Session 10: An Eruptive and Intrusive History of Scotland

<u>So what is a volcano</u>? A naturally-occurring vent (a circular pipe) or fissure (a long crack) at the Earth's surface through which erupt molten lava, carrying solid fragments and gases, mainly steam and carbon dioxide. The viscosity, gas content and rate of extrusion of the **<u>magma</u>** usually determines the shape of the mountain built by successive eruptions. Once erupted, the magma is termed **<u>lava</u>**.

<u>Magma:</u> is a hot silicate (or carbonate or sulphide) melt containing dissolved volatiles and some suspended crystals. Magma is formed by partial melting of the Earth's crust or mantle and when it cools down and crystallises to a solid, it forms **<u>igneous</u>** rocks.

<u>Lava:</u> If magma escapes onto the surface, it is now called lava.

If low viscosity, it can flow faster than water. Low viscosity implies low silica, high temperature c. 1,200°C, high gas content; volcano shape also tends to be low profile and very broad (up to 100km!), e.g. Hawaii, some Icelandic volcanoes.

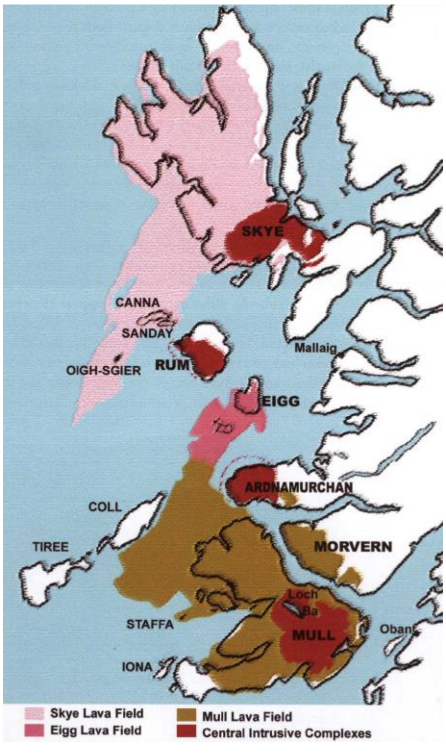
If high viscosity, it will have a higher silica content, and will flow relatively slowly, at a lower temperature (c. 800°C) and the trapped gases escape as violent explosions,
e.g. continental volcanoes, like Vesuvius, Montserrat or Mount St Helens.

<u>Extrusive rocks:</u> Lava forms various igneous rocks on the surface.
<u>Intrusive rocks:</u> Magma crystallises underground emplaced within other bedrocks

<u>Active volcanoes:</u> There are no active ('live') volcanoes in Scotland today, the nearest are in Iceland to the NW and Italy to the SE. UK is not on the margin of crustal plates at present and hence our volcanoes are extinct. In the geological past however, volcanoes were important.

<u>Overview</u>

61-58 Ma: The Palaeogene – Hebrides
360-290 Ma: Permian & Carboniferous – Midland Valley, S Kintyre, W Highlands, Orkney, Barra, S Uplands, Borders, etc
420-360 Ma: Old Red Sandstone – Lorn, Ochils, Glen Coe, Ben Nevis
500- 420 Ma: Lower Palaeozoic – Southern Uplands, Ballantrae, Highland Border
600-595 Ma: Dalradian – Tayvallich, Loch Avich
2500-635 Ma: Proterozoic – Loch Maree, Scourie, Colonsay, Islay, etc



Why do vents and fissures break through the crust?

