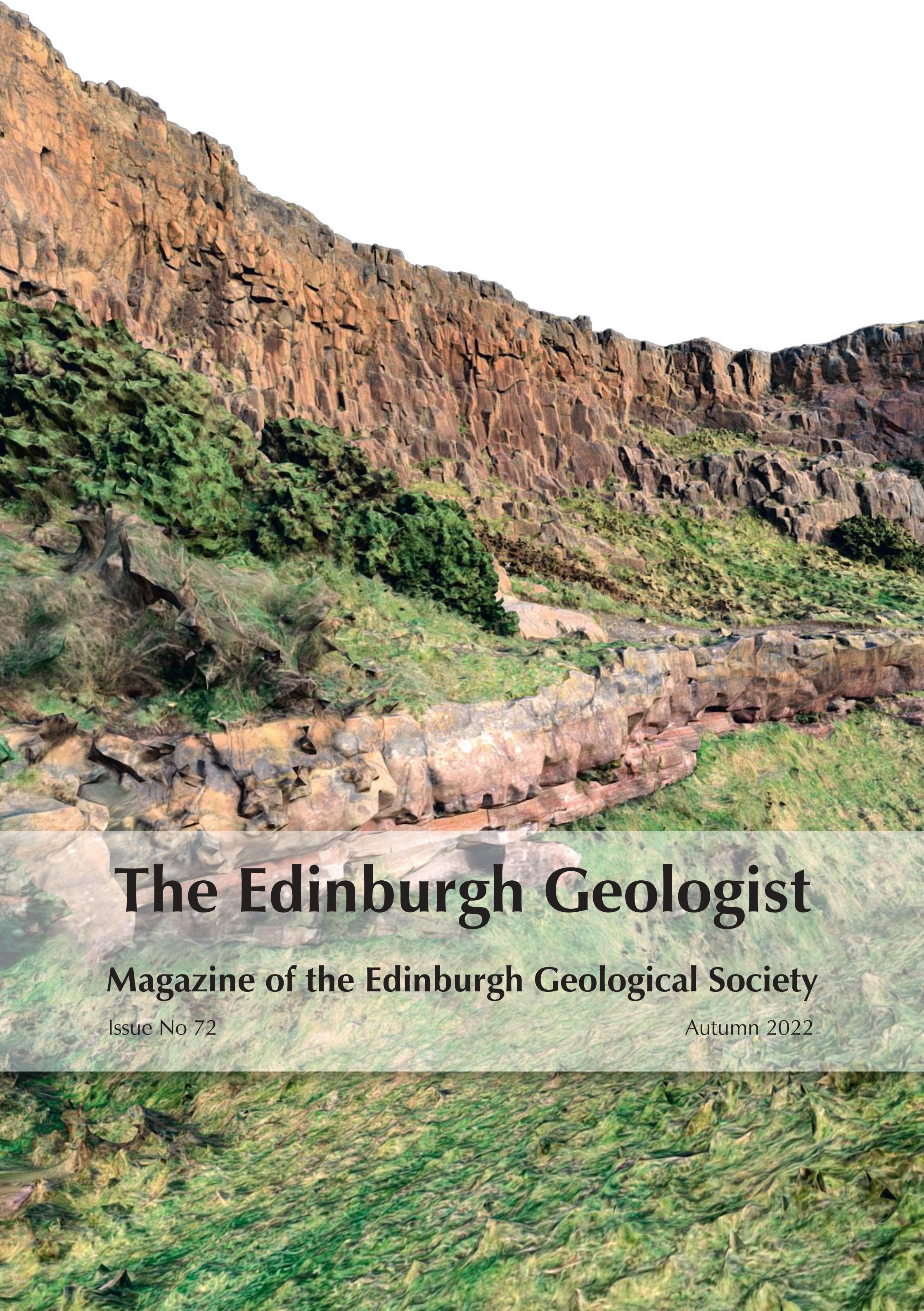

The Edinburgh Geologist

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Cover Illustration

3D model of the Hutton Section and Salisbury Crags, Holyrood Park.
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The Edinburgh Geological Society was founded in 1834 with the twin aims of stimulating public interest in geology and advancing geological knowledge. We organise a programme of lectures and excursions and also publish leaflets and excursion guides. For more information about the Society and membership, please visit www.edinburghgeolsoc.org.

Field Guide Articles

By Robert Gatliff

Edinburgh and the Borders are endowed with many field guides written by some excellent geologists with very detailed analysis of the local structure and stratigraphy, so why have I started a new set of short guides in *'The Edinburgh Geologist'* with an article on Dob's Linn? In many cases the descriptions of palaeontology, stratigraphy and structure are comprehensive. However, these days when hammering and sampling is not allowed at so many localities, we go to see not just the detail in the rocks, but to think about plate tectonics, climate and depositional environments and what was happening on not only the local, but also the regional and global scales.

I want these guides to tell us about research, new ideas and how what we see fits into a larger model of Earth history, and help our members get the message across to the wide community about our geological heritage and provide a new awareness and sense of place about our environment. The intention is to limit the detailed structure, stratigraphy and lists of fossils and to complement any existing guides.

I was asked by an EGS member if I would take him to Dob's Linn to explain its importance as a 'golden spike'. I was hardly the right person to lead such an expedition as I was last there as an undergraduate in the 1970s. Instead, Tom Challands volunteered to lead an EGS field trip, and it was a fantastic experience, with discussions on plate tectonics, the Ordovician ice ages, the Silurian — Ordovician boundary, anoxic bottom water, and the lives of graptolites. This encouraged me to start this series with an article on Dob's Linn. I'm delighted that Tom (a graptolite expert), and Phil Stone (lead author for the Ordovician-Silurian of southern Scotland in the forthcoming 5th edition of the *Geology of Scotland*) agreed to help.

In the Austrian Tyrol, the definitive boundary between the Jurassic and Triassic is marked by a golden-topped spike, hammered-in by geologists. At Dob's Linn, we have the equivalent boundary between the Ordovician and the Silurian. No golden spike, not even a display board….a missed opportunity for outreach….

Digital access to the Hutton Section and Hutton's Rock: A temporary solution to challenging conservation issues

By Dr Ewan Hyslop, Dr Lyn Wilson and Barry McPherson, Historic Environment Scotland

Introduction

Holyrood Park, in central Edinburgh, is an iconic city park with hills and crags which shape Edinburgh's skyline. It is extremely popular with local communities and visitors alike, containing archaeological evidence dating back to the Neolithic period. However, it is the park's geological features which help make it world renowned. The volcanic vent and associated lavas of Arthur's Seat created the unique geological landscape of the area, including the Salisbury Crags Sill intrusion where the Hutton Section lies, near the south end of the historic path, the Radical Road.

