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Avon Gorge

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Objectives

The purpose of the excursion is to examine the classic Lower Carboniferous sequence on the eastern side of the Avon Gorge, and to walk up section, exploring also the Avon Thrust, which repeats a large portion of the section, and the unconformity with the overlying Triassic. On the way, important aspects of engineering geology will be seen in terms of rock bolting to prevent the gorge sides falling on to the Portway road (A4) at the bottom, as well as in and around the classic Clifton Suspension Bridge.

Risk analysis

The main risks are traffic and rockfalls. This is a walking excursion, and participants must be super-careful in crossing the Portway, the A4 road. Traffic is fast, and there are central reservation refuges only in some places. At some points, it is possible to work on both sides of the road, but in others, there is no footway on the side of the road nearest the exposures; this is true for the Portway near the Clifton Suspension Bridge, and on Bridge Valley Road. Trip leaders must be prepared with sensible plans to usher groups, especially children, across the roads safely, and such parties ought to be equipped with high-visibility jackets. In addition, the entire section is a high cliff, and rockfalls could occur, so hard hats must be worn when people are examining the quarry sections. Apart from the obvious danger of causing rockfalls from high cliffs, nearly all the locations to be visited are SSSIs (see Discussion), and there should be **no hammering of anything other than fallen debris at any of the localities**.

Maps

OS Landranger 172	1:50 000 Bristol & Bath
Explorer Sheets 154	1:25 000 Bristol West & Portishead or 155 Bristol & Bath
BGS Sheet 264	1:50 000 Bristol

Main references

Vaughan (1905); Bradshaw & Frey (1987); Hawkins (1987); Kellaway & Welch (1993); Waters *et al*. (2009).

Locations

This trip focuses on the east side of the Avon Gorge, where there is continuous exposure in a series of natural and quarried sections along 1 km of roadside section, working upstream to the Clifton Suspension Bridge, and then up the hill to see the Carboniferous–Triassic unconformity, and then to work down through the succession on the old Zig Zag path to the south of the bridge (Fig. 1). The rock succession starts with SSW-dipping Upper Devonian rocks in the north and continues through the Lower Carboniferous succession towards Bridge Valley Road, which crosses a major thrust fault which repeats the upper part of the succession. This is all overlain by flat-lying Triassic in the east and south of the section.

The Avon Gorge has long been admired for its spectacular scenery, where the River Avon cuts down sharply to expose Devonian, Carboniferous and Triassic rocks, leaving cliffs as much as 85 m high. The whole gorge, some 2.5 km long, runs from Bristol Harbour northwards downstream to Avonmouth, and it shows a substantial tidal range of up to 11.5 m, compared to the maximum 15 m range of the Severn Estuary, where the daily tides are funnelled into an ever-narrower channel. These tides enter the Avon Gorge and reach the Cumberland Basin, and at low tide the Avon river bed can be very low.

Outline Geology

The Avon Gorge was recorded by geologists from the earliest days of the subject. For example, Bright (1817) noted excellent exposures on the right (eastward) bank as a result of extensive quarrying, and Cumberland (1821) gave the first account of the famous Carboniferous limestone succession. Many other authors reported their studies of the limestones and their fossils during Victorian times and identified the key units of the Devonian, Carboniferous and Triassic.

In fact, the Avon Gorge field trip offers a synoptic view of the principal aspects of the geology of the Bristol area (Bradshaw & Frey, 1987), namely the relatively complete succession through the Late Devonian and Early Carboniferous, followed by massive uplift and folding of the whole region during the Hercynian (Variscan) Orogeny of the latest Carboniferous and Early Permian, when major supercontinents collided and as Gondwana was driven under Laurasia, pushing from south northwards. Great folds oriented with east-west axes are found across southern Ireland, southern England and central Europe, and these same folds are also found in North America which was then attached at a time before the opening of the Atlantic. The folding was associated with widespread faulting, including major thrust faults, one of which, the Avon Thrust, will be seen on this excursion. This massive tectonic upheaval raised landscapes that proceeded to erode during the Permian and Triassic. Near horizontally bedded Late Triassic sediments are seen here on top of the dipping Carboniferous limestones, especially around the Clifton Suspension Bridge.

There is a succession of Devonian rocks (e.g. Portishead Formation, Brownstones Formation) around Shirehampton and Westbury-on-Trym, in the northern part of our section (Fig. 1). These rocks were heavily studied by Victorian geologists, often in the then fresh railway cuttings and in pits around Sneyd Park as the great Victorian mansions were being constructed, and here the Sneyd Park Fish Bed, for example, was identified. However, only limited exposures can be seen now, and we do not include these units in this field trip, and they can be seen in the Portishead excursion, where it is known as the Woodhill Bay Fish Bed (Trip XXX).

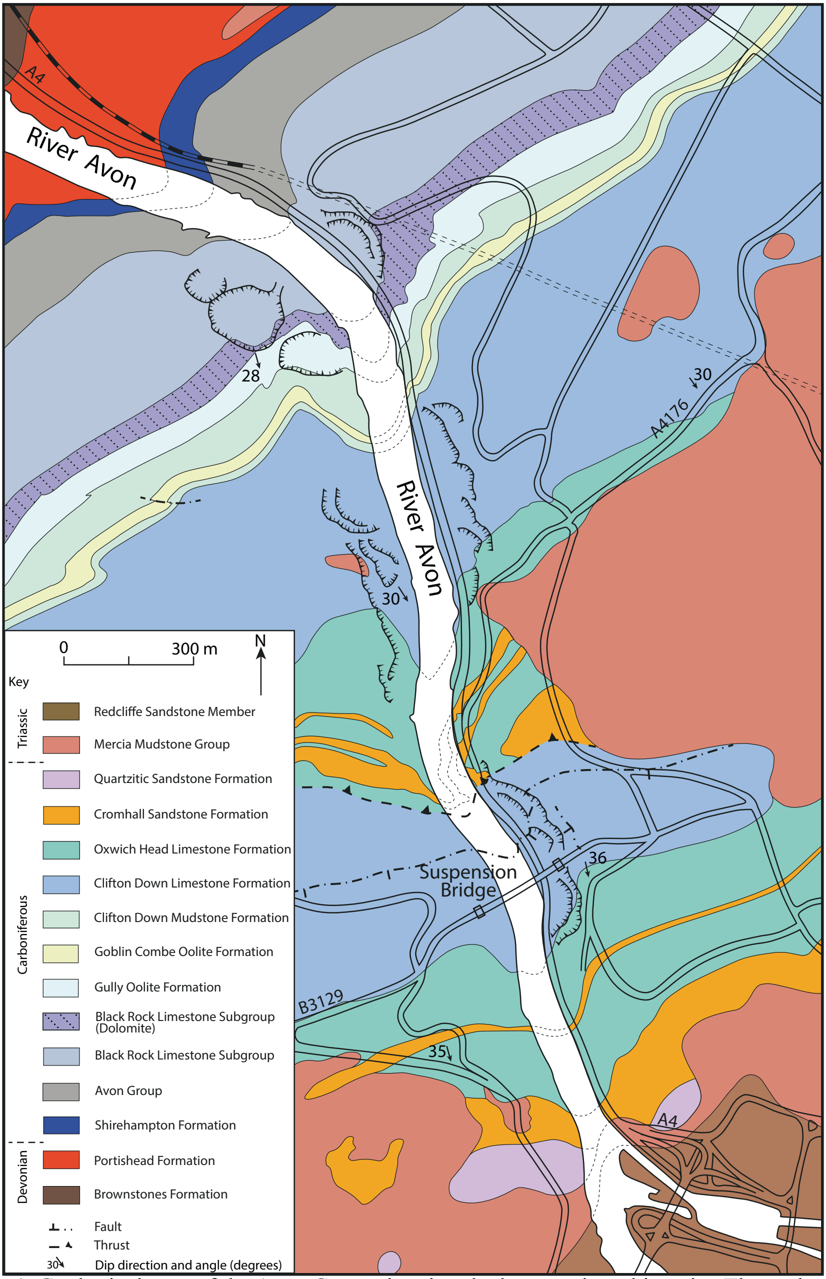

Figure 1. Geological map of the Avon Gorge showing the key stratigraphic units. The rock succession begins at the north-west corner and youngs to the south-west. The Avon Thrust in the lower portion of the diagram repeats the upper part of the succession. (*Drawn by Susan Marriott from BGS data from Digimap © Ordnance Survey and British Geological Survey.*)

The classic publication on the Avon Gorge Carboniferous limestones was Vaughan (1905), who established a zonal system for the entire Early Carboniferous, using the Avon Gorge section as his template. In this paper, and two others (Vaughan, 1906; Vaughan & Reynolds, 1935), the authors noted the diverse fauna of the Carboniferous limestones, including algae, plants, foraminifera, sponge spicules, corals, worms, crinoids, echinoids, bryozoans, brachiopods, bivalves, gastropods, pteropods, cephalopods, trilobites, crustaceans, ostracods, conodonts and fishes. In these papers, Vaughan established the use of corals and brachiopods as the key zonal indicators, as well as bryozoans and foraminifera to a lesser extent. Vaughan's zones ran from the *Cleistopora* K_m Zone at the base of the Carboniferous to the *Dibunophyllum* D_2 Zone near the top of the Early Carboniferous succession. However, these zones, while forming the basis for biostratigraphic subdivision of the Lower Carboniferous worldwide, are hard to apply, and the British Geological Survey found this difficulty when mapping, and they developed a scheme of equivalent formations based on lithology, and we use these here (Fig. 2).