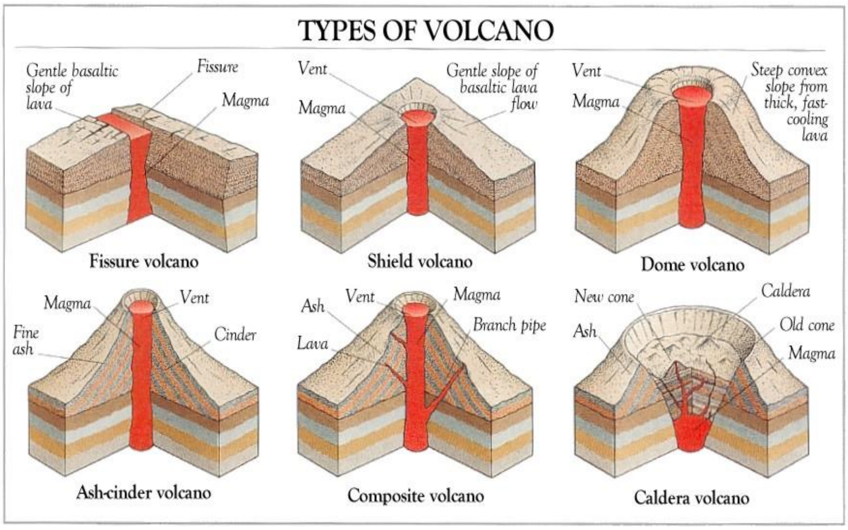
- At depth, the lithospheric rocks are solid and at high temperature, kept solid by very high pressure from the weight of overlying rocks.
- If the rocks above are put under sideways tension and then fracture, there is a local reduction of pressure. The hot solid material at depth then melts.
- The magma (molten material) is less dense than solid rock and rises up through the fractures, and making new routes as it goes.
- At lower pressure, the volatiles in the magma escape as gases.
- This is a positive-feedback system. Once it gets going, more rising causing more de-gassing, less dense, more rising etc.
- The gases provide the energy for the upward movement and may cause the lavas to spray out like a froth!

The Palaeogene Igneous Province of Britain - the early opening of the North Atlantic Ocean, c.60-50 Ma

Volcanic centres of the Inner Hebrides, with several more to the west – St Kilda, Rockall, etc – while to the south lies Arran

Mull: shield volcano possibly 5000 m from sea-floor to summit at maximum, up to 50 km diameter including lava flows. Three successive centres migrated to NW as plate moved SE. Comparable in size to Mauna Loa! Centre is related to the nearby Great Glen fault, a steep-angled fault providing a feeder route.

The Mull volcano provides an excellent example of a **ring dyke** – the **Loch Ba ring dyke** which runs in a giant mis-shapen circle around Centre 3. This enormous dyke was formed when the centre 3 of the volcano subsided into the emptied magma chamber below, squishing the remaining magma up the ring fault created by the subsidence. What is now seen is the eroded core of great central type of volcano (as opposed to fissure type). Most of present surface rocks formed as deep intrusions.



The types of material which accumulate on the surface depend on the dominant processes and the chemistry of the melt. High pressure from below produces radial fracturing and concentric fracturing around the central vent.
Magma rises through the fractures to form **radial dyke swarms** and **cone sheets.**

Types of magma

Basaltic: Geochemically called 'basic'. No free quartz, mainly iron and magnesium silicates. High temperatures (~1,200°C), low viscosity - moves fast, can flow for many kms and accumulate into enormous structures. Gases escape relatively quietly.

Acidic: Higher proportions of quartz and feldspars make them much more viscous. Lower temperature (600° C), unable to de-gas, unable to flow quickly, and prone to explosions. Result is a conical volcano, with alternating phases of explosive activity producing blasted solids – **pyroclastics** – then a later lava flow. Can be destructively violent.

