BATH GEOLOGICAL SOCIETY

Journal

No 37, Winter 2019

Contents

Chairman's Report for the Bath Geological Society, 2018/19

2018

As we have not published a Journal since for almost two years, I have combined the last two year's programmes.

We started the year 2018, following the AGM, with Dr Daniel Field from the University of Bath discussing his research into modern birds and their dinosaurian ancestors and how they survived the end-Cretaceous mass extinction. We were unable to have a lecture in March owing to violent arctic weather in Northern Europe and our speaker was unable to travel from Germany. Fortunately the weather improved in April and we were able to hear Dr Michael Taylor, from the University of Bristol, talk to us about the scientific reasons for the extreme neck length of sauropod dinosaurs compared to modern mammals,

The May lecture by Dr Lucy Clarke, from the University of Gloucestershire was on the Antarctic Peninsula Glacial Change, made possible by the comparison of modern satellite data to a large amount of 1940's aerial photography. In June, Lisa McNeill, from the National Oceanography Centre of the University of Southampton reviewed the available geological and geophysical data of the Sumatran subduction zone and the related major tsunami and earthquakes in this area of Indonesia.

We continued into July with the earth's natural hazards with a talk by Dr Simon Wakefield, Cardiff University, on the 'Dangerous Earth' on which we all live. September's meeting was our annual joint meeting with the BRLSI, given by Dave Green, on the Earth's Oceans, Past and Present, and our understanding of the geological processes operating in the oceans.

October brought us another member of staff from the University of Bristol, Dr Heather Buss, who spoke to us about that critical zone between the treetops and where rocks begin to weather, and its importance in this time of environmental change. November's talk saw us return to palaeontology with Dr Aaron Hunter, University of Cambridge, speaking about new fossils discoveries in France and Morocco improving our understanding of the development of starfish and brittle stars in the Great Ordovician Biodiversification Event. Our last talk of the year was given by T.M. Gernon from the University of Southampton, concerning Diamond Eruptions and kimberlite eruptions.

Three field trips were organised during the year, our usual annual clean-up of Brown's Folly, and thanks to Professor Maurice Tucker for leading the trip and to our members who helped. Maurice was busy with the trips this year and took us down to Watchet to examine the Upper Triassic and Lower Jurassic sediments of the North Somerset Coast. The last field trip of the year was to Dead Maid's Quarry, Mere to see the Upper Greensand and Lower Chalk, and to help clean up this SSSI site.

I would like to thank Maurice Tucker for including Brown's Folly in the national GeoWeek listing, in early May.

2019

We started the year, following the AGM in February, with our Chairman for the last few years, Professor Maurice Tucker, giving us a talk on 'Limestones, Microbes and Viruses'. His talk explored the potential role of viruses in carbonate precipitation. This was followed in March with Dr Tiago Alves from Cardiff University with a talk on 'Oil and Gas Fields for the 22nd Century' on the dramatic changes in the more sustainable way these fields will be exploited and how governments, industry and the public are investing in new technologies and approaches to energy production. Keeping to the theme of 'energy', April's meeting was given by Dr. James Verdon, from the University of Bristol on the worldwide boom in shale gas and the history of 'fracking'.

Our May meeting brought us a little closer to ourselves with Professor Phillip Toms from the University of Gloucestershire, talking to us about Luminescence dating, Climate Change and Hominins, concentrating on where this has played a central role in past climate change and evolution and dispersal of Hominins. In June Dr. Mike Fowler from the University of Portsmouth gave us a fascinating talk on 'Granite Petrogenesis', highlighting recent work on juvenile granites that may represent unrecognised long-term crustal growth, with attendant implications for the evolution of the planet (well, bits of it anyhow…).

In July, Dr. Alison Mcleod from the University of |Reading gave us a talk on 'Climate, chronology and conundrums in the \north \Atlantic region' which may be giving us a look into the world's concerns regarding Global warming. Following our 'August' holiday from talks, we returned to an excellent talk by Professor Michael Benton from the University of Bristol, in September on 'The Dinosaurs Rediscovered: How a Scientific Revolution is Rewriting History'. He explained how the study of dinosaurs has transformed into a true scientific discipline, where new technologies have revealed secrets locked in prehistoric bones that no one could have previously predicted. Members were able to order and purchase copies of his book.

In October, Dr. Peter Wigley gave us a talk on our 'father of English geology' William Smth, concentrating on his activities in Somerset and the production of the early geological maps of this area, particularly of Bath in late 1799. Professor Malcom Hart, University of Plymouth, returned to us in November to talk about 'Jurassic calamari: death and preservation of fossil squid in the Jurassic rocks of the Wessex Basin'. He discussed the great importance of the cephalopods in the Jurassic ecosystem and the excellently preserved specimens found within the local area. The final talk of the year, in December, was given by our own member, Graham Hickman, on his time in the islands of Trinidad and Tobago and the continuing successful hunt for gas in the offshore region within the Columbus basin.

We have had a number of Field Trips this year, including our February clean-up of Brown's Folly, a visit to the Etches Museum and Kimmeridge Bay in Dorset. A few other field trips were made with other local societies.

We have had another successful year, with a range of topics for talks and fieldtrips. However, membership remains at about 60 members after a brief reduction during the year. We have had to keep to the smaller room for our lectures, as attendance is usually around 45. Once again, we have had an excellent selection of speakers and topics and I would like to thank our Committee Members for their help in suggesting and arranging the speakers.

Finally, I would like to thank all the committee members for all of their help and to Melissa Freeman for producing the Journal.

Our stand at the Festival of Geology, UCL, 2018 by Mellissa Freeman

Browns Folly, site 5. Some of the crew hard at work!. By Mellissa Freeman

Kaikoura Earthquake and after
By Isabel Buckingham

On 14th November 2016 at 2 minutes after midnight an earthquake started 60 km south of Kaikoura off the east coast of South Island New Zealand. The rupture spread north and lasted about 2 minutes. The strongest part of the quake was felt north of the epicentre near Seddon a few km south of Blenheim. This 7.8M quake was the second largest to hit NZ since European settlement and also caused damage in Wellington and Lower Hutt in North Island. In all 21 faults moved and in one case by >10m. What is less widely appreciated is that a tsunami followed, this being recorded by the tide gauge at Kaikoura, and debris lines. Initially the sea withdrew then water returned in waves. The highest 7m was recorded at Goose Bay which is south of Kaikoura from stranded debris. The drop was 2.5m complicated by the land lifting by 1m at the gauge site. At Goose Bay, unlike the rest of NZ there is no continental shelf, as the Hikurangi trench starts 1.6km offshore at a depth of <2,000m and extends north to just off Gisborne as it continues as the deeper Kermadoc trench. *This shows well on Google Earth.*

Image by Isabel Buckingham: Large Slide , full height

This trench had just been surveyed at the time of the earthquake. Part of the interest is the similarity with the sea bed off Japan. Unlike the area off the west coast of USA little is known of the frequency of earthquakes, so geologist look for turbidites off shore, raised sea beds and tsunami deposits. There seems for example to be a tsunami deposit from about 800 BP at Lake Grassmere a salt lake near Seddon The most recent orogeny is called the Kaikoura Orogeny and is known to have been at an increasing rate over the last 5 million years.

Many images can be found by searching *Kaikoura quake images.* The damage at Wellington led to several demolitions and put the container port out of action for 10 months. Kaikoura was totally cut off by road and rail and a naval exercise was diverted to evacuate many people, the town being a popular destination for marine wildlife watching. Water and sewage were affected. The main N-S road State Highway 1 goes through Kaikoura as does the rail link from Picton, the port for the inter-island ferry, to Christchurch. Innumerable landslides, damaged bridges, blocked rail tunnels and movement along faults damaged rail and road. Heroic efforts resulted in some land access being possible but the main road was not opened to "selected" day time traffic for 5 months. The innumerable aftershocks kept the rocks falling and many parts are still single lane with major engineering works underway. Whole hillsides have just slipped down and seem to be rebuilt from scratch. Innumerable smaller slips scar the hillsides. Some rotational slips, and wash outs add variety. Bridges are being replaced and the movement along faults smoothed out. Gullies scar the bare graded slopes despite efforts at planting.