Since then, thanks to widespread efforts by the British Geological Survey across the UK, the Lower Carboniferous limestones have been correlated with each other and a standard terminology established (Waters *et al.*, 2009). Because of the importance of the Avon Gorge section, many of the standard formation names used across southern England and South Wales derive from the Avon Gorge succession. All the Carboniferous units in the Avon Gorge are subdivisions of the Pembroke Limestone Group (Fig. 2).

Carboniferous limestones dominate the Avon Gorge because of their resistance to erosion. Their fundamental structure is associated with the Westbury-on-Trym anticline which trends at 065° and plunges gently to the ENE, crossing the River Avon just north of our section. The anticline is asymmetrical, with steep to vertical and even overturned dips to the north, and more gentle dips of 25–40° to the SSW, and these are the dips we see throughout the Avon Gorge section. The same dipping rocks also extend under much of Clifton and under Abbots Leigh on the far bank. This anticline is one of the Hercynian-age folds of the wider Bristol–Mendips area, and it is propagated through our section in the dips of the limestones, as seen on both banks of the river. At the southern end of the section (near Bridge Valley Road) the succession is repeated by a major thrust fault and this ramps up the Clifton Down Limestone, Oxwich Head Limestone, and Upper Cromhall Sandstone formations (Figs 1, 2). The Triassic 'Dolomitic Conglomerate' and Redcliffe Sandstone Member sit unconformably on top of these successions, but have largely been eroded, surviving to the south and east.

Itinerary

Introduction

This is a perfect field trip to conduct entirely on foot, even with a party, and buses can be taken to and from the start and end points. If you drive, you can park either along the side of the road at Sea Walls or at any point between there and the Clifton Suspension Bridge, where the trip ends, or in the small car park in Black Rock Quarry, accessible from the southbound carriageway of the Portway. You can begin either at the top of the cliff (Sea Walls) or below at Black Rock Quarry. The key locations (Fig. 3) take us on a meandering walk from north to south along the Gorge, sampling the key stratigraphic units as they are exposed in succession (Fig. 4).

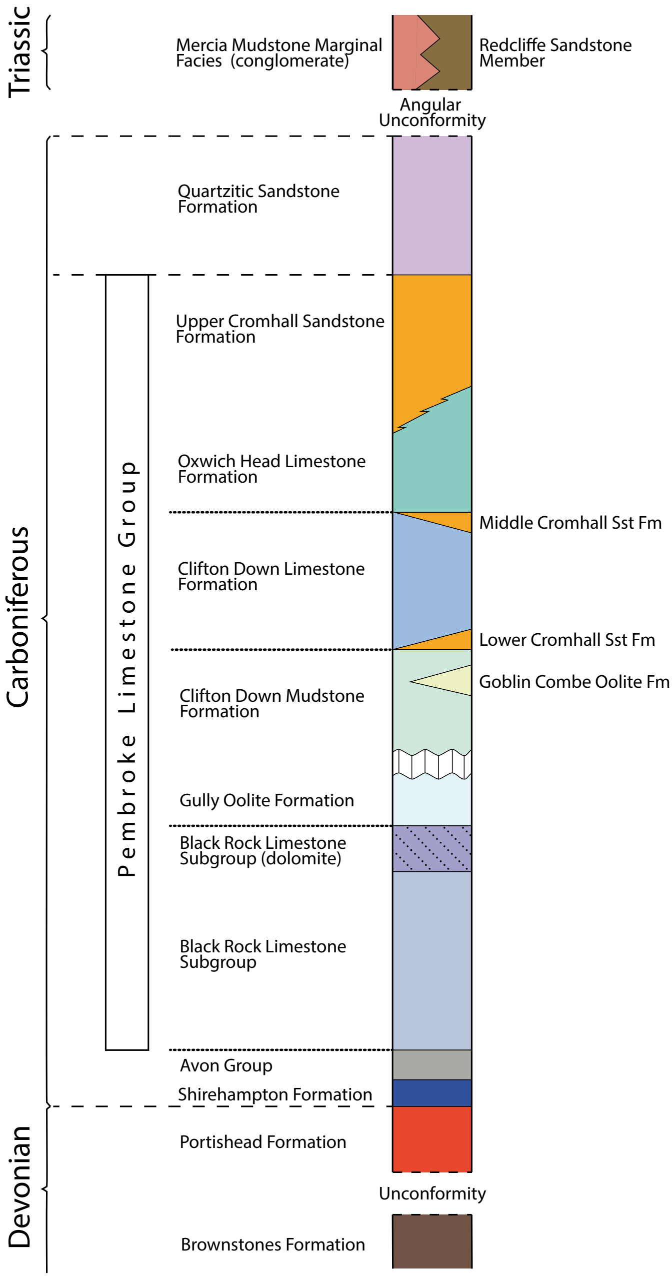

Figure 2. Succession from Late Devonian to Late Triassic as seen along the Avon Gorge. Based on information in Bradshaw and Frey (1987), Waters *et al*. (2009) and the BGS Lexicon. (*Drawn by Susan Marriott.*)

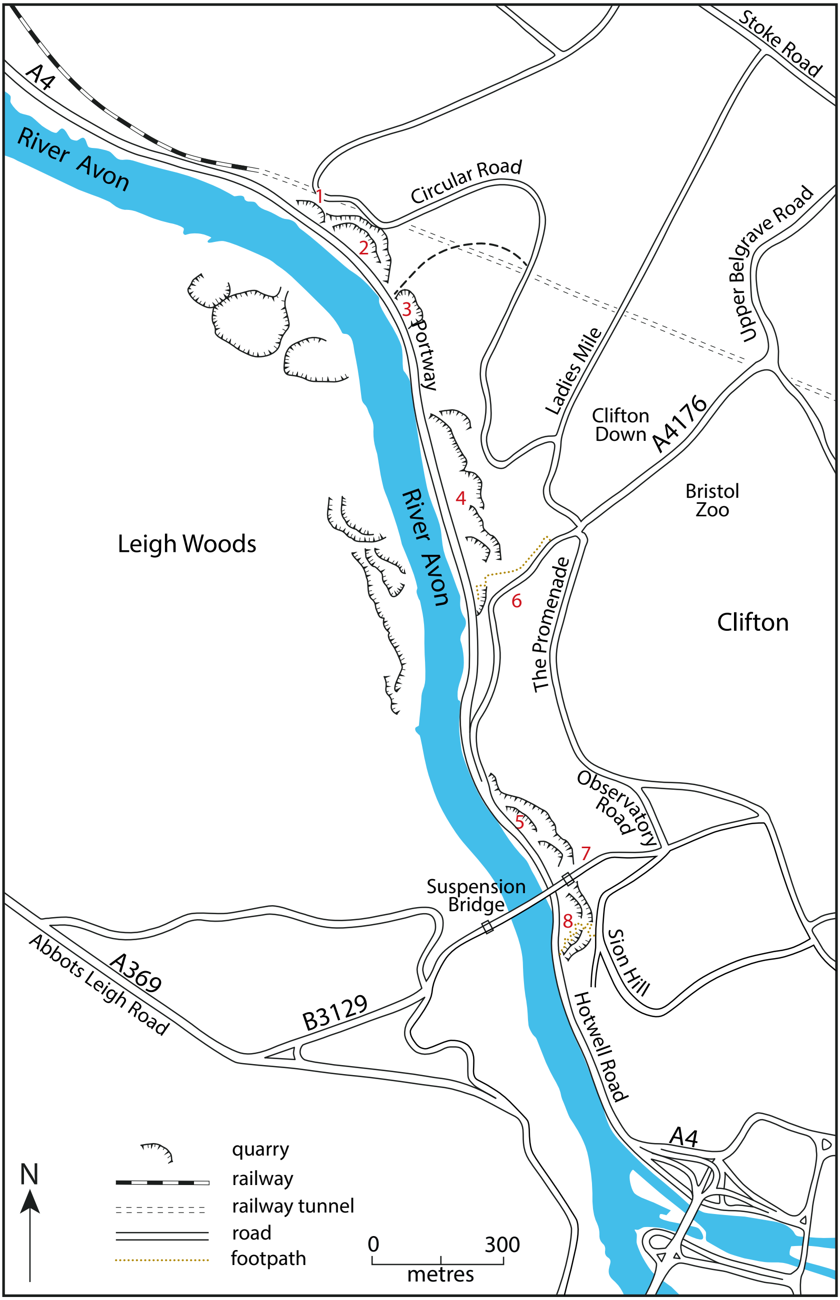

Figure 3. Sketch map showing the main geographic features, including quarries, and the excursion stops, numbered as in the text. (*Drawn by Susan Marriott.*)