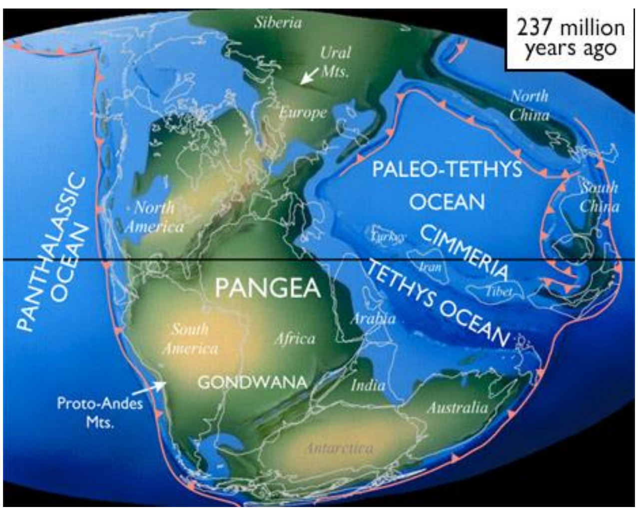
Arran: This volcano produced intermediate lavas (andesites) progressing to acid lavas (rhyolites), and pyroclastics. Siting linked to the nearby active Highland Boundary Fault, where movements allowed some melting to occur. This fault is very steep, bringing up magma from deep below.

Ardnamurchan: Complicated, mainly intruded, and interpreted as the eroded cores of **3** central volcanoes. Early basaltic magmas may have forced their way up the thrust faults of the Moine Thrust belt. Rocks to **west** are undeformed, but to **east** were involved in the Caledonian orogeny, leading to the nappe overfolds of the Grampians. **Centre 1:** pyroclastics mixed with dolerite blocks, both with large size variations; some deep basement rocks brought up with the lavas. **Centres 2 and 3:** what remains are mainly intrusive rocks.

Rum: Early basaltic flood-lavas aided by the Long Loch fault running across the island - fissure-type volcanism. Then a central vent volcano, and now the early flood-basalts have been almost totally eroded away. Acidic lavas of the cone thought to be from melting of Lewisian gneisses and overlying sandstones at depth. Finally, unusually hot basaltic magmas. (Reverse of the usual progression in igneous sites!)

Skye: four volcanic centres. The plateau of N. Skye formed by early flood-basalt lavas from fissures, fed by large dyke swarms for > 1.5 Ma. The Camasunary Fault provided a route upwards for the magmas. Then shield volcanoes - more basalts. As the melting rose higher in the mantle and crust, unusual acidic types of basalts formed.

Cuillins (dark coloured gabbros and peridotites) and the Red Hills (granites etc) formed mainly from coarse-grained intrusive rocks which crystallised 2 km below the shield volcanoes erupting on the surface. These centres migrated erratically over time through a distance of about 15km! The lavas above have now been eroded away.



Palaeozoic – Permian and Carboniferous

- Dating from 360 Ma BP to 290 Ma BP, the remains of hundreds of volcanoes litter the landscape of Scotland – from Orkney to Kelso, from St Andrews to Barra!
- So where did all this activity come from?

Mainly intra-plate vulcanism!

The Early Carboniferous *plate collision imminent!*

- Pangaea not yet formed, but Gondwana and Laurasia are about to collide – hold tight!
- Complex collision, lots of bumping, grinding and rotating!
- New mountains chains formed in the crumple zone – the Variscan Orogeny, affecting England, Wales & Ireland
- Scotland buried in the middle of a continental tectonic plate
- But under Scotland, the plate was stretched and thinned instead, allowing magma to escape!

Volcanoes of the Early Carboniferous...

...tend to be small, with localised eruptions and limited quantities of lava produced.

...are located to each side of the Solway-Tweed line, the buried site of the post-Iapetus suture between England and Scotland.

...are probably related to the faults associated with this suture line, with magma rising through fault lines that are under tension.