Image 2: Gulley in slide by Isabel Buckingham

The hope/plan is to open the rail link by 1st December 2018 with a crew riding in advance of the train to check the track and deal with minor falls. In places the workers are protected by shipping containers piled two deep and filled with boulders. I observed some of the people with the stop go board using binoculars to check the slopes above. Unused equipment was being stored in the tunnels to protect from falling rocks.

Serious consideration was given to just abandoning the route and going inland, but then the Alpine fault would have to be dealt with. On places further north I could see where the railway ballast had been replaced having been washed away by the tsunami.

Kaikoura itself was up and functioning and tourists were back by road. I'd revisited Christchurch where I'd been before the earthquake and seen the changes and on going work. This really brought home to me the long term effects of an earthquake in which luckily only two were killed. All in NZ should keep an emergency pack at home for 2 days minimum survival. When my little granddaughter went to Nursery in NZ there was a weekly earthquake drill so they knew what to do.

We all see the news when it happens. The long term aftermath is not reported.

Image 3: tackling small slide by Isabel Buckingham

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Interesting Geological Localities in West Wales – a much Belated Postscript
By Charles Hiscock

In the autumn 2014 edition of the Bath Geological Society Journal, I wrote about three localities in west Wales, one of which was the coast between Newquay and Aberaeron. I described and showed photographs of the fascinating formations seen in the cliff a short distance south of Aberaeron harbour in which the Aberystwyth Grits had been folded and faulted. The structures, folding and faulting seemed so complicated that I was unable to explain what had happened and expressed the hope that someone reading the article could interpret the rocks for me.

In October 2017, I was on the field trip to Ogmore-by-Sea and Dunraven, on the Glamorgan Heritage coast, led by Dr. Geriant Owen of Swansea University. During our walk across the beach at Dunraven, I asked him if he knew the locality at Aberaeron and he agreed that he did and that he takes students there to look at the sedimentology of the Aberystwyth Grits along that section of coast. As a result of our conversation, I sent my photographs of the outcrop to him for his interpretation. His reply was very comprehensive and, now with his help, I have a much better understanding of the processes that had occurred at Aberaeron south beach.

Dr. Owen starts by emphasising that he is a sedimentologist! However, he goes on to say "It has been suggested that the folds had formed in unconsolidated sediment, near the surface, in response to slopes, as opposed to 'tectonic' deformation structures formed slowly in rock at depth. However, the structural geologists rejected the idea due to cleavage, veins and fracture patterns.

Image 1 is easiest to interpret. The folds are highly asymmetrical. Looking at the anticline in the centre left, the left limb dips gently to the left; the right limb is vertical (and in some folds at Aberaeron it is overturned, so dips steeply to the left) The right limb of the anticline is very short, and just to the right of the anticline the beds again dip gently to the left – so this is an anticline-syncline pair. And it looks as though there is another anticline-syncline pair at the right-hand edge in the middle distance. The folds are Z-shaped as you are looking at them. Rocks that are thinly interbedded tend to produce 'chevron' folds, which have very tight hinge regions – that is, they form a zig-zag pattern rather than gently curved folds. The hinge regions (where all the bending occurs) therefore often form faults if the folding is very tight.

Image 1: Large overturned anticline, compressed syncline and Z structure

These elements explain your other images, I think – chevron folds with one gently dipping and one steeply dipping limb, with an inequality of limb length and some fold 'cores' represented by faults. Image 2 looks a complete mess but the left side of the cliff in the background is a gently dipping limb and the steeply dipping rocks in the foreground are the steep limb (here slightly overturned); you can see the hinge region of an anticline just to the left of the cave in the centre. The jumble to the right of the central cave must be a syncline, and another anticline is visible at the extreme right end of the cliff at eye level. I think the hinge of this anticline forms the raised rock on the right hand side of the foreground platform. There may be a fault running across the image between the foreground and the cliff, offsetting the structures slightly.

Image 2: Overturned fold, highly compressed syncline with thrust above

Image 3, the annotated one, shows similar features. It shows that the syncline is really squashed. Not surprisingly, when such tight folding occurs, thrust faults are common, and I think this explains the discontinuity half-way up the cliff."

Image 3: Annotated to show intense folding and faulting

Dr. Owen concludes by calling this "Terrific stuff" and that he should be getting his students to make field sketches of the features as well as looking at the sedimentary features in the cliffs and the sea-defence blocks.

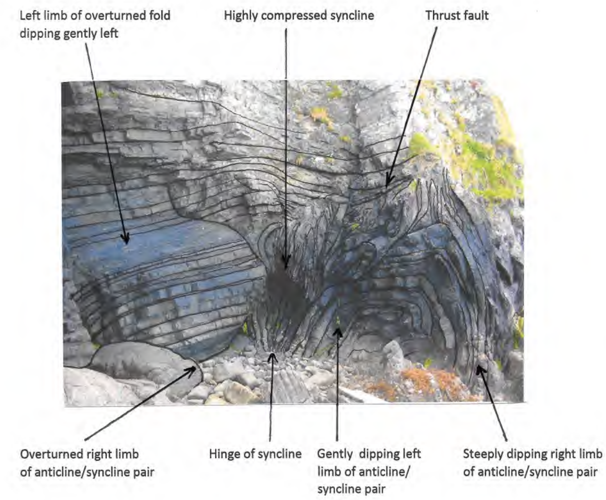

Image 4: Cationed to show structural details

I thank Dr. Owen for taking the time to interpret my photographs and for giving such a comprehensive summary.

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Kimmeridge Bay Field Trip 4th May 2019 led by Graham Hickman.
By Phil Burge

Introduction

A group of 15 members met at the car park at Kimmeridge Bay after an enjoyable drive through the country side on a glorious spring day. Having met, we walked eastwards to gather at the Wild Seas Centre where we reviewed the regional structural and tectonic history of southern England from the Variscan to the Alpine orogeny. This set the scene for the subsequent observations of the structural geology of the Bay and the origin of the thickness of the Kimmeridge Clay. Following this scene setting we walked back along the cliff top, past the car park and down the path at Gaulters Gap onto the beach. The first item of interest on the beach is the Mk25 pill box. A relic of the fears of an invasion during the early years of WW2. Apparently there were seven types of pill box designated, in true military fashion as Type 22 to Type 28.

Having contemplated on the potential efficacy of such a defensive structure the group reviewed the stratigraphy visible along the cliffs moving from east to west before being let loose to explore and, without the aid of hammers look for fossils. The Kimmeridge Clay is abundant in fossils. Although it is always exciting to find a fossil, our finds were as nothing compared to the fantastic exhibits to be seen in the Etches collection which was visited in the afternoon.

Structural Geology

There are two major structural features. The first is the fault system to the north, a product of the Variscan orogeny which occurred during the Carboniferous. It was likely reactivated during the Jurassic resulting in a downward throw to the south. Eroded sediments from

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land masses found in Wales, South East England and Scotland extending south into Yorkshire fed into a deep (+/-100m) boreal to sub-tropical sea, with the basin deepening as the fault moved. This resulted in, amongst other things, deposits of Kimmeridge Clay up to 550m in thickness.

The second major event is the folding along an east – west line during the Alpine orogeny of the late Cretaceous and thereafter. This tectonic event produced the anticlines of the North and South Downs and the syncline of the Weald. This tectonic event at Kimmeridge Bay formed a shallow dipping anticline as can be clearly seen in the cliff exposure.

Image 1: Car park at Kimmeridge Bay, Type 25 pill box, tank traps and formation dipping to the east

Kimmeridge Clay

The late Jurassic Kimmeridge dates from around 157 Ma to 150 Ma. The lower boundary is the Inconstans Bed of the Oxfordian and the Upper boundary is the Portland Sand of the Tithonian. Kimmeridge Bay is the type locality.

