BATH GEOLOGICAL SOCIETY

# Journal


## No 40, Winter 2022

# SOCIETY ACTIVITIES 2022

## LECTURE PROGRAMME

**February 3rd**
Mud volcanoes as a surface expression of subterranean forces - speaker: Professor Richard Swarbrick, University of Durham

**March 3rd**
Geology and war: an exploration of how the ground influences battles - speaker: Professor Paul Nathanail, University of Nottingham

**April 7th**
Mining magmas for metals and energy - a novel strategy for achieving net zero. The 50th Anniversary Lecture given by Professor Jon Blundy, Royal Society Research Professor, Department of Earth Sciences, University of Oxford

**May 5th**
The day after tomorrow – is the Gulf Stream set to shut down? Speaker: Dr. Jon Robson, University of Reading

**June 1st**
The Fogo volcanoes, Cape Verde Islands. Speaker: Professor Peter Worsley, University of Reading

**July 7th**
Bilston Stone Quarries- Digging up the past- Geology and Genealogy. Speaker: Graham Hickman, Bath Geological Society

**September 1st**: A conversation Geology and Poetry. Speaker: Alyson Hallet, prize-winning poet and Hawthornden Fellow

**October 6th**
The 'real' value of microfossils. Speaker: Dr Haydon W. Bailey, Consultant Micropalaeontologist & Honorary Lecturer, University of Birmingham

**November 3rd**
Volcano-Sedimentary processes / The Evolution of Volcanic Systems Speaker: Dr. David Buchs, University of Cardiff

**December 1st**
Petra – the stories in its rocks: Speaker: Professor Maurice Tucker

## FIELD MEETINGS

**March 5th**
Torr Hill and Wookey Hole. Leader Dr Doug Robinson

**March 10th**
Bristol Museum, behind the scenes. Leader Deborah Hutchinson

**April 9th**
50th anniversary FieldTrip. Combe Hay circular walk. Leader: Professor Maurice Tucker

**May 29th**
Lilstock Bay. North Somerset. Leader David Hall

**July 2nd**
Forest of Dean (Eastern part). Leader Dave Green

**October 8th**
Pen Hill, near Wells. Leader Dr Doug Robinson

The Society held six field trips during 2022. Those at the beginning of 2022 were very well attended as people ventured out again after the winter. Several had to be rearranged as we experienced severe weather warnings (extreme heat in the summer as well as storms at the start of the year). One trip to the Forest of Dean had to be cancelled due to lack of people signing up. We thank all the leaders for sharing their time and expertise with us. We thank too Sue Harvey and Bob Mustow for arranging trips, advertising, sign-up and safety in the field.

# Contents



*Cover photo: Group photo from the March field trip to Tor Hill & Wookey Hole Caves, led by Doug Robinson. Photograph taken by Graham Hickman*

## Chairman's Report for 2022

2022 has been another unusual year as we have emerged from the Covid 19 pandemic only to be plunged into a cost of living/energy crisis and the death of Queen Elizabeth II. We have witnessed the shortest serving PM in history, record breaking heatwaves and the Russian invasion of Ukraine. These are all unsettling events that affect our lives - just when we were hoping things would go back to how they were before COVID.

Despite all of these uncertainties the Society has continued to hold a full programme of lectures and field trips. Our membership currently stands at 74, a healthy number and reflects the enthusiasm that the committee have shown in putting together the programme. The committee has continued to meet on a regular basis, remotely, to conduct the business of the Society.

In February we held the 2022 AGM over Zoom. We had a good discussion about how members felt about hybrid lectures; the committee proposed that lectures be held on Zoom only over Winter and then in-person over Spring/Summer. The purchase of a Bluetooth microphone by the Society has overcome the poor sound quality of hybrid lectures for those listening online. It was decided that in-person lectures would also be hybrid. Technically, hybrid lectures have been quite difficult to host as there are many things that can go wrong, but feedback from those watching online has been positive so we have continued with them throughout the summer.

Our lecture programme has covered a wide range of geological topics and we hope you have found them stimulating. We are grateful to the speakers who have provided some excellent and interesting presentations. We are grateful to Anne Hunt, our Program Secretary, for her efforts in securing a successful lecture program. In April the Society held our long awaited 50th Anniversary celebrations. (2020 was the original anniversary date). The celebrations consisted of a lecture by Professor Jon Blundy, followed by cake and drinks. At the weekend a Field Trip was held led by Professor Maurice Tucker. Both events were very enjoyable and well attended. With the assistance of the GA regional groups grant we were able to cover the costs and invite our neighbouring geology groups to share in this milestone event.

The Society held six field trips during 2022. Those at the beginning of 2022 were very well attended as people ventured out again after the winter and the 'Omicron wave'. Several Field Trips had to be rearranged as we experienced severe weather warnings (extreme heat in the summer as well as storms at the start of the year). One trip to the Forest of Dean had to be cancelled due to lack of people signing up. We thank all the leaders for sharing their time and expertise with us. We thank too Sue Harvey and Bob Mustow for arranging trips, advertising, sign-up and safety in the field.

I have been very grateful to the hard work and commitment of the Committee during the year. Their efforts have resulted in the delivery of a full programme of lectures and field trips.

The committee has met about 6 times during the year using the Zoom virtual conference technology. This seems to have worked well and assisted with communications and keeping track of our finances.

The strength of a Society like ours is measured by those who volunteer their time, and I am indebted to those on the committee.

**The 2022 Committee**

Chairman: Graham Hickman
Treasurer: Phil Burge
Secretary: Katie Munday
Membership Secretary: Polly Sternbauer
Meetings Secretary: Anne Hunt
Journal & Zoom: Mellissa Freeman
Field Trip Secretary: Sue Harvey
Field Trip Safety: Bob Mustow
Webmaster: James McVeigh
Linda Drummond-Harris
Professor Maurice Tucker

On a personal note, many of you may be aware that in May 2022 I was elected as the President of the Geologists' Association. This has been an honour for me but also an additional responsibility. In February 2023 I intend to stand down as Chairman of the Bath Geological Society having served three years. This is the normal term of office as set out in our constitution.

If you have any comments or suggestions, I would love to hear from you. On behalf of your committee, thank you again for your support.

Graham P Hickman
chairman@bathgeolsoc.org.uk

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## A quick note from the Journal Editor

I really hope you enjoy the articles in this years Journal and I would like to thank everyone who has contributed. It has been an absolute pleasure to edit.

It was always going to be tough to get anywhere near the same number of articles following our bumper edition last year. But, we did it, even if it was a little touch and go up until September/October time.

I really hope you enjoy them and don't forgot we can add anything to future journals; places you have visited, photographs, a book review etc. I am grateful for all.

Thanks again,
Mellissa Freeman
journal@bathgeolsoc.org.uk

# Obituary

Written by Elizabeth Devon & Mellissa Freeman

## Jacoba Sherriff

I have known Jacoba and her daughters since we moved to Middlehill in 1978. However, I did not know her well until she joined the evening geology course I was running at Stonar School in the summer of 1998. She was a very enthusiastic participant and, after the course, she joined the Bath Geological Society and, from then on, we travelled to meetings and field trips together. Jacoba often accompanied me on my 'recce' outings for field trips I was running for various groups and I always enjoyed her calm, cheerful and interesting company. She often told me about her involvement with the Miniature Needlework Society. In fact one of the last communications I had with her was receipt of a copy of their March 22 Newsletter which featured The Jonesonian Museum in Tasmania, an amazing 1/12th scale museum crammed full of miniature specimens of all sorts including, rocks, minerals and fossils. We also shared an interest in gardening and for the last few years, since we moved to Northumberland, we exchanged photos of our gardens at various times of the year. She had a great love of nature and landscape, she saw beauty everywhere and I shall miss her.

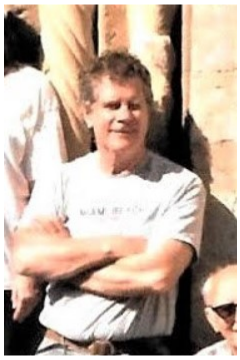
Elizabeth Devon

I have given Jacoba a lift to our Bath Geological Society meetings for many years. Those of us in the car would often put the world to rights, we had many laughs and always a post lecture discussions on the way home. Jacoba became sick with cancer several of years ago. She was treated and recovered up until recently when she was given the news that it was back. Her optimism and spirit were shining through right up until the end. She leaves behind 3 daughters Abi, Ali & Fran who she was immensely proud of. One of her daughters shared a lovely story; she named her two cats Pally & Tolly after her love for palaeontology.

Her funeral was held at the West Wiltshire Crematorium, Semington at 14:30 on Wednesday 27th July followed afterwards with refreshments at Selwyn Hall, Box.

Mellissa Freeman

## Tom Ralph Remembered



William Thomas Ralph, died on 15 May 2020, aged 76

Charles Hiscock remembers ''He was a very pleasant chap, always a pleasure to chat to him. I didn't know him well but he obviously was a keen geologist particularly as he was FRGS. I think he joined the Society about the same time as me, 1982- ish.''

The last couple of years have taken away some of our long time members.

Graham Hickman

# Sand to Rock the Making of Bath Stone: Cementation, Burial and Uplift of the Great Oolite, Middle Jurassic, England.

**By Maurice Tucker, School of Earth Sciences, Bristol University, Bristol BS8 1RJ.**
**maurice.tucker@bristol.ac.uk**

The City of Bath is famous for its buildings of Bath stone, a Middle Jurassic oolite deposited around 168 million years ago as an oolitic sand in a warm, shallow sea. The stone, used for building and sculptures since Roman times (Tucker et al. 2020), is one of three designated *Global Heritage Stone Resources* in the UK, along with its 'rival' Portland stone and Welsh Slate. But what happened to that loose sand deposited on a tropical beach all those millions of years ago to transform it into the freestone much used and favoured by architects and builders? The sand was cemented first in the shallow subsurface, and then lithified further with burial to many 100s of metres depth, where it was also fractured. There then followed uplift in the Tertiary to bring the Great Oolite to its present location at the surface in the area from Bath to Bradford-on-Avon to Box, where it has been exploited for millennia.

This article tells the story of the origin of Bath stone and the evidence of its long journey over millions of years until it was quarried and mined as a building resource.

### Bath stone stratigraphy

Bath stone occurs within the Great Oolite (Bathonian stage of the Middle Jurassic) and there are two freestone horizons; the Combe Down Oolite and the Bath Oolite, with the Twinhoe Beds between. These 3 members are now referred to as the Chalfield Oolite Formation. Below this is the Fuller's Earth, and above is the Upper Rags, Forest Marble and Cornbrash Formations. The whole succession is referred to as the Great Oolite Group (Barron et al. 2012; BGS 2015).

### Bath oolite deposition

The sediment forming Bath stone is an oolitic sand, composed of ooids, around 0.5 mm in diameter (see Figure 1), along with small shell fragments (bioclastic grains) (Green & Donovan 1969; Tucker et al. 2020). These ooids were formed in a moderate energy shallow sea, as they are today in places like the Bahamas (Figure 2) and the Trucial Coast of Abu Dhabi. The sediment was moved around by waves and currents as ripples and sand dunes to give rise to cross-lamination and cross-beds frequently seen in cut-blocks of the stone (Figure 3). The ooids themselves were precipitated from seawater, although this process may have been encouraged by the presence of microbes (bacteria and viruses). Animals lived upon and within the sediment so that burrows are commonly present in the stone (Figure 3).

*Figure 1. Ooids clearly visible on fresh surface of Bath stone. Corsham, Wilts. Field of view 20 mm across.*

*Figure 2. Modern ooids from Joulters Cay, Bahamas. Field of view*

*Figure 3. Cross-bedding in the upper part (from migration of a small dune on the seafloor) and vertical burrows, lined by lime mud, below. Oldfield Park, Bath. Field of view 40 cm across.*

### Bath oolite early diagenesis

Soon after deposition, just below the seafloor to a few metres depth in the sediment, a thin fringe of calcite cement was precipitated around the grains. This stabilised the sediment and prevented any significant compaction (Figure 4). There is evidence at outcrop for seafloor lithification of the Bath oolite and the formation of hardgrounds, and these are seen as flat surfaces encrusted with oysters and bored by lithophagid bivalves and polychaete worms. They are well seen at Brown's Folly, Bathford. Where bivalve shells are present in the sediment and there has not been an early cement, these may be broken as a result of the over-burden (i.e., mechanical compaction) during burial to a few 10s of metres (e.g., Figure 5).

The early fringe cements around the grains are likely to be of marine origin. They would have formed through seawater, which was supersaturated r.e. calcite, being pumped through the porous sediments by waves and storms, and the degassing of the water, possibly with some contribution from microbes. After the first cement generation, lime mud was frequently washed into the partly lithified sediment to form a layer upon the ooids, arranged in a geopetal fashion (Figure 4).

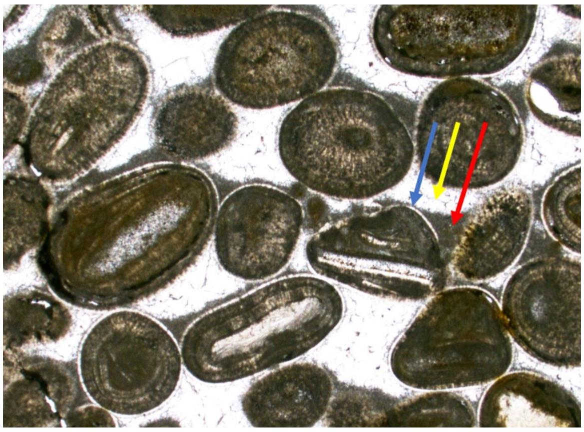


*Figure 4. Bath oolite showing ooids formed around peloids and bioclast fragments, with a thin, fine white calcite cement fringe around the grains (e.g., blue arrow), precipitated there soon after deposition. Some lime mud (grey, e.g., red arrow) then infiltrated to be deposited upon the ooids in a geopetal arrangement. The remaining porosity was filled later during burial by coarse calcite spar (the white areas between the ooids, e.g., yellow arrow). Brown's Folly, Bathford. Field of view 3 mm across.*

*Figure 5. Bioclastic limestone with dark peloidal lime mud. The bivalve shells are broken as a result of mechanical compaction. Note that the shells are stained pink, that is indicating calcite, whereas the cement precipitated after the compaction is stained blue; this is ferroan calcite, which is a typical burial cement. Burial porewaters are usually reducing so that if iron is present in solution this is incorporated into calcite when that is precipitated as a cement. Forest Marble, Brown's Folly, Bathford. Field of view 4 mm across.*

**Bath oolite later burial diagenesis**

With continued burial, probably to depths of several 100 metres, more calcite cement was precipitated between the grains to reduce the porosity and lithify the sediment further. This cement is a clear drusy sparry calcite, the most common type of calcite, with fine to coarse crystals filling the pores (Figures 4, 5). This cement is a ferroan calcite, turning blue with an Alizarin Red S + potassium ferricyanide stain (Figure 5). However, compared to other limestones, the Bath oolite is still quite porous at around 15-20%; hence it does have good reservoir qualities for water and hydrocarbons. Much of this porosity, however, is a microporosity, occurring within the ooids and between the cement crystals.

With still further burial and increasing overburden pressure, the now lithified Bath oolite was affected by fracturing. These fractures are generally vertical to sub-vertical to the bedding (Figure 6). This may have been in response to extensional tectonic movements on faults in the region inducing stresses and local rock failure. The cracks opened but were filled with further calcite cement contributing to the strength of the stone from porewater migrating through. These veins with their calcite fill are conspicuous where the stone has weathered (Figure 6).
In thin-section, the fractures are seen to cut sharply through the grains and shells in the limestone indicating that it was now well-cemented (Figure 7).

*Figure 6. A near-vertical fracture in oolitic-bioclastic Bath Stone,*

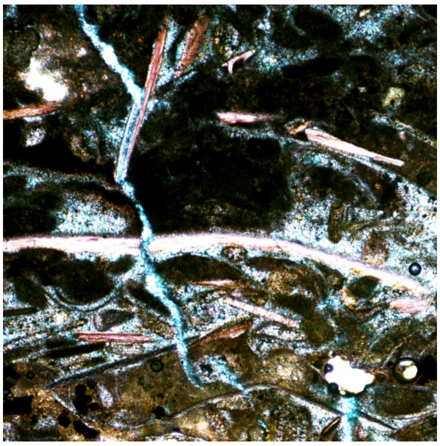


*Figure 7. A fracture filled with ferroan calcite (blue) cutting through the Combe Down Oolite, demonstrating that the rock was fully cemented when fractured. Brown's Folly, Bathford. Field of view 2 mm across.*

Also developed during burial, but at depths in excess of 500 m, are stylolites. These are formed through pressure dissolution and chemical compaction. They are rare in the Bath stone but can be easily recognised as horizontal to sub-horizontal sutured cracks in the limestone. There is usually a very thin layer of clay (the insoluble residue) along the stylolite. Figure 8 shows an example where the stylolite has offset a near-vertical fracture, demonstrating its later formation, probably at a greater depth (and so higher overburden pressure). In very rare cases, the stylolites are vertical (Figure 9). This orientation is unusual since it suggests the rock was subjected to a maximum horizontal stress rather than a vertical one as from overburden. Such horizontal stresses are normally related to tectonic pressure, so this is intriguing for the Bath oolite, which is mostly flat lying and not folded. However, there are major faults, commonly compressional, in the Palaeozoic strata of the Bath-Bristol – Wiltshire – Somerset region, and these were later reactivated as a result of Jurassic extension likely causing the calcite-filled fractures. Much later, during the Tertiary, compression affected the region as a result of Alpine movements and plate collision in southern Europe; such horizontal compression could have affected the Jurassic strata and given rise to the vertical stylolites in the Bath stone.

*Fig. 8: A subvertical fracture in shelly bioclastic Bath stone filled with calcite, which is offset by a sub-horizontal sutured stylolite, along which there is a thin insoluble residue (clay). Great Pulteney Street, Bath. Field of view 40 cm across.*

*Fig. 9: Horizontal stylolite in oolitic-bioclastic Bath stone. Belvoir Castle public house, Lower Bristol Road, Bath. Field of view 30 cm across*

**Burial depth and uplift history**

The Bath oolite is now located at 150 to 200 metres towards the tops of the seven hills around Bath, at Lansdown, Odd Down, Combe Down, Bathwick Hill, Bathampton Down, Claverton Down and Solsbury Hill (Tucker 2019). But how deep was the Bath oolite buried before it was uplifted to where it is now, above sea level? To deduce the burial history of Bath stone one needs to determine the thickness of the rocks deposited on top of the Bath oolite, but of course the problem here is that they have been eroded. Nevertheless, estimates of the thicknesses can be made for these younger rocks where they do occur, notably to the east and southeast of Bath (data from BGS 1996, 2015).

The region around Bath has generally been a relatively ‘positive’, slowly subsiding area for many 100s of millions of years. In mid to upper Palaeozoic times, the Mid-Wales Massif was situated to the west with the London platform (‘St George’s Land’) / Anglo-Brabant (in Belgium) massif to the east. Against these highs, Devonian (Old Red Sandstone) and Carboniferous (Limestone and Coal Measures) strata were deposited, now exposed in the Mendips and Bristol area. After the compressive end-Carboniferous Variscan orogenic events, resulting from the closure of the Rheic ocean to the south, causing northward thrusting and folding (forming the Mendip Hills), the Bath region was re-established as a positive area through the Mesozoic. This contrasts with the Wessex Basin to the south (Dorset-Hampshire) and the Wealden Basin to the southeast (Sussex-Kent) where rifting and extension along old Variscan fault-lines created rapidly subsiding troughs where thick packages of mudrock, plus some sandstone and limestone accumulated in the Jurassic (see Cosgrove et al. 2021 for a review of the deformation history of southern England).

Thus, Bath is located on a relatively solid foundation of folded Carboniferous strata located at relatively shallow depths (50 m). Indeed, there are exposures of Pennant Sandstone at Willsbridge and Saltford a few km to the west and coal was exploited in shallow mines at Twerton and in the Somerset coalfield to the SW. The Mesozoic strata of Wiltshire have a gentle dip to the east/south-east, a result of regional tilting in that direction during the Tertiary. This was the time of formation of the Thames Valley-London Basin (and Hampshire Basin) when a thick succession of mudrocks and some sandstones was deposited, mostly in the Eocene, e.g., the London Clay. From the post-Bath oolite strata exposed to the east and southeast of Bath, towards Swindon, Devizes and Warminster, maximum and minimum thicknesses of the various formations can be determined (Table 1) and from this information a burial history plot can be compiled (Figure 10).