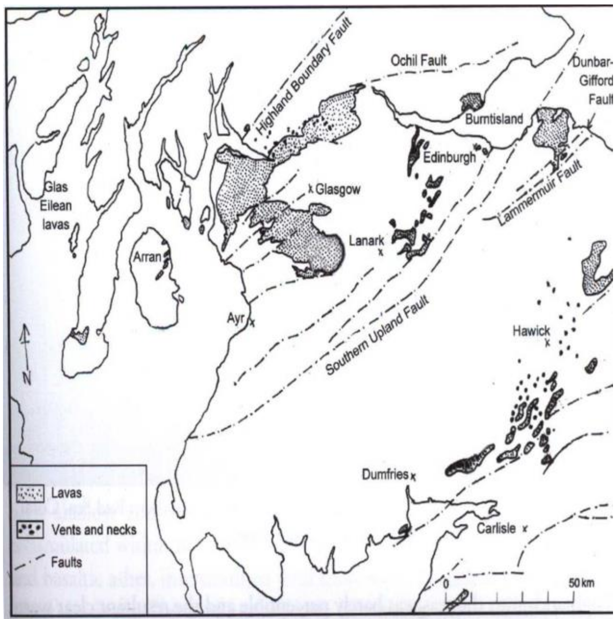


Fig. 8.1 Map of South and Central Scotland showing distribution of early Carboniferous volcanic rocks. *(After W. A. Read et al., 2002)*

Bathgate: 600m thick
Clyde plateau: 1000m thick
Macrihanish: 400 m thick
Heads of Ayr: Cliff section through vent
Edinburgh: The classic volcano!
North Berwick: 500+m thick
Eildon Hills: Trachyte/ rhyolite sills

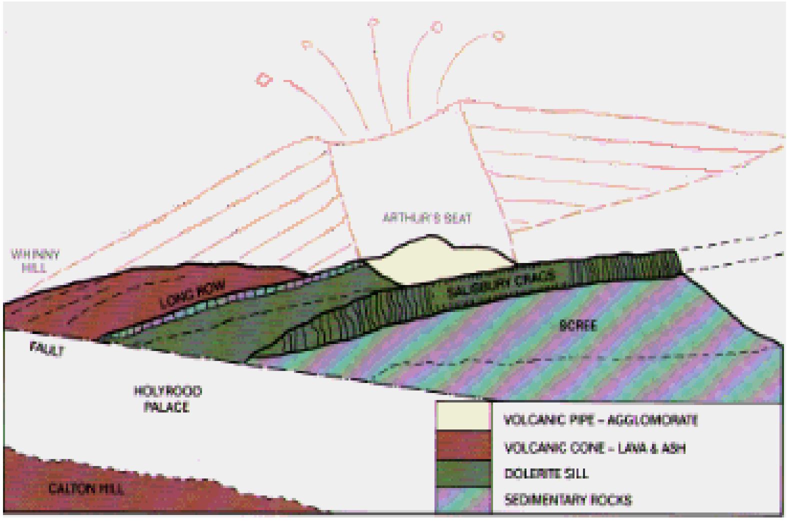
Mid-Carboniferous Volcanoes ...

... active 355 – 320 Ma.

... much larger in scale than those of the early Carboniferous, with great thicknesses of basalt lavas erupted over wide areas.

...mainly related to the Southern Upland Fault, and parallel faults in the Midland Valley.

...left remains that form major landscape features at the present time.



Edinburgh – Arthur's Seat

Evolution of the Clyde Plateau

- Probable major fault line Stirling-Dumbarton buried below later sediments provided the conduit for rising magma.
- Low-lying area in mid-Carboniferous, with surface water and waterlogged sediments.
- Rising magma encounters wet sediments – 'boiler explosions'!
- Basaltic ash propelled up and out by the superheated steam.
- Cone of basaltic ash builds up around the vent.
- Gradually the water-table recedes, and quieter eruptions of extensive basalt lava flows occur.
- Successive lava flows (mainly *aa* type – slightly more viscous, slaggy top) build up the plateau.
- Weathering and erosion of weaker flow-tops produces stepped profile of the escarpment.

....

Upper Carboniferous and Permian Volcanoes...

...active 320 – 290 Ma, generally smaller but much more numerous than earlier in the Carboniferous

...associated with emplacement of extensive dyke swarms and thick sills

...so in total accounted for the largest volume of basaltic magma generated before the Palaeogene event in Scotland.

...mainly occur on SE side of the Midland Valley, but scattered all over Scotland from Shetland to Stranraer.