This formation is the major source rock of the North Sea Central Graben Oil Fields and is extensive across the UK from Dorset, (where it is exposed), north east towards Lincolnshire and out into the North Sea. The formation at Kimmeridge has been thermally immature for oil although historically 1 m thick highly organic black shale known as the Blackstone has been mined. Known locally as Kimmeridge Clay it burns with an unpleasant sulphurous smell. During the 19th century commercial mining extracted and refined paraffin wax.

The sediments are predominantly clays, calcareous clays, calcareous mudstones, organic-rich shale and limestone or dolomite beds. More detail is found in Fig 1.

Rock type	**Description**
Marl	Medium dark - dark grey
Shale	Medium dark - dark grey - greenish black
Shale	Dark grey - greenish black – olive black - laminated
Mudstone	Greyish black – brownish black
Limestone	Medium to dark grey or medium bluish grey
Dolostone	Olive grey or dark yellowish

Figure 1

Image 2: Interbedded mudstones and dolostones

Image 3: Close up of dolostone (45 cm thick) showing massive texture

Cyclicity

A distinct cyclicity is evident in the Kimmeridge Clay as measured by total organic carbon content and radioactivity levels, gamma ray logs from boreholes and magnetic susceptibility measurements. Within this sequence changes in magnetic susceptibility are due to changes in ferrocalcite concentrations.
Numerous explanations have been given for this cyclicity. The Etches museum states one option being changes in sea level. This was challenged during our trip by both Graham Hickman, our leader, and Professor Tucker.

The accepted interpretation is that the reason is due to Milankovitch cycles. Over known frequencies the Earths movement changes in terms of eccentricity of orbit, axial tilt (obliquity) and precession of the orbit. These variations in orbit and tilt occur approximately every 19ka and 23ka. Both effect climate. *Warming ocean temperature increases the volume of carbonaceous plankton (coccoliths) which are a major component of the dolostones.*

Interesting structures are exhibited on the exposed upper boundary of the “Flats” dolostone as shown in Images 4, 5 and 6.

Image 4: Dolostone clasts "floating in displasive sparry ferroan dolomite. Photo from author, description from Bellamy J., 1977. Subsurface expansion megapolygons in Upper Jurassic Dolostone (Kimmerdige, UK), Journal of Sedimentary Geology, Vol 47, No 3.

Image 5: Sinuous ridges running predominantly East –West on top boundary of Flats Dolostone

Beyond saying that these structures appear to be the consequence of some form of burial expansion, readers are invited to pursue their own further research!

Image 6: Portion of "megapolygon" of approximately 6 8 meters in diameter

Image 7: Side elevation of Dolostone showing distinctively different structure of structure

Fossil Hunting

The Kimmeridge Clay is richly fossiliferous, though it takes an expert of the calibre of Steve Etches to find and prepare exquisite specimens.

The dominant and easy to find fossils are Ammonites. These have generally been crushed. The Upper Kimmeridge can be classified using the Ammonite zone Autissiodorensis.

Image 8: Typical crushed Ammonites found in dark grey mudstone (Beach rubble)

Image 9: Poorly preserved bivalves

For truly superb fossils a trip to the Etches collection is well worth it. We did this after eating lunch on the beach, admiring those hardy souls braving a swim in the sea off of the convenient limestone ledges.

The range of fossils found at Kimmeridge includes, not only the common bivalves and Ammonites but larger species including various fish, (e.g. Thrissops; see Photo 10), marine reptiles including plesiosaurs, pliosaurs and ichthyosaurs. The state of preservation and the effort required to excavate and prepare the specimens is awe inspiring. A must see visit.

Image 10 above: Scales of Lepidotes fish (Etches Collection)
Image 11 below: Ray finned fish Thrissops (Etches Collection)

Image 12: Pliosaur vertebrae and paddles (Etches Collection)

Oil Exploration at Kimmeridge

This section was taken from Graham Hickman's field trip guide and an extract from *The Hydrocarbon Prospectivity of Britain's onshore Basins, DECC.,2013 pg. 8*

Following the award of the first prospecting license under the Petroleum Production Act. (1934), drilling was carried out during 1936-1937 at Broadbench, in Kimmeridge Bay with traces of oil noted on joints in grey sandstone in the Upper Jurassic, (Corallian beds; Sandsfoot Grit), at a depth of about 825 feet (250m). The well was plugged and abandoned at 943 feet (287m), still in the Corallian, (Osmingtom Oolite), as the limit of the rig had been reached. Twenty two years elapsed before the full significance of this discovery was appreciated. In 1958, shows of oil in the Upper Lias, (Lower Jurassic), sandstones from a well to the west of Radipole, near Weymouth, led to renewed interest in Kimmeridge Bay. Three wells were drilled as part of a programme; Broadbench 2 (later renamed Kimmeridge-1) in 1959, ENE of Broadbench-1. Oil was encountered at a depth of 1,880 feet (570m) in the Cornbrash Limestone, top of the Middle Jurassic. Core oozed oil from partially leached calcite veins and a series of production tests and acid treatments yielded between 30 and 4,300 bopd. The well was completed as a producer in the Cornbrash. Two other wells were drilled to the producing horizon to the east (Kimmeridge 2) and southwest (Kimmeridge 3), proving the extent of the oilfield. Kimmeridge 4 was an appraisal well drilled in 1960, to further test the geological structure, but it was terminated due to mechanical difficulties.

The field began producing in 1961 and following the discovery and successful appraisal of the Wytch Farm Oilfield, there was renewed interest in the prospectivity of deeper reservoirs in the area. In 1980, Kimmeridge 5 was drilled as an exploration well to test the deeper potential of the Kimmeridge structure in the Sherwood Sandstone (Lower Triassic), with the Bridport Sands (Lower Jurassic) as a secondary target. Weak gas shows and minor fluorescence were recorded throughout the Jurassic. The Sherwood sandstone, encountered deeper than prognosed, had weak soil shows but reservoir quality was significantly poorer than at Wytch Farm.

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Landscape and Geology of the Burren: Co Clare Ireland
By Isobel Buckingham

I first went to the dramatic landscape of the Burren as a student in 1968, and have returned several times. There was little change when I visited in 1973, but dramatic differences when I visited in May 2018. A great deal of information is found at http://www.burrengeopark.ie/ . The Irish know how to market geology with walks, information boards and a Centre. To the south east and abutting, is the Burren National Park, just under 2,000 hectares, bought by the Government before they ran out of money and run on traditional lines. More information can be found at http://www.burrengeopark.ie/.

A Cromwellian Officer described the country "as not enough water to drown a man, wood to hang one, nor earth enough to bury them. This last is so scarce that the inhabitants steal it form one another yet their cattle are very fat. The grass grows in tufts of earth two or three foot square that lies beneath the limestone rocks and is very nourishing". It is a fairly apt summary.

Image 1: Dryas octopetala usually a Boreal plant—Part of the May flower extravaganza in the Burren

The Carboniferous Limestone dips very gently to the south east, never more than 5 degrees, but often less. This area is a long way from the Variscan Front. A layer of the impervious Clare shales is found above the limestone, and on some hill tops the Gronagort sandstones form the summit area. This area has been glaciated several times, has Galway granite erratics and also from the most recent glaciation, the ice sweeping round from the north and heading west to the sea. Some of the higher ground may have been ice free during the last glaciation and the terminal moraine can be seen in the Shannon Estuary. There is a clearly marked alignment to striations and glacial deposits.

Traditional Karst scenery is better developed than in England, because of the large area and depth of Carboniferous Limestone and also the very gentle dip. One unusual feature is the Turloughs. These seasonally fill up with water in winter and drain away in the summer when rainfall is less. Some have peat development but the lush summer grazing is important in the cattle rearing economy. The largest is at Carran being 4.5km^2. After prolonged or heavy rain the Polje fills up to form the turlough, but when less wet the Castletown river flows over the surface before going underground.