The park's natural and cultural assets are under the care and management of Historic Environment Scotland (HES). HES is the lead public body set up to investigate, care for and promote Scotland's historic environment. Providing safe access is central to HES's stewardship role. Since a significant rockfall event in 2018, it has not been possible to ensure safe access to the Radical Road, and therefore to the Hutton Section. This area is currently fenced to prevent entry to the dangerous areas whilst further investigations are carried out into the rock stability.

James Hutton's influence and geological significance of Hutton's Section

James Hutton's life (1726–1797) spanned the period of the Scottish Enlightenment which marked advances and discoveries in industry, commerce, agriculture, science and the arts. James Hutton made a considerable contribution to our understanding of Earth processes and of the immensity of 'deep time'. He suggested that the Earth was very old, and continually changing—a startling new idea that changed forever the way people thought about our planet. This had a major influence on other scientists such as Charles Darwin. James Hutton is now recognised as the 'father of modern geology'.

Hutton's Section in Holyrood Park, Edinburgh is a key site that supported Hutton's new understanding of geology. Found at the south end of Salisbury Crags, it holds a special place in the history of science, for it was here in the late 18th century that James Hutton found evidence to support his theories about the workings of the Earth. At Salisbury Crags, he observed igneous and sedimentary rocks and understood that they had been formed at different times by different processes (*Figure 1*).

He believed that molten rock (magma) could be 'intruded' between or across sedimentary rocks, sometimes reaching the surface as lava flows. He found evidence to support this at the base of the Salisbury Crags Sill, where magma intruded between sedimentary layers has cooled to form tough igneous rock (dolerite or whinstone). The junction between the dolerite and sandstone shows that the magma was intruded forcefully, disrupting the existing sedimentary layers. Such a dynamic contact feature is incompatible with the common view in Hutton's time that igneous rocks 'crystallised like salt from sea water.'

Figure 1** **Illustration of Dr Hutton at a rock. © The Trustees of the British Museum. NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0).

The Crags are thought to have been formed by a horizontal igneous intrusion of dolerite called the Salisbury Crags Sill, in Carboniferous times about 325 million years ago. This dolerite formed long after the main lavas and the volcanic vent of the Arthur's Seat volcano, by the process of magma intrusion deep underground. Magma rose to this level, then spread out horizontally, forcing its way between layers of existing rock causing the buckling of the strata. James Hutton was fascinated by the process, and explored Salisbury Crags in detail.

In the quarries for roadstone along the front of the Crags, Hutton found the exposed lower junction between existing Carboniferous sedimentary rocks and the dolerite of the Crags.

One important exposure, now the world-famous Hutton Section (*Figure 2*), helped him explain the relationship between the different rocks, and supported his assertion that igneous rocks were crystallised from molten magma. The locality has been visited by generations of geologists and today is included in the Arthur's Seat Volcano Site of Special Scientific Interest within Holyrood Park.

Reasons for closures and what HES is doing about it

The park's famous Radical Road, which leads to the Hutton Section is currently closed to public access due to a safety risk from rock failure adjacent to the path on Salisbury Crags. Due to the nature of the site, a degree of ongoing degradation of the rock face is a natural process and to be expected, but aspects such as climate change is accelerating the problem over time.

***Figure 2** The Radical Road and Hutton Section below Salisbury Crags within Holyrood Park. ©Crown Copyright HES.*

To help address this, Historic Environment Scotland (HES)—who manage Holyrood Park—conducts regular de-scaling work as part of its management approach, along with other forms of physical intervention to ensure the safety of visitors. As part of this work, HES has looked at various ways to provide greater insight into this area of the Park including via a digital scanning project and producing detailed 3D models of the area, which are now available online.

However, the ongoing management of the rock face is increasingly challenging and HES has commissioned further specialist input and is currently reviewing this. In the interim, HES is actively considering various options to mitigate the rockfall risk, including discussions with other relevant regulatory bodies. As HES has a statutory obligation to manage risk across Holyrood Park to ensure public safety, this has meant restricting access in certain areas for now—including the Radical Road, where an additional barrier system remains in place restricting general public access to what is presently an area of significant risk of rockfall within the park.

While the Hutton Section and Hutton's Rock remain temporarily affected by the wider closure of this section of the park, to provide managed access for specific groups, there are plans to start risk assessed, park ranger led educational visits to the site for students and educational groups with relevant personal protective equipment, over the next few months.

3D survey to enable virtual access

At HES, we look after 336 historic properties across Scotland and it is our aim to use a range of digital technologies to capture accurate, highly detailed and colourised 3D spatial information for them all. In addition, we record our collections objects in 3D. To do this, we primarily use laser scanning and photogrammetry to create 3D point clouds and 3D models. Photogrammetry (or Structure from Motion as it is also known) is achieved by taking a large number of overlapping photographs either from the ground or using a UAV (or drone). Within HES, this programme is known as the *Rae Project*, after John Rae, the Orcadian explorer and surveyor. We use this approach to record everything from small museum objects to buildings, archaeological sites and landscapes.

The 3D data created through this programme is used for a range of different purposes. First and foremost, the data supports conservation decision-making and site safety. By comparing point clouds captured over two or more periods of time, we can carry out quantitative comparisons to measure whether a building or site has changed in that time. One practical example of this is at Skara Brae in Orkney, where we have been regularly monitoring coastal change since 2010. Having an accurate baseline of a site's condition in 3D means we are better prepared for response to any disaster situation or salvage operation. *Figure 3* shows the laser scanning process in progress at St Anthony's Chapel in Holyrood Park and the point cloud generated. We also use point clouds to support our interpretation and education programmes, helping to explain construction phasing in a historic building for example.

Another application of this data which is becoming increasingly important is to provide virtual access to places and buildings. We use this approach successfully at Maeshowe Chambered Cairn in Orkney where some visitors with physical accessibility issues may not be able to get inside via the long, low passageway entrance. In these cases, a virtual tour of the interior is offered by our visitor staff on either a tablet or a virtual reality (VR) headset.

In 2019, we carried out a 3D survey at Salisbury Crags and the Radical Road in particular. This comprised 40 laser scans undertaken by the HES team over a 1.5 km route tied into permanent survey markers to georeference the data to real-world coordinates. Remote survey

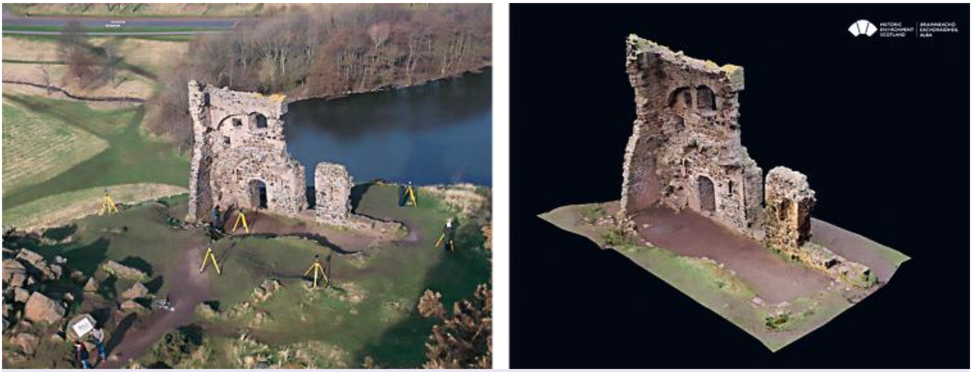


***Figure 3* (left) Laser scanning at St Anthony's Chapel, Holyrood Park as part of the Rae Project in 2017 and (right) The 3D point cloud created. ©Historic Environment Scotland.**

allows the safest data capture, so we commissioned a high-resolution UAV photogrammetry survey of Salisbury Crags, following the line of the Radical Road (*Figure 4*). An Intel Falcon 8 UAV was used with a Sony A7 mirrorless camera attached. Timing of the survey was guided by Nature Scot to ensure there were no nesting birds which could be disturbed. This UAV survey gave us approximately 14,000 overlapping photographs which were combined into one 3D model, accurate to 5mm—representing an accurate baseline of surface condition at that time.