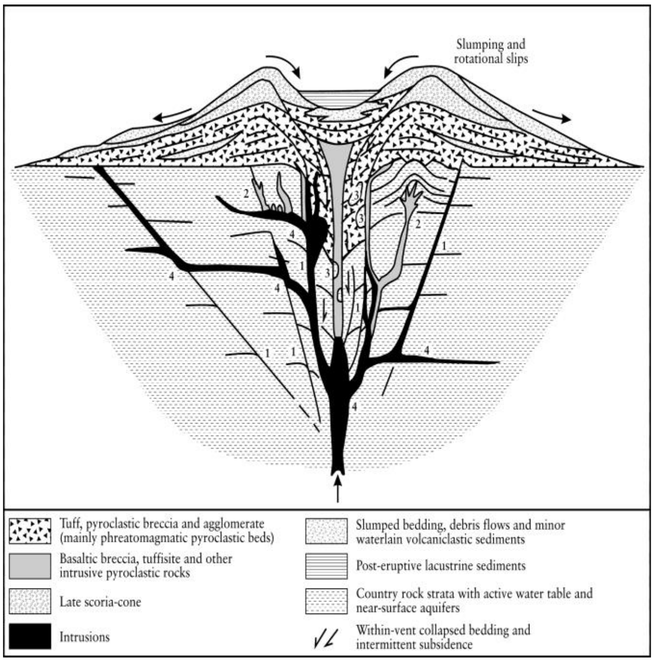
Upper Carboniferous and Permian Volcanics of the Midland Valley

... all situated *intra-plate* in Pangaea.

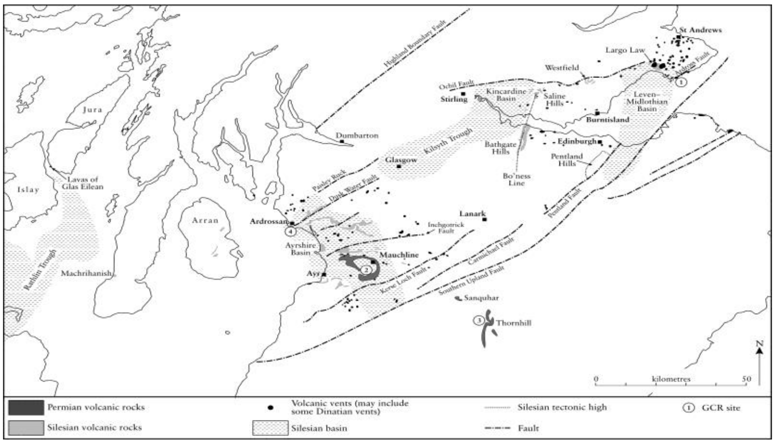
... mostly related to extensional plate thinning and faulting to relieve mantle pressure – hence sills & dyke swarms.

...occurred (320 – 300 Ma) in low-lying wet landscape, which led to repeated explosive steam-driven events.