Image 2: Folded limestone on Mullaghmore Burren National Park

Image 3: Edge of a turlough in May. Water was rapidly drying, but warm and I'd never seen so many tadpoles. A thin film of silt covered the hard rock.

Caves range from the very recent and superficial at the present shale/limestone boundary to well-developed systems with several levels, some under sea-level. Many are wet and prone to flooding.

Image 4: View from Mullaghmore to Lough Gealain

There are marked surface valleys in the limestone.

What you immediately see however is the limestone pavement, and in May the spectacular unique flora. What is not appreciated is that the limestone pavement has developed under a soil cover. The high CO^2 level in soil air facilitates the chemical erosion. In the Burren this soil cover was removed about 2,500 BC when the Beaker people cleared the wooded cover. Residual soil has been dated from the base of the grykes.

There is the strange sight of stone walls dividing fields that seem to consist just of limestone pavement. Mound walls are 30-80 cms high and 80 to 100 cms across. They date from the early Bronze Age 2,500 to 1,500 BC, rest on bedrock and seem associated with the Beaker People. The fields were small and irregular and aligned NW/SE. Slab Walls made from upended slabs of limestone predate the parish system but are more recent than the tumble walls. These are linear, made of stone and standing one or two courses high. They are associated with the ring and stone forts that date 400AD to C17th. Early Christian sites are often associated with a precious spring where a clay band in the limestone brings water to the surface.

Cattle traditionally are grazed on the hills in winter. There are no frosts, and in summer they are moved to the low ground to graze land that is flooded in winter. The desperate search for feed in winter means any tree shoots are nibbled down. No sheep have been kept here since about 1950.

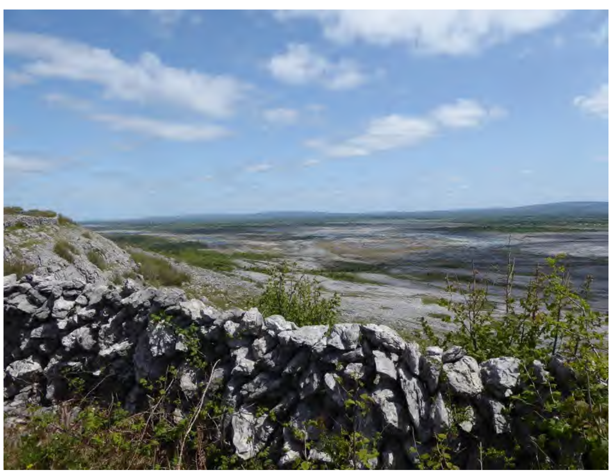

Image 5: View from Mullaghmore of bare limestone inside the national park

The general population of Carron was >1,000 in 1841 before the potato famine. In 2011, that figure had dropped to 106 and is still falling. It is the intense traditional grazing that led to deforestation in the area and kept the limestone pavement visible. It is reckoned the amount of pavement was twice present levels in 1841.

The average annual rainfall is approximately 1163mm p.a. Once tree cover was removed erosion of the thin soil, developed on glacial deposits, must have been rapid. So much slab limestone has been used in walls, monuments and forts it is hard to find the expected sculptures limestone pavement. In places limestone boulder erratics are left on the surface when all the smaller particles have been removed. On Slieve Elva there are boulders of Galway granite from an earlier glaciation.

A decreased population and changed agricultural practise has resulted in much recent growth of hazel shrub on areas previously exposed limestone pavement. This is from either a lowering of grazing intensity, or using a bred of beef cattle not able to thrive in these conditions on the winterage. Lack of summer grazing means the flowers grow without being trampled. Steps are being taken with EU funding, to encourage traditional farming methods to maintain the pavement. The feral goats do not help. Not only do they follow each other and jump over the wall at the same place, necessitating future repair, but they graze the good valley land the farmer wants for his stock.

Image 6: Feral goats are a problem

The limestone pavement is the result of Bronze Age clearance and a very particular agricultural regime. The unique flora is a mix of Ice Age remnants, woodland floor and southern European. This area now depends on the visitors, so do visit.

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My Top 5 Geological Sites of Pembrokeshire
By Megan Taylor (Year 13 Wells Cathedral)

Pembrokeshire is a small, yet beautiful county located in Southwest Wales on the coast of the Irish Sea. The county is home to Pembrokeshire Coast National Park designated in 1952, which is the only coastal national park in the United Kingdom. The Pembrokeshire Coast National Park was also recently ranked the second best coastline in the world by the National Geographic magazine and thousands of tourists visit it every year to visit its stunning beaches, castles and seas. However, there is more to Pembrokeshire than beautiful scenery and high levels of biodiversity. It is also renowned for its spectacular geology with a wide range of lithologies from different geological time periods. Travelling from the south of the county to the north it is possible to travel back in time through cross millions of years of geological history from Devonian and Carboniferous to Silurian, Ordovician, Cambrian and even Precambrian periods. This has led to the Pembrokeshire Coast becoming one of the UK's most important venues for geological fieldwork and research. My mum's family is from Pembrokeshire and I've been there every summer since I was born, but it was only recently when I started A Level Geology in 2018 that I started to realise how diverse its geology. In the Easter holiday and this summer, I spent a lot of time re-visiting my favourite places and looking at their different geological features using advice from my school teacher and a helpful handbook (George, 2008). This has allowed me to write this article with my Top 5 Geological Sites of Pembrokeshire shown in Figure 1 below. I hope you enjoy it!

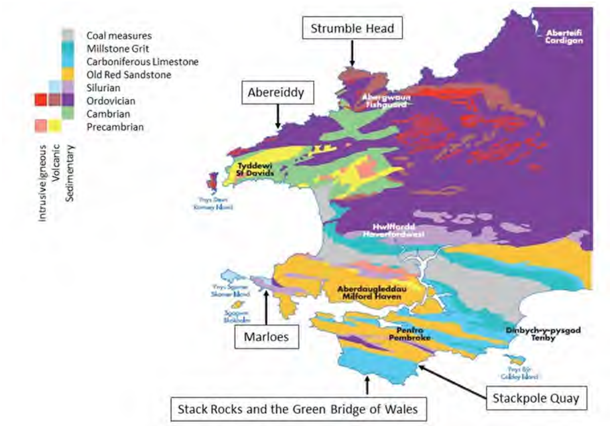

Figure 1: The Geology of Pembrokeshire, based on a map produced by the Pembrokeshire Coast National Park Authority

Image 1: 'Tuning fork' graptolite. The didymograptus murchisoni' graptolite is the most abundant species found at Abereiddy Bay found in the Ordovician Shales there. (Source: https://commons.wikimedia.org/wiki/

Image 2: The Blue Lagoon at Abereiddy Bay. Once an old slate quarry this sheltered harbour is now an SSSI and a popular spot for swimming, diving and cliff jumping with holidaymakers. (Source: https://www.countryfile.com/go-outdoors/days-out/day-out-abereiddy-bay-pembrokeshire/)

Abereiddy Bay

Abereiddy Bay is located in North Pembrokeshire (Figure 1) and has become a popular spot in recent years for geologists and holidaymakers alike. In the 19th Century, Abereiddy was the site of an important slate quarry employing many people locally. However when the slate production ceased in 1901 the quarry was blasted open to make a harbour entrance. This flooded quarry, a designated SSSI for its marine ecosystems, has now become known as the Blue Lagoon and is a popular diving, swimming and cliff diving area, a place my brother and I have visited many a time over the years. Abereiddy has also become known for its abundant collection of graptolite fossils, a colonial planktonic creature common in the Lower Paleozoic. Graptolites are very important zone fossils used in relative dating methods due to their high abundance, rapid evolution, well preserved fossils and that they were facies-free when alive which has led to them becoming geologically widespread. The most abundant graptolites at Abereiddy are the Tuning-Fork Graptolite, Didymograptus murchisoni. This species existed for a relatively short period of time, during the Middle Ordovician, between 470 to 464 mya. The graptolites at Abereiddy are found in the Ordovician Black Shales between the slate and volcanic rocks on either headland of Abereiddy Bay which form the fold limbs of the asymmetrical Llanrian Syncline, the axis of which is found at the southern end of the bay.

