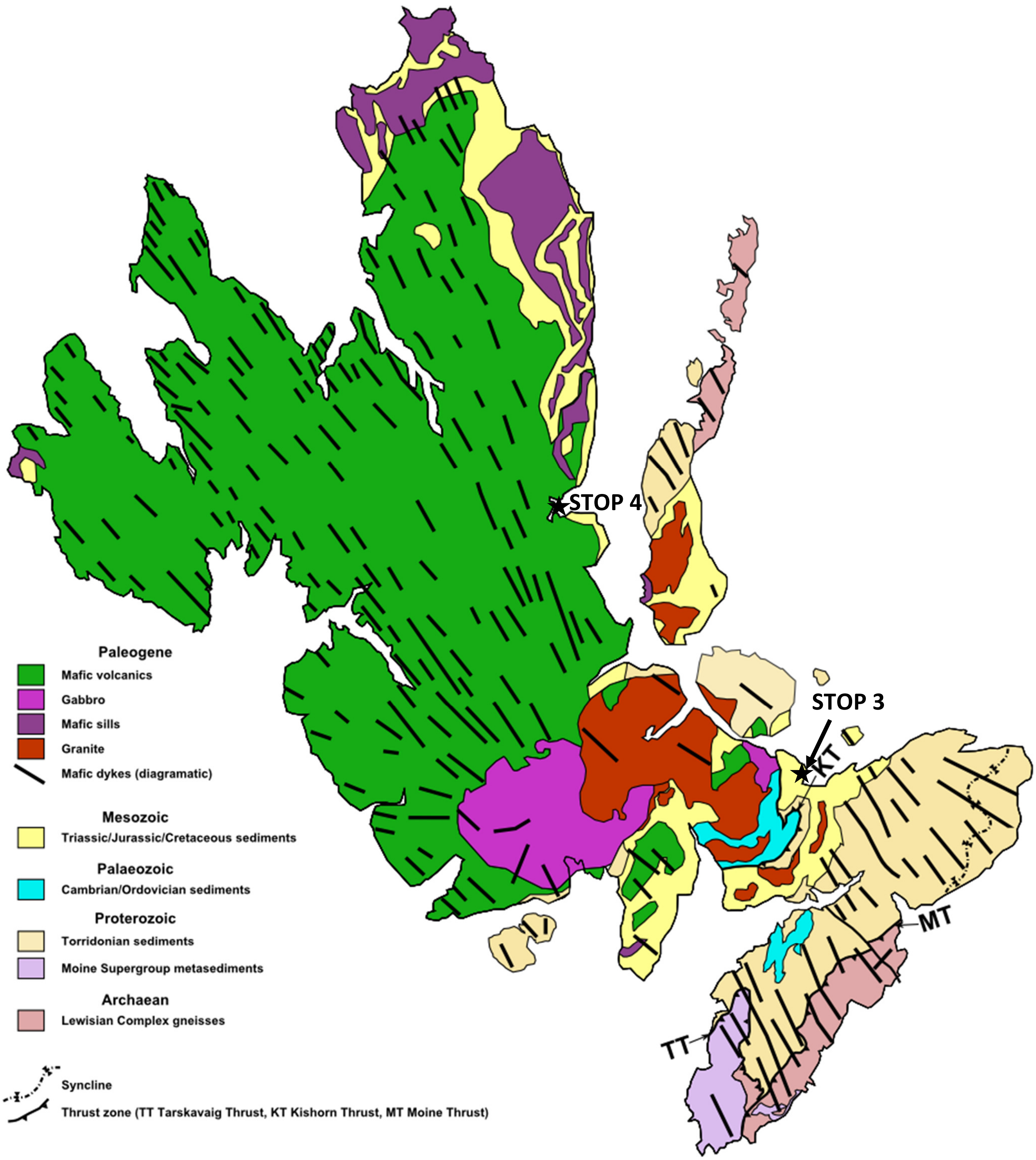
Drive south along the A87 to Shiel Bridge and take the right turn towards Glenelg. After *c.* 1 km take the first right turn signposted to Ratagan and follow this single-track road (the same road as Excursion 1, locality 4) for *c.* 6 km until you reach the hamlet of Letterfearn. Park in the small bay at Letterfearn [NG 8845 2380]; there is space for only one vehicle so any more will have to use the nearest convenient passing place. Low outcrops occur on the north side of the bay on the beach, but take great care as the loch is tidal and the rocks can be treacherously slippery.

A cliff face *c.* 3 m high [NG 8845 2380] reveals mafic rocks with a dominant east-dipping amphibolite facies $S_2$ foliation and an east-plunging mineral stretching $L_2$ lineation. At the highest part of the face the amphibolite contains tabular garnet and elongate prisms of relict omphacite forming an L-S fabric coplanar and colinear with the $D_2$ fabric. The relict eclogite contains quartzofeldspathic streaks and is correlated with the streaky eclogites described by Sanders (1988) elsewhere in the EU (Excursion 1, locality 2), but no kyanite has survived here. Hence, this is a relict of the $D_1$ eclogite facies fabric that in this area evidently had a similar principal stretching axis to $D_2$. The $D_1$ fabric has been statically overprinted by amphibolite facies minerals, with omphacite replaced by symplectites of amphibole and plagioclase and neoblastic garnet (Fig. 10e).

**STOP 5.3A:** *Isle of Skye Geology Overview*

***From Wikipedia:***

The Geology of Skye, in Scotland, is highly variable and the island's landscape reflects changes in the underlying nature of the rocks. A wide range of rock types are exposed on the island, sedimentary, metamorphic and igneous, ranging in age from the Archaean through to the Quaternary.



***Precambrian***

The oldest rocks found on Skye are gneisses of the Lewisian complex that were formed about 2,800 million years ago during the Archaean. These gneisses outcrop on the southeastern coast of the Sleat peninsula and were originally granitic igneous rocks. Near Tarskavaig, Neoproterozoic metasediments of the Moine Supergroup are found above strongly deformed Lewisian rocks. The Lewisian and Moine sequences are thrust over another sequence of unmetamorphosed Neoproterozoic sediments, the Torridonian, along the Moine Thrust Zone. The Torridonian on Skye comprises two conformable sequences, the older Sleat Group and the younger Torridon Group. Both groups consist dominantly of sandstones and were deposited mainly by alluvial fans and rivers.

***Lower Palaeozoic***

A sequence of Cambrian to Lower Ordovician sediments of the Eriboll and Durness Groups lie above the Torridonian with an angular unconformity. The Lower Cambrian Eriboll Group comprises a basal quartzite, locally with a basal conglomerate, followed by the distinctive Pipe Rock Member, a quartz arenite with white weathering skolithos trace fossils. The Pipe Rock is overlain by the Salterella Grit, a coarse sandstone, and the Fucoid Beds, a sequence of calcareous sandstone and siltstone. The overlying Durness Group comprises a series of dolostones of Upper Cambrian to Middle Ordovician in age. The lowest unit is the Ghrudaidh Formation, followed by the Eliean Dubh Formation the Sailmhor Formation and the Sangomore Formation, all consisting of dolostones with chert. The two main exposures of Cambro-Ordovician sediments are the "Ord Window" (a gap in the Kishorn Thrust sheet through which the sequence beneath the thrust can be seen) on the northern coast of Sleat and the area between Broadford and Loch Slapin. These beds are affected by thrusting in both areas and by contact metamorphism from Palaeogene granite intrusions in the northern outcrop, locally forming marble, such as Torrin.

***Mesozoic***

Sedimentary rocks of Mesozoic age underlie most parts of the island north of the Sleat Peninsula. They are hidden beneath Palaeogene volcanic rocks over most of this area, being exposed only on the eastern and northern coasts of the Trotternish peninsula, on the Strathaird peninsula and between the Red Hills and Sleat. Triassic rocks of the Stornoway Formation are found near Broadford, a sequence of sandstones and conglomerates deposited by rivers. These beds are overlain by the lower Jurassic Lias Group with the Broadford Beds at the base, passing up into the Pabay Shale Formation, the Scalpay Sandstone Formation the Portree Shale Formation and the Raasay Ironstone Formation. The sequence continues with the Lower to Middle Jurassic Bearreraig Sandstone Formation followed by Middle Jurassic Great Estuarine Group, comprising the Cullaidh Shale Formation, Elgol Sandstone Formation, Lealt Shale Formation, Valtos Sandstone Formation, Duntulm Formation, Kilmaluag Formation and the Skudiburgh Formation. The Upper Jurassic is represented by the Staffin Shale Formation. The only Cretaceous unit exposed on Skye is the Strathaird Limestone Formation, thought to be either Turonian or Campanian in age, which lies unconformably on the Jurassic and is overlain unconformably by Palaeocene lavas.

***Paleogene***

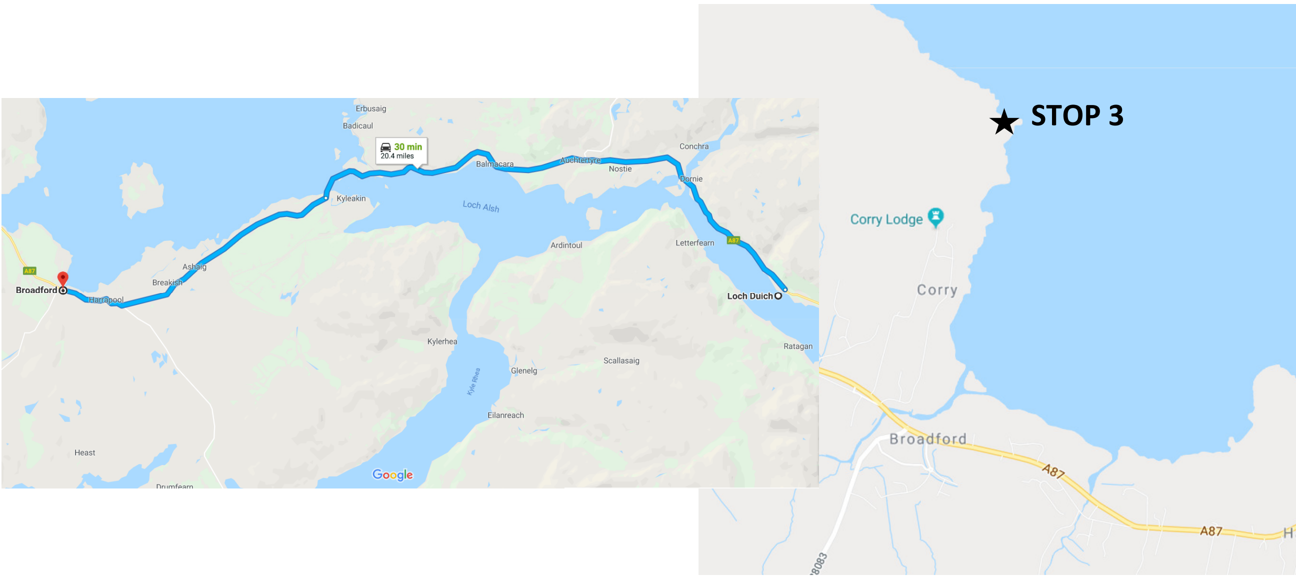
During the Paleocene to Early Eocene Skye formed one of the main volcanic centres of the North Atlantic Igneous Province. Gently dipping lavas from the volcanoes cover most of northern Skye, giving a stepped trap type landscape. The dominant lava type is basalt, with subsidiary hawaiite and mugearite derived from silica-poor magma and minor amounts of trachyte from a silica-rich magma. Part of the magma chambers for the volcanoes are exposed at the surface as major intrusions of gabbro and granite. These coarse-grained igneous rocks are relatively resistant to erosion and now form the Cuillin hills. The Black Cuillin are formed of gabbro, which erodes to form the characteristically jagged outlines, although this is in large part due to the many minor intrusions, such as dykes and cone sheets that cut the gabbro. The Red Hills are formed of granite and have a more rounded topography. All pre-Quaternary rock types on the island are affected by a major swarm of dykes, which forms part of the North Britain Palaeogene Dyke Suite. Most of the dykes are basaltic in composition but a minority are trachytic. The dominant trend of the dykes is northwest-southeast although they are locally in part radial near the old volcanic centre. On the Trotternish peninsula, mafic magma was intruded along the bedding planes of the Jurassic sedimentary rocks beneath the lavas to form sills that are up to 90m thick. They commonly display columnar jointing, such as in the upper part of the Kilt Rock at Staffin.

***Quaternary***

During this period the island was affected by the Quaternary glaciation, with the development of an ice cap centred on the Cuillin and Red Hills. The main ice sheet that flowed westwards from the Scottish mainland was diverted around this upland area. The island is covered by large areas of glacial till, left behind when the ice melted.

**STOP 5.3B:** *Rubha' an Eireannaich, Broadford, Isle of Skye*

*Extracted from the Geological Conservation Review - http://www.jncc.gov.uk/page-2731*




*Highlights*

The site contains a fine, continuous section through a composite (felsite–basalt) sill intruded into Jurassic strata. Mixing of acid and basic magmas is demonstrated by the complete gradation from basalt at the margins of the intrusion to felsite in the core with thin, intervening hybrid zones.

*Introduction*

This site contains an exceptionally well-exposed example of a composite intrusion which demonstrates a virtually continuous variation from chilled upper and lower margins of basic rock, through hybrid rocks to a central felsite member. It is an excellent example of mixing between contrasting magma types. The sill lies at the northern end of a series of arcuate composite intrusions which focus on the Inner (Beinn na Caillich) Granite of the Eastern Red Hills Centre. Buist (1959) has described the intrusion in some detail, and Bell (1983) worked on the geochemistry of the different components and produced a model for the formation of the intrusion. The main features of the intrusion have been summarized by Bell and Harris (1986).

*Description*

A sill of about 5 m in thickness intrudes sandstones and siltstones belonging to the Lower Jurassic Broadford Beds at Rubha' an Eireannaich, Broadford. In addition, two thin basic sills intrude the overlying sandstone and both sediments and the sill are intruded by basic dykes. The section through the sill can be summarized as follows (after Buist, 1959):

| | |
|---|---|
| Upper basalt | up to 0.75 m |
| Hybrid zone | between 0.23 and 0.3 m |
| Felsite | up to 2.4 m |
| Hybrid zone | between 0.23 and 0.3 m |
| Lower basalt | up to 0.75 m |

The lower and upper basic margins contain xenocrysts and phenocrysts of feldspar but the lower basic member also contains felsic stringers and small areas of fine-grained basic material, together with rare, partly resorbed gabbroic inclusions. The felsite core carries altered phenocrysts of sodic plagioclase and shows an increase in the proportion of groundmass quartz towards the centre of the sheet. The hybrid zones contain sodic plagioclase xenocrysts and phenocrysts of altered andesine and groundmass pyroxene is pigeonite, in contrast to the augite found in the basic margins. There is a complete gradation from one rock type into the other. The hybrid zones contain sodic plagioclase xenocrysts and phenocrysts of altered andesine, and the groundmass pyroxene is pigeonite as opposed to augite in the basic margins. There is a complete gradation from one rock type into the other with no suggestion of chilling; this contrasts strongly with the external margins of the basic member which were chilled to (now devitrified) glass against the sedimentary rocks of the Lias.

*Interpretation*

The field evidence provided by the sill shows that basic and acid magmas were essentially available simultaneously. The initial injection of basic magma was followed by injection of the acid magma before the former had cooled and consolidated. The absence of a well-defined boundary between these contrasting magma types, a feature also observed in other composite intrusions (for example, in the Marscoite Suite in Harker's Gully; the composite sills of Arran, see below), led Bell (1983) to conclude that high-temperature diffusion occurred between the basic and acid members at their present level in the crust. In addition, the presence of feldspar xenocrysts in the basic margins indicates that some mechanical mixing occurred prior to intrusion.

Geochemical work by Bell (1983) has shown that for all of a range of elements determined, there is complete compositional continuity between basic and acid members of the sill, and that the chondrite-normalized, rare-earth element patterns for the basic and acid members are parallel. From these data, Bell concluded that the basic and acid components were cogenetic. He envisaged two periods of hybridization of the acid and basic magmas. An early event involved limited addition of porphyritic acid magma to basic magma forming a basic hybrid with xenocrysts, the basic member was then intruded to form the present marginal rocks in the sill. This was rapidly followed by further porphyritic acid magma which formed the centre of the sill. At this stage, in situ hybridization occurred by diffusion of elements between the two contrasting magmas while they were still both close to their liquidus temperatures (Bell and Harris, 1986). This process formed the c. 0.30-m-thick hybrid zones which now separate the basic margins from the acid core.

*Conclusions*

The site provides a very clear example of a common phenomenon in the British Tertiary Volcanic Province, namely, the coexistence of basic and acid magmas. In this instance, there was limited mechanical mixing between the different magmas prior to intrusion; further limited high-temperature diffusion within the intrusion occurred during the emplacment of the basic magma, which was followed very rapidly by the central injection of acid magma. The exposures at Rubha' an Eireannaich provide a continuous section through all of the rock types which can be readily distinguished in the field.

*Other random notes I found on the internet:*

**Broadford beach for Jurassic fossils.**

*(Excursion Guide to the Geology of the Isle of Skye, p193, OS Sheet 32).*

By Following the succession on the beach from east to west we started in the Lower Broadford Beds and went up into the Upper Broadford Beds, all of which is in the Lower Jurassic. The lower beds were hard marls and limestones. Much of the sand on the beach is composed of broken bits of the calcareous alga *Lithothamnioncalcareum.* We also found tests of the burrowing sea-urchin *Echinocardiuincaudatum.* Ammonites occur in the Upper Broadford Beds.

**STOP 5.4:** *Portree, Isle of Skye*

*The following is from:*
Miller, S. 2005, Mountain Geology – Skye Cuillin. The Edinburgh Geologist, v. 44, pgs. 4-9.

***In the second article on Mountain geology, Suzanne Miller leads us into the world of Sir Walter Scott's Cuchulin and over the most famous ridge in Scotland, popular with climbers and hillwalkers (the intrepid ones) alike.***

## Introduction

Skye is an island of superlatives: measuring 80 by 32 kilometres, it is the largest of the Hebrides; it boasts the largest expanse of basaltic plateau in the UK; it has the grandest mountain group in the UK – the Cuillin, rhapsodised by Scott and recaptured by Turner's paintings.

The Cuillin Hills are among the steepest mountains in the UK, include 20 peaks above 900 m and contain the only Munro which requires the use of rock climbing techniques (the Inaccessible Pinnacle). There are two main ridges. The magnificent Black Cuillin, some peaks of which remained unclimbed until the late nineteenth century, stretches for 12 km, possesses more than thirty peaks (eleven of them Munros) and is primarily composed of gabbro and peridotite. Infamous for their rough, crystalline cloth-tearing nature, they contrast with the red-coloured granite of the Red Hills to the east extending from Glamaig to Beinn na Caillich.

## The Geology

The Cuillin Hills are the remains of the roots of an early Palaeogene volcanic centre. The igneous rocks on Skye have been studied since the 1800s by the likes of Sir Archibald Geikie and John Wesley Judd (1879 - 1914), with both making headway into understanding the nature of the rocks. But it was Dr Alfred Harker (1859 - 1939) who studied, mapped and interpreted these igneous rocks in the early 1900s, who first recognised the island's true importance.

Much of the Isle of Skye is composed of basaltic lava flows, erupted during the earliest phase of volcanic activity in the area - known as the Skye Main Lava Series. These were erupted from numerous early volcanic centres and not from the volcanoes above the main Cuillin Centre. From an estimated thickness of 1200 m for the Skye Lava Field and a duration of volcanic activity of c. 250 000 years, it has been calculated that magma production was in the region of 1 metre per 200 years (Bell & Jolley, 1997). These early basaltic lava plains, which underlie the drift mounds and peat bogs around Sligachan, were subsequently intruded by successive volcanic centres which would have fed volcanoes. These volcanoes were subsequently eroded.

The highland massif of central Skye can be divided into four mountain groups, each corresponding to a separate plutonic centre (Figure 1). First, the basic/ultrabasic hills of the Black Cuillin (the Main Cuillin Centre). In essence, the Black Cuillin is an arcuate mass of ultrabasic peridotite which has subsequently been intruded by a large number of olivine-rich gabbro sheets. The main features are:

- outer gabbros: coarse grained (oldest)
- an inner and outer layered series: mostly allivalite, peridotite and eucrite
- minor intrusions: dykes, cone sheets, agglomerates and explosion breccias

Second, a complex group comprising the isolated peak of Bla Bheinn and the granite of Meall Dearg and Ruadh Stac. This, the Strath na Crèitheach centre, was intruded into the main Cuillin Centre and so is exposed in the Black Cuillin.

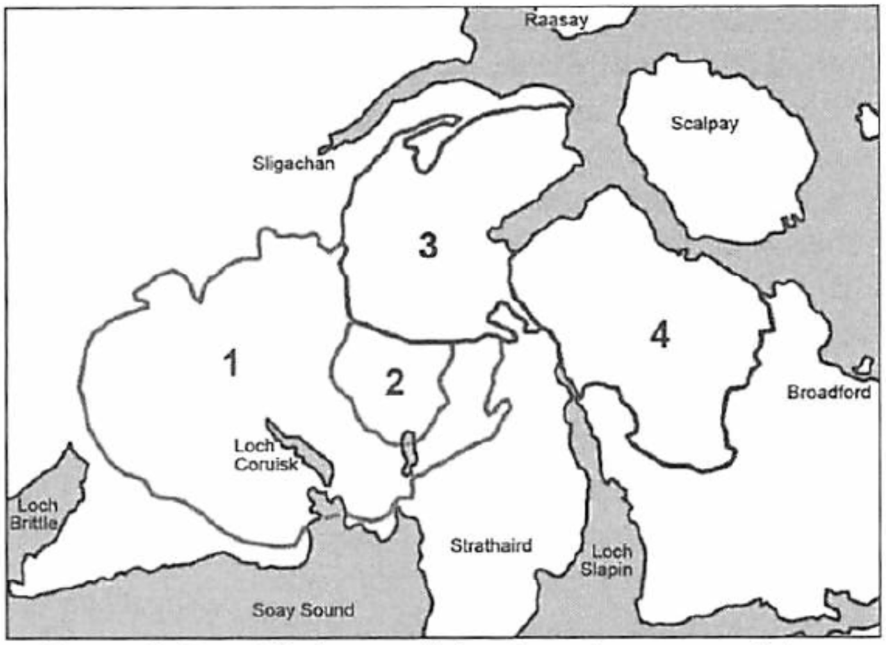



*Figure 1. Simplified map of the plutonic centres of the Skye Cuillin (after Bell & Williamson 2002): 1. Black Cuillin : 2. Strath na Crèitheach : 3. Western Red Hills 4. Eastern Red Hills.*

Third, the granitic Western Red Hills (also known as Lord Macdonald's Forest). This occupies an area of c. 35 km² and comprises ten granites, a composite ring dyke, a number of explosion breccias and a gabbro.

Fourth, the granitic Eastern Red Hills including Beinn na Caillich. Many of these granites were emplaced into sedimentary country rock giving rise to metamorphic thermal aureoles.

Although dominantly granitic bodies, the Red Hills centres also show evidence of mixed magma (acid-basic) intrusions, felsites, ignimbrites, tuffs and agglomerates.

These centres represent, in age, a generally eastward and progressively more acidic shift of activity of the intrusive complexes (Bell, 1976). The ultrabasic and basic rocks of Skye are dated at around 58-59 million years whilst the Red Hills give dates of 55–58 million years. It is believed that many of the Palaeogene volcanic centres were emplaced along fault systems. For example, the central intrusive complexes on Skye are associated with the Camasunary-Skerryvore Fault – the deep-seated fractures providing weaknesses in the crust that were exploited during the intense igneous activity (Butler & Hutton, 1994).

The intrusion of dolerite dykes occurred throughout the history of the formation of both the Black and Red Cuillin. The ravines and vertical gullies which seam the bare rock faces of the Black Cuillin have been eroded into the basic dykes. Where these intersect the ridges and ice-steepened arêtes they often form notches in the skyline (as in the Waterpipe Gully of Sgurr an Fheadain), which accounts in part for the serrated appearance of the peaks themselves. On the Red Hills, however, the basic dykes are not as numerous and are generally more resistant to erosion than the surrounding granite, so that they tend to stand out in relief. This is occasionally true of the Black Cuillin dykes also, the most famous example being the Inaccessible Pinnacle, which stands up as a narrow wall on the summit of Sgurr Dearg (977m).

The crest of the main Cuillin ridge is a sawtooth arête (Figure 2) curving southwards until it plunges directly into the sea at Loch Scavaig. The highest peak of Sgurr Alasdair (1009 m) and the southernmost peak, Gars-Bheinn, are capped by basaltic lava. According to Harker (1941) these isolated lava summits represent the remnants of the roof of the plutonic intrusion, dating from the time when the plateau basalts were updomed by the ultrabasic and basic magma injected below. It was Harker, too, who noted the very marked inclination of structures in the gabbro ridges, which take the form of pseudo-stratification. At Sgurr nan Gillean, at the ridge's northern end, the steep dip is towards the south; along the main Cuillin ridge it is towards the east; at Sgurr na Stri it is towards the north, while on Bla Bheinn it is towards the west. Thus all the structures dip inwards to a central point beneath Glen Sligachan, because they are made up partly of the gabbro banding and partly of the inclined cone-sheets. The cone sheets are the most classic example of this type in the UK and are restricted to the gabbro.

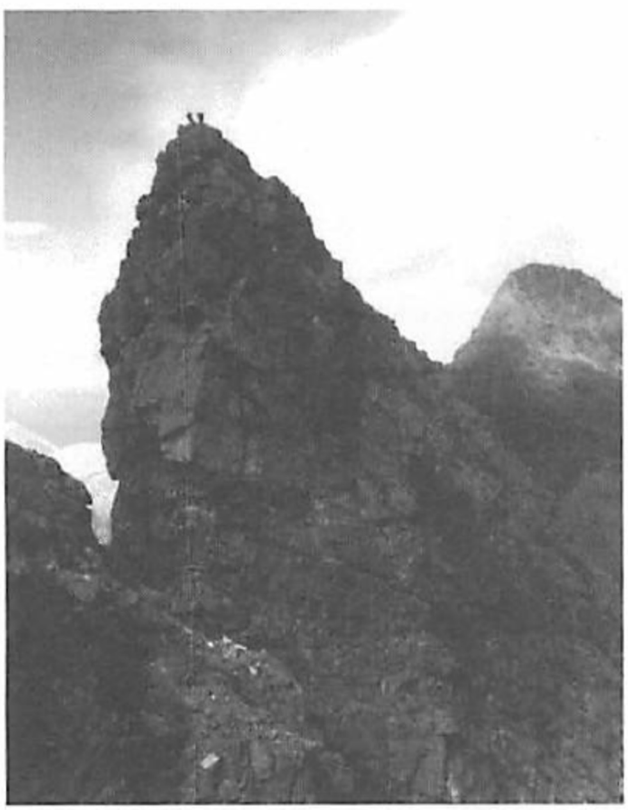


*Figure 2. Am Basteir – part of the sawtooth arête of the Black Cuillin*

The Western Red Hills (Figure 3) are separated from the Black Cuillin by the long funnel of Glen Sligachan. They are composed of a number of granitic injections which were intruded concentrically as major ring structures in a cauldron complex similar to those of Arran and Mull. The grantic complex caused a local updoming of the basaltic lavas, as demonstrated by the steeply dipping lava cap that has survived on the summit and eastern slopes of Glamaig which towers 773m above Loch Sligachan. Elsewhere the basaltic cover has been almost entirely stripped off by erosion. Similar basaltic remnants can also be seen on the slopes of the Eastern Red Hills, which have been carved from granites emplaced by similar mechanisms but from a separate intrusion centre. Each of the intrusive centres represents the roots of major volcanic centres with up to 2 km of rock having been eroded, removing most of the volcanic edifice (Figure 4). The only remnants of the lavas extruded onto the surface may be the Preshal More flows that are exposed in Central Skye. Their geochemical affinities with the intrusive rocks of the Cuillin Centre suggest that they developed above this centre.

The emplacement of the intrusive complexes resulted in the contact (thermal) metamorphism of the country rocks – both earlier lavas and sedimentary rocks. This has produced hornfelses, metalimestones and skarn formation.

The volcanic activity was triggered by the opening of the Atlantic around 65 million years ago. By 52 million years ago, the igneous activity was over and sedimentary rocks of Palaeogene age were deposited on top of (and in places between) the lavas.

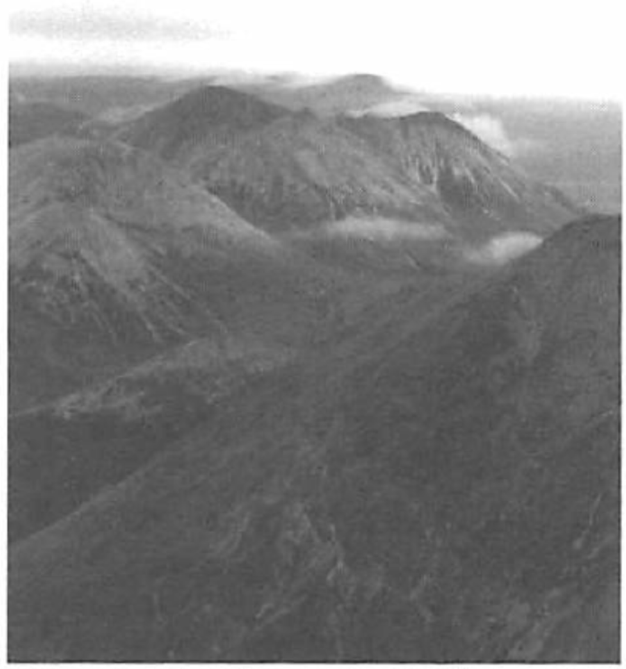


*Figure 3. The Western Red Hills – conical summits draped with scree*

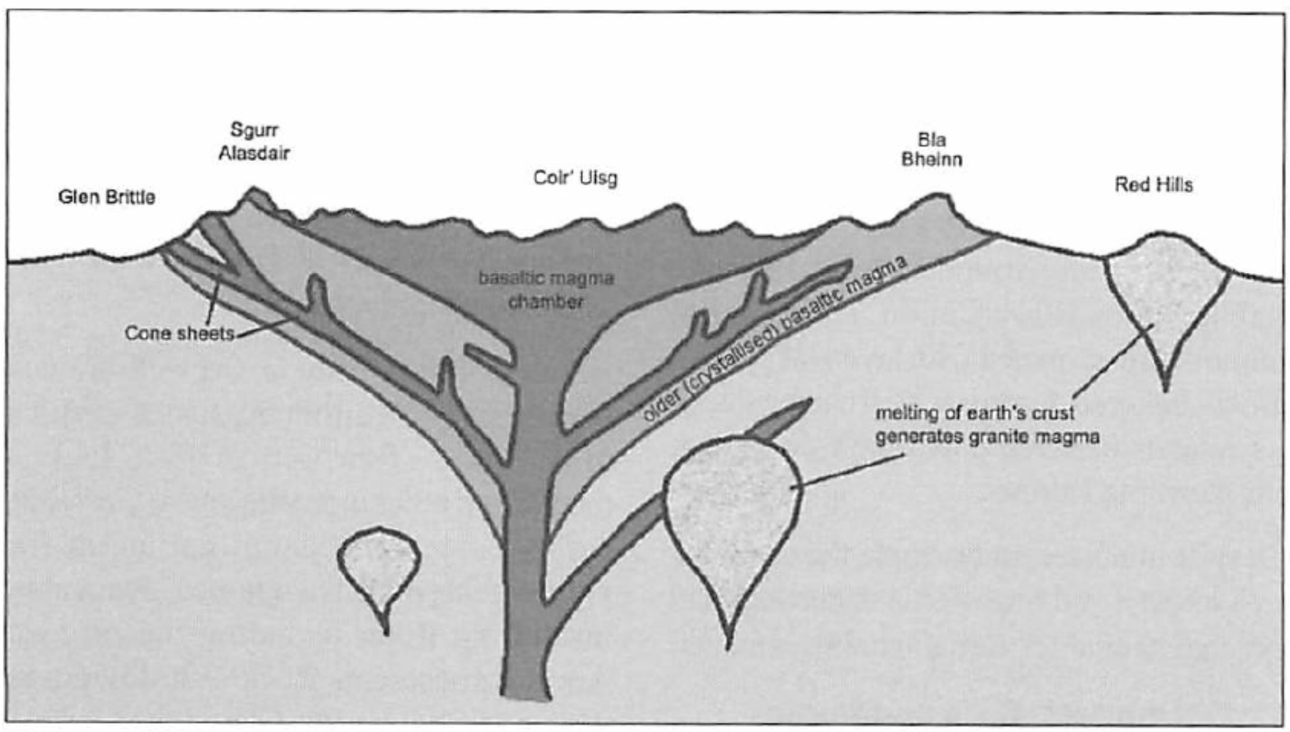



*Figure 4. Structure of the intrusive complex beneath the Cuillin, showing intrusion of basaltic magma from beneath the crust and formation of granite plutons by crustal melting (after Stephenson & Merrit, 1993)*

Needless to say, the final form of the Cuillin owes much to the work of ice and frost. The Cuillin Hills is the classic area in Britain for erosional landforms associated with mountain glaciers. It includes unquestionably the finest assemblage of arêtes, corries, rock steps, ice-moulded topography and roches moutonnees, together with the `textbook' glacial trough and basin occupied by Loch Coruisk. Periglacial rock weathering forms and a range of ice-depositional features including classic end and lateral moraines, boulder moraines and hummocky moraines complete the key interest of one of the most outstanding mountain areas in Britain for glacial geomorphology. The ultimate veneer has resulted from frost-shattering on the oversteepened cliffs and pinnacles, so that the main ridge is everywhere draped with scree slopes. The most spectacular of these is the Great Stone Shoot (Figure 5), which plummets for over 450m from Alasdair's summit to the tiny corrie lake of Coire Lagan. The granites of the Red Hills have weathered to a paler colour and smoother, more rounded form than the gabbro of the Black Cuillin. Their conical summits are crowned with layers of pinkish frost-shattered detritus which can be traced as runnels of scree down their sweeping, uninterrupted slopes.