The burial history plot shows stratal thickness against time and indicates that by the end of the Cretaceous (after deposition of the Chalk, probably in a sea around 100 m deep, 65 million years ago), the Bath oolite was buried to a depth of 500-700 m. The amount of sediment deposited in the Bath area in the Tertiary was probably quite small (10s of m), but then the region was uplifted, through northward compression related to the Alpine deformation and closure of the Tethys ocean. The younger strata were eroded over the next 20 million

**Burial History of the Chalfield Oolite, Bath District**

| Stratigraphic unit | thickness range | date at end of unit | cumulative thickness min thick | cumulative thickness max thick | depo depth |
|---|---|---|---|---|---|
| Paleogene – non-marine, sarsens | 20-100 m | 40 Ma | 520 m | 820 m | subaerial |
| Chalk, Up Cretaceous | 100-200 m | 65 Ma | 500 m | 720 m | 100 m water depth |
| Upper Greensand–Gault | 50 m Devizes | 100 Ma | 400 m | 520 m | 50 m depth |
| Lower Greensand | 20 m Devizes | | | | shelf-50 m |
| Purbeck - limestone | 10 m near Swindon | 145 Ma | 330 m | 450 m | shallow sea to lake |
| Portland - limestone | 40 m near Swindon | | | | shallow sea |
| Kimmeridge +Ampthill Clay | 100-200 m near Calne | 152 Ma | 280 m | 400 m | 50 m water depth |
| Corallian - limestone | 35 m near Calne | | | | shallow sea |
| Oxford Clay | 50 m | | | | 50 m depth |
| Kellaways Clay | 25 m | | | | 50 m depth |
| Cornbrash - limestone | 5 m Chippenham | 162 Ma | | | shallow sea |
| Forest Marble + clay | 25 m | 166 Ma | 65 m | 85 m | shallow sea |
| Bath+CDO (Chalfield) oolite | 40-60 m | | 0 | 0 | shallow sea |
| Fuller's Earth | 50 m | 168 Ma | | | 50 m water depth |

*Table 1. Stratigraphy, thickness ranges, age data and depositional depth for the Middle Jurassic to Paleogene strata for the area of Bath and county of Wiltshire to the east/southeast. Stratal thicknesses from the BGS (1996, 2015). Blue triangles indicate the 3 shallowing-upward cycles in the Middle-Upper Jurassic succession.*

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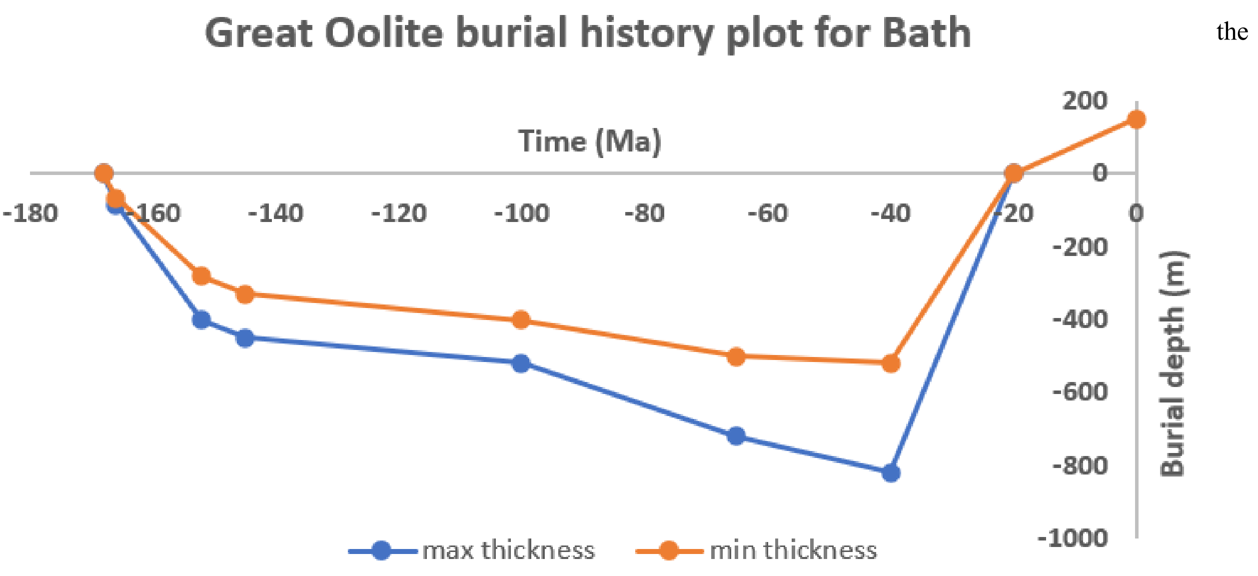


*Figure 10. Burial history plot for the Great Oolite in the Bath area.*

years or so to bring the Bath oolite up to the surface where we see it today, mostly above 150 m above sea level.

In the Weald Basin, the Great Oolite is still at considerable depths; there was no major phase of Tertiary uplift there as occurred in the Bath region. In fact, the Great Oolite is an oil reservoir at several sites in Sussex (e.g., Humbly Grove, Storrington), occurring at depths of 1500 to 2000 metres (Goffey & Gluyas 2020). Some are now gas storage facilities.

After the uplift of the Great Oolite in the mid to late Tertiary, several 10s of millions of years ago, glaciation affected much of the northern hemisphere during the Pleistocene, with many glacial advances and retreats over the last few million years. There was much erosion of the landscape during these ice ages, although the Bath area itself was probably not affected by ice directly. Bath was close to the margin of the ice sheets affected more by periglacial conditions and intense erosion during periods of deglaciation. There will also have been some effects of ice loading to the north during glacial times and rebound after ice melting during interglacial periods. But that story of Quaternary history of Bath is one for another time!

Nevertheless, another phase of fracturing affected the Great Oolite during the late Tertiary-Quaternary uplift. There are prominent fractures and joints seen at outcrop, but particularly in the underground quarries, which are planar and laterally extensive (Farrant & Self 2016). Their orientations are NNW-ENE in the area of Box. These are extensional features, with openings of 1 to 20 cm, and spacings of 5 to 10 m. Some of these have opened up further through movement and cambering in the vicinity of gentle slopes and valley sides to develop into gull or rift caves (e.g., Sally's Rift, Bathford, Figure 11A). These typically form a rectilinear, maze pattern, where straight passageways may be a metre or more wide, extend for many 10s of m, with right-angle passages off to the side or cutting across. These uplift-related fractures-joints are not filled with calcite spar cement, like the fractures-veins formed during burial, commonly seen in Bath stone (Figure 6). Indeed, the fracture surface, forming the wall of a gull cave, may be etched by descending rainwater, as seen in Figure 11B, revealing the largescale cross-bedding of an oolitic sand-wave cut by a vertical vein (a burial fracture). That surface in Figure 11B was then covered by a layer of flowstone, precipitated from meteoric (rain) water, when saturated with calcite, descending down the rock-face. The change from dissolution to precipitation on the wall of the cave probably reflects a climate change (rainfall/temperature) during the Quaternary.


*Fig. 11:. A: A gull or rift cave formed by the opening up of a late fracture in the Bath stone. B: The wall of a gull cave showing the largescale cross-bedding of an oolitic sand-wave cut by a vertical vein (a burial fracture), revealed by etching of the cave wall. That surface is then covered by a layer of flowstone, precipitated from meteoric (rain) water descending down the rock-face. Sally's Rift, Bathford.*

### Summary

The Bath stone formed in a warm shallow sea 168 Ma and then was buried to 500 m or more and cemented early on it way down over the next 100 million years. The stone was affected by fracturing, and chemical compaction and pressure dissolution resulted in stylolites. Uplift of the region over the last 50 million years, accompanied by much erosion, resulted in the Bath stone now being 150-200 metres above sea level, capping the 7 hills around Bath.

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# The Lower Greensand of Seend

**By Veronica Cleverly**

Seend is a small, quiet village between Devizes and Melksham in Wiltshire. It sits on a small ridge of land,

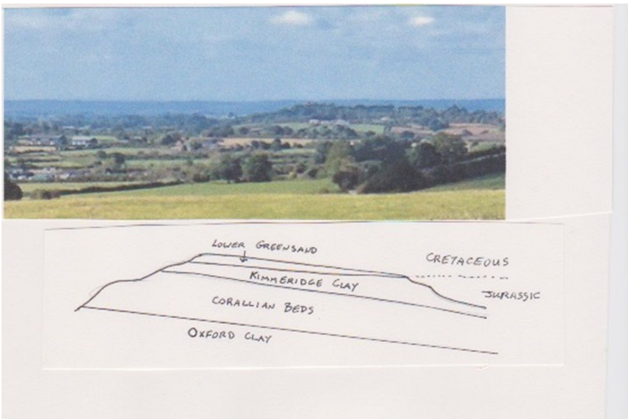


*Figure 1: Seend looking west*

an outlier of the Lower Greensand, sitting on Kimmeridge Clay over the Coralian beds.

The Kimmeridge clay surface had been eroded into a hollowed surface over which the sea gradually en-

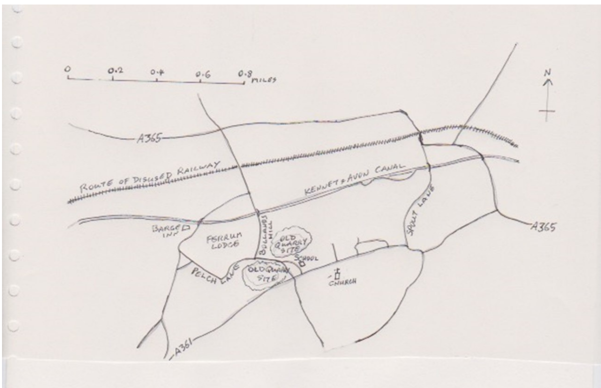


*Figure 2: Sketch map of Seend*

croached from the south east laying down a bed of Lower Greensand of varying thickness, which was then eroded back to leave a patchy deposit in the Wiltshire area varying between 0 and 15 metres thickness. The

Greensands got their name because the sand originally contained a green material called glauconite (an iron-potassium silicate). This, on exposure to air, decom-

*Figure 3: Box shaped weathering approximately 1.5cm squares*

poses to form iron oxides which stain the sandstone a rusty brown, as can be seen here in Seend. The Lower Greensand at Seend is notable because it contains a rich layer of ironstone.

The village sits mainly along the top of the ridge, the houses having wells dug down through the Greensand to the clay layer. If visiting the village, an easy way to find the base of the Lower Greensand is to visit after a rainstorm, when in many places along the roads and footpath bank sides, water pours out when it hits the clay layer. This is easily seen in the well named Spout Lane.

There was an attempt in the seventeenth century to promote the healing properties of the iron rich spring waters of Seend. Unfortunately for the promoters of the scheme, Royalty preferred to take the healing waters of Bath. This set the fashion for Bath Spa waters and the venture failed.

Although there are some traces of Romano-British iron extraction at Seend, it was not until 1857, after the Kennet and Avon canal had been constructed, that anyone looked seriously at iron ore extraction from Seend. The railway quickly followed in 1858, making transport much quicker.

The Lower Greensand at Seend has 65% iron oxide in concretions which are found in irregular bands up to 7 metres thick. The iron stones weather into a rough box shaped formations. These are supposed to form in this shape because the iron deposits form along the horizontal and vertical cracks in the rocks. But, as all iron stones weather this way, it is likely there is some other mechanism at work. The rock pieces I found were only 2cm sided squares, although from literature they form with sides up to 12cm long

The first person to extract the ore commercially was J.E. Holloway, but he did not attempt to smelt it on site. In 1856 he extracted 10,000 tons of ore and moved it by canal to Bristol to ship it to South Wales. A tramway was constructed from the quarry to the canal and operated with windlasses and ropes.

This inspired several people to try and cash in on the iron ore with the building of two furnaces to smelt iron ore on site. They were built in the area near the canal where Ferrum Lodge now stands. The quarry was south of Pelch Lane near the top of Bollands Hill. A railway line was constructed from the works to the railway station with a bridge over the canal close to the road bridge.

Iron smelting began in 1860. By 1866, several short lived ventures had gone bankrupt. By 1868 the works were no longer in use.

The next attempt was in 1870 producing 300 tons of iron a week. By now the quarrying had spread further to the area just north of the school. This failed in 1873.

The next operators worked from 1873-1888. It is believed that at the start, they still used the blast furnaces, but they soon ceased to be used and the ore was transported away for smelting.

There are no further records of quarrying until 1905 when the Seend Iron Mines Company started operations in the Bradley Lane quarries, but that failed within a year.

The next quarrying was during the 1914-18 war when an overhead cable was constructed to take the ore down in large iron buckets to sidings east of Seend station. After the war demand dropped again and quarrying ceased.

Unfortunately, from a geologists point of view, all the old quarries are overgrown. There are footpaths through them and even a seat. Bits of ironstone can still be found lying around and possibly more rock would be visible in winter when the vegetation dies back.

For anyone wishing to research the old iron production companies the Wiltshire Heritage Museum in Devizes and the Wiltshire Record Office hold a lot of the history of the site.

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# Crummack Dale, the Norber Erratics

## By Charles Hiscock

A few miles east of Ingleton, and just north of the A65 main road from Kendal to Skipton in the northern Yorkshire Dales, is the small stone-built village of Austwick. Almost all the houses and cottages are built from millstone grit or limestone quarried from the local area. Many of the garden walls are topped with grey limestone blocks etched into the curious shapes typical of the karstic environment of the northern Dales. At the top of the village Townhead Lane rises steeply towards the limestone scarps and hills, and after about half a mile from the houses, intersects with a green lane. Turning left into the green lane takes the walker west towards the village of Clapham but after about 50 yards a footpath goes right through a gate, up the fields towards the top of the scarp known as Thwaite Scar (Figure 1).

*Fig. 1: In Crummack Dale*

The gradient is gentle at first but gradually steepens until a small wooden gate is reached alongside the ancient stone wall. Having passed through the gate and taking care to ensure it is bolted after passing through, (Swaledale yows and their lambs are adept at finding ways through seemingly sheep proof walls and fences), the path rises steeply over rough limestone paths, over rocks and boulders in places involving some scrambling (Figure 2).

*Fig. 2: Climbing Norber Fell*

Eventually, the indistinct footpath becomes less steep and winds through rocks and boulders. Curiously, the boulders and rocks are at all angles, the bedding within them being in all directions relative to the underlying nearly level beds of limestone. Also, they are darker grey and of finer particle size than the pale grey to white limestone and many display features typical of turbidite successions; slumps, rills and load casts (Figure 3). This is the Norber Erratics field (Figure 4), an area of the Carboniferous Garsdale Limestone Formation of the Yorkshire dales that has a scattering of Silurian rocks and boulders deposited when the ice melted at the end of the last ice age. Some of the erratics are sitting on pedestals of the limestone with one supported by just three small 'feet' (Figures 5 and 6). Many of the boulders have been split by ice action with one very large boulder being split in half, one half still in place but the other having toppled over (Figure 7). All around are large numbers of blue Harebell flowers and in a small corner, a few white versions all dancing in the warm brisk breeze.

*Fig. 3: Slump fold in base of erratic boulder*

*Fig. 4: Norber erratics field*

*Fig. 5: Silurian glacial erratic, Norber*

*Fig. 6: Silurian erratic on three limestone feet*

*Fig. 7: Ice split erratic*

The geology of Crummack Dale is formed by two Silurian/Ordovician anticlines and a syncline in the bottom of the dale, bounded on both edges by almost level Carboniferous (359 – 299 mya) limestone successions. On the northern edge of the anticlines, the Silurian Austwick Formation of siltstones and turbidites (440 – 416 mya) dip at 70 degrees steeply north under the limestone of the Danny Bridge Formation of Moughton Scar while on the southern edge the North Craven Fault has dropped the Garsdale Limestone Formation allowing erosion to strip off the younger limestone on the south side. This has exposed the underlying folded Silurian and Ordovician (488 – 440 mya) rocks on the south side. The passage of the ice during the last Ice Age ripped up the rocks and boulders from the Silurian outcrop, raising them onto the top of the limestone. When the ice thawed the suspended load of Silurian debris was deposited on the surface of the Carboniferous limestone.

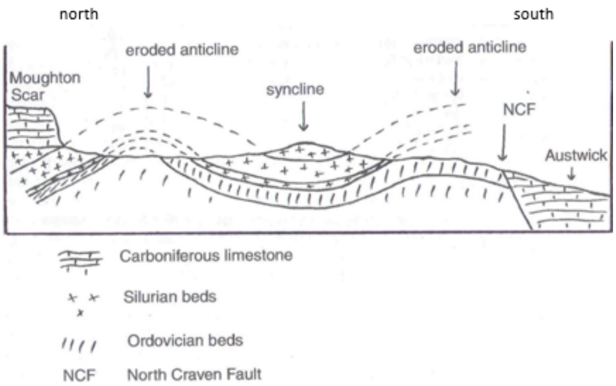


*Fig. 8: Cross section N – S of Crummack Dale (North Craven Heritage Trust 2009)*

Leaving the erratics field to follow a footpath down into the dale takes the walker along the vertiginous edge of Nappa Scar, a vertical cliff in the Carboniferous limestone of the Kilnsey Formation. The path passes along a cleft etched out of the cliff in which the limestone can be seen to sit unconformably on steeply tilted Ordovician siltstone beds, the Norber Formation. In Figure 8 the black line marks the unconformity between the Ordovician and the Carboniferous and represents a break of about 145 million years. Of particular interest is the bottom bed about 1 metre thick which is a coarse conglomerate of angular (rip up?) clasts of the underlying Ordovician cemented with calcium carbonate. It is eroded back into a notch along the length of the cliff while immediately above the notch is another conglomerate bed approximately 0.3 metres thick composed of small well-rounded pebbles, also carbonate cemented in photo 8 between the blue and yellow lines. Above this lies the first bed of the Carboniferous Kilnsey limestone.

Walks through the Yorkshire Dales always provide much detail for the interested person but in Crummack Dale there is a whole new perspective provided by the Norber Erratics Field. However, it was disappointing that there was no interpretation board or other information on the history and geology of this unique area. While talking to other walkers it became clear that they were aware that Crummack Dale was different to other dales but they did not know why or how its unique situation arose. Needless to say, we were very happy to enlighten those who asked!

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# The Evolution of Flight in Vertebrates

**By Katie Munday and Phil Burge**

**Introduction**

Locomotion through the air can take the form of parachuting, gliding, soaring and flight using the flapping motion of wings. The former means of locomotion have been adopted by a range of vertebrates, but true flight has evolved three times (convergent evolution) in vertebrates namely the Pterosaurs, avian dinosaurs (birds) and mammalian bats.

Pterosaurs arose during the Triassic and survived and prospered until the end Cretaceous extinction. Over 120 species have been found around the world ranging in size from a small sparrow to ones with wingspans of 12 metres (*Quetzalcoatlus*). Birds arose from small theropod dinosaurs looking like small, feathered dinosaurs. Non-avian dinosaurs survived the end Cretaceous extinction and there are around 10,000 extant species. The origin of bats is completely unknown at this time. Early examples of recognisable complete bats show that they were developed by 50 million years.

This paper looks at the evolution of flight through the lens of these three vertebrate groups and examines the common morphological features required to make flight possible.

**Common Ancestors**

The common ancestor of Pterosaurs and birds is the Archosauria, a major group of diapsids that originated in the late Permian and survived the end Permian mass extinction. Birds and crocodiles are the only extant group descendent from the Archosauria. The Archosauria are differentiated from other diapsids by changes in the skull including the development of the anteriororbital fenestrae openings in front of the eyes and fusion of skull bones to lighten the skull which provide more space for muscles to aid eating. The lower jaw develops a further opening (mandibular fenestra), the skull narrows, teeth are set in sockets and the ankle joint is modified.

Pterosaurs evolved from a small reptile of the group Lagerpetids that existed between 237 and 210 million years ago in the Early Triassic. Two legged and wingless, they shared anatomical features with the Pterosaurs including hollow bones and agility enhancing characteristics such as the shape of the inner ear and brain. An example of an early ancestor of the Pterosaurs is the *Scleromochlus taylori* (Figure 1), a fossil discovered in Scottish Triassic rocks in 1907 but only recently analysed in any detail using CT scanning techniques. As yet there is no intermediate fossil between Lagerpetids and Pterosaurs that would show how the Pterosaur long wing finger evolved .

*Fig. 1: Scleromochus taylori*

Avian dinosaurs evolved from the Paraves group of therapods around 150 million years ago in the Jurassic. The basal bird fossil is *Archaeopteryx* (Figure 2) displaying characteristics of flight potential but not the complete morphology of birds.

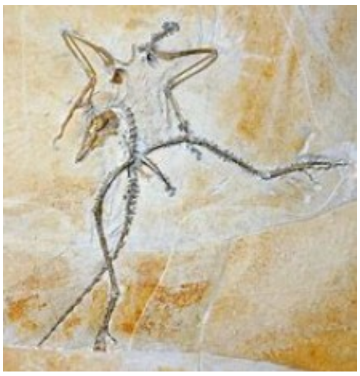

*Fig. 2: Archaeopteryx*

The common ancestor of bats (Chiroptera) is a scientific conundrum. Bats appear in the fossil record around 50 – 55 million years ago. One of the oldest complete specimens is *Onychonicteris finneryi* (Figure 3) 52 million years old from the Eocene. It is possible that early bats lived in forested areas which are not good sites for fossil preservation. All we can say at this time is that bats emerged probably between the end of the Cretaceous and 50 million years ago from a quadruped shrew like mammal. Of interest is that these early bats show no skull structures associated with echo location.