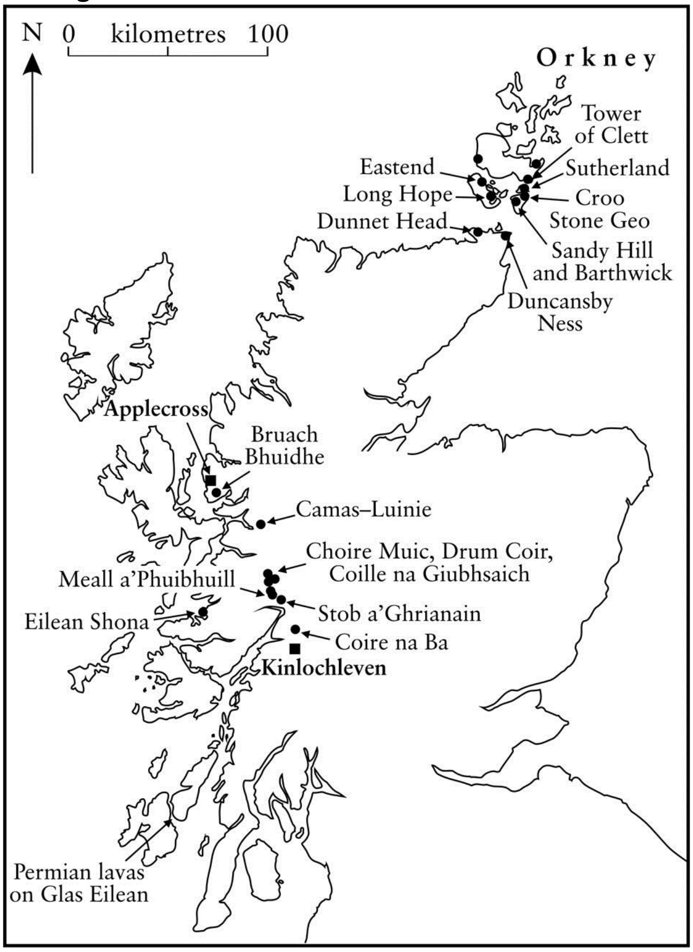
...occurred (295 – 290 Ma) in a sandy desert landscape overlying the wet sediments, still giving explosive activity.



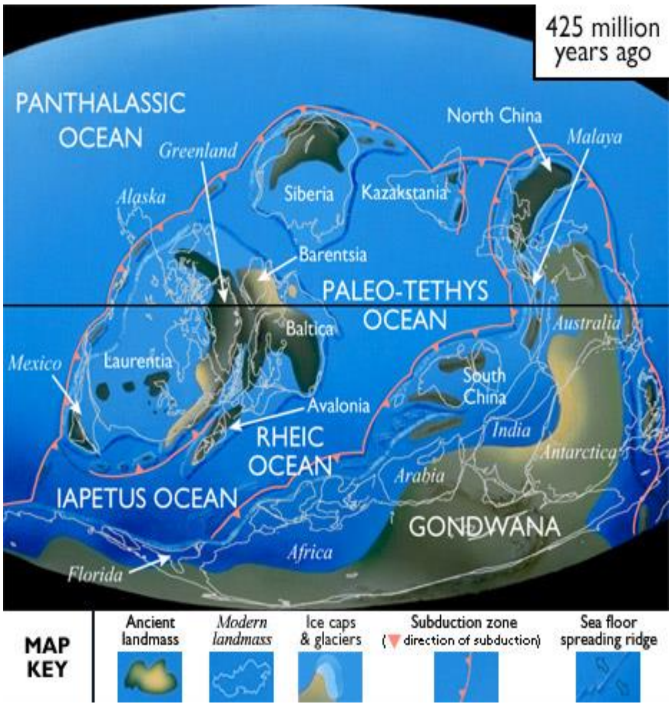
...which created a distinctive type of small vent called a **diatreme** with a relatively short life.
...left a legacy of several hundred diatremes, now seen as eroded remnants of their deep cores.