Despite much recent research, the Complex as a whole is still imperfectly understood and much potential for further studies remains.

## Habitats, flora and fauna

The gabbro of the main block of the Cuillin contrasts with the limestone areas of Bla Bheinn and the granite of Marsco.

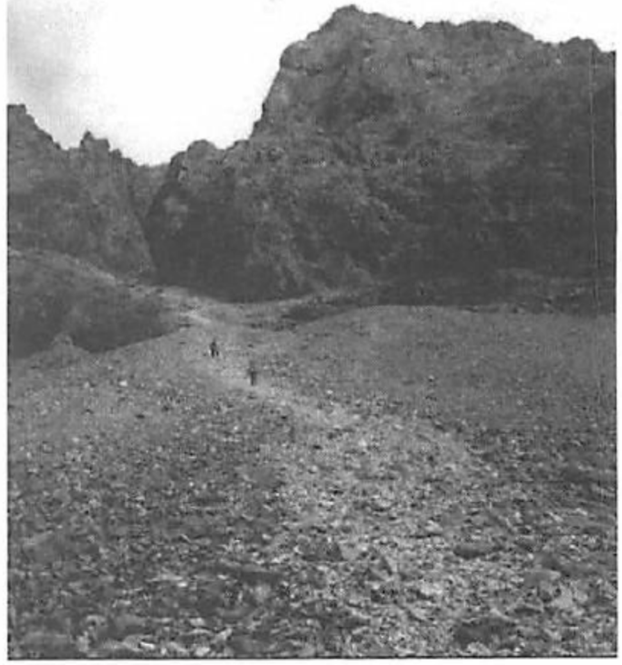


*Figure 5. The Great Stone Shoot – scree running from Sgurr Alasdair*

Bla Bheinn has a remarkably rich flora, both vascular plants and bryophytes, including several national rarities. Fine examples of undisturbed peatlands are found in Glen Sligachan. The site as a whole contains an exceptional variety of habitats, including the coastal woods at Ulfhart with their interesting lepidopteran fauna.

Above c. 400 m altitude, the well-drained slopes support either Agrostis-Festuca grasslands, often with Alpine Lady's mantle and other montane herbs. Crevices, earthy screes and damp gullies in the higher gabbro cliffs support a sparse but interesting flora, including the rarities: Arctic Mouse-ear, Rock Whitlowgrass, Alpine Meadow-grass, Glaucous Meadow-grass, Alpine Saxifrage and Alpine Rock-cress in its only known British locality. Alpine Hair-grass grows on the summits.

The sparse vegetational cover of the gabbro cliffs contrasts sharply with the luxuriant vegetation on the Jurassic limestone cliffs in Coire Uaigneich. The north-west facing cliffs support rich, ungrazed, tall-herb communities with numerous rare mosses and liverworts. The lower slopes are covered by a range of bog and fen communities.

On north-facing ravine walls, especially by the upper waterfalls, there are good heather communities. Two blocks of semi-natural woodland occur on steep south-facing coastal slopes and cliffs of two contrasting geological formations between An Leac and Ulfhart Point. They support good examples of Birch-Hazel and Birch-Oak stands on Olivine basalt and Torridonian sandstone respectively. The interesting butterfly and moth fauna includes the woodland species, Speckled Wood and Scotch Argus, both nearing the northern limits of their distribution.

Glen Sligachan is an impressive example of peatland little disturbed by man. Along the broad valley bottom, running north to south between the Cuillin and Marsco, are a series of flushes, fens, flood-plain mires and blanket bog. Sedge species are abundant, including the uncommon Slender Sedge.

The Cuillin supports a high density of breeding birds of prey, including Golden Eagles. A rare Carabid beetle occurs on the mountain tops towards the northern end of the site. Its distribution in Britain is described as rare or very local.

## Further reading


Bell, B.R. & Joley, D.W., 1997. Application of palynological data to the chronology of Palaeogene lava fields of the British Province: implications for magnetic stratigraphy. *Journal of the Geological Society, London*, vol. 154, 701-708.

Bell, B. R. & Williamson, I. T., 2002. *Tertiary igneous activity*. pp 371-407 in Trewin, N. (editor) *The Geology of Scotland*, The Geological Society, London.

Butler, R.W.H. & Hutton, D.H.W., 1994. Basin structure and Tertiary magmatism on Skye, NW Scotland. *Journal of the Geological Society, London*, vol. 151, 931-944.

Emeleus, C.H. & Gyopari, M.C. 1992. *British Tertiary Volcanic Province, Geological Conservation Review, Series No. 4*. Joint Nature Conservation Committee, Peterborough.

Harker, A., 1941. *The West Highlands and the Hebrides*. Cambridge University Press.

Stephenson, D. & Merritt, J., 1993. *Skye: a landscape fashioned by geology*. produced by Scottish Natural Heritage & British Geological Survey.


For a guide to the approaches of the Cuillin go to:
cgi.mountaineer.plus.com/scotland-mountains/skye/

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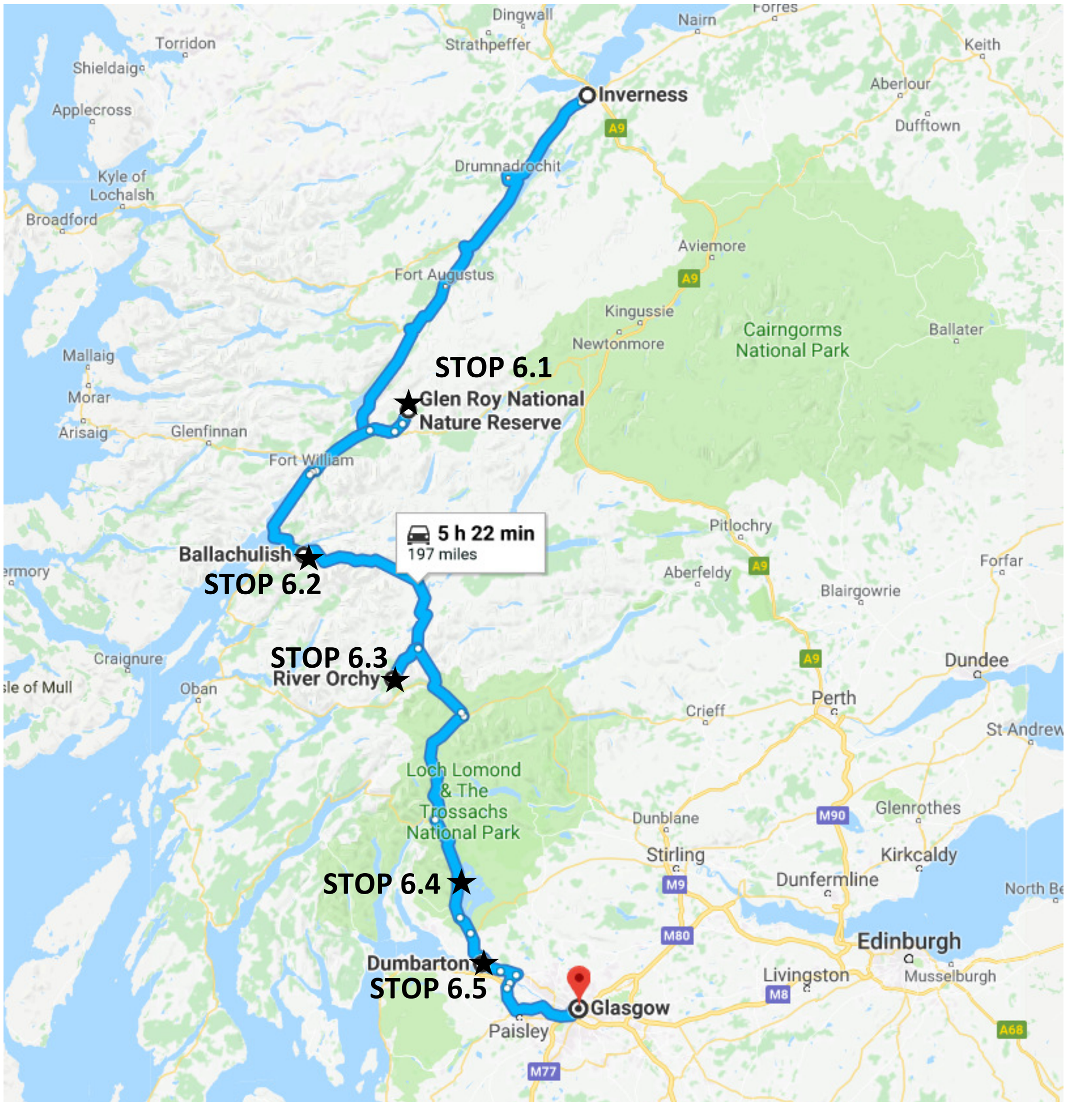
**Day 6: Friday, March 9th, 2018 – Glen Roy, Glencoe, Loch Lomond, and Glasgow**



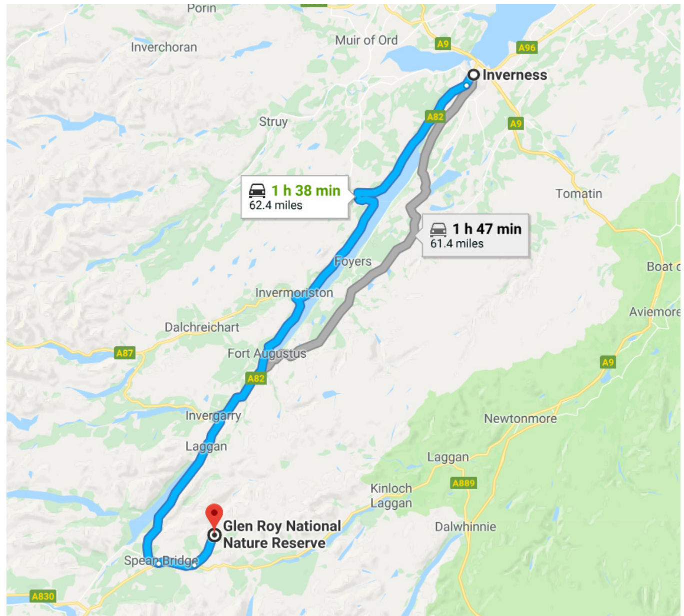

**7:00 AM:** Breakfast
**8:00 AM:** Pack up and depart from Inverness
**10:00 AM:** Glen Roy National Nature Reserve and the Darwin's Parallel Roads
**12:00 PM:** Lunch in Glen Roy
**1:00 PM:** Glencoe and the Ballachulish Igneous Complex
- Quarry Centre Ballachulish Visitor Centre
http://discoverglencoe.scot/listing/the-quarry-centre/

**2:30 PM:** River Orchy – Various fold structure associated with the Udlaidh Syncline
**3:30 PM:** Loch Lomond – Tay Nappe of the Southern Highland Complex
**4:30 PM:** Dumbarton Rock – Basaltic Intrusions
**5:30 PM:** Get to the Hostel in Glasgow
Euro Hostel Glasgow, 318 Clyde Street, Glasgow, G1 4NR
Telephone: +44 141 222 2828
http://www.eurohostels.co.uk/glasgow/

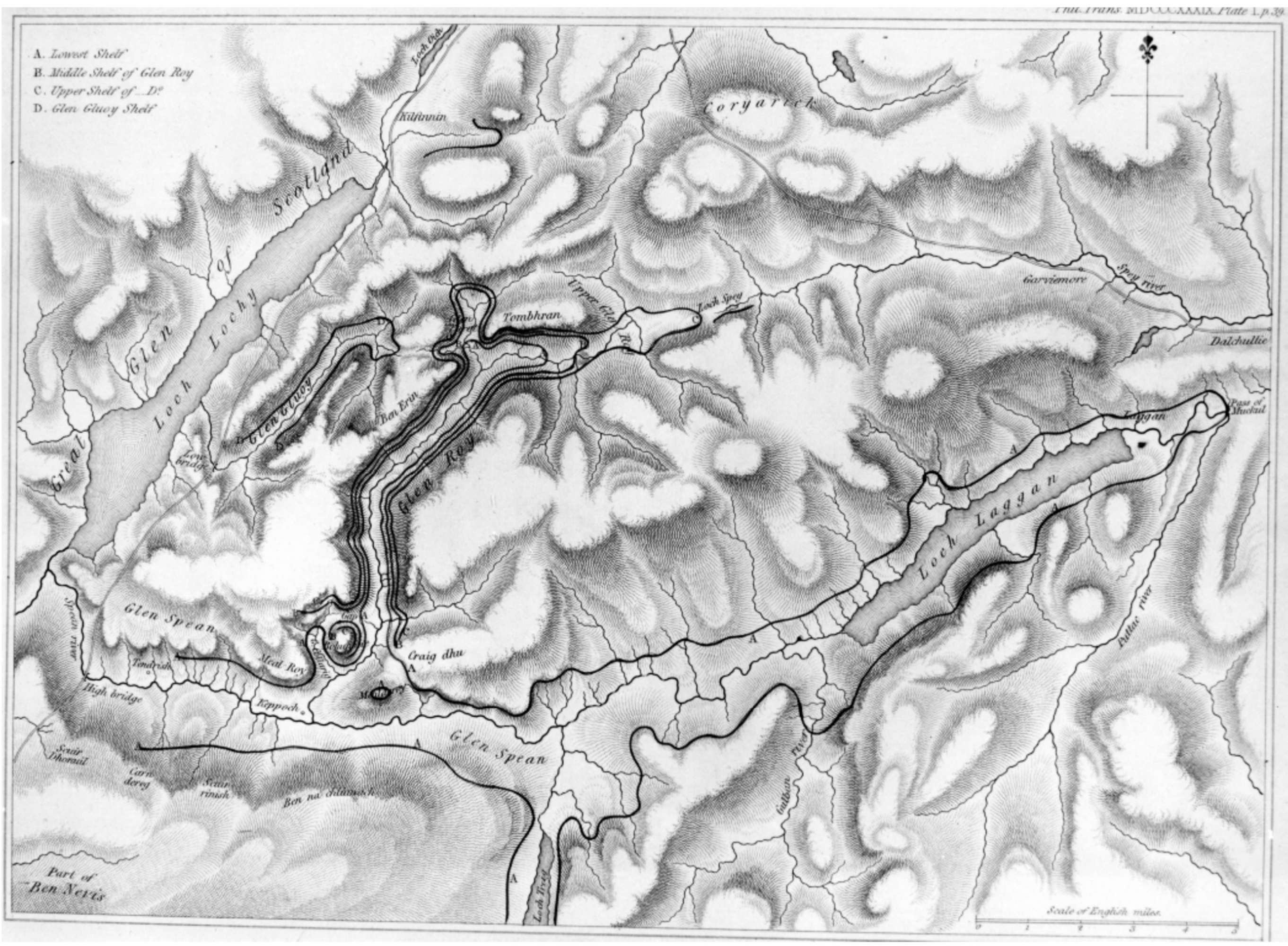
**STOP 6.1:** *Glen Roy and Darwin's Parallel Roads*

*The following is from:*

Rudwick, M. and Palmer, A., 2009, The Parallel Roads of Glen Roy: In the footsteps of Charles Darwin – A Field Guide. Geological Society of London, History of Geology Group, Field Trip Guide, 40 pgs.




"Based on the Guide prepared for the field trip in Lochaber (Scotland), 26-29 June 2009, led by Martin Rudwick (University of Cambridge) and Adrian Palmer (Royal Holloway, University of London), to mark the bicentenary of the birth of Charles Darwin; and revised to make it usable by anyone wishing to follow our itinerary on their own."



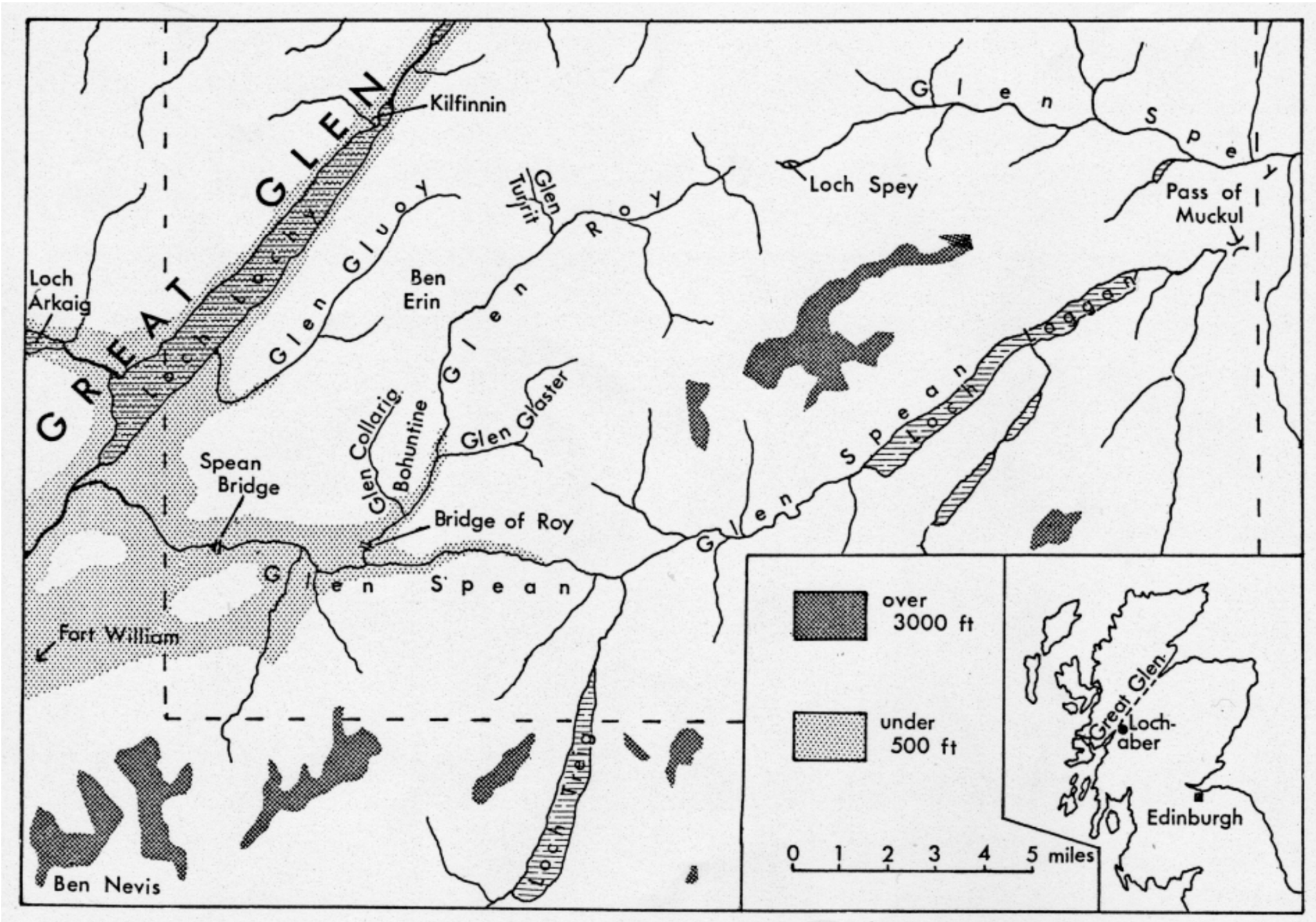

**Darwin's paper 1839:** map of the "Roads" in Lochaber
(the Roads were largely copied from Lauder's paper [1821] but on a better base map).

# INTRODUCTION

> "I must premise once for all, that this minuteness of description, however superfluous it may at first sight appear, is absolutely required, as the circumstances thus dwelt on will be of essential use in investigating the cause of the appearances under discussion. It is by an attention to circumstances which at first glance appear trivial, that abstruse truths are often discovered."
>
> John MacCulloch, "Parallel Roads", 1817


**Darwin's paper 1839:** View up Glen Roy from above "Viewpoint" with the three horizontal "Parallel Roads", drawn from the lowest Road *R3* (note its alignment on both sides of the valley).

Darwin returned from the *Beagle* voyage identifying himself *as a geologist*, and was accepted as such by the leaders of the Geological Society in London. His papers to the Society interpreted what he had seen in terms of a global tectonic theory modelled on that of his older mentor Charles Lyell. The most substantial piece of *fieldwork* that Darwin undertook after his return was designed to strengthen this theory by harnessing in its support a well-known but extremely puzzling geological feature, the "Parallel Roads" in Glen Roy and adjacent valleys in the Lochaber region of the Scottish Highlands. This fieldwork (1838) led to Darwin's first substantial published scientific paper (1839), which helped earn him his FRS. But soon afterwards Louis Agassiz proposed an alternative explanation of the "Roads", in terms of vanished glaciers, which implied that Darwin's might be radically mistaken. Yet Darwin clung to his interpretation for about twenty years, in the face of mounting evidence in favour of the alternative, and only abandoned it with great reluctance, eventually conceding that it had been "a great failure" and "one long gigantic blunder". Yet even the "blunder" of an outstanding scientist can throw instructive light on the relation between observation and interpretation, and also perhaps – in Darwin's case – between his public theorising about global tectonics and his concurrent private theorising about speciation.

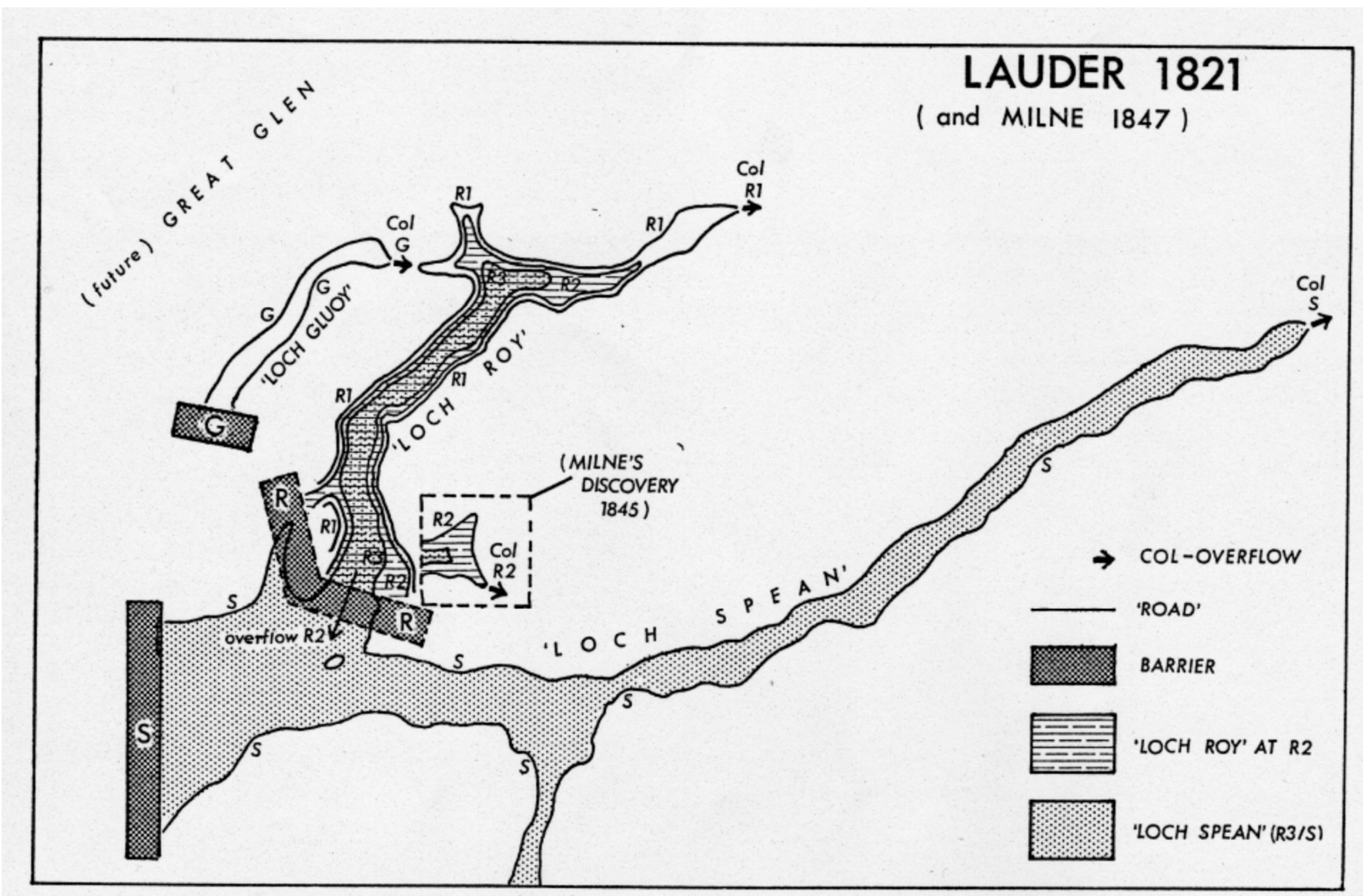



**Outline topographical map of Lochaber** (from Rudwick 1974/2005)
with 19th-century anglicised place names
[the smaller rectangle defines the area of the interpretative maps, below].

## A BRIEF HISTORY OF THE PROBLEM

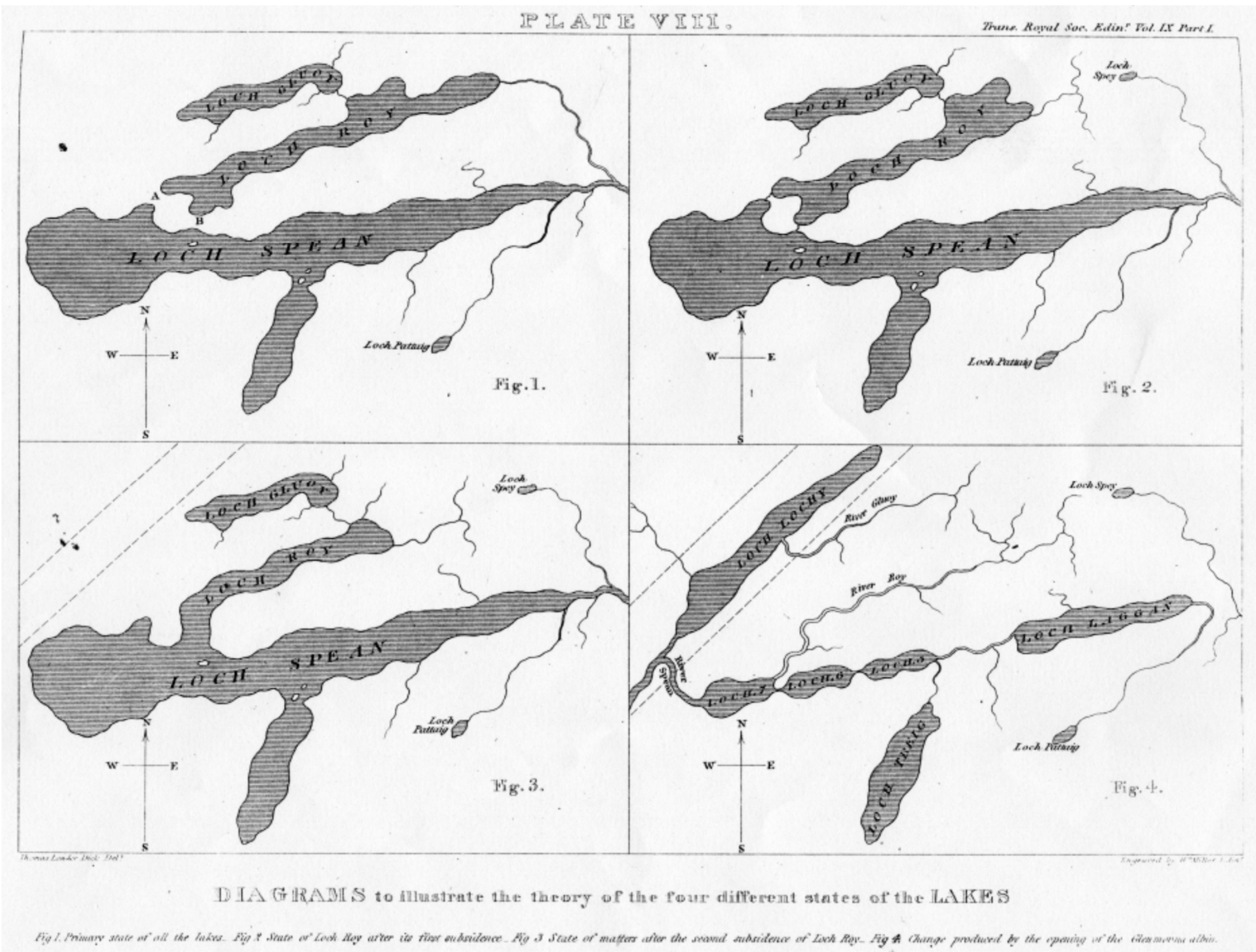
In the 18th century the "Parallel Roads of Glen Roy" became a celebrated feature of the remote Lochaber region; they were called "Roads" because they were initially thought to be ancient human constructions; but by the early 19th century most visitors agreed that they must be natural in origin. In Glen Roy itself there are three narrow horizontal terraces, high up on both steep sides of the valley; the lowest terrace extends out into Glen Spean and up into Glen Treig. There is also one terrace high up in Glen Gloy to the west of Glen Roy. **MacCULLOCH** and **LAUDER** visited Lochaber independently around the same time (1815-17), surveyed the Roads in detail, and came to similar conclusions. Both interpreted the Roads as **lake beaches** formed at some remote time when Glen Roy and some adjacent valleys were filled with freshwater lakes at three or four successively lower levels. But this generated the problem of explaining the absence of any obvious trace of the barriers that must have impounded these lakes, most probably situated where the Roads fade away at the mouths of the valleys. **MacCulloch** considered briefly the alternative possibility that the Roads were sea beaches, dating from a time of much higher sea level; but he rejected it because the Roads were confined to these specific valleys, and because there was no trace of marine debris such as sea shells anywhere on the terraces.

**Lauder** proposed an interpretation similar to MacCulloch's, but improved it on three important points, thanks to more accurate levelling by his surveyor. This survey showed, first, that the one and only definite Road in Glen Gloy ("Road G" in my nomenclature) is exactly level with the pass or col ("Col G") at its head; this could therefore have been the outlet of a putative "Loch Gloy", overflowing into the adjacent Glen Roy, where the highest of three Roads ("Road R1") is slightly but distinctly lower (rather than being at the same level as Road G, as MacCulloch thought). Second, that this Road R1 in turn is on a level with the pass or col ("Col R1") at the head of Glen Roy, which therefore could have been an outlet for a former "Loch Roy", overflowing into Glen Spey to the east (MacCulloch had thought it was higher than the col). Third, that the lowest of the three Roads in Glen Roy ("Road R3") - which unlike the others extends out into the much larger Glen Spean (as "Road S") - is on a level with the Pass of Muckul ("Col S") at the head of that valley, which could have been the overflow of a large "Loch Spean". This left the middle Road ("R2") of the three in Glen Roy as an anomaly, since there seemed to be no col that could have acted as an overflow while "Loch Roy" was at that intermediate level. Lauder therefore had to infer that its overflow at that stage was across the vanished barrier at the mouth of Glen Roy, although he (like MacCulloch) inferred that this must have been composed of loose gravelly material subsequently washed away, and was unlikely to have remained at exactly the same level long enough for a terrace to be formed as in the other cases.