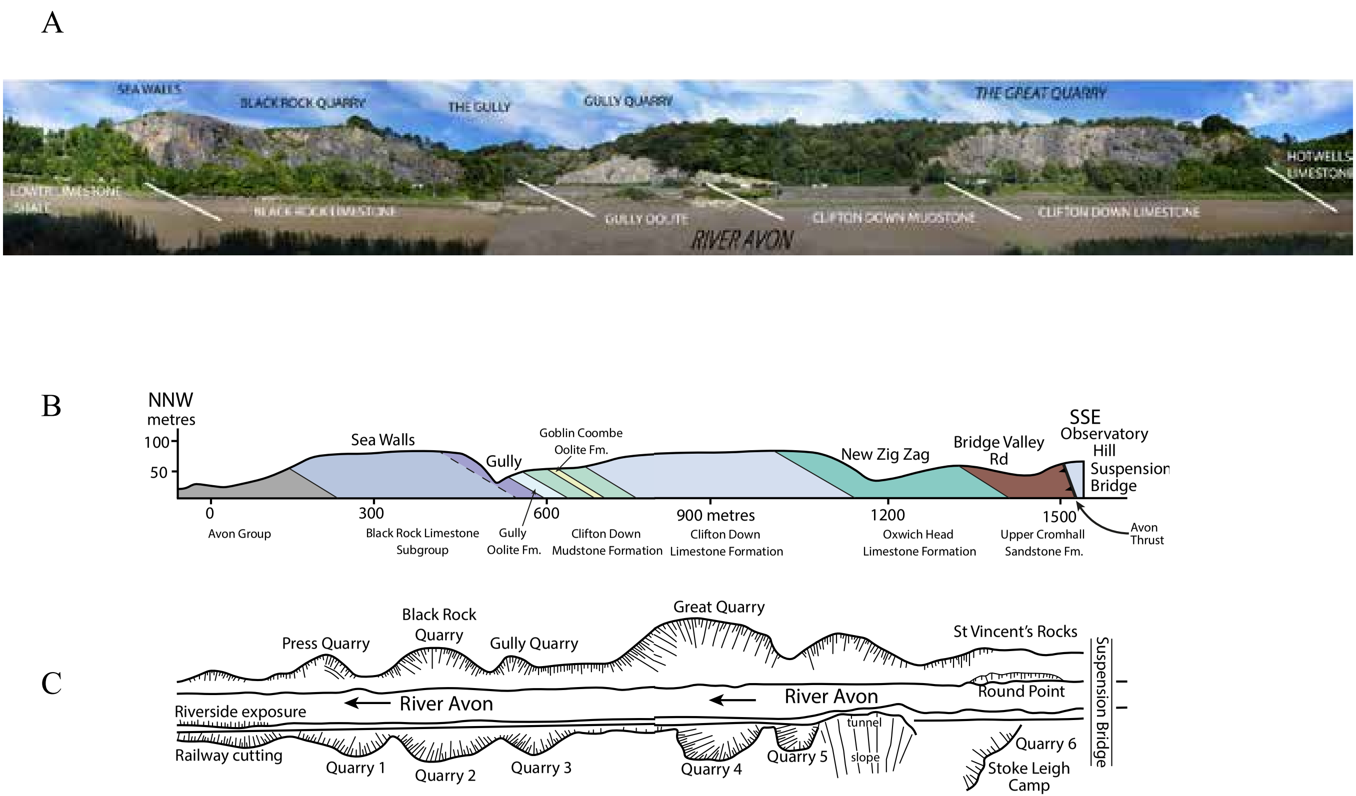

Figure 4. Representation of the Lower Carboniferous section along the eastern (right-hand) bank of the Avon, showing the entire section as a photograph (A), a summary sketch (B), and a plan view relating the named quarries and river to the sections. (*Photograph by Richard Arthur and drawings by Susan Marriott from Bradshaw and Frey (1987) and other sources.*)

1. Sea Walls

A good place to begin is the viewpoint at Sea Walls [ST 560 747]. Here you can look over the railings to the River Avon below, and to the Clifton Suspension Bridge upstream (Fig. 5) and Avonmouth and the confluence with the River Severn downstream. Notice directly below you the large inclined bedding planes in the Black Rock Limestone Subgroup which end near a wooded side valley. The scar of the Great Quarry exposing Clifton Down Limestone Formation is in the middle distance to the south. Also notice how the Avon Gorge cuts at a right angle to the strike of the rocks, and the wooded bank of Leigh Woods lies opposite.

Looking behind you, the extraordinarily level grassed area of the Clifton Downs playing fields is a peneplain. This level surface is seen at many locations where Carboniferous Limestone has been elevated and skimmed flat by a combination of marine erosion in places, subaerial erosion in others. Undulations in the otherwise remarkably flat surface are traces of old quarries and pits associated with the extraction of lead ore and building stone all over the Downs, especially at their south-western corner.

Walk east along the edge of the Downs on Circular Road, and as the road bends south then south-west round the head of the wooded valley, look for a path leading down this valley locally called the Gulley. Pass through a gate in a high deer fence and descend the valley, passing grey cream well-bedded limestone and mudstone on the left and high cliffs of massive white limestone on the right. Screes near the chimney, actually an air shaft for the Clifton Railway line that lies below, provide clear samples of oolitic texture which can be seen with the naked eye. Continue down the valley and pass through another gate to arrive at the Portway. A short distance on the right is the entrance to Black Rock Quarry.

Figure 5. The view from Sea Walls looking south towards the Clifton Suspension Bridge, and showing the main features visible in the Black Rock Quarry (foreground), Gully Quarry (Gully Oolite), Great Quarry (Clifton Down Limestone Formation), and St Vincent's Rocks (Oxwich Head Limestone Formation) beyond. (*Photograph by Richard Arthur.*)

2. Black Rock Quarry

There are four named quarries along the right-hand (eastern) side of the Avon Gorge (Fig. 4). The first is Press Quarry [ST 559 747], but this is now entirely overgrown, so it is hard for us to inspect the 'Lower Limestone Shale', now seen as equivalent to the undivided Avon Group, the lowest unit of the Avon Gorge Lower Carboniferous succession (Fig. 2). The Avon Group here is <100 m of dark grey and black interbedded mudstones and thin- to medium-bedded skeletal packstones with one to several thick units of ooidal and skeletal grainstones. Thin units of calcite mudstone and mudstone are locally present, as well as sparse thin ironstones. These mudstones and limestones indicate deposition in shallow sea waters of the mid to inner shelf/ramp, associated with coeval barrier, back barrier and coastal plain sediments (BGS Lexicon).

Black Rock Quarry [ST 561 746] is the type locality for the Black Rock Limestone Subgroup. The limestones here are black, hence the name given centuries ago by the quarrymen; the black colour is associated with a high hydrocarbon content and samples can give a foetid, sulphurous odour when struck. The limestones are thin- to thick-bedded, dark grey to black in colour, fine- to coarse-grained skeletal packstones, grain-supported limestone with rare micritic component. These limestones were deposited in shallow tropical seas on an inner to mid ramp setting with local ooid shoal development. The Black Rock Limestone Subgroup occurs widely in south-west England and across South Wales and is associated with heavy dolomitisation in the Monmouth and Chepstow areas, ooidal limestones in the Gower Peninsula and volcanic tuffs in the Weston-super-Mare area (BGS Lexicon) (See Middlehope excursion YY).

Key features of the geology can be seen in the relatively clean vertical faces in the quarry, including the thick bedding, joint faces, limestone textures and fossils. The main fossils are crinoid debris (Fig. 6A), corals (Fig. 6B), and brachiopods, visible as sections through pairs of valves (Fig. 6C) or isolated valves (Fig. 6D). The corals include rare examples of the characteristic coral that defines the age of these rocks, *Zaphrentis*, a classic rugose coral (Fig. 6B). Individual specimens have a sharply pointed lower end and expand rapidly into a slightly curved cone-shape. The living chamber end is broadest and nearly perfectly circular when viewed from above, with dozens of symmetrically radiating septa. Sometimes, in the rocks, visitors can see longitudinal and cross sections of the corals, measuring 2–5 cm across .

3. Gully Quarry

It is easy to walk beside the road south into the next smaller quarry, where we move up-section into the overlying Gully Oolite and Clifton Down Mudstone formations. This location [ST 562 744] is the type locality for the first two formations, showing a 26-metre-thick section of the Gully Oolite Formation, named after the Gulley lying to the side of the quarry and down which we walked; this formation is widespread, recorded from the Mendips to many locations across South Wales. The overlying Clifton Down Mudstone Formation is complete here, and it is reported around Bristol, but transitions into the Burrington Combe Oolite Formation in the Mendips and the Llanelly Formation in South Wales (BGS Lexicon).