Stack Rocks and the Green Bridge of Wales

This part of the Pembrokeshire Coast National Park is located in the Castlemartin Artillery Range in South Pembrokeshire (see Figure 1). It is still actively used by the military for training purposes, and as a result the land is not fertilised and is very biodiverse. It is designated as a Site of Special Scientific Interest (SSSI), a Special Protected Area (SPA), and a Special Area of Conservation (SAC) to protect its rich geological and fossil heritage. The area is comprised of high, dramatic Carboniferous Limestone cliffs forming some of the most famous geomorphological features in the UK including wave cut platforms, stacks, blow holes and limestone cave systems. These cliffs are also very important for wildlife as they provide habitats for vast colonies of seabirds such as guillemots, razorbills and fulmars and nesting sites of choughs, ravens and peregrines. This area is also very well known for rock climbing and it is quite common to see a person scaling vertical 40m cliffs, formed by differential marine erosion along vertical joints and small faults, during the summer months. The Green Bridge of Wales is an almost textbook example of a natural sea arch with a span of roughly 25m. This arch is mostly massively bedded Carboniferous Limestone, known as Stackpole Limestone, with interbedded mudstone. Eventually this arch will collapse to form two sea stacks due to weathering and erosion by the wind, rain and, of course, the sea with its powerful wave action. I've visited this spot in very stormy weather, where the winds are so strong it's tricky to stand up and the spray from the waves drenches you as you near the edge! Stack Rocks is located about 300m away to the East and is an example of two limestone pinnacles known as the Elegug Stacks. 'Elegug' is the Welsh name for guillemots. There is a fault that separates the two stacks which downthrows to the East. This is shown by a prominent palaeokarst on the surface of the larger stack while it is also visible in the centre of the smaller stack.

Image 3: The sheer limestone cliffs near Stack Rocks. (Photo taken by the author, 21/04/19).

Strumble Head

Strumble Head is located in North Pembrokeshire, West of Fishguard (see Figure 1). This area is known as the Pencaer Peninsula, though it isn't actually a peninsula, with the Strumble Head lighthouse creating a focal point on the coast. This area is part of the Strumble Head Volcanic Group and compromises a mixture of subaqueous felsic tuffs, rhyolites and felsic-mafic pillow lavas which are interbedded with black shales and turbidites.

Image 4: Pillow Lava at Strumble Head. (Photo taken 13/08/19).

These rocks were formed in an elongated caldera with the southern margin marked by the Fishguard-Cardigan Fault. The volcanic and sedimentary rocks of this area are both interrupted by dolerite and gabbro intrusions which occurred at the same time as the volcanic activity. At the Strumble Head lighthouse there is a large area of pillow lava. Pillow lava is formed when basalt lava is extruded from fault-defined submarine fissures. When the lava comes into contact with the sea water it cools rapidly forming concentric fractures and a glassy outer layer which then acts to insulate the inner pillow so it cools more slowly. As this outer glassy obsidian layer insulated the inner pillow, it also trapped gas volatiles which were exsolved from the lava creating vesicular texture.

Image 5: Vesicular texture found at Strumble Head, below the car park, at the large pillow lava area. (Photo taken by the author, 13/08/19)

Image 6: Amygdaloidal texture found at Strumble Head, mineral unidentified. (Photo taken by the author, 13/08/19)

Some of these vesicles were then later infilled by precipitated minerals such as calcite or chlorite creating an amygdaloidal texture however many of the amygdales were then later removed by weathering.

Stackpole Quay

Stackpole Quay is located in South Pembrokeshire and is owned by the National Trust. It is part of the Stackpole Estate SAC, SPA and has multiple SSSI designations for both its geology and biodiversity. This area of coastline is particularly interesting as there are many faults and folds and dramatic coastal features which show the tectonic history of the area.

Image 7: Syncline in the Visean Limestone at the Northern Bay of Stackpole Quay with fold axis running SEE to NWW and plunging to the SEE. (Photo taken by the author, 23/04/19).

At Stackpole Quay it is possible to see the boundary between the Old Red Sandstone containing conglomerates and sandstones and mudstones laid down in the Devonian and Silurian periods between 408-427 Ma and the Grey Carboniferous Limestone (from the Visean Age) containing coral fossils, brachiopods, fishes, bivalves and many other less abundant fossils. This shows that at this time the area was submarine in a tropical latitude due to the presence of the corals. Also at the North Cove of Stackpole Quay there is a dramatic exposed syncline which, along with the 2m fault breccia and gouge (in the Quay Harbour) and the slickensides, present both here and at nearby Barafundle Bay, show the forceful tectonic activity that this area underwent in the Variscan Orogeny in the Late Paleozoic and subsequent tectonic forces after this event.

Image 8: Solitary Rugose Coral fossil in the Carboniferous Limestone at Stackpole Quay. Approximately 2cm in diameter (Photo taken by the author, 23/04/19).

Marloes Beach

Marloes is a long, sandy, tidal beach located in West Pembrokeshire which is about 1.5 km long and very popular with tourists, nature lovers and geologists alike. This beach is located near the Deer Park at Martin's Haven where the boats for day trips to the Skomer Island Marine Nature Reserve and Skokholm just offshore and Grassholm lying 7 nautical miles out to the West, leave to see the internationally important seabird colonies on the islands. There are over 350,000 nesting pairs of Manx Shearwaters alone on Skomer, and 39,000 pairs of gannets breeding on Grassholm. The area is also famous for its Atlantic Grey Seal colony, and in the Deer Park it is possible to see Grey Seal pups in the Autumn with good eyesight and a pair of binoculars!

Marloes is very important for geology as the lithology changes several times along the beach, allowing several different rock types to be examined in a relatively short walking distance. Starting at the NW end of the beach there is Matthew's Slade, a small grassy hollow comprised of the Silurian Coralliferous Group. Moving along the beach to the SE the Silurian lithology changes to Grey Sandstone, then the Skomer Volcanic Group containing many small dyke intrusions, and then a larger intrusion of Microgabbro. This is then followed by the Coralliferous Group and the Grey Sandstone again, and southern end of the beach the headland is made of the Ordovician Albion Sands Formation. There are also several faults along the beach all of which run from SWW to NEE, parallel to the bed direction.

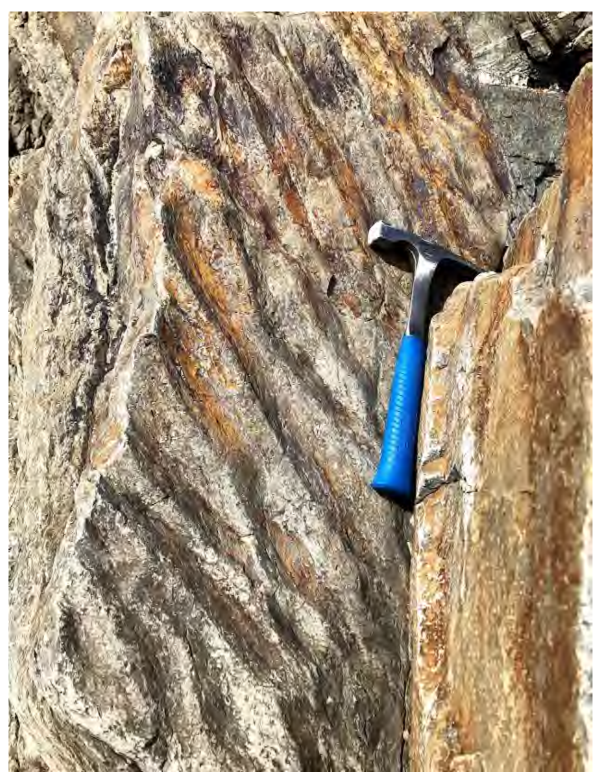

Image 9: Symmetrical Ripple marks in the Ordovician Coralliferous Group. Hammer for scale. (Photo taken by the author,

Image 10: The Three Chimneys feature at Marloes Sands. (Photo taken by the author, 20/04/19)

As there are so many things to talk about at Marloes, I am going to focus on a couple of places. Firstly, as soon as you reach the beach it is very easy to spot one of the many large Coralliferous boulders which litter the beach showing clear symmetrical ripple marks. This shows that at the time of deposition this area was submarine in a tidal area, not so different to today! Further down the beach is a famous feature known as The Three Chimneys which are three, almost vertical, beds of weathered ferruginous sandstones. The bases of the sandstone show low level load casts. In the early Silurian, Marloes was located near the northern edge of a large landmass with several Basaltic Volcanoes on nearby Skomer Island. This explains the marine features such as the symmetrical ripple marks and also the minor and major intrusions of the area.