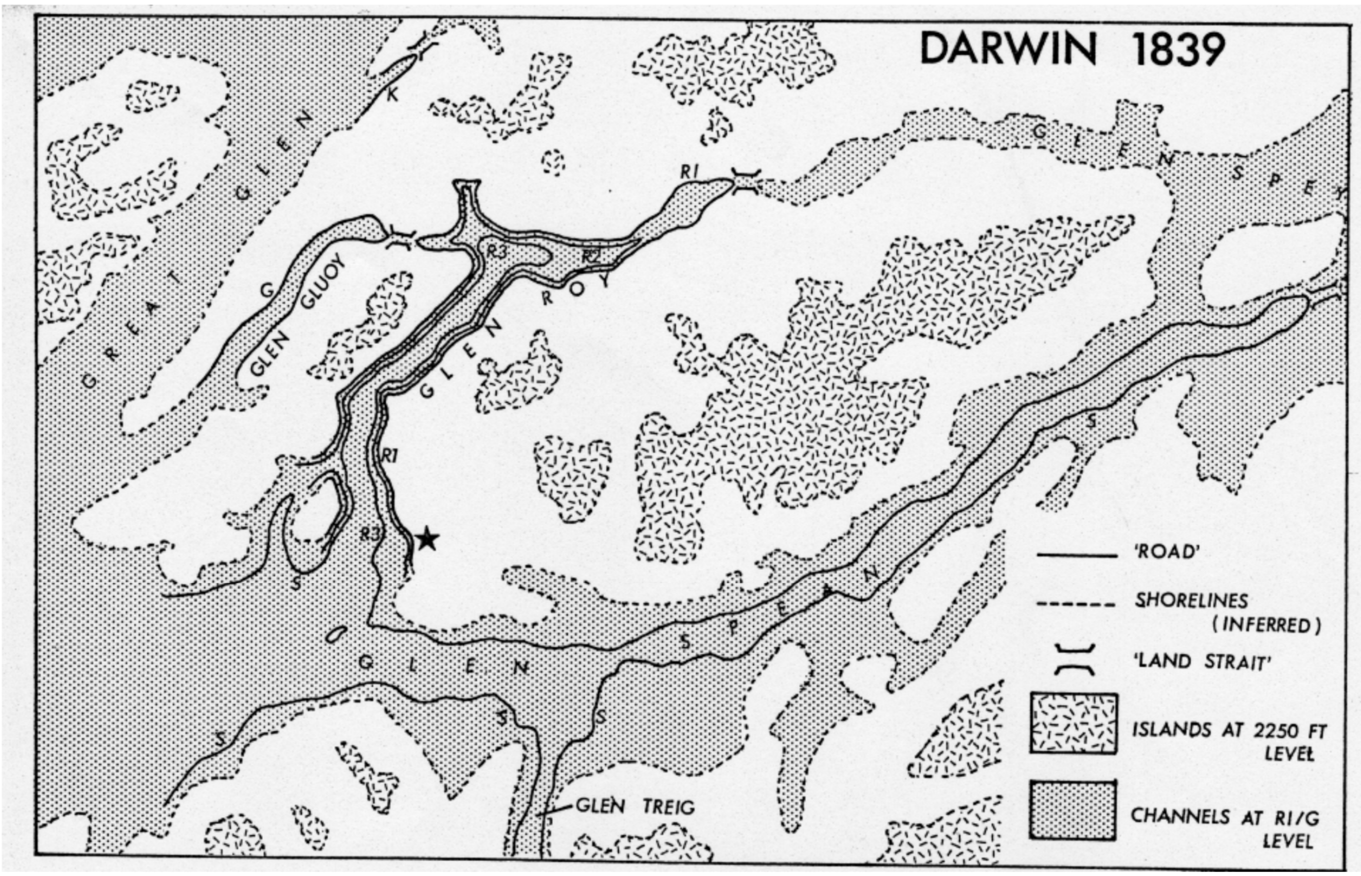

**Map to illustrate Lauder's lake theory** (from Rudwick 1974/2005)
(and also its improvement by Milne in 1847).

MacCulloch's and Lauder's **LAKE THEORY** was accepted by most other geologists at the time, and in subsequent years, as the best explanation available, despite the unresolved puzzle of the vanished lake barriers. Neither author was cramped for geological time: the whole sequence of lakes in Lochaber was tacitly assumed to have been extremely remote and probably pre-human, although very recent in terms of total Earth-history. And both authors were as actualistic ("the present is the key to the past") in their reasoning as they could be, citing analogous cases of former beaches above various modern lakes. Lauder invoked a "catastrophe" only where he thought there was no alternative: he explained the final disappearance of the huge putative barrier at the mouth of Glen Spean as possibly the result of a sudden opening-up of the Great Glen beyond it (to the north-west).



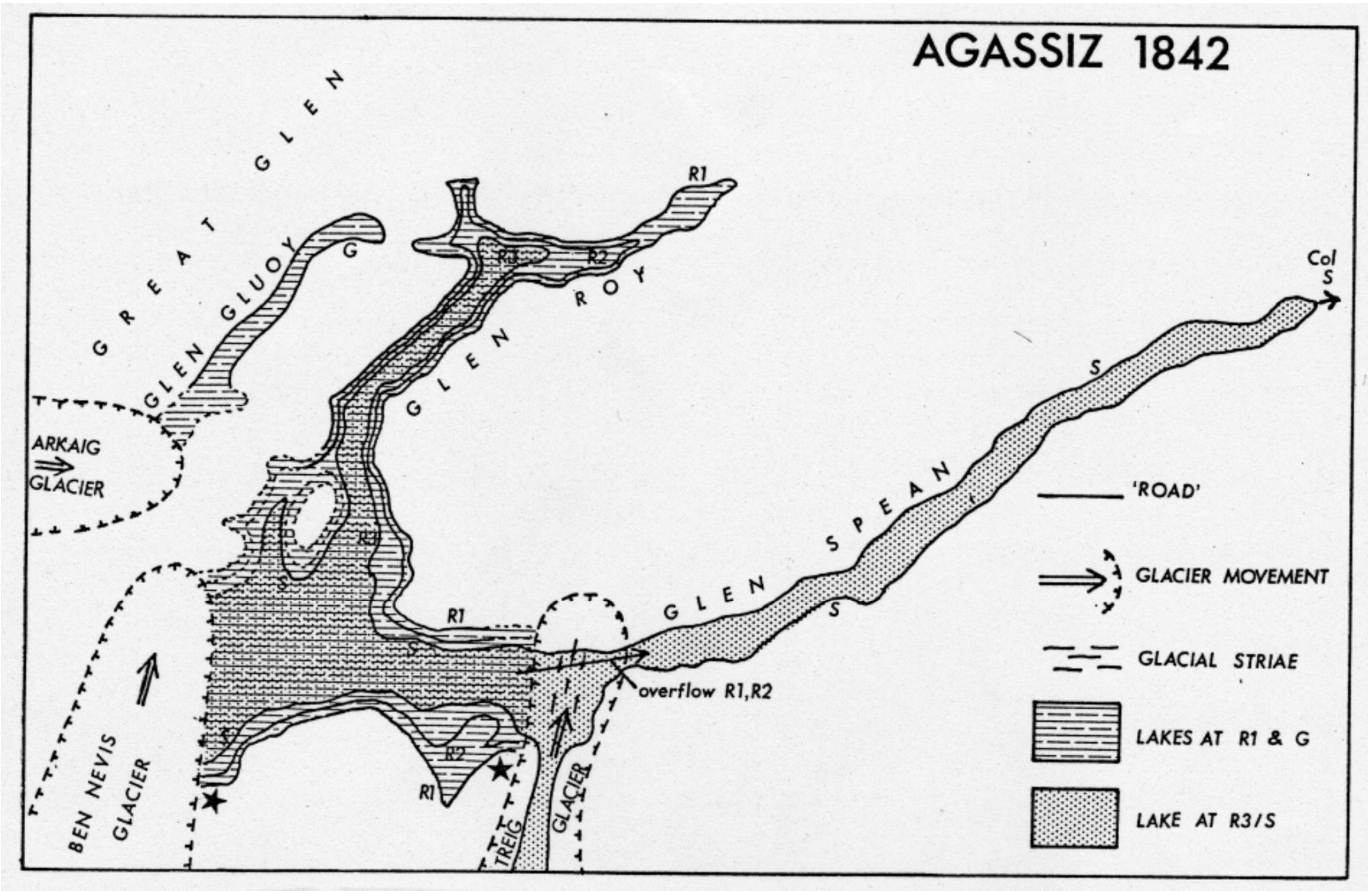

**Lauder's paper 1821:** Reconstructions of lakes at four successive periods:
**1** , at R1 level; **2**, at R2 level; **3,** at R3/S level;
**4**, after "catastrophic" opening of Great Glen
(at which point three small lakes remained in Glen Spean, since filled in).

Two decades later, in 1838, **DARWIN** interrupted the most creative phase of his private theorising about speciation in order to visit Lochaber, because he regarded its Roads as valuable potential evidence for his global tectonic theory - inspired by Lyell's - of crustal plates slowly oscillating up and down in a perpetually balanced steady state (which in turn was an important substrate for Darwin's theorising at this time about speciation). With the terraces he had seen at Coquimbo in Chile as a relevant analogue, he hoped to prove that Scotland was part of a slowly but intermittently *rising* crustal plate like South America (his famous explanation of Indo-Pacific coral reefs and atolls made them corresponding indicators of slowly *subsiding* plates). This entailed adopting the **MARINE THEORY** that MacCulloch had considered but rejected. Darwin's manuscript agenda, written after he tudied MacCulloch's and Lauder's papers but before his own visit to Lochaber, proves that he intended to look specifically for evidence that the Roads were indeed **sea beaches** and that their localised distribution could be "explained away" in terms of differential preservation. In the field, he duly convinced himself, although he failed to find any marine debris at all, and had to re-interpret Lauder's overflow cols as "*land-straits*" and explain them away as mere "coincidences" of level. He wrote up his work as his first major scientific paper, and gave it – such was its importance to him – not to the Geological but to the Royal Society (1839).




**Map to illustrate Darwin's marine theory** (from Rudwick 1974/2005)
This illustrates the former topography of islands, channels and fiords that he reconstructed
(1) for an early phase in the uplift of the crust, when icebergs drifting among scattered islands might have deposited the highest of the erratic blocks now found on some of the hills; and
(2) for a later phase when the sea was confined to a network of channels which, he thought, would have been like the Beagle Channel and others around Tierra del Fuego.

The following year **AGASSIZ**, while visiting Britain primarily for his research on fossil fish, expounded his sensational "Ice Age" theory in London and Glasgow (in outline it was already well known to British geologists, including Darwin). He argued that in the final waning phase of this geologically recent "Snowball-Earth" episode there would have been extensive valley glaciers in many upland regions. Agassiz and Buckland (the latter a new convert to Agassiz's Ice Age theory) then toured the Highlands and duly found widespread glacial traces (scratched bedrock [*striae*], moraines, erratic blocks etc). A brief visit to Lochaber convinced them that the Roads were traces of successive levels of a **glacial lake** impounded by glaciers, like ones that had been, or would be, produced by analogous extensions of present Alpine glaciers (the actualistic method again, as usual). This **GLACIAL THEORY** of the Roads purported to solve both the puzzle of the vanished barriers on the (non-glacial) lake theory – they had left no trace because they had simply melted away - and also the curiously limited extent of the Roads, which was such a puzzle on the marine theory.

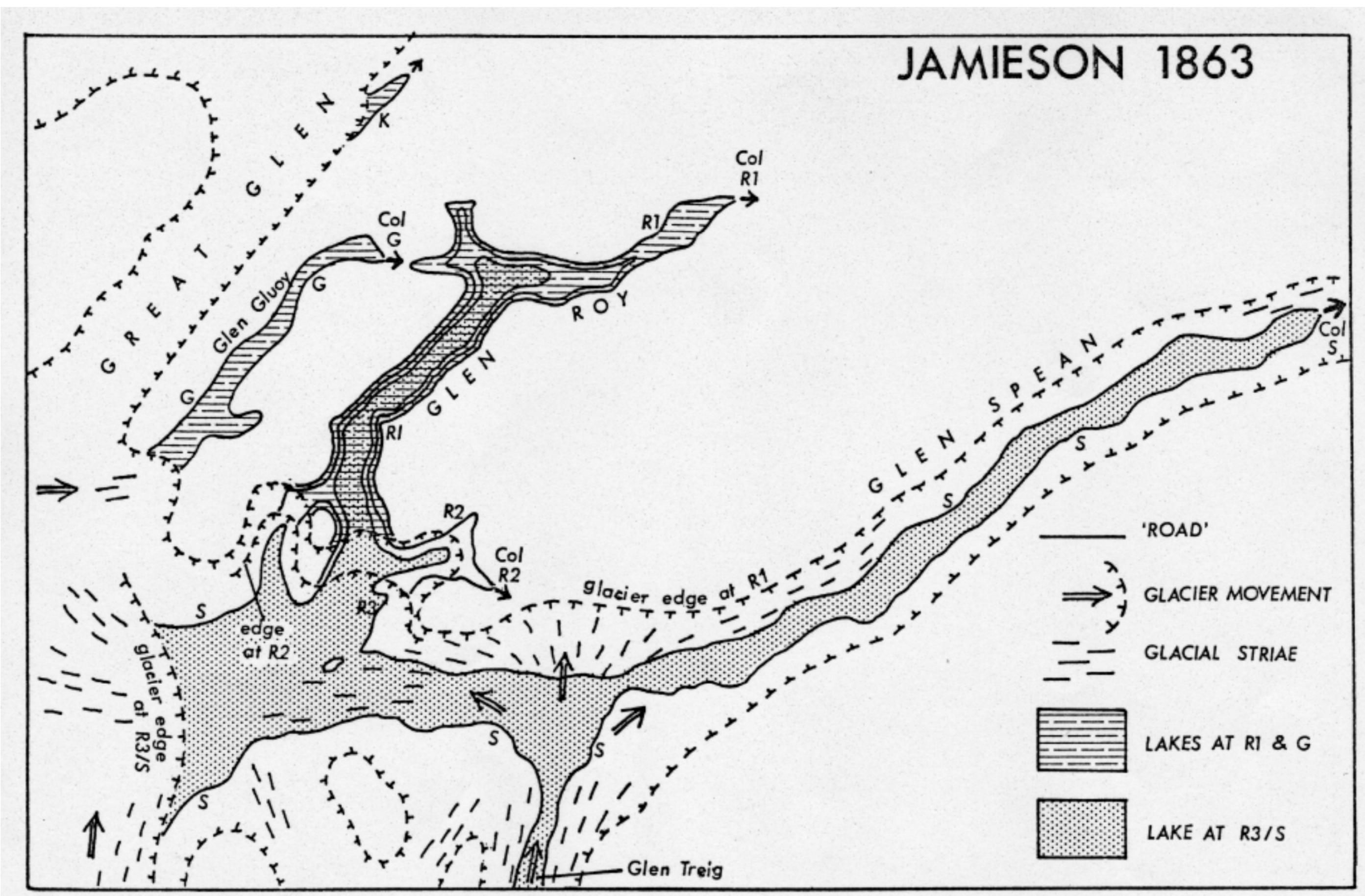



**Map to illustrate Agassiz's glacial theory** (from Rudwick 1974/2005)
This reconstruction required that the upper Roads in Glen Roy
should extend on to the south side of Glen Spean (between the asterisks),
where no one else had reported seeing them (see, above, the map for Lauder's interpretation).

But Agassiz's full-blown (Snowball-Earth) Ice Age theory had been rejected outright – and with good reason - by most geologists other than Buckland, and even its more limited version (of vanished upland valley glaciers) was therefore treated with caution. In Lochaber, specifically, Agassiz's reconstruction of two glaciers acting as lake dams implied a distribution of Roads that did not match what others had seen on the spot. So the (non glacial) lake theory, and Darwin's marine theory, each continued to enjoy some support among geologists; both were seen to have defects, but they seemed rather evenly matched.

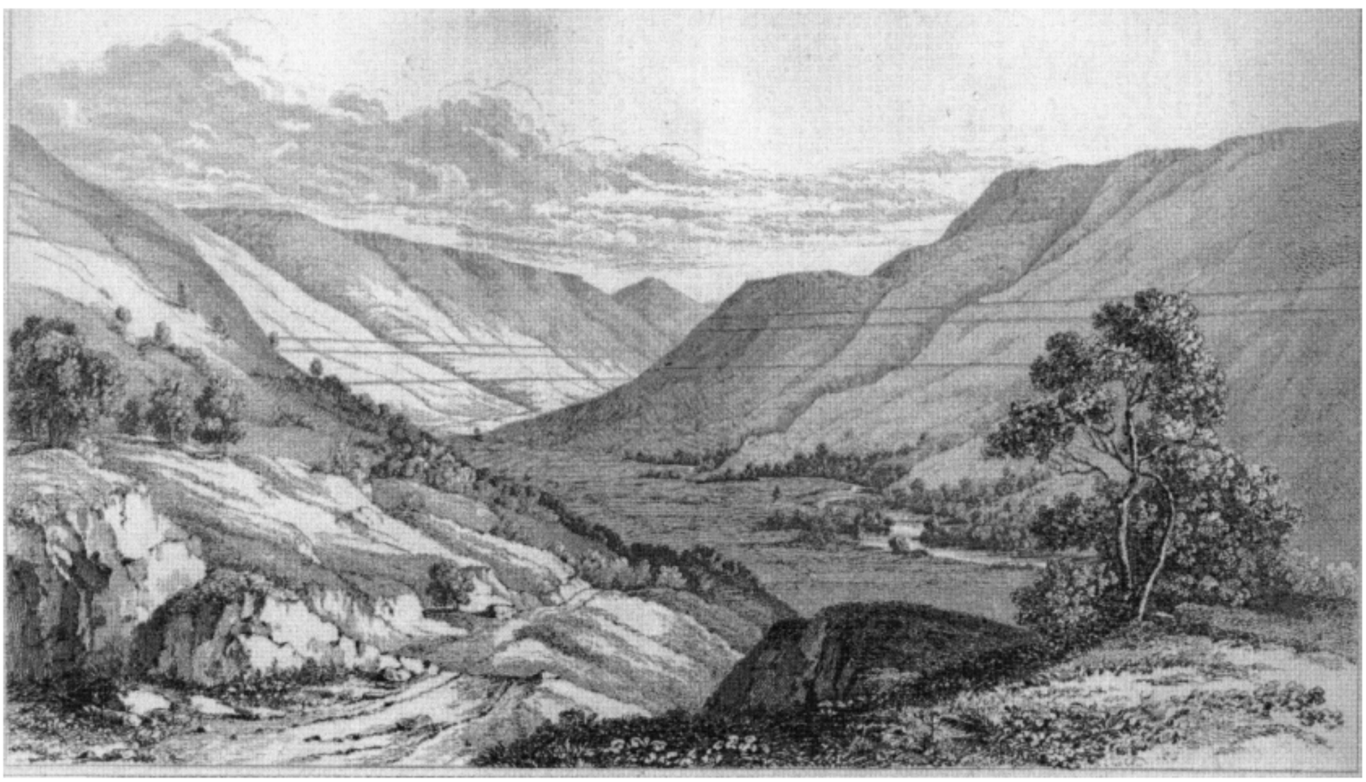
A few years later, in 1845, **MILNE** visited Lochaber, convinced beforehand that Darwin's marine theory was correct and the (non-glacial) lake theory untenable; he was also unconvinced by the glacial interpretation, arguing that some of Agassiz's putative moraines were in fact relics of former barriers of loose gravelly material. However, in the field Milne changed his mind, and then (1847) published an improved version of Lauder's lake theory (see the map, above, for Lauder's theory). Most importantly, he resolved its major anomaly, by discovering a previously unnoticed pass or col ("Col R2") on the level of Road R2 in Glen Roy, and clear evidence that it had indeed been an overflow from "Loch Roy" into "Loch Spean" at that phase. He also confirmed Lauder's interpretation of the Pass of Muckul (Col S) as the overflow channel from "Loch Spean" into Glen Spey to the east, with evidence that was inexplicable on Darwin's marine theory.

The coup-de-grace for Darwin's theory (and also for that of non-glacial lakes) came a decade and a half later, in 1861, when **JAMIESON** applied to Lochaber the much improved understanding of glacial flow (that ice *en masse* acts as a viscous fluid) that Alpine geologists had meanwhile been developing. He made a new and more thorough survey of the Roads and other features, particularly scratched bedrock surfaces, moraines and erratics, which enabled him to reconstruct former glaciers that could have dammed the vanished "Loch Gloy", "Loch Roy" and "Loch Spean" in a complex sequence of phases that accounted for all classes of evidence: Roads, overflow cols, scratched bedrock, moraines etc (1863). Darwin then abandoned his marine explanation, though with great reluctance. But by this time his species theory had long overtaken his global tectonic theory as the focus of his research, and anyway the former no longer required the biogeographical model that had in part motivated the latter.



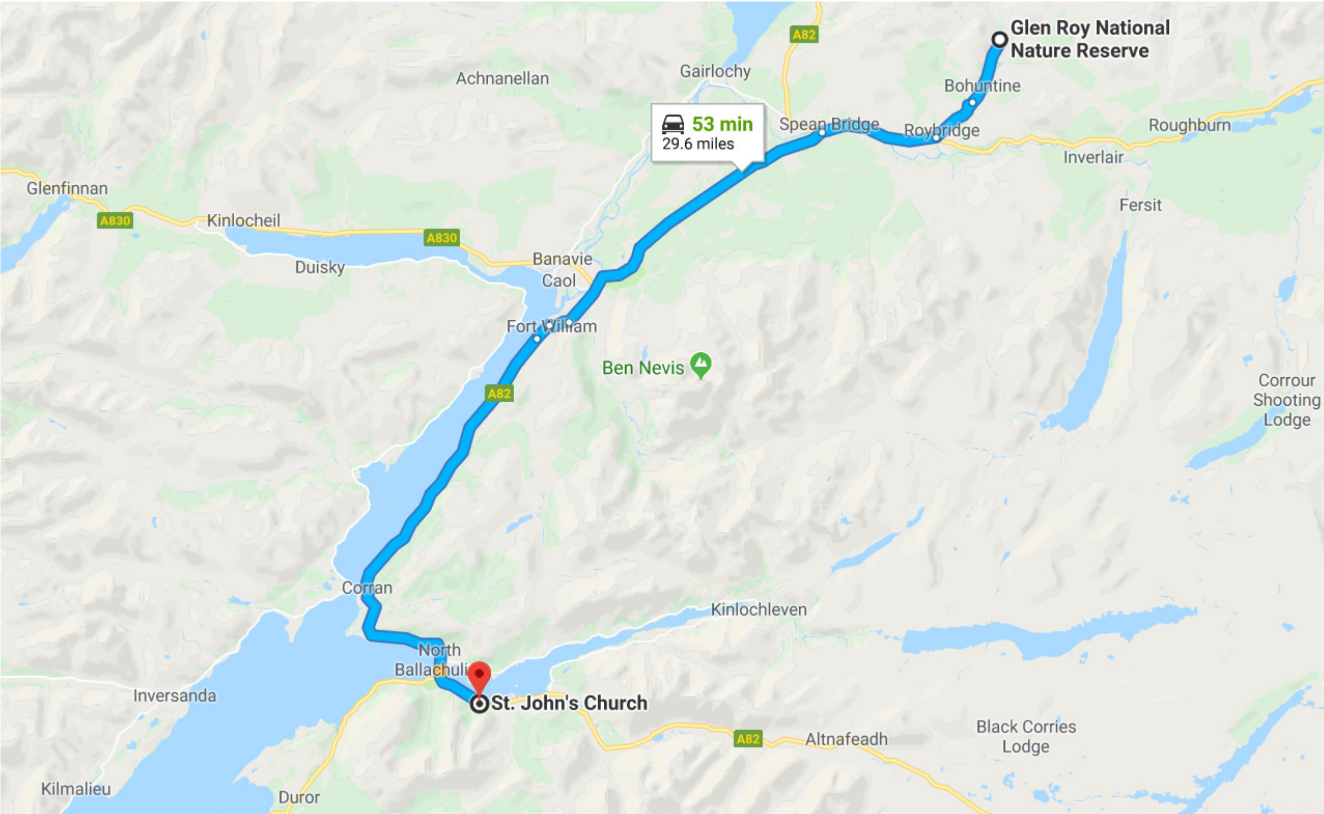

**Map to illustrate Jamieson's improved glacial theory** (from Rudwick 1974/2005).

Subsequent research in Lochaber, in the rest of the 19th century and through the 20th into the 21st, has elaborated Jamieson's sequence, reconstructed it with much greater precision, and set it in a wider context of Pleistocene glaciations, both locally and globally. But this research was, and still is, based on what was so fruitfully observed, sketched, mapped and argued about in the half-century stretching from Jamieson's fieldwork back to Lauder's and MacCulloch's. Darwin was surely too self-critical when in retrospect he condemned his own contribution as “a great failure” and “one long gigantic blunder”. Even if he got his fingers burnt, it was invaluable training in how to observe in the field and how to reason about his observations; and even, perhaps, a useful dry run for *On the Origin of Species.* His error, if it was one, was to have been over-committed to his tectonic theory, and to have rejected the lake theory on inadequate grounds, even before the glacial theory introduced a new range of possibilities into the puzzle. The episode as a whole is a neat illustration of a widespread pattern in scientific argument. Of two incompatible initial alternatives - the lake and marine theories for the Roads – the first was progressively improved by further fieldwork and its anomalies resolved, whereas the second was reduced to explaining *away* its anomalies. In the end, the first was decisively improved and indeed transformed by the introduction of a new explanatory resource (glacial action) unforeseen on either of the earlier theories.



**MacCulloch’s paper 1817:** View up Glen Roy (accurate but for the conventional vertical exaggeration): this drawing was made – judging by the non-alignment of the Roads - from the “Viewpoint” on the flank of Bohuntine hill, *below* the lowest Road *R3.*

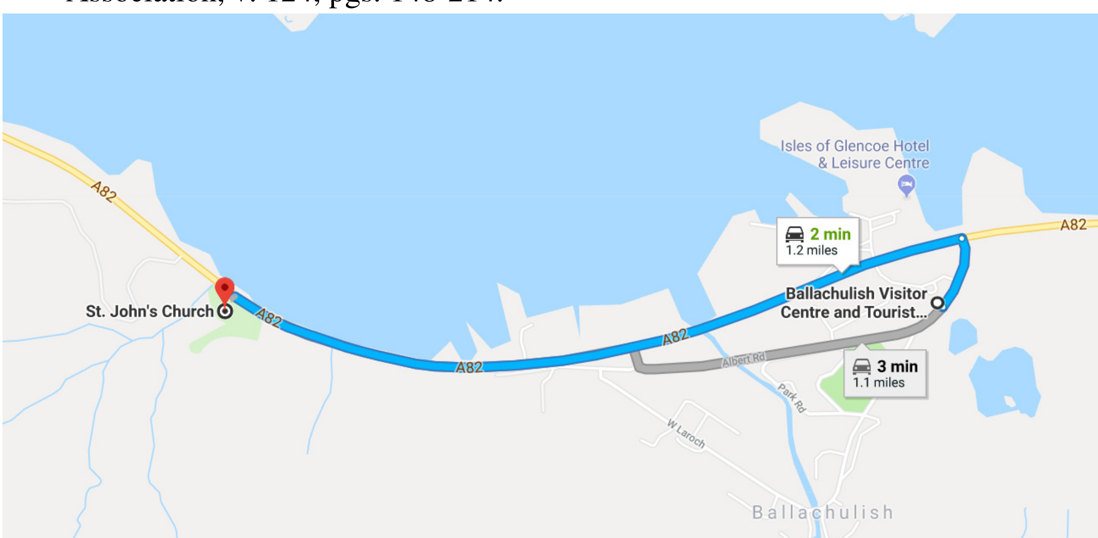
**STOP 6.2:** *Ballachulish and Glencoe*




***STOP 6.2A – St John's Church Ballachulish***

*This stop was taken from:*

Treagus, J.E., Tanner, P.W.G., Thomas, P.R., Scott, R.A., Stephenson, D. 2013, The Dalradian rocks of the central Grampian Highlands of Scotland. Proceedings of the Geologists' Association, v. 124, pgs. 148-214.




***STOP 6.2B –Ballachulish Visitor's Center***

*This stop is supposed to have a really good exhibit about the mining history of the area – this area is particularly known for its slate deposits.*

## STOP 6.2A – St John's Church Ballachulish

**7. St John's Church, Loch Leven (NN 065 587) (J.E. Treagus)**

*7.1. Introduction*

The St John's Church GCR site, on the south shore of Loch Leven 1.5 km south-east of the Ballachulish Bridge, provides a rare section across one of the 'slides' (synmetamorphic low-angled faults) that are a major feature of the Dalradian in the western part of the central Grampian Highlands. An Appin Group succession from the lower part of the Leven Schists up to the base of the Appin Quartzite, is exposed across the core of one of the major recumbent nappes of the area, the Ballachulish Syncline; the Ballachulish Slide occurs on the lower limb of this fold. Here the fold core and the slide are turned into a steeply dipping attitude as a result of later folding.

The exposures were described and the structure was illustrated by Bailey (1960, pp. 58–59, fig. 7G); Roberts (1976) and Roberts and Treagus (1977b) have described the general context.

*7.2. Description*

The exposures on the eastern side of the GCR site provide a section from the Ballachulish Slates through transitional beds (the Appin Transition Formation) at the base of the Appin Quartzite, which lies on what was originally the upper limb of the Ballachulish Syncline. To the west, two tectonic junctions bring in respectively, a thin slice of Ballachulish Limestone and the basal facies of the Leven Schists (Fig. 15). The former lies in the core of the syncline; the latter lies on the original lower limb. The bedding and a penetrative schistosity dominantly dip steeply to the north-west, an attitude acquired during later folding. The section is described from south-east to north-west from the shore opposite St John's church.

A group of exposures on the first peninsula on the south-east side of the GCR site (Fig. 15, locality A; NN 0669 5869) expose phyllitic graphitic pelites with thin semipelite beds, which are attributed to the upper part of the Ballachulish Slate Formation. Thin beds of gritty quartzite, typical of the transition into the Appin Quartzite Formation, occur at the north-western end of this peninsula. Strongly deformed ripple-drift lamination can be discerned, but way-up is not easily determined. The bedding, together with the penetrative schistosity, strike north-east and dip steeply north-westwards at 80–85°; rarely, the two planar surfaces can be seen at a narrow angle to one another and to be axial planar to tight folds plunging steeply to the south-west. A strongly developed stretching lineation (pyrite blebs and mica) and possibly the intersection lineation pitch down the dip of the schistosity. The schistosity is folded by minor tight folds, which plunge subvertically and dominantly have a 'Z' geometry and an axial-planar crenulation cleavage.

After a gap of some 50 m, the rocks at the south-eastern end of the second peninsula (Fig. 15, locality B; NN 0665 5875) are black phyllitic pelites, with a more variable strike than in the previously described exposures. They become more-dominated by beds of gritty quartzite, up to 70 cm thick, towards the north-west. Here too, the penetrative schistosity is very close to the bedding and their cross-cutting relationships and the direction of their intersection are difficult to determine. The outcrop of these transitional beds ends at a NE-trending, 4 m-thick microdiorite dyke. Between this dyke and a second 5 m-thick dyke, occurs a 10 m-thick unit of yellow-weathered, grey metacarbonate rock, which is interbanded with millimetre- to centimetre-thick beds of dark semipelite, a lithological association typical of the Ballachulish Limestone Formation. These NE-striking beds are locally strongly folded by steeply plunging minor folds exhibiting both 'S' and 'Z' geometries. A critical locality (NN 0663 5882) occurs at the junction of the metalimestone with the western dyke where, over a distance of about 1 m, a few centimetres of platy quartzose schist are seen (Fig. 16). This schist is interpreted as a slither of the basal facies of the Leven Schists, which crop out over the remainder of the peninsula to the west of the dyke. The Leven Schists here consist of quartz-rich psammite interbedded on a centimetre scale with ribs of semipelite; no way-up criteria have been established. One well-exposed minor fold has a plunge of 40° to the north-east and an 'S' geometry, but otherwise there are no well-developed minor structures.

