Summary of geology

Dalradian

The oldest rocks in the area belong to the Dalradian Supergroup. In these excursions, we see only sections in the Southern Highland and Trossachs groups (Excursions 12, 18). The overall sense of younging within the Dalradian is to the SE. They are separated from younger rocks to the south by the Highland Boundary Fault, considered to be a major terrane boundary. Dalradian rocks constitute a sequence of Neoproterozoic (late Precambrian) to early Cambrian and possibly Early Ordovician (Arenig) age, cumulatively 25–30 km thick, deposited in separate but adjacent basins (Stephenson *et al*., 2013; Tanner *et al*., 2013). The strata consist mainly of marine sedimentary rocks with minor basic igneous components that developed on the SE side of the ancient continent of Pannotia, part of which became Laurentia when the Iapetus Ocean opened some 600 million years ago (Woodcock & Strachan, 2012, fig. 2.5). Sedimentation took place in marginal basins in an extensional tectonic regime. Age constraints are provided by the 601±4 Ma date for the Tayvallich Volcanic Formation (top Argyll Group), and the early Cambrian age (*c*.520 Ma) of the Leny Limestone trilobite fauna. It is now recognised that the Leny Limestone is near the top of the Dalradian in the basal part of the Trossachs Group (Woodcock & Strachan, 2012, fig 5.8).

The rocks subsequently underwent four phases of deformation during the Caledonian Orogeny, when Laurentia collided with several volcanic arcs and finally with the continent of Avalonia. During this event, the rocks were modified by folding accompanied by prograde and later retrograde regional metamorphism (Plate S.1). The earliest deformation (D_1) produced a large

SE-facing recumbent fold, the Tay Nappe (Figure S.2). Most of the Dalradian rocks lie on the lower limb of this fold, and as a result are regionally flat lying and form an inverted stratigraphical sequence. However, some re-inversion of the succession occurred as a result of later folding, notably the F_2 Ben Lui Fold and the F_4 Highland Border Downbend. The northern part of the Flat Belt is also locally steepened by broad-scale upright F_4 folds including the Ben Lawers Synform and the Loch Tay Antiform. Most of the fold phases produced a penetrative planar fabric, particularly in the more-chloritic and -micaceous (pelitic) lithologies. Fabrics associated with D_3 are developed only locally. The dominant fabric seen in most rocks is an S_1/S_2 composite schistosity or foliation. The D_4 structures produce a distinctive vertical to steeply inclined crenulation cleavage, although the earlier fabric is well preserved between the later cleavage planes (Excursion 18).

Prograde metamorphism occurred during the Mid Ordovician, probably peaking between D_2 and D_3 and increasing in intensity from greenschist facies in the SE to lower amphibolite facies in the NW. The main effects of the metamorphism ranged from simple recrystallisation of quartzo-feldspathic rocks and the development of chlorite and muscovite in more-clayrich (pelitic) protoliths at lower grades, to new growth of biotite and garnet at higher pressures and temperatures. Local retrogression of some of these metamorphic minerals, notably garnet to chlorite, probably coincided with the first major uplift of the Caledonian Orogeny in the Late Ordovician. Major and rapid uplift of the Dalradian rocks followed in the Silurian, when copious volumes of granitic and dioritic magmas were emplaced in the crust. For an up-to-date discussion of the geology of Dalradian and Highland Border rocks, see the *Dalradian of Scotland* Geological Conservation Review (GCR) (Stephenson *et al*., 2013).

The Highland Border

A sequence of mainly fault-bounded mafic, ultramafic and sedimentary rocks along the Highland Boundary Fault were previously know as the Highland Border Complex. More-recent re-investigations, notably by Tanner (2011) and Bluck (2010, 2011), produced radically different interpretations; the current consensus appears to lie with the former author. According to this interpretation, the Highland Border Complex is made up of the Highland Border Ophiolite and the bulk of the newly defined Trossachs Group (see Tanner *et al*., 2013 for a discussion and references). In this area, only the serpentinite component of the ophiolite exists. However, in the Braeleny excursion (Excursion 12), highly tectonised black mudstones adjacent to the Highland Boundary Fault might conceivably be part of the complex. For excursions to the

Highland Border Complex (Balmaha and Aberfoyle district), see Lawson & Weedon (1992). For an alternative excursion to Little Glen Shee and Rotmell, see Treagus (2009).