In the northern part of the quarry, it is hard to identify the contact with the underlying Black Rock Limestone Subgroup with confidence because its upper beds and the lower beds of the Gully Oolite Formation are dolomitised. It can be difficult to see the ooliths and fossils because they have been largely destroyed by the dolomitization, but both may be seen in loose fragments up the Gulley path. The Gully Oolite Formation comprises medium- to thick-bedded, pale grey, oolitic grainstones with subordinate beds

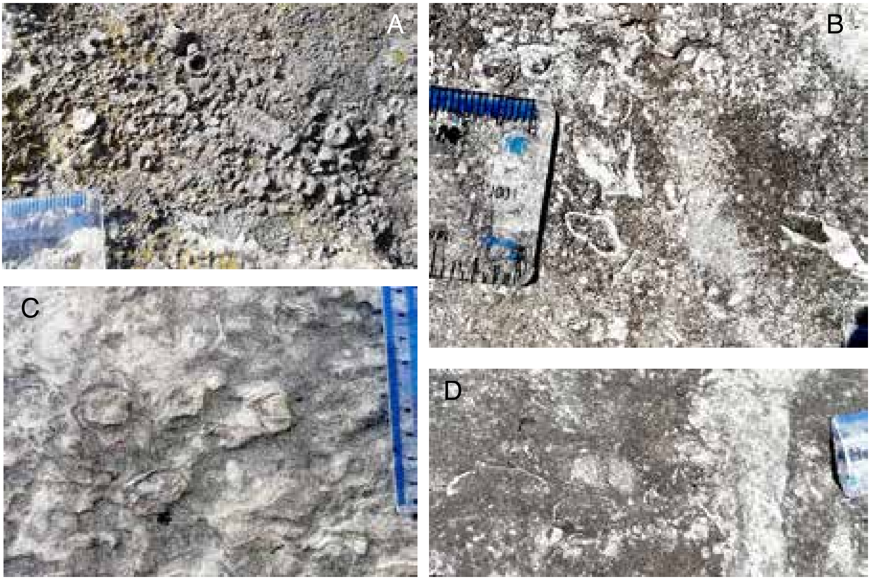

Figure 6. Fossils from the Black Rock Limestone Subgroup of Black Rock Quarry: crinoid debris (A), corals including *Zaphrentis*, beside the ruler (B), brachiopods in section of both valves (C), and two brachiopod valves in section (D). (*Photographs by Michael J. Benton.*)

of fine-grained skeletal packstones. If you look closely, you can see in places that it is cross-laminated and cross-bedded, and there are some burrows. The succession is capped by a palaeokarstic surface overlain by a green/red mudstone/clay palaeosol, marking the top of the unit and its contact with the Clifton Down Mudstone Formation (Fig. 7); this can only be viewed from a distance. Bedding at the top of the Gully Oolite Formation, especially towards the right-hand (southern) end of the exposed face, appears to be at an angle to the disconformity between both formations, suggesting the contact is an angular unconformity.

The Clifton Down Mudstone Formation in this quarry comprises thin- to medium-bedded poorly fossiliferous, calcite mudstones, dolomite mudstones and mudstones. A unit of crinoidal and oolitic limestones occurs in the middle of the Formation, and a 15-m-thick unit of oolitic and crinoidal limestone occurs in the upper part, correlated with a lithologically identical unit in the Weston–Bradfield Down area, termed the Goblin Combe Oolite Formation. This cannot be seen readily now because of overgrown vegetation. The mudstones were deposited mainly in a back-barrier setting, and the ooliths indicate higher energy conditions in more open water. At the southern margin of the quarry, near the road, can be seen the sharp contact with the overlying Clifton Down Limestone Formation comprising a basal sandy limestone. These units cannot be studied directly, but visitors can look for small fallen pieces in the Gulley above.

It is not possible to reach the next quarry directly, and it is necessary to cross the road (with great care) and walk along the footpath by the riverside, and then cross back into the Great Quarry. Before doing so, look back at the cliff below the Sea Walls, and the extensive rock netting and bolting are clearly seen. These date from the time of a great rock fall in 1972, and when a 3000-tonne block was removed from the upper half of the cliff in 1974. The fresh surfaces were bolted and netted at that time (Hawkins, 1978).

Figure 7. Photograph of Gully Quarry showing the Gully Oolite Formation overlain by the Clifton Down Mudstone Formation, which rests on a red-stained palaeokarstic contact surface. (*Photograph by Richard Arthur.*)

4. Great Quarry

The Great Quarry [ST 563 741] is the largest quarry in the series, and it is the type locality of the 266-m thick Clifton Down Limestone Formation, where most of the unit can be seen, except for its lower part where it contacts the underlying Clifton Down Mudstone Formation. The quarry formerly housed tennis courts, and then was a public car park, but now is abandoned and overgrown, and it is hard to approach the rock faces.

The sediments are splintery dark grey calcite and dolomitic mudstones, pale grey oolitic, dark grey bioclastic and oncolitic limestones and some mudstones. Scattered cherts and silicified fossils are found in the lower half, and a sandy limestone at the base, as seen at the top of the Gully Quarry sequence. The limestones were deposited in a barrier/back barrier/shelf lagoonal setting (BGS Lexicon). The Clifton Down Limestone Formation is recognised over a wide area of the Mendips and passes laterally into the Hunts Bay Oolite Group in the Monmouth and Chepstow area.

In this great thickness of limestone, three subdivisions have been recognised (Fig. 8), although they are quite difficult to distinguish in the Great Quarry because of weathering and recent black algal growth, and are easier to see in Cheddar Gorge.

1. There is a lower well-bedded succession of calcite and dolomite mudstones, with common stromatolites similar to those in the underlying Clifton Down Mudstone Formation. The unit is poor in fossils and lacks muddy partings. These indicate deposition in a very shallow-water, peritidal or lagoonal environment.
2. This is succeeded by a massive or very thickly bedded, poorly sorted limestone with horizons of abundant *Lithostrotion* colonial corals that are often silicified and protrude from the rock faces, especially in Cheddar. In this middle portion of the succession are the so-called Seminula Pisolite and Seminula Oolite, units identified by Vaughan (1905, 1906) as biostratigraphically important because they contain the brachiopod *Composita* (formerly called *Seminula*). This facies represents more open-sea conditions, though the recurrence of peritidal conditions from time to time is shown by the presence of the algal 'Seminula Pisolite' and beds of calcite mudstone with *Composita*. The Seminula Oolite may represent an ooid shoal or bank deposit.

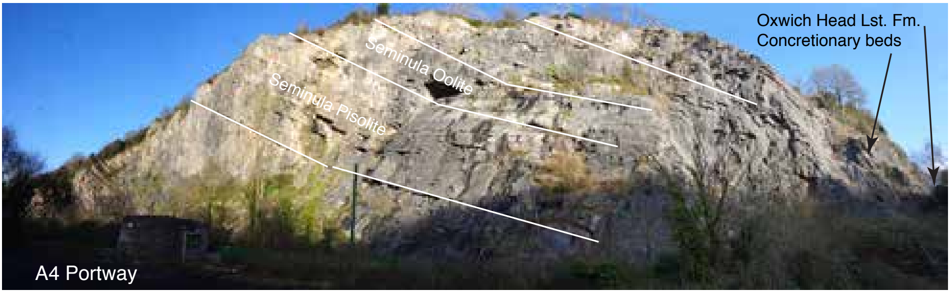

Figure 8. The complete section in the Great Quarry, comprising the entire thickness of the Clifton Down Limestone Formation, with the Seminula Pisolite and Seminula Oolite indicated. (*Photograph by Richard Arthur.)*

3. Finally, the upper portion comprises a calcitic mudstone-algal sequence known as the 'Concretionary Beds', in thick units, sometimes with algal mats, and showing clear jointing. These sediments can be seen in the clifftop footpath above the quarry. They represents a return to peritidal conditions of deposition.

Sometimes, other units with exciting-sounding names such as the fluorite band and the trilobite bed are noted in the older literature, but these are difficult (and dangerous) to locate because of weathering of the unstable rock faces.

5. St Vincent's Rocks

Walk further south along the pavement beside the River Avon, until you reach the traffic lights at the foot of Bridge Valley Road. The high cliff facing this point and extending to beyond the Clifton Suspension Bridge has long been known as St Vincent's Rocks. It's not clear whether there ever was a true 'Saint' Vincent, but there are many legends about two local giants called Vincent and Goram who undertook to drain away a great lake of water around Bradford-on-Avon and Bristol in order to impress a lady giant and, while Goram chose a route through Henbury, Vincent chose to excavate the Avon Gorge. Presumably in doing so, he dug out a great cutting forming the Carboniferous cliffs on both sides.

In the northern part of St Vincent's Rocks just opposite the traffic lights [ST 5643 7324] we study the geology at a distance from the riverside path. First, on the right, and sloping up the face of the cliff is the substantial Avon Thrust, with a downthrow to the north of 335 m (Fig. 9). Here, there are two subparallel thrust faults, with a shatter zone between. The Avon Thrust is matched by at least one further substantial parallel fault, the St Vincent's fault, some 60 m south, and the fault zone is traceable across the Avon Gorge in the Nightingale Valley opposite. The Avon Thrust is at the base of a great block of the Clifton Down Limestone Formation, here the Seminula Oolite, which continues south and under the Clifton Suspension Bridge. The rocks beneath the thrust fault belong to the Cromhall Sandstone Formation, which here is younger than the Clifton Down Limestone Formation, and so this is evidence of the amount of movement of the overlying block along the thrust plane (Fig. 1).