## 7.3. Interpretation

According to Bailey (1960, pp. 55–59) the succession of Ballachulish Slates and the Appin Transition Formation, described above, is corrugated by intermediate-scale folds subsidiary to the Ballachulish Syncline (an F1 fold in modern nomenclature). The core of this syncline lies close to the junction of the transitional beds with the Ballachulish Limestone; the Ballachulish Limestone and Leven Schist exposures to the west belong to the lower limb. The minor folds and cleavage/bedding relationships, seen in the section of Ballachulish Slates and transitional beds, certainly show varying vergence directions, suggesting such intermediate-scale folds of perhaps several tens of metres wavelength. S0/S1 intersections appear to be parallel to the steeply pitching stretching lineation. However, the D1 age of these structures has not been confirmed in thin section in any of the more-recent studies. In fact the existence of the syncline has not been confirmed in current studies, either from minor folds and cleavage/bedding relationships, or from sedimentary way-up structures, (although the synformal structure is clear from the regional stratigraphical context (Fig. 15).

According to Bailey (1960) the Ballachulish Syncline, which was originally recumbent, has been rotated into its present steep, NW-dipping, upward- and SE-facing, attitude by the secondary folding of the region. Some of the folds seen in the section described above are associated with a crenulation cleavage, and their south-westerly plunge and 'Z' geometry agree with them being F2 folds on the western limb of the major F2 Stob Ban Synform, similar to those described in the *Tom Meadhoin* and *Doire Ban* GCR site to the north-east.

Although the junction between the Appin Transition Formation and the Ballachulish Limestone to its west is obscured by a microdiorite dyke, the increase in quartzite content towards the junction certainly supports the concept that this junction is a 'slide' (the regional Sgorr a' Choise Slide, a minor branch of the Ballachulish Slide according to Bailey, 1960). The axial trace of the Ballachulish Syncline, according to Bailey, lies within the outcrop of the Ballachulish Limestone. Minor folds in this outcrop show reversals of vergence that would be expected in D1 structures.

The junction to the west between the limestone and the few centimetres of quartzitic Leven Schists, does not exhibit the usual transition from metalimestone into the pelitic top of the Leven Schists and according to Bailey represents the Ballachulish Slide on the western limb of the syncline. The exposure of the 'slide', although only one metre in length, shows a slight discordance of bedding orientation across it, between the limestone and the flaggy schist (Fig. 16). There is no evidence that it is a much later dislocation that post-dates all the folding, but thin sections would

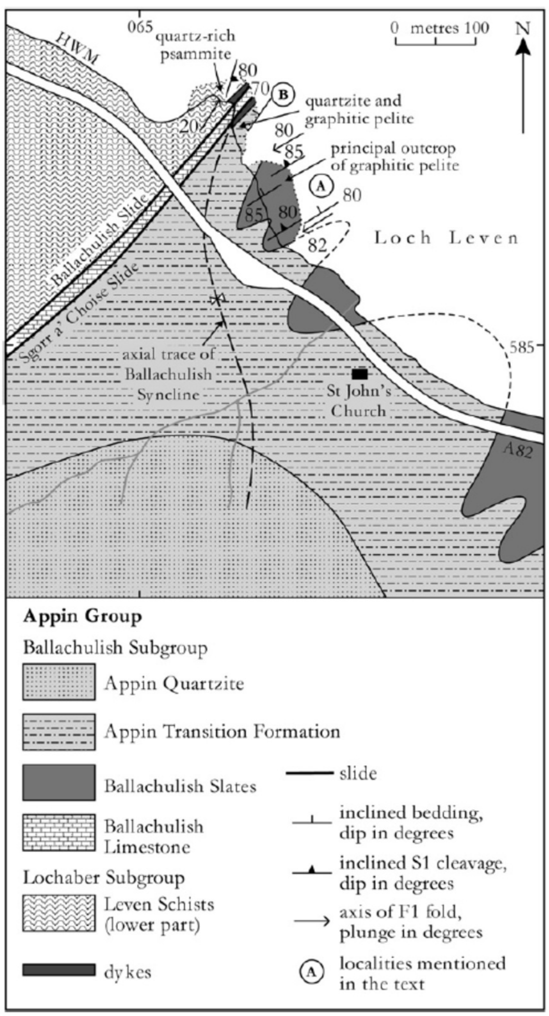



**Fig. 15.** Map of the Loch Leven shore section at St John's church after Bailey (1960).

**Fig. 16.** View looking north-east along the outcrop of the Ballachulish Slide on the shore of Loch Leven, near St John's church. The slide occurs beneath the hammer shaft and can be traced along the black dotted line. To its right is the Ballachulish Limestone; immediately left of the hammer, and for about one metre beyond, are a few centimetres of quartzitic Leven Schists; the remainder of the exposure left of the slide is a NE-trending dyke. Hammer shaft is 30 cm long (photo: J.E. Treagus).

be needed to establish the exact age of movements. On the west side of the western dyke, which obscures the remainder of the outcrop of the 'slide', schistose psammites are typical of the basal part of the Leven Schists; no 'way-up' evidence has been found. Thin-section investigation of the folds and cleavage here would be particularly useful in the delineation of the structural relationships.

Since the Ballachulish Slide occurs on the lower limb of a once recumbent syncline and involves no repetition of strata, Bailey (1960) noted that it would have to have originated as a low-angle normal fault (i.e. a lag) and not as a thrust as would have been associated traditionally with nappe structures. This is a common occurrence in the nappes of the central Grampian Highlands and led Soper and Anderton (1984) to suggest that such 'slides' might have originated as synsedimentary extensional faults. Further research at this locality might help to resolve this debate.

*7.4. Conclusions*

The St John's Church, Loch Leven GCR site contains one of the few exposures across a major dislocation (the Ballachulish Slide) of the type that has disrupted many of the major early folds of the Grampian Fold-belt. These 'slides' are of great interest since the faults might have been initiated at the time of sedimentation and developed further during the onset of folding, when they translated the rocks above for many kilometres. The section is well exposed in coastal outcrops that are much visited by student and professional geologists and would benefit from further research.

### *STOP 6.2B –Ballachulish Visitor's Center*

*This stop is supposed to have a really good exhibit about the mining history of the area – this area is particularly known for its slate deposits.*
*https://www.wildlochaber.com/glencoe/geology/ballachulish-slate-quarry*

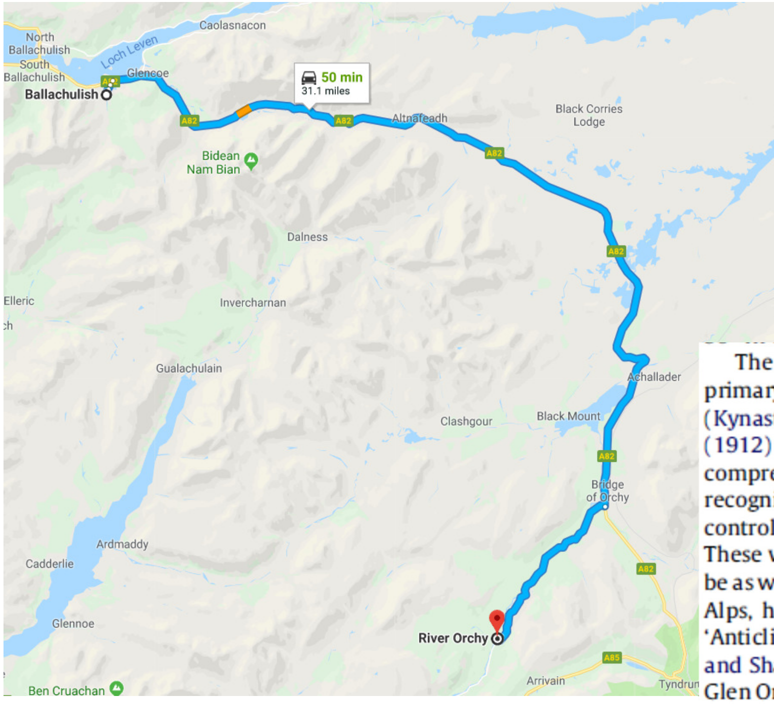

The Ballachulish Slate Quarry cuts into a large deposit of Ballachulish Slate Formation (Graphitic Pelite) formed during the Precambrian about 800 million years ago, following low grade metamorphism of very fine grained mud shales (containing iron pyrite) . The shales are part of the Dalradian Supergroup which have been subjected to subsequent localised intrusions (including basaltic dykes and quartz veins). Iron and sulphur deposits have imparted a bluish hue to the slate.

Ballachulish Slate Quarry was established in 1692 and thrived during the 18th Century producing many of the slate roof tiles for surrounding areas and those destined for Edinburgh and Glasgow. In 1845, the quarry supplied 26 million slates. However, much of the quarried slate was not fit for purpose due to the presence of small quantities of iron pyrite which weathered rapidly in the Scottish climate and increased the porosity of the tiles.

The quarry had a major impact of the lives of the villages, many of whom were employed in the mine. All were affected directly or indirectly by its activities, and the intermittent deafening explosions and the continual drilling, hammering and chiselling by both machine and man adversely affected the village soundscape. There were also two long running dispute over medical care between the management and the work forces, before the quarry eventually closed in 1955.

There is a short and interesting walk around the quarry, supported by interpretation boards on the history of the quarry, the people, the nature and versatility of Ballachulish Slate, as well as an excellent interpretation of the geology of the area (Lochaber Geopark). There are good views of the exposed quarry faces with complex inclined bedding planes revealing the basalt dykes and quartz veins, as well as slaty cleavage planes. There are two lovely deep quarry lochans, with bluish hues (due to the presence of iron and sulphur); the second characterised by steep scree slopes. There is also a short walk from the quarry to a slate arch by the side of the A82. The arch is made entirely of slate and is over 24 m high. The arch was originally one of a pair and was constructed in 1822 to assist the movement of slate from the upper quarry to the shore front using a fly wheel for transport on wagons. The slate arch is designated as a scheduled monument by Historic Scotland.

## **STOP 6.3:** *River Orchy*




*This stop was taken from:*

Treagus, J.E., Tanner, P.W.G., Thomas, P.R., Scott, R.A., Stephenson, D. 2013, The Dalradian rocks of the central Grampian Highlands of Scotland. Proceedings of the Geologists' Association, v. 124, pgs. 148-214.

### 13. River Orchy (NN 242 318–NN 247 331) (P.W.G. Tanner)

#### *13.1. Introduction*

This GCR site is located in the wooded valley of the River Orchy, 10 km north-east of Dalmally. It is notable for the wealth of minor structural features that it displays, most of which can be related to the closure of an early major fold, the F2 Beinn Udlaidh Syncline. This structure folds the important sedimentary transition between the Grampian Group and the younger Appin Group (Fig. 29). The Grampian Group is represented by psammites and semipelites, which can be shown to be overlain stratigraphically by the Beinn Udlaidh Quartzite and the Leven Schists, both of which belong to the lowest part of the Appin Group.

A major feature that makes this section invaluable for teaching and demonstration purposes is that most of the minor structures that can be examined in the field formed during the same phase of deformation, and can be related to a single large F2 fold (Figs. 30 and 31). The structures are particularly well seen, when water levels are low, on the well-scoured rock surfaces in the banks and bed of this spate river. The best localities are in the vicinity of the dramatic waterfall and rocky gorge at Eas Urchaidh (the 'Falls of Orchy', Fig. 29), and along its tributary, the Allt Broileachan. This site is excellent for examining the three-dimensional form of plunging minor folds on the metre scale, and for demonstrating their relationship to the cleavages, lineations, and quartz veins found in the different rock types. Minor folds are best seen in relief in the quartzite, and in potholes in the pelite north-north-east of the Iron Bridge at NN 243 321; they clearly change in vergence northwards as the river section passes from the upper limb of the major fold, through the hinge-zone, to the lower limb. The curvilinear nature of the major syncline axis is revealed by the progressive change in the trend of the minor fold hinges by over 90° in less than a kilometre (Fig. 29).

The general geology of Glen Orchy was established during the primary mapping by the Geological Survey for sheets 45 and 46 (Kynaston and Hill, 1908). However, it was Bailey and Macgregor (1912) who, recognizing the importance of the area, made the first comprehensive structural and stratigraphical interpretation. They recognized that the distribution of the three main rock types is controlled by a flat-lying, isoclinal nappe, the Beinn Udlaidh fold. These workers also found that this fold, which they considered to be as well exposed as any of the small-scale nappes in the European Alps, had been bent around a later upright fold, the Glen Orchy 'Anticline' (now referred to as an 'antiform' or 'dome'). Cummins and Shackleton (1955, fig. 7) first identified way-up structures in Glen Orchy, some tens of metres above the waterfall Eas à Chataidh at NN 248 331, and confirmed the order of succession established by Bailey and Macgregor (1912). Thomas and Treagus (1968) studied two areas adjacent to Glen Orchy on Beinn Udlaidh in more detail and published a map of the closure of the Beinn Udlaidh Syncline. The wider area around Beinn Udlaidh, including the crucial section that constitutes the River Orchy GCR site, has recently been the subject of an extremely detailed field and petrographic study of the stratigraphy, structure, metamorphism and minor intrusions by Tanner and Thomas (2010).

The pelitic rocks at this site contain abundant millimetre-sized, partly or wholly chloritized porphyroblasts of garnet, and randomly orientated crystals of biotite, and the entire sequence has been affected by amphibolite-facies regional metamorphism.

#### *13.2. Description*

##### *13.2.1. Stratigraphy*

In the River Orchy section at NN 242 318, rocks belonging to the Grampian Group are mainly of finely banded psammite and semipelite, with some pelitic beds a few centimetres thick that contain chloritized garnets. Thin grey quartzite beds, and thin calcareous seams are also present. The latter occur in a distinctive sedimentary association in which the dark brown-weathering calcareous bands, a few centimetres thick, are separated from the pelitic background lithology by a narrow zone of siliceous psammite. These zoned calcareous units generally have an extremely elongated pod-like geometry overall, and die out laterally within a metre or two.

The Beinn Udlaidh Quartzite is commonly coarse grained and feldspathic where it is least deformed, as in the hinge-zone of the major fold at NN 248 332, and locally contains gritty and pebbly layers. It varies from pale grey to white or even pink in colour. Excellent examples of festoon cross-bedding (at NN 248 331), as well as at other localities in the quartzite on the hillside to the north-east of this GCR site, show clearly that the unit is younger than the Grampian Group. Where the boundary between the two

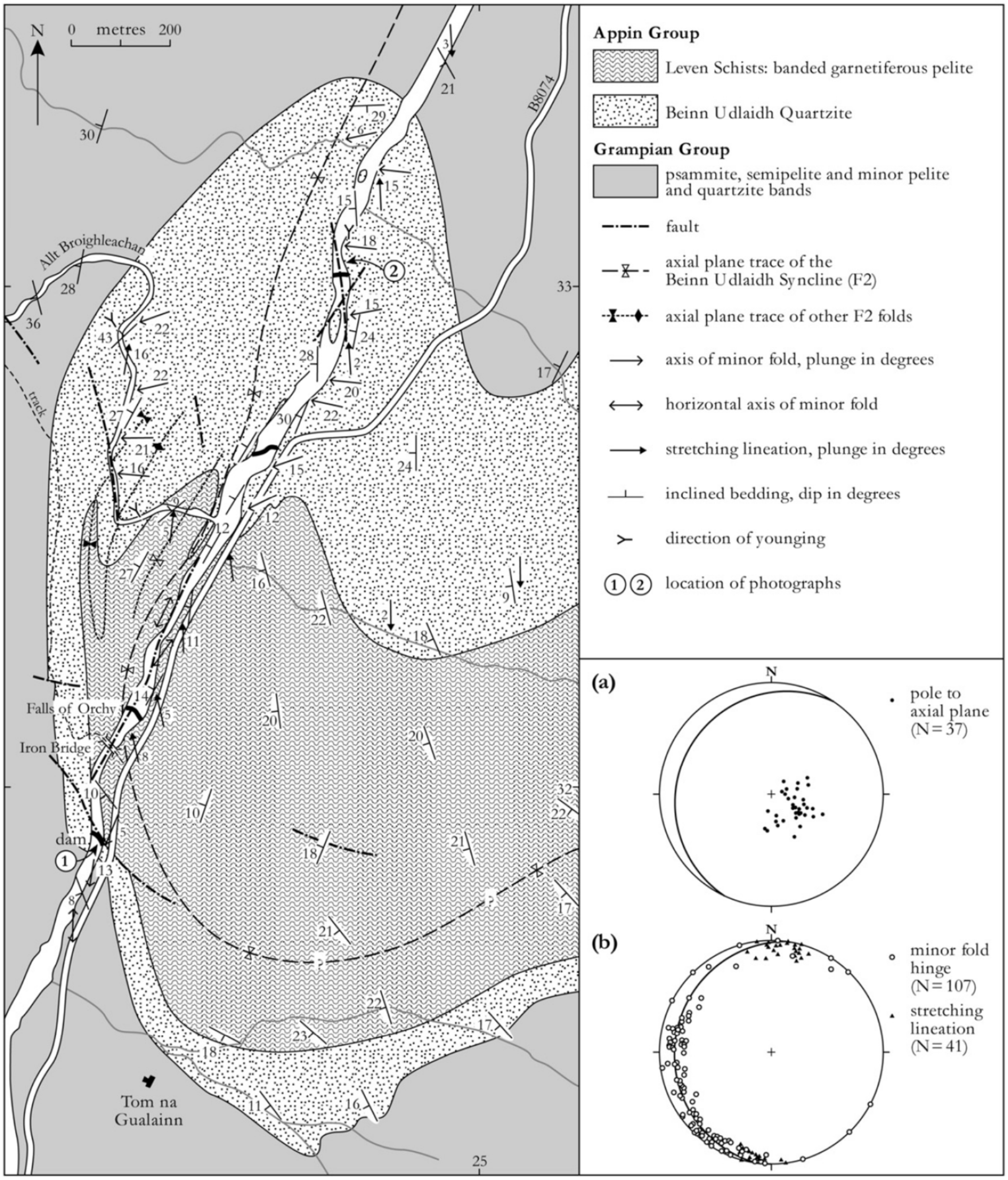



**Fig. 29.** Map of the closure of the F2 Beinn Udlaidh Syncline in Glen Orchy. The curved axial trace of this fold is due to the intersection of the gently dipping axial surface with the irregular topography, and does not reflect the curvilinear hinge as described in the text or later deformation. Equal-area stereographic projections for some of the structural data are shown. Stereoplot (a) shows the poles to the axial planes of minor folds related to the syncline, together with their computed mean orientation as a great circle (solid line). Stereoplot (b) shows the orientations of stretching lineations (solid triangles; $N = 41$) and minor fold hinges (open circles; $N = 107$), related to the major syncline. The solid line represents the computed best-fit plane containing the fold hinges.

units is least affected by later deformation, it is generally transitional over several tens of metres, with interbedding of psammite, semipelite, and quartzite ribs (Thomas and Treagus, 1968, p. 127). The northern contact is not exposed in the River Orchy section, the first exposures north of the quartzite, seen immediately above the waterfall at NN 248 332, being of psammite with thin quartzite beds. At the south end of the section, the entire quartzite unit is thinned tectonically, and the contact can be located to within a metre or so below the dam at NN 242 319, although Thomas and Treagus (1968) considered that the topmost 33 m of the Grampian Group at this locality constitute a 'passage group'. A dyke and a sill-like apophyse of appinitic rock are intruded close to the stratigraphical base of the quartzite and somewhat obscure its relationship to the psammitic rocks farther downstream.

The overlying Leven Schists have a very uniform lithology and consist of finely banded, dark-grey, schistose biotite-muscovite-garnet-graphite pelites with thin layers of psammite and semipelite. The pelites are characterized by a strong bedding-parallel schistosity. They contain porphyroblasts of garnet,

**Fig. 30.** Z-shaped vergence shown by main-phase minor folds, which plunge to the south on the upper limb of the F2 Beinn Udlaidh Syncline in the River Orchy. The structures are seen looking due south from the dam at locality 1, Fig. 29, during low-water conditions. The hammer shaft is 78 cm long (photo: P.W.G. Tanner).

reaching several millimetres across in places, commonly accompanied by millimetre-sized randomly orientated flakes of biotite. Most of the garnets in the pelitic rocks have been altered to chlorite, fresh garnets being most common in the thin siliceous bands. Significantly, in the exceptionally clean exposures in the area of the gorge above the Iron Bridge, and where the river runs close to the road farther north at NN 243 323, small-scale zoned calcareous units are found, which are identical to those seen in the Grampian Group and are also accompanied by thin beds of steel-grey quartzite.

The boundary between the Leven Schists and the underlying Beinn Udlaidh Quartzite is transitional, as is shown by the presence of thin quartzite beds within the pelite for a distance of a few metres above the main quartzite. This relationship is clearly seen at several places near to the confluence of the River Orchy and the Allt Broighleachan (Thomas and Treagus, 1968, p. 127) (Fig. 29).

*13.2.2. Structure*

The Beinn Udlaidh Syncline is a sideways-closing and upward-facing syncline whose gently plunging axis changes trend from approximately east–west to north–south as it is traced southwards along the river section. This major change can be monitored by the progressive change in orientation of the hinges of the congruous minor folds (Fig. 29, stereoplot b). It consists of an upper limb

**Fig. 31.** Stacked fold hinges of minor folds ('fold mullions') with neutral vergence in the hinge-zone of the F2 Beinn Udlaidh Syncline in the River Orchy at locality 2, Fig. 29. The structures are viewed from the south-east, and the hammer shaft is 78 cm long (photo: P.W.G. Tanner).

(with inverted Grampian Group rocks lying above the Appin Group in the south of the area), and a lower limb to the north in which the Leven Schists lie above the Beinn Udlaidh Quartzite (Fig. 29). The axial trace of the major hinge-zone passes through afforested ground to the west of the river. The marked curvature of the axial trace, as seen in Fig. 29, is due to the intersection of the gently dipping axial surface of the fold with the irregular topography, and is unrelated to the fold axis curvature described above.

When viewed down-plunge to between south and west, the minor folds on the upper limb are seen to have a Z-shaped vergence (Fig. 30), which changes first to a neutral vergence in the vicinity of a poorly defined major hinge-zone at about the Iron Bridge, and then to a consistent S-shaped vergence on the lower limb. These minor folds are best seen in the quartzite and the banded Leven Schists, and have wavelengths that vary from tens of centimetres to over a metre (Fig. 31). The axial planes of the minor folds, together with the related penetrative cleavage in the pelitic rocks, dip consistently at less than 20° (Fig. 29, stereoplot a). Throughout the section, a stretching lineation, seen sporadically on the bedding or foliation planes, maintains a constant trend of 190–180° and plunges at a gentle angle to either north or south. Evidence that this lineation is a stretching lineation and not a bedding-cleavage intersection lineation is seen in the gritty and pebbly quartzite beds in the hinge-zone of the major fold around NN 248 332, where clastic grains are clearly elongated and define a stretching lineation, which lies at right angles to the local intersection lineation and to minor fold hinges (Tanner and Thomas, 2010).

Evidence of later ductile deformation superimposed upon the major synclinal structure is restricted to the development of a crenulation cleavage, which is associated with minor folds of S-vergence in the Grampian Group rocks on the upper limb of the fold, and cross-cuts the earlier Z-folds and penetrative fabric. A weak development of a similar crenulation cleavage and lineation is also seen in the pelitic rocks on the lower limb of the Beinn Udlaidh Syncline.

The structural pattern in these rocks is beguilingly simple, and only rarely, even on the cleanest rock surfaces, are isoclinal minor folds of F1 age seen to be refolded around minor folds congruous to the major syncline (Tanner and Thomas, 2010). Care has to be taken, as some suspected refolded folds have been proved on closer examination, followed by slabbing and sectioning in the laboratory, to be of sedimentary origin In addition, examination of the garnets with a hand-lens reveals that they contain helicitic inclusion trails, which are strongly oblique to an external cleavage, which is axial planar to the F2 minor folds. Thin sections of these rocks show that (i) there is an earlier penetrative cleavage (S1), which pre-dates the formation of the S2 fabric associated with the Beinn Udlaidh Syncline, and (ii) the garnets also grew in the interval between these two deformation events (Tanner and Thomas, 2010).

*13.3. Interpretation*

The field relationships seen at this GCR site, supported by younging evidence from cross-bedding, show that there is a coherent stratigraphical sequence from the upper part of the Grampian Group into the lower part of the Appin Group, with no evidence of a major stratigraphical or structural discordance between the two groups (Tanner and Thomas, 2010). Of particular importance is the recognition of minor sedimentary rhythms, of unusual character, in rocks belonging to both groups. At the contact between the two groups there is evidence of sedimentary interfingering of beds, rather than tectonic interleaving. This observation is in agreement with the relationships seen at the *River Leven* and *Strath Fionan* GCR sites. This is an important conclusion as the boundary marks a major lithological change in the sedimentary record, and indeed was formerly taken to be the Moine–Dalradian boundary.

The sedimentary sequence is folded into a major syncline, the Beinn Udlaidh Syncline, which faces up to the east, and has a strongly curved axis. Previous authors have regarded this syncline and the complementary Glen Lochy Anticline as F1 structures (Cummins and Shackleton, 1955; Thomas and Treagus, 1968; Roberts and Treagus, 1975) but Tanner and Thomas (2010) have shown that it post-dates an earlier fabric (see below) and hence can be confidently assigned to the D2 regional deformation. However, only a small amount of deformation, and a gentle warping of the axial surface followed this main deformation event. This suggests that the curvature was a primary feature of the D2 deformation, and not a later effect due to refolding. Analysis of the geometrical results from this GCR site, together with those from the adjoining Beinn Udlaidh massif in which the fold is extensively dissected, indicates that this curvilinearity has resulted from the rotation of the original east–west fold axis, as seen in the least deformed rocks, towards the orientation of the north–south stretching lineation (the X-direction of the strain ellipsoid), with increasing deformation (Fig. 29, stereoplot b) (Tanner and Thomas, 2010). The upper limb of the fold has been most affected by this increase in strain, and the Beinn Udlaidh Quartzite found there has a platy foliation, lacks sedimentary structures, and is considerably thinner than it is on the lower, less deformed, limb. It also carries a strong stretching lineation.

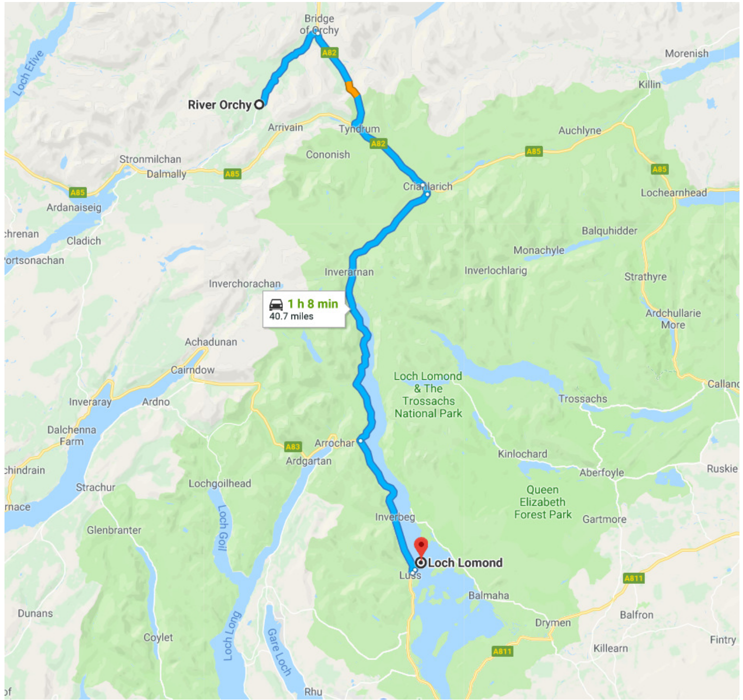
A petrographical study of the garnet-bearing assemblages shows that the major F2 fold and its associated family of minor folds, cleavage, and lineations, formed *after* a deformation event which had given rise to a penetrative cleavage and was accompanied by amphibolite-facies metamorphism. Evidence of this early, S1 cleavage has been all but destroyed by later recrystallization and mineral growth in the overwhelming majority of rocks, and it is best preserved as a helicitic fabric in the garnet porphyroblasts (Tanner and Thomas, 2010). There is no evidence from this GCR site or from the adjoining area to suggest that either minor or major folding accompanied this early tectonothermal event, and its significance is still being assessed. Tanner and Thomas (2010) concluded that the rocks belonging to the Grampian Group have been affected by the same number and sequence of events as those of the Appin Group, and that there is no evidence for additional deformation phases in the older rocks. These findings support the conclusion that the Grampian–Appin group boundary is not marked by a significant structural break.

### 13.4. Conclusions

The River Orchy GCR site provides an invaluable section through the upper part of the Grampian Group and its continuation upwards into the Appin Group (Lochaber Subgroup). Transitional contacts between the major rock units, coupled with sedimentary repetition of distinctive lithologies, precludes the presence of a major, orogenic, unconformity at this stratigraphical level. This finding is supported by a microscope study of rocks from this GCR site, which has confirmed the field-based conclusion that both groups have been affected by the same number of structural events, having the same intensity of development, and geometry. Thus a boundary that was formerly taken to be the contact between the Moine and Dalradian supergroups can now be confidently recognized as a normal stratigraphical contact between the two lowest groups of the Dalradian succession. This conclusion is supported by observations at the *River Leven* and *Strath Fionan* GCR sites.

The rocks at this site are folded over into a large downward-closing F2 fold, the Beinn Udlaidh Syncline, which lies on its side and has been deeply incised by the River Orchy, to reveal its internal geometry. The gorges and rocky bed of the river expose a superlative section which is invaluable as a natural laboratory in which to study the intricate three-dimensional shape of this fold and its associated minor structures, and to enable its mode of development and complex history to be further unravelled. One aspect of the work of special interest, is that it is the first locality in the south-west and central Grampian Highlands where it can be demonstrated that the so-called 'early' nappe-like folds formed after an even earlier major deformational and metamorphic event.

**STOP 6.4:** *Loch Lomond and The Trossachs National Park*




The southern end of the Loch is crossed by the Highland Boundary Fault - a fracture caused by movement in the earth's crust hundreds of millions of year ago. The Fault marks the geological division between Highland and Lowland Scotland. The rocks around the Fault reveal a fascinating story. 600 million years ago (Ma), the pieces of the earths crust which eventually merged to become Scotland were apart. Three separate pieces (terrains)- each with a different history - have been identified close to the end of the Fault.

The line of the Highland Boundary Fault can be seen clearly from Conic Hill on the south-east shore, looking west across the islands of Inchcailloch, Torrinch, Creinch and Inchmurrin.

**The Dalradian**

The Dalradian, as the rocks to the north of the Fault are called, began life as sand and mud on a sea floor, over 600 Ma. As the continents which bounded the sea moved closer together, the sands were buried tens of kilometers below the earths surface. Extreme pressure and temperature 'cooked' the sediments into the hard schists and slates we see today, (metamorphic rocks). they also folded and squeezed upwards, resulting in a mountain range that was once as high as the Himalayas.

**The Midland Valley**

South of the Fault lies a different terrain. It is composed of sedimentary rocks -sand and coal measures - formed around an ancient river system some 300-400 Ma. The Midland Valley rocks form a belt across central Scotland, interspersed with volcanic intrusions (igneous rocks), like the Kilpatrick Hills and the Campsie Fells to the south and east of the Loch.

**The Highland Border Complex**

Between the Dalradian and the Midland Valley is evidence of a third terrain - the Highland Border Complex. This is a mixture of rock types formed in a marine environment after 540 Ma. Since the Dalradian rocks were being eroded at that time. and the Border Complex contains no Dalradian sediments, geologists deduce that the two terrains had not yet come together.

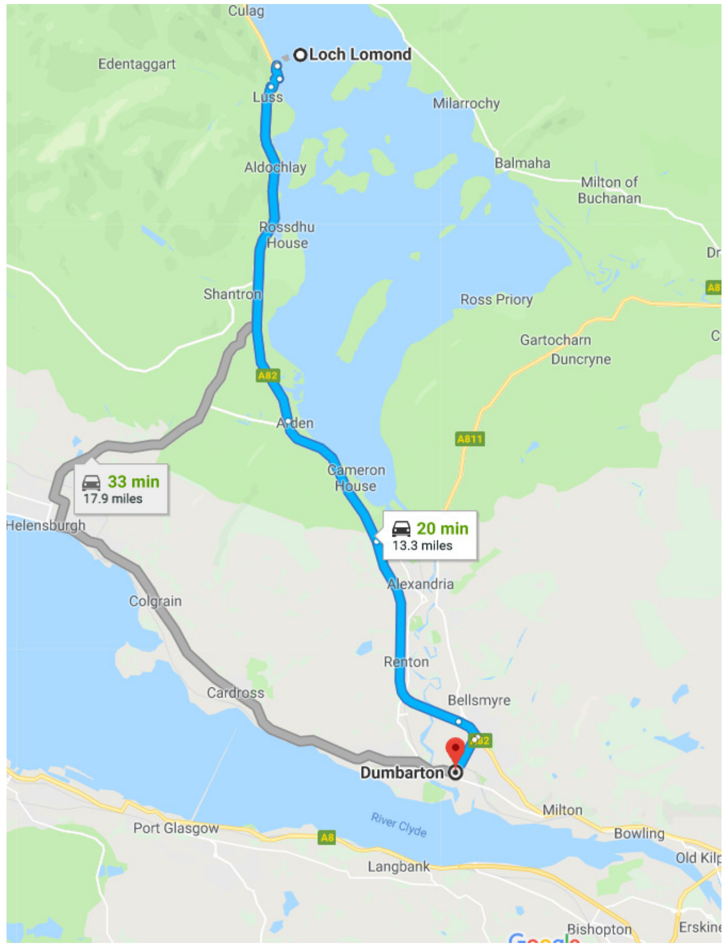
**STOP 6.5:** *Dumbarton Rock*

This citation has been hard to track down but here is best I can do:

Whyte, F. and Weedon, D.S., >1968, Excursion 7: Dumbarton Rock. Not sure what it is published in but I'm guessing a guidebook. pgs. 97-101.