Devonian

The Devonian is represented in the district by thick terrestrial deposits of the Lower Old Red Sandstone lithofacies. These deposits were eroded from mountains formed in the Caledonian Orogeny and deposited in the actively subsiding Strathmore Basin in a left-lateral transtensional tectonic regime. Scotland then lay 30° south of the Equator on the eastern margin of the continent of Laurussia (Woodcock & Strachan, 2012, fig. 12.1). A major braided river system flowed south-westwards along the basin axis, joined by lateral streams from the Grampian Highlands, which deposited alluvial fans. Muds, silts and fine sands were laid down in lakes, some of which contain fossil fish and plants that illustrate the colonisation of the land by larger and more-complex forms, i.e. vascular plants and rooting systems.

(Table S.1) Lower Devonian Lithostratigraphy

Group	**Formation**
Stratheden	Stockiemuir Sandstone
Unconformity	
Strathmore	Teith Sandstone
	Cromlix Mudstone
Arbuthnott–Garvock	Scone Sandstone
	Craig of Monievreckie Conglomerate
	Ochil Volcanic

The Lower Old Red Sandstone of the Midland Valley is divided into four groups, the lowest of which may be mid Silurian, but only the two highest, the Arbuthnott–Garvock and Strathmore groups (Lower Devonian), crop out within the district ((Table S.1); Browne *et al*., 2002; Barclay *et al*., 2005). They are best developed on the south-eastern flank of the Strathmore Syncline. The Ochil Volcanic Formation, which lies at the base of the Arbuthnott–Garvock Group (Excursions 5, 6, 7, 14) consists of subaerial andesitic and basaltic lava flows, with subordinate volcaniclastic sedimentary intercalations. These rocks belong to a calc-alkaline geochemical suite and are associated with end subduction along the Iapetus Suture (Stephenson *et al*., 1999). They are now well exposed along the southern Ochil escarpment, where a number of small stocks and bosses of quartz-diorite have been intruded.

The oldest rocks cropping out in the Stirling area comprise the Ochil Volcanic Formation (Arbuthnott–Garvock Group), which dip to the NW at 15°; near Tillicoultry they are *c*.2400 m thick (Francis *et al*., 1970). They are succeeded by over 4000 m of Lower Devonian sedimentary rocks. Upper Devonian and Lower Carboniferous rocks are present mainly beneath Quaternary deposits, on the south side of the West Ochil Fault. The Ochil Volcanic Formation consists of lava flows with interdigitating coarse volcaniclastic rocks (Plate S.2) cut by minor intrusions. The flows are mainly of a chemical composition near the andesite–basalt boundary. Several varieties of andesite occur (pyroxene andesite, with or without feldspar phenocrysts, and hornblende andesite), together with subordinate trachyandesite and rhyodacite.

Many of the flows include irregular masses of sandstone and siltstone, many of which have lobate margins. These are examples of peperite, which indicates interaction between wet sediment and hot magma. Most of the lavas show alteration with replacement by carbonate minerals and chlorite, and albitisation is particularly prevalent. The volcaniclastic rocks are coarsest and thickest along the southern margin of the Ochil Hills. The composition of the fragmental material in the volcaniclastic rocks is largely comparable with that of the lavas but also includes some fragments of a felsitic nature which cannot be matched locally. The volcanic rocks are cut by many intrusions, the most important of which are diorite stocks near Tillicoultry (Excursion 7). The stocks are cut off by the West Ochil Fault but geophysical evidence (McQuillin in Francis *et al*., 1970) suggests that they extend at depth under younger rocks south of the fault. There is a metamorphic aureole around the stocks, with the development of feldspar porphyroblasts and microgranitic veins which, at the present level of erosion, extends outwards for *c*.400 m. There are also many dykes, mostly albitised microdiorites. Textural and petrological evidence suggests a genetic relationship between the diorites and the dykes (Francis *et al*., 1970). The latter display a crude radial relationship to the diorite stocks and also a marked concentration parallel to the main fault trends. This suggests that the structural grain was already established before the intrusions were emplaced.

A number of faults affect the Ochil Volcanic Formation and are most frequent along the southern margin. Two main trends of fracturing occur, one NW–SE and the other roughly NE–SW. These are considered to be of Early Devonian age because of their close association with the Early Devonian dykes. A third, less common trend occurs, roughly E–W, which is thought to be of Permo-Carboniferous age, including the West Ochil Fault, a major fault with a maximum downthrow of possibly 4000 m near Alva. Limited mining and field evidence indicates a normal fault hading at 60–70° to the south, to at least 2.5 km depth. Comparatively shallow seismic activity also appears to have been centred north of the fault (Burton & Neilson, 1979) and along the fault. Evidence from structure, vulcanicity, sedimentation and geophysical data suggests that a zone along the West Ochil Fault has had a long and complex history.