*Fig. 3: Onychonycteris finneryi*

**Evolutionary advantage of flight**

Although completely untestable, there are five hypothesis as to why flight evolved: as an advantage in escape from predators, to catch flying of faster prey, to enable the hind legs to be used in defence or attack, to be able to access a new source of food or migrate to an unoccupied ecological niche, or more simply as a means of rapid locomotion. Each of these alone or in combination may suggest why flight evolved in three distinct groups but finding evidence in the fossil record is problematic.

The more detailed and interesting question is not why flight evolved nor whether flight evolved from leaping and gliding to powered flight, but how the flight stroke evolved.

**Common Morphological Characteristics**

For efficient flight, that is the active movement of wings to provide lift, forward motion and lateral control, three morphological and physiological are required: low body mass in relation to wing efficiency to reduce muscle and metabolic demands, maximisation of oxygen uptake given the high metabolic demands, balance mechanisms to maintain steady flight, and endothermy to maintain a constant or near constant body temperature.

Saurischian dinosaurs including Therapods, avian dinosaurs and birds have uni-directional air flow in the lungs in conjunction with a network of air sacs within bones . This feature is also shared by the Pterosaurs and is called pneumaticity. Ornithischian dinosaurs did not have air sacs. Pneumaticity provides two advantages, namely a reduction in bone volume which reduces body mass and an improvement in oxygen uptake. Modern birds have the most efficient respiratory system of all vertebrates. That Pterosaurs and Saurichians developed a similar respiratory system is intriguing. Did these two groups develop pneumaticity independently or did an ancestor Archosaur develop this feature which was then lost in the Ornithischians?

As the earliest Pterosaurs show evidence of at least some pneumaticity it suggests that the common ancestor of all Pterosaurs also showed pneumaticity, which as these ancestor forms were flightless, begs the question as to what the evolutionary advantage might have been.

The reason for the evolution of air sacs in certain groups of Archosaurs may lie in the change in $O_2$ levels at the Permian- Triassic boundary. Bird like respiratory systems would have tolerated lower $O_2$ levels given the thinner blood-gas barrier associated with this type of system. It would appear that the evolution of lighter bones and a more efficient respiratory system were enablers of future flight evolution.

Bats have characteristically mammalian respiratory systems which are functionally inferior to avian respiratory systems for flight. However, they have developed modifications to increase efficiency of $O_2$ uptake, thus allowing them to obtain the large amounts of oxygen required for such an energy intensive form of transport. Among these are a very large lung capacity upwards of 70% greater than mammals of similar size, the ability to rapidly increase lung ventilation as flight begins and very thin blood-gas barriers not too dissimilar to that of birds . Certain species of bats have also been found to demonstrate synchronicity between wingbeat frequency, respiratory rate and heart rate which allows the action of locomotion to mechanically assist the respiratory muscles. This synchronisation of the respiratory cycle and wing beat enables some bats to oxygenise their lungs more efficiently and with lower expenditure of energy.

## Wing anatomy and evolution

Pterosaurs, birds and bats share broadly similar wing anatomies in that they all have primary arm wings consisting of components that occur within the human arm, namely the upper arm, forearm, wrist, hand and finger bones. However, the precise structures of these wings vary considerably (Fig 4).

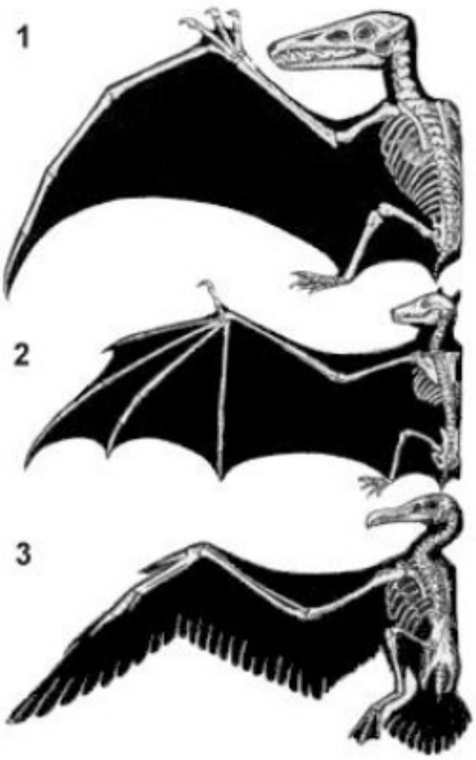


*Fig. 4: General bone structures of pterosaur (1), bat (2) and bird (3) wings*[x]

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The success and longevity of the Pterosaurs was due, in part, to their well-developed wing anatomy. They had long and narrow wings which would have produced large aerodynamic forces. The wing extended from an elongated fourth finger and the fossil record shows that the wings were connected to the hind limbs on at least some Pterosaurs, if not most. These primary wings had a membranous structure (patagium) composed of skin, blood vessels, muscle and stiffening fibres. The elasticity of the wing membranes allowed them to change shape under aerodynamic load. This act of changing shape, or passive cambering, would have produced a change in the wing curvature and thus an increase in lift. It is also possible that the amount of camber could have been controlled across different sections of the wing, allowing the wing to adapt during flight to maintain optimum efficiency.

Unlike most other flying animals, Pterosaurs were quadrupedal, meaning that their folded wings could act as another pair of legs. This gave them terrestrial hunting abilities and the capacity to launch off the ground using their forelimbs. Birds on the other hand have to take off with their hind legs meaning both sets of limbs are required to be strong. Pterosaurs could instead focus their muscle mass into their forelimbs.

Birds do not have membranous wings but rather musculature around the arm bones with a variety of functional feathers making up the remainder of the wing. They have extended forearm bones compared to Pterosaurs, and reduced fingers. The main wing feathers, the primary and secondary feathers, work in harmony to enable locomotive flight. It is hypothesised that birds first developed feathers for display purposes before becoming capable of gliding or parachuting thanks to their aerodynamic properties. Certainly the fossil record suggests that early birds were not as well-adapted for flight as modern birds and would not have been strong fliers. The adaptions we see in modern birds are highly specialised and relate to the shapes of the wings, which in turn relates to the individual's environment and survival needs (Figure 5). As well as the development of these specific adaptations, birds are also interesting because of the number of times they have given up flight. Many species, such as penguins, ostriches and kiwis, became flightless independently. Perhaps the metabolic needs of flight were simply too high. Or perhaps their strong launching legs allowed them to easily adapt to a terrestrial lifestyle.

Bats are the only mammals capable of powered flight and little is known about their evolutionary journey. Similarly, to Pterosaurs, bats have membranous wings which are attached to their hind limbs, but the bone structure resembles that of an outstretched hand, with sections of membrane between the elongated digits. This structure gives bats a far greater level of control over the shape of their wings than any other vertebrates, increasing their agility during flight. Because of this, the hunting technique of bats differs from that of birds. Whilst birds often catch prey in their beaks, bats catch insects with their wing or tail membranes before passing it to their mouths, all while maintaining flight. Although bats are extremely agile, they are largely inefficient fliers compared to birds due to their relatively heavy skeletons and mammalian respiratory systems. Some bats, such as the New Zealand lesser short-tailed bat have adapted to terrestrial habitats as well as aerial. It is thought that this was due to the lack of predation risk on the island. Without risk of predation on the ground, this species has been able to utilise both environments for foraging purposes.

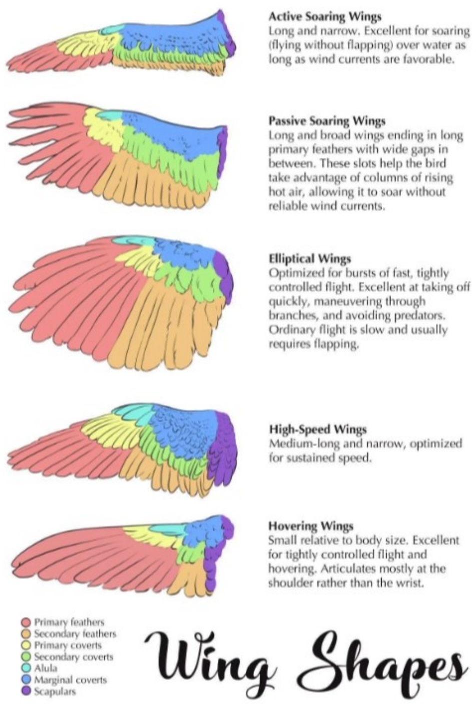


*Fig. 5: Common wing shapes of modern birds*[xi]

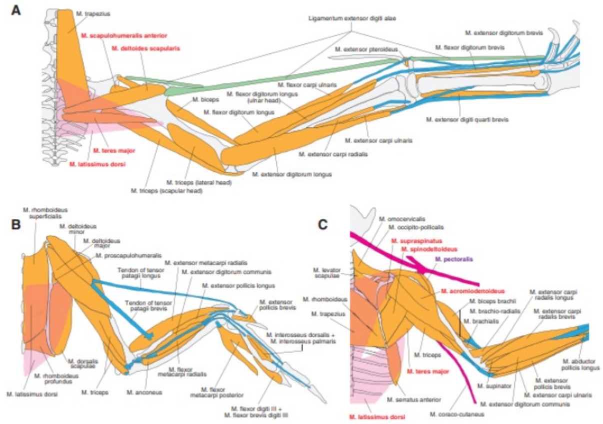

*Fig. 6: Forelimb and pectoral girdle muscles of Pterosaurs (A), birds (B) and Bats (c)*[xii]

In contrast to bats and Pterosaurs, birds utilise two primary muscles to flap their wings, rather than by co-ordination of several muscle groups. Although the wing musculature of birds is large relative to their body mass, the structural arrangement is simple. Both muscles are anchored to different parts of the keel, which is an extension of the sternum, as well as the clavicle, coracoid, ribs and humerus. One muscle is responsible for the downstroke and the other, the upstroke. Pterosaurs also possessed a keeled sternum which acted in the same way, as an anchor for strong flight muscles. However, the movement of a bird's wing is the result of a simple up-and-down pulley-like system whereas the movement of the Pterosaur arm seems to involve depression, flexion and then medial rotation of the arm, as we see in extant reptiles.

**Flight musculature**

In addition to the skeletal and compositional differences between the wings of birds, bats and pterosaurs, there are also differences in musculature (Figure 6). Evidence from the fossil record indicates that Pterosaurs may have been able to employ a patagial ligament system which automatically opened and closed their wings as the elbow was moved, requiring less energy consumption. We also know that Pterosaurs retained a basic tetrapod pattern of pectoral and forelimb muscles, similar to that of crocodiles and lizards. As the pectoral girdles and forelimbs of Pterosaurs made up a disproportionate percentage of their mass, it is reasonable to assume that the corresponding muscles would have been well-developed and strong. It is thought that the wing was lifted by muscles attached to the scapula and back and lowered by muscles attached to the keeled sternum and coracoid. Bats also achieve the 'flapping' motion by utilising an array of muscles across the pectoral girdle and arm, but they also have muscles distributed throughout their wing membranes. Electrophysical studies have found that these muscles may be responsible for adjusting wing stiffness, reducing passive membrane deformation. Another unique feature of the bat wing is the presence of a muscle complex which changes the shape of the leading edge of the wing, adding to their aerial agility.

**Conclusion**

The exact reasons for the convergent evolution of flight are unknown. However, the fossil record indicates that birds and Pterosaurs were likely to have glided or parachuted before developing powered flight. Several theories suggest that these animals were leaping to reach prey and gliding thanks to their membranous limb attachments, or the presence of display feathers, and that this continuous hunting technique lead to the strengthening of 'flapping' pectoral muscles which in turn allowed true flight. We are yet to discover any fossils which show that bats evolved from gliding ancestors, however it is widely accepted that they evolved from arboreal mammals that dropped from trees to initiate gliding, rather than taking off from the ground like birds and pterosaurs.

It is intriguing to speculate on the convergent evolution of powered flight within three very separate groups. The mammalian ancestors of bats diverged from the line that developed into Archosaurs and Dinosaurs in the Carboniferous and flying Pterosaurs preceded the *Archaeopteryx* by some 50 million years. As we see with all three groups, the ecospace opened up by powered flight is a fertile one.

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# Biofilms and Minerals in the hot springs of Bath, England: Bacteria-EPS-Viruses, Calcite, Ferrihydrite

**By Maurice Tucker and Leon Bowen**
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The hot springs in Bath have been attracting visitors for several 1000 years ever since the diseased Prince Bladud, father of King Lear, arrived here with his pigs in 863 BCE and was magically cured of leprosy (the pigs as well) through wallowing in the hot mineral-rich sulphurous muddy waters. The hot waters of Bath became a leisure centre for the Romans not long after their arrival in 43 CE, with the construction of their bath complex and the Temple to Sulis-Minerva in their new settlement, *Aquae Sulis*. Bath as a pleasure centre for taking the waters, in view of the supposed benefits to health, as well as for bathing and partying, reached new heights in Georgian times as described by Jane Austen and featured in Bridgerton, with its acme in the 1700s to early 1800s. However, there are several aspects of the hot springs and Roman Baths of particular interest to Earth Scientists, apart from the fact that this is the only true thermal spring (since water temperature is > 37°C) in the UK. There are spectacular biofilms developing in the baths and associated with them are mineral precipitates and travertines, the subjects of this article.

Many mineral deposits in the geological record are related to hydrothermal fluids rising up through faults, the lead–zinc mineralisation in the Mendips for example, and some iron ores in the Forest of Dean. There is also huge interest in biomineralisation these days, not just in the formation of sediment by bacteria, but in its application to bioengineered water treatment, concrete repair, and biomedical matters. The hot springs have been of interest to microbiologists too, in view of the microalgae present in the water in terms of their suitability for the production of biodiesel and the possibility of developing antiviral drugs from the bacteria and viruses there.

**Bath's hot springs and water**

There are 3 principal springs (King's, Hetling and Cross Bath) in the centre of Bath where hot water gushes out of the ground at a temperature of around 46 °C and a rate of 1.3 million litres per day. The water is considered to be derived from a depth of 2500 metres subsurface from the level of the Carboniferous limestone; it then ascends up a major fracture system through the Coal Measures, Triassic red beds and Lower Jurassic mudrocks and limestones. There is a major synclinal structure in the Palaeozoic rocks beneath this region whereby rain falling in the Mendips on to the Carboniferous limestone descends through a karstic fracture-cave system. This is driven by a hydraulic head where it is heated up to 80 °C, before rising through a major fracture conduit to emerge at the surface. Dating of the hot spring water in Bath suggests that it is up to 10,000 years old, that is the date of when the rain fell on the Mendips and the time it has taken to travel from the

Mendips down to 2.5 km and back up to Bath.

Bath spring water has a distinctly unpleasant, malodorous smell and horrible taste (to some), as one visitor Celia Fiennes complained in the 1670s it is "very hot and tastes like the water that boils eggs, and such a smell." The composition of the spring water is a reflection of the rocks it has passed through. There are seven major ions present: anions $SO_4$, Cl and $HCO_3$, and cations Na, Ca, Mg and K. Also present is a relatively high content of Fe. The Ca, Mg and $HCO_3$ will be derived from limestone, and the SO4, Cl, Na, K and Fe (plus some Ca, Mg) will be from the Triassic red beds which locally contain evaporites, such as gypsum and minor halite. The water temperature in the Roman baths is in the range of $45^{o}$ to 38 $^{o}$C, with a higher value in the Sacred Spring (King's Bath) where the water emerges and a lower figure in the Great Bath, some 30 metres away. The pH of the water is 6.7 (slightly acidic) and the redox potential (Eh) in the Stall Street borehole is -200 mV, indicating reducing conditions at depth (Edmunds et al. 2014).

## Biofilms

Biofilms are organic layers of various micro-organisms, but especially cyanobacteria and sulphate reducing bacteria, along with EPS (i.e., extracellular polymeric substances or mucilage) plus viruses, and other organisms such as archaea, micro-algae, fungi and diatoms. The EPS are generated by the bacteria and their degradation. All bacteria have their viruses (also called bacteriophages). Minerals are commonly precipitated within the biofilm as a result of bacterial processes, including photosynthesis and bacterial sulphate reduction, with water chemistry an important factor in which minerals are formed. Biofilms occur in many environments; they form the microbial mats which give rise to stromatolites, famously forming today in Shark Bay (NW Australia), the Bahamas and the Trucial Coast (Abu Dhabi), as well as in lakes notably Great Salt Lake (Utah). Stromatolites extend right back in time to the early Archaean, around 4000 million years ago, thus providing evidence of the first organisms and life itself on Earth.

The Great Bath is cleaned out every few months. The water is completely drained out and the biofilm that has grown on the floor and steps of the Bath, and any accumulated sediment, are swept out and the bath hosed down. Biofilms then start growing again, the rate probably not varying much through the year since the water temperature is relatively constant. It is interesting to note the rapid regrowth of the biofilms in the bath.

## Biofilms in the Roman Baths of Aquae Sulis

Biofilms are growing extensively in the Roman Baths on surfaces covered by the hot-spring water. In the Sacred Spring (King's Bath), green-red biofilm covers the floor and sides, visible recently when a heat exchanger was being fitted there to provide energy to Bath Abbey (March 2022) and when the bath is being cleaned out (Figure 1). Biofilm also grows in the channel that runs from the Sacred Spring to the Great Bath. Frequently, remarkable patterns are developed there by the various filamentous cyanobacteria growing in the fast-flowing shallow water (Figure 2).

*Fig. 1: Biofilm seen on the floor of the King's Bath / Sacred Spring, at a time of maintenance. Although the biofilm has been disturbed to reveal red-orange lower layers (from the presence of ferrihydrite), there are large areas of smooth in-situ mat with a green (cyanobacterial) surface and some small pinnacles / tufts growing up.*

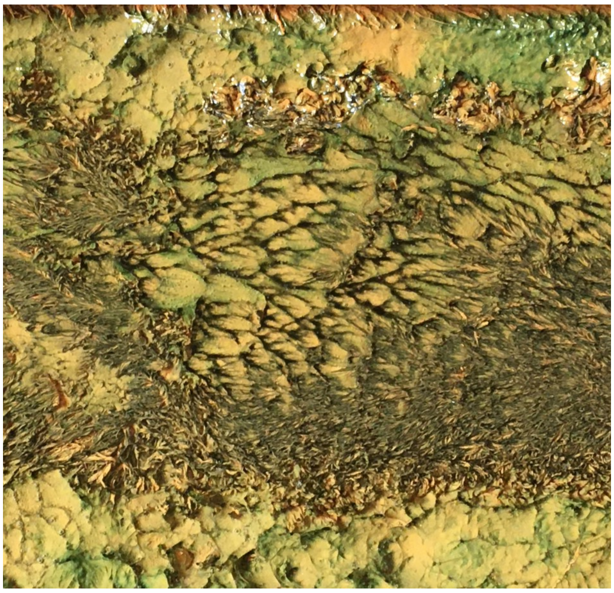

*Fig. 2: A pretty pattern in the filamentous cyanobacterial biofilm in the channel from the King's Bath to the Great Bath where the hot water is flowing swiftly (left to right); water depth 5 cm.*

Perhaps most remarkable and conspicuous when present, are the biofilms apparently floating on the surface of the water in the Great Bath. Where biofilms are growing in the shallow-water on the steps around the bath (water depths 5 to 20 cm), then small growths, like fingers or shoots, may be seen extending up from the biofilm carpet covering the step, towards the light (Figure 3). In fact, they do seem to grow upward preferentially from the edge of a step (Figure 4). When these upward-growing shoots of cyanobacteria reach the water surface they then begin to spread out (Figure 4). Concentric growth patterns are developed, shown by the density of the biofilm and subtle colour differences in shades of orange-yellow-brown (Figures 4, 5). These patterns, consisting of lines with widths of 1-3 mm, reflect incremental growth of the biofilm, perhaps even a daily record. Counting the lines (30-50 even), it could be that growth has been over several weeks. Some floating biofilms show an asymmetry, presumably reflecting a gentle current or wind that affected the direction of growth (Figure 5). A similar feature is seen with ancient stromatolites, growth affected by currents.

*Fig. 3: Biofilm-microbial 'shoot' (10 cm high) growing upwards from the edge of a step, at the side of the Great Bath, towards the water surface. Notice floating wisps of biofilm. Water depth 20 cm.*

*Fig. 4: A biofilm (20 cm cross) floating on the water surface of the Great Bath with its 'root' rising up from the microbial mat on the step clearly visible. Biofilm shows numerous incremental growth lines. Gas bubbles trapped by the biofilm in the earlier thicker part. Gas bubbles are also present in the mat on the step itself, about 20 cm below.*

*Figure 5. A floating biofilm (30 cm across) with numerous (>50?) incremental concentric then eccentric growth lines. Green-brown filamentous bacteria visible in the mat on the step surface about 20 cm below.*

Biofilms on the steps around the Great Bath do vary from having a smooth surface to areas where there are many bumps and pimples from gas bubbles trapped in the mat, to areas where the biofilm consists of very loose collections of bacterial filaments, tufts and clumps with much space within the mat. Gas bubbles are common within the biofilms (the floating ones too, Figure 4) and will have formed where oxygen, produced through photosynthesis by the cyanobacteria, and $CO_2$ from bacterial respiration, have been trapped within the mat, beneath the surficial bacterial-EPS layer. Decomposition of the mat itself will also release $CO_2$. Bubbles can occasionally be seen appearing at the water surface of the Great Bath, presumably coming from the bacterial mats on the floor.