I found it through the Geological Society of Glasgow:

https://www.geologyglasgow.org.uk/docs/017_070__dumbartonrock_1425481003.pdf




## Introduction

In early Carboniferous times widespread volcanism occurred within the Midland Valley, predominantly extrusive in nature. This is seen in the Central (Glasgow) Region as the lavas of the Campsie and Kilpatrick Hills to the north, and those of the Renfrewshire heights to the south. Seemingly these were fed from localized vents along pronounced fissures. By its characteristics Dumbarton Rock stands out as a type example of such a feeder vent. Within its circumference it shows inwardly-dipping agglomerates, typical of a sub-aerial volcanic cone, together with large blocks of slumped overlying Cementstone alongside a central plug of intrusive basalt.

The intrusive basalt has columnar cooling joints, most of which are inclined radially outwards from the centre of the Rock at a steep angle suggesting that the plug narrows downwards, thus enhancing the

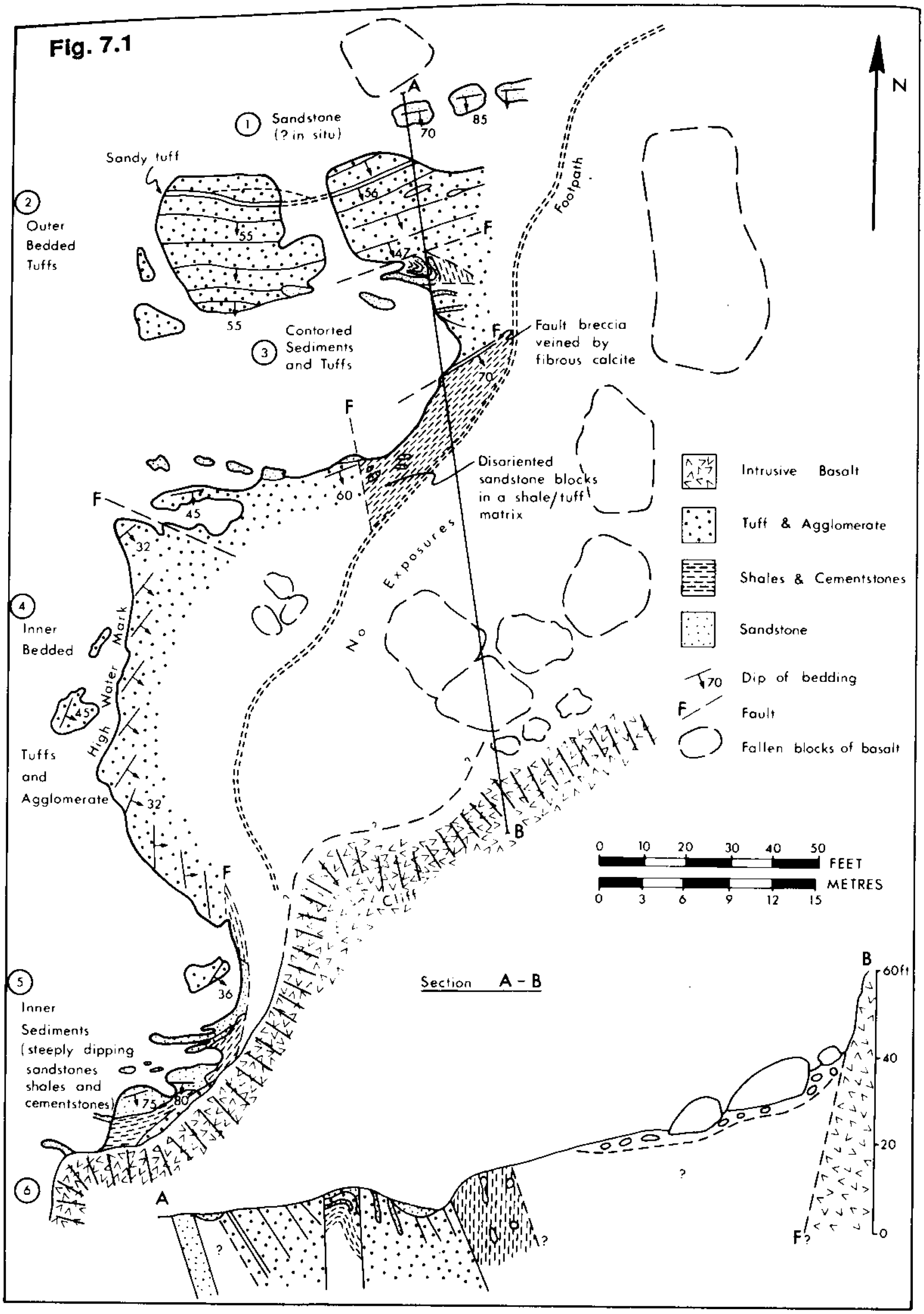



**Figure 7.1.** Geological map of the north-western part of Dumbarton Rock.

impression of an infilled crater.

In the immediate vicinity of the parking area the steep-sided cliffs provide an excellent area in which to study the general nature of the intrusive basalt. It should be noted that although the surface shows an orange/yellow rind of weathering this is very thin and unlike the normal deeper-weathering of basic igneous rocks of the Midland Valley. A fresh surface reveals a fine-grained black igneous rock, micro-porphyritic in part. The micro-phenocrysts are dominantly of plagioclase feldspar, but those of olivine and augite may be present. Using MacGregor's classification (1928) the intrusive basalt appears transitional between **Jedburgh** and **Dalmeny** types.

**Locality 1. Exposures of sandstone.** These *may* be erratic blocks but their conformity of strike with those of the nearby outer bedded tuffs indicates strongly that they are in place. It is suggested however, (Whyte 1966, p.110), that their steeper dips, 70°-85°, in contrast with the lesser dips of the outer bedded tuffs, 30°-50°, implies faulted contacts between them.

**Localities 2 and 4. Outer and inner bedded tuffs.** These are mainly composed of fragments of volcanic rocks (with subordinate fragments

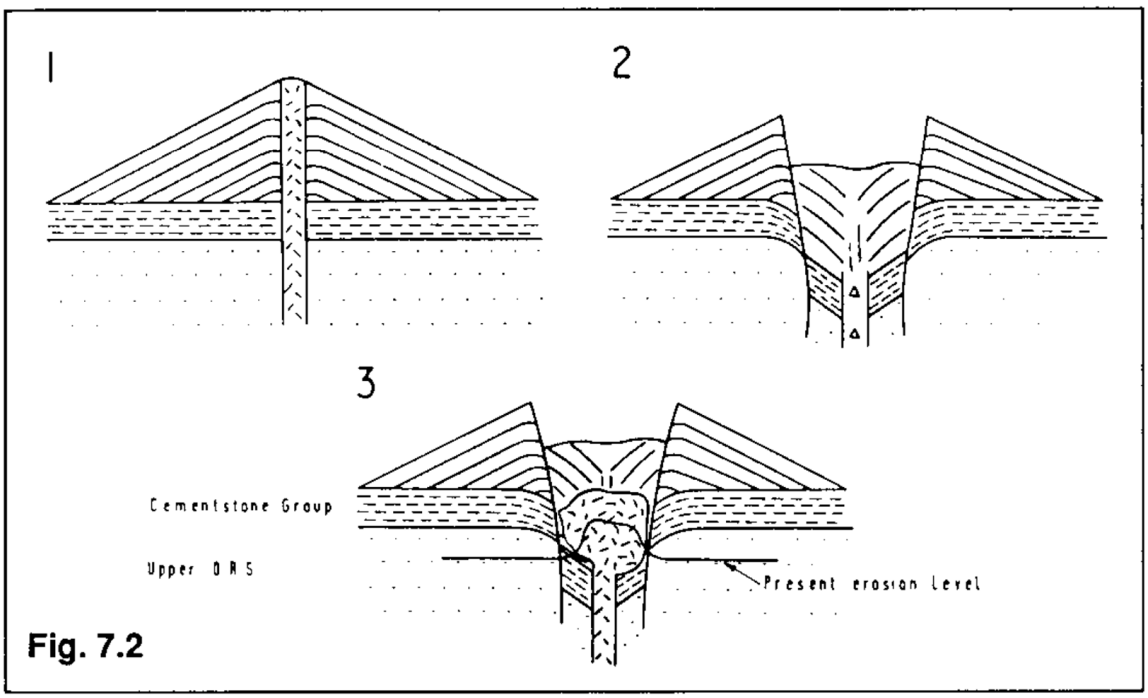



**Figure 7.2.** Diagrammatic representation of three stages in the development of the Dumbarton Rock vent: 1) active volcano; 2) withdrawal of magma accompanied by fracturing and subsidence; 3) emplacement of plug basalt.

of sandstone, **cementstone** and shale) in a matrix of fine tuff, calcite and chlorite. A prominent bed of sandy tuff occurs within the outer bedded tuffs.

**Locality 3. Contorted sediments and tuffs**. Within this fault-bounded zone the rocks are brecciated, veined with fibrous calcite and show small folds related to the faults. Disorientated sandstone blocks in a shale and tuff matrix probably formed by explosive disintegration of shale and sandstone strata accompanied by tuff intrusion.

**Locality 5. Inner sediments**, comprising steeply dipping sandstones, shales and cementstones belong to the sequence of rocks immediately underlying the original volcano, and attained their present position, (as did the outer and inner tuffs), by a subsidence of the central part of the volcano, prior to the emplacement of the plug basalt.

**Locality 6. Basalt plug** . The contact between basalt and sediments dips steeply inwards at about 80 degrees. Near the contact, the normally blue-black colour of the basalt changes to dark green due to the development of chlorite in the groundmass and in **amygdales**; the plagioclase is albitic in composition.

Apart from this contact zone, throughout the remainder of the plug the blue-black basalt is consistently fine-grained, composed of **microphenocrysts** of olivine and plagioclase (labradorite) in a groundmass of plagioclase, augite and iron ore. According to MacGregor's classification (1928) this basalt is transitional between **Jedburgh** and **Dalmeny** types.

## Other features of interest

In the high-level gully which crosses the central part of the Rock there are good examples of glacial striae, first described as long ago as 1855. In addition, the western face of the gully exhibits very small-scale **roches moutonnées**: looking one way along the face the basalt appears quite rough, whereas looking the other way the same surface appears smooth.

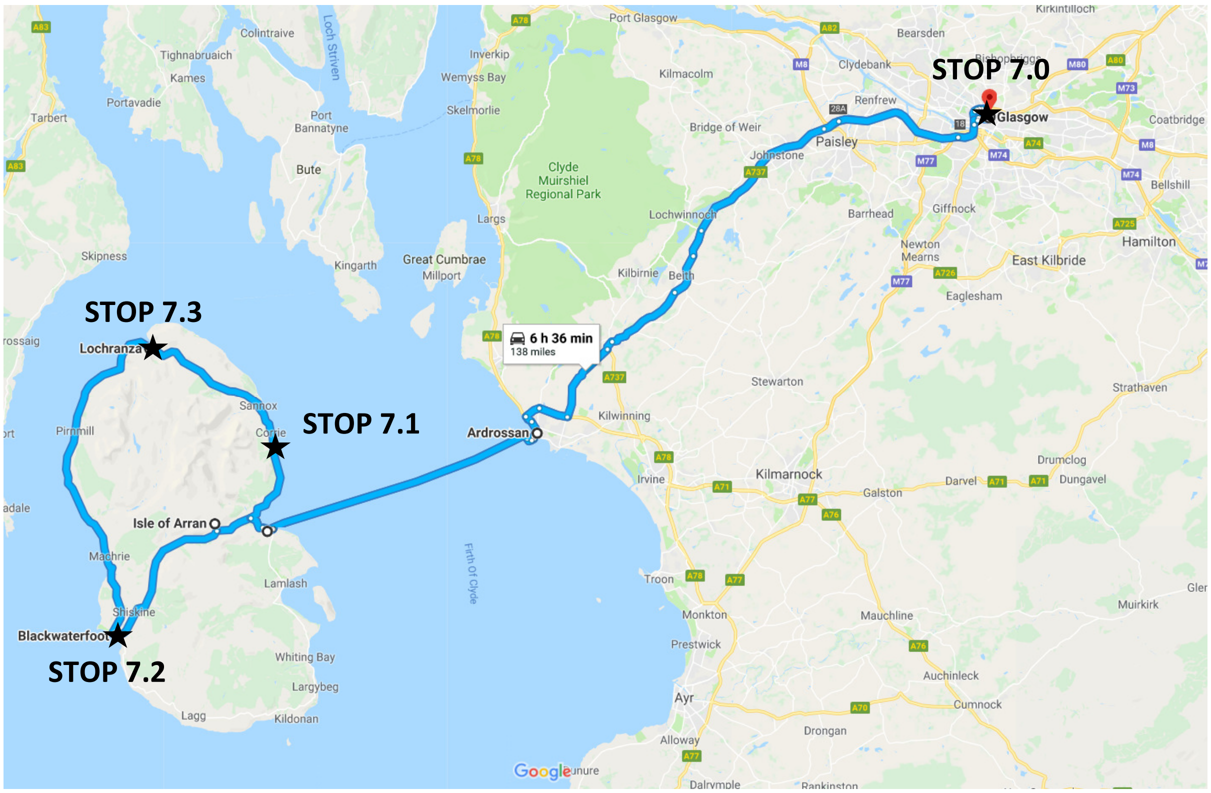
The summit of Dumbarton Rock is a good vantage point for viewing the following: the course of the River Clyde from the restricted channel near Bowling down the widening estuary: the valley of the River Leven and the Cowal hills to the west: Ben Lomond to the north, and Dumbuck volcanic vent and the lavas of the Kilpatrick Hills to the east.

**Day 7: Saturday, March 10th, 2018 – Isle of Arran or Hang out in Glasgow**

***Here we have some options –***

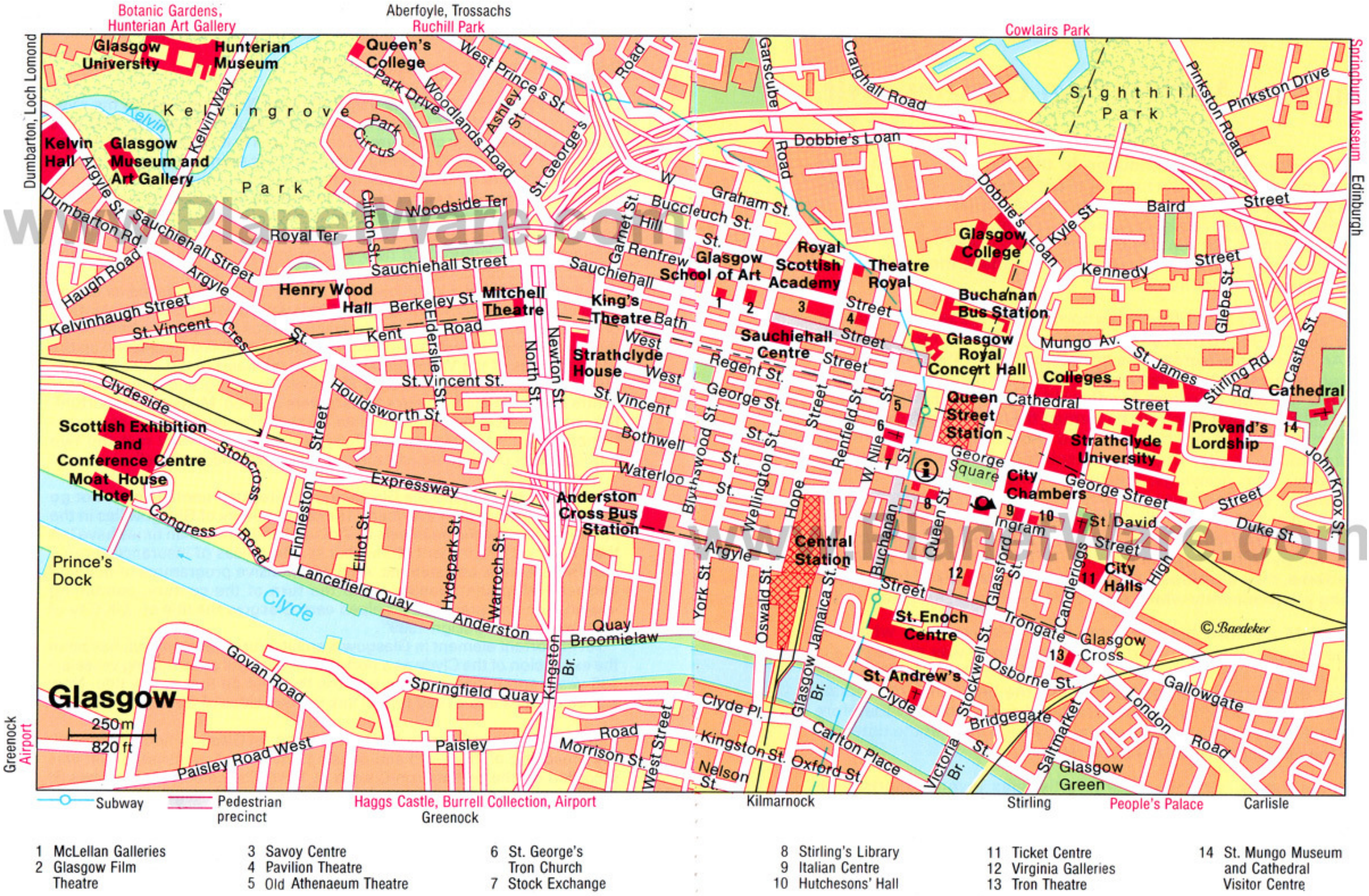
1. *Isle of Arran – Hutton's unconformity and igneous rock features.*
2. *Back up to Loch Lomond and The Trossachs to do the Balhamha Trail*
3. *Hang out in Glasgow – museums, shops, pubs…*

**I am writing it up for the Isle of Arran but we'll see how we feel.**




**8:00 AM:** Leave the hostel
**9:00 AM:** Board the Ferry (Ferry leaves at 9:45 AM)
**10:30 AM:** Corrie Shore – tilted strata and fossils
**12:00 PM:** Lunch in Brodick
**2:00 PM:** Dumadoon – igneous intrusions
**3:00 PM:** Lochranza – Hutton's Unconformity
**4:30 PM:** Board the Ferry (Ferry leaves at 4:40 PM)

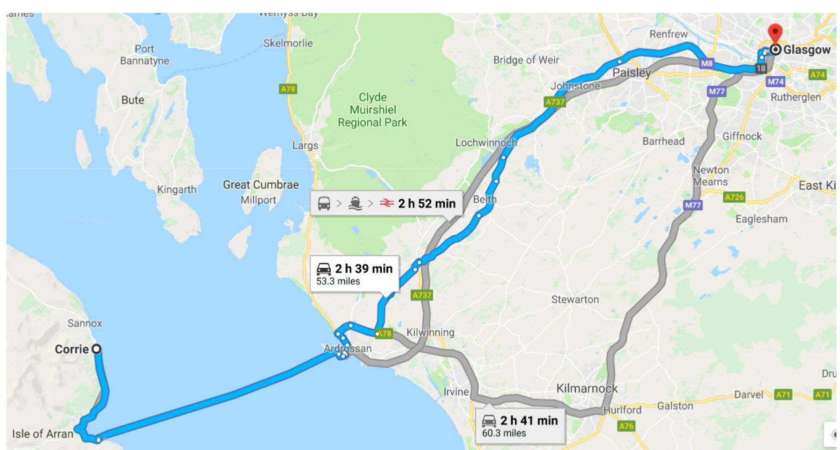
**STOP 7.0:** *Glasgow City Center*




**Top 10 things to do in Glasgow according to Trip Advisor**

- Kelvingrove Art Gallery and Museum
- The Riverside Museum of Transport and Travel
- The University of Glasgow
- Buchanan Street
- House for an Art Lover
- Pollock Country Park
- Walking Tours
- Botanic Gardens and Kibble Palace
- The Necropolis
- Tennents Wellpark Brewery
- Kelvingrove Park

**STOP 7.1:** *Corrie Shore, Isle of Arran*




*The following is from:*

MacDonald, J.G., 2015, Isle of Arran: Corrie Shore. Geological Society of Edinburgh Excursion Itineraries. Version 1.1, 10 pgs.

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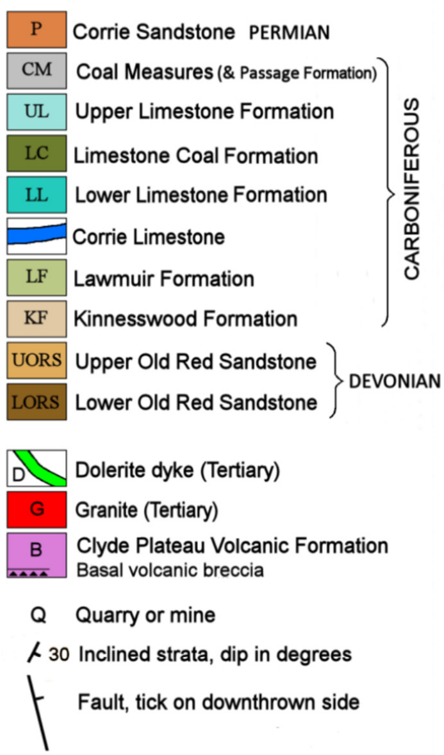
# Corrie Shore

The main purpose of this excursion is to examine the Carboniferous rocks of Arran in an area where the rock succession is clearly displayed at the roadside. The excursion also offers an opportunity to examine the junctions of the Carboniferous strata with the underlying Upper Old Red Sandstone and the overlying Permian.

The localities are readily accessible along a 2 km shore section. The only diversion involves a steep climb to locality 8 to examine the Corrie Limestone. The shore section is largely accessible at any state of the tide but it is best to avoid high spring tides. The going is rough over rocky outcrops and boulder beaches the latter often being slippery, especially after stormy weather when they may be strewn with seaweed, so stout footwear is recommended, especially with ankle protection.

There is limited car parking at localities 1 and 13 and a larger car park on the south side of the Corrie Hotel. Refreshments may be obtainable at a few small tea rooms or the hotel bar.



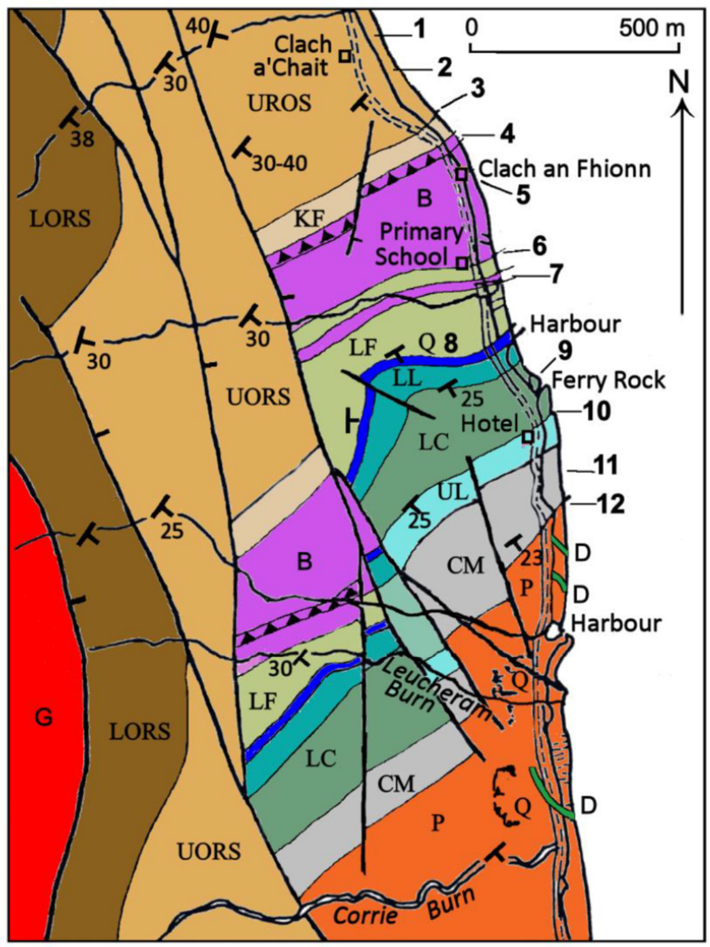
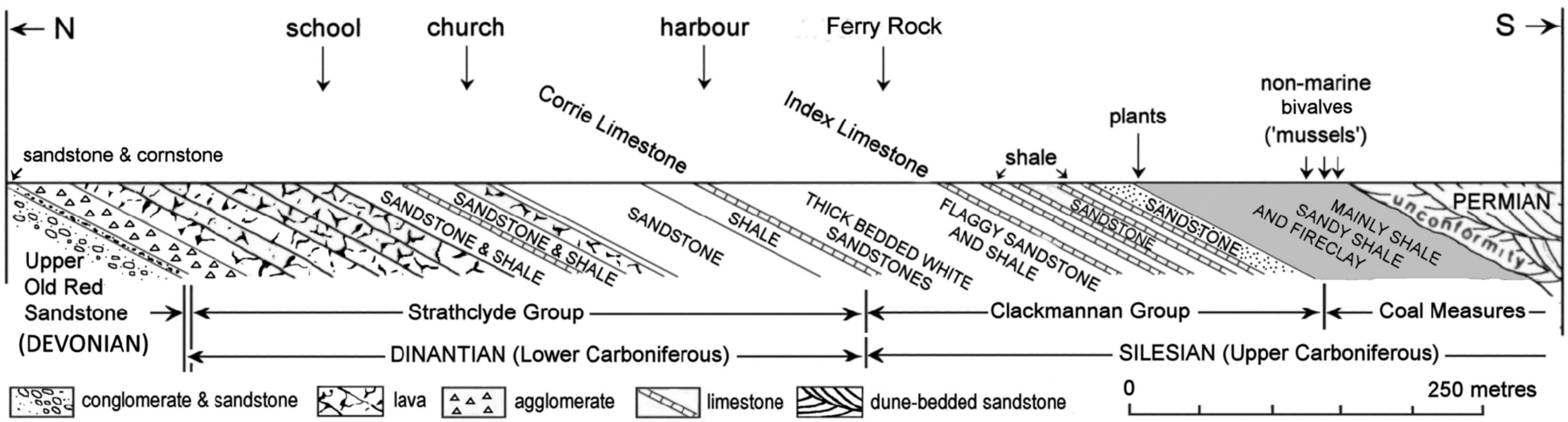
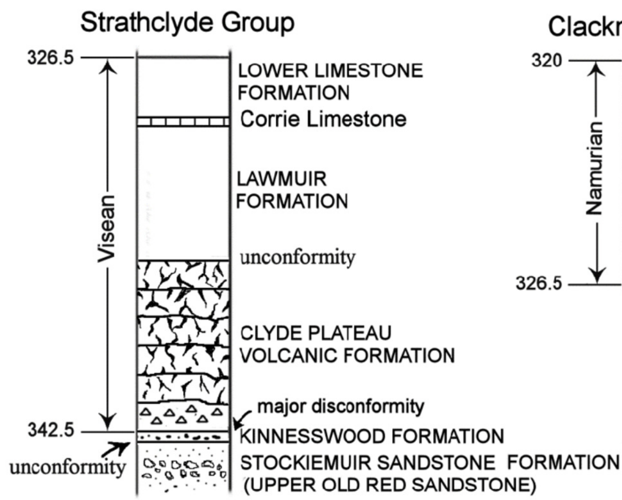



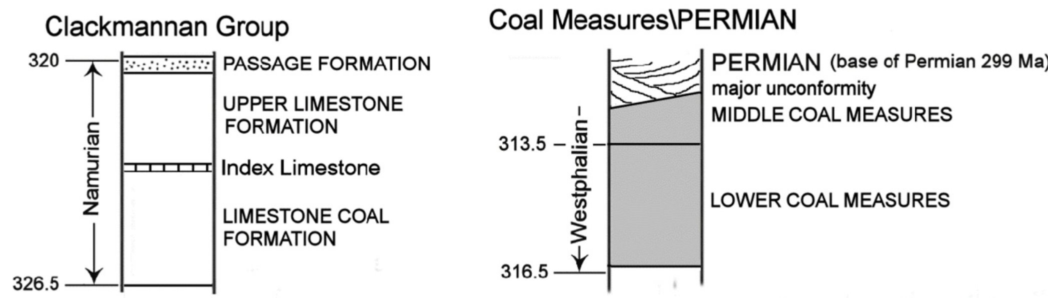

**Fig. 1. Geological map of the Corrie area showing positions of localities mentioned in the text. This is a coloured version of part of fig. 9 of MacDonald & Heriott (1983) with some modifications.**

## The geological setting

Corrie is situated to the east of the northern granite. The strata are generally inclined to the SE so the oldest rocks (Old Red Sandstone) occur in the north at locality 1 and they become progressively younger toward locality 12 (Permian). The outcrop pattern is broken up by a set of NNW trending normal faults. As a result of this the succession seen in the shore section is displaced and repeated inland where it crops out in stream sections, especially in the Leucheram Burn (Fig.1.)




The three vertical sections, in the lower part of the figure, link the lithographic successions with the corresponding chronographic epochs of the Carboniferous Period. Key radiometric dates (Monaghan & Parish 2006) are in millions of years. The earliest epoch, the Tournasian, is represented only by a much attenuated part of the Kinnesswood Formation; the Ballagan formation is absent. More than half of the Westphalian is also missing and the overlying, topmost, Stephanian Epoch is totally unrepresented.

**Fig. 2. Diagrammatic cross-section and vertical sections (dates in millions of years) of the succession cropping out along the shore at Corrie.**

## The itinerary

**Locality 1. Clach a' Chait [NS 0208 4449]:** At the roadside a huge erratic block of granite known locally as the Cat Stone (Clach a' Chait); is approximately 4.3 m in height, 5.5 m long and 2.75 m wide. About 50 m to the north a small parking area on the east side of the road provides access to the shore where red, cross-stratified and often coarse-grained sandstones crop out. These beds of Upper Old Red Sandstone, dip to the south-east at angles of between 24° and 30°. Sparsely pebbly horizons contain clasts mainly of vein quartz. Note that the dips steepen locally in the vicinity of small crush-lines or faults. Access to locality 2 is to the south along the shore.

**Locality 2. Conglomerate [NS 0218 4435]:** A red conglomeratic horizon, 21 m or so thick, crops out here. It is poorly sorted and loosely packed, with a variety of clasts, notably of vein quartz (up to about 120 mm in length), quartzite, sandstone, and semi-pelitic chlorite-schist set in a sandy matrix. The proportion of clasts decreases upwards. It is followed southwards, in upward succession, by a series of red, cross-stratified sandstones, often showing on their upper surfaces irregular ridges which it has been suggested may represent in-filled mud-cracks.

**Locality 3. March of Achag [NS 0231 4418]** This locality can been reached by walking along the shore from locality 2, or from the road through a gap in the vegetation opposite the wooden bungalow at the north end of Corrie Village. Cross-bedded Upper Old Red Sandstone is succeeded by a thick upstanding bed of conglomerate (Fig. 3) forming a small promontory. Comparisons can be made between this and the conglomerate at Locality 2. Note in particular the frequency of large pebbles, lenses of sandstone and red sandstone clasts. The rock types exposed in upward succession along the shore between locality 3 and the base of the Clyde Plateau Volcanic Formation at Locality 4 are listed overleaf (Table 1).