Francis (1983) envisaged the Ochils as having Andean-style volcanoes aligned along fractures. He thought the area was an example of asymmetrical subsidence in continental environments; they were the end-products of marginal hinge-line subsidence. The diorites at Tillicoultry (Excursion 7) may represent material belonging to the roots of one such volcano. Upton (2004) thought that the main eruptive centre was south of the West Ochil Fault. Clarkson & Upton (2006, fig. 7.3) showed an artist's impression of an Early Devonian volcanic landscape.

Lower Devonian volcaniclastic rocks were described traditionally as 'volcanic sandstones' or 'volcanic conglomerates' where fluvial processes of deposition are obvious from evidence such as rounding and bedform. The continued use of the terms tuff and agglomerate for the angular volcaniclastic rocks, as in published BGS 1:50,000-scale maps for Stirling and Alloa, is more questionable because their poor sorting and crudeness or absence of layering is compatible more with deposition from debris flows than from true pyroclastic processes such as ash-fall or ash-flow. However, pyroclastic processes cannot be excluded entirely, if the rocks of the western Ochils are proximal to the original centres of eruption. In this case, some of the coarsest unbedded rocks may represent deposits formed at the site of eruptive column collapse, as they would consist of pyroclastic blocks and slabs too large to be carried away in resulting flows (Wright & Walker, 1977). The succeeding Scone Sandstone Formation (Excursions 15, 17) is composed mainly of brownish or grey cross-stratified sandstones laid down by braided rivers (Plate S.3). Finer grained sedimentary rocks in the middle of the formation may include lake and floodplain deposits. Calcareous soil profiles, or calcretes, which occur towards the top of the Arbuthnott– Garvock Group indicate a somewhat arid climate with markedly seasonal rainfall. The Strathmore Group at the top of the Lower Old Red Sandstone is now preserved only in the axis of the Strathmore Syncline. Here the fine-grained, poorly sorted, poorly stratified deposits of the Cromlix Mudstone Formation at the base may include distal mudflows. They are overlain by grey, purple and dull-red sandstones of the Teith Sandstone Formation, deposited by braided rivers.

On the steep northern limb of the asymmetrical Strathmore Syncline, close against the Highland Boundary Fault, basaltic and andesitic lavas at the base of the section are overlain by thick conglomerates and sandstones, probably deposited in alluvial fans, with subordinate siltstones and mudstones (Excursions 12, 13). These are part of the Craig of Monievreckie Conglomerate Formation.

No Middle Devonian rocks are preserved in the Midland Valley of Scotland, where deposition was cut short by the far-field effects of the Acadian Event of the Caledonian Orogeny, when the Strathmore Syncline and the Sidlaw Anticline on its south-eastern flank were formed in a sinistral transpressional regime (Woodcock & Strachan, 2012, fig. 13.2). After a prolonged period of uplift and erosion marked by a basal unconformity, the Late Devonian red beds of the Stockiemuir Sandstone Formation (Stratheden Group), were laid down in an arid climate (Browne *et al.*, 2002). West of Stirling (Excursion 9), where the formation is more than 600 m thick, it consists of interdigitating wedges of alluvial fan conglomerates (near the base), sandstones with abundant mudstone clasts deposited by ephemeral braided streams, and aeolian sandstones. All are predominantly brick red or pale red in colour. The topmost Upper Devonian strata pass up without break into Carboniferous strata, so that the actual time boundary is ill defined.

(Table S.2) Carboniferous Lithostratigraphy

Group	Formation

Scottish Coal Measures	Scottish Middle Coal Measures
	Scottish Lower Coal Measures
Clackmannan	Passage
	Upper Limestone
	Limestone Coal
	Lower Limestone
Strathclyde	Lawmuir
	Clyde Plateau Volcanic
	Kirkwood
Unconformity	
Inverclyde	Clyde Sandstone
Inverclyde	Clyde Sandstone
	Ballagan
	Kinnesswood

Carboniferous

The Carboniferous succession is divided into four groups; the outline stratigraphy is given in (Table S.2) (for more detail, especially of Geological Conservation Review sites, see Browne *et al*., 1999; Cleal & Thomas, 1996; Cossey *et al*., 2004; Stephenson *et al*., 2003; Waters *et al*., 2007, 2011). The strata were deposited in a mainly dextral transtensional regime, in contrast to that of the Early Devonian (sinistral). The area was located close to the Equator in an environment with a progressively more-tropical climate (Woodcock & Strachan, 2012, fig. 14.1).