The Cromhall Sandstone Formation partially interfingers with the Clifton Down Limestone and Oxwich Head Limestone formations and partly overlies them (Fig. 2). In its type area around Cromhall, north of Bristol, the Cromhall Sandstone Formation comprises three tongues, the lower two of which insert below and above the Clifton Down

Limestone Formation, and the upper of which lies above the overlying Oxwich Head Limestone Formation. The reason for this complex interfingering relationship is that the two limestone formations are marine, whereas the Cromhall Sandstone Formation is a terrestrial deposit laid down by a sporadically active fluvial system. In the Avon Gorge and elsewhere, these three tongues of the Cromhall Sandstone Formation are named formally as Lower, Middle, and Upper portions of the Formation (Fig. 2). At this location, the Upper and Middle Cromhall Sandstones sit below the thrust plane and are younger than the lower portions of the Clifton Down Limestone Formation above. XXXX

We cannot inspect the Cromhall Sandstone Formation directly here, but the lower and middle portions comprise brown and red fine- to coarse-grained quartzitic sandstone with subordinate mudstones and sparse thin limestones. The base of the Lower Cromhall Sandstone is locally conglomeratic, and the Middle Cromhall Sandstone contains units of dolomitised limestone. The Upper Cromhall Sandstone, as here, comprises grey and red coarse-grained quartzitic sandstones, sandy crinoidal and oolitic limestones, mudstones, siltstones and grey seatearths arranged in cyclic sequences. Units of crinoidal and oolitic limestone are locally developed (BGS Lexicon).

The Cromhall Sandstone Formation units are much affected by the large thrust fault above. First, there is an excellent U-shaped drag fold just below the thrust fault (Fig. 9). This shows how friction caused by the force of movement of the overlying limestones dragged underlying consolidated limestones and sandstones out of place and pulled whole

Figure 9. The north end of St Vincent's Rocks, showing the plane of the Avon Thrust fault, with which the Clifton Down Limestone Formation (right) was thrust over the younger Middle Cromhall Sandstone and Oxwich Head Limestone formations (left). Note the steepening of dip and the drag fold in the Cromhall Sandstone beds under the thrust. This view is taken from the traffic lights at the foot of Bridge Valley Road. (*Photograph by Richard Arthur.)*

beds over as if they were loose rugs. Just below and still within the active tectonic zone, the beds are over-steepened in places, with a higher-than-normal dip as a result of the thrust forces. The over-steepened and typical dips can be compared (Fig. 9). Slickensides are prominent on the underside of the hanging wall of the thrust fault; these indicate that the direction of movement on the thrust plane was complex.

In engineering terms, the St Vincent's Rocks section has caused endless trouble over the centuries. Faulting has caused joints to form that are more closely spaced than usual, so increasing the risk of rockfalls. At one time, the rocks jutted into the river, and this was the danger spot for great sailing ships as they rushed in and out of Bristol docks; frequently if they missed their tide they would run ashore or break their backs at this point. Blasting of the cliffs in the 1830s and at other times removed this obstacle to shipping and cleared the cliffs of loose blocks before the footings for the Clifton Suspension Bridge were put in place in 1831. Nonetheless, the cliffs continued to shed rocks onto the railway line and road below, as noted earlier. When the Hotwells to Avonmouth railway was built, its station lay tight under the cliffs and just north of the Clifton Suspension Bridge, and tunnels pass under the thrust fault and under Bridge Valley Road, and blasting in the 1860s cleared the face we have just been inspecting. When the Clifton Rocks Railway was built in the 1890s in tunnels in the rock face, running from the Portway up to Clifton, to the south of the Clifton Suspension Bridge, further rockfalls occurred, as they did during the building of the Portway in the 1920s. The road is now protected by extensive rock bolting and netting, and the canopy under the Clifton Suspension Bridge protects that part of the road. Even so, the Portway is sometimes closed in winter to enable rock climbers to scour the cliffs for loose blocks and knock them off.

6. Bridge Valley Road

Proceed back to the traffic lights, cross and walk up Bridge Valley Road (A4176). Here, we view the rock succession from across the road all the way to the top. On both sides of Bridge Valley Road are limestones of the Oxwich Head Limestone Formation, here formerly termed the 'Hotwells Limestone', a hard dark grey crinoidal oolitic bioclastic limestone with interbedded dark grey shales and mudstones. These limestones are overlaid by the Upper Cromhall Sandstone Formation here and elsewhere. The high block wall on the right conceals most of the Upper Cromhall Sandstone Formation which comprises the wedge of sediments at the bottom of the hill, with some Oxwich Limestone Formation exposed at the foot of the wall beside the Portway.

As we walk up the hill, keep an eye on the metre-thick limestone and sandstone beds with their apparent dip of 45°, and notice how the rocks and vegetation change as we approach the right-hand bend in Bridge Valley Road just above halfway up [ST 5639 7376]. Below the low retaining wall are the Oxwich Head Limestone and Cromhall Sandstone formations (Fig. 10A), and just round the corner the rocks look quite different, being apparently a chaotic mass of limestone blocks in a red matrix (Fig. 10B).

We have just crossed the Carboniferous–Triassic unconformity. These chaotic sedimentary rocks are the lower units of the 'Dolomitic Conglomerate', an informal division of the littoral facies of the Mercia Mudstone Group. This is an unusual breccia, known extensively around Bristol and the Mendips, but also in South Wales. It typically consists of angular, and rarely rounded, clasts derived locally from rocks lying immediately below the unconformable base of these deposits, in this case primarily irregular brecciated chunks of the Oxwich Head Limestone Formation. The red-coloured matrix of the 'Dolomitic Conglomerate' generally consists of finer-grained rock fragments or, less commonly, siltstone, sandstone or micritic limestone. The clasts are matrix supported and indicate

Figure 10. The Carboniferous–Triassic contact. In the lower and middle parts of Bridge Valley Road, dipping units of the Cromhall Sandstone and Oxwich Head Limestone formations are seen (A), overlain by the chaotic conglomerate facies of the Mercia Mudstone Formation (marginal 'Dolomitic Conglomerate' facies), showing boulders of 1 m and more in diameter (B). Near Clifton Suspension Bridge, the Carboniferous is topographically higher, showing a mineral adit (C), the famous rock slide (D), and fissures (E) beside the approach road to the Clifton Suspension Bridge. The fissures contain recrystallised calcite showing fan-like structures (F) and nail-heads (G). (*Photographs by Michael J. Benton.)*

transport by debris flow, the sand, silt and water mixture acting as a high viscosity liquid capable of entraining much larger particles than water could. Both the matrix and limestone clasts are dolomitized, hence the name 'Dolomitic Conglomerate'. Individual clasts can range up to several cubic metres in size. Even from the other side of the road, at least three upwards-fining cycles of conglomerate can be seen, indicating several high-energy depositional events. The lower boundary of this unit always sits unconformably on Carboniferous rocks, and it interdigitates on a broader scale with the reddish-brown mudstones of the Mercia Mudstone Group (BGS Lexicon). The exposure on the bend of the Bridge Valley Road is particularly striking (Fig. 10B) as the 'Dolomitic Conglomerate' here consists of a very coarse breccia, with irregular, sharp-edged boulders of reworked Carboniferous limestone up to 150 cm across. It was probably deposited in an alluvial fan expanding outwards from the mouth of a wadi following a major flood event.

The Carboniferous–Triassic contact here is highly irregular, differing by 20–30 m in height. The exposure on Bridge Valley Road is much lower than the contact on top, around the observatory, probably reflecting surface erosional irregularities that depend on the varying hardnesses and solubilities of the Carboniferous units enhanced by erosion by the flash-floods that created the gullies full of coarse debris.

The upper parts of the Clifton Down Limestone Formation and the overlying units, the Oxwich Head Limestone and Cromhall Sandstone formations (Figs 1–4) occur in the overgrown slopes to the south of the Great Quarry but are generally not readily accessible in the sections between the Great Quarry and Bridge Valley Road. If you have time, you can locate these in the woods to the north of Bridge Valley Road, by diving down the Zig-Zag Path on the left [ST 5653 7390]. This is not suitable for beginners or for a large party as the exposures are overgrown and poorly accessible.

It is possible to explore the 'Dolomitic Conglomerate' and patches of Redcliffe Sandstone, also Triassic in age, in more detail in the woods above the road to the south; enter the footpaths at the top of the hill, just before the road junction or from the Promenade. At this point, visitors can either proceed along the Promenade to locality 7, or go back down Bridge Valley Road, and walk under the Clifton Suspension Bridge to the foot of the Zig Zag Path (locality 8) and complete Locality 7 after that.