Biofilms are also extensively developed in the Great Bath itself, across the floor (water depth of 1.6 m), in addition to the steps. Frequently, slabs of these mats, 1-2 cm thick, are seen floating in the water, and they gradually drift towards the outlet of the bath in the northeast corner and collect there (Figure 6). These mats look like old pieces of carpet, rucked up and folded, with the green colour being the top surface and the orange-brown the underside (Figure 6). The mat surface ranges from smooth to covered in pimples-bumps-small domes from where gas bubbles have been trapped. The pieces of mat may have lifted themselves off from the bath floor, naturally, through the development of the gas bubbles within the mat. This happens with microbial mats growing on the floors of lagoons and ponds today. At the time of the cleaning out of the bath, on some occasions the biofilm-microbial mat on the floor can be observed before the sweeping begins. The mat is seen as a pale brown colour and relatively smooth, but there are cracks and places where the surface layer of the mat has lifted off (Figure 7). Some vertical biofilm 'shoots' are present too, up to a few cm high.

*Figure 6. Large pieces of biofilm-microbial mat, some with gas bubbles, green upper surface, orange-brown under surface, floating near the outlet of the Great Bath in the NE corner, derived from the floor of the Bath, depth 1.6 m.*

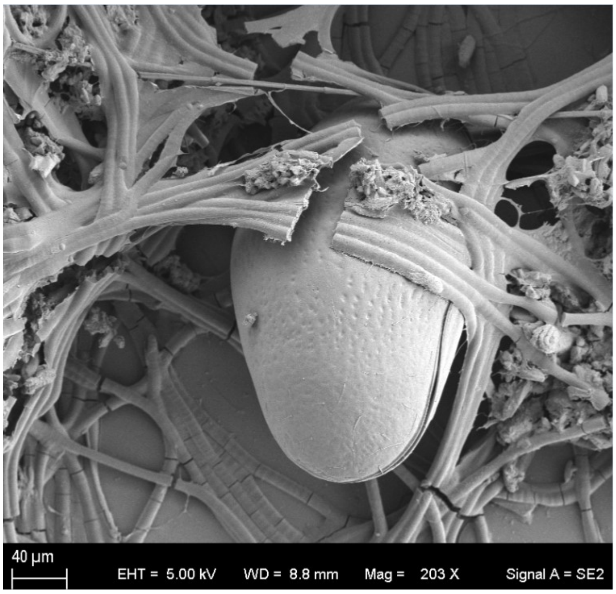


*Fig 8: An SEM image of biofilm showing bacterial filaments, an ostracod and some mineral precipitates. Scale bar is 40 microns.*

*Figure 7. Biofilm on the floor of the Great Bath when the water is down to 5 cm deep, just before the Bath is swept clean and hosed down. Notice the biofilm is torn / broken in places and some pinnacles are beginning to grow up (see close-up). The faint rectilinear lines in the mat are junctions between the lead sheets (Roman) lining the floor of the Bath. Image courtesy of Todd.*

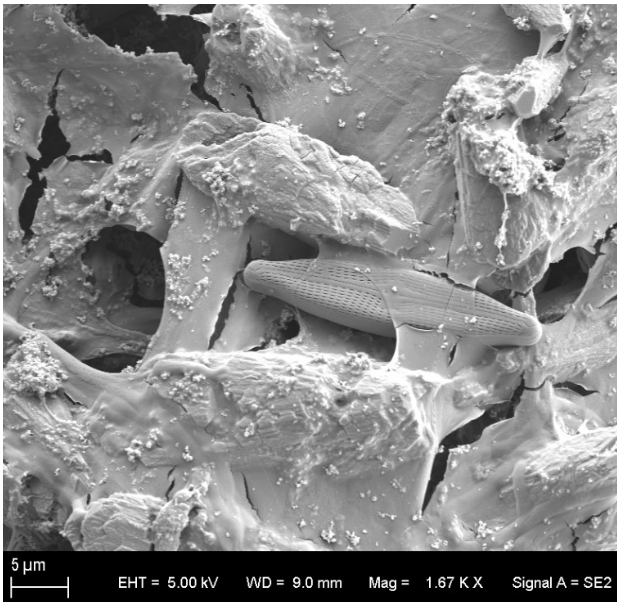


*Fig. 9: An SEM image of a diatom, bacterial filaments and 2 calcite crystals covered in EPS just above the diatom. Scale bar is 5 microns.*

The biofilms in the Roman Baths are mainly composed of cyanobacteria (formerly called blue-green algae) and these include the filamentous forms of the common genera *Oscillatoria* and *Microcoleus*, as well as coccoid forms, such as *Coelastrella* (Smith-Badörf et al. 2013). There are many other bacterial types too, including sulphate reducing and sulphur oxidising bacteria, and eukaryotes including amoeba. Scanning electron microscope (SEM) images of the biofilms clearly show the filamentous nature of the cyanobacteria and irregular sheets of the mucus-like EPS, along with ostracods and diatoms (Figures 8, 9). The high water temperature of the baths is close to the tolerance level of some of these organisms. Perhaps surprisingly, gastropods (snails) are also present in the Great Bath, likely introduced when plants (lilies) were imported from North America in the late 19$^{th}$ C. The lilies can be seen growing in the Great Bath on old photographs from the time. The gastropods are very small and mostly live just at or a little above the water-line around the Bath, where the water will be a little cooler. The snails graze on the biofilm that grows there. The evolution of the gastropods in the early Cambrian is one of the reasons that microbial mats / stromatolites suffered a great decline after the end of the Precambrian, so that since then they have been best developed in the more inhospitable environments, notably along hot arid coastlines, in hypersaline lagoons and saline lakes.

**Mineral precipitates within the biofilms**

Two mineral types are observed with the SEM within the biofilms-microbial mats of the Roman Baths: calcite and ferrihydrite. The calcite forms crystals, 3 to 20 microns in length, with flat crystal faces, clear sub-crystals and cleavage developed (Figures 10, 11).

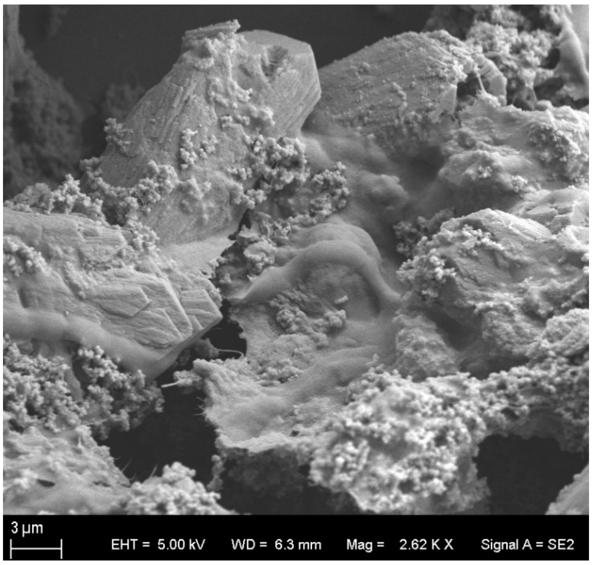


*Fig. 10: Bacterial filaments and EPS with calcite crystals and tiny iron-rich nanospheres and clusters. Scale bar is 3 microns.*

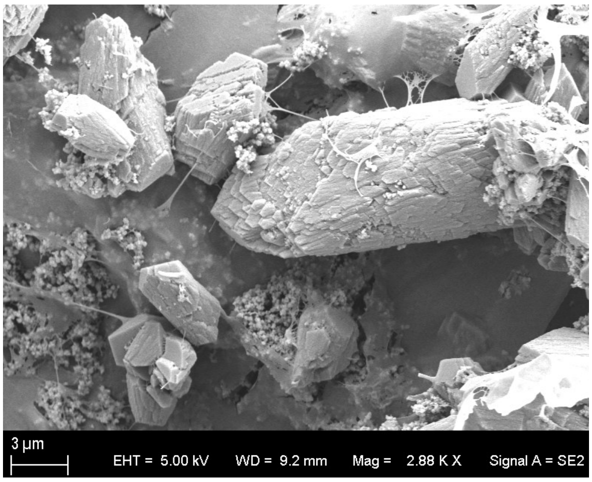


*Fig. 11: Calcite crystals showing subcrystals and cleavage, relics of EPS and nanosphere iron-rich particles. Scale bar is 3 microns.*

This is calcite, as shown by a spot analysis using X-rays (EDS) under the SEM which gives high Ca, C and O, and low Mg, and XRD identifies calcite with 6 mol % $MgCO_3$ from peak displacement. The calcite crystals are commonly wrapped in EPS and bacterial filaments, suggesting an association. It is likely that the precipitation is related to the extraction of $CO_2$ from the water by the cyanobacteria during photosynthesis; this is a process which drives the precipitation of $CaCO_3$ through increasing the alkalinity.

The other mineral present in the biofilm consists of nano-scale particles, around 50-80 nanometres in diameter. They are spherical in shape, but they have commonly coalesced to form clusters, several 100 nm in diameter (Figure 12). These particles are also closely associated with EPS (Figure 13), being enclosed within and growing upon the mucus material. These particles are iron-rich; SEM-EDS analysis gives high Fe, high O, minor Si, Mg, K and Na, very minor Al, and no Mn. This analysis suggests that these particles are ferrihydrite; this is an iron oxide-hydroxide ($Fe^{3+}_{4-5}(OH,O)_{12}$) and almost certainly this mineral is the orange-red mud in the baths generally. However, in terms of its origin here in the biofilm, the clear association of the ferrihydrite with the EPS suggests that it is likely to have been precipitated as a result of the microbial processes going on there, notably the production of oxygen through photosynthesis by the cyanobacteria. Of note, perhaps coincidentally though, the ferrihydrite nanospheres are the same general size as viruses, and there must be 10s of millions of viruses present in a cubic cm (1 cc) of Bath spring water, which would contain a million bacteria per 1 cc, or more (Tucker 2020). Thus, it is tempting to suggest that the ferrihydrite nanospheres are ferruginised viruses, in a similar process of biomineralisation of viruses invoked to explain calcite nanospheres in tufa (Perri et al. 2022). Indeed, the possibility of viruses being involved in iron precipitation was demonstrated by Kyle et al. back in 2008. Viruses, like EPS and bacteria, have a negative charge and can attract cations such as the $Fe^{2+}$ in solution.

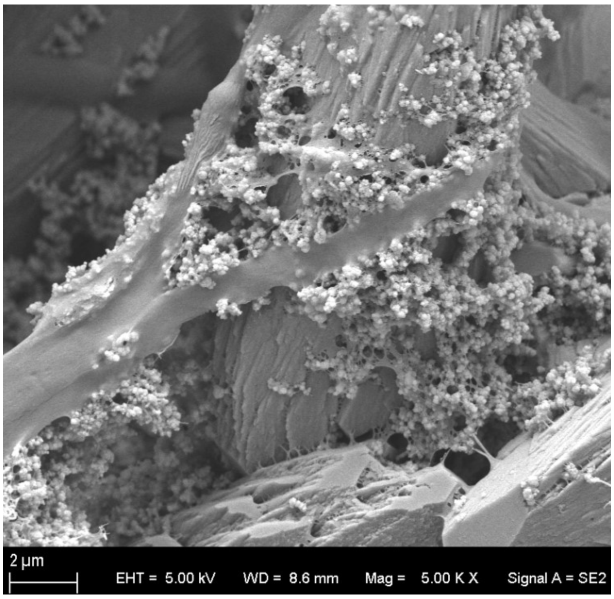


*Fig. 12: Spheroidal particles and clusters (ferrihydrite) upon calcite crystals and within matrix of bacterial filaments and EPS. Scale bar 2 microns.*

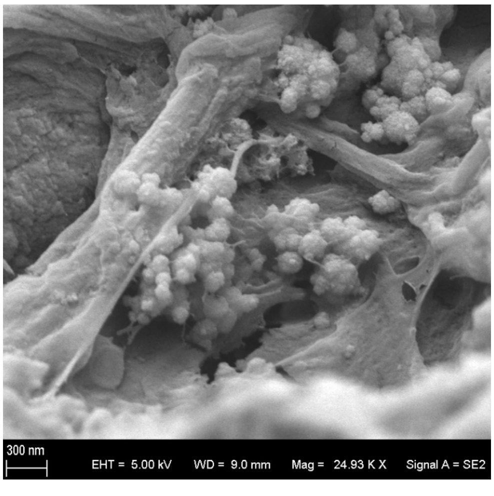


*Fig. 13: Ferrihydrite, spheroidal iron-rich particles and clusters within and upon EPS and bacterial filaments. Scale bar is 300 nanometres.*

Iron can also be precipitated abiotically. The iron in solution in the slightly acidic-reducing water as it is rising up the conduit would have been in the ferrous form ($Fe^{2+}$). On emerging into the oxic atmosphere, this iron would have oxidised to be precipitated as the ferric iron ($Fe^{3+}$) in the insoluble oxide-hydroxide form (the red-orange mud). This is well seen in the Sacred Spring (King's Bath, Figure 1) and at the Spring Overflow (Figure 14) and along the Great Drain. It is a similar process to that happening with acid mine drainage (AMD) where old coal mines are being flooded and mine waters enter streams, but bacteria may also be involved in this precipitation. Ferrihydrite can also be observed when the Great Bath is being swept out: clouds of fine suspended orangey-brown sediment in the water, along with fragments of biofilm, and an orange sludge needing to be hosed out in the final cleaning process. Ferrihydrite is likely to have been the initial precipitate for the huge deposits of hematite ($Fe_2O_3$) that formed the extensive Banded Iron Formations (BIFs) in the late Archaean and early Proterozoic.

*Fig. 14: The Overflow of the Sacred Spring where travertine has been precipitated on the stones and ferrihydrite mud (orange-red colour) has accumulated. Close-up showing micro-terraces.*

**Travertine at the Roman Baths**

Where hot hydrothermal water from the deep subsurface emerges at the Earth's surface as a spring there are commonly extensive mineral deposits. Think of Pamukkale (Turkey) or Yellowstone (U.S.) or Rotorua (New Zealand). Travertine (mostly composed of calcite) is a common deposit where the water has come through limestones, as is the case with the Bath springs. Sinter is another common spring deposit, made of silica (typical of volcanic areas). There are few conspicuous spring deposits in the Roman Baths, but travertine does occur at the Spring Overflow, where water from the Sacred Spring flows over a waterfall to the Great Drain. This channel was built by the Romans to carry excess water to the River Avon, some 500 m away. This is testament to Roman engineering; the tunnel is still there and working well. At the waterfall (Figure 14), travertine has been precipitated with one of its characteristic features: terracettes (small gours), developed on the sloping surface where the water rushes down. Thin, smooth laminae of calcite in a rippled arrangement are deposited here along with fine bright orange-red ferrihydrite mud.

There are also carbonate deposits on the vertical sides of the steps around the Great Bath (Figure 15), easily visible to the curious. These calcite precipitates can also be called travertine, but they are very rough, sharp, almost cindery, and very hard, forming a crust around 5-10 mm thick. These were precipitated within / below a biofilm, but not a smooth-flat biofilm, rather one which had a more irregular, loose, tangled, arrangement of bacterial filaments, with a micro-topography of mm-cm organic pinnacles and tufts. The biofilm from which this travertine has formed through microbial calcification is cleaned of every few months (Figure 15).

*Fig. 15: Cindery – spikey travertine (see close-up) on the vertical sides of the steps around the Great Bath, with the steps themselves having just been cleaned of biofilm-microbial mat, which is still present on the lowest step.*

Of particular interest is that travertine, similar to that on the sides of the Great Bath, also occurs on some surfaces of the roof tiles in the large chunk of Roman roof that is on display in an alcove on the north side of the Great Bath (Figure 16). This travertine could have been precipitated when the roof was in place back in the 2nd-4th centuries CE, from water vapour condensing within the roof structure and a biofilm developing there. Alternatively, the travertine could have formed when the roof collapsed into the bath, sometime after the Romans left in the early 5th Century and abandoned Aquae Sulis. Indeed, surprisingly perhaps, pieces of the roof and piles of odd tiles were left in the Great Bath following its excavation in 1880 until the 1950s (see old photos on the website *Bath in Time*). There are many 100s of Roman tiles in BANES' stone collection, behind the scenes, and many of these are covered in travertine too. This is mostly of the cindery type (Figure 17) but there are areas of smooth travertine and air-bubble travertine, reflecting the changes in the nature of the surficial biofilm at the time of biomineralisation (see Figure 18). Under the SEM, this cindery material is dominantly calcite but there are small clusters of sub-micron pyrite crystals and framboids. These are likely formed through bacterial sulphate reduction in a local anoxic micro-environment. There are also nanospheres which could be calcified viruses, as well as filaments and EPS.

*Fig. 16: Large piece of the roof which once covered the Roman Bath, with travertine coating the box tiles on the inside, on display in an alcove on the north side of the Great Bath today.*

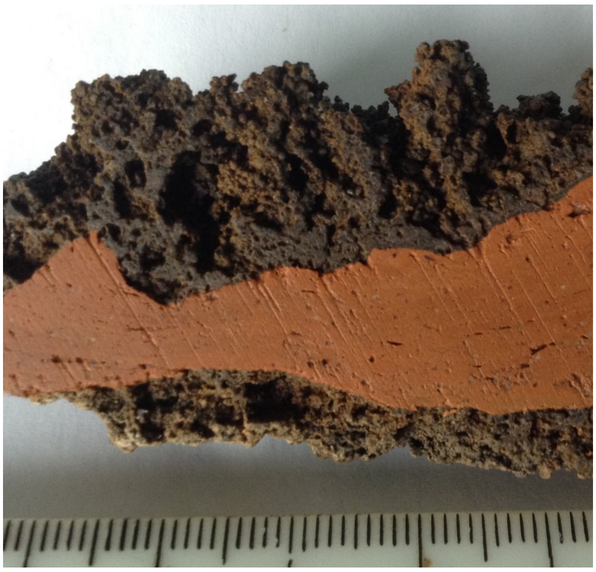

*Fig. 17: Travertine precipitated on a Roman tile through calcification of the original biofilm which clearly passed from being smooth to one with trapped gas bubbles upon which tufts developed to give a cindery type of travertine on biomineralisation.*

*Fig. 18: Roman tile with dark cindery travertine formed on the upper and lower surfaces from the calcification of a porous tufted biofilm.*

**Summary and significance**

The biofilms in the Roman Baths, widely developed in shallow and deeper water and on the surface of the water too, are of several different types in terms of their surface appearance, colour and texture, reflecting the subtle changes in the microbial community and local water conditions. Travertine is being precipitated on hard surfaces in the baths, and the minerals calcite and ferrihydrite are forming within the biofilms through microbial processes.

Within the Roman Baths complex, one is seeing several significant geological processes operating. Apart from the precipitation of minerals, hot springs are regarded by many as one of the most likely places where life on Earth may have originated, around 4 billion years (see Damer & Deamer 2020). Springs, whether subaerial (like Bath or Yellowstone) or submarine (like the black and white smokers of the mid-ocean ridges), are sources of hot water, gases ($CO_2$, $NH_3$, $O_2$, $H_2$, $H_2S$), nutrients and metals, all contributing to Darwin's 'warm little pond' or the 'primordial soup', where life is thought to have started. Spring deposits on Mars are probably the best location to find the evidence of life up there. And there is clear evidence in the Roman Baths for microbes (with EPS and viruses) being involved in mineral precipitation; this biomineralisation is being recognised as a major process which can be directed to mitigating some of the world's significant problems.

**Acknowledgements**

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## The Fossil

**by Charles Hiscock**

I walked across the hard cold stone,
With distant thoughts, deep, alone,
Then I saw that lifeless form
Upon the rock as if just born
Or died, in an ageless time
Of life, a different clime.

I knelt upon the hard cold rock
To gaze upon this form, this block
Of ancient life, preserved in stone.
For me, the first to see in time, alone,
This wondrous shape of life foregone
Now lying there, still, hard, forlorn.

I dwelt upon that hapless life
Lost in distant time of constant strife.
Like child with new found shiny toy,
I, an old man, full of new found joy
Looked upon that gazeless form
In cold hard rock, as if just born.

This little ditty was inspired by the talk 'Poetry and Stones' given by Alycon Hallett to the Society on Thursday 1st September 2022. The title 'Poetry and Stones' initially seemed to me to be strange bedfellows but as she spoke I soon saw the connections and her inspirations.

For me, a poetic wilderness, who once scornfully dismissed Wordsworth's 'Daffodils', when told to learn it as school homework, as 'soppy stuff', it came as a bit of a surprise when, the morning after her presentation, the words above just flowed from my mind.