The Inverclyde Group is about 900 m in total thickness. The Kinnesswood Formation was deposited by meandering and braided rivers, and consists of repeated laterally impersistent, upward-fining cycles. In each cycle an erosive-based pale-red or white channel sandstone grades upwards into dull-red or purple overbank siltstone and mudstone, containing beds and nodules of calcrete. Some of the beds show mature calcareous soil profiles, formed during prolonged periods of subaerial exposure under the influence of markedly seasonal rainfall.

In addition to fluvial environments, the Ballagan Formation includes hypersaline lake, lagoon, and coastal plain environments (Plate S.4). The base is gradational. The unit consists of thin beds and nodules of argillaceous dolostone and limestone within a predominantly silty mudstone succession (Belt *et al*., 1967). Thin wedges of fine sandstone represent sand brought in by rivers during wetter periods. Pseudomorphs after salt crystals, desiccation cracks and subaerially weathered and reddened horizons indicate periods of evaporation, soil formation and lowered water level. The overlying Clyde Sandstone Formation cuts down erosively into the Ballagan Formation and represents a return to the river environments of the Kinnesswood Formation.

Further tectonic activity caused minor uplift that produced an unconformity at the base of the Strathclyde Group, and led to the initiation of widespread vulcanicity about 335 million years ago ((Plate S.5); Monaghan & Parrish, 2006). In the Campsie Fells, the Clyde Plateau Volcanic Formation rests unconformably on successively older strata towards the SE. The Clyde Sandstone Formation is absent along the southern scarp eastwards from Fin Glen. From there, the volcanic rocks rest on the Ballagan Formation and on sandstones of the Kinnesswood Formation farther west in the Garrel Burn north of Kilsyth. Evidence from palynological and radiometric dating suggests that the volcanic formation may have accumulated within the space of a few million years in Viséan times.

The Clyde Plateau Volcanic Formation at the base of the group (Excursions 9, 10, 11) consists of an 800 m-thick pile of subaerial basaltic lavas (Stephenson *et al*., 2003). The lavas were extruded from a series of WSW-trending linear vent systems, which included multiple dykes and numerous small vents and plugs, together with wedges of tuff. The Waterhead Caldera developed along one of those systems at a later stage.

All of the flows and associated intrusive rocks belong to a transitional to alkaline, mildly sodic suite. Differentiation of this type of primary basaltic magma produces increasingly felsic fractions belonging to the sequence:

olivine basalt —basaltic hawaiite —hawaiite — mugearite benmoreite —trachyte —rhyolite

Nearly all of the extrusive rocks of the Campsie Block can be classified as one or other of the first four members of this sequence. It is difficult to distinguish between the first four without chemical analyses. The mostfelsic types are mostly dykes or other intrusions.

After volcanic activity ceased, the lava pile was subjected to intense humid tropical weathering. The resulting bole-like cover was reworked to form the volcaniclastic detritus of the diachronous Kirkwood Formation, resting on the eroded volcanic landscape (Plate S.6). The succeeding onlapping Lawmuir Formation contains thin marine limestones interbedded with sandstones and mudstones.

The Clackmannan Group is characterised by cyclical sedimentation, most of which reflects repeated oscillations in relative sea level. The regional stress system changed to one with a strong component of E–W tension, so that a new set of structural elements became apparent, with fault blocks in the west and centre of the Midland Valley and basins in the north and east. The fault blocks included the graben-like Kilsyth Trough, south of the West Campsie Fault, and the basins included the N–S Kincardine Basin east of Stirling, which was the most rapidly subsiding basin in Scotland during the Namurian (Trewin, 2002, fig. 9.24).

The Lower Limestone Formation contains seven laterally persistent limestones, indicating that marine influences were stronger at this time than during any other time during the Carboniferous. The limestones are generally overlain by marine mudstones which pass upwards by alternation through siltstones into fine-grained, upward-coarsening sheet sandstones, capped by fossil soils (seatearths) and thin coals. These upward-coarsening cycles reflect marine transgression followed by fluviodeltaic progradation.

The succeeding Limestone Coal (550 m) and Upper Limestone (600 m) formations are poorly exposed and known mostly from boreholes. Most of the Limestone Coal succession is composed of upward-coarsening cycles, similar to those in the Lower Limestone Formation but considerably thinner and lacking limestones. Erosive-based channel sandstones cut through many of the sheet sandstones. Thick coals formed as domed peats under an equatorial, ever-wet climate. The cycles probably reflect glacio-eustatic oscillations in sea level related to the advances and retreats of a continental-scale South Polar ice sheet in Gondwanaland.