7. Clifton Suspension Bridge Cutting

Here, it is possible to explore several geologically important themes. Walk up towards the Observatory [ST 5657 7326], a converted former windmill built as a snuff mill about 1729, and now converted to a restaurant, camera obscura and cave access. Here, you can go down through the Clifton Down Limestone in a natural cave linked by manmade tunnels and look out over the Gorge from a viewing platform. Just south of the Observatory, on the right of the path is a children's playground [ST 5667 7325] in the remains of a limestone quarry. In the back wall is a bricked-up adit, presumably representing the entrance to a former iron ore or lead mine (Fig. 10C). The roof of the adit is fissured and sparry, crystalline calcite can be seen in fissures. On the other side of the path is the natural rockslide [ST 5660 7321], used by generations of Clifton children, a bedding plane within the Clifton Down Limestone Formation (Fig. 10D). It is protected on the west side by a vertically standing, reddish-coloured, crystalline rock wall, representing hardened rock between a set of vertical joint planes; note the presence of mineralisation around sectioned phreatic water tubes.

Walk back to the pavement either side of the public toilets [ST 5666 7320], where the low rock walls represent fissured upper portions of the peneplained Carboniferous, with red staining coming from the formerly overlying Triassic. There are several fissures here, some represented simply by red-stained narrow cracks (Fig. 10E), sometimes associated with calcite-filled veins and others containing small amounts of Triassic-aged sediments. The calcite has recrystallised from the surrounding limestones under pressure to form layers of crystals transverse to the fissure orientation in three different morphologies, fibrous isopachous, bladed isopachous (Fig. 10F) and botryoidal (Fig. 10G).

The fissures could be similar in age and occurrence to those found in the limestone quarries along Worrall Road in Clifton, the source of the famous 'Bristol dinosaur' *Thecodontosaurus*, as well as smaller bones of lizard-like rhynchocephalians, and teeth of early crocodile-like animals and dinosaurs (Foffa *et al*., 2014). Whiteside and Marshall (2008) reported Rhaetian-aged palynomorphs from the fissures here, beside the bridge.

This site is more famous for the 'Bristol diamonds', quartz crystals found in nodules within the 'Dolomitic Conglomerate' and in fissures in the underlying Carboniferous limestones, as here. The Bristol diamonds became famous collectable items among tourists when Clifton and especially nearby Hotwells were noted spas. They were reported as early as 1586, and the English traveller Celia Fiennes wrote in 1698, "They Digg ye Bristol Diamonds wch Look very Bright and sparkling and in their native Rudeness have a great Lustre and are pointed and Like ye Diamond Cutting."

They are not diamonds of course, but quartz crystals that grew in geodes within nodules that had been interpreted as resulting from decreasing pore-water salinity and dehydration of silica gel, but were reinterpreted by Tucker (1976) as examples of quartz replacement of anhydrite nodules. Evidence is seen in the composition of the 'diamonds' in which some show abundant anhydrite inclusions that are relics of larger lath-shaped anhydrite crystals. Replacement proceeded from the outside inwards, and central voids developed in cases where silica replacement was slower than anhydrite dissolution. Tucker (1976) suggested that the anhydrite had formed first by precipitation of sulphate from hypersaline pore waters, probably in marginal playas of the Mercia Mudstone Group, and then pore waters rich in silica and poor in sulphate later passed through the fissures and cracks of the Triassic marginal rocks, causing the replacement of anhydrite by quartz.

It is unlikely you will find any Bristol diamonds in view of their longstanding popularity, but you can see the red-stained joints and calcite crystals around narrow fissures, denoting the karstic top of the exposed Carboniferous limestones here. The low cliff beside the public toilets is also netted and rock-bolted to prevent loose blocks from falling.

For the next location, walk south across the grass towards Sion Hill and the Avon Gorge Hotel; walk as far as the circular paved area which acts as a viewing point to enjoy the Clifton Suspension Bridge

8. Old Zig Zag Path

There are two zigzag paths from Clifton down to the Portway, a newer one beside Bridge Valley Road, and the original, or 'Old' Zig Zag Path starting from Sion Hill just north of the Avon Gorge Hotel (Fig. 11). This path begins below the paved viewing point and sweeps through six or seven Z-shapes on its way down.

Knowing that the Clifton Down Limestone Formation forms much of the exposed limestone around the Observatory and the base of the Clifton Suspension Bridge, and the overlying Oxwich Head Limestone Formation covers much of Hotwells, we should look for the contact of these two great limestone formations, and determine any unusual sediments near the contact.

The two major limestone formations are relatively easy to identify, the Clifton Down Limestone Formation in the top three or four sweeps of the path as it descends (Fig. 11), and the Oxwich Head Limestone Formation (formerly the Hotwells Limestone here) at

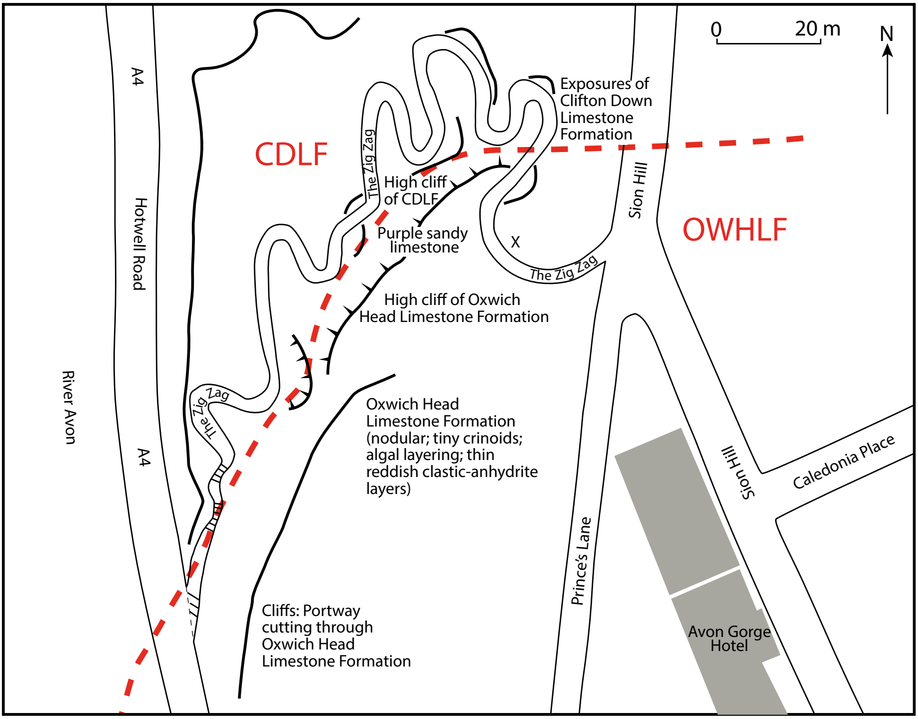

Figure 11. The Zig Zag Path from Sion Hill down to the Portway. Sketch showing the key exposures. (*Drawing by Susan Marriott.)*

the bottom, forming the high cliffs immediately at the edge of Hotwells Road (the Portway) and up the side of the steps in the lower part of the Zig Zag Path. The Clifton Down Limestone (Fig. 12A) shows darker grey and brown weathering colours, with sandy limestones at its base in the Bristol area, and occasional cherts and silicified fossils near the base also. The Oxwich Head Limestone (Fig. 12C, D) shows thicker beds (*c*. 2 m) than the Clifton Down Limestone (30–100 cm), it is lighter in colour (white, grey), it can be ooidal, pseudobrecciated, and show occasional shaly partings. These are seen especially at the base of the unit, where thin red clastic siltstone beds are interleaved with crystalline anhydrite bands a few millimetres thick, as well as some hints of algal layering and thin layers with small crinoid debris. These lie just below some recrystallised, pseudobrecciated bands that mark the base of the Oxwich Head Limestone Formation (Fig. 12B).

The two limestones can be identified definitively at top and bottom of the Zig Zag respectively, and the exercise is to determine where they meet. In fact, there are some ambiguous units at mid-height of the Zig Zag Path, showing shaley, wavy bedding in places (Fig. 12A), and evidence of clastic grains in others, presumably near the top of the Clifton Down Limestone Formation. Above these is a thin band of calcareous sandstone (fizzes with acid, but shows quartz and feldspar grains) no more than 1 m thick here. This marks the contact of the Clifton Down Limestone Formation and the overlying Oxwich Head Limestone Formation, marked by some shaley and sandy beds at the top of the former, overlain by the concretionary-pseudobrecciated base of the latter (Fig. 11).