Once we have these 3D models created, we can process them further to make them sharable and accessible online. We use a popular and free online platform called *Sketchfab* which currently has over 10 million unique users worldwide. On Sketchfab, users can virtually explore 3D environments from their phone, tablet or laptop or in a VR headset for an immersive experience. We have shared our accurate 3D data for the Hutton Section and Hutton's Rock here and annotated the models with a number of key points of interest (*Figure 5*).

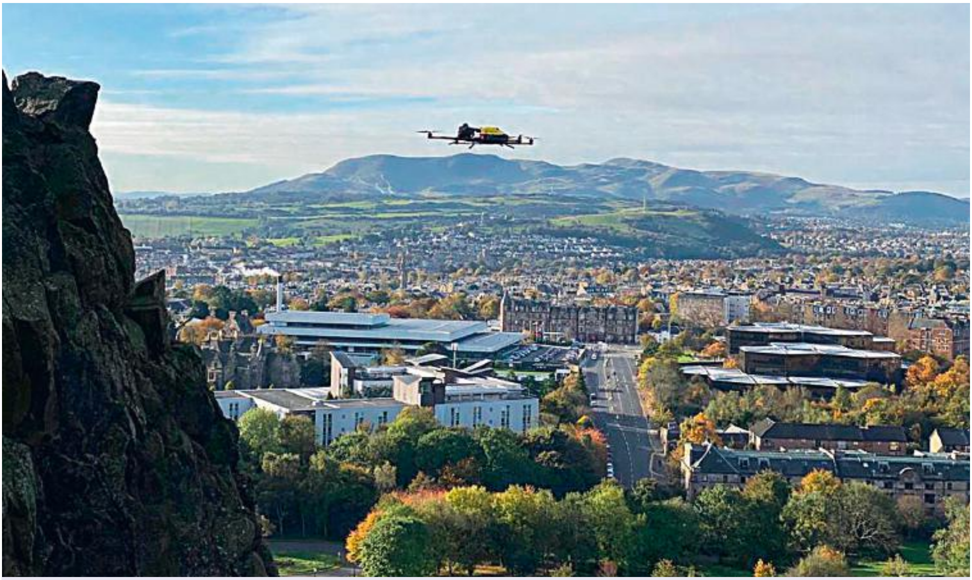
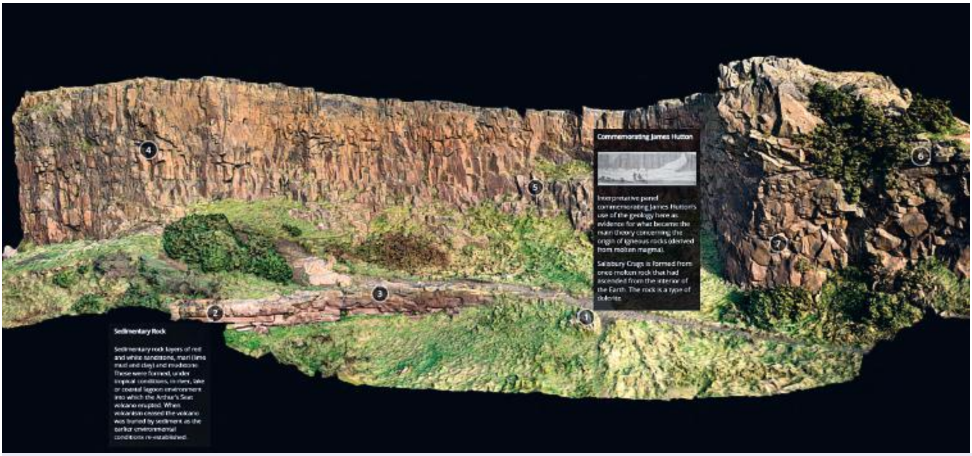


***Figure 4** UAV photogrammetry survey in progress at the Radical Road, Holyrood Park. ©Christians Geomatics.*



Interpretative panel commemorating James Hutton's use of the geology here as evidence for what became the main theory concerning the origin of igneous rocks (derived from molten magma).

Salisbury Crags is formed from once-molten rock that had ascended from the interior of the Earth. The rock is a type of dolerite.

Figure 5 Snapshot from the online Sketchfab 3D model of the Hutton Section, Holyrood Park. ©Historic Environment Scotland.

A digital model can never replace the real thing. However, it is our hope that until such time as we can safely reopen the Radical Road, virtual access can support the geological community to continue their enjoyment and understanding of this critically important geological feature. We hope too that this will be a way to engage new audiences with the significance of James Hutton and the geology of Salisbury Crags and Arthur's Seat. Explore the Hutton Section and Hutton's Rock on Sketchfab in the links below:

- Hutton Section: https://sketchfab.com/3d-models/huttonarea02-4978e5069fac4a16893ffb27833fda59
- Hutton's Rock: https://sketchfab.com/3d-models/rr-huttonarea01-08afeff0a15343cbb850f62e9530d1c7

Find out more

Historic Environment Scotland's *Rae Project*: https://www.engineshed.scot/about-us/teams/digital-documentation-and-digital-innovation/the-rae-project/

Historic Environment Scotland's *Applied Digital Documentation in the Historic Environment—Best Practice Guide*: https://www.engineshed.scot/publications/ublication/?publicationId=9b35b799-4221-446fa-80d6-a8a8009d802d

Scotland's Golden Spike at Dob's Linn: the last vestiges of the Iapetus Ocean

By Tom Challands, Robert Gatliff & Phil Stone

Before you head to Dob's Linn perhaps your first stop could be to look online at the PALEOMAP project (Plate tectonic maps and Continental drift animations by C. R. Scotese, www.scotese.com; Scotese, C.R., 2001). These continually updated maps show the latest compilation of plate tectonic reconstructions. At the end of the Ordovician the Iapetus Ocean was closing between Laurentia (including north and central Scotland) to the north-west and several continental fragments to the south-east including Avalonia (wherein lay England and Wales) and Baltica (*Figure 1*).