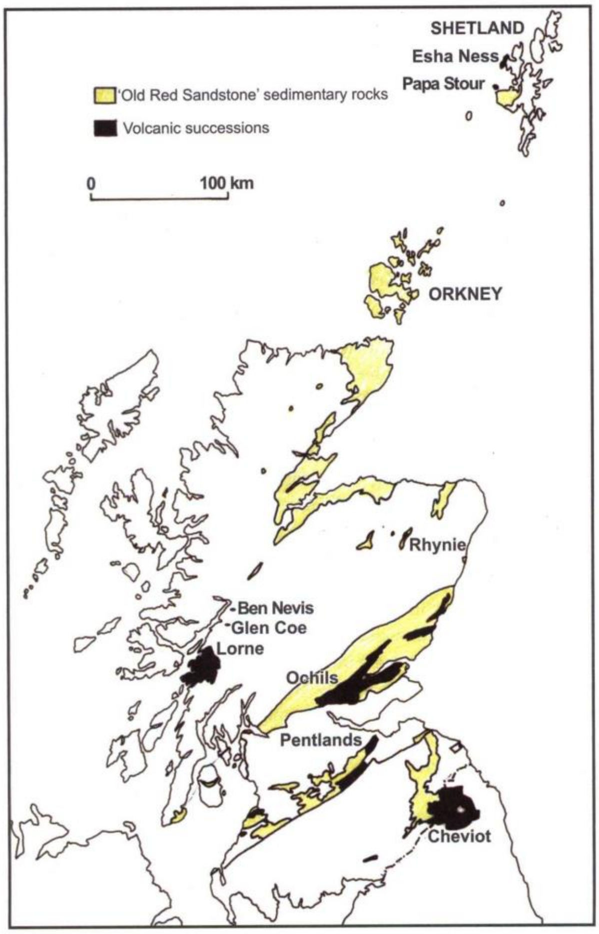
Upper Carboniferous and Permian plugs and vents in the Highlands and Islands

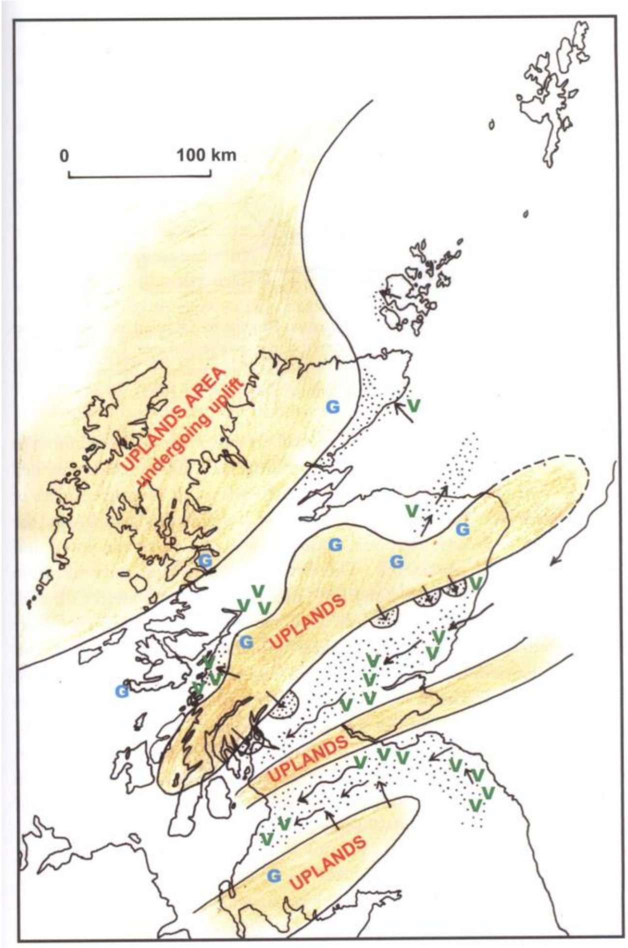


Volcanoes and the Old Red Sandstone Continent



- Active in the period 425 – 360 Ma
- Scattered from Shetland to Cheviot
- Wide variety of scales of activity
- Many inferred from feeder intrusions - erosion has removed direct evidence of extrusive events.
- Volcanoes widespread after Caledonian mountain building caused by plate collision as the Iapetus Ocean closed.
- As previously, volcanic activity relates to plate extension and thinning due to underlying mantle pressures, with magma feeding up deep faults.
- Major movements of blocks along major faults – Great Glen, Highland Boundary, etc.





Supra-Subduction Volcanism

- Modern type-example of supra-subduction volcanism – the Andes of S America.
- Magma generation for this involves material from the subducting plate melting and rising through the continental plate above, giving andesites, dacites and rhyolites – generally more viscous giving more explosive volcanism.
- Erosion has largely removed the volcanic evidence, but possible to infer from the underlying intrusive materials that remain.
- But a few clear examples of such volcanism can be found...