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# First Planetary Field Trip to Mars 2030

**By Phil Burge**

For the first time the Bath Geological Society is planning a field trip to Mars scheduled for the year 2030. The logistics for such a trip are more complex than that of a trip to the Mendips but to experience the geology and geomorphology of another of the four terrestrial planets in the Solar System will be worth the effort. In preparation for this trip the accompanying field trip notes have been provided. Until fairly recently exploration of Mars has been done using static and robotic explorers. This field trip guide draws on the results of the Curiosity and Perseverance Rover expeditions. The intention is to fly over the Southern Highlands and view the major features before visiting Gale and Jezera Crater to explore the sedimentology and stratigraphy of a period when the landscape of Mars was formed by water.

**Of Mars and the Earth**

Mars and the Earth were formed by the accretion of enstatite and then chondritic meteorites around 4.5 billion years ago (bya). Both planets were subjected to the period known as the Late Heavy Bombardment and both started as a molten basaltic/tholeitic magma planet. As the planets cooled a magnetic field developed and surface water began to accumulate forming oceans. A thin crust and a molten interior were features of both planets. The early atmosphere would have been made up of $CO_2$ and $CH_4$. From this point the evolution of the two planets began to differ, largely due to the difference in size – Mars has a diameter of 6,790 km, Earth 12,750km.

The geological history of Mars is divided into four main Periods. The Pre-Noachian from 4.5 to 4.1 bya was the period of accretion, initial cooling and condensing of water vapour to form oceans, possibly covering the planet as once was the case on the Earth.

The Noachian Period from 4.1 to 3.7 bya is named after the Noachis Terra, a period of continued bombardment and volcanic activity. Gas and ash erupted into the atmosphere creating greenhouse effects warming the planet. At this time the atmosphere must have been at a suitable temperature and pressure to allow free water to exist. The planet cooled and the magmatic dynamo was stilled with the loss of the magnetic field. The highland regions in the southern hemisphere were formed around the Ahyre and Hellas impact sites. Large scale volcanic activity in the Tharsis Montes region created huge volcanic mounds – Olympus Mons is 3 time higher than Mount Everest. The combination of volcanic uplands, precipitation and oceans allowed rivers to cut deep valleys, weathering to produce clay minerals and sediments to be deposited in fluvial, lacustrine and oceanic environments.

The Hesperian period from 3.7 to 2.9 bya is named after a region of ridged plains found to the north east of the Hellas Planitia impact basin. Although the planet was cooling and magma circulation in the mantle had stopped, volcanic activity continued. Exploration on Mars shows that volcanic plains were extensive particularly in the Northern lowlands. Acid rain caused by volcanic $SO_2$ created sulphate deposits in for instance the Valles Marineris and Meridiani regions. During this period Mars experienced massive flash floods caused by the release of water following meteorite impacts. Extremely large outflow channels can be seen around Chryse Planitia and east of Hellas Planitia

The Amazonian Period from 2.9 bya to the present is named after the featureless plains in the Northern Hemisphere. Over this long period of time the planet has been largely dry and the planet's surface arid. Geological and geomorphological change is largely down to weathering, erosion and deposition by the wind. Smaller scale glacial influences can be seen but are limited in extent than on Earth due to the low gravity that results in very slow glacial movement.

**Evidence for Martian Tectonics**

Plate tectonics on Earth as we see it today is defined as being a theory of global tectonics powered by subduction in which the lithosphere is divided into a mosaic of plates which move on and sink into weaker ductile asthenosphere. Three types of plate boundaries form the network of plates. Older lithosphere sinks back into the mantle at subduction zones, plates can slide passed each other along transform faults and oceanic crust is created at mid-ocean ridges . On Earth the evidence for plate tectonics includes the presence of HTHP metamorphic rocks (blueschist and eclogites), serpentinite (subduction of peridotite), the horizontal movement of plates (mid-ocean ridges and palaeomagnetism), dyke swarms, collision orogenesis and the build up of sedimentary basins.

When plate tectonics started on Earth is open to debate with some claiming that the onset of plate tectonics began during the Hadean (>4bya), the Archean or a more recent onset of subduction during the Neoproterozoic (< 1bya). An analysis of global cratons indicates that the bulk of the indicators for plate tectonics can be seen in rocks of between 2.8 and 2.5 billion years old [1].

Before that time the type of tectonic activity on Earth would have been that of a stagnant lid (continuous solid crust) with delamination of crust (drips) into the mantle and plumes of molten magma erupting on the surface . In all likelihood this was the form of tectonics through the more active period of the life of Mars until the Amazonian Period.

Mars does not exhibit the range of tectonic geological and geomorphological features compared to the complexity found on Earth, limited to volcanoes, rifting and faults associated with slumping.

**Crust and Mantle**

Results from the 2018 Insight Lander, designed to measure the presence and scale of Marsquakes has revealed that the Martian crust and mantle is distinctly different from that of Earth. Many Marsquakes of less than Richter 4.0 have been measured. It has been shown that the Martian crust has two layers – the top layer is about 6 miles thick made up of fractured impact material. The second layer is a further 6 miles thick and represents the original crustal material that did not suffer the effects of meteorite impact. Below this there is some uncertainty in that there may be a further 12 miles of crustal material or this layer represents the transition to the mantle. Seismic results indicate that the Martian mantle is between 248 – 373 miles thick. It would seem that the Martian mantle differs chemically from the Earth in having a higher iron content. Analysis of the core suggests that it is made up of iron and lighter elements making it less dense than the Earth's core. Compared to Earth the Martian core is proportionately larger and this might explain why Mars cooled so quickly, lost its magnetic field allowing solar winds to strip away the atmosphere and water .

**Major Landforms and Features**

Figure 1 shows the major topographical features on the Martian surface. The distinctive features of the southern hemisphere (impact dominated) and the flatter northern plains can be clearly seen. In the west there are three very significant features. The impressive mass of the Solar Systems largest shield volcano Olympus Mons, part of the Tharsis Montes volcanic region, rising 25km above the surface. Olympus Mons formed during the Hesperian Period. The volcano's impressive height (achievable due to Mars' low gravity) is matched 624km width. Although in some ways comparable to a hot-spot volcano on Earth, Martian shield volcanoes have grown to enormous sizes as, in combination with low gravity, there is no plate movement to transport the growing volcano away from the hot-spot. By comparison, the largest shield volcano on Earth is Mauna Loa at 10km high and 120 km across. In the centre of Olympus Mons is a caldera 3km deep. It is likely that the volcano became extinct about 3.5 bya.

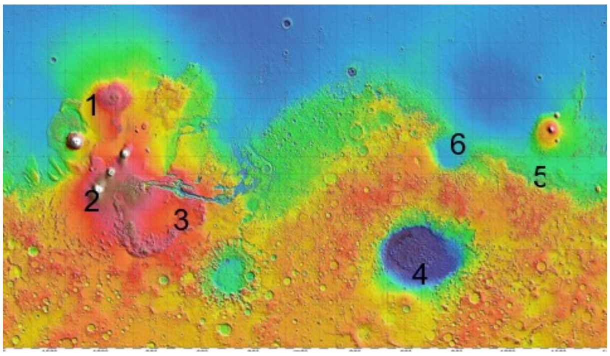


Fig 1: Topographical map of Mars – NASA Mars Global Surveyor

1. Olyimpus Mons
2. Tharsis Montes
3. Valles Marineris
4. Hellas Basin
5. Gale Crater (Curiosity Rover)
6. Jezera Crater (Perseverance Rover)

To the south east of Olympus Mons is a string of three volcanoes 10 km high and aligned north east to south west and named Ascraeus Mons, Pavonis Mons and Arsia Mons. They are located on a crustal bulge with summits at the same elevation as Olympus Mons. Although having similarities to the Hawaiian chain of volcanic islands these Martian aligned volcanoes were not formed by plate movement over a mantle hot spot.

To the east of Tharsis Montes is the massive "rift valley" known as Valles Marineris (Fig 2). The valley is 3,000 km long (about 20% of the width of the planet), up to 8 km deep and up to 600 km wide in places. The rift was formed due to extensional tectonics as the crust in the Tharsis region cooled and thickened. Analysis of mineral assemblages either side of the rift taken from the CRISM orbiter (Compact Resonance Imaging Spectrometer for Mars) shows an alignment of minerals across the rift indicating that this feature is not a strike-slip fault. The valley was enlarged due to erosional forces (water and ice).

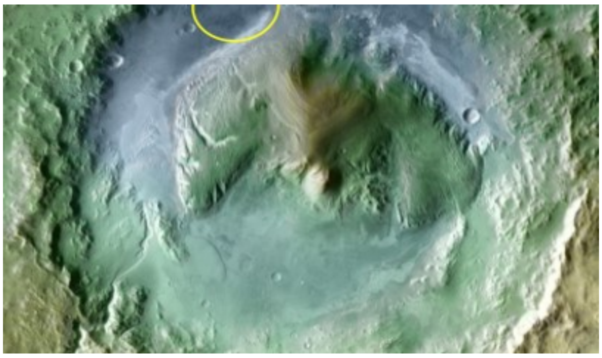

*Fig 2: Gale Crater and Mount Sharp showing landing site of Curiosity Lander*

The Hellas Crater is the largest impact crater on Mars at 2,200 km wide and the lowest elevations on the planet at 8km below the Martian datum. The crater was formed around 3.9 to 4.6bya and since formation has been subjected to infilling by aeolian, glacial, fluvial and volcanic material. Sadly, no rover has been sent into the Hellas Crater.

**Sedimentology and Stratigraphy**

**The Gale Crater**

We now come to our first location of the field trip, having passed over the features above before landing in Gale Crater (location 5 in Fig 1). This crater has been extensively mapped by the Curiosity Rover and much of the sedimentology and stratigraphy has been mapped and interpreted.

The Gale Crater (5) is 155 km wide and sits at the boundary between the southern highlands and the northern lowlands. It was formed around 3.7 bya. In the centre of the crater is a 5km high peak Aeolis Mons (Mount Sharp Fig 2) made up of layered sediments being an erosional remnant of extensive fluvial or glacial crater filling. A stratigraphic column 400 m metres thick (datum 4,560 – 4,140) has been mapped. Three groups have been recognised. At the base, the Bradbury Group consists of fluvio-deltaic mudstones to conglomerates deposited in systems that flowed from the north rim of the crater. The sediments are dominated by high AL basaltic material. There is little evidence for chemical weathering suggesting a cold climate and minimal rock- water interaction.

Above lies the Mount Sharp Group. The Murray Formation of this Group is at least 315 m thick comprising laminated mudstones with low angle cross bedded sandstones. On average the Murray Formations has slightly enriched K and depleted Ca, Na and Mg and enriched traces of Ni and Zn. There is clear evidence of diagenesis throughout the Murray Members.

Lying unconformably above both these groups is the Siccar Point Group comprising the Stimson formation made up of basaltic aeolian sandstone. These formations cut across the Mount Sharp group between 4,460m and 4,290m (Fig 3). The upper boundary of the Stimpson is an erosion surface. The unconformity forms an undulating palaeo-surface showing a regional rise of about 140m. Within the Stimson four sedimentary facies have been identified distinguished by lithology and sedimentary structures. Facies 1 (Figure 4) comprises metre scale cross-bedded medium grained sandstone within some places up to 5% coarse to very coarse sand grains. The cross-stratification is arranged as repetitive stack sets from 0.3 – 1.0 m thick. The sets are bounded by sub -horizontal bounding surfaces. These structures are interpreted as being the preserved lower lee slopes of migrating aeolian sand dunes.

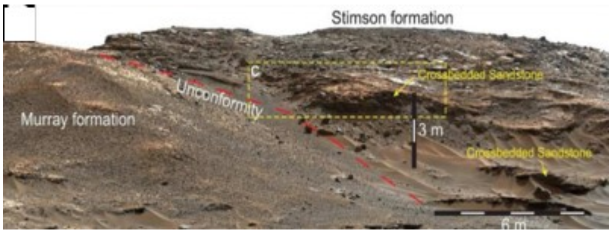


*Fig 3: Gale Crater, Mount Sharp showing clear erosional unconformity between Murray and Stimson Formations*

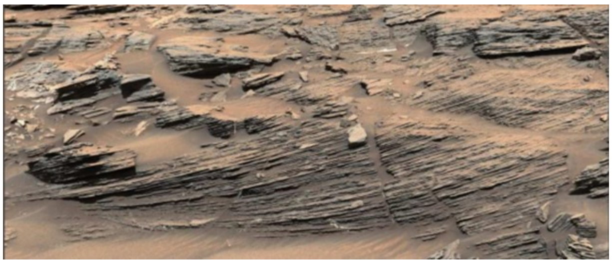

*Fig 4: Facies 1 Gale Crater, Stimpson Formation showing asymptotic metre scale cross bedding*

Facies 2 sediments are similar in appearance to those in Facies 1 but at a much smaller scale with cross bedding between 0.05m and 0.2m thick. Cross laminations terminate asymptotically at the base of each set. These features represent the small preserved sections of large scale aeolian bedforms, the preserved section of small sinuous crested aeolian dunes or large ripples or wind drag ripples (Fig 5).

Facies 3 is a sandstone of metre and decimetre scale cross bedding with abundant sub-spheroidal to oblate concretions (Fig 6) giving a characteristic knobbly texture. Rocks of this type are found immediately overlying the basal unconformity. The concretions are between 20 – 40 mm in diameter. This facies is interpreted as being the result of post depositional diagenesis.

Facies 4 consists of medium to coarse grained sandstone containing rounded clasts of Murray Formation mudstones. A possible interpretation is that the clasts were formed by exfoliation and abrasion in an inter-dune area and were incorporated into the base of a migrating dune .

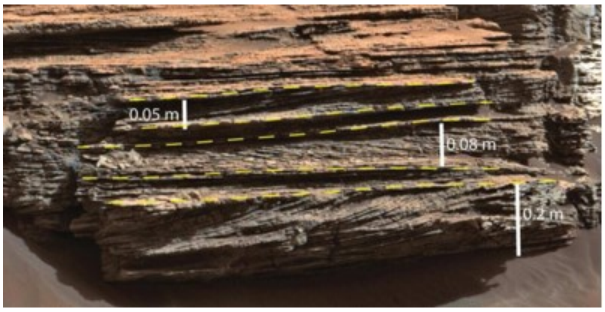


*Fig 5: Facies 2 Gale Crater Stimpson Formation showing small scale cross bedding*

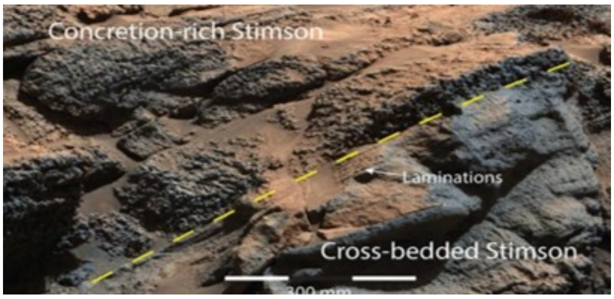


*Fig 6: Facies 3 Gale Crater, Stimpson Formation showing concretions and boundary with cross beds*

**The Jezera Crater**

The NASA Rover Perseverance is currently exploring the Jezera Crater located to the north of the Hellas Basin and at the boundary between the Southern Highlands and the Northern Plains. The crater is about 45km wide and is thought to have been a lake during the Late Noachian Period with water entering the crater from the north west and flowing out from the north east. Fig 7 shows the crater as it may have looked when a lake and as it is now revealing clear evidence of deltaic deposits.

*Fig 7: Jezera Crater as it may have looked showing inflow and exit channels*

Perseverance images show a large butte, named Kodiak Butte 1km south of the main delta fan deposit. This is likely an erosional remnant of a former large fan deposit. From two outcrop sections of the Butte 5 stratigraphic bodies (k1 – k5) have been identified. K1 (lowest) is a 17m thick unit of plane-parallel horizontal to low angle thinly bedded strata of mudstone or fine-grained sandstone. Above this (K2) is a 10m series of strata of steeply inclined beds with southward dips up to $35^o$. Individual beds have thicknesses of 10-50 cm. These beds are sandstone with scattered cobbles. The lower section of K3 consists of thin, gently dipping and horizontal mudstone or sandstone strata. Local boulders and cobbles up to 40cm in diameter can be seen. The base of these beds show a downward asymptotic decrease in inclination into the lower horizontal strata. A horizontal truncation surface leads to the K4 strata of low angle to locally cross stratified strata. The top bed, K5 erosionally truncates K4 and is made up of unsorted conglomerate with large boulders up to 1.5 m in size. The deposition of K1-K5 is consistent with that of a Gilbert type delta (mountain deposits into lake delta) and consistent with the geomorphology of the inlet valley and delta fan seen from orbiter photos.

Within the fan deposits are found boulder rich beds and coarse-grained sandstone providing evidence that at least some of the fan deposits were formed during repeated flash floods of variable intensity (Fig 8). There is no clear evidence for the mechanism responsible for the flood events. Rounded boulders suggest substantial abrasion during transport. Mechanisms could include intense rainfall events, rapid snow melt or heating from volcanism or impact. The transition in flow intensity could be due to palaeoclimate changes or changes in watershed hydrology .


*Fig 8: Kodiak Butte, Jezera Crater showing fan deposits including corss bedding and massive boulder conglomerates*

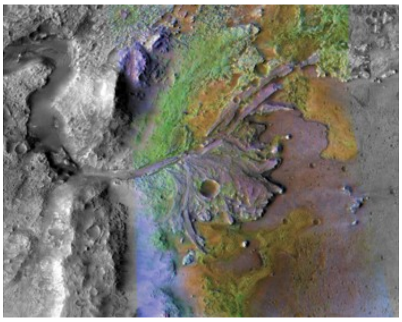

Fig 9: *Jezera Crater showing evidence of deltaic deposits. Colours identify different mineralogy*

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# Dinosaur trackways and landslides - the geology around Rovereto, Northern Italy

**By Graham Hickman**

In September my wife and I embarked on an epic train adventure across Europe. We purchased interrail tickets which allowed us to travel across Europe's train network for two months. Our aim was to travel to Slovenia and follow the sunshine south, beyond that we were flexible to visit whatever places that caught our interest. Rovereto, in northern Italy, was one such place. We had traveled south from Innsbruck, visiting Bolzano, then Trento. By chance, one of my searches threw up a mention of dinosaur footprints near Rovereto- I had to investigate!

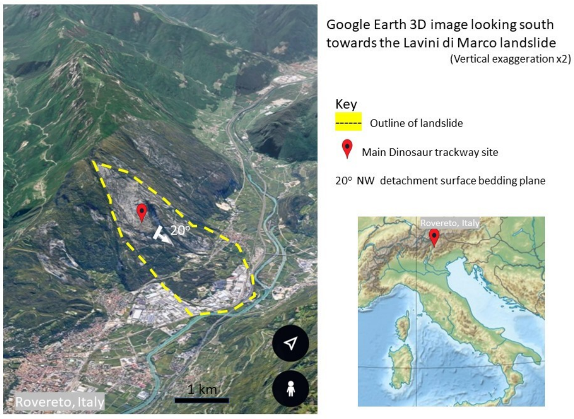


*Fig. 1: location map*

Until the early 1990s there was only one dinosaur footprint known in Italy, it was interpreted that during the Mesozoic Italy's palaeography was predominantly marine with wide carbonate platforms. This all changed in 1989 when an amateur geologist named Luciano Chemini came across a series of symmetric holes with raised edges and recognised them to be dinosaur footprints.

*Fig. 2: dinosaur trackways main site at Lavini di Marco*

The experts were brought in and the hillside studied in detail. An abundance of trackways were identified. It currently amounts to around 70 identified trackways and individual footprints.

The most abundant footprints are interpreted to be from theropods followed by sauropods and some bipedal dinosaurs (possibly small-size primitive ornithopods).

The footprints occur in a grey-white limestone within the Monte Zugna Formation of the Calcari Grigi Group. They have been dated as early Jurassic, Hettangian Stage, around 200Ma. Kustatscher (2016) gives a very detailed account of the stratigraphy. The environment of deposition is interpreted to be a wide tidal plain with an emergent area inferred to the north and east. Following the discovery of the dinosaur footprints similar age rocks have been examined in the region and several more sites identified.

The outcrop where the dinosaur footprints occur is of geological interest in it's own right. The bedding surfaces dip around 20 degrees to the NW into the valley forming a large monocline. As with many areas in the Alps the overly steep topography is unstable and prone to landslides. This area is called Lavini di Marco and has been recognised as a landslide since early times (technically it is a rock avalanche deposit). In Latin Labina means slippery place or landslide. A historical reference describes a landslide in the 6th Century which blocked the river. It is a complex landslide involving an area over 5km$^2$. Further geological dating has suggested dates of 3,000 years, 1,600 years and 1,400 years for periods of movement, probably associated with wet climatic conditions or triggered by earthquakes. The weaker formations just above the dinosaur footprints form the detachment surface of this large landslide

*Fig. 3: Lavini di Marco landslide showing the boulder field* .

The relatively recent, (<3,000years), exposure of the rocks along this landslide detachment has also meant the dinosaur footprints have not been eroded as they were not exposed during harsh glacial conditions more than 12,000years ago.

This was an extremely interesting site to visit with great views and other points of historical interest nearby such as the Peace Bell.