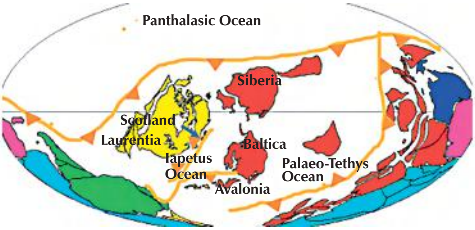


Figure 1 450MY (Late Ordovician) reconstruction. Subduction in direction of triangles; Simplified from PALEOMAP www.scotese.com.

Overall, the stratigraphy and structure at active plate margins can be very complicated. As subduction proceeds there may be collisions with seamounts, spreading ridges, fracture zones or continental fragments, which can have a huge impact on the forearc geology. A forearc basin typically contains extensive volcanic detritus, commonly redeposited by turbidity currents, but may also contain shallow water clastic rocks and/or shelf or reef limestones as well as non-marine deposits. The ocean crust, including the sediments may be subducted and consumed within the mantle or parts may be obducted on to the continental forearc. For example, at Ballantrae, the Early Ordovician volcanic and ultramafic rocks are interpreted as obducted relicts of oceanic crust and mantle, an assemblage known as an ophiolite.

By the Late Ordovician, subduction of the Iapetus Ocean was established towards the north-west under Laurentia and Scotland, and at the plate boundary an extensive volcanic arc developed beneath what is now the Midland Valley with a forearc basin on the seaward side, parts of which are preserved around Girvan. The ocean crust on the oceanic plate in front of Laurentia was relatively sediment starved with fine grained sediments falling out of suspension. When the ocean crust was nearing the subduction zone, we could expect thicker deposits and more evidence of ash layers from the arc volcanoes. Indeed, if the trench is filled with forearc sediments and/or an accretionary prism then we may see more turbidite deposits in and above the ocean floor sediments. We would also predict that the mudstones would get siltier as the ocean floor got closer to the forearc. At Dob's Linn the ash layers are fairly evenly distributed through the Llandovery succession of shales (now termed the Moffat Shale Group). Then close to the top of the mudstone there are a couple of thin turbidite sandstones before the main sandstone successions (now called the Gala Group) starts abruptly.

In the Southern Uplands we see the ocean floor mudstone and chert, overlain by a thick cover of turbidite sandstone, in successions that have been scraped off and accreted to the forearc in a series of thrust sheets to build-up an accretionary prism. The main thrust faults utilised the base of the Moffat Shale Group mudstones and have been tectonically rotated so that the thrust sheets are now more or less vertical and elongated SW-NE. Within each thrust sheet the strata young to the north-west, but with the successively older successions also appearing to the north-west (*Figure 2*). Generally, the transition from the mudstones to the overlying sandstones is progressively younger southwards, as successive thrust sheets incorporated younger ocean crust as it approached the subducting plate margin. The section at Dob's Linn traverses the base of one of these thrust sheets,

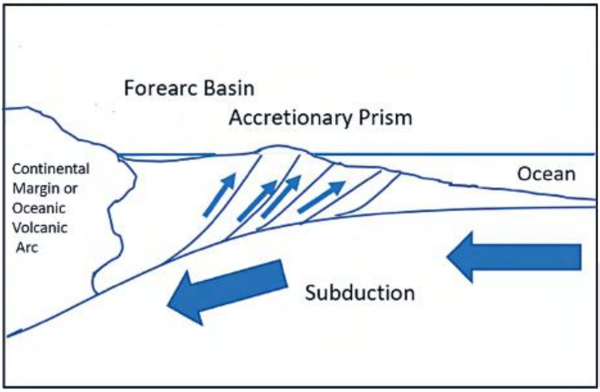


***Figure 2** Schematic illustration of thrust sheets in an accretionary prism.*

and the main (rotated) thrust fault runs along the Moffat Water Valley. It is one of the best exposures of the Moffat Shale Group and its cover of turbidite sandstones and within the Moffat Shale lies the Ordovician-Silurian boundary.

For a summary of the stratigraphy and structure of the Southern Uplands your second stop should be the BGS Regional Guide, South of Scotland (2012) or the review paper by Stone (2014). In the forthcoming new, 5th edition of 'Geology of Scotland' see chapter 7, *Middle Ordovician to mid-Silurian active margin geology of the Southern Uplands and southern Midland Valley*.

The Dob's Linn section

Dob's Linn is a small valley off the northern side of the A708 Moffat to Selkirk Road in the heart of the Southern Uplands. It was made famous by Charles Lapworth (1842–1920) who, in 1864, came to Galashiels from Berkshire as a teacher. Through his interest in geology, he became a world expert in graptolites and despite no formal geological training, Lapworth was appointed Professor of Geology at Mason College in Birmingham (later to become the University of Birmingham) in 1881. There is now a Lapworth Museum of Geology in Birmingham, and there is a plaque erected in 1930 to commemorate his work at Birkhill Cottage, where he stayed whilst working at Dob's Linn. There is a newer (2019) plaque in Galashiels on the wall of the school where he was headmaster (now Galashiels Social Work Office) at the eastern end of Church Street (*Figure 3*).

Lapworth was able to sort out the stratigraphy and realised that he could use graptolites to demonstrate that the thin successions of mudstone and chert, apparently alternating with thick successions of sandstone, were not what they seemed, but were instead a single succession repeated by faulting and folding. This laid the foundation for our modern interpretation of steeply inclined, faulted slices, the mudstone and chert at the base of each slice succeeded by younger sandstones, with the top of each sandstone succession abruptly faulted against the much older Moffat Shale at the

***Figure 3* Plaque to Charles Lapworth, Galashiels.**

base of the overlying thrust sheet to the north.

There is room for several cars in a small rough lay-by at the side of the A708 road (GR196154) or alternatively there is pay and display carpark (GR187145) at the entrance to Grey Mare's Tail about a mile towards Moffat. In this brief guide there are three stops (*Figure 4*). You can use other guides for more localities and more detail (e.g. Strachan, 1960; Clarkson & Taylor, 1992; see also http://earthwise.bgs.ac.uk/index.php/Dob's_Linn_-_an_excursion).

Stop 1 is a short walk down the grassy slope and a hop across the stream. Following the path north along the stream there are several piles of shaly rockfall at the foot of the slope where you should be able to find graptolites and even better specimens may be found further north in the scree running down into the Long Burn (*Figure 4*). There are really two types of shale: one dark grey and one paler grey. In addition, there are some thin cherts. All the clay sediments would have looked similar at time of deposition on the floor of the Iapetus Ocean. However, at times the ocean floor was oxygenated and most of the organic material was oxidised. Searching for graptolites in these pale shales will probably be unsuccessful. You will have more success in the darker, very organic-rich shales. These have kept their very high original organic content. They would once have been a very good hydrocarbon source rock but they are now over-mature after burial and heating during the later Palaeozoic or Mesozoic.