Some examples of inferred volcanoes

Cheviots – 395 Ma
The deep remnant of a giant volcano, possibly 60 km in diameter, up to 3 km high, which produced andesite, dacite and rhyolite lavas, and left a core of diorite and granite.

Distinkhorn, Ayrshire - 413 Ma
Rhyolite intrusion surrounded by extensive baked sedimentary rocks, implying that overlying extrusives have been eroded away.

Lorne Lavas – 420-415 Ma BP

Basalt and andesite lava flows originating from NE-SW fissures across Lorn, possibly sourced from the descending subducted Iapetus oceanic slab.

The Big Boys!

Glen Coe

- Classic example of caldera collapse
- Caldera roughly oval, 14 x 8 km
- Subsiding fault blocks initially produced a graben.
- River flowed along graben; rising magma reacted explosively with water → ignimbrite eruptions.
- Happened 5 times → a succession of ash layers.
- Sills intruded in ash layers as caldera floor subsided.
- The caldera continued to subside 0.5 km per My

The Etive Complex

- Two shallow, concentric intrusions with surrounding lavas, probably of Lorne origin.
- Later than Glen Coe
- Possibly the last stage of NE to SW migration of magmatic activity from Rannoch Moor granite to Etive
- If so, all this may represent the deep structure of an enormous siliceous volcano, with a diameter ~70km

Ben Nevis

- 7km diameter suite of intrusive granite and diorite surrounding a 2km diameter central volcanic plug
- Plug forms the mountain summit
- Ring dyke indicates caldera subsidence
- So original volcano must have been at least 1000 m higher than the present mountain

Volcanoes during the Iapetus Ocean period

- Highland Boundary Complex – from Arran and Bute to Stonehaven (430-420 Ma). Related to the welding together of the Midland Valley and Grampian terranes.
- Ballantrae Complex (576-470 Ma). Related to southern margin of the Midland Valley terrane and its collison with other plates in the history of the Iapetus Ocean.
- Southern Uplands – Moorfoot and Lammermuir Hills, among others
- Tayvallich Volcanics (600-595 Ma). Related to opening of the Iapetus Ocean.

Volcanoes in the Proterozoic

- Such a long time ago! So much evidence has been eroded and recycled, so little is left in such fragmentary form!
- Moine volcanism: rocks with basaltic composition and relict gabbro textures, called amphibolites. Indications of a major magmatic event ~870 Ma
- Torridonian times: some evidence for magmatic events in the Stoer Group, perhaps ~1200 Ma
- Early Proterozoic volcanism – Loch Maree and Gairloch area, but only tantalising hints around 2000 Ma.
- Scourie dyke swarm – but what was that all about around 2200 Ma?
- ...what a remarkable collection of the best landscape features of Scotland have been produced by volcanism
- ...so when you go touring, take a good guide to the volcanoes of Scotland with you, and see if you can make the connection between ancient volcanic events and the wonderful scenery

But the other key influence on our landscape is yet to come... ICE

Books

Volcanoes and the Making of Scotland: Brian Upton, Dunedin Academic Press
Geology and Landscapes of Scotland: Con Gillen, Terra Publishing
SNH/BGS Landscape Fashioned by Geology series:
  Scotland: The Creation of its Natural Landscape
  East Lothian & Borders
  Edinburgh
  Skye
  Fife & Tayside
  Loch Lomond to Stirling
  Mull & Iona
  Orkney & Shetland
  Rum & Small Isles
  Argyll and the Islands
Mull in the Making: Rosalind Jones (private publication)
Volcanoes: Susannah Van Rose & Ian Mercer, Natural History Museum, London

Field trips and holidays with volcanoes in mind

Geosupplies (www.geosupplies.co.uk) for Iceland, Tenerife, UK (See Down to Earth magazine)
Geowalks (www.geowalks.co.uk) for Scotland
Shetland Geotours (www.shetlandgeology.com) for Shetland