Reference:

Kustatscher 2016 - Geo.Alp, Vol. 13, page 102-108. Late Paleozoic and Mesozoic terrestrial environments in the Dolomites and surrounding areas.

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# 50th Anniversary Field Excursion to Midford, led by Dr Maurice Tucker on Saturday 9th April, 2022

**by Charles Hiscock**

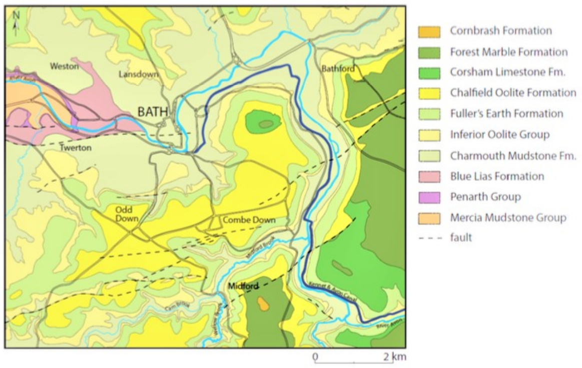
Eighteen members and visitors met at the Odd Down, Bath, park-and-ride site on Saturday 9th April 2022 for the 50th anniversary field excursion of the Bath Geological Society, albeit two years late due to the 'lockdowns' of the Coronavirus pandemic which had seriously disrupted life for two years. At Odd Down, our leader for the field trip, Professor Maurice Tucker of the Society and Bristol University, started the day by describing the walk and the geological sequences we would be considering, explaining that we were standing on the Chalfield Oolite Formation of the Great Oolite Group, otherwise known as Bath Stone. We would be walking down the sequence through the Fuller's Earth Formation, where we would examine some of the remains of the many Fuller's Earth workings, onto the Inferior Oolite and then Midford Sands. We would then be in the valley of the Cam Brook where it runs through the Sands and the Inferior Oolite and was alongside the Somersetshire Coal Canal (SCC) and subsequently the Limpley Stoke to Camerton branch of the Great Western Railway (GWR).

| | | |
|---|---|---|
| Cornbrash | Cornbrash Fm | Great Oolite Group |
| Forest Marble | Forest Marble Fm | |
| Upper Rags/Corsham Lst | Corsham Lst Fm | |
| **Bath Oolite Mbr** | Chalfield Oolite Fm | |
| Twinhoe Mbr | | |
| **Combe Down Mbr** | | |
| Fuller's Earth | Fuller's Earth Fm | |
| Inferior Oolite | Inferior Oolite | Inferior Oo Gp |
| Midford Sands | Bridport Sand Fm | Lias Group |
| Lias Clay | Charmouth Mudst Fm | |
| Blue Lias | Blue Lias Fm | |
| Rhaetic | Penarth Group | TRIASSIC |
| Mercia Mudstone | Mercia Mudst Gp | |
| **Carboniferous: Coal Measures, Pennant Sandstone, Limestone** | | |

**Jurassic stratigraphy in the Bath area.**
**Figures from Tucker 2022 (GA Field Guide in prep), drawn by Sue Marriott.**

*Fig. 1: Jurassic stratigraphy in the Bath area. (from Tucker 2022, GA Field Guide in preparation)*

Maurice also reminded us that William Smith had conducted his early surveys of the canal route following which he produced his first geological map (1799) and also realised the importance of fossils in biostratigraphy. We were shown a reproduction of Smith's




**Geological map of the area around Bath, main roads, rivers and Kennet & Avon Canal.**

*Fig. 2: Geological map of the area around Bath including main roads, rivers and the Kennet and Avon Canal. (from Tucker 2022, GA Field Guide in preparation).*

first map and it was interesting to see that many of the colours used for the rock formations are still used today by the British Geological Survey.

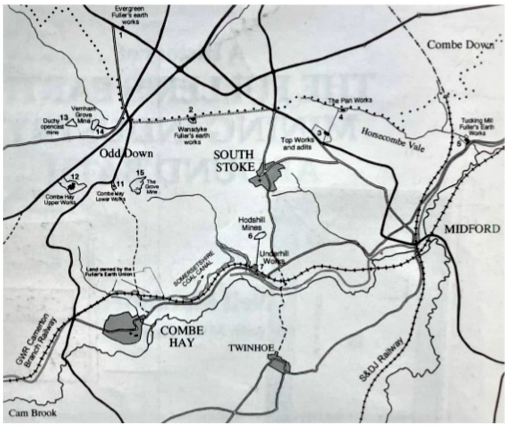
The Great Oolite (160mya) was laid down in conditions very similar to those today in the Bahamas and the Middle East, very warm seas on the edge of a shallow basin where small fragments of shell, sand and corals where being washed back and forth in carbonate rich water. Calcium carbonate was precipitated on the fragments and wave movement formed the rounded grains called 'ooliths' or 'ooids'. The formation is very fossiliferous with many terebratulid brachiopods of which Maurice had a few in his pocket which he produced for us to see (plus a few sweets, no doubt intended to sustain him through the day)!

Leaving the park and ride we walked through the small wood and down the lane to the point where a quarry in the Chalfield Formation could be seen on the right. At this point, we turned left down a trackway until arriving at a level area about 10 metres below the hilltop, where there was evidence of old buildings which was the site of the Grove Mine where Fuller's Earth had been extracted (Figure 3).

*Fig. 3: Maurice Tucker explaining the Fuller's Earth industry at Grove Mine.*

There were many Fuller's Earth mines around Bath, almost all being at the top of the slopes just beneath the oolite. It is a 'swelling clay' that varies in colour and is formed of the minerals smectite and montmorillonite, subaerial volcanic dust deposited in deep water during the early extension of the north Atlantic. The workings, of which few remains now exist, often went into the hills for great distances and had been in existence for 100's of years with evidence that they had been used since Roman times.

Up to the 17th century Fuller's Earth had been used for cleaning and degreasing wool (the process of 'fulling'). Bath was the centre of the industry and from the 1800's it started to be used for cleaning an increasing range of materials. It is now used in the oil industry, pharmaceuticals, plastics and cosmetics. In 1988 a huge stack of 100.000's of documents of the Fuller's Earth Union, the largest company in the industry, was found in the derelict buildings at Combe Hay Upper Works. They have been preserved and a book was published in 2008 documenting the industry (MacMillen and Chapman 2009).




Sites of Fuller's Earth Mines and Works to the south of Bath. From Macmillen & Chapman (2009).

*Fig 4: Sites of Fuller's Earth mines and works to the south of Bath (from MacMillen and Chapman 2009). Map drawn by Mike Chapman, reproduced with permission of Lightmoor Press.*

From the Grove mine, we followed the old dramway steeply down towards the Somersetshire Coal Canal at Combe Hay where the Fuller's Earth was unloaded onto barges and, after the railway was built, railway wagons (Figure 5).

*Fig. 5: Walking down the dramway to Combe Hay.*

Maurice drew our attention to the floor of the dramway which had been paved with what looked like broken bricks, but which turned out to be very fine-grained laminated rock. The stone, the origin of which is not known, had been used to build and line the furnaces for the drying process and the firing had produced the brick red colour caused by the oxidation of iron in the stone. A sample was taken and examined under a binocular microscope at X10 and confirmed the very fine particle size (Figure 6).

*Fig. 6: A sample of the fire reddened rock.*

Also found in the dramway amongst the red stone were lumps of black/grey friable rock in which were discovered plant remains, indicating that waste rock from local Coal Measures deposits used to fire the drying kilns had been placed on the track. In a poor exposure alongside the dramway were lumps of yellow limestone containing large fossils which Maurice attributed to a dropped level of the Forest Marble due to the several faults that have been mapped in the area.

Continuing our walk down the dramway we arrived at the village of Combe Hay where a very sturdy brick bridge had been constructed by the GWR to carry the railway on the line of the SCC formation. The canal was completed in 1805 and ran from Camerton, through Combe Hay and Tucking Mill to a junction with the Avon and Kennet Canal at the Dundas aqueduct. In the mid 1800's, 100,000 tons per year were being transported on the canal and it was the most profitable canal in the UK. However, by the 1890's trade had drastically reduced so the canal was bought by the GWR on which it built the Limpley Stoke to Camerton branch line. The line operated from 1910 to 1954, being closed well before the 'Beeching cuts', but was used in 1955 to film the classic story of the 'Titfield Thunderbolt'. At Combe Hay we turned left on to a lane and, following the course of a railway cutting in the Inferior Oolite on our left, arrived at Rowley Farm. Here the railway diverged from the course of the canal, the latter following the contours above the railway for some distance towards the east. At the farm, we had an excellent view of Lock no 1 which started the series to drop the canal to the level of Cam Brook, 40 metres lower. In the foreground, the canal was seen to diverge, the left-hand branch being level while the right passed into the lock. The left-hand branch was the original course and followed the contour to past a house, now called 'Caisson House' (Figure 7).

*Fig. 7: Lock 1 showing the original divergence to the left.*

*Fig. 8: Hardground in bioclastic limestone with bivalve borings*

*Fig. 9: Sharp bend in the canal between locks 10 and 11.*

However, the canal builders encountered a series of problems, some of which should have been foreseen during surveying of the route for the canal. At a location near the house, a vertical stone cistern or tube was built to connect the upper level of the canal vertically with the lower some 13 metres (40 feet) down, within which a wooden ‘caisson’ or box was raised, into which barges were floated. A steam engine located some distance from the cistern pumped water from the Cam Brook to the canal. Unfortunately, the cistern had been constructed in the Fuller’s Earth and, after a wet summer, the clay became swollen and the cistern leaked causing a barge containing William Smith and officers of the SCC to stick in the cistern. Although no lives were lost, the plan for two further caissons was aborted and the whole scheme abandoned. This, however, caused great delays to the canal traffic so a series of 15 locks were constructed to drop the canal the 45 metres (about 150 feet) down to the Cam Brook valley bottom. Until the locks were ready, an inclined plane was used to raise and lower the drams.

Our walk continued along the line of the canal to the approximate location of the cistern, of which there is no trace although the bases of the walls of the engine shed can be seen. The footpath dropped steeply down the hillside past a small quarry on the left where Maurice explained that the upper part is in the Fuller’s Earth Rock but the lower is a bit of a puzzle as it is an oolitic limestone. Possibly a fault had downthrown the limestone or there had been a major landslip at some time. A microscopic examination of the rock from the quarry shows bioclastic material but only very sparse ooids. On the floor of the quarry a block of the limestone displayed a hard ground bored by *Lithophaga* sp., valves similar to the modern piddock (Figure 8).

As we reached the bottom, from the footpath we could see a very sharp bend in the canal between locks 10 and 11 which was necessary to allow the canal to drop at a steady rate through the series of locks thus obviating the need for a very deep lock or even an inclined plane (Figure 9).

Our walk continued along the wide valley of the Cam Brook where, out of the chilly wind we had experienced on the hill tops, it was very pleasantly warm. After we had passed the location of lock 15, we went beneath another fine railway bridge, reading on the interpretation board that the canal passed through the bridge and continued through a further seven locks to eventually a total of 22. Very soon, we were approaching Midford (and lunchtime) and passed under the fine viaduct carrying the Camerton branch over Cam Brook. It was worth noting that the GWR never did things by halves, the quality and sturdiness of the bridges and viaducts being the evidence. By now, the route of the canal was a little to the north of us as it approached Midford and it turned sharply north under the trackbed of the Somerset and Dorset Joint Railway (S&D) towards Tucking Mill. The platform edge of the old S&D station at Midford provided an excellent spot to hang legs to enjoy our picnic lunches and watch large numbers of walkers and cyclists pass by on the line of the old S&D railway (Figure 10).

Before we moved off a very obliging gent was happy to take photos of us as we posed in the sun on the platform end (Figure 11).

The station was built at the southern end of a cutting in the Inferior Oolite of which a couple of small exposures still exist where we saw moulds of bivalves, particularly *Trigonia* sp. and small corals. From Midford station we picked up the route of the canal, passing a bay where the barges were weighed so that the owners could be charged. We also saw the site of a siding on the S&D where Fuller's Earth brought down by dramway from a mine was loaded onto railway wagons.

*Fig. 10: Lunchtime at Midford station.*

*Fig. 11: The customary group photo, courtesy of a passer-by.*

The canal from Midford is not well defined so we pressed on to Tucking Mill, famous for being the location where William Smith lived as recorded on the plaque fixed to the wall of Tucking Mill Cottage. However, he actually lived in the tall house just up the hill (Figure 12) but the plaque was moved to the cottage in 1932 by the Geological Society of London and the Bath Royal Literary and Scientific Institute (Figure 13) after the stone mill buildings were demolished.

*Fig. 12: William Smith's house (right side) at Tucking Mill.*


*Fig. 13: The plaque recording that William Smith lived at Tucking Mill*

Behind the cottage a large reservoir now occupies the site of settling ponds into which Fuller's Earth slurry was pumped along pipes from the mines high on the hill. Maurice told us that William Smith had opened a quarry near the hilltop with a tramway bringing the stone down to the cutting mill after which it was loaded onto barges. However, Smith's quarry was opened in poor quality stone due to faults and joints, and despite tunnelling well into the hill, no quality stone was found. Smith went bankrupt and was sent to a debtors' prison for a stretch. The Combe Down Heritage Society, in conjunction with the Bath Geological Society, produced a leaflet in 2016 'William Smith and the landscape of Combe Down' which Maurice made available to members.

Leaving Tucking Mill by the footpath at the west side of the cottage, we climbed to the walking and cycling trail now occupying the S&D railway trackbed where it passed across a high viaduct over Horsecombe Vale. The trail passes from the southern end of the viaduct into a cutting where Inferior Oolite overlies the strongly bioturbated Midford Sands, the equivalent of the Bridport Sands Formation. Between 1700 and 1800 the fineness of the sands was exploited as a cleaning agent for saucepans. Looking back from the cutting over the viaduct to the Fuller's Earth outcrop on the hillside, the undulating nature of the hill slope indicated regular landslips had occurred. At the top and overlying the Fuller's Earth is the Great Oolite where a paper mill, now a large house, had been built to exploit spring water to produce artists' quality paper. From the S&D trail we climbed the steep hillside of Horsecombe Vale through a large wood that had been largely felled due to ash die-back disease and, just below the top of the hill, past the Pan Works Fuller's Earth mine. Once at the top it was a steady level walk back to Odd Down park and ride where our chairman, Graham Hickman, gave a vote of thanks for a very interesting and rewarding 50th Anniversary Field Excursion.

We thank Maurice Tucker for leading us on this excursion which to a certain extent was intended to mirror the field trip led by Bob Whitaker during the 25th anniversary celebrations. We also thank the Curry Fund of the Geologists' Association for providing funding to enable the Society to celebrate our 50th anniversary.

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# Corndon Hill

**By Jonathan Slack**

Corndon Hill is 513m high and lies within a small salient of Powys projecting into England east of Montgomery. It is part of the Shelve area: west of the major north-south faults that pass near Church Stretton. The hill itself is a product of vulcanism which occurred in the Ordovician period in connection with the closure of the Iapetus Ocean, the process which eventually knitted Scotland and Northern Ireland together with England and Wales. The igneous rocks are partly plutonic, and partly extrusive, the latter belonging to the Stapeley volcanic member, whose epicentre is at Stapeley Hill, a few km to the north-east. The non-volcanic sedimentary rock in the vicinity is the Hope shale which is a fine-grained shale of the Llanvirn series laid down in a shallow Ordovician Sea north-west of the Midland platform and south-east of the Iapetus ocean.

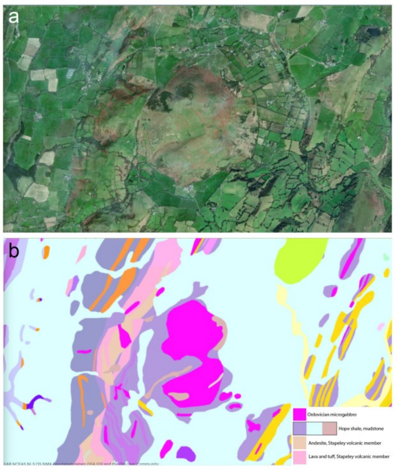


*Fig. 1: (a) Corndon Hill from the air. (b) Geological map taken from the BGS public access Geology Viewer. Note the dumb-bell shaped mass of dolerite (microgabbro) in magenta, the lava and tuff to the west, and the Hope shales surrounding.*

According to the geological map (Figure 1), the area comprising the two main summits of the hill is composed of dolerite, also known as microgabbro, and, in the USA, as diabase. Dolerite is a plutonic or hypabyssal rock with similar composition to gabbro but smaller crystals due to more rapid cooling. The intrusion passes through the Hope shale and, at the junction, has baked it to a hard flagstone which has been extensively quarried for roofing slates.

In connection with a walk up the Offa's Dyke footpath, I visited Corndon Hill in 2021 to collect some rock samples. The best exposures of igneous rock are found on the southern summit and the outlying western summit, which is known as Lan Fawr. Also, in the northern part of the complex, lies a valley containing some exposures of andesitic tuff (Figure 2).


*Fig. 2: (a) Corndon Hill from the south. (b) the south summit. (c) The Lan Fawr summit. (d) the northern valley. (e) Close up of south summit. (f) close up of Lan Fawr summit, note the layering. (g) slate quarry, note the horizontal fracturing. (h) andesitic scree slope.*

I collected samples from the south summit, from the Lan Fawr summit, and from the northern valley. These were taken home and processed to make thin sections, as described in my article for this journal last year. The South summit outcrop appears plutonic, in that it is completely crystalline, and does have the composition of a dolerite, mostly consisting of clinopyroxene and plagioclase (Figure 3a). There is some ophitic texture, in which crystals of plagioclase lie within crystals of pyroxene, a phenomenon characteristic of dolerite (Figure 3b). In fact, the mineral composition is on the more "acidic" side for a dolerite as it contains a little quartz and no discernible olivine. It is probably classified as a dolerite rather than a microdiorite on the basis of its high content of pyroxene and the absence of biotite. All the minerals have been substantially altered, with much of the clinopyroxene changed to a greenish-yellow chlorite, and all of the plagioclase strongly sericitized with inclusions of mica (Figure 3c). The Lan Fawr outcrop contains the same minerals and is rather better preserved (Figure 4a,b). However, in addition to the crystals the thin sections from Lan Fawr show numerous small zones of glassy matrix indicating that this is actually a lava, presumably a very stiff one since most of the content is

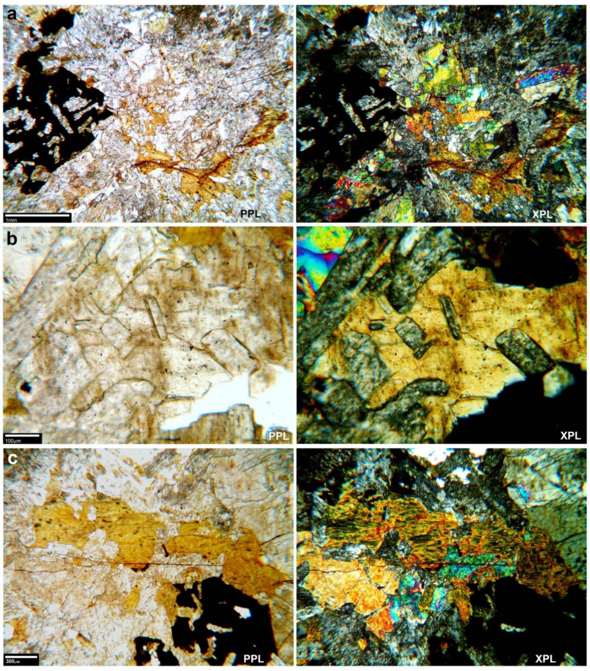


*Fig. 3: Thin sections from a sample from the south summit, CH1. Plane polarised light views are shown on the left and crossed polarised light views on the right. (a) Interlocking crystal structure indicating a plutonic origin. On the left is a skeletal opaque mineral, probably ilmenite. In the centre are crystals of clinopyroxene. (b) Ophitic texture. Several crystals of plagioclase lie within a larger crystal of pyroxene. (c) Extensive replacement of clinopyroxene by chlorite. The chlorite appears yellow in PPL and dark with orange highlighting the former cleavage planes in the XPL view.*

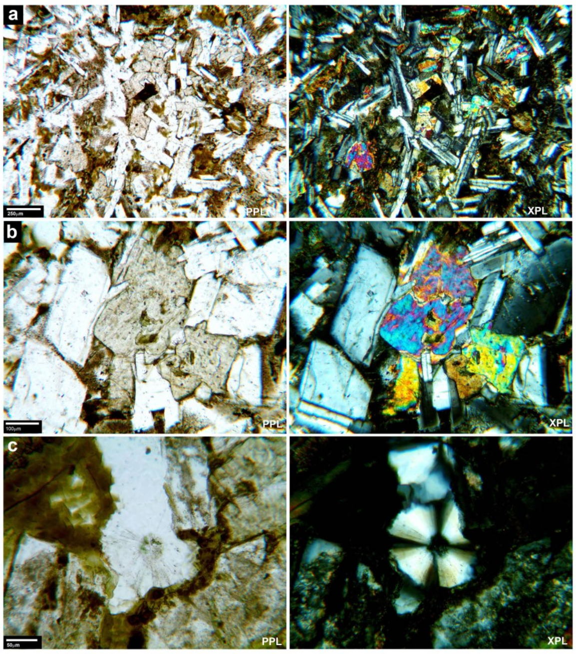


*Fig. 4: Thin sections of samples from Lan Fawr. (a) Sample CH6. Although mostly crystalline there are also areas of glassy matrix, which appear brown in the PPL view. (b) Sample CH6 at higher power. This rock is relatively "fresh" with crystals of unaltered plagioclase (grey and stripey), and clinopyroxene (blue, green, yellow). (c) Sample CH7 from a few metres away. This contains many spherulites showing a "Maltese Cross" appearance in XPL.*

Crystalline (Figure 4a). The macroscopic appearance also suggests a lava because it shows prominent layering (Figure 2f). At Lan Fawr, samples taken from neighbouring positions appeared somewhat different from each other, with some containing many spherulites. These are radial arrays of aligned fibres which give a "Maltese Cross" appearance in polarised light (Figure 4c). They are probably composed of quartz fibres which have recrystallised from a glass.