***Figure 4* Google satellite image of Dob's Linn.**

What are graptolites? How did they live? How are they preserved? How did they evolve?

Graptolites are marine colonial invertebrate animals that either lived attached to rock, mud, shells on the sea floor (sessile) or floated in the water column (planktonic). The earliest fossil records of graptolites are from the Middle Cambrian and they appeared to be extinct in the Carboniferous. However, their

Figure 5 ***Graptolites (Diplograptus truncatus BGS image P521143).***

modern relatives are still found today (Maletz, 2017) represented by the genera *Cephalodiscus* (found in the Japan Sea) and *Rhabdopleura* (found around the north Atlantic and Mediterranean).

All the graptolites at Dob's Linn were free floating and planktonic. Because they floated throughout the ancient oceans they were susceptible to ocean currents that distributed them throughout the world. Because of this, you can often find the same type of graptolites at Dob's Linn and elsewhere. The *Normalograptus persculptus* graptolite Biozone, for instance, is the last diagnostic graptolite for the Ordovician period and can be found the world over. The first time the graptolite *Akidograptus ascensus* appears in rocks marks and defines the boundary of the Ordovician and Silurian periods. This is what we see at Dob's Linn (*Figure* 6).

In order for the graptolites to have value in dividing the rocks up into suitable chunks of time, they must also have evolved rapidly. That is, a distinct species must appear abruptly, exist for a small amount of time and then become extinct abruptly. If a species existed for a long time (e.g. from the Cambrian to the Silurian) we would only be able to say that the rock was deposited sometime between the Cambrian and Silurian where we found that graptolite alone. That is no good if we are trying to pin down boundaries between geological periods.

Though the rocks at Dob's Linn have been carefully divided according to the graptolites found in them, you will likely not be able to find graptolites at the Ordovician-Silurian section itself at Dob's Linn. Indeed, hammering is not allowed there, but rest assured researchers have meticulously chipped away at the section (with permission) and identified the groups of graptolites present in the layers and how they change. This is how we are able to identify that the Ordovician-Silurian boundary is 1.6 m above the base of a series of dark, rusty weathering shales, named the Birkhill Shales by Lapworth.

Plentiful graptolites from other parts of the section can be found in the scree slopes along the main burn leading up to the GSSP (Global Stratotype Section and Point). These graptolites represent a selection from the Ordovician and Silurian which have been eroded from the cliffs above and mixed up in the scree below. You will see that they are typically preserved as either a fine white film or a black shiny impression in the rock (*Figure 5*). The former arises when the organic structure of the organism has been replaced by the clay mineral kaolinite at some point during the fossilisation process. The black carbon films are the

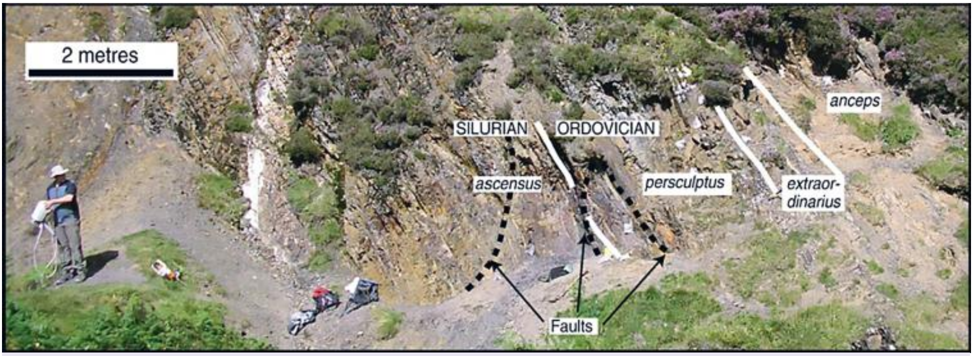


Figure 6 ***Steeply dipping overturned interbedded shales and ash layers and the golden spike at the Ordovician-Silurian boundary (Photo by Tom Challands).***

original organic material of the fossil that has become compressed and heated during burial and fossilisation to leave only an inert carbon impression. There are also examples of pyritised graptolites.

Still, many of the details of the structure of the animal colony can be seen using a hand lens. The shape of the individual 'homes' (the thecae) that the colonial graptolite animal (the zooid) lived in are often very clear and their varied shapes are often used to classify the graptolites. Besides the details of the thecae, the overall structure of the graptolite is another important diagnostic feature and you will be able to find examples of graptolites with two rows of thecae (biserial) or one row of thecae (uniserial). The various graptolites exhibit different ways of arranging the rows of thecae which, again, can be used to diagnose the genus and species.

Graptolites at Dob's Linn allow us to date the rocks in relative terms i.e. which layers are younger/older than others in the area. It was only recently that an absolute age (a number in millions of years) for the Ordovician-Silurian boundary at Dob's Linn was obtained. Typically dates from sections such as Dob's Linn rely on sampling and analysing zircons from the ash layers. At Dob's Linn, there are many ash layers but none of them lie exactly on the boundary as represented by the graptolites. Nevertheless, dates from two of the ash layers close to it have contributed to an international consensus age for the boundary of 443.8+/- 1.5Ma (https://stratigraphy.org/chart, Ogg *et al*., 2008; Melchin *et al*., 2012). A technique that analyses the ratios of the elements rhenium and osmium directly found in the clay of the boundary shales has yielded an age of 449 +/- 22 million years (Finlay *et al*. 2010) but the uncertainty is quite substantial on this measurement.

The graptolites lived in the surface waters which would have been oxygenated all the time, but it is intriguing to consider why the bottom waters were at times oxic and at other times anoxic. Recent research suggests there may be a link been the anoxic conditions and episodes of major volcanic activity, which may also have been important in graptolite evolution. In addition, there is widespread evidence of a late Ordovician ice age and in the upper Ordovician part of the Dob's Linn succession there are more oxidised pale shales. At that time sea levels were lower, the amount of CO_2 in the atmosphere was lower and the oceans were more aerated.

Stop 2 is the cliff section on the north side of Dob's Linn a few metres east of the tributary from the NW.

It is a bit of a scramble up to the outcrop so take care. Once you arrive have a good look but please don't touch and certainly don't get your hammer out! In 1985 this short section was designated as the world's type locality (*Figure* 6) for defining the boundary between the Ordovician and the Silurian. Such a boundary is known informally as a 'Golden Spike'. There are more exposures to both sides higher up the valley but they are difficult to access and you can get a really good impression of the rock types from the relatively easily accessible section. By looking south across the valley you get a good impression of the style of bedding.

Stop 3 is the famous Dob's Linn waterfall (*Figure 7*) where the main waterfall is on the base of a steeply dipping turbidite sandstone from the overlying Gala Group succession. There are excellent, large sole marks on the exposed bedding plane. There is no need to climb up!