Pembrokeshire is such a special place. It is both geodiverse and biodiverse. For the geologist it provides a fantastic opportunity to see evidence of several different paleoclimates and geological features in one relatively small area. For me, Pembrokeshire is a really special place for all of these reasons and several personal ones. It is a landscape I've grown up knowing, but I've seen it with different eyes since I started my A Level Geology course. It is really easy to see why this area was been designated as the UK's only coastal National Park, and hosts so many SSSI, SPA and SAC designated sites. It is an extraordinary place, beautiful, awe-inspiring and fascinating. I hope you will consider visiting it to explore it for yourself!

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O'ahu, Hawaii. May 2018
By Mellissa Freeman

The Open University Geological Society ran a trip to Hawaii that I was lucky enough to be on in May 2018. We spent a few days exploring the geology on O'ahu before heading on an un-successful lava hunting quest to Big Island. We arrived just after the large earthquake and the start of fissure eruptions that dominated the news for a few weeks. Anyway, it's not all about volcanos! This is just a whistle stop tour of some of the locations we visited along the south and west of the island.

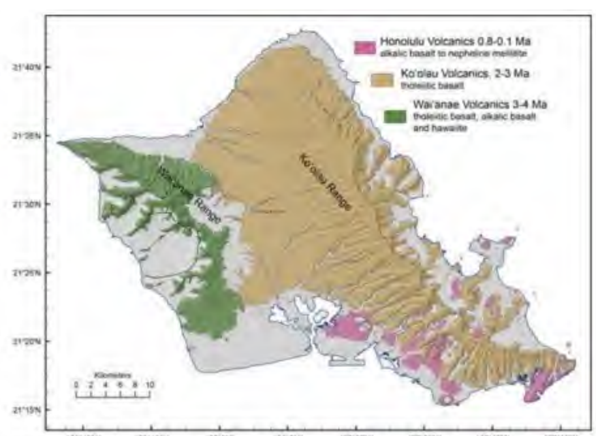
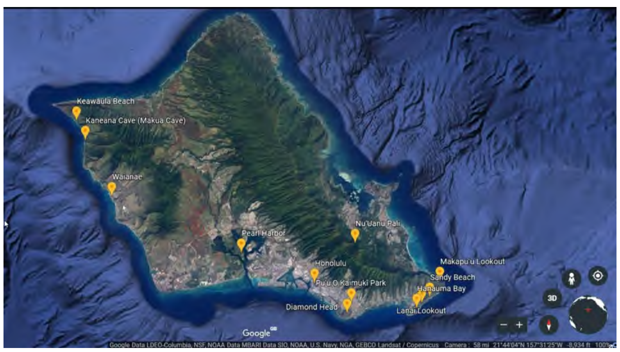


Figure 1. The island of O'ahu, Hawai'i, showing the distribution of principal physiographic and geological units. The Wai'anae and Ko'olau ranges represent the remnants of individual major shield volcanoes.

O'ahu is the third largest of the Hawaiian Islands and is known as 'The Gathering Place'. The island is made up of two deeply eroded shield volcanos; these forming the mountain ranges along both sides of the island (east and west). Wai'anaea is the oldest and is on the west of the island. It would have risen above sea level approximately 4 MA ago producing mainly alkalic basalts before becoming dormant. A rejuvenation phase started approx. 2.9 – 2.75MA before going extinct.

Ko'olau runs along the east of O'ahu and started erupting around 2.7MA ago just as Wai'anaea became extinct. Over time there was a series of inflation and deflation episodes at this volcano. It is thought that this caused the east side of the island to become unstable causing one of the largest landslides in Earth's history, (that we know of), with debris travelling some 120 miles into the Pacific Ocean; there would have been tsunami as a result. The scene may have been similar to what we have seen recently in Indonesia with the devastating landslide at Anak Kratatoa and the tsunami it generated. The last major activity was approximately 1.8MA ago. This was then followed by vigorous rejuvenation episodes approximately 850,000 years ago that produced the Honolulu Volcanic Series. The largest craters formed include Punchbowl, which is now a military cemetery, Sugarloaf (Pu'u Kahea), Tantalus Peak (Pu'u 'Ohi'a), Roundtop (Pu'u 'Ualaka'a) and Diamond Head (Le'ahi). Running through the middle of the island is the Leilelua Plateau.

Here are some of the locations we visited.



Southern coast of O'ahu

Diamond Head:

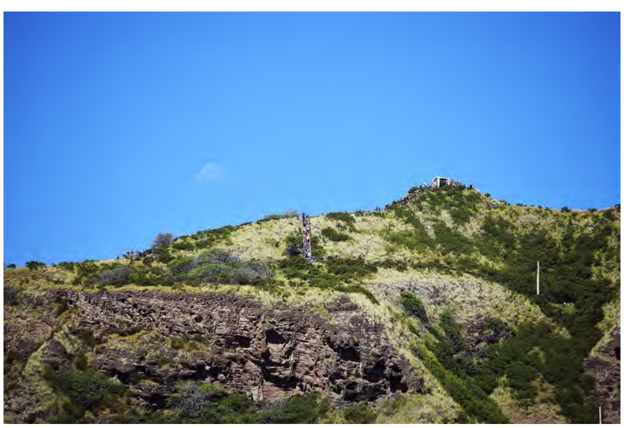


Image 1: View from the car park of the steps leading up the well-known local landmark Diamond Head – as you can see it is very popular with tourists! We were standing in the centre of the crater.

Diamond Head sits 761 ft above sea level and is a tuff ring associated with the system of cones, vents and flows that are collectively known as the Honolulu Volcanic Series. It was formed during the post shield stage of Ko'ola Volcano and has an estimated age around 4 to 500,000 years. The broad crater was formed around 300,000 years ago during a single eruption. Diamond Head gets its name from a group of 19^{th} century British sailors who through the crystals shining in the rock that makes up Diamond Head were actually diamonds. In reality, hot water and steam circulating through the ash beds dissolved the calcite found in fragments of reef limestone that had been incorporated into the volcanic debris – this then precipitated out to form calcite crystals.

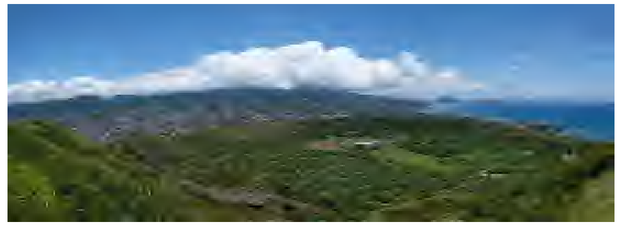


Image 2: View from the top of Diamond Head following the climb to the top

Hanauma Bay:

Hanauma Bay is a small inlet formed in an old flooded volcanic crater in the South East of O'ahu. The inner part of the bay, recently designated a marine sanctuary, has a coral reef that nearly reaches the shore making it a popular snorkeling spot. It has a white sandy beach that is backed on one side with volcanic ash deposits with a small exposure of green sand near at the outcrop edge made up of tiny olivine crystals (see pic). Some glacial deposits are to be found on the right hand side of the bay (looking out to sea). These are sand blown deposits, (aeolianites), which were deposited around 10,000 years ago as a result of sea level being lowered because of glaciation in the northern hemisphere. You can clearly see plant roots is this deposit.