The Upper Limestone Formation shows stronger marine influences, with six major marine transgressions, each marked by a laterally persistent limestone, and many more minor transgressions. The relatively thick Castlecary Limestone defines the top of the formation. During the greatest transgressions, the sea entered the Midland Valley from both east and west and it became a tidally influenced marine strait. Sedimentary cycles are still dominant, with thick, multistorey sandstones marking prolonged low sea levels during glacial periods in Gondwanaland. Where present, coal seams are mostly thin.

The Passage Formation (360 m) is characterised by thick sandstones and fireclays formed in a monsoonal climate. Tectonic activity continued intermittently during deposition. To the north, a mountainous terrane was uplifted and eroded, sending a surge of sand into the Midland Valley. Three sedimentary cycles with thin marine limestones mark minor transgressions at the base of the formation. However, after the last of these (No. 2 Marine Band), meandering rivers gave rise to upward-fining cycles in which erosive-based channel sandstones are overlain by thick overbank siltstones and mudstones reworked by roots. Most of the overbank deposits were subaerially exposed, leached and oxidised, giving rise to variegated dull-red, purple and ochreous colours. This part of the succession has distinct clusters of thin coals overlain by marine bands with impoverished faunas. The highest band is thought to mark the base of the Westphalian. Some of the mudstones were formerly mined as high-alumina refractories, and sandstones are still quarried for glass sand.

The Lowstone Marine Band is the local base of the Scottish Coal Measures Group. About 400 m of Coal Measures are preserved in the Clackmannan Syncline. At this time, Scotland represented only a small part of a vast, flat, alluvial plain that covered much of western Europe. The environments in the Scottish Lower Coal Measures (Excursion 3) were similar to those in the Limestone Coal Formation. Equatorial, ever-wet climates returned and there was a regular succession of laterally persistent, upward-coarsening cycles capped by thick coals (Plate S.7). Marine incursions were few, and when they ceased altogether the cycles became less regular and the coals somewhat thicker.

Most of the tectonic structures present in Carboniferous strata in this area assumed their present form during end-Carboniferous movements (Plate S.8). These coincided approximately with the major Variscan Orogeny, when intense N–S compression affected southernmost Britain. The synsedimentary fold of the Kincardine Basin was modified into the present Clackmannan Syncline, suggesting a component of E–W compression, and part of its sedimentary fill was probably squeezed upwards (basin inversion) and subsequently eroded. Right-lateral displacements along the East Campsie and West Ochil faults relate to a similar regional stress system (Rippon *et al*., 1996, Ritchie *et al*., 2003, Underhill *et al*., 2008).

Somewhat later, a change to N–S tension created or modified prominent E–W faults, including the West Ochil Fault (although some of these fractures also seem to have moved earlier in the Carboniferous). A major phase of latest-Carboniferous tholeiitic (quartz-dolerite) intrusion produced the thick Midland Valley Sill-complex, dated to about 307 million years ((Plate S.9); Monaghan & Parrish, 2006). The sills, seen for example at Abbey Craig, Stirling Castle and Sauchie Craig (Excursions 4, 5), followed some of these fractures and the West Ochil Fault-intrusion (Excursion 7) probably acted as a major feeder (Stephenson *et al*., 2003). The sill-complex thickens towards synclinal axes, which Francis (1982) suggested was due to gravity flow caused by a head of magma in the feeder dykes. The associated dyke suite is seen on the Perth and Stanley excursions ((Plate S.10); Excursions 15, 17).

Post-Permian

From the Permian onwards, Scotland was considered to have been a positive landmass, with sedimentation only on the fringes. However, Underhill *et al*. (2008) and Vincent *et al*. (2010) provided different views. The latter in particular estimated that 1300–1800 m of strata were laid down in the Lothian and Fife area during the Permian to the Palaeogene, which have been since eroded. During this time, the landmass continued to drift northwards through regions corresponding to the present day Sahara and into the temperate belt.

The igneous activity associated with the break-up of the continental mass of Pangaea that started in the Jurassic and continued with the opening of the Atlantic Ocean in Palaeogene and Neogene (Tertiary) times is not represented in the area (see Woodcock & Strachan, 2012, fig. 17.1). However, the basic topographic configuration of the Devon and Forth valleys may have been fashioned by prolonged erosion during this period. The ultimate consequences of the northward shift in latitude are the ice ages that occurred in the last 2.6 million years, during the Quaternary Period.