Golden Spikes

The major boundaries between the different Geological Periods mark significant events in Earth history, often associated with drastic changes in global ecosystems. Geologists

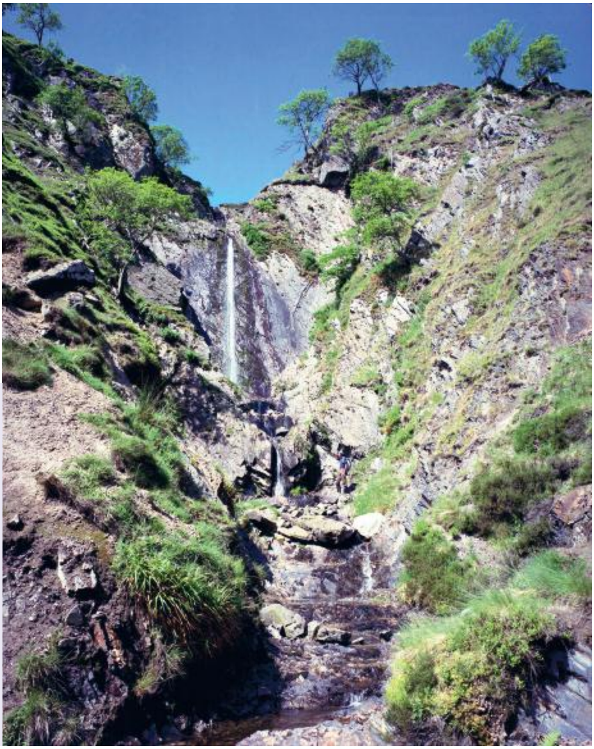


Figure 7   The Dob's Linn waterfall displaying a steeply inclined turbidite sandstone, with large sole marks, at the base of the Queensberry Formation, Gala Group, where it abruptly overlies the top of the Moffat Shale Group (BGS image P220190).

have worked to agree type sections where the boundaries are clearly defined by fossil changes backed up by accurate radiometric dating to help correlations around the world. The oldest of these based on fossils is the base of the Precambrian Ediacaran Period, where the type section is now a famous locality in Australia. The defined bases of the younger Periods are scattered throughout the world, but the Ordovician-Silurian boundary is the only one defined in Britain. Surely such a boundary and geological feature should be well known and a key piece of Earth Science history, used to enthuse people about our planet's past? Dob's Linn lies on National Trust land, but alas there is nothing at the site to indicate its importance and only minimal reference to it at the Grey Mare's Tail NT car park.

The golden spike locality didn't even make it into Scotland's '51 best places to see geology in Scotland' (although Grey Mare's Tail did: https://www.scottishgeology.com/best-places/loch-skeen-grey-mares-tail/). It might not be spectacular, but Dob's Linn is certainly one of the most important sites in Scotland.

It is unusual to see Golden Spikes located in such a thin and tectonically disturbed section, and there was an extended debate around geopolitics, history of geology and the claims of some other thicker sections in other parts of the world. The important contribution of Charles Lapworth may have swung the decision. The detailed graptolite stratigraphy, the availability of interbedded and dated volcanic ash layers through a thin but continuous, deep ocean succession provides a complete section across the Ordovician-Silurian boundary, even though the post depositional tectonic history was rather complicated.

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See also

Scotese's latest animation: https://www.youtube.com/watch?v=bzvOMee9D1o

Visualize Earth System History: https://www.climatearchive.org

Check out the interactive paleoglobes at: http://dinosaurpictures.org/ancient-earth/. You can see where your home was located at the time of the Permo-Triassic extinction or any other time in Earth History.

A complete set of the paleogeographic maps and digital elevation models can be found at: https://doi.org/10.5281/zenodo.5460860

View >50 Scotese animations at: https://www.youtube.com/user/cscotese

This ESRI website features my maps & animations and has some nice interactives: https://apl.maps.arcgis.com/apps/MapJournal/index.tml?appid=3c784abfe153444ca7bda3f53cbeef33

An archive of Scotese publications can be found at: https://www.researchgate.net/profile/Christopher_Scotese3

Download Google Earth (kml) versions of maps at: http://www.globalgeology.com/

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A giant dyke swarm in Scotland: the late-Carboniferous quartz dolerites

By Douglas Fettes, Brian Upton and Ray Macdonald

The Palaeocene Mull dyke swarm qualifies as a giant dyke swarm, extending as it does for ~1000 km from the Outer Hebrides to Dutch international waters (Macdonald et al., 2015). Here we draw attention to another set of dykes, of which Smythe (1994, p.20) claims "The swarm is probably as extensive and voluminous as the well-known and better-exposed Palaeocene swarm", and which Upton et al. (2004, p.201) describe as constituting "one of the major Phanerozoic dyke swarms of NW Europe". We contend that the late-Carboniferous quartz dolerite dykes (Westphalian; 307.6 ± 4.8 Ma) deserve renewed study, and we outline some specific potential areas of research.

In central Scotland, you are never far from a quartz dolerite intrusion; they are exposed in numerous quarries (e.g. Ratho, *Figure 1*), road and railway cuttings and riverbeds. Given that the rocks make excellent sets, it is difficult to walk for any distance around Edinburgh without encountering them as pavements or kerbstones. A pleasant day-out from Edinburgh would be to visit the Longniddry (NT 438768) and Dunbar dykes (NT 662792). Closer to home, but less impressive at 1 and 3 m wide, are the dykes cutting the Water of Leith at the Dean, and the 2 m dyke cutting the Salisbury Crags sill near the Cat's Nick. Further afield, *Figure 2* shows a fine outcrop of a dyke between Crieff and Muthill.

In the west the swarm extends from Barra to Kintyre; it then crosses the country to the east coast, a distance of approximately 300 km (Figure 35, Midland Valley Guide, 1985). The distribution is arcuate: the dominant

Figure 1 **Sill at Craigpark Quarry, near Ratho.**

E-W trend changes near the Highland Boundary Fault to ENE-WSW from Strathmore to Buchan. The dykes generally range in width from 1–2 m to ~50 m, although they can be up to 75 m wide; individual dykes are as much as 130 km long. Aeromagnetic data in the North Sea show that the dykes can be traced eastwards as far as the Central Graben, adding 200 km to the overall length of the swarm, which then totals ~500 km (Smythe, 1994). The length and thicknesses easily qualify them as being part of a giant dyke swarm, which Ernst et al. (2001) defined as having a length of ≥300 km and an average dyke width of ~10 m.

Offshore the dykes are even more impressive than onshore. Some individual intrusions are over 1 km thick, as inferred from geophysical modelling, and the cumulative width of the swarm is ~10 km (Smythe, 1994). The Dunbar anomaly (*Figure 4*), comprising one or two dykes, has a cumulative width of 2–3 km over a length of 200 km, making it (or them) as large volumetrically as any intracontinental dyke modelled (Smythe, 1994). If you visit the Dunbar dykes, take along Figures 4 and 5 and reflect on how little the surface outcrops of the dykes tell us about their true size.