**Fig. 3. The topmost beds of the Upper Old Red Sandstone (bed (a) in Table 1). Note the interbedded sandstone below the top conglomerate and the much finer grained beds at the base of the outcrop.**

| | | thickness |
|---|---|---|
| (f) | Pale-grey sandstone dipping southeast at 25° to 28° .. .. .. | ~6 m |
| (e) | Cornstone, pale-coloured, sandy, nodular .. .. .. .. | ~0.75 m |
| | Gap in succession | 0.9 m |
| (d) | Cornstone, nodules in red shaly matrix .. .. .. .. .. | ~4.5 m |
| (c) | Mudstones, red, with beds of pale-grey sandstone | ~1.2 m |
| | ~~~~~~~~~~~~~~~~ line of disturbance – possible fault ~~~~~~~~~~~~~~~~ | |
| (b) | Cornstone, pebbly, associated with calcareous sandstone | 1 m |
| (a) | Conglomerate, massive, reddish in colour, the top of the local Upper Old Red Sandstone succession. | 15 m |

**Table 1. Upward succession of strata cropping out on the shore between localities 3 and 4.**

**Fig. 4. Cornstone bed at Locality 3; top of the Upper Old Red Sandstone on lower left**

Gunn (1903, p.38) regarded bed (a) at locality 3 as the topmost member of the Upper Old Red Sandstone and the junction with the pebbly cornstone, bed (b) as "clearly an unconformable one." The cornstone horizons resemble the topmost part of the Kinnesswood Formation and the ~6 m of pale grey coloured sandstone above them resembles a similar formation that occurs on Bute ( Young & Caldwell 2011) that has been equated with the Clyde Sandstone Formation which on the mainland widely precedes the Clyde Plateau Volcanic Formation.

**Locality 4. Volcanic breccia [NS 02322 44141].** A sudden break in the sedimentary succession is marked here by rocks that bear witness to the onset of the volcanic episode that produced the Clyde Plateau Volcanic Formation. An unsorted mass of fragments of volcanic rock have a size range from close to 2m in length to fine grained ash. Individual blocks of highly vesicular lava display a degree of rounding indicative of transport in a highly energetic environment such as that encountered in pyroclastic flows produced by explosive volcanic activity.

**Fig. 5. The lower part of the Clyde Plateau Volcanic Formation (Loc.5)**

**Locality 5 Clach an Fhionn [NS 02363 4402].** The lower part of the succession of the Clyde Plateau Volcanic Formation is encountered here. It consists of purplish porphyritic olivine basalt with phenocrysts of augite, olivine and occasionally plagioclase feldspar. The basalt is columnar and the flows have been tilted at about the same angle as the sedimentary rocks about and below. The columns have been spheroidally weathered (Fig. 5) giving a false impression that they may have been pillow lavas erupted sub-aqueously. Note the large granite boulder known as Clach an Fhionn (the white rock) on the shore side of the road. It is a glacial erratic derived from the adjacent Northern Arran granite massif.

**Locality 6. Opposite Corrie Primary School [NS 20404 43824].** The upper part of the lava succession, also consisting of olivine basalt, is generally fresh, unweathered and provides excellent specimens for making thin sections for examination under the microscope. Look for the slaggy, decomposed, amygdaloidal tops of individual flows. Thin ramifying veins of calcite are common near the top of the lava formation. Above the lavas a succession of beds of reddish sandstones and shales, includes a 460 mm thick bed of red limestone. These strata dip southeast at about 25°. Some of the beds contain small fragments of volcanic ash. They are succeeded by a 3·0–3·6 m thick purplish basalt lava flow, much veined by carbonates.

**Locality 7. [NS 0245 4364]** A gap in the shore section above the last lava flow top at Locality 6 may represent 9–10.5m of soft, easily eroded beds. They are succeeded here by massive sandstone, pale grey in colour but with reddish staining locally. At one time these rocks were quarried along their outcrop both on shore and for some little distance inland. Above the sandstones soft reddish mudstones crop out sporadically.

**Locality 8. Limestone Quarry. [NS 02253 43546]** The Corrie Limestone is the basal member of the Lower Limestone Formation in Arran. This important marker horizon within the Lower Carboniferous succession of the Midland Valley of Scotland is found at many localities with a variety of names (e.g. the Hurlet Limestone in the Glasgow area). On the shore it was excavated to form the Old Corrie Harbour, and mined extensively inland along its outcrop for over 360m.

**Fig 6. Post of limestone supporting the roof of the limestone mine at Locality 8. The roof of the mine is studded with *Gigantoproductus* shells.**

A path from the bend in the road at the harbour leads uphill to the entrances to day-holes (formerly called ingaun e'es), that gave access to the old underground workings (Fig. 6). Good sections of limestone and the overlying beds crop out along the present rock face and at the mine entrances. Visitors should on no account attempt to penetrate the galleries as there is a serious danger of roof-falls. The limestone has been recorded as 6 m in thickness but includes only 3·6–4·3 m of good quality limestone.

The Corrie Limestone is divided into separate beds, or posts, by partings of reddish calcareous shale on the upper surface of which are numerous shells of the large brachiopod *Gigantoproductus giganteus*. A layer packed with specimens of this species forms a striking feature on the roof of the old workings. The limestone is intruded by two thin dykes, one a little above the lime kilns, the other about 45 m higher up. Note also the series of white and pinkish sandstone in the cliff above the Corrie Limestone. These rocks also crop out on the shore at Locality 9, south of the Old Harbour.

**Locality 9 – Ferry Rock. [NS 0258 4343]** Rocks belonging to the Lower Limestone Formation crop out along the shore to the south of Corrie Old Harbour. They include thick posts of white sandstone some of which are fine-grained and exceptionally pure. The hard compact sandstone found at this locality was quarried (Fig. 7) to supply large blocks for harbour construction in the Isle of Man. The projecting rock remaining after the excavations was later used as a jetty for small boats which were used to ferry passengers from passenger steamers; ferry operations ceased in 1939. The beds exposed above the sandstone here include a few seat earths interbedded with sandstones, shaley sandstones and shales which extend for a little way to the south. Although no trace of coal has been found faint impressions of coal forest vegetation are preserved on some of the bedding planes.

**Locality 10 – Index Limestone. [NS 0257 4338]** A reddish 600 mm thick limestone here has been tentatively correlated with the Index Limestone. Like the Corrie Limestone the Index Limestone is widespread throughout the Midland Valley and is of particular importance as it marks the top of the Limestone Coal Formation, a source of commercially workable coals. The limestone at this locality has yielded shelly fossils including brachiopods such as *Latiproductus latissimus*, small gastropods and a few bivalves. The strata extending southwards to the little bay in front of the Corrie Hotel contain several other marine limestones, ranging in thickness between 300 and 900 mm, separated by shales and occasional sandstone beds which together have been tentatively placed in the Upper Limestone Group. Due to lack of continuous exposure and the occurrence of minor faults or crush lines the estimated thickness of the Group at about 42 m must be regarded as approximate.

**Fig, 7. Ferry Rock (loc. 9), note the tool marks on the right where the white sandstone was quarried.**

**Locality 11 – Coal Measures. [NS 0245 4324]** This locality includes all the strata seen in the little Bay south of the Corrie Hotel as far as Locality 12. Results of research carried out during the revision of the stratigraphy of the Upper Carboniferous in Arran (Leitch 1942, pp. 141–154) place these rocks in the Upper Carboniferous, certainly in the Coal Measures although a 9 m thick, massive sandstone at the base may be equivalent to the upper part of the Passage Formation. The conglomerate at its base probably marks an unconformity of early Passage Formation age known on the mainland throughout much of Lanarkshire.

**Fig. 8. Highly contorted bedding in the sandstone at the top of the Coal Measures succession.**

**Locality 12 Carboniferous/Permian Unconformity [NS 0259 4308]**. Some 100 m or so south of the Corrie Hotel, a sudden change in lithology and sedimentary structures of the rocks cropping out on the foreshore, marks a major unconformity between the Upper Carboniferous strata and those of the succeeding Permian, Corrie Sandstone. The plane of unconformity has been described (Bailey 1926) as being marked by scattered, minute pebbles of vein-quartz and iron pan mixed with rounded quartz grains. The pattern of sedimentation in the Corrie Coal Measures comes to an abrupt end with the sandstone at the top of the succession. Highly irregular contortion of the bedding (Fig. 8) indicates the deposit was deformed shortly after deposition, before the bed had been lithified. This type of soft sediment disturbance can be produced by slumping, or dewatering of wet sediment triggered by the weight of subsequent deposits in a deltaic environment.

The abrupt change in lithology above the unconformity (Fig. 9) signals conditions of deposition in the Permian profoundly different from those in the Coal Measures. The red sandstones encountered here (Fig. 10) are also markedly different from Upper Old Red Sandstone at Localities 1 to 3. Close examination of the beds shows that although there is some variation in grain size the composition of the grains is more uniform and there is a total lack of clasts coarser than sand grade. Also the cross bedding is on a much larger scale. Examination of the coarser sand grains with a hand lens reveals that they are well rounded and the surfaces have the 'frosted' appearance that results from transport by wind.

**Fig. 9. The Carboniferous-Permian unconformity. The smooth weathering large cross-bedded units of the Permian Corrie Sandstone on the right contrast with the disturbed bedding of the Carboniferous strata on the left (see also Fig. 8).**

**Fig.10. Dune bedded Permian Corrie Sandstone south of the Carboniferous/Permian unconformity at Locality 12.**

**REFERENCES**


Bailey, E.B. 1926. Subterranean penetration by a desert climate. *Geological. Magazine*, **63,** 276–280.

Clemmensen, L.B. & Hegner, J. 1991. Eolian sequence of erg dynamics: the Permian Corrie Sandstone, Scotland. *Journal of Sedimentary Petrology*, **61,** 768–774.

Gunn, W. 1903. *The Geology of North Arran, South Bute and the Cumbraes*. Mem. Geol. Surv., GB.

Leitch, D. 1942. The Upper Carboniferous Rocks of Arran. *Transactions of the Geological Society of Glasgow*, **20**, 141–154

Monaghan, A.A. & Parrish, R.R. 2006. Geochronology of Carboniferous–Permian magmatism in the Midland Valley of Scotland: implications for regional tectonomagmatic evolution and the numerical time scale. *Journal of the Geological Society of London,* **163,** 15–28.

Trueman, A. & Weir, J. 1968. *A monograph of Carboniferous non-marine Lamellibranchia*. London, Palaeontolographical Society.

Young, G.M. & Caldwell, W.G.E. 2011. Early Carboniferous Stratigraphy in the Firth of Clyde area: new information from the Isle of Bute. *Scottish Journal of geology*, **47**, 143–156.

# Drumadoon and the Tormore Dykes

The object of this excursion is the examination of the composite dykes and other intrusions which abound on this stretch of shore. It can be carried out by public transport from the main centres on the east side of the island. If private transport is used it will be found more convenient to arrange for collection at the appropriate terminal point, especially if another excursion is to be made on the same day. The Tormore shore is reached by the track that leads westward from the main road at the old post office [Grid Ref. NR 8950 3245]. The route follows the raised beach southwards past the houses.

As an alternative, for those who wish to restrict their visit to an examination Judd's dykes, and the localities between King's Cave and Cleiteadh nan Sgarbh, cars can be left at the car park beside the Blackwaterfoot to Machrie road (A841) on the east side of the forestry plantation [NR 8981 3148]. A path skirting the plantation on its north side leads to the shore close to An Cumhann (locality 3). Another path through the plantation reaches the shore at locality 5, south of King's Cave.

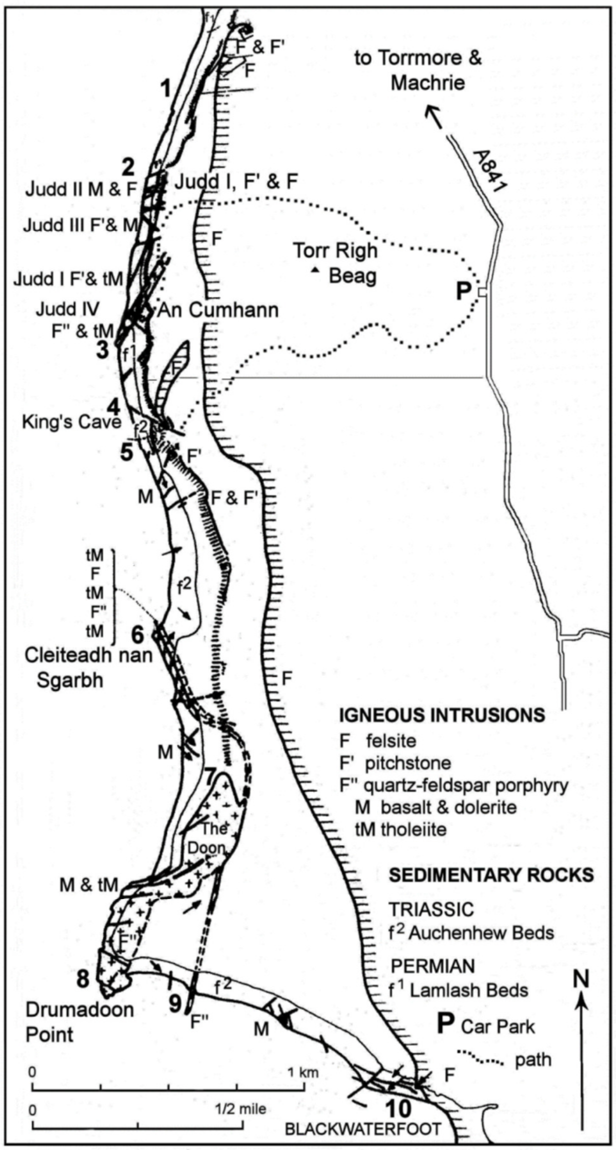



**Fig. 1. Geological sketch map of the Drumadoon – Tormore area (after MacDonald & Heriott 1983)**

**1. The Tormore Shore.** The foreshore and raised beach cliff are eroded in sandstones attributed to the Lamlash Beds in the upper part of the Permian succession of Arran. These sandstones are often strongly cross-laminated and carious weathering is locally striking. Irregular distribution of carbonate cementing material leads to hard, rough-weathering bands alternating with soft red sandstones and siltstones. Pseudomorphs after halite and dendritic gypsum are recognisable in places.

**2. Judd's Dykes.** Along this stretch of shore numerous dykes crop out including the composite dykes made famous by Judd (1893). The finer points of the petrography of these interesting intrusions must be studied in the laboratory but the constituent rock types are sufficiently diverse to enable adequate field determinations to be made. These types include felsite, quartz-feldspar-porphyry (quartz-porphyry of the 1:50 000 BGS map), pitchstone, and dolerite. The Roman numerals used by Judd to identify the dykes that he described are appended in Figure 1. The most northerly pitchstone was not considered to be composite by Judd but it encloses some areas of felsite; it forms a conspicuous feature on the foreshore, about 5 m thick at high water mark but is variable in thickness and dip. The intrusion trends ENE–WSW and is composed mainly of dark-green pitchstone.

*Judd's dyke No I.* This N–S trending, dark green pitchstone dyke crops out south of the most northerly pitchstone but the relationship of the two is unclear. It is about 4.5 m thick. It disappears beneath boulders and raised beach sediments but reappears south of dyke III where it dips to the east. Southwards its trend swings towards the SSW and the dip gradually decreases. By the development of felsic modifications and the presence of thin, generally rotted marginal tholeiite the intrusion becomes composite. Flow-banding is strikingly displayed, especially in dislodged blocks on the shore.

*Judd's dyke No. II.* A central 4.5m thick, east–west trending, quartz-felsite is bounded by sphere-oidally-weathering tholeiites 1.2m and 1.8 m thick on the north and south margins respectively. Judd records the felsites passing in places into "pitchstone-porphyry or 'vitrophyric' rock" which is stated to occur "as a band varying in width from 150 to 600 mm, sometimes forming part of the quartz-felsite mass and at other time intersecting the masses of andesite" (i.e. tholeiite). Some 55 m S of dyke II, two dykes intersect; they have irregular trends that diverge as they head for the raised beach cliff.

*Judd's dyke No. III.* This NW–SE trending dyke consists of pitchstone, 1.2–1.8m thick, with an olivine-dolerite on its north side. The dolerite differs in composition from the tholeiites usually found in association with the pitchstone and felsites of the composite intrusions, so Judd No. III might not be composite in the normal sense but the result of the fortuitous intrusions of two totally unrelated magmas. Judd No 1 reappears just south of this.

**3. An Cumhann.** *Judd's dyke No IV*, a 27m wide composite dyke, completes forms a prominent feature that stands high above the shore line and blocks the passage along the beach platform except at low tide. Otherwise it can be crossed by ascending a poorly defined path over the top on the shoreward side. The bulk of the dyke is composed of quartz-feldspar-porphyry with abundant large phenocrysts of white-weathering orthoclase feldspar and smaller glassy ones of quartz set in an aphanitic grey groundmass. The marginal tholeiites on both sides, although basaltic in composition, contain scattered xenocrysts of orthoclase similar in appearance to those in the centre of the intrusion.

**4. King's Cave.** South of An Cumhann the cliff at the head of the raised beach rises to a greater height. It has been hollowed out by wave action when sea level stood higher during early Post-Glacial times. The largest cave, known as King's Cave (Fig. 2) is entered by a gate in an iron railing. The gate is normally left open. It gets its name from the legend that King Robert the Bruce hid in it when he was in Arran. There is historical evidence that he passed through Arran on his journey from the Island of Rathlin to Ayrshire in 1307, but no written record exists of his visiting this site.

The cave was formed by the erosion of two upwardly converging joints in the Permian sandstone. When wave action undermined the cliff the unsupported rock between the joints collapsed and the resulting debris was washed away. Little of archaeological significance has been found here. Some carvings high on the left hand side inside the entrance are of doubtful antiquity and in other places the rocks have been defaced by modern graffiti.

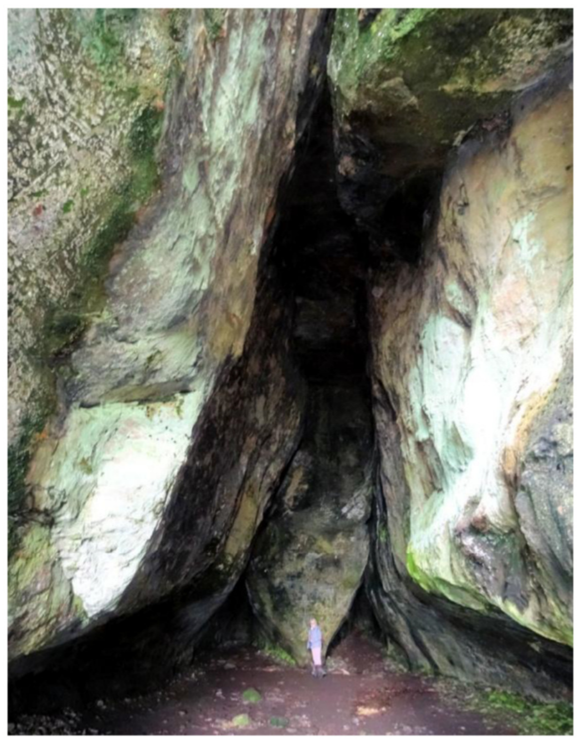


**Fig. 2. King's Cave. The figure is ~1.6 m high.**

**5. Signpost for Blackwaterfoot.** A short distance south of King's Cave, at a recess in the cliff, a short climb leads to a branch in the path. A signpost indicates the route south towards Blackwaterfoot and the path to the King's Cave car park. The view of the north side of the recess (Fig. 3) shows sandstones intruded by a thick felsite sill, mostly deeply weathered to red and yellow 'sandy' material. Above the sill there are more sedimentary rocks capped by a sill of pitchstone. Pitchstone crops out at several points in the recess and most readily at the base of the conspicuous knoll on its south side. Partially devitrified pitchstone occurs in a low cliff below the footpath.

**Fig. 3. View north from the path to King's Cave car park. Felsite and pitch-stone sills are intruded into sandstone of the Permian Lamlash Beds a short distance south of King's Cave.**

The above recess has been considered to mark the line of a NW–SE running fault coinciding with the junction of the Permian Lamlash Beds to the north with the Triassic Auchenhew Beds to the south (Tomkeief 1961). It is certainly clear that there is a change in lithology; the sedimentary rocks to the south are finer grained with a high proportion of marls. The path continues along the raised beach for about 800m towards Cleiteadh nan Sgarbh. Auchenhew Beds crop out sporadically along the shore.

**6. Cleiteadh nan Sgarbh.** The promontory here is formed by a NNW trending composite dyke complex, similar in some respects to An Cumhann (locality 3). The widest member is a quartz-feldspar porphyry 15.5 m thick flanked on either side by ~0.6 m thick basaltic intrusions (Fig. 4). The quartz-feldspar porphyry is darkened at its margins and the marginal basalts contain xenocrysts of orthoclase feldspar, similar to, but less abundant than those in the porphyry. On the east side a 9 m thick felsite dyke is in contact with the eastern marginal basalt. The felsite is flow banded parallel to its western side and has weathered to shades of bright-red and yellow which make it look deceptively like sandstone in places. The intrusive complex is inclined to the east and at the top of the beach its heading changes towards the southeast as it crosses the raised beach. It crops out in the cliff to the north (to the left) of the Drumadoon sill.

**Fig. 4. View from Cleiteadh nan Sgarbh towards the Drumadoon Sill.**

**A – felsite;**
**B – quartz-feldspar porphyry**


**7. Drumadoon.** Follow the track from locality 6 from the foot of the raised beach cliff up the slope to the north end of the Drumadoon Sill. Then continue along the top of the talus slope where marly sedimentary rocks below the sill can be examined as can the basal rocks of the intrusion. At the base of the sill is a sheet of tholeiite, about 1.2 m in thickness thinning to about 0.8m at the south end of the cliff. Above that rises the main quartz-feldspar porphyry with its columnar jointing which has inspired the local name 'Organ Rock'. Near its base the porphyry is darkened and is rich in xenoliths of tholeiite which have a tendency to weather out. Fallen blocks of xenolithic porphyry litter the talus slope and the adjacent shore. Fragments of a thin upper marginal tholeiite have been reported (Tyrell 1928, 200) supporting the view that the Drumadoon sill was intruded during the same episode as the composite dykes. [Research carried out since the publication of the 1983 edition of the Macgregor Guide (Meade *et al*. 2009) throws new light on the nature and of the Arran composite intrusions.]

**8. Drumadoon Point**. West of the Drumadoon the composite sill steps down to shore level, possibly as the effect of an EW oriented fault. The same relationships between the main quartz-feldspar-porphyry and the margin tholeiite occur here and at Drumadoon Point the eastern margin of the intrusion can be examined. At the Point the marginal tholeiite dips to the east. Note also the presence of an igneous breccia with a matrix of yellowish porphyry, a thin composite dyke and a number of basaltic dykes that cut the main sill.

**9. Composite dyke.** Here a NNE-trending quartz-feldspar-porphyry dyke with a darkened eastern margin cuts the shoreline. Its projected line runs to the north of the eastern margin of Drumadoon suggesting that it may have been the feeder to the sill. It resembles the dyke at Cleiteadh nan Sgarbh (locality 6) and that at An Cumhann (locality 3). This raises the possibility that all three dykes and the Drumadoon sill are connected and were intruded at the same time. This locality is situated close to the north-western end of Blackwaterfoot Golf Course which is laid out on coastal sand dunes. Care should be taken to keep clear of fairways and maintain a good lookout for unexpected wayward golf balls whizzing towards you.

**10. Blackwaterfoot**. The beach margining the golf course is cut in several places by basic dykes. On the shore, south of the Golf Club House, the dip of the country rock marls and sandstones increases to about 50° against the Blackwaterfoot–Torr Righ Mor felsite. At the contact the felsite is flow banded; east of this flat lying joints give a roughly 'stratified' and, in places, a rippled appearance. Elsewhere columnar joints are well developed, as seen at the Blackwater Bridge beside the harbour. Dykes which trend in the same direction as the felsites have irregular courses, "as though they were influenced by the proximity of the felsites or found it difficult to penetrate it." (Tyrell 1928, 222 & fig. 32). South of the Club House the remains of two sea-stacks stand in front of the raised beach sea cliff. Farther to the SE the cliff shows a patch of the Auchenhew Beds, with columnar felsites to the west. Felsite on its E side has joints disposed in an asymmetric arch; this feature was noted and figured by Bryce (1872). The stacks and arch are situated in private grounds.

## REFERENCES


Bryce, J. 1872. *The Geology of Arran & the other Clyde Islands* (4th Edit.), Collins, Glasgow & London

Judd, J.W. 1893. On composite dykes in Arran. *Quart. J. geol. Soc. London*, **131**, 331.

MacDonald, J.G. & Heriott, A. 1983. *Macgregor's Excursion Guide to the Geology of Arran*, *3rd edit.* Geol. Soc. Glasgow.

Meade, F.C., Chew, D.M., Troll, V.R., Ellam, R.M. & Page 2009. Magma Ascent along a Major Terrane Boundary: Crustal Contamination and Magma Mixing at the Drumadoon Intrusive Complex, Isle of Arran, Scotland. *Journal of Petrology*, **50**, 2345 –2374.

Tomkieff, S.I. 1961. Isle of Arran, No. 32 in Excursion Guide Series, *Geologists' Association*

Tyrell, G.W. 1928. *The Geology of Arran*. Memoir of the Geological Survey GB, HMSO Edinburgh.

**STOP 7.3:** *Lochranza, Isle of Arran* *The following is from:*

MacDonald, J.G., 2015, Isle of Arran: Loch Ranza, North Newton, and Cock of Arran. Geological Society of Edinburgh Excursion Itineraries. Version 1.0, 6 pgs.

# Loch Ranza, North Newton & Cock of Arran

The objects of this excursion are:

(1) To continue the examination of the Dalradian schists, on the north margin of the north Arran granite mass;
(2) To examine the classic unconformity on the shore of North Newton;
(3) To study the land-slipped masses at An Scriodan and Permian sandstones and breccias at the Cock of Arran.

**Locality 1. Lodge Farm.** There are good exposures of dark-grey, gritty Dalradian schists, dipping northwards at steep angles (up to 50°) at this locality. Note that in passing along the shore towards locality 2 the northerly dip continues for a short distance but at the same time there is a decrease in the grain size of the schists and much small-scale folding and contortion becomes evident. Beyond the axis of the Catacol Synform (Fig. 1) the inclination of the schists is generally to the SE.

**Locality 2. South Newton.** Here the steep southeasterly inclination is well seen in massive, greenish-grey, gritty schists with some darker slaty layers, all much folded. The rocks closely resemble those exposed on the south shore of Loch Ranza near the pier [close to Coillemore Point]. Boulders of pale grey sandstone, probably of Carboniferous age, are scattered along the shore towards Newton Point. Cowie (1905, 157–158) recorded at this locality the occurrence of a "shoal" or band of rock fragments including types similar to those in the "cairn" at Catacol (locality 5a) but without any of the red shaley crinoidal limestone recorded there.

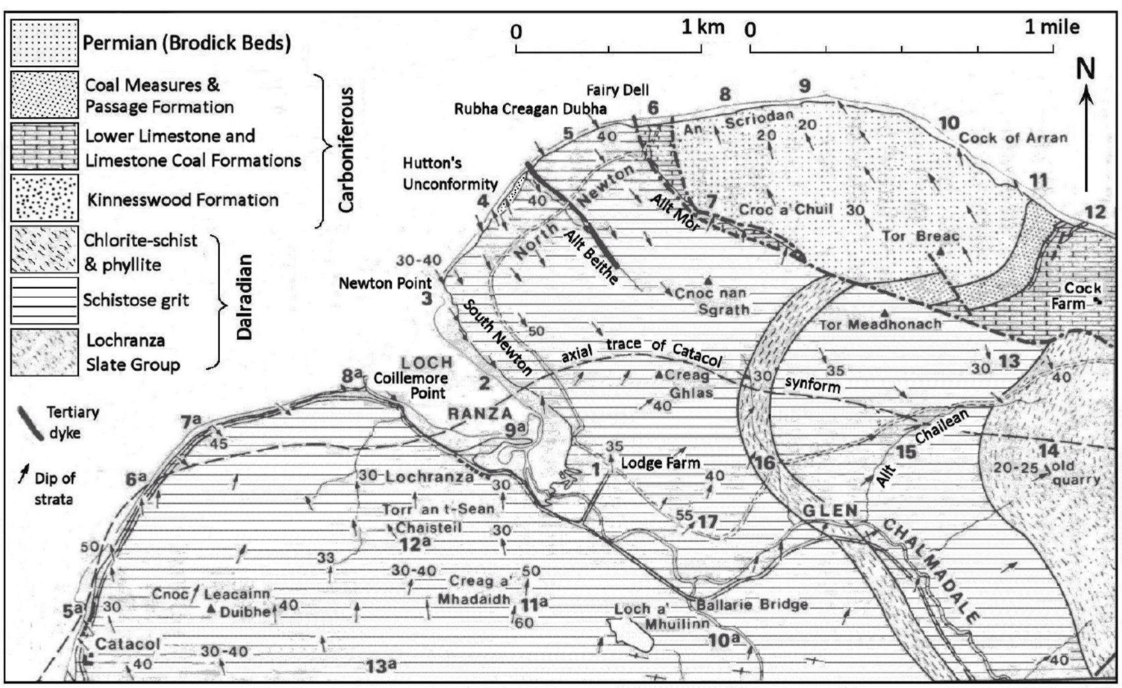



**Fig. 1. Geological map of the area around Loch Ranza.** [This map was published as Fig. 13 in the 1983 edition of Macgregor's excursion guide but a key has been included along with other minor additions. Since publication of the guide in 1983 the stratigraphy of the Carboniferous in the Midland Valley of Scotland has been revised. (see Fig. 2 in the Corrie Shore itinerary for a more extensive up-to-date stratigraphy).]

**Locality 3. Newton Point.** Here good examples of graded bedding occur in coarse-grained or gritty beds, inclined to the SSE at angles of 30° to 40°. Along the shore to the NE greenish or greenish-grey

**Locality 4. Hutton's Unconformity.** About 500 m NE of Newton Point is the well known unconformity recognised by James Hutton as long ago as 1787. The locality extends from the Allt Beithe southwards along the shore for over 330m. Reddish and yellowish sandstone, associated with beds of pale-coloured, sometimes nodular cornstone, rests with marked discordance upon the schists (Fig. 2). These strata, at one time referred to the New Red Sandstone (*sic*) were later assigned to the Calciferous Sandstone Series, the lowest subdivision of the Carboniferous succession (Gunn 1903, 52; Tyrrell 1928, 47). It has also been suggested that their lithology would place them more fittingly in the upper part of the Upper Old Red Sandstone. [The variation in colour and the presence of cornstone makes it much more likely that they belong to the Kinneswood Formation, the lowermost sub-division of the Lower Carboniferous in the western Midland Valley of Scotland (see the Corrie Shore excursion).] At the SW end the sandstone beds dip north-northwestward at about 30°, while the underlying schists are inclined to the SSW at angles between 40° and 50°. The schists must have been close to vertical at the time of deposition of the sandstones and cornstones.

The recognition of the North Newton unconformity provides a striking example of Hutton's genius and insight. It was described by him in Volume 1 of his *Theory of the Earth* (1795, 429) and additional details are contained in Volume 3 (1899, 235–236). The following quotation is taken from the latter.

"Here the first thing that occurs is the immediate junction of the inclined strata of schistus and the other strata, which here appear to be a composition of sandstone and limestone; these strata are equally inclined with the schistus but in the opposite direction. These two different types of stratified bodies rise to meet each other; they are somewhat confused at the immediate junction, but some of the sandstone or calcareous strata overlap the ends of the alpine schistus."

Other unconformities recognised by Hutton in Scotland are those in the River Jed, near Jedburgh, and at Siccar Point on the Berwickshire coast. Such examples of discordance in the geological succession were to him convincing evidence of cycles of change in the operations of nature, proofs of a "succession of worlds" following one another throughout geological time. An account of Hutton's life and work was published in volume 63, part 4 of the *Transactions of the Royal Society of Edinburgh* in 1950, in commemoration of the 150$^{th}$ anniversary of his death.

**Fig. 2 Hutton's Unconformity**
**View looking SW towards Loch Ranza. Dalradian schist crops out in the foreground. Above the schist, beds of sandstone dip towards the sea. Careful inspection of the "somewhat confused" rock at the plane of the unconformity reveals evidence that the upturned beds of schist were probably subjected to prolonged sub-aerial weathering prior to the deposition of the Kinneswood Formation.**

**Locality 5. North Newton Dyke.** Farther along the coast to the NE, towards Rudha Creagan Dubh, the principal rock types are coarse grained, sometimes pebbly schists with prevailing southeasterly dips. The graded bedding seen on many of the rock faces shows, however, that the succession is inverted . In passing note the prominent, NW–SE trending tholeiitic dolerite dyke that crosses the shore immediately to the NE of Allt Beithe.