Quaternary

Most of the Quaternary deposits and landforms in this area are less than 31,000 years old (Late Devensian and Holocene) (Evans, 2003). However, there may be sand and gravel and glacial till that pre-date the Main Late Devensian Glaciation in deep glacially scoured bedrock depressions. These exist under the Devon valley (100 m below OD) from Menstrie to Tillicoultry, and under the Forth valley west of Stirling and east of Kincardine Bridge. Details of the Quaternary stratigraphy can be found in McMillan *et al*. (2011). For an overall description of the Scottish Quaternary and extensive references, see Gordon & Sutherland (1993) and Trewin (2002).

The Main Late Devensian ice sheet of the Dimlington Stadial (31,000– 14,500 years ago) eroded the landscape, producing striated bedrock surfaces, roches moutonées and crag-and-tail features. The cliffs of Stirling Castle and Abbey Craig are examples of crag-and-tail (Excursion 1). The ice spread substantial amounts of glacial till at its base (Wilderness Till For-mation), and sculpted it into streamlined mounds called drumlins that indicate easterly ice flow, such as that at Clackmannan Tower (Plate S.11). The till is generally 4–18 m thick but reaches 56 m locally. It is generally a dark grey matrix-supported sandy clay, with clasts ranging up to boulder size.

At its maximum, the 1–2 km-thick Main Late Devensian ice sheet extended into the North Sea and merged with Scandinavian ice (Woodcock & Strachan, 2012, fig. 21.10). After this ice sheet began to retreat, about 21,000 years ago, substantial volumes of sand and gravel (Broomhouse Sand and Gravel Formation) were deposited by the meltwaters.

These ice-contact deposits commonly have characteristic landforms such as mounds, eskers (ridges) and kettleholes (Aitken & Shaw, 1983; Merritt & Laxton, 1982). When a thick ice sheet forms, it imposes a heavy load on the Earth's crust, which responds by warping downwards. Unloading by melting of the ice is accompanied by crustal uplift (isostatic recovery) and the return of water to the oceans. The interplay of isostatic recovery with sea-level changes causes fluctuations in relative sea level that are marked by raised beaches and marine deposits.

During deglaciation, local relative sea level was high in central Scotland, with marine sediments up to 40–45 m above OD in the Forth and Devon valleys. The decaying glaciers retreated westwards towards the Highlands, and by about 13,500 years ago the sea had reached Aberfoyle. The retreat appears to have halted at Stirling, where the valley is constricted by the Castle Rock. The characteristic marine sediment associated with deglaciation is red clay (Errol Clay Formation), with fossils that indicate an arctic climate.

Marine sediments deposited during the Windermere Interstadial (14,500–12,900 years ago) are massive silty clays (Forth Clay Formation), containing fossils that indicate a warmer climate. Dropstones in the sediments were probably from the melting of rafts of winter shore ice. Raised beaches and river terraces, mainly composed of sand and gravel, show that relative sea level fell from about 40 m above OD to the present level. The local landscape would have been scrubby, rather than densely forested.

The Loch Lomond Stadial ice (12,900–11,500 years ago) accumulated on Rannoch Moor and in the high corries of the SW Highlands and advanced into lowland areas to reach Callander and the Lake of Menteith in the Teith and Forth valleys, where the Gartocharn Till Formation and the Drumbeg Sand and Gravel Formation were laid down, and ice-terminal landforms formed, such as at Callander ((Plate S.12); Excursion 8) (Evans, 2003). Beyond the ice margins, the interstadial soils would have been destroyed and eroded as the local vegetation was killed by the cold. Frozen ground (permafrost) would have developed. Relative sea level in the Forth valley fell below that of the present day.