The dykes can be examined at various points but one of the best is around the small headland projecting from the golf course (*Figure 5*).

The dyke swarm is associated with, and presumably fed, the Midland

***Figure 2** Dyke between Muthill and Crieff.*

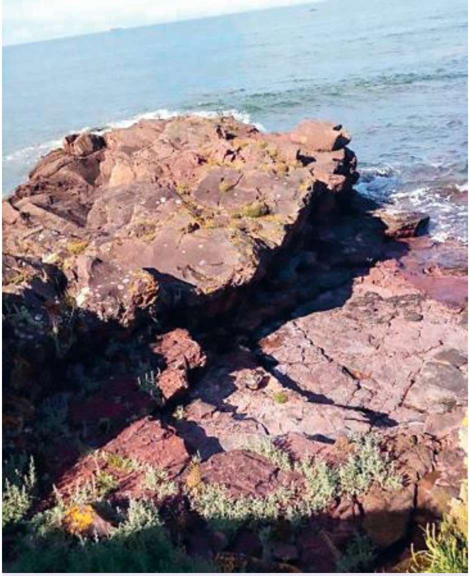

***Figure 3** The 'Big' Dyke near Dunbar.*

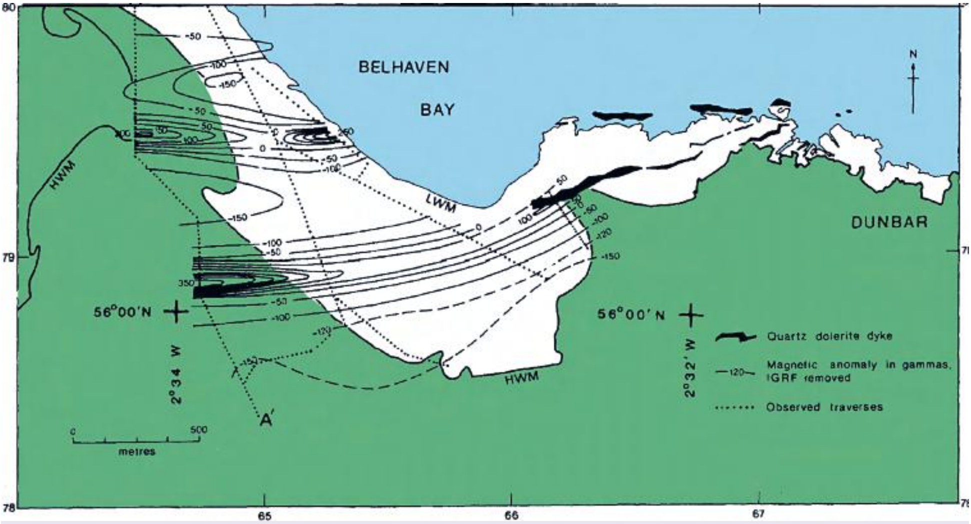

Figure 4 The Dunbar Anomaly (from Xu & Tarling, 1987).

Valley Sill-complex, which occupies an area of 1900 km^2 in the eastern Midland Valley (Fig. 35, Cameron and Stephenson, 1985). The complex is some 200 m thick and has an estimated volume of >300 km^3 (Francis, 1982). Impressive road cuts through the sill occur at the northern end of the Forth Road Bridge and, of course, Stirling Castle sits on it.

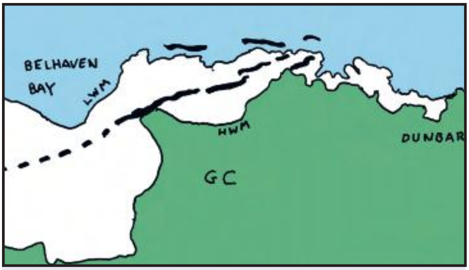

Figure 5 Location of best outcrop north-west of the golf course (GC).

So far as we know, nobody has published recently an estimate of the total volume of the quartz dolerites. This is perfectly understandable, given that much of the swarm lies offshore and that we have little idea of its vertical extent. However, a 1 km wide dyke, extending for 200 km and with a depth of 5 km (surely a minimum) would have a volume of 1000 km^3. The total volume must be in the range 10^4-10^5 km^3. That was a major contribution to the growth of Scotland, reflecting some super-event in the mantle. The activity can even be figuratively regarded as a late Palaeozoic rehearsal of the much greater events some 150 Ma later that resulted in continental rupture and the initiation of the North Atlantic Ocean.

A major unknown is the source of the dyke magmas. The fact that the dykes thicken eastwards may be consistent with the idea, promoted by Ernst and Buchan (1997), that in association with swarms of similar age in Norway and Sweden, they were generated in a hypothesized plume arising beneath the Skaggerrak area (*Figure 6*).

Evidence for a plume origin is not, however, strong; the trace element compositions and the isotopic evidence point to a major lithospheric input (Macdonald et al., 1981; Kirstein et al., 2004, 2006).

***Figure 6* Distribution of Permo-Carboniferous igneous rocks — taken from Obst et al, 2005.**

Furthermore, Macdonald et al. (1981) used trace element evidence to show that there is a small, but real, non-systematic variation in trace element compositions in the dykes; some dykes are uniquely fingerprinted by their chemical composition, e.g. the Campsie Linn (NO125340, *Figure 7*) and Twenty-shilling (NN763227) dykes. They envisaged the dykes as being erupted from a plexus of small, partly independent, magma reservoirs. It is challenging to envisage the distribution of such reservoirs both within the crust and lithospheric mantle and to speculate on how they contributed to the filling of the various dyke segments.

Along-dyke and across-dyke compositional variations in the Mull Dyke Swarm have been used to infer the mechanisms of dyke emplacement, the nature of the reservoirs from which the magmas were emplaced, and the information they provide on the major differentiation processes affecting the magmas. Macdonald et al. (1981) did some preliminary

Figure 7 Campsie Linn on the Tay (BGS image P219945).

work in this area, indicating that some dykes (e.g. the Loch Long-Auchterarder and Campsie Fells dykes) show variation along strike, while others (e.g. the Longniddry and Craigmakerran dykes) are internally differentiated. However, their sampling was rather limited and did not reveal the detailed nature of the variations. There is considerable scope for extending these studies; suggested targets might be (i) the Tyndrum dyke, which on the basis of variations in magnetization, might be a composite body (Smythe, 1994); (ii) a 12 m thick dyke extending 65 km en échelon from Rhynie to Boddam, near Peterhead (Buchan, 1932); and (iii) the Craigmakerran dyke (NO142322).

An important feature of the Mull Dyke Swarm is that the Southern Uplands Fault had a major influence on dyke propagation, variably affecting magma movement either laterally or vertically (Macdonald et al., 2015). The feature was related to changes in crustal structure across the block. Are there analogies in the late-Carboniferous swarm? Specimens of the Loch Fyne—Perth quartz dolerite dyke from west of the Highland Boundary Fault are less evolved than those further east, prompting Macdonald et al. (1981) to suggest that if the dyke represents one magma pulse, the magma was differentiated either prior to intrusion (and intruded W → E) or post-intrusion, the geographical differences representing different vertical horizons in the body. A further study of dykes on either side of the Highland Boundary Fault might reveal similar crustal heterogeneities.