Image 3: plants roots in the glacial deposits at Hanauma Bay

Image 4: Green olivine rich sand on Hanauma Bay

radiocarbon dating has been done in this area on some of the volcanic rocks with ages ranging from 32,000 to 7,000 years. Some of the ash deposits contains blasted bits of reef material from around 7000 years.

Lana'I Lookout:

Lana'I lookout is on the southern flanks of both Koko & Kahauloa craters, within the Koko Rift Zone and is within the region where the most recent volcanic activity on O'ahu has taken place. The volcanoclastic sediments found here have been analysed and found to have come Kahauloa Crater. These sediments show evidence of explosive, hydromagmatic volcanic activity with each explosive event sufficiently violent to fragment lava into sand-sized particles called pisolites (small pellets). The larger pea sized pellets are called accretionary lapilli. Formed from clumping of ash by falling raindrops/ moisture.

Image 5 & 6: Ash deposits at Lana'I Lookout

More evidence of this explosive activity can be found a little further along this beach. There are large fragments of old coral reef that have been ripped up and incorporated into the ash deposits. These were quite spectacular. I don't think I have ever seen anything quite like it.

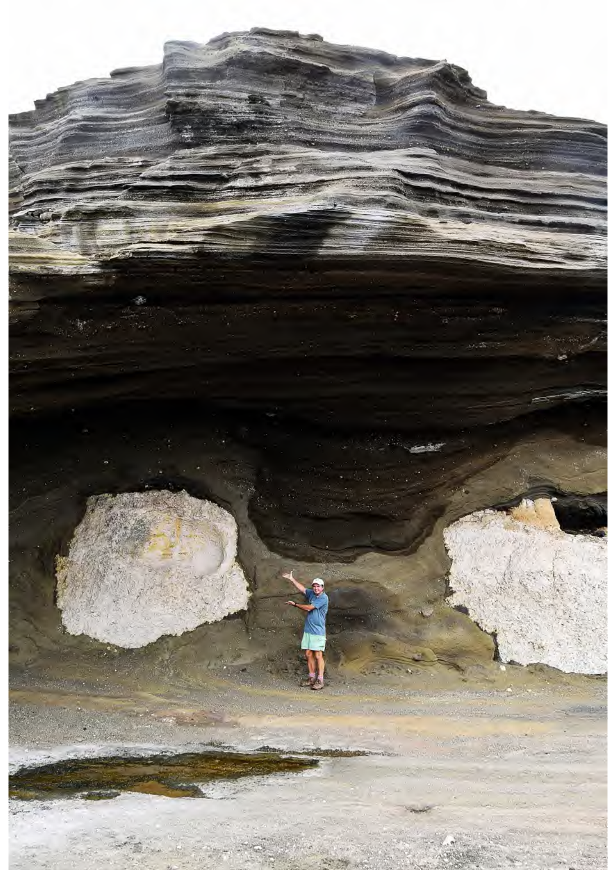


Image 7: Large coral fragments with Prof. Scott Rowland, our trip leader, for scale.

Below are some of the coral close up.

Image 8 & 9 are fossil corals within the ash deposits at Lana'I lookout

Western coast of O’ahu

Wai‘anae:

The Wai’anae mountains sit along the west / south west of Oahu. At one time the shield’s summit caldera was approximately 4.5km wide. The Wai‘anae mountain range has a south to north spine, which is made up of tholeiite basalt lava flows cut across with more resistant dykes forming the oldest terrain on the island.

We stopped just outside of a naval comms base close to the town on Waianae to get some idea of the scale of the caldera. We couldn’t get any closer to actually look at the rocks as it was all fenced off so we were relying on Scott. From our vantage point we could see the remnants of the caldera. There is a gravity anomaly here which indicates the location of the magmatic centre of the volcano. The rocks here are also all dipping away from this central point. In its youth, this volcano would have been approximately 3km in height which is difficult to imagine now.

The small peak in the centre of the photo below is called *Mauna Kūwale “Mountain standing alone”.* The top layers of rock are rhyodacite and are around 3.3ma – possibly formed by crustal melting. There is a finer layer of lava on the top that is compositionally different indicating a regime change between pre and post caldera formation.

Image 10: Centre of the photograph is the small peak “*Mauna Kūwale*” .

Makua Cave:

Makua Cave (or cave of the God Kāne) is a sea cave rather than the expected lava tube. It was formed around 500,000 years ago when sea level was approximately 30m higher than today during the Ka’ena highstand when ocean waters would have exploited fractures to open a passage which has grown to approximately 450 feet long, 20 feet high**.**

Image 11: Inside Makua Cave

Just as you enter the cave there are large rounded boulders (6.7m high) that have been cemented in place by lithified sand and above these boulders is a layer crumbly clinker followed by a layer of basalt. All of this is cross cut by tholiitic dykes which are light grey in colour and are compositionally similar to the country rock. Remnants of older fragmented country rock can be found on the beach just across the road from the cave.

Image 12: one of the visible dykes at the entrance of the cave

This whole area lies within the north west rift zone of wai'anae volcano which extends nearly 70 miles from the caldera to the ocean floor, just north west of the older island Kaua'i. Only about 15 miles of this rift zone are above sea level.

Keawa'ula Beach:

The last stop was to Keawa'ula Beach. This is also known as Yokohama Bay after a Japanese fisherman who was a regular visitor to the beach in the early 1900's. Keawa'ula also means red harbour. This beach sits at the very end of the Farringdon way which is the main coastal road on the west coast of the island. Beyond the road is an old railway track, now just a dirt track that leads to the most northern point on the island. The shoreline here is rocky. At one end you have a raised reef terrace composed of fossilised corals, coral rubble & shell fragments. Just above the corals is a thin layer of calcareous sandstone. Parts of the reef have been buried by (now cemented) sand from the nearby beach and dunes.

Image 13: the group fossil hunting on Keawa'ula Beach

Image 14: fossilised coral

It doesn't take long before we are back to igneous rock – just a little further along the beach there are a lot of basalt with cross cutting dykes.

Image 15 & 16 show some of the weather dykes on the foreshore

This was the last stop on our Oahu trip before we caught a plane to the chaos that was awaiting us on "Big Island" where Kilauea had woken up making headlines all over the world. That is another article for another time.

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Field Excursion to the Vale of Glamorgan Coast, led by Dr.Geraint Owen of Swansea University on Saturday 7th October 2017
by Charles Hiscock

Thirteen members of the Bath Geological Society met at the eastern car park in Ogmore-by-Sea, on the Vale of Glamorgan Heritage coast, in a blustery wind which was driving drizzle and heavier showers in from the sea. After dressing as best we could against the weather, the party walked down the slope to the cliffs which lie at the back of the beach. The cliffs are a series of stepped bedding planes in the Carboniferous Limestone, ranging from about a half to a metre in height, separated by thin beds of mudstone. The car park at the western end of Ogmore-by-Sea marks the start of the Carboniferous Limestone outcrop which is exposed in the cliffs and at the back of the beach for about 1 mile to the south east until it is overstepped by the early Jurassic marginal Lias formations. The unconformity between the Triassic and the Jurassic is not seen on this stretch of coast

Image 1: Carboniferous limestone bedding

The Carboniferous outcrop extends inland in an easterly direction and, apart from a short outcrop of the Blue Lias south of Bridgend, forms the southern boundary of the South Wales coalfield. At the top of the cliff section below Ogmore, the beds of the High Tor Limestone Formation (339 – 343 mya) are quite thin and lie on top of the much thicker beds of the Gully Oolite (343 – 352 mya) which extend in almost flat ledges towards the sea. Both formations were formed in warm, shallow seas with limestone deposited on shelves and slopes (image 1). The top of the bed forming the wide ledge is highly fossiliferous, showing many fine specimens of corals and brachiopods. The sea worn surface had exposes the fossils and many were in cross-section so that, particularly in the corals, the structures were clearly seen (images 2, 3).