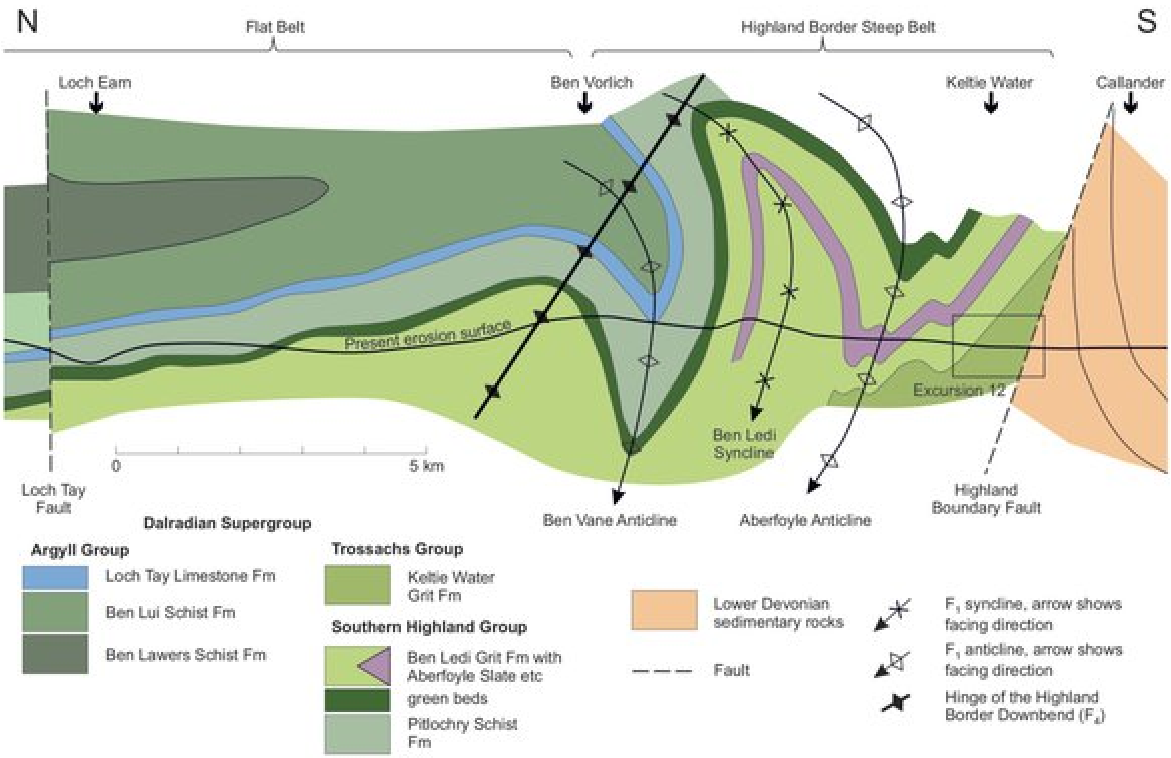
About 11,500 years ago, in the Holocene, there was a major climate change that may have taken place in as little as 100 years as the ice disappeared (Hansom & Evans, 2000). A marine transgression that started about 8000 years ago drowned the Sub-carse Peat that had grown on earlier beach deposits. Extensive deposits of clay were laid down in the estuary (Carse Clay Formation). Fossils include the remains of large whales, which have been found as far west as Cardross near Menteith. In the period between 8000 years ago and the peak of the transgression, around 6500 years ago, when the climate was warmer and wetter than today, the whole of the Forth valley floor west of Stirling silted up, as did the Devon valley. Relative sea level reached a maximum of about 16 m above OD in the Aberfoyle area and 13 m above OD in the Devon valley.

The Main Holocene (Flandrian) Shoreline, with which these levels are associated, has been widely recognised in the Forth valley from east of Grangemouth to Aberfoyle. However, much of the Grangemouth area silted up later, and here lower shorelines and raised mudflats are found. The Grangemouth Formation, which consists of clay, silt and sand, includes the contemporary intertidal and subtidal sediments.

The guide is completed by including walking excursions to look at the wonderful selection of building and facing stones used in the construction of the cities of Stirling and Perth (Plate S.13).

References

(Plate S.1) Downward-facing F_1 folds close to the downbent hinge zone of the Tay Nappe in Dalradian rocks at Little Glen Shee. See [(Figure 18.3).]



(Figure S.2) Cross-section of the Tay Nappe from Callander due north to Loch Earn, showing the Flat Belt, Highland Border Downbend (F_4) and major downward-facing F_1 folds in the Highland Border Steep Belt (adapted from Tanner et al, 2013, fig. 13).

Table S.1	
Lower Devonian Lithostratigraphy	
Group	**Formation**
Stratheden	Stockiemuir Sandstone
Unconformity	
Strathmore	Teith Sandstone
	Cromlix Mudstone
Arbuthnott–Garvock	Scone Sandstone
	Craig of Monievreckie Conglomerate
	Ochil Volcanic

(Table S.1) Lower Devonian Lithostratigraphy.

(Plate S.2) *Lower Devonian volcaniclastic conglomerate at cave east of Dumyat summit. See Excursion 5.*

(Plate S.3) Trough cross bedding in Lower Devonian sandstone, A9 road cutting at Crossgates, Perth.