In the northern valley the scree consisted of rocks bearing large phenocrysts scattered in a dark matrix. Thin sections showed they had the composition of andesitic lavas or tuffs, the phenocrysts being much altered plagioclase and occasional pyroxene (Figure 5a). A sample of the Hope shale from a slate quarry on the hill was very hard and had a speckled appearance indicating some separation of minerals, presumably due to baking by the nearby magma that gave rise to the dolerite (Figure 5b). There are many other slate quarries on the hill, particularly on the west side.

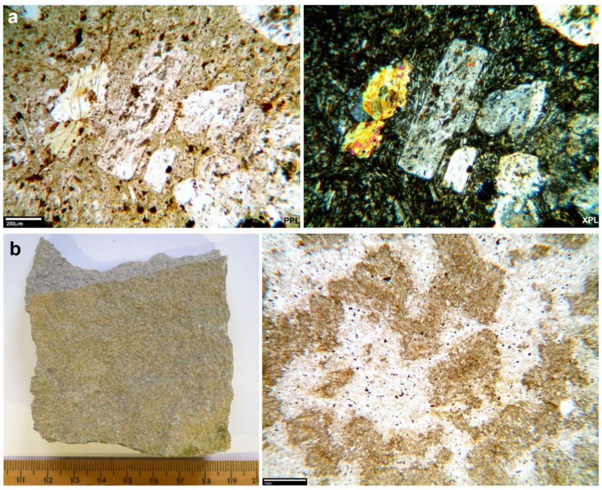


*Fig. 5: (a) Andesite from the scree slope in the northern valley. This thin section from sample CH12 shows a crystal of altered pyroxene on the left, and several altered plagioclase crystals, the phenocrysts being surrounded by a dark matrix containing small plagioclase laths. (b) Specimen CH5 from the slate quarry. On the right, the thin section shows segregation of the clay minerals presumably as a result of contact metamorphism.*

To me, Corndon Hill is of interest since the dolerite at Lan Fawr is of unusually good quality and shows little alteration, giving a pleasing appearance down the microscope. But Corndon Hill is actually better known as a site of Bronze Age stone axe manufacture, although I was unaware of this at the time of my visit. There are remains of several Bronze Age burial cairns on the principal summit, and a stone circle at Mitchell's Fold 2km to the north. The stone axes were made of picrite, an ultrabasic rock, the source of which was apparently near Hyssington, a few kilometres to the south. Regrettably, I did not visit Hyssington, but I note that the OS map does not show any rock exposure there today.

If you have any comments on this article, please let me know at j.m.w.slack@bath.ac.uk.

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# Some Short Notes on Shale Gas in the UK

**By Phil Burge**

The year 2022 has thrown into sharp focus the need for energy security stemming from an over reliance on imported energy in the form of imported fossil fuels or imported electricity via interconnectors. The shale gas revolution has transformed the oil and gas industry in the USA and turned the country from a net importer to a net exporter. Natural gas exports increased from 2014 and in 2017 became the USA became a net exporter of natural gas. Major US shale gas basins include the Appalachian, Permian and Williston with other basins in Texas and Louisiana. As an indicative snapshot of production rates from US shale gas wells, data for October 2022 shows that on average new wells produce 5.5 million cubic feet/day with lower rates of 2 million cubic feet per day and highs of 28 million cubic feet per day from Appalachian Basin wells. At the end of 2020 US shale gas reserves were estimated to be 318 billion cubic feet .

The success of shale gas production in the USA has generated interest and controversy in the UK. This paper reviews the technology of shale gas drilling and production, the potential productivity of UK shale and looks at two major environmental issues – induced seismicity and water. Some author observations on energy security are also discussed.

**The Technology**

That shale contains oil and gas has been known for a long time, bearing in mind that shale is the source rock for oil and gas reservoirs (e.g., Kimmeridge Shale for North Sea production). The problem with shale is the very low permeability. Two technologies combine to improve the effective permeability and allow gas to flow, namely horizontal drilling and hydraulic fracturing (fracking). Prior to the late 1980's wells were either vertical or deviated, with the deviated wells not exceeding about 600 of inclination. From the mid to late 1980's the use of Measurement While Drilling (MWD) tools in combination with steerable motors allowed wells to be drilled horizontally thus exposing far more reservoir and increasing production. Early success in the naturally vertically fractured Austin Chalk in Texas demonstrated quite clearly the production benefits of horizontal drilling. Horizontal drilling has allowed old fields to be redeveloped and prolong the life of these fields (e.g., Ekofisk). Hydraulic fracturing has long been used to inject wastewater.

Hydraulic fracturing has been used to increase the permeability of tight sands and limestone since the first successful commercial application in 1949. As such it is not a new technology. Fracking involves pumping a mixture of water, chemicals (viscosifiers) and proppant (sand) into a well at a pressure high enough to overcome the fracture pressure of the rock thus creating extended horizontal fractures around the wellbore. Experiments in the 1980's and 1990's by Mitchell Energy in the Barnett Shale Formation (Carboniferous shale in Texas) using water without viscosifiers and pumping at higher pressure were effective in producing economic quantities of gas from shale.

**UK Shale Gas Potential**

Four areas in the UK have been identified as having potential: the Carboniferous Bowland-Hodder area in the north west of England, the Carboniferous Midland Valley in Scotland, the Jurassic Weald Basin and the Wessex area in England. These two latter basins have not reached the "gas window" and the lack of maturity would indicate that they are unlikely to be of major interest.

Estimates of gas in place and total recoverable gas vary enormously, for instance the early estimate for total gas in the Bowland-Hodder range from 822 to 2,281 trillion cubic feet (tcf) and the later estimate is 140 tcf. The reason for this uncertainty is that there have been so few wells drilled and tested. Additionally, the early estimates were based on results from US wells when there may be significant differences between US and UK shale productivity. These differences include, composition of the shales, geochemistry, amount of geological faulting, mechanical properties and the ability to correlate shale successions. All we can say for now is that UK reserves could range from zero to substantial and without extensive drilling and testing we will not know .

**Environmental Issues - Induced Seismicity**

Induced seismic events can occur as a result of a number of human operations including water loading behind new dams, mining, geothermal, conventional oil and gas operations, wastewater injection and hydraulic fracturing.

Within the UK there are many hundreds of natural earthquakes every year of low magnitude. The BGS reports that for the 50 days up to the 26th October 2022 there were 36 recorded earthquakes in the UK, many of them at depths far deeper than associated with oil and gas drilling and hydraulic fracturing operations, ranging in magnitude from 0.3 to 2.4. Over the same period there were no reported induced seismic events as no hydraulic fracturing or wastewater injection operations have taken place .

In the USA the USGS monitors and reports on earthquake activity and since 2009 there has been an increase in number of earthquakes. For the period 1973-2008 there were 25 earthquakes of magnitude 3 or greater in the central and eastern USA. Since 2009 at least 58 earthquakes of this size have been recorded each year and at least 100 each year after 2013. A few larger earthquakes, magnitude 5.0+ have occurred in Oklahoma in 2016. Most of the larger earthquakes are associated with wastewater injection from conventional and non-conventional oil and gas operations with a large cluster in Oklahoma.

That earthquakes can be attributed to human activity is not in doubt. Governments and regulatory authorities tend to use a traffic light monitoring system to mitigate the effects. In the UK the threshold has been set at magnitude 0.5 at which point operations cease for a period of time before recommencing. In comparison the limit in California is 2.7 and in Illinois, Alberta and British Columbia it is 4.0 .

Understanding the potential for induced seismicity from hydraulic fracturing is difficult in shale rocks due to the heterogeneity of the rock (lithology, stress state). On top of this modelling the size and location of existing faults, understanding the local stress state and the mechanical properties of the rock such as coefficient of friction is problematic. The mechanical properties of shale are related to the geological setting – stratigraphy, composition and structure. The geology of UK shale is variable and complex making prediction more challenging.

Rock failure occurs when shear stress exceeds the critical values, namely the angle of internal friction and the inherent shear strength (or cohesion) of the rock. Critically the shear stress is affected by the pore pressure, thus the effective stress is the shear stress minus pore pressure. As pore pressure increases so the effective stress reduces. This means that the rock is easier to fracture and or fault planes become more susceptible to movement. In principle the results of injecting water at high pressure into a formation will increase the pore pressure, reduce the effective stress and possibly induce measurable movement (seismic). Estimating the probability of fault activation requires measurements of the orientation and magnitude of the principal stresses, the pore pressure, coefficient of friction along the fault plane and orientation of the fault.

**Environmental Issues – Water**

Hydraulic fracturing in shale requires water – a lot of water. In the Marcellus Shale in the USA 3 – 5 million gallons of water is required for each fracturing operation and there may be more than one for each well. Although shale gas fracturing is primarily with clear or “slick” water there are some chemical additives along with sand proppant to keep the fracture open. When the well starts to produce about 75% of the injected water returns to surface where is has to be collected, cleaned up for further fracturing operations or disposal. This disposal might be back into the water course or into a wastewater reinjection site (see above commentary on induced seismicity). Access to these high volumes of water means extracting water from natural sources or drilling a water well into a nearby aquifer. Given the pressure that the UK’s water system is under neither of these options is without problems. Notwithstanding the issue of availability and disposal, is the transport of this volume of water to and from the drill site. One can see why people in rural areas with narrow roads would be upset at the thought of potentially hundreds of deliveries of water.

**Summary**

There may well be potential in UK shale gas operations. The many unknowns of geology, geomechanics, production test data and so on make it impossible to make any categorical assessment of the production potential, operations safety and impact on the UK economy. The only way to reduce the uncertainty is to drill and test many more wells than have been completed to date and to establish a track record of environmental safety that satisfies residents. It is unlikely that shale gas will form any significant part of the UK’s energy mix within the next decade.

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i U.S. Energy Information Administration

ii Houses of Parliament, Parliamentary Office of Science and Technology, 2013

iii BGS website

iv Recent Scientific Advances in The Understanding of induced Seismicity from Hydraulic Fracturing of Shales, Open Report OR/22/050 British Geological Survey, 2022


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# Greenland field trip with the Geological Society of Glasgow

**By Mellissa Freeman**

Earlier this year, after several failed attempts because of the pandemic, I finally got to visit Greenland on a field trip with the Geological Society of Glasgow, led by Dr. Iain Allison.

We travelled to the west coast of Greenland, Disko Bugt area, starting in Ilulissat then travelling by boat to Qasigiannguit, Qeqertarsuaq on Disko Island, then back to Ilulissat. It’s strange trying to get your brain to adapt to 24 hours sunlight and I can imagine it is actually quite grim up there during the winter months.

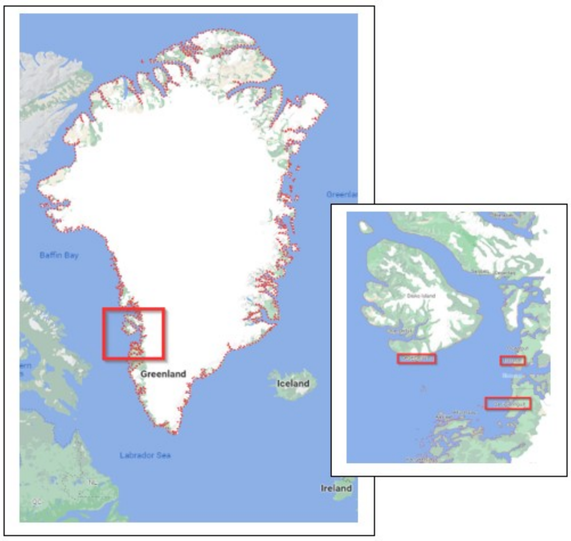


*Fig. 1: Google maps image of Greenland and the locations visited*

*Fig. 2: Ilullisat—houses built on the Precambrian basement rocks*

Greenland geology is quite diverse, but the island is so large we only saw a tiny section on the mainland; the Precambrian basement rocks which are predominantly granite gneiss and granites. This set the scene for start and end of our trip! The geology around Ilullisat is very similar to the Cuillins on Skye (fig 3). Here, and at Qasigiannguit, we saw folded gneisses and other metamorphic features (see fig. 4), some marble, the occasional vein of epidot, granite slabs, large mica crystals etc. Fantastic for hiking on – the grip you get on your boots is amazing, even when wet!

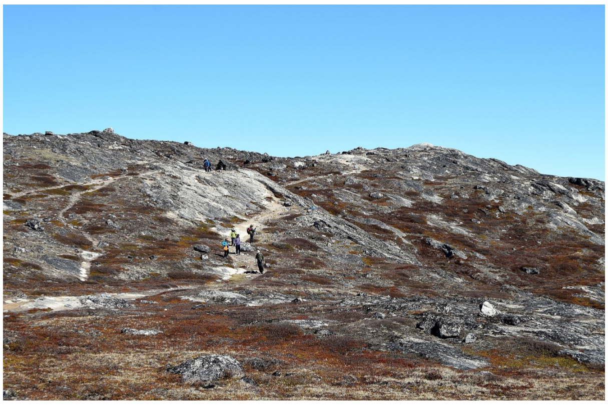

*Fig. 3: our group hiking near Ilullisat*

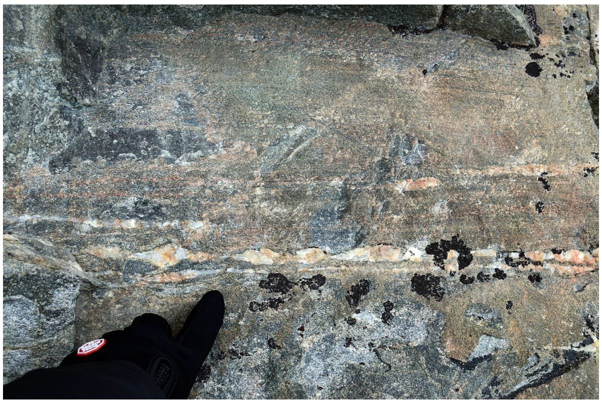

*Fig. 4: Boudinage in gneiss at Qasigiannguit*

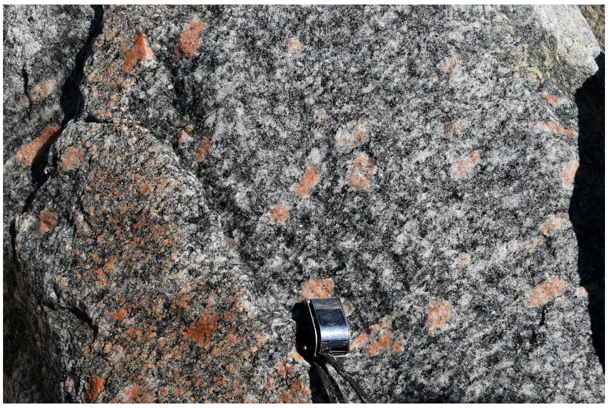

*Fig. 6: Granite, Ilulliset*

*Fig. 7: Epidot vein in granite*

*Fig. 8: Gneiss, Ilullisat*

Our trip to Disko Island was a little different. Although there are still gneisses on which the town of Qeqertarsuaq is built, we were surrounded by volcanics sitting on top of Cretaceous sediments. I will also mention here the large mica crystals we spotted in the odd exposure in the bay area (fig 9 & 10).

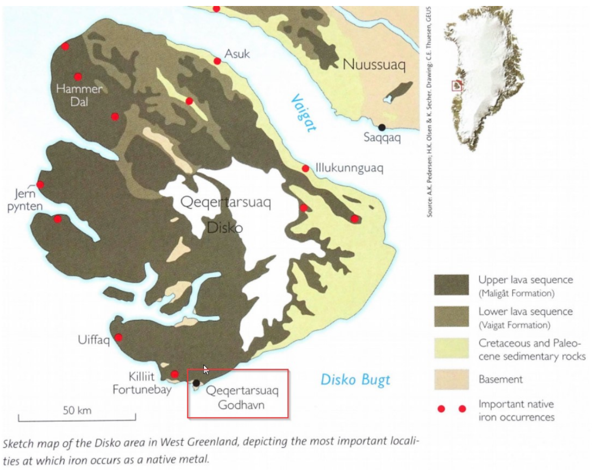


*Fig. 9: Simple geological map of Disko Island*

*Fig. 10: House in Qeqertarsuaq, Disko Island*

Disko island is situated in the Nuusuaq basin. There are cretaceous sediments here which are overlain by approx. 4km of flood basalts. These are known to extend from Disko Island into central West Greenland. The main volcanic sequences we see on coast at Qeqertasuaq were formed during the Palaeocene, approx. 60 MA, with a smaller sequence sitting on top from the Eocene that has been dated to approx. 55 MA. All these flood basalt deposits are related to sea floor spreading and the formation of the Davis Strait (fig 11).

*Fig. 11: Flood basalt deposits, Qeqertarsuaq, Disko Island*

The basalts on Disko Island are tholeiitic in composition with very few olivine crystals visible. Whereas the basalts found further into the basin are more primitive in origin and are from earlier volcanic episodes. We saw the more evolved basalts on the black sand beach at Qeqertarsuaq (add photo). It was quite bazaar to be standing on a beach made up of black sand that was littered with large chunks of ice – quite a contrasting picture (fig 12 & 13).

*Fig. 12: basalt with plagioclase feldspar*

*Fig. 13: black sand beach littered with lumps of ice that had broken off icebergs, Qeqertarsuaq, Disko Island*

Looking inland from the beach are the series upon series of flood basalt deposits which are easily identified by columnar jointing. These show the typical colonnade structures, straight columns with parallel sides and the entablature stacks on top which are smaller and often curved. (fig, 14 & 15). As the columns grow upwards, stress in the cooling lava starts to create cracks and contraction takes place. The growth of the columns is perpendicular to the surface flow of the lava which creates the hexagonal shape. The smaller Entablature at the top of the flow gives the hint that fresh water would have been present causing the lava to cool at a quicker rate from the top down, slower cooling from the base up and rapid cooling from the top down.

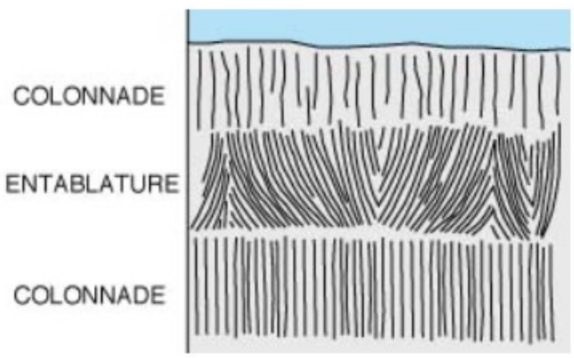


*Fig. 14: sketch showing the two different types of columnar jointing*

*Fig. 15: Columnar Jointing, (colonnade & entablature) Disko Island*

*Fig. 16: Columnar Jointing and hot spring. The hot spring is shown in the red box where the plant life is green*

The rocks here are also iron rich which is evident from the rusty colours you can see. Large deposits of metallic iron have also been found on Disko Island attracting lots of attention from those looking to capitalise over the last couple of centuries. Disko Island also boasts several hot springs where the water temperature reaches around18ºC where the water reaches the surface, and they are easily spotted by the plant life growing nearby. One that is locally picked and shipped over to the mainland and Denmark is the herb, Angelica. What really stole the show for me though was the spectacular icebergs. Each one was different, they changed with the light. Absolutely stunning!

*Fig. 17: Icebergs just off the bay at Qeqertarsuaq, Disko Island*

And finally…

**References**


Geological History of Greenland - Four billion years of earth evolution by *Niels Henriksen*

https://volcano.oregonstate.edu/columnar-jointing


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# Corals in Bath Stone and their Taphonomy (Great Oolite, Jurassic, England)


**By Maurice Tucker, School of Earth Sciences, Bristol University, Bristol BS8 1RJ.**
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Bath Stone is an oolitic limestone from the Middle Jurassic composed of ooids with variable amounts of shell debris, extracted from open and underground quarries in the vicinity of Bath, Box and Corsham, in northeast Somerset and Wiltshire. This stone is an iconic English building stone, used for nearly 2000 years since the Romans arrived in England and set up their Baths and Temple complex at Aquae Sulis, attracted by the natural hot springs occurring there. However, within the Great Oolite succession, there are small coral reefs and within the Bath Stone itself there are rare isolated pebbles and cobbles of coral. This article explores the coral beds and clasts in the Great Oolite and the preservation (taphonomy) of the corals themselves.