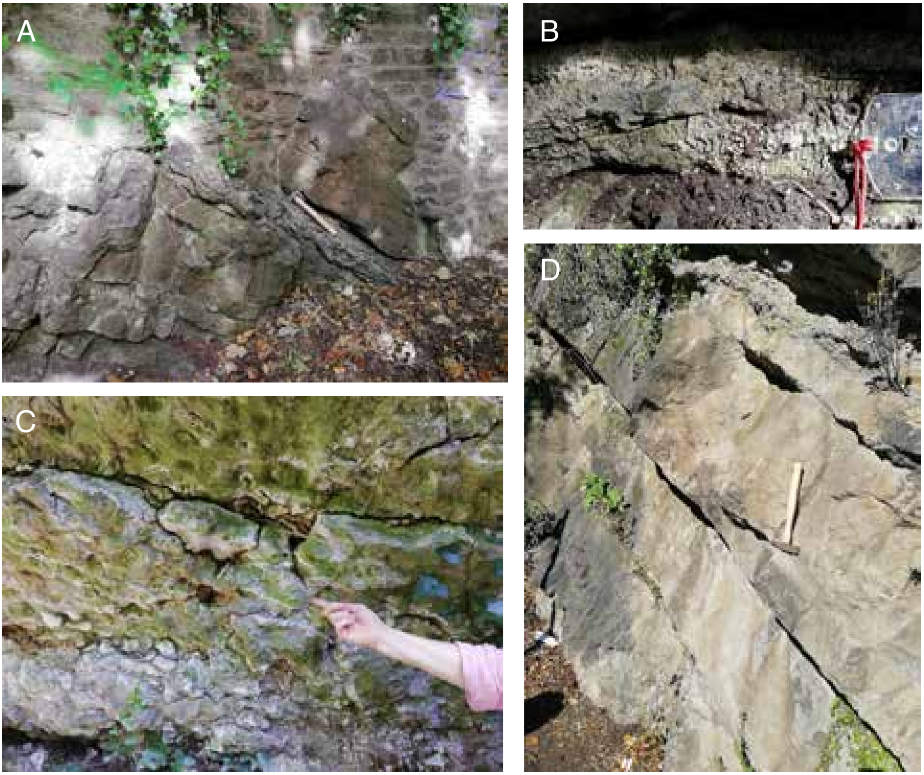

Figure 12. Photographs of exposures from top to bottom of the Zig Zag Path, showing (A) shaley beds near the top of the Clifton Down Limestone Formation; recrystallised, sparry calcite layer beneath the Oxwich Head Limestone Formation (B); nodular undersurface of a bed near the base of the Oxwich Limestone Formation (C); and thickly bedded Oxwich Limestone Formation at the foot of the Zig Zag Path and side of the Portway (D). (*Photographs by Michael J. Benton.*)

It is worth recording dips and strikes on each exposure down the path – dips vary from 17–38° SE and strikes from 035–066, suggesting that the beds are generally conformably arranged, but with some complexity. In fact, the exposed edge of the Oxwich Head Limestone Formation where it is mapped by the BGS (Fig. 11), is seen as a 5–10 m high cliff slanting up the slope, and visible behind the bushes and trees at southern sweeps of the Zig Zag Path; this must represent an edge where rock fell away, exposing the underlying Clifton Down Limestone Formation and marking the southern margin of the path.

Discussion

Having examined the whole section, some further points concerning the scientific and engineering significance of the Avon Gorge will be considered.

1. Engineering aspects of the gorge

The field excursion focuses on the rock succession, but it is important also to note engineering aspects. The Avon Gorge has long been a site of quarrying, transport links, and building, and all these activities have highlighted aspects of the instability of the cliffs, slopes, and banks of the River Avon.

Quarrying in the Gorge began long before 1800, and Bright (1817) noted extensive limestone quarries along the eastern side. That side was presumably worked more than the west because of easier access back to Bristol (in the absence of a bridge across the lower reaches of the Avon) and perhaps because there were also long-established quarries above the Gorge in the Clifton Downs. Quarries on the western bank were sporadic, although some were large, and their form can be seen although now overgrown; when operational they had to load the limestone blocks and rubble onto barges served by small jetties.

The Black Rock Limestone Subgroup was quarried in the early nineteenth century for paving stones, and the Clifton Down Limestone was burnt to produce a very pure lime that was even exported to the West Indies for sugar refining (Bright, 1817). Otherwise, various of the limestones from both sides of the river were used locally for rough building stone, more often garden walls than houses, and as a bed for road building. The last active quarry on the Bristol side was Black Rocks, which closed in 1877.

In a famous painting, Norwich artist John Sell Cotman (1782–1842) painted a watercolour in 1830 called ‘Blasting St Vincent’s Rock, Clifton’ in which he shows the Avon Gorge, looking downstream from a viewpoint beside the river and roughly below the location of the Clifton Suspension Bridge (which began construction a year later, in 1831), and showing two sailing boats heading out to sea on a full tide, while above on the right-hand bank huge rocks fly through the air amidst a great puff of smoke. A guidebook of 1793 had acknowledged the exciting drama of the explosions and crashing rocks associated with the quarrying, but warned that “those sublime wonders of nature, the admiration of past ages, whose fame has excited thousands of strangers to visit the Hotwell and Clifton” were being “wholly demolished”. So extensive was the quarrying in the Gorge that the poet Robert Southey (1774–1843) wrote in 1807, “The people of Bristol sell everything that can be sold…and here they sell the sublime and beautiful by the boatload”. As a Bristolian, he could say this. In the 1840s, complaints were made in the Bristol newspapers about the noise and danger of the seemingly unregulated quarrying along and above the Gorge, when blasting would send rocks flying through the air. One correspondent wrote in, “expressing sorrow and surprise that for trifling gain so much beautiful and almost unequalled scenery should be destroyed”.

The dominant engineering work of this part of the Avon Gorge is the Clifton Suspension Bridge, built in bursts of activity from 1831 to 1864, when it opened. The Clifton tower sits more or less on bedrock whereas the Leigh Woods tower sits on top of a massive red sandstone box structure, 34 m high. The construction involved heavy engineering works, including blasting away part of St Vincent’s Rock on the Clifton side. The tower at each end is 26 m tall, and the chains that support the road bed pass over roller-mounted saddles on top of each tower, to allow movement of the chains as winds and traffic move the road bed. The chains are secured in tunnels at each end of the bridge, descending 18 m below ground level. The weight of the bridge, including the chains, rods, girders and road deck is estimated at 1500 tonnes.

In terms of transport links, for a long time, there were tracks on either side of the Avon, but primarily on the eastern side where villages such as Seamills and Shirehampton were connected to Bristol to the south and Avonmouth to the north. The Bristol to Portishead railway along the western side of the Avon opened in 1867, closed around 1990, but was rebuilt and still operates to transport cars from the Portbury docks, and should resume passenger transport at some point. On the eastern side, there were two railways, first the

Hotwells to Avonmouth line, which opened in 1865 and closed in 1922. It had been rendered redundant by the fact that it did not continue into the dock area of Bristol, and by the construction of the Bristol to Severn Beach line, and especially the tunnel under the Downs from Clifton Down Station to open in the cliff below the Sea Walls viewing point. This line opened to Clifton Down Station in 1874, and the tunnel was built and opened to good traffic in 1877 as far as Avonmouth and extended to Severn Beach in 1900. The Hotwells to Avonmouth line closed in 1922, because it had been largely subsumed into the new Bristol to Avonmouth line and much of its track bed became part of the Portway which was built in the 1920s as an extension of the A4 road from Bristol to Avonmouth, and now a major connecting route to the M5.

The building of roads, quarrying, and the Suspension Bridge revealed numerous engineering weaknesses in the Avon Gorge (Hawkins, 1987). For example, during the building of the Portway in the 1920s, retaining walls gave way and rock debris, earth and filling materials slumped into the river. Now there is a substantial retaining wall along the river side of the Portway. The railways escaped such damage to a large extent as they are built further back from the river bank. However, the cliffs themselves are heavily jointed and frequently give way, shedding loose blocks down their slopes. At times, more substantial rockfalls have occurred. For example, in 1972, some 60 tonnes of rock fell onto the Portway below Sea Walls, and those portions of the cliffs were made safe by the removal of an unstable mass of some 3000 tonnes at the top of the cliff, and then the remaining rock face was netted and bolted. The rock faces at the southern end are much more unstable because of fault-generated fracturing and they were stabilised in the 1970s and 1980s by removing all loose debris, and by further netting and rock bolting, especially around the foot of Bridge Valley Road, where further stabilisation had to be carried out to the high retaining wall around 2015.

2. Site of Special Scientific Interest

The entire area visited during this field trip falls within the Avon Gorge Site of Special Scientific Interest (SSSI), including the park land and slopes and cliffs on the east side from Sneyd Park to the Suspension Bridge, and the matching slopes on the west side, but running further from the edge of the Gorge to include much of Leigh Woods through to Paradise Bottom, a total of 155.4 hectares. According to the official SSSI designation, "The Gorge has natural cliffs and quarry exposures of Carboniferous Limestone, which are of great geological interest and, together with the screes, scrub, pockets of grassland and adjacent woodland, support an exceptional number of nationally rare and scarce plant species." The plants include unique species such as the Round-headed Leek (= Bristol onion), *Allium sphaerocephalon* and Bristol Rock-cress, *Arabis stricta*, as well as diverse ecosystems that rely on the limestones.

The geological interest of the SSSI is officially summarised: "This site shows the complete local succession of the Carboniferous Limestone. The classic work of Vaughan and Reynolds on the marine fossils of the limestones, and the adoption of the sections as the standard for the 'Avonian' (= Dinantian), makes this one of Britain's historic geological sites, important for both the study and development of stratigraphy. The section spans (with gaps) the entire Tournaisian and Visean series (Courceyan–Brigantian stages), and also includes the Old Red Sandstone Portishead Beds below. The Avon Gorge affords one of the best opportunities for the study of Carboniferous rocks in Britain, studies which have continued since the early 19th century."