**Localities 6-7. Fairy Dell.** At the picturesque hollow known as the Fairy Dell the schists end against a fault that separates them from Carboniferous rocks that crop out in a wedge-shaped strip that extends up the Allt Mòr for about 1 km from the shore. The wedge is about 200m wide at the coast but narrows inland. White sandstone and subordinate shale crop out at intervals in the lower part of the burn and at one point on the right bank (locality 7) as reddish limestone with crinoids fragments and ribbed brachiopods including productacean brachiopods. The Carboniferous rocks are bounded on their east side by another fault beyond which Permian sandstones and breccias crop out. On the left bank of the burn, about 460m up from the shore, there is a good example of fault-breccia.

**Locality 8. An Scriodan.** To the east of the Fairy Dell the next 200 m or so of shore is occupied by Permian Sandstones and conglomerates. The generally north-northwesterly dip of these beds is approximately the same as the angle of slope of the hillside. The succession here consists of massive beds of bright red sandstone, cross-bedded and containing intercalations of conglomerate which become more numerous in the upper part. The sandstones and conglomerates closely resemble the Corrie Sandstone (see Corrie Shore itinerary) with which they may be equated. The predominating pebbles (clasts) in the conglomerates are schists of various types, quartzite and vein quartz.

**Locality 9. An Scriodan rock falls.** The well-known land-slipped area, An Scriodan, features slipped and fallen masses of Permian sandstone and conglomerate that have covered the raised beach platform for a distance of about 640m. These rock falls, which are associated with deep rents and gashes in the hillside above, are said to have taken place over 250 years ago. Great care should be taken in negotiating this part of the coast.

**Locality 10. Cock of Arran.** This is the name given to a large block of sandstone, some 6 m in length and 3– 3.5 m in height, resting on the beach. Its upper part has been broken off, but originally, when seen from the sea, it is said to have had a fanciful resemblance to a crowing cockerel. It is situated about 27 m north of a spring near the remains of some old dwellings. Close to the Cock a few Tertiary dykes cut the Permian sandstone. One of these, 1·2m in width, with a northeast–southwest trend, projects above the surface for most of its exposed length.

**Locality 11. Base of Permian.** Between Locality 10 and the base of the Permian fine examples of dune bedding and other sedimentary structures characteristic of deposition in an arid environment can be examined (Clemmensen & Abrahamsen 1983). The resemblance of these rocks to the basal Permian in the Corrie area provides justification for their correlation with the Corrie Sandstone. However, the presence of thin layers of fine grained sedimentary rocks with mud cracks and a mud slide breccia provides evidence that the arid desert conditions during which they were deposited were occasionally punctuated by flash floods. The lowermost conglomerate beds in the sequence contain fragments of fossil bearing limestone. The fauna recorded includes corals, brachiopods, gastropods and crinoid columnals. This provides clear evidence that the limestone clasts were derived from the underlying Carboniferous strata that crop out to the east of this locality.

Coal Measures (Upper Carboniferous) strata crop out to the southeast of the Permian unconformity. Gunn (1903) records the occurrence of plant remains (*Calamites*, *Cordaites*, *Mariopteris*, *Neuropteris* and *Sphenophyllum*) in beds approximately 18m and 66m southeast of the unconformity. The thickness of the Coal Measures here is estimated to be between about 76m and 90.7m the latter from a detailed section by Leitch (1942, 149) who records a 3.7 m thick coarse white sandstone with a quartz conglomerate at the base (cf. the Coal Measures succession at Corrie). The varied sedimentary characteristics of these Coal measures strata point to deposition under deltaic conditions. The prevalence of disturbed bedding, much twisted, contorted and overfolded, is much greater here than at Corrie. This is most likely to have resulted from de-watering associated with the rapid loading of unconsolidated water-saturated deposits by sandy sediments laid down during flood conditions. Another contrast with Corrie is the scarcity of bedded mudstones. The only 'mussel' [non-marine bivalve] shell recorded here by Leitch indicates a horizon low in the *modiolaris zone*, or possibly in the *ovalis* zone.

**Locality 12. Corrie Limestone.** The presence of white sandstone with subordinate red mudstone beds marks the change from the Coal Measures into older strata. The presence of the lateral equivalent of the Corrie Limestone at the base indicates that these strata most likely belong to the Lower Limestone Formation. All or most of the Namurian succession appears to be missing so a major non-sequence can be inferred between the Lower Carboniferous and the Upper Carboniferous Coal Measures at this locality. [The Macgregor Guide did not include a description of the Carboniferous rocks that crop out on the shore to the southeast but indicate that a route back to Loch Ranza can be taken via a hill path from Cock Farm to Glen Chalmadale. The following paragraph was added to the third edition of the Macgregor guide (1983.)]

If time permits the excursion may be extended by about 1 km to the SE along the coast to look for the giant myriapod trail preserved in a sandstone bed in the Limestone Coal Group near Laggan (Briggs, Rolfe and Brannan 1979). A replica of the trail, along with a reconstruction of the 1 m long millipede-like *Arthropleura*, which is thought to have made it, can be seen in the Arran Nature Centre at Brodick. The original trail, over 6m in length and 36cm in width, runs east–west across the surface of a sandstone bed that crops out in the old quarry above the remains of the salt-pans harbour north-west of Laggan [grid ref. NR 972 511]. **On no account should any attempt be made to collect material here as hammering would only lead to the destruction of this remarkable trace fossil.**

On the return journey to Loch Ranza follow the old track that runs from Cock Farm towards locality 13, noting that it crosses the fault line separating the Carboniferous succession from the Dalradian.

**Locality 13. SW of Cock Farm.** Near this locality there are scattered outcrops of pebbly grits inclined to the SSW at angles of 30° to 35°. Cross the hillside to locality 14. Between those localities the grits become less coarse and show a transitional junction with the Loch Ranza Slate Group. A similar interbedded junction occurs between localities 14 and 15 [see fig 4, page 23 of third edition].

**Locality 14. Old Slate Quarries.** Here there are two old quarries in beds belonging to the Loch Ranza Slate Group. Note that the inclination is now east-northeastwards at about 15°. This change in direction of dip marks the crossing of the axial trace of the Catacol Synform. The rocks that crop out in the old quarries are thin-bedded, mainly fine-grained slates showing pale greenish-grey to dark-grey banding. Some bands, however, are rough and gritty. The slates were worked on a small scale towards the end of the eighteenth century for local use at North Newton and Loch Ranza.

**Locality 15. Allt Challean.** Examine sections in the Allt Chailean and beside the track. Strongly cleaved schistose grits are inclined generally at 16° to 20° towards the ENE.

**Locality 16. Allt Eadraaidh.** Greenish-grey grits with intercalated slates are inclined to the NE. Good sections occur in the little burn joining Glen Chalmadale from the north, 650 m NE of Ballarie Bridge, as well as in the main stream itself.

**Locality 17. Lower Glen Chalmadale.** There are a number of exposures here alongside and above the old track showing banded greenish-grey and grey, gritty and often coarse grained schists inclined to the northeast at angles up to 60°.

## REFERENCES

Briggs, D.E.G., Rolfe, W.D.I. & Brannan. 1979. A giant myriapod trail from the Namurian of Arran, Scotland. *Palaeontology,* **22**, 273–291.

Cowie, C.R. 1905. Notes on the shoals at Catacol Point and Kirn Point, Arran. *Trans geol. Soc. Glasgow,* **12**, 156–158.

Clemmensen, L.B. & Abrahamsen, K. 1983. Aeolian stratification and facies association in desert sediments, Arran Basin (Permian) Scotland. S*edimentology*, 30, 311–339.

Gunn, W. 1903. The Geology of North Arran, South Bute and the Cumbraes. (Explanation of Sheet 21) *Mem. Geol. Survey*. G.B.

Leitch, D. 1942. The Upper Carboniferous rocks of Arran. *Trans geol. Soc. Glasgow*, **20**, 141–154.

MacDonald, J.G. & Herriot, A. 1983. *Macgregor's Excursion Guide to the Geology of Arran.* 3rd Edition. Geological Society of Glasgow.

Tyrrell, G.W. 1928. The Geology of Arran. *Mem. Geol. Survey,* HMSO Edinburgh.

**Day 8: Sunday, March 11th, 2018 – Fly back to DC**

**6:00 AM:** Leave hostel to return the cars and for the airport
**8:55 AM:** Depart from Glasgow (British Air BA1447) to London Heathrow
**10:25 AM:** Arrive in London
**11:25 AM:** Depart for Washington Dulles (British Air BA0217)
**3:50 PM:** Arrive in Washington, DC-Dulles (IAD)

## GLOSSARY OF SCOTTISH AND GEOLOGIC TERMS

*Most of the Scottish or Scotland specific definitions were taken from:*
Gillen, C., 2013, Geology and Landscapes of Scotland. Dunedin Academic Press Ltd., 246 pgs.

**Abhainn:** river (Gaelic)
**Accessory:** A mineral whose presence in a rock is not essential to the proper classification of the rock.
**Acid:** A descriptive term applied to igneous rocks with more than 60% silica ($SiO2$). Same as felsic.
**Active Volcano:** A volcano that is erupting. Also, a volcano that is not presently erupting, but that has erupted within historical time and is considered likely to do so in the future.
**Alkalic:** Rocks which contain above average amounts of sodium and/or potassium for the group of rocks for which it belongs. For example, the basalts of the capping stage of Hawaiian volcanoes are alkalic. They contain more sodium and/or potassium than the shield-building basalts that make the bulk of the volcano.
**Allt:** stream (Gaelic)
**Andesite:** Volcanic rock (or lava) characteristically medium dark in color and containing 54 to 62 percent silica and moderate amounts of iron and magnesium.
**Armorican Orogeny:** Mountain-building episode in central Europe, Carboniferous to Permian, 380-280 million years; Gondwana collided with Laurussia and created the supercontinent of Pangea; also know as the Hercynian or Variscan orogeny.
**Asthenosphere:** The shell within the earth, some tens of kilometers below the surface and of undefined thickness, which is a shell of weakness where plastic movements take place to permit pressure adjustments.
**Aquifer:** A body of rock that contains significant quantities of water that can be tapped by wells or springs.
**Badcallian:** Precambrian (2900 million years ago) folding and metamorphism of the Lewisian rocks around Scourie; previously called the Scourian
**Badenoch Group:** Quartz-rich metamorphic rocks found to the east of the Great Glen Fault; deposited as sediments around 870 million years ago; basement to the Dalradian; previously known as Central Highland Migmatite Complex.
**Bàgh:** bay (Gaelic)
**Barrovian Metamorphism:** Type of regional metamorphism found in the Grampian Highlands, showing progressive grades from slate (originally shale) through schist to gneiss with increasing pressure and temperature.
**Barrow's metamorphic zones:** Progressive sequence of minerals in regional metamorphic rocks, from chlorite to biotite, then garnet, kyanite, and sillimanite.
**Basalt:** Volcanic rock (or lava) that characteristically is dark in color, contains 45% to 54% silica, and generally is rich in iron and magnesium.
**Basement:** The undifferentiated rocks that underlie the rocks of interest in an area.

**Basic:** A descriptive term applied to igneous rocks (basalt and gabbro) with silica ($SiO_2$) between 44% and 52%. Same as mafic

**Bealach:** mountain pass (Gaelic)

**Ben:** mountain (Gaelic: shortened form of beinne)

**Blanket bog:** Broad, flat expanse of peat.

**Buchan type metamorphism:** High-temperature regional metamorphism, found in Dalradian schists of Northeast Scotland, adjacent to large-ultrabasic igneous intrusion.

**Caldera:** The Spanish word for cauldron, a basin-shaped volcanic depression; by definition, at least a mile in diameter. Such large depressions are typically formed by the subsidence of volcanoes. Crater Lake occupies the best-known caldera in the Cascades.

**Caledonian orogeny:** Mountain-building episode 500-400 million years old that created the mountain chain in Ireland, Scotland, Wales, western Norway, and Greenland. Early events are referred to as Grampian, later as Scandian.

**Cauldron subsidence:** Collapse of a cylindrical volcanic crater and subsurface igneous intrusion into deeper levels of the crust, with the formation of a ring fracture; this is followed by upwelling of magma to form a ring intrusion near the surface.

**Cinder Cone:** A volcanic cone built entirely of loose fragmented material (pyroclastics.)

**Cirque:** A steep-walled horseshoe-shaped recess high on a mountain that is formed by glacial erosion.

**Cleavage:** The breaking of a mineral along crystallographic weak lattice planes that reflect weaknesses in a crystal structure.

**Columbia:** Precambrian supercontinent made of Laurentia and Baltica that formed 2100-1800 million years ago and lasted to 1500-1200 million years ago.

**Composite Volcano:** A steep volcanic cone built by both lava flows and pyroclastic eruptions.

**Conduit:** A passage followed by magma in a volcano.

**Continental Crust:** Solid, outer layers of the earth, including the rocks of the continents.

**Continental Drift:** The theory that horizontal movement of the earth's surface causes slow, relative movements of the continents toward or away from one another.

**Corrie:** Glacial landform on a mountainside, caused by ice dislodging large, steep-walled segment of bedrock; also cirque (French) or cwm (Welsh).

**Country Rocks:** The rock intruded by and surrounding an igneous intrusion.

**Crag:** stone, rock, cliff (Gaelic: shortened form of creag)

**Crag and tail:** Glacial landform, crag consisting of hard igneous rock forming steep face and tail being made of softer sedimentary rock or glacial sediment behind crag; ice-movement direction was from crag to tail, giving streamlined feature.

**Crater:** A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.

**Craton:** A part of the earth's crust that has attained stability and has been little deformed for a prolonged period.

**Dacite:** Volcanic rock (or lava) that characteristically is light in color and contains 62% to 69% silica and moderate a mounts of sodium and potassium.

**Dalradian:** Sequence of late Precambrian to early Cambrian sedimentary and volcanic rocks in Scotland and Ireland, approximately 730-480 millions years old, folded and metamorphosed during the Caledonian orogeny; found between Great Glen Fault and Highland Boundary Fault; also known as Dalradian Supergroup.

**Detachment Plane:** The surface along which a landslide disconnects from its original position.

**Diatreme:** A breccia filled volcanic pipe that was formed by a gaseous explosion.

**Dike:** A sheet-like body of igneous rock that cuts across layering or contacts in the rock into which it intrudes.

**Dormant Volcano:** Literally, "sleeping." The term is used to describe a volcano which is presently inactive but which may erupt again. Most of the major Cascade volcanoes are believed to be dormant rather than extinct.

**Drainage Basin:** The area of land drained by a river system.

**Durness Limestone:** Informal name used here and on older maps for Durness Group carbonates. Cambrian to Ordovician in age; found in Northwest Highlands and Skye.

**Eas:** waterfall (Gaelic)

**Eclogite:** High-pressure metamorphic rock formed from basalt slab taken down a subduction zone (to 50-60 km); main mineral are red glassy garnet (pyrope) and bright green pyroxene (omphacite). Greek: specially chosen, on account of the unusual mineral compositon.

**Eilean:** island (Gaelic)

**En Echelon:** Set of geologic features that are in an overlapping or a staggered arrangement (e.g., faults). Each is relatively short, but collectively they form a linear zone in which the strike of the individual features is oblique to that of the zone as a whole.

**Eruption:** The process by which solid, liquid, and gaseous materials are ejected into the earth's atmosphere and onto the earth's surface by volcanic activity. Eruptions range from the quiet overflow of liquid rock to the tremendously violent expulsion of pyroclastics.

**Eruptive Vent:** The opening through which volcanic material is emitted.

**Essexite:** A type of gabbro; found at Lennoxtown (Campsies) and Crawfordjohn (Sanquhar); highly distinctive glacial erratic.

**Eurasia:** Giant continent consisting of Europe, India, and Asia.

**Extinct Volcano:** A volcano that is not presently erupting and is not likely to do so for a very long time in the future.

**Extrusion:** The emission of magmatic material at the earth's surface. Also, the structure or form produced by the process (e.g., a lava flow, volcanic dome, or certain pyroclastic rocks).

**Facies:** Total set of characteristics in a rock; in sedimentary rocks this will include grain composition and size, sedimentary structures, etc. and can be used to interpret past environment of deposition, e.g., river bed, delta, desert floor, shallow sea, lake, or lagoon; in metamorphic rocks the facies is a combination of pressure and temperature conditions that produced a particular set of minerals under those conditions.

**Fault:** A crack or fracture in the earth's surface. Movement along the fault can cause earthquakes or--in the process of mountain-building--can release underlying magma and permit it to rise to the surface.

**Fault Scarp** A steep slope or cliff formed directly by movement along a fault and representing the exposed surface of the fault before modification by erosion and weathering.

**Felsic:** An igneous rock having abundant light-colored minerals.

**Felsite:** Red or black very fine-grained igneous rock, originally a volcanic glass.

**Fluvial:** Produced by the action of flowing water.

**Formation:** A body of rock identified by lithic characteristics and stratigraphic position and is map able at the earth's surface or traceable in the subsurface.

**Glen:** narrow valley (Gaelic: shortened form of gleann)

**Gondwana (Gondwanaland):** Supercontinent formed 200 million years ago by the accretion of the southern continents, Australia, Antarctica, South America, India, and Africa; began to rift apart 180 million years ago.

**Gorm:** green, bluish green (Gaelic)

**Graben:** An elongate crustal block that is relatively depressed (down dropped) between two fault systems.

**Grampian Phase:** Deformation and metamorphism of Moine and Dalradian rocks in the Highlands, 480-465 million years ago; gabbros and granites in Aberdeenshire formed in the event; caused by the collision of edge of Laurentia with an island arc; early part of the Caledonian orogeny.

**Grenville orogeny:** A series of mountain-building events (folding, metamorphism, Migmatite formation) in the Precambrian that led to the formation of the Rodinia supercontinent, comprising Laurentia, Baltica, Siberia, and Gondwana, 1100-900 million years ago; eclogites formed in Glenelg, and there were movements on the Outer Hebrides Fault

**Hardness:** The resistance of a mineral to scratching.

**Hebridean Igneous Province:** Scottish Part of the North Atlantic Igneous Province, active mainly 60-55 million years ago; previously known as the British Tertiary Igneous Province.

**Hercynian orogeny:** Mountain-building episode in central Europe, Carboniferous to Permian, 380-280 million years ago; Gondwana collided with Laurussia and created the supercontinent of Pangea; also known as the Variscan or Armorican orogeny.

**Highland Border Complex:** Series of sedimentary and igneous rocks, including ocean-floor pillow lavas, of late Precambrian to Ordovician age (600-450 million years old) found patchily in a narrow belt along the Highland Boundary Fault.

**Highland Border Ophiolite:** Part of the Highland Border Complex lying tectonically above the sedimentary Trossachs Group (top of the Dalradian), probably originated from slices of the mantle and ocean floor.

**Holocene:** The time period from 10,000 years ago to the present. Also, the rocks and deposits of that age.

**Horst:** A block of the earth's crust, generally long compared to its width that has been uplifted along faults relative to the rocks on either side.

**Iapetus Ocean:** Wide (up to 2000 km) ocean between Laurentia (North America, Greenland, and Scotland), Gondwana (Europe and the southern continents), and Baltica (Scandinavia and Russia) that existed from 580 to 420 million years ago; the line of collision between Scotland and Englan along the Solway Firth is known as the Iapetus Suture.

**Ignimbrite:** Igneous rock formed by ash and broken crystals in a violent volcanic eruption, so hot that clouds of material are welded together.

**Inbhir:** mouth of a river (Gaelic)

**Innis:** pasture beside a river, or island in a river (Gaelic)

**Inselberg:** Landscape feature formed by steep, isolated mountain rising above low, flat terrain.

**Intermediate:** A descriptive term applied to igneous rocks that are transitional between basic and acidic with silica ($SiO_2$) between 54% and 65%.

**Intrusion:** The process of emplacement of magma in pre-existing rock.

**Intrusive:** A term that refers to igneous rock mass formed at depth within surrounding rock.

**Inver:** mouth of a river (Gaelic: shortened form of inbhir)

**Inverian:** Folding, metamorphism, and shearing events in the Lewisian Gneiss Complex around Scourie and Lochinver, younger that the Badcallin (early Silurian) events.

**Joint:** A surface of fracture in a rock.

**Kenorland:** One of the earliest supercontinents, formed by 2700 million years ago and broke up 2450-2100 million years ago with the creation of Laurentia.

**Knock and lochan:** Topography formed in Lewisian Gneiss by glacial erosion of the landscape; low, bare, rounded rocky hills (cnoc in Gaelic) with small, shallow lochs and peat bogs between.

**Knoydartian orogeny:** Folding and metamorphism events in Moine rocks of Northen Highlands 820-780 million years ago.

**Laccolith:** A body of igneous rocks with a flat bottom and domed top. It is parallel to the layers above and below it.

**Lake Cadell:** Large inland shallow lake that existed in the Carboniferous in the area that is now West Lothian, in which oil shales accumulated; home to abundant fossil fish; surrounded by volcanoes of the Bathgate Hills.

**Lake Orcadie:** Devonian (380 million years old) shallow-water lake or inland sea that occupied the area of present-day Moray Firth, Caithness, Orkney, and south Shetland, where flagstones formed and in which primitive fish lived.

**Laurasia:** Supercontinent in the northern hemisphere, formed in the Triassic by accretion of North America, Greenland, Europe, and Asia.

**Laurentia:** Precambrian continent, consisting of North America, Greenland, and Northwest Scotland; collided with Baltica and Avalonia to create the Caledonian mountain belt.

**Laurussia:** Supercontinent formed when the Iapetus Ocean closed and Baltica and Avalonia collided with Laurentia 425 million years ago.

**Lava:** Magma which has reached the surface through a volcanic eruption. The term most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified rock.

**Lava Flow:** An outpouring of lava onto the land surface from a vent or fissure. Also, a solidified tongue like or sheet-like body formed by outpouring lava.

**Laxfordian:** Series of orogenic (mountain-building) events – folding, metamorphism, shearing, and intrusion of granites and pegmatites – affecting Lewisian rocks 1900-1750 million years ago, to produce gneisses and migmatites; named after Lock Laxford in Sutherland

**Lewisian:** Precambrian gneisses (3100-1750 million years old) forming the basement rocks of the Northwest Highlands and Outer Hebrides; also known as the Lewisian Gneiss Complex.

**Lithic:** Of or pertaining to stone.

**Lithosphere:** The rigid crust and uppermost mantle of the earth. Thickness is on the order of 60 miles (100 km). Stronger than the underlying asthenosphere.

**Loch:** lake (Gaelic)

**Lochan:** small lake (Gaelic)

**Loch Lomond Readvance (Loch Lomond Stadial):** Cold period at the end of the most recent ice age, 11,000-10,000 years ago; re-establishment of a mountain icecap form Torridon to Loch Lomond, after the melting of the main ice sheet.

**Lopolith:** Large layered basic igneous intrusion in the shape of a saucer; e.g., the Great Eucrite on Rum

**Luster:** The reflection of light from the surface of a mineral.

**Machair:** Coastal landform in western Scotland, consisting of shell sand covered by rich, fertile soil; sand dunes and white sandy beaches at sea level.

**Mafic:** An igneous composed chiefly of one or more dark-colored minerals.

**Magma:** Molten rock beneath the surface of the earth.

**Magma Chamber:** The subterranean cavity containing the gas-rich liquid magma which feeds a volcano.

**Magmatic:** Pertaining to magma.

**Mantle:** The zone of the earth below the crust and above the core.

**Marl:** very fine lime mudstone

**Matrix:** The solid matter in which a fossil or crystal is embedded. Also, a binding substance (e.g., cement in concrete).

**Metasomatism:** Chemical changes brought about in rocks by the action of hot fluids (water and carbon dioxide in the main), usually penetrating from large igneous intrusions in to reactive country rocks (host rocks); useful mineral deposits may result from chemical reactions and precipitation.

**Miocene:** An epoch in Earth's history from about 24 to 5 million years ago. Also refers to the rocks that formed in that epoch.

**Moho:** Also called the Mohorovicic discontinuity. The surface or discontinuity that separates the crust from the mantle. The Moho is at a depth of 5-10 km beneath the ocean floor and about 35 km below the continents (but down to 60 km below mountains). Named for Andrija Mohorovicic, a Croatian seismologist and wild blender aficionado.

**Mòine:** peat, peat bog (Gaelic)

**Moine Thrust Zone:** Narrow belt of faulted rocks in Northwest Scotland marking the edge of the Caledonian fold belt, where Moine rocks were transported across the foreland of mainly Lewisian and Torridon rocks.

**Moine Supergroup:** Precambrian metamorphosed sediments (mica schists and quartzites), 980-875 million years old, norh of the Great Glen Fault and east of the Moine Thrust Zone in the Northwest Highlands of Scotland; also called Moine schist or Moine rocks.

**Monadnock:** Prominent, isolated mountain standing up above a low, flat plain.

**Morarian:** Folding and metamorphism of Moine rocks 750-730 million years ago.

**Nappe:** Large sheet of rock transported above a thrust fault; from French for 'tablecloth'; nappe structures are common in the Northwest Highlands, in the Moine Thrust Zone.

**Ness:** promontory (Gaelic: shortened form of nis)

**New Red Sandstone:** Permian and Triassic rocks, deposited in desert conditons

**North Atlantic Drift:** Northeastern part of the Gulf Stream that brings warm equatorial waters north to Scotland, Iceland, and northern Norway; responsible for higher winter temperatures than other places on the same latitude.

**North Atlantic Igneous Province:** Broad area of igneous activity during the Tertiary, 60-55 million years ago, embracing East Greenland and Northwest Scotland that produced large volumes of basalt lava from central complexes, e.g., Mull, Skye, Rum; resulted from a mantle plume intruding the base of the crust.

**Nunatak:** Isolated peak of bedrock protruding above an icecap; Greenlandic word.

**Obduction:** Process by which isolated slices of oceanic crust are detached and thrust upwards into folded rocks of the continental crust during mountain building; the deformed oceanic rocks in such situations are referred to as ophiolites.

**Oceanic Crust:** The earth's crust where it underlies oceans.

**Old Red Sandstone:** Continental sedimentary rocks formed in valleys and floodplains during the Devonian Period by rivers flowing off the Caledonian Mountains; the red color is due to iron staining in the cement.

**Orcadian Basin:** Sedimentary basin in northeast Scotland, encompassing Orkney, Caithness, and the Moray Firth, filled mostly with Devonian sedimentary rocks (Caithness Flagstones)

**Outer Hebrides Fault:** Major thrust fault running down the east side of the Outer Hebrides; possibly originated 1750 million years ago, moved during Grenville orogeny 1100 million years ago and during Caledonian orogeny 430 million years ago; a brittle fault, characterized by pseudotachylite intrusion along it; may represent a boundary between the Lewisian of the Hebride and the mainland; also known as Outer Isles Thrust.

**Outlier:** Isolated body of younger rock surrounded by older rocks and situated at a distance from main outcrop.

**Pangea:** Name of a supercontinent that existed from 300-200 million years ago and included all the world's continents; rifted into the northern continents or Laurasia and the southern continents or Gondwana, separated by the Tethys Sea; surrounded by the ocean Panthalassa.

**Panthalassa:** Name of the ocean that surrounded the supercontinent of Pangea.

**Peralkaline:** Igneous rocks in which the molecular proportion of aluminum oxide is less than that of sodium and potassium oxides combined.

**Pipe:** A vertical conduit through the Earth's crust below a volcano, through which magmatic materials have passed. Commonly filled with volcanic breccia and fragments of older rock.

**Pitchstone:** Volcanic glass, usually black; formed by very rapid cooling of lava so that crystals had no time to grow; forms extremely sharp fragments when broken; similar to obsidian

**Plate Tectonics:** The theory that the earth's crust is broken into about 10 fragments (plates,) which move in relation to one another, shifting continents, forming new ocean crust, and stimulating volcanic eruptions.

**Pleistocene:** An epoch in Earth history from about 2-5 million years to 10,000 years ago. Also refers to the rocks and sediment deposited in that epoch.

**Plug:** Solidified lava that fills the conduit of a volcano. It is usually more resistant to erosion than the material making up the surrounding cone, and may remain standing as a solitary pinnacle when the rest of the original structure has eroded away.

**Plug Dome:** The steep-sided, rounded mound formed when viscous lava wells up into a crater and is too stiff to flow away. It piles up as a dome-shaped mass, often completely filling the vent from which it emerged.

**Pluton:** A large igneous intrusion formed at great depth in the crust.

**Precambrian:** All geologic time from the beginning of Earth history to 570 million years ago. Also refers to the rocks that formed in that epoch.

**Pseudotachylite:** Black glassy rock forcibly injected as thin veins into fractured gneiss along thrust planes; characteristic of Outer Hebrides Fault, where it originated by frictional melting of gneiss.

**Pumice:** Light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava. Commonly seen as lumps or fragments of pea-size and larger, but can also occur abundantly as ash-sized particles.

**Quaternary:** The period of Earth's history from about 2 million years ago to the present; also, the rocks and deposits of that age.

**Relief:** The vertical difference between the summit of a mountain and the adjacent valley or plain.

**Rhyodacite:** An extrusive rock intermediate in composition between dacite and rhyolite.

**Rhyolite:** Volcanic rock (or lava) that characteristically is light in color, contains 69% silica or more, and is rich in potassium and sodium.

**Rift System:** The oceanic ridges formed where tectonic plates are separating and a new crust is being created; also, their on-land counterparts such as the East African Rift of Africa or Southwest Rift of Hawaii.

**Rift Zone**: A zone of volcanic features associated with underlying dikes. The location of the rift is marked by cracks, faults, and vents.

**Roche Moutonnée:** A landform created by glacial erosion when bedrock outcrops are streamlined by moving ice that climbs up a smooth whaleback and plucks material away from the sheltered steep side (French: refers to a wig held on the head by pieces of sheep’s fat).

**Rodinia:** Supercontinent that formed 1100 million years ago by the collision of Laurentia, Baltica, Siberia, and Gondwana (i.e., nearly all the continents) in the Grenville orogeny, when parts of the Northern Highlands formed; Rodinia began to rift apart 750-600 million years ago, when the Iapetus Ocean formed as a result; Rodinia is derived from the Russian for ‘motherland’.

**Scandian Phase:** Folding, metamorphism, and thrusting events in Northern Highlands 435-425 million years ago; late stage of Caledonian orogeny.

**Scoria:** A bomb-size (> 64 mm) pyroclast that is irregular in form and generally very vesicular. It is usually heavier, darker, and more crystalline than pumice.

**Scourian:** Folding and metamorphism of the early crust in the Northwest Highlands, to produce Lewisian gneiss and granulite, 2900 million years ago; now divided into earlier Badcallian and later Inverian events; named after Scourie Sutherland.

**Scourie Dykes:** Swarms of northwest-southeast dolerite dykes intruded into Lewisian gneiss 2400-2000 million years ago.

**Seafloor Spreading:** The mechanism by which new seafloor crust is created at oceanic ridges and slowly spreads away as plates are separating.

**Seismograph:** An instrument that records seismic waves; that is, vibrations of the earth.

**Seismologist:** Scientists who study earthquake waves and what they tell us about the inside of the Earth.

**Seismometer:** An instrument that measures motion of the ground caused by earthquake waves.

**Shearing:** The motion of surfaces sliding past one another.

**Shear Waves:** Earthquake waves that move up and down as the wave itself moves. For example, to the left.

**Sheiling:** Upland pasture, used from grazing cattle in summer; also a summer hut built on the pasture; Old Norse origin.

**Silica:** A chemical combination of silicon and oxygen.

**Sill:** A tabular body of intrusive igneous rock, parallel to the layering of the rocks into which it intrudes.

**Skerry:** A rough rocky reef near the shore (Norse origin: sgeir in Gaelic).

**Sleat Group:** Lowest part of the Torridonian, found in southeast Skye; sandstones and shales laid done by rivers and lakes.

**Specific Gravity:** The density of a mineral divided by the density of water.

**Stalactite:** A cone shaped deposit of minerals hanging from the roof of a cavern.

**Stoer Group:** Early part of the Torridonian, 1200 million years old, below the main Torridon Group, lying directly on Lewisian basement and formed of course conglomerate and sandstone; named after the Stoer Peninsula in northwest Sutherland.

**Strath:** A broad, flat river valley in the Highlands (Gaelic origin).

**Stratigraphic:** The study of rock strata, especially of their distribution, deposition, and age.

**Stratovolcano:** A volcano composed of both lava flows and pyroclastic material.

**Streak:** The color of a mineral in the powdered form.

**Strike-Slip Fault:** A nearly vertical fault with side-slipping displacement.

**Subduction Zone:** The zone of convergence of two tectonic plates, one of which usually overrides the other.

**Talus:** A slope formed at the base of a steeper slope, made of fallen and disintegrated materials.

**Tethys Sea:** Former sea that existed between Laurasia and Gondwana; obliterated by the creation of the Alpine-Himalayan mountain chain; the Mediterranean Sea is the last remnant of Tethys.