Table S.2

Carboniferous Lithostratigraphy

Group	Formation
Scottish Coal Measures	Scottish Middle Coal Measures Scottish Lower Coal Measures
Clackmannan	Passage Upper Limestone Limestone Coal Lower Limestone
Strathclyde	Lawmuir Clyde Plateau Volcanic Kirkwood
Unconformity	
Inverclyde	Clyde Sandstone Ballagan Kinnesswood

(Table S.2) Carboniferous Lithostratigraphy.

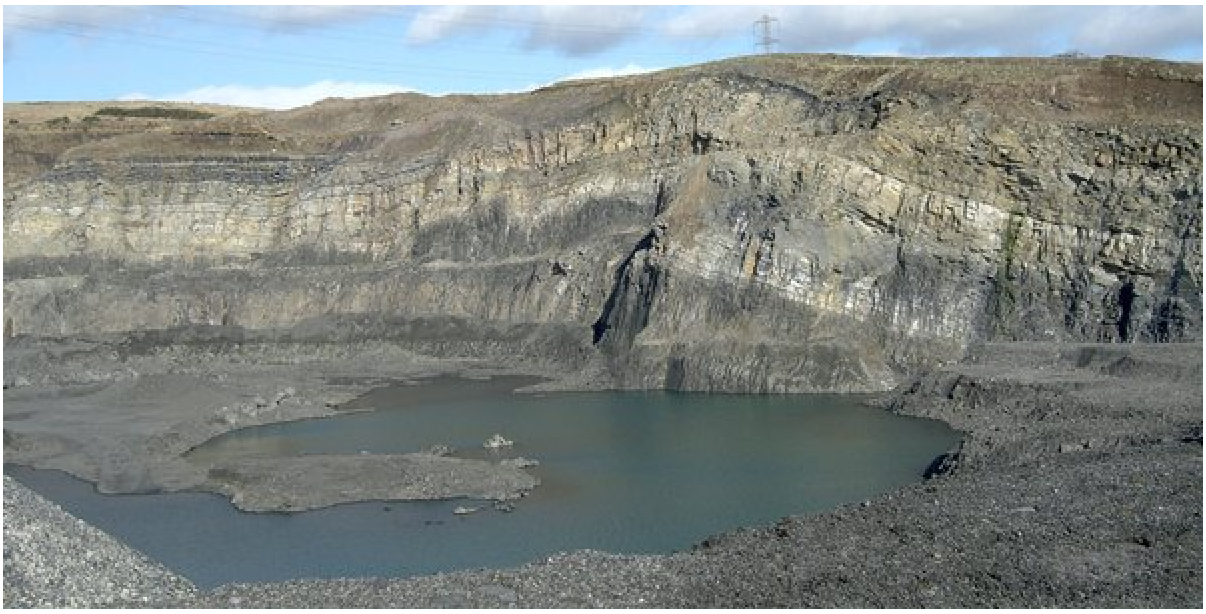
(Plate S.4) Lower Carboniferous Ballagan Formation mudstones with beds of dolostone (cementstone) in Banton Burn. See Excursion 11.

(Plate S.5) Trap featuring in Lower Carboniferous Clyde Plateau Volcanic Formation, north side of Gargunnock Hills.

(Plate S.6) Disconformity between Kirkwood Formation and the overlying Lawmuir Formation. Outlines of clamp kilns in foreground; Lewis Hill Quartz-dolerite Sill forms crags in background. See Excursion 2.

(Plate S.7) Meadowhill opencast coal site (Clackmannanshire), Lower Coal Measures, now infilled.

(Plate S.8) Meadowhill opencast coal site showing Langfauld Fault, separating Middle Coal Measures (left), from Passage Formation (right). (Plate 5.9) (opposite page, middle) Quartz-dolerite of the Midland Valley Sill-complex with overlying Upper Limestone Formation, Kilsyth.



(Plate S.9) Quartz-dolerite of the Midland Valley Sill-complex with overlying Upper Limestone Formation, Kilsyth.

(Plate S.10) (opposite page, below) Late Carboniferous quartz-dolerite dyke, showing right-lateral stepped contact and horizontal columnar joints, River Tay east bank, Campsie Linn. See Excursion 17.

(Plate S.11) Drumlin sculpted from glacial till at Clackmannan Tower, 500 m west of Clackmannan town; Holocene raised Carse Clay in foreground.

(Plate S.12) Terminal (push) moraine at Drumdhu Wood, Callander. See Excursion 8.

(Plate S.13) Perth Old City Hall, built of Lower Devonian sandstone from Leoch Quarry, West Dundee. See Excursion 16.