3. Carboniferous oceans and coasts

We will not discuss the somewhat contorted history of the stratigraphic divisions and nomenclature of the Avon Gorge section any further. This can be reviewed in the cited papers (e.g. Vaughan, 1905, 1906; Vaughan & Reynolds, 1937; Kellaway & Welch, 1955, 1993; Waters *et al*., 2009). More interesting perhaps is the geological interpretation of the environments of deposition of this great thickness of limestones, and how a wider view across the area can build a more detailed picture of the world 350 Ma.

At this time, the UK and much of Europe lay south of the Equator, but in tropical latitudes. At a basic level, that explains why corals and other fossils usually associated with warm waters are so abundant. Marine ooids are confined to the tropics today, requiring gently agitating warm waters for their precipitation and growth and the same was probably true also in the Early Carboniferous.

The whole Lower Carboniferous succession here, and further south, was deposited on the Mendip Shelf, which was a southerly sloping ramp. The Avon Gorge section lay closer to the land margin to the north, so most of the named units we have seen on this excursion are much thicker to the south, around Burrington Combe and throughout the Mendips where they also display deeper water facies.

The landward nature of the sections is shown both by the interplay of fully marine with terrestrial deposits, and by a number of non-sequences representing missing deposition when the area was uplifted or exposed above sea level. The sequence begins with the largely terrigenous Shirehampton Beds (Fig. 1), which we did not inspect, and is followed by the open marine Avon Group, whose limestones include some fine-grained detrital material. These land-derived components diminished during deposition of the dark-coloured limestones of the Black Rock Limestone Subgroup, which represents deposition in deeper waters probably below wave base. The Gully Oolite Formation represents substantial shallowing, with ooliths forming in an active shoal where the movement of waves and bottom sediment prevented many organisms taking hold. The overlying Clifton Down Mudstone Formation was also deposited under lower energy conditions, sometimes stagnant, and with limited fauna. Conditions returned to more open, deeper sea waters during deposition of the Clifton Down Limestone Formation, characterised by bioclastic limestones in the lower part and then the Seminula Oolite and Pisolite represent lower-energy lagoonal conditions. The overlying Oxwich Head Limestone Formation represents open-shelf conditions of fairly high energy, supporting an abundant and diverse fauna (Kellaway & Welch, 1993). At this level, the three units of the Cromhall Sandstone Formation show the closeness to land as these are fluvial units that interfinger with the upper limestones.

The coastal setting of much of the succession is confirmed by several disconformities, or gaps in deposition, generally marked by erosive surfaces. The first disconformity is on top of the Shirehampton Beds where the unclassified Avon Group sits above an eroded surface. The second disconformity is at the top of the Black Rock Subgroup, where some 130 m of limestones seen at Burrington Combe are absent here and representing a substantial span of latest Tournaisian and earliest Viséan time. The third disconformity is at the top of the Gully Oolite Formation where the overlying Clifton Mudstone Formation rests on an eroded surface. The fourth stratigraphic break occurs within the Clifton Down Limestone Formation at the base of the Seminula Oolite, and the fifth at the base of the Oxwich Head Limestone Formation.

4. Triassic deserts

The Triassic in Europe is often characterised as a time of desert-like, or at least dry conditions. We see some evidence for this in the 'Dolomitic Conglomerate' around the Clifton Suspension Bridge. Whereas at Aust Cliff (Excursion XXX), classic Mercia Mudstone Group (MMG) red beds are seen, some of them with deep cracks produced by drying sediments, and gypsum beds and infills produced from evaporating seawater, across Clifton the 'Dolomitic Conglomerate' represents a littoral or coastal facies of the Mercia Mudstone Group.

The 'Dolomitic Conglomerate' facies interfingers with red clastics of the Mercia Mudstone Group. Deposits occur on the flanks of the Mercia Mudstone Group outcrop, where these red beds overstep onto Palaeozoic or Proterozoic rocks; the thickest deposits lie unconformably on Carboniferous limestones in Somerset and South Wales, and around the flanks of the Charnwood Forest in Leicestershire (BGS Lexicon). Thicknesses are highly variable owing to the interdigitating relationship with the Mercia Mudstone Group; they range from 1 m or less at some exposures to over 100 m where these deposits fill buried valleys in the underlying pre-Triassic topography.

The dating of the 'Dolomitic Conglomerate' is uncertain because it lacks fossils and any other indicator of age. Because it is an erosive, brecciated deposit and generally sits on an unconformable eroded and often karstified surface of uplifted, folded, faulted, and planed Carboniferous limestones, the lower boundary provides no useful age constraint. Further, the 'Dolomitic Conglomerate' often forms the top of a succession because it is hard, having often been cemented and dolomitised and, as here, is not overlain by younger sediments of the Triassic or Jurassic. The unit is dated as having been deposited at some time in the Late Triassic, as with the Mercia Mudstone Group in general. However, the Late Triassic is a long time, lasting from 236–201 Ma, and current views would perhaps suggest it is either late Carnian (233–227 Ma) to late Norian (215–206 Ma) in age.

The older, Carnian, age assignment is based on an assumption that much or all of the Triassic-aged karstification around Bristol took place at the time of the Carnian Pluvial Event, 233–232 Ma (Ruffell *et al*., 2016) and so all the fissures we saw, together with the staining, mineralisation, formation of Bristol 'diamonds' and deposition of the 'Dolomitic Conglomerate' happened at the same time. It cannot be excluded, however, that the breccias are considerably younger, as they appear to occur in association with upper parts of the Mercia Mudstone Group red beds, and in Bristol are commonly associated with fissures and palynomorph fossils of likely early Rhaetian age (Whiteside & Marshall, 2008; Foffa *et al*., 2014). These last are most significant if the age of the sediments within the fissures are similar in age to the karstification and possibly also to the 'Dolomitic Conglomerate' itself.

References

BGS Lexicon. The BGS Lexicon of Named Rock Units. https://www.bgs.ac.uk/lexicon/

Bradshaw, R. 1966. The Avon Gorge. *Proceedings of the Bristol Naturalists' Society,* **31**, 203–220.

Bradshaw, R. & Frey, A.E. 1987. The geology and evolution of the Avon Gorge. *Proceedings of the Bristol Naturalists' Society*, **47**, 45–64.

Bright, R. 1817. On the strata in the neighbourhood of Bristol. *Transactions of the Geological Society of London*, Series 1 **4**, 193–205.

Cumberland, G. 1821. On the limestone beds of the River Avon, near Bristol. *Transactions of the Geological Society of London*, Series 1 **5**, 95–113.

Foffa, D., Whiteside, D.I., Viegas, P.A. & Benton, M.J. 2014. Vertebrates from the Late Triassic Thecodontosaurus-bearing rocks of Durdham Down, Clifton (Bristol, UK). *Proceedings of the Geologists' Association*, **125**, 317–328.

Hawkins, A.B. 1987. Rock slope and stability in the Avon Gorge. *Proceedings of the Bristol Naturalists' Society*, **47**, 65–78.

Kellaway, G.A. & Welch, F.B.A. 1955. The Upper Old Red Sandstone and Lower Carboniferous rocks of the Bristol and the Mendips compared with those of Chepstow and the Forest of Dean. *Bulletin of the Geological Survey of Great Britain*, **9**, 1–21.

Kellaway, G.A. & Welch, F.B.A. 1993. *Geology of the Bristol district*. Memoir of the British Geological Survey. HMSO, London, 199 pp.

Ruffell, A., Simms, M.J. & Wignall, P.B. 2016. The Carnian Humid Episode of the late Triassic: a review. *Geological Magazine*, **153**, 271–284.

Tucker, M.E. 1976. Quartz replaced anhydrite nodules ('Bristol Diamonds') from the Triassic of the Bristol District". *Geological Magazine*, **113**, 569–574.

Vaughan, A. 1905. On the palaeontological sequence in the Carboniferous Limestone of the Bristol area. *Quarterly Journal of the Geological Society*, **61**, 181–305.

Vaughan, A. 1906. The Avonian of the Avon Gorge. *Proceedings of the Bristol Naturalists' Society*, Series 4 **1**, 87–100.

Vaughan, A. & Reynolds, S.H. 1935. The Carboniferous Limestone Series (Avonian) of the Avon Gorge. *Proceedings of the Bristol Naturalists' Society*, Series 4 **8**, 29–90.

Waters, C. N., Waters, R. A., Barclay, W. J. & Davies, J. R. 2009. *A lithostratigraphical framework for the Carboniferous successions of southern Great Britain (Onshore)*. British Geological Survey Research Report, RR/09/01, 184 pp.

Whiteside, D.I. & Marshall, J.E.A. 2008. The age, fauna and palaeoenvironment of the late Triassic fissure deposits of Tytherington, South Gloucestershire, UK. *Geological Magazine*, **145**, 105–147.