**Stratigraphy**

The Great Oolite Group of the Bathonian, Middle Jurassic, consists of the Fuller's Earth Formation, 15-40 m thick, passing up into the Chalfield Oolite Fm. (15-30 m), wherein the Bath Stone occurs, succeeded by the Forest Marble (24-30 m) and the Cornbrash (4-6 m) (Figure 1) (Barron et al. 2012; BGS 2015). There are two units with exploited freestone beds: the Combe Down Oolite and the Bath Oolite, separated by the

Twinhoe Member. Above the Chalfield Oolite is the Corsham Limestone Fm. (formerly the Upper Rags), which is divided into three members, a lower Corsham Coral Bed, a middle White/Ancliff Oolite and an upper Bradford Coral Bed.

| | | |
|---|---|---|
| | Cornbrash Fm. | bioclastic limestone |
| GREAT | Forest Marble Fm. | shelly limest + clay beds |
| | | **Bradford Coral Bed** |
| | Corsham Limest Fm. | White / Ancliff Oolite |
| OOLITE | | **Corsham Coral Bed** |
| | | Bath Oolite |
| | Chalfield Oolite Fm. | Twinhoe Beds |
| GROUP | | Combe Down Oolite **CD corals** |
| | Fuller's Earth Fm. | mudrock, clay, limestone |

*Fig. 1: Stratigraphic divisions of the Great Oolite Group in the Bath region (from BGS 2015), showing the location of coral units. Corals in the Combe Down Oolite occur as thin lenses within the Oolite itself and in uppermost beds/lowest Twinhoe Beds. (CD = Combe Down).*

The Bath Stone of the Chalfield Oolite is largely composed of oolitic and oolitic-bioclastic grainstones deposited on a shallow shelf extending across much of northern Wiltshire to just south of Bath, from Hinton Charterhouse towards Bradford on Avon and Trowbridge. South of here the limestones pass rapidly into clays (Frome Clay) deposited in deeper water. The Combe Down Oolite has a larger amount of skeletal material than the Bath Oolite, and the ooids are generally better sorted and larger in the Bath Oolite. On the whole there are very few large fossils present; scattered bivalves reach 5 cm, otherwise all skeletal debris is finely comminuted.

**Coral reefs and coralliferous beds**

Coral reefal buildups and coralliferous beds occur at several horizons within the Chalfield Oolite-Corsham Limestone Fm. Within and towards the top of the Combe Down Oolite local patch reefs and coral debris beds have been recorded in the Combe Down area (Tomes 1885; Green & Donovan 1969). 21 different species were described by Tomes from a bed 1.5 m thick, resting on oolite, in an old quarry on the south side of Combe Down. Some common middle Jurassic genera there are *Isastrea, Stylosmilia* and *Thamnasteria*, shown in Figure 2. Tomes noted that most corals he found were broken up and reworked, rather than in their growth position. There were probably small patch reefs developed in this area with storm waves reworking the buildups and generating coral debris, in water a little deeper than the main area of ooid and bioclast production in shallower more agitated waters.

Immediately above the Bath Oolite, in the lower part of the Corsham Limestone, the Corsham Coral Bed Member is present, 0.7 to 2 m thick. This unit is extremely hard and forms the roof bed of the stone mines / underground quarries in the Monkton Farleigh and Bathampton areas (Figure 3). It is well seen at Brown's Folly Nature Reserve (Grid ref: ST 798-664), near Bathford, at sites 5 and 10 (Tucker 2023). This coral bed is also well developed in the Corsham area, north of Box (Green & Donovan 1969). This brownish, often ferruginous-looking limestone has many large bivalves and crystalline coral masses with ochreous cavities and holes, centimetres in diameter, giving a vuggy weathered appearance. This bed has sharp, flat lower and upper surfaces, and on the top surface there are perforations from the boring activities of bivalves (*Lithophaga*, *Gastrocoenites*), sponges and annelids. There are also encrustations on the flat top surface from oysters and serpulids. This is a hardground surface, a cemented seafloor, planned off and corraded by currents.

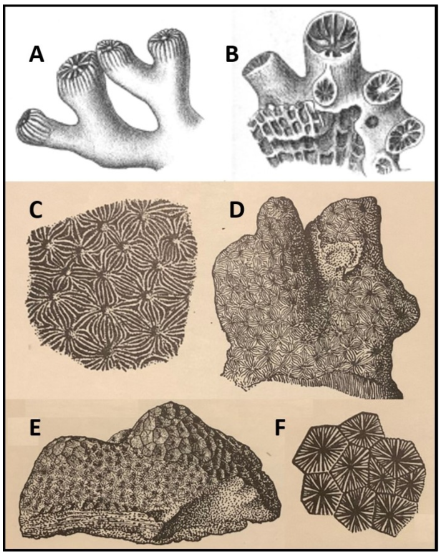


*Fig. 2: Typical Middle Jurassic corals, as reported by Tomes (1885) and Green & Donovan (1969) from the Combe Down coralliferous unit. A: Stylosmilia, B: Thamnocaenia, C and D: Thamnasteria and E and F: Isastrea. From Tomes (1885) and BMNH (1962).*


*Fig. 3: The Corsham Coral Bed ('roof bed') above the Bath Oolite, with Ancliff Oolite above. Brown's Folly site 10, near Bathford.*

The upper part of the Corsham Limestone, above the Ancliff Oolite (2 to 5 m thick), is the Bradford Coral Bed (0 to 2.5 m thick); this unit is developed across the area and as far south as a line from Hinton Charterhouse to Trowbridge. This coral unit is well exposed at Brown's Folly (site 8, Tucker 2023) and rests on a unit of large-scale cross-bedded oolite (cross-beds directed southwards, Figure 4). This coral reefal unit is also seen in old quarries around the top of Midford Hill (ST 763-594), towards Hinton Charterhouse (Green & Donovan 1969). Large masses of hard crystalline limestone showing ochreous cavities, commonly of the coral *Thamnasteria,* form patch reefs up to 2 m high, interfingering laterally with rubbly oolitic-bioclastic limestone. Many corals appear to be *in situ* (rounded masses up to 50 cm across), but there are lenses of coral debris too (Figure 5). Tomes (1885) listed 19 species of coral from this coral buildup at Brown's Folly.

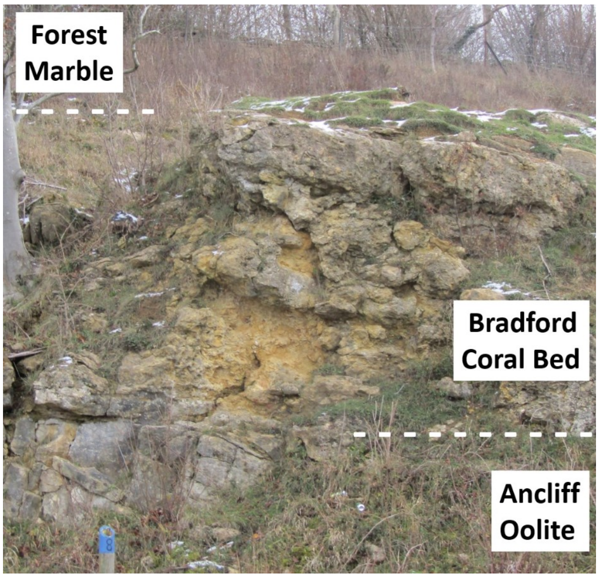


*Fig. 4: The Bradford Coral Bed occurring above the Ancliff Oolite, with largescale cross-bedding dipping to the right (south), and Forest Marble higher up the slope. Brown's Folly site 8, near Bathford.*

*Fig. 5: Broken fragments of platy coral from the Bradford Coral Bed.*

In polished surfaces, the corals are clear, and they commonly show the effects of boring by bivalves (Figure 6). In some cases, the outer margins of a coral colony are quite irregular on a mm-scale (Figure 6), with a scalloped appearance. This is probably the result of clionid sponges living on and boring into the coral skeleton. The breakdown of coral skeletons by a range of organisms (bioerosion), including parrot fish, is common in coral-reef environments today, and generates significant amounts of fine sediment. Thick-shelled bivalves (e.g., Figure 7), brachiopods and crinoids are common between the coral heads in the bioclastic-oolitic limestone.

*Fig. 6: Polished hand-specimen of a coral (probably Thamnasteria) with the internal network and growth lines just visible. Note the central 'blue-hearted' area of the coral, where the skeleton is composed of ferroan calcite, contrasting with the areas around with the 'rusted' orange-brown colour. Borings from lithophagid bivalves occur in the lower part of the coral (several filled with geopetal sediment below and calcite cement above), and shells of the bivalves still present. Note the irregular outer margin of the coral (upper left), adjacent to coarse sandy orange sediment, resulting from sponge borings. Sample 6 cm across.*

*Fig. 7: Large bivalve (6 cm across), similar to Plagiostoma, from the Bradford Coral Bed in a weathered ferruginous limestone. Brown's Folly, Bathford.*

**Isolated coral clasts, like geodes, within the Bath Stone**

The Combe Down and Bath Oolites are mostly uniform well-sorted oolitic grainstones, formed of sediment composed of ooids with variable amounts of shell debris (bioclasts). Cross-bedding is present, best observed on weathered surfaces, as a result of sediment transport by tidal currents and waves and the migration of sand-waves and dunes on a shallow high to moderate energy seafloor. There are burrow structures, likely from crustaceans and annelids. Larger fossils, however, are rarely seen; there are bivalve shells, several cm across, and many of these were burrowers. However, rarely, there are pieces of coral present in the Bath Stone, pebbles-cobbles randomly distributed. These clasts are eye-catching and conspicuous, occurring as empty cavities in the well-sorted oolitic grainstone, lined by calcite crystals (Figure 8), looking somewhat like geodes. They are generally 5 to 10 cm across and have a round to irregular shape. The calcite crystals form a near-isopachous (equal thickness) fringe around the margins of the cavities; it is noteworthy that there is no internal sediment present in the cavity.

*Fig. 8: Calcite-filled cavity ('geode'), cut from a recently extracted block of Bath Stone from Park Lane Quarry, Corsham, formed from the dissolution of a 10-cm sized coral clast, likely derived from a nearby patch reef. Note the bivalve fossil at the top, and the digitate coral lower right. Scale in mm; sample 8 cm across.*

That these cavities were originally a lump of coral is clear where the internal structure of coral is observed in the calcite at the margin of the cavity (Figure 9). Here, fine micritic sediment (lime mud) has infiltrated the coral skeleton, in all likelihood soon after the organism died. In addition, in some cases within the coarse calcite, the sediment fills of bivalve borings are present (Figure 10). Thus, it is clear, these large cavity features were once pieces of coral. The question, however, is when and why the dissolution of the coral took place.

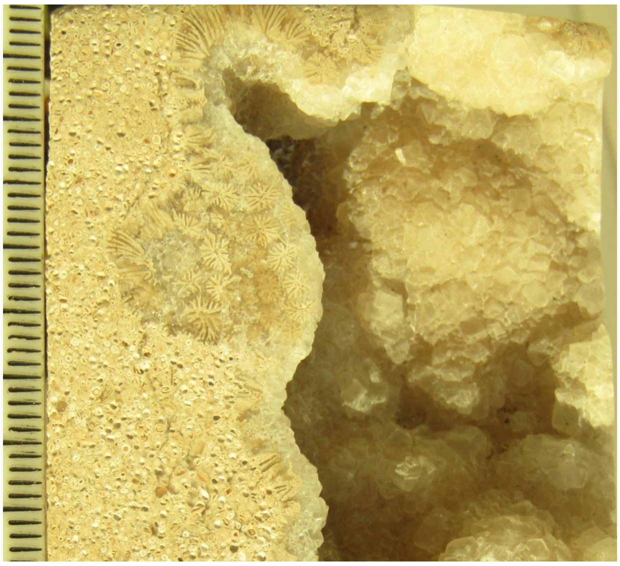

*Fig. 9: Close-up of the calcite crystals at the margin of a cavity formed from the dissolution of a colonial coral clast, where the coral septal structure is preserved through the infiltration of lime mud. Scale in mm.*

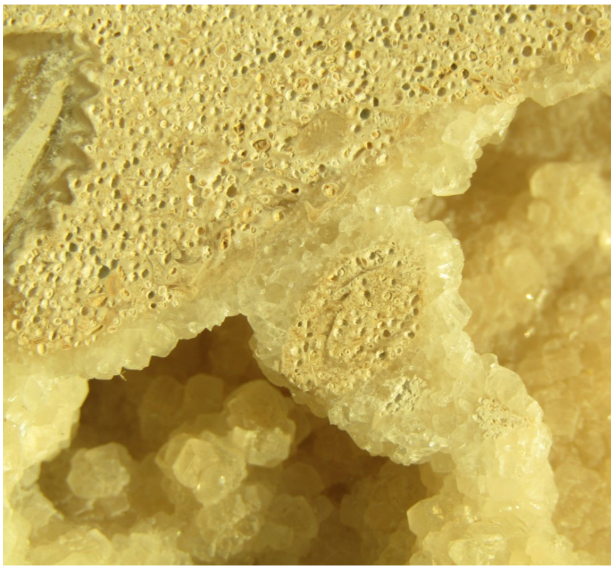

*Fig. 10: Close-up of a boring made by a bivalve (shells still present) and filled with ooids, into a coral (now preserved as coarse calcite crystals) from the margin of the cavity in Figure 8. Large bivalve fossil upper left. Field of view 30 mm across.*

**Coral skeleton preservation**

Modern shallow-water corals and those that lived in the Mesozoic are / were made of aragonite. These are scleractinian corals as opposed to the rugose and tabulate corals which existed in the Palaeozoic and were made of calcite. Aragonite is a less stable form of $CaCO_3$ compared to calcite; it is the mineral of many marine subtropical invertebrate skeletons in addition to corals (many bivalves, gastropods and green calcareous algae for example), and it is the mineralogy of marine ooids forming at the present time. Aragonite is also a cement precipitated in reefs today and in carbonate sands to form beachrock and hardgrounds in low latitudes. In time, however, especially through contact with freshwater, aragonite is either replaced by calcite or it dissolves out to leave a cavity, which may later be filled by calcite (then a cement) or even sediment, or just left empty (as in Figures 8 and 9). The replacement of aragonite by calcite is referred to as *calcitisation*, and then the finely-crystalline original coral aragonite skeleton gradually changes to a coarser calcite fabric, resulting in a loss of detail of the original coral structure. This process takes place across a thin migrating front with dissolution of aragonite on one side and precipitation of calcite on the other, to produce a mosaic of coarse calcite crystals. Some relics of the coral structure may be retained in the replacement calcite, through the presence of organic matter in the original skeleton. If the coral skeleton contains some sediment between the septa, then this will be preserved so that a former coral colony can be identified (as in Figure 9). The coral colonies in the Corsham and Bradford Coral Beds have mostly been replaced by coarse mosaics of calcite with some relics of the coral structure remaining; some do have open cavities though.

In a thin-section of coral from a Brown's Folly reef, the coarse calcite replacing the coral skeleton is clearly observed (Figures 11, 12). This thin-section has been stained with Alizarin Red S + potassium ferricyanide to distinguish between non-ferroan 'normal' calcite (pink) and ferroan calcite (blue). The latter type of the calcite contains iron ($Fe^{2+}$), reflecting precipitation in a reducing (anoxic) environment with the iron being released from clay minerals and organic matter. Non-ferroan calcite indicates oxic porewaters (or an absence of iron). Aragonite is especially susceptible to replacement and dissolution if it comes into contact with freshwater. Near-surface groundwater is usually oxic, but this commonly becomes anoxic with depth through decomposition of organic matter within the sediment. If there is much freshwater present then wholesale dissolution will occur, to leave a cavity, but if there is less water, or it is moving very slowly through the carbonate sediment, then replacement by calcite can take place with the calcium released from the dissolving aragonite used in the precipitating calcite. In the photomicrograph of Figure 11, it can be seen that the early calcite cement has a pink stain whereas the later calcite is blue (clearly seen where occupying the centre of a cavity); this suggests that the freshwater from which the calcite was being precipitated changed through time from oxic to anoxic.

The Corsham limestone coral beds generally have a yellowish-brown colour (seen in Figure 4), contrasting with the very pale, cream or white colour of the Bath and Ancliff oolites. The orange-brown colour is the result of oxidation of ferrous iron in the calcite to ferric iron, producing to limonite-goethite. In Figure 7, a bluish-grey colour is observed within the central part of a coral colony where ferroan calcite is still present. This feature, commonly seen in quarried or mined building stones, is referred to as 'blue-hearted' and is typical of limestones affected by near-surface weathering, the blue colour being the original subsurface colour and the surrounding / outer orange colour being the 'rusting' (oxidation) of ferrous iron.

As noted above, the aragonite of the coral is likely to have dissolved / been replaced by calcite on contact with meteoric water. This could have taken place soon after deposition, if there was a sea-level fall exposing the oolitic shelf, or during shallow burial if there was a

*Fig. 11: Photomicrograph of a colonial coral showing its poorly preserved state as a result of the replacement of the original aragonite by calcite. The coral has 2 bivalve borings (black), filled by dense lime mud (now micrite). Note that the staining by Alizarin Red S + potassium cyanide reveals an early non-ferroan calcite replacement (pink) followed by a later ferroan calcite (blue) filling cavity centres and replacing corallites. Thin-section from the collection of Ron Smith. Brown's Folly, Bathford. Field of view 1.5 mm across.*

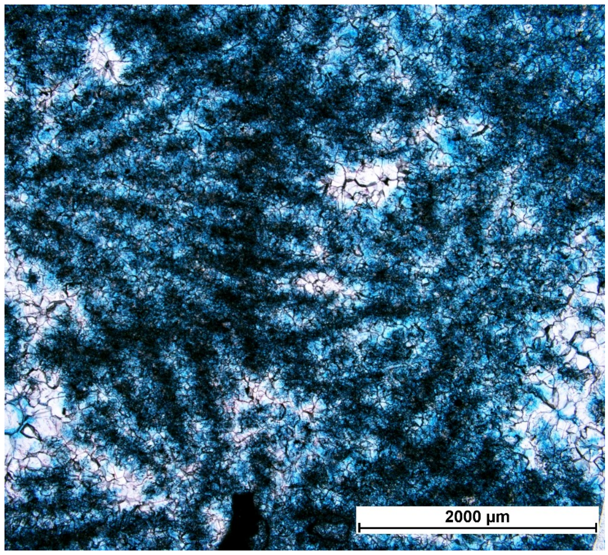


*Fig. 12: Photomicrograph of an Isastrea-type coral showing the septal arrangement, replaced by ferroan calcite (blue). Thin-section from the collection of Ron Smith. Brown's Folly, Bathford.*

change in porewater chemistry, from seawater to freshwater. This could have been induced through a drop in sea level, or uplift farther afield (in this case N/NW) allowing a hydraulic head to drive meteoric fluids into the subsurface. There is a disconformable contact between the top of the Corsham Limestone and the overlying Forest Marble for example which could be a subaerial exposure surface. The lack of sediment filling the coral cavities suggests the dissolution was not directly a surface effect, but likely to have taken place at several to many metres of burial. The host oolitic sediment was clearly cemented, since there was no later compaction / fracture of the cavities, but not so cemented that porewater could not travel through the rock. Bath Stone now has a porosity of around 20% (the porosity of a good oil reservoir or water aquifer), so fluid flow within the rock would certainly be expected. The other point of interest is that the cavities are empty and are not filled by calcite cement. This suggests that the dissolution of the coral aragonite took place from the outside of the coral inwards, and the reprecipitation of its $CaCO_3$ as calcite, replacing the coral margin, reached a point where the porewater became undersaturated with respect to calcite so that wholesale aragonite dissolution took place with no calcite replacement / reprecipitation, so that empty cavities were produced. This indicates that the flow of water was sufficient to carry away the Ca and $CO_3$ ions; these may well have been precipitated from the water as cements farther down the flow path.

The possibility that the coral clasts were dissolved out when the Bath Stone was uplifted to its present position in the last few 10s of millions of years seems unlikely. The Bath Stone, deposited some 166-168 Ma ago, was buried to around 500 to 700 m over time, and then from the mid Tertiary (20 million years ago) uplifted to its present position (Tucker 2022). The coral aragonite would not be expected to survive through such a long burial history, with changing pore-fluids and higher temperatures and pressures at depth.

**Summary**

The Bath Stone was deposited on a shallow shelf with high to moderate energy currents and waves where ooids were precipitated in abundance and bioclastic sand was produced from comminution of shells and other skeletal grains. Coral patch reefs existed here locally in slightly deeper water and corals were likely broken up by storms and wave action. The coral clasts in the Bath Stone are conspicuous and tell a story of deposition, coral aragonite dissolution and calcite replacement, producing attractive items for display on the mantelpiece.

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## Photo's from the Winter Social, 15th December 2022

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