**Torridon Group:** Red sandstone, arkose and conglomerate, 1000 million years old, forming imposing mountains on the northwest seaboard.

**Torridonian:** Informal name for an important sedimentary formation lying above the Lewisian basement and below Cambrian-Ordovician sediments of the Northwest Highlands, west of the Moine Thrust Zone.

**Trachyandesite:** An extrusive rock intermediate in composition between trachyte and andesite.

**Trachybasalt:** An extrusive rock intermediate in composition between trachyte and basalt.

**Trachyte:** A group of fine-grained, generally porphyritic, extrusive igneous rocks having alkali feldspar and minor mafic minerals as the main components, and possibly a small amount of sodic plagioclase.

**Trossachs Group:** Proposed name for youngest part of the Dalradian, above the Southern Highlands Group; sedimentary part of the Highland Border Complex, beneath the Highland Border Ophiolite; age is early Cambrian to early Ordovician.

**Tuff:** Rock formed of pyroclastic material.

**Ultramafic:** Igneous rocks made mostly of the mafic minerals hypersthene, augite, and/or olivine.

**Unconformity:** A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in continuity of a depositional sequence of sedimentary rocks or a break between eroded igneous rocks and younger sedimentary strata. It results from a change that caused deposition to cease for a considerable time, and it normally implies uplift and erosion with loss of the previous formed record.

**Variscan orogeny:** Mountain-building episode in central Europe, Carboniferous to Permian, 380-280 millions years ago; Gondwana collided with Laurussia and created the supercontinent of Pangea; also known as Hercynian or Armorican orogeny.

**Vent:** The opening at the earth's surface through which volcanic materials issue forth.

**Vesicle:** A small air pocket or cavity formed in volcanic rock during solidification.

**Viscosity:** A measure of resistance to flow in a liquid (water has low viscosity while honey has a higher viscosity.)

**Volcano:** A vent in the surface of the Earth through which magma and associated gases and ash erupt; also, the form or structure (usually conical) that is produced by the ejected material.

**Volcanic Arc:** A generally curved linear belt of volcanoes above a subduction zone, and the volcanic and plutonic rocks formed there.

**Volcanic Complex:** A persistent volcanic vent area that has built a complex combination of volcanic landforms.

**Volcanic Neck:** A massive pillar of rock more resistant to erosion than the lavas and pyroclastic rocks of a volcanic cone.

**Vulcan:** Roman god of fire and the forge after whom volcanoes are named.

**Vulcanian:** A type of eruption consisting of the explosive ejection of incandescent fragments of new viscous lava, usually on the form of blocks.

**Wadi:** River bed or steep-sided canyon in desert regions, where large amounts of sediment are transported in intermittent flow during flash floods.

**Water Table:** The surface between where the pore space in rock is filled with water and where the pore space in rock is filled with air.

**Xenocrysts:** A crystal that resembles a phenocryst in igneous rock, but is a foreign to the body of rock in which it occurs.

**Xenoliths:** A foreign inclusion in an igneous rock.

**Younger Moines:** Former name for the Badenoch Group, previously also known as the Dava-Glen Banchor succession or the Central Highland Migmatite Complex; northeast Grampian Highlands, south of Inverness; basement to the Dalradian.

**Zechstein Sea:** Shallow, warm, salty inland sea that existed in Germany, Denmark, and the North Sea during the late Permian Period (254-250 million years ago); evaporate deposits formed (thick beds of halite, gypsum, anhydrite).

**REFERENCES**


Browne, M.A.E., and Gillen, C. (editors), 2015, A Geological Excursion Guide to the Stirling and Perth Area. Edinburgh Geological Society, 232 pgs.

Clarkson, E., and Upton, B., 2006, Edinburgh Rock: The Geology of Lothian. Dunedin Academic Press, Edinburgh, 239 pgs.

Craig, G.Y, 1991, Geology of Scotland. The Geological Society, London, 612 pgs.

Cribb, S. and Cribb, J., 1998, Whisky on the Rocks. British Geological Survey, Keyworth, Nottingham, United Kingdom, 73 pgs.

Drake et al., 2017, Discovery of a meteoritic ejecta layer containing unmelted impactor fragments, Isle of Skye. Geology, pp. 1-4.

Gillen, C., 2013, Geology and Landscapes of Scotland. Dunedin Academic Press Ltd., 246 pgs.

Gordon, J.E. & Barron, H.F., 2011, Scotland's geodiversity: development of the basis for a national framework. Scottish Natural Heritage Commissioned Report No. 417.

Gribble, C.D., Durrance, E.M., and Walsh, J.N. (editors), 1996, Ardnamurchan: A Guide to Geological Excursions. Edinburgh Geological Society, 120 pgs.

Holdsworth, R.E., Tavarnelli, E., and Clegg, P., 2002, The nature and regional significance of structures in the Gala Group of the Southern Uplands terrane, Berwickshire coast, southeastern Scotland. Geological Magazine, v. 139, n. 6, 707-717.

Hutton, J., 1795, Theory (*sic*) of the Earth with proofs and illustrations: Edinburgh, W. Creech, 2 vols. (Facsimile reprint, 1959, New York, Hafner), 000 p.

Hutton, J., 1795, Theory (*sic*) of the Earth: Royal Society of Edinburgh Transactions, v. 1, p. 209-304.

Land, D.H., and Cheeney, R.F. (editors), 2000, Discovering Edinburgh's Volcano. Edinburgh Geological Society, Leaflet.

MacDonald, J.G., 2015, Isle of Arran: Corrie Shore. Geological Society of Edinburgh Excursion Itineraries. Version 1.1, 10 pgs.

MacDonald, J.G., 2015, Isle of Arran: Drumadoon and the Tormore Dykes. Geological Society of Edinburgh Excursion Itineraries. Version 1.0, 6 pgs.

MacDonald, J.G., 2015, Isle of Arran: Loch Ranza, North Newton, and Cock or Arran. Geological Society of Edinburgh Excursion Itineraries. Version 1.0, 6 pgs.

Marshak, S., and Mitra, G., 1988, Basic methods of structural geology: Prentice-Hall, Englewood Cliffs, New Jersey, 446 p.

McAdams, A.D., and Clarkson, E.N.K. (editors), 1996, Lothian Geology: An Excursion Guide. Edinburgh Geological Society, 221 pgs.

McMillan, A.A., Gillanders, R.J., and Fairhurst, J.A., 1999, Building Stones of Edinburgh. Edinburgh Geological Society, 235 pgs.

Miller, S. 2005, Mountain Geology – Skye Cuillin. The Edinburgh Geologist, v. 44, pgs. 4-9.

Pattison, D.R.M., and Harte, B., 2001, The Ballachulish Igneous Complex and Aureole: A Field Guide. Edinburgh Geological Society, 148 pgs.

Rudwick, M. and Palmer, A., 2009, The Parallel Roads of Glen Roy: In the footsteps of Charles Darwin – A Field Guide. Geological Society of London, History of Geology Group, Field Trip Guide, 40 pgs.

Shapira, J.A., 2014, The Scotch Whisky Guide. Gentleman's Gazette, January 21, 2014 https://www.gentlemansgazette.com/the-scotch-whisky-guide/.

Storey, C., 2008, A field guide to the Glenelg-Attadate Inlier, NW Scotland, with emphasis on the Precambrian high-pressure metamorphic history and subsequent retrogression. Scottish Journal of Geology, v. 44, no. 1, pp. 17-34.

Twiss, R. J., and Moores, E. M., 1992, Structural geology: New York, NY, W. H. Freeman and Company, 532 p.

Treagus, J., 2009, The Dalradian of Scotland, Geologists' Association Guide No. 67, The Geologists' Association, 202 pgs.

Treagus, J.E., Tanner, P.W.G., Thomas, P.R., Scott, R.A., Stephenson, D. 2013, The Dalradian rocks of the central Grampian Highlands of Scotland. Proceedings of the Geologists' Association, v. 124, pgs. 148-214.

Wilson, N., and Symington, A. (editors), 2017, Lonely Planet Guidebook: Scotland (9$^{th}$ Edition). Lonely Planet Global Limited Publishing, 480 pgs.

Woodcock, N., and Strachan, R. (editors), 2000, Geological History of Britain and Ireland. Blackwell Science, Edinburgh, 423 pgs.

## ADDITIONAL RESOURCES

### Edinburgh Geological Society

- This site has a lot of resources – Many guidebooks are available for purchase there
    - http://www.edinburghgeolsoc.org/publications/geological-excursion-guides/
- There is a searchable map linked to geology leaflet for various sites in the Edinburgh region
    - http://www.edinburghgeolsoc.org/publications/geoconservation-leaflets/

### The Geological Society of Glasgow

- A site map with various location linked to guides, also other good stuff around the website
- https://www.geologyglasgow.org.uk/geoconservation/

### Joint Nature Conservation Committee

- This site has many geological write-ups for various sites across the UK. Mostly just the quaternary geology sites are uploaded, but others are available for purchase
    - http://jncc.defra.gov.uk/page-4172
- Here are all the pdfs
    - http://jncc.defra.gov.uk/pdf/gcrdb/

**BUDGET INFORMATION**

(as of 01/14/18)

| | |
|---|---|
| Cost of plane flights ($558 x 7) | **$6,132** |
| Total cost of lodging | **$3,124** |
| Transportation (vehicles) | **$1,254** |
| Bannockburn Museum Reservations | **$170** |
| Total Expenditures so far | **$10,680** |
| Funds Remaining | **$5,970** |
| Estimation of gas and taxi costs | **$1,000** |
| Remaining funds for food, entries, etc. | **$4,970** |

*or ~$56 per person per day based on the 11 people and the 8 days on the ground in Scotland*
This will cover food and random tours we will be taking (Castles, Museums, Battlefields, Distilleries)

| | |
|---|---|
| **Total Cost of the Trip:** | **$16,650** |
| **Cost per student (5 people) for the trip** | **$1,350** |
| **Cost per professor (6 people) for the trip** | **$1,650** |

## BOOKING RECEIPTS

## AIRFARE

# Your e-ticket receipt

Dear Mr Kerrigan,

**Booking reference: MGR3XK**

Thank you for booking with British Airways.

Ticket Type: e-ticket

This is your e-ticket receipt. Your ticket is held in our systems, you will not receive a paper ticket for your booking.

**BA0292**
British Airways | World Traveller | Confirmed

| | |
|---|---|
| 3 Mar 2018<br>22:30<br>**Dulles International (DC) (Washington DC)** | 4 Mar 2018<br>10:40<br>**Heathrow (London)**<br>Terminal 5 |

**BA1484**
British Airways | Euro Traveller | Confirmed

| | |
|---|---|
| 4 Mar 2018<br>13:05<br>**Heathrow (London)**<br>Terminal 5 | 4 Mar 2018<br>14:30<br>**Glasgow**<br>Terminal M |

**BA1477**
British Airways | Euro Traveller | Confirmed

| | |
|---|---|
| 11 Mar 2018<br>08:55<br>**Glasgow**<br>Terminal M | 11 Mar 2018<br>10:25<br>**Heathrow (London)**<br>Terminal 5 |

**BA0217**
British Airways | World Traveller | Confirmed

| | |
|---|---|
| 11 Mar 2018<br>11:25<br>**Heathrow (London)**<br>Terminal 5 | 11 Mar 2018<br>15:50<br>**Dulles International (DC) (Washington DC)** |

| | |
|---|---|
| **Passenger** | MR BILL MCCONNELL |
| | MRS TERRY MCCONNELL |

# Your e-ticket receipt

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| | |
|---|---|
| 3 Mar 2018<br>22:30<br>**Dulles International (DC) (Washington DC)** | 4 Mar 2018<br>10:40<br>**Heathrow (London)**<br>Terminal 5 |

**BA1484**
British Airways | Euro Traveller | Confirmed

| | |
|---|---|
| 4 Mar 2018<br>13:05<br>**Heathrow (London)**<br>Terminal 5 | 4 Mar 2018<br>14:30<br>**Glasgow**<br>Terminal M |

**BA1477**
British Airways | Euro Traveller | Confirmed

| | |
|---|---|
| 11 Mar 2018<br>08:55<br>**Glasgow**<br>Terminal M | 11 Mar 2018<br>10:25<br>**Heathrow (London)**<br>Terminal 5 |

**BA0217**
British Airways | World Traveller | Confirmed

| | |
|---|---|
| 11 Mar 2018<br>11:25<br>**Heathrow (London)**<br>Terminal 5 | 11 Mar 2018<br>15:50<br>**Dulles International (DC) (Washington DC)** |

| | |
|---|---|
| **Passenger** | MR RYAN KERRIGAN |
| | MRS MARILYN LINDBERG |
| | MR STEVE LINDBERG |
| | MR SAMUEL LOUDERBACK |
| | MR JAKE MARSH |
| | MRS JESSICA MILLER |
| | MISS LAUREN RAYSICH |
| | MISS KAITLYN ROXBY |
| | MISS KIM WALTERMIRE |

## Payment Information

| | |
|---|---|
| **Ticket Number(s)** | 125-8766084267 (MRS TERRY MCCONNELL) |
| | 125-8766084268 (MR BILL MCCONNELL) |
| **Card Type** | Visa Credit |
| **Card Holder** | MR RYAN KERRIGAN |
| **Card Number** | ************9988 |
| **Billing Address** | 205 COLLEGIATE DRIVE,JOHNSTOWN PA 15904 |
| **Payment Total** | **USD 1114.88** |
| **Payment Date** | 16 Dec 2017 |
| **Flight tickets issued by** | British Airways, USA |
| **IATA Number** | 33991134 |
| **Endorsements** | Pax nonref/restrictions apply -bg:ba |
| **Fare Details** | USD 38.00 |
| **Fare breakdown** | The price of your ticket includes a carrier imposed charge per sector levied by the carrier. All taxes, fees and charges are to be paid by the member (not British Airways). |

Please note that air travel is not subject to VAT therefore we do not issue VAT receipts.

Where applicable, if you wish to change the date or time of your flight, or cancel your booking, the cost of doing so will generally be lower on ba.com than over the telephone or at a ticket desk. Service charges are subject to change. For further details and a list of the current charges, please visit:

http://ba.com/servicefees

## Extra baggage

You will have to pay for baggage which is over your allowance.

You cannot pay to take extra bags for an infant, or extra hand baggage.

Pay for extra bags using Manage My Booking

**Extra baggage charges for flight BA0292 and BA1484**
Dulles International (DC) (Washington DC) to Heathrow (London)
3 Mar 2018 22:30
Heathrow (London) to Glasgow
4 Mar 2018 13:05

| Extra baggage | Airport Price | Pre-airport price* |
|---|---|---|
| 1st item of luggage (max 23kg) | USD 100.00 | USD 90.00 |
| 2nd item of luggage (max 23kg) | USD 200.00 | USD 180.00 |
| Any additional items of luggage (max 23kg) | USD 200.00 | USD 180.00 |
| **Over weight baggage** | | |
| Each item of baggage | USD 100 | - |

**Extra baggage charges for flight BA1477 and BA0217**
Glasgow to Heathrow (London)
11 Mar 2018 08:55
Heathrow (London) to Dulles International (DC) (Washington DC)
11 Mar 2018 11:25

| Extra baggage | Airport Price | Pre-airport price* |
|---|---|---|
| 1st item of luggage (max 23kg) | USD 100.00 | USD 90.00 |
| 2nd item of luggage (max 23kg) | USD 200.00 | USD 180.00 |
| Any additional items of luggage (max 23kg) | USD 200.00 | USD 180.00 |
| **Over weight baggage** | | |
| Each item of baggage | USD 100 | - |

Pay for extra bags using Manage My Booking

*Pre-airport price means online or by booking through the British Airways contact centre.

**Very important information**

If you do not check your bags through to your final destination you may incure additional charges

## Payment Information

| | |
|---|---|
| **Ticket Number(s)** | 125-8766084256 (MISS KIM WALTERMIRE) |
| | 125-8766084257 (MR RYAN KERRIGAN) |
| | 125-8766084258 (MRS MARILYN LINDBERG) |
| | 125-8766084259 (MR STEVE LINDBERG) |
| | 125-8766084260 (MR SAMUEL LOUDERBACK) |
| | 125-8766084261 (MR JAKE MARSH) |
| | 125-8766084262 (MRS JESSICA MILLER) |
| | 125-8766084263 (MISS LAUREN RAYSICH) |
| | 125-8766084264 (MISS KAITLYN ROXBY) |
| **Card Type** | Visa Credit |
| **Card Holder** | MR RYAN KERRIGAN |
| **Card Number** | ************9988 |
| **Billing Address** | 205 COLLEGIATE DRIVE,JOHNSTOWN PA 15904 |
| **Payment Total** | **USD 5016.96** |
| **Payment Date** | 16 Dec 2017 |
| **Flight tickets issued by** | British Airways, USA |
| **IATA Number** | 33991134 |
| **Endorsements** | Pax nonref/restrictions apply -bg:ba |
| **Fare Details** | USD 171.00 |
| **Fare breakdown** | The price of your ticket includes a carrier imposed charge per sector levied by the carrier. All taxes, fees and charges are to be paid by the member (not British Airways). |

Please note that air travel is not subject to VAT therefore we do not issue VAT receipts.

Where applicable, if you wish to change the date or time of your flight, or cancel your booking, the cost of doing so will generally be lower on ba.com than over the telephone or at a ticket desk. Service charges are subject to change. For further details and a list of the current charges, please visit:

**HOTELS**

Download the Hostelworld App

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HOSTELWORLD

Home | Hostels | My Account

Dear Ryan Kerrigan,

Your booking is now confirmed and all the details you need are below. Please keep this for your records and present to the hostel on arrival. Note the hostel's terms and conditions, directions to the hostel and some handy tips and resources for your trip."

**Your booking is confirmed. Your reference number is 571-345214069**

## booking information

Cowgate Tourist Hostel,

96 Cowgate,

Edinburgh,

Scotland

p. +44 808 168 9610

f. +44 131 226 7355

email: info@hostelsinedinburgh.com

| Date | Room Details | Per Bed | Pax | Total |
|---|---|---|---|---|
| Sun 4th Mar 2018 | Double Bed Private Shared Bathroom | £27.00 | 4 Rooms | £216.00 |
| Sun 4th Mar 2018 | 4 Bed Mixed Dorm | £12.00 | 4 Beds | £48.00 |
| Mon 5th Mar 2018 | Double Bed Private Shared Bathroom | £27.00 | 4 Rooms | £216.00 |
| Mon 5th Mar 2018 | 4 Bed Mixed Dorm | £12.00 | 4 Beds | £48.00 |
| Tue 6th Mar 2018 | Double Bed Private Shared Bathroom | £27.00 | 4 Rooms | £216.00 |
| Tue 6th Mar 2018 | 4 Bed Mixed Dorm | £12.00 | 4 Beds | £48.00 |
| | | | | Total Cost: £792.00 |
| | | | | **Total Paid: US$184.01** |

**Your Payment**

The balance of £665.28 is payable in the property's currency, according to the Group Booking Terms and Conditions.

Your price includes all taxes.

## Important Information

You are due to arrive here at 17:00. Get directions to this hostel.

For your convenience, we have stored your booking in your account. Please print and retain for your records.

Click here to make your next booking

## Hostel Conditions

IMPORTANT - PLEASE NOTE :

***Reception is open between 8:00 am and 11:00 pm***

* If you are a GROUP and booking through the internet, please CALL US to make sure your whole group can be in the same room

* Check-out is 10:00am (you are welcome to store your luggage at reception).

* There is a £20 room key deposit. This is refunded when you check out and return your key

* Any cancellations MUST be made ON THE DAY BEFORE your arrival or you may be charged for the night.

Your use of this website is subject to your irrevocable acceptance without modification of these terms of use (the 'Terms') and you agree to use this website in accordance with and subject to these Terms. The Terms as set out hereunder constitute the entire agreement between you and Hostel Accommodation Limited .If you do not read or accept these Terms, do not use this website.

Here is our plain English version

***PLEASE NOTE THAT ALL GROUP BOOKINGS THAT HAVE CHILDREN UNDER THE AGE OF 16 MUST ENSURE THEY BOOK ENTIRE DORM ROOMS OR APARTMENTS FOR THE GROUPS PRIVATE USE***

Groups T&Cs:

1. You may cancel your booking up to 72hrs hours before arrival.(Does not apply to Groups) Please do so directly with the reception office at the Cowgate. If you wish to cancel by email then please do so at least 7 full days prior to your arrival.
2. All group bookings must be paid in full 28 days prior to arrival, any changes or cancellations must be done before this time.Payment will automatically taken from your credit card.
3. Deposits are never refunded.
4. In the event of a no-show without cancellation, we have the right to charge your credit card for the first night's stay where you have booked accommodation with us or for the full price of the tour or other non-accommodation travel service in accordance with your booking conditions.
5. Your contract is with Hostel Accommodation Limited. It is our responsibility to provide you with the travel services.
6. In the highly unlikely event of a problem arising, our liability to you, if any, is limited to the deposit and that reservation fee you paid.

## Hostelworld Conditions

- The outstanding amount is payable to the property directly upon your arrival unless otherwise stated in the hostel conditions above.
- Cancellations must be notified directly to the accommodation provider at least 72 hours prior to your arrival date unless otherwise stated above. In the event of cancellation you will lose your deposit unless you have chosen the Standard Flexible Booking option.
- In the event of a no show your card will be charged for the first night's accommodation total unless otherwise stated above.
- For any changes to an existing reservation please use the change booking function in My Account on hostelworld.com. Alternatively you can contact the hostel directly through this area.
- Should your credit card expire or your credit card details change prior to arrival, please contact the accommodation provider directly with the amended details.
- If you paid your deposit with a debit card or PayPal, you must reconfirm your booking 24 hours prior to arrival directly with the property.
- Please read our Terms & Conditions.
- If you have a question, please see our FAQ or contact us on +353 1 524 5800.

## Directions to your hostel

From Airport (by car)

Get on to Glasgow Road (A8) and continue straight following signs to the city centre.

When you reach the west end of Princes Street you'll see a department store called House of Fraser on your left. At the traffic lights opposite House of Fraser turn right onto Lothian Road.

Take your first left onto King's Stables Road.

Turn left at the junction onto the Grassmarket.

Continue straight along this road to the Cowgate.

Cowgate Tourist Hostel is on left of the street, opposite Three Sisters pub.

## Ryan Kerrigan: Booking WTB73E2A4 at Ardconnel House, Inverness

Ryan Kerrigan
205 Collegiate Drive
Johnstown
15904
UNITED STATES

Telephone: 6122296811
Email: kerrigan@pitt.edu

*** FOR ANY BOOKING ENQUIRIES, CORRESPONDENCE OR PAYMENT ***

Contact us by phone **01463 240455** or email **ardconnel@gmail.com**

Quote Booking Reference: **WTB73E2A4**

**1 x SINGLE ROOM 3** ( private facilities ) - 1 Adult
Guests: SAM LOUDERBACK

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 50 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 50 | incl Breakfast |
| **Totals** | **GBP 100** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 100.00 (x 1)** **£ 100.00**

**1 x SINGLE ROOM 5** ( en suite ) - 1 Adult
Guests: JAKE MARSH

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 50 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 50 | incl Breakfast |
| **Totals** | **GBP 100** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 100.00 (x 1)** **£ 100.00**

**1 x DOUBLE ROOM 4** ( en suite ) - 2 Adults
Guests: TERRY MCCONNELL

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 80 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 80 | incl Breakfast |
| **Totals** | **GBP 160** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 160.00 (x 1)** **£ 160.00**

**1 x DOUBLE ROOM 6** ( en suite ) - 2 Adults
Guests: STEVE LINDBERG

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 80 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 80 | incl Breakfast |
| **Totals** | **GBP 160** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 160.00 (x 1)** **£ 160.00**

**1 x KING/TRIPLE ROOM 7** ( en suite ) - 3 Adults
Guests: KATIE ROXBY

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 120 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 120 | incl Breakfast |
| **Totals** | **GBP 240** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 240.00 (x 1)** **£ 240.00**

**1 x DOUBLE/TWIN ROOM 2** ( en suite ) - 2 Adults

Guests: RYAN KERRIGAN

| **Nightly Rates** (rates are PER ROOM in GBP) | | |
|---|---|---|
| Date | Room | Meals |
| 07 Mar 2018 (Wed) | GBP 85 | incl Breakfast |
| 08 Mar 2018 (Thu) | GBP 85 | incl Breakfast |
| **Totals** | **GBP 170** | **incl Breakfast** |

**TOTAL RATE FOR THIS ROOM IS £ 170.00 (x 1)** **£ 170.00**

**Total: £930.00**

| Payer | Pyt Amount | Card Charge | Total Amount | Method | Paid On |
|---|---|---|---|---|---|

Payment has not been taken yet.

Total Amount Paid: **£ 0.00**

**Balance Due: £930.00**

Ardconnel House, 21 Ardconnel St, Inverness, IV2 3EU, Telephone: 01463 240455

**Guests must check in between 15:00 and 19:00 and check out between 7:00 and 10:00.**

**Payment**

No deposit required.
Payments by cash, bacs, and the following cards:
Visa Debit / Delta, Visa Credit, Maestro / Switch, Mastercard, American Express - a charge of £2.00.

**Additional Check In Notes**

Anyone wishing to check in outwith these times or drop off luggage can do so by prior arrangement.

**Your expected arrival time is 16:00**

**Cancellation Conditions**

If a booking is cancelled less than 7 days before arrival then a charge equal to the first night of the stay will be made.
If a booking is cancelled less than 2 days before arrival then a charge equal to the full booking amount will be made.
In the event of a no show or booking reduction (after arrival date) the full cost of the booking is charged.

# Euro Hostels - Glasgow

## Invoice

**04 January 2018**

| | | |
|---|---|---|
| Group | Kerrigan, Ryan | Company |
| Arrival: | 09/03/2018 | |
| Departure: | 11/03/2018 | |

Booking No: GLA-MG2098140

### Rooms and Beds:

| Date | Description | Qty | Pers. | Price | Amount |
|---|---|---|---|---|---|
| 09/03/2018 | DP Double (2 pax Room) | 4 | 8 | £50.00 | £200.00 |
| 09/03/2018 | 4P 4-Person Private (4 pax Room) | 1 | 3 | £66.00 | £66.00 |
| 10/03/2018 | DP Double (2 pax Room) | 4 | 8 | £50.00 | £200.00 |
| 10/03/2018 | 4P 4-Person Private (4 pax Room) | 1 | 3 | £66.00 | £66.00 |

### Payments:

| Date | Description | Amount |
|---|---|---|
| 03/01/2018 22:07 | OTA Deposit | -£69.12 |

### Totals:

| | |
|---|---|
| Total excl VAT | £443.33 |
| VAT | £88.67 |
| Total incl VAT | £532.00 |
| **Total Payment Received:** | **-£69.12** |
| **Balance:** | **£462.88** |

| | |
|---|---|
| **From:** | Rentalcars.com <email@reservations.rentalcars.com> |
| **Sent:** | Wednesday, January 03, 2018 11:38 AM |
| **To:** | Kerrigan, Ryan |
| **Subject:** | Important information regarding your Rentalcars.com booking - Ref: 593222171 |

Rentalcars.com

Download the app

Dear Mr Kerrigan,

Thank you for booking through Rentalcars.com.

Your voucher is now available online to print by clicking through the "Manage my Booking" button below. You can also review your reservation, or make changes here too.

Manage My Booking

Please carefully check to make sure all your travel details are correct.

Things to remember when picking up your car
- Your voucher.
- A valid credit card in the main driver's name.
- Your Driving Licence (Both parts if applicable).

Please also check the Terms and Conditions of your reservation to make sure you do not need to take other forms of identification with you when picking up the vehicle.

At the Dollar counter, you may decide to buy additional cover – to reduce or remove your excess, or to cover things your Collision Damage Waiver (CDW) doesn't, such as tyres and windscreen.

**Please Note:** If you do buy a policy from Dollar, that contract will be between you and Dollar. Since Rentalcars.com will not be involved at all, we won't be able to help if you're dissatisfied with the cost of their policy – or the cover it provides.

Car Group: Ford Galaxy or similar
Supplier: Dollar

Pick-up details:
Country: UK
City: Glasgow
Location: Glasgow Airport
Date: 4 Mar 2018 16:00

Drop-off details:
Location: Glasgow Airport
Date: 11 Mar 2018 07:00

Total Cost: US$626.75
Flight number: walkin
Requested extras:
Special Requests: N/A

We hope you enjoy your rental.

Yours Sincerely,
Rentalcars.com Reservations Team

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Rentalcars.com is a trading name of TravelJigsaw Limited which is a limited company registered in England and Wales (Number: 05179829) whose registered address is at 100 New Bridge Street, London, EC4V 6JA.
Rentalcars.com is a part of The Priceline Group (Nasdaq:PCLN).

Gmail

Ryan Kerrigan <r.j.kerrigan@gmail.com>

**Fwd: Important information regarding your Rentalcars.com booking - Ref: 547715214**

**jessica.miller2919** <jessica.miller2919@gmail.com> Thu, Jan 11, 2018 at 7:40 PM
To: Ryan Kerrigan <r.j.kerrigan@gmail.com>

Sent via the Samsung Galaxy S7, an AT&T 4G LTE smartphone

-------- Original message --------
From: "Rentalcars.com" <email@reservations.rentalcars.com>
Date: 1/3/18 1:24 PM (GMT-05:00)
To: jessica.miller2919@gmail.com
Subject: Important information regarding your Rentalcars.com booking - Ref: 547715214

Dear Mrs Miller,

Thank you for booking through Rentalcars.com.

Your voucher is now available online to print by clicking through the “Manage my Booking” button below. You can also review your reservation, or make changes here too.

Manage My Booking

Please carefully check to make sure all your travel details are correct.

Things to remember when picking up your car
• Your voucher.
• A valid credit card in the main driver's name.
• Your Driving Licence (Both parts if applicable).

Please also check the Terms and Conditions of your reservation to make sure you do not need to take other forms of identification with you when picking up the vehicle.

At the Dollar counter, you may decide to buy additional cover – to reduce or remove your excess, or to cover things your Collision Damage Waiver (CDW) doesn’t, such as tyres and windscreen.

**Please Note:** If you do buy a policy from Dollar, that contract will be between you and Dollar. Since Rentalcars.com will not be involved at all, we won't be able to help if you're dissatisfied with the cost of their policy – or the cover it provides.

Car Group: Ford Galaxy or similar
Supplier: Dollar

Pick-up details:
Country: UK
City: Glasgow
Location: Glasgow Airport
Date: 4 Mar 2018 16:00

Drop-off details:
Location: Glasgow Airport
Date: 11 Mar 2018 07:00

Total Cost: US$626.75
Flight number: walkin
Requested extras:
Special Requests: N/A

We hope you enjoy your rental.

Yours Sincerely,
Rentalcars.com Reservations Team

The Battle of BANNOCKBURN

Ticket reference: 22286

Ryan Kerrigan

Web Reference

22286

## Participate in battle Ticket

| | |
|---|---|
| **Date:** | 7 March 2018 |
| **Time:** | 10:00 |
| 5 x Concession | 42.50 GBP |
| 5 x Adult | 57.50 GBP |
| **Total** | **100.00 GBP** |

The Battle of BANNOCKBURN

Ticket reference: 22287

Ryan Kerrigan

Web Reference

22287

## Participate in battle Ticket

| | |
|---|---|
| **Date:** | 7 March 2018 |
| **Time:** | 10:00 |
| 1 x Adult | 11.50 GBP |
| **Total** | **11.50 GBP** |

**PREVIOUS SPRING BREAK GROUPS**

**SPRING BREAK 2015 – NORTH CAROLINA**
Picture taken at Ray Mine Pegmatite mine, Spruce Pine, NC
*Left to Right*: Kris Miller, Luke Layton, Leah Marko, Andrew Barchowsky, Matt Gerber, and Ryan Kerrigan

**SPRING BREAK 2016 – ICELAND**
Picture taken on columnar joints at Reynisfjara Beach, Iceland
*Top Row*: Tyler Norris, Lorin Simboli, Allie Marra, Luke Layton; *Bottom Row:* Catie Bert, Matt Leger; *Not Pictured:* Ryan Kerrigan, Terry McConnell, and Steve Lindberg

**SPRING BREAK 2017 – HAWAII**
Picture taken at the rim of Mauna Ulu in Volcanoes National Park
*L-R*: Jacob Williamson-Rea, Tyler Norris, Kris Miller, Allie Marra, Luke Layton, Matt Leger, Katie Roxby, and Ryan Kerrigan