On a broader scale, do the dyke compositions reflect in any way the structural terranes they cross (Hebridean, Northern Highlands, Grampian, Midland Valley and Southern Uplands)? The quest might be rather futile: Scotland's lithosphere has endured >3 Ga of melting, re-enrichment, metasomatism and delamination; geochemical signatures imparted to its magmatic products of whatever age and in whichever terrane are bound to be an amalgam of this long history.

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Hugh Miller: Two limericks from Portobello

By Jim Hurford

Hugh Miller studied the substrate
and deduced a much older date
for fossils and rock
than the biblical clock,
prompting ingenious religious debate.

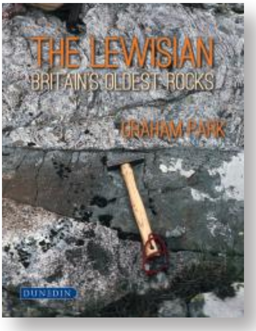
That debate fed mental strife
and Hugh Miller took his own life.
A gun to the chest
put him at rest;
his work was pushed on by his wife.

Many thanks to Jim Hurford who has pulled together and published a book of 400 limericks about life in Portobello.

For a copy of the book contact the author at jimporty@gmail.com

Book review

The Lewisian: Britain's Oldest Rocks. Graham Park. Dunedin Academic Press, Edinburgh, 2022. Hardback, xix + 315 pages, £38.



This new book by Professor Graham Park, formerly of Keele University, presents a comprehensive account of the geology of the Lewisian Gneiss Complex, from the earliest work up until the present, a period covering 200 years of research. The author himself has been a major contributor to Lewisian research for over 60 years, and this book demonstrates his extensive knowledge of the geology of what is a small region, but is important globally on account of the development of ideas and the employment of novel techniques that have influenced Precambrian research around the world.

It begins with a brief introduction, to set the scene, showing the extent of Lewisian rocks onshore and offshore, and the regional context in relation to the North Atlantic Craton. The main body of the text is divided into 19 chapters within three major sections.

Part I, the Pioneers, describes the work of MacCulloch, Murchison, Nicol, Lapworth, BGS geologists (Peach and Horne in particular) and the ground-breaking 1907 memoir on the Northwest Highlands. The contribution of John MacCulloch is given a prominent and well-deserved place in the development of early ideas. After the 1907 memoir, there was a lull in research until the work of John Sutton and Janet Watson in the 1950s, who introduced the terms Scourian and Laxfordian tectonic events, separated by a swarm of dolerite dykes, the Scourie dyke suite, which they used, for the first time anywhere, as a time marker separating the two tectonic events. Research into the rocks of the Outer Hebrides was undertaken by Jehu and Craig, Raymond Dearnley, and the Janet Watson school at Imperial College. The author singles out the late, great Janet Watson for particular praise.

Part II, collecting the data, is a thorough discussion of how ideas on the age, origin, structure and metamorphism of the Lewisian developed over time as more material was collected and new laboratory techniques were applied. Graham Park himself was instrumental in this research, although he is very modest about his own work. All the main players and their contributions are covered, with discussion of the key papers and the conclusions of a series of international conferences, convened by the author. Since he knew and worked with many of these geologists, he introduces them on first name terms and gives brief biographies, which is a nice touch. Extracts from the key papers, with relevant maps, provide a truly comprehensive account of the Lewisian of the Mainland and the Outer and Inner Hebrides. Much of this material is difficult to access these days, so this is hugely important for readers. There is good coverage of the Loch Maree Group, the introduction of the Badcallian and Inverian to replace the Scourian, and the problems associated with the Scourie dykes and their age. Geochronology, geochemistry, structural geology and metamorphism are all covered, with the South Harris igneous complex and the adjacent Langavat and Leverburgh belts of metasediments given good treatment. A notable feature is the set of clear diagrams on folding and refolding, and the various attempts at structural correlation. Using different text colours and boxes, the main research results are summarised, and Graham Park's own clear comments show how ideas have shifted over time, and how certain controversies were resolved by the use of new techniques and methods, and discussions in the field.

Part III deals with models and hypotheses, and the author shows how key concepts in structural geology have shaped the subsequent development of ideas, starting with the shear zone model, which is explained with great clarity. Much of this was based on the work of the late Mike Coward, who made major contributions to the Lewisian of the Outer Hebrides. There then follows an account of the geochemistry and metamorphism of the various components of the complex—Scourian granulites, Badcallian and Inverian metamorphism, the Loch Maree Group and other metasediments, Scourie dykes, the South Harris igneous complex, Laxfordian gneisses, migmatites, granites and pegmatites. A chapter on chronology deals with the age-dating methods employed at different times, especially modern zircon studies, and how these influenced ideas on the age and evolution of the Lewisian complex. Similarly, the introduction of rare-earth studies produced a step change in research. The vexed issue of 'terranes' is well covered, including Graham's own contribution to the debate, which remains incompletely resolved. Tectonic models are covered in the final chapter, including the Scotland–Greenland connection, and Canada–Scandinavia. This is illustrated with a set of coloured maps showing possible reconstructions of Precambrian supercontinents, and the location of the Scottish segment of the North Atlantic Craton. Ideas for future research and unanswered questions complete the text.

A comprehensive glossary, thoroughly up-to-date references section and a superb, three-level, professional index covering topics, people and localities are included.

I noted very few typos and formatting errors; accents on Gaelic and Greenlandic words are missed throughout. Most of the field photographs (in colour) are the author's own, from his mapping areas around Gairloch; I could not find any from the Outer Hebrides. More photos would have been nice of course, but this would have added to the size and cost of the book. Maps from older publications are sometimes greatly reduced to fit the page size, resulting in some loss of definition, but the main outlines are clear. A touch of colour to show lochs and the sea would have helped, but again this would have been a major task. I could not find any references to the Geological Conservation Review programme, although a major volume, edited by the late John Mendum, was published in 2009 with 20 Lewisian sites in the Outer Hebrides and the Mainland, and the current series on the Mineralogy of Scotland now appearing in the Proceedings of the Geologists Association, which covers quite a few Lewisian sites in the Hebrides.

Overall, this is an outstanding major new contribution to the geology of the Lewisian that will stand the test of time and will be of use to anyone interested in the Lewisian, or Precambrian geology in general, and in the development of ideas in structural and metamorphic geology and geochronology. Graham Park is to be congratulated on producing a work of the highest academic standard that will remain a key reference, and is a tribute to his life's work. I recommend it wholeheartedly, it has been a pleasure to read it, and I will doubtless re-read it several times over. The publisher's production team also deserve a huge vote of thanks.

Con Gillen, Edinburgh, July 2022.

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