Image 2: Coral assemblage

Image 3: Rugose coral assemblage

One particular coral, a *Siphonophyllia* species, had a bend in it of about 90 degrees, telling us that it had grown to approximately 22cm and had then toppled over and continued to grow a further 20cm or so (image 4).

Image 4: Large bent 'Siphonophyllia'

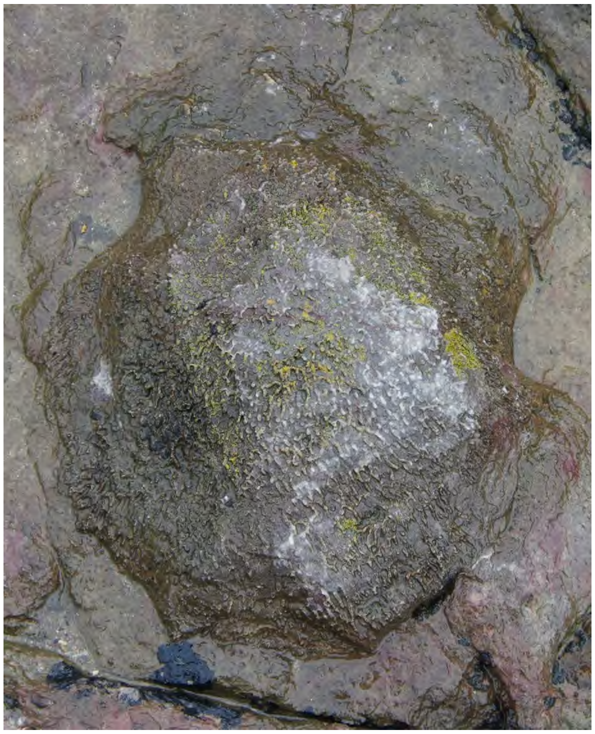

Image 5: Colonial coral 'Syringopora'

Image 6: Rugose coral 'Michelinia'

Also on the bedding surface were specimens of colonial corals *Syringopora, Lithostrotion* and *Michelinia* (images 05, 06). The large brachiopods on the bedding plane were mostly productid brachiopods specimens but what was particularly interesting was seeing a specimen in cross-section, showing that both valves lay in a concave fashion, rather than being concave/convex (image 07). Also on the bedding surfaces were many trace fossils, mostly of burrows of varying sizes, and clearly displayed specimens of *Zoophycus* (image 08). The fan shaped marks on the bedding surfaces are considered to be feeding traces of the tentacles of an organism which lived in a cylindrical, vertical or sub-vertical burrow and waved or spread the tentacles out to extract food from the substrate.

Image 7: Productid brachiopod in cross section

Image 8: Trace fossil 'Zoophycus'

The Carboniferous Limestone of the Glamorgan coast, much like other localities in the Carboniferous, shows evidence of erosion by water during the Triassic. In the High Tor Limestone an almost vertical 'tube' sectioned by the erosion of the cliff (image 09) shows red staining of the beds and ends in a vug at the base containing red Triassic mudstone with mineral deposits around the edges (image 10). It is assumed that the 'tube' went much deeper into the limestone but we were only able to view the top 3 or 4 metres. A few metres east another example contained baryte with crystals of galena. During the Triassic which had a predominantly arid climate, the Carboniferous mountains, possibly as high as 15000 feet, were eroded and formed large deposits of conglomerates and breccias which were swept down by flash floods during seasonal very wet periods onto the eroded surfaces of the limestone. The boundary between the Carboniferous Limestone and the Triassic conglomerates represent an unconformity of approximately 150 million years. Here, on the Glamorgan coast, the beds are conglomerates of Triassic marginal facies of the Mercia Mudstone

Group (200 – 210mya) are roughly equivalent to the Dolomitic Conglomerate on the south side of the river Severn and Bristol Channel. At Ogmore, the stone is not dolomitised and is a coarse mix of limestone clasts draped over the stepped beds of Carboniferous Limestone as a tongue for about 200 metres or so along the coast. The deposit had been formed as the result of severe flooding driving the limestone debris down a steep-sided wadi (dry river bed) on the edges of an island in the Triassic period (image 11).

Image 9: Karstic tube in limestone

Image 10: Triassic deposit in karstic tube in limestone

Image 11: Triassic breccia on Carboniferous limestone

Walking to the east along the top limestone bed for about 200 metres brought us to another unconformity where the Carboniferous Limestone is overlain by the Sutton Stone of lowest Jurassic, marginal facies of the Blue Lias (190 – 197mya). At the end of the Triassic period, sea level had risen, flooding the Mercia Mudstone deposits. During the early Jurassic, the marginal facies were developed around areas that were islands of Carboniferous Limestone, forming rocky shorelines of coarse breccias and conglomerates. Along the cliff top, erosion had disrupted the Blue Lias bedding so that it was seen as loose blocks of shelly limestone breccia emerging from the grass. Within the limestone were many small pebbles of sandstone and limestone, many displaying flask-like borings of the bivalve *Lithophaga* species (piddock), with fragments of corals and bivalves. Similar borings were also seen in the top surface of the Carboniferous Limestone on which the Blue Lias had been deposited. As we walked eastwards, the Carboniferous Limestone dropped progressively downwards to the south east, reflecting the relief on the unconformity surface, while the Sutton Stone thickened so that, at one point, we were able to examine a bedding face exposing stylolites. These features are accepted to have formed by some kind of pressure-controlled solution followed by local redeposition which produced a boundary, independent of bedding planes, where the rock masses on each side appear to fit together as 'teeth and sockets'. At this point there was a steep drop on to a lower ledge of limestone which effectively brought our walk to an end. So after examining a bottom bed of the Sutton Stone which was displaying coral encrustation, we retraced our steps to the car park. Walking back we saw the resident pair of Choughs, relatives of jackdaws with bright red beak and legs which only inhabit cliffs in Wales and Cornwall where the sward is closely cropped by sheep.

As the promised sunny periods had at last swept the rain away, it was decided that lunch would be taken at our next stop, Dunraven Bay, about 2 miles further east. The broad sandy bay, also called Seamouth, is backed by steep cliffs of Blue Lias, a succession of hard limestone bands alternating with shales, exposed on either side of the car park. Access to the sand is along a wide concrete causeway down which we walked, striking out southwards to the rocky point at the extremity of the headland known as Trywn-y-Witch (the Witches Nose). As we approached the cliffs, boulders half buried in the sand supported little 'reefs' of *Sabellarid* worm colonies, looking like fairy sand castles, where the worms had cemented sand grains into conical tubes (image 12). Exposed by the receding tide, the worms had retreated into the tubes but would emerge, waving their fan-like tentacles in the water to entrap food when the tide had returned.

Image 12: Sabellarid worm 'reef'

The headland on the south side of Dunraven Bay is formed of Carboniferous Gully Oolite unconformably overlain by thick beds of the Sutton Stone, the lowest formation in the Jurassic of Glamorgan, in which a thin bed of black chert pebbles, derived from the Carboniferous limestone, was exposed high in the cliff. The Sutton Stone, a white to cream-coloured conglomerate, is itself overlain by the grey to brown limestone of the Southerndown Beds, also part of the marginal Lias succession. Some distance back from the headland, the Sutton Stone is folded downwards to beach level and overlain by the Southerndown Beds which are also folded and squeezed towards the major fault zone at the back the of bay. On the north side of the fault zone Blue Lias limestone and shale beds (190 – 197mya) have been dropped by as much as 50 metres (image 13). Some distance to the north of the main fault, two more faults drop the Blue Lias beds down by 20 to 30 metres. The faults occurred after the end of the Jurassic, possibly in the early Cretaceous. Close under the cliff, we were able to examine the Sutton Stone and Blue Lias fault breccias, the colour difference highlighting the fault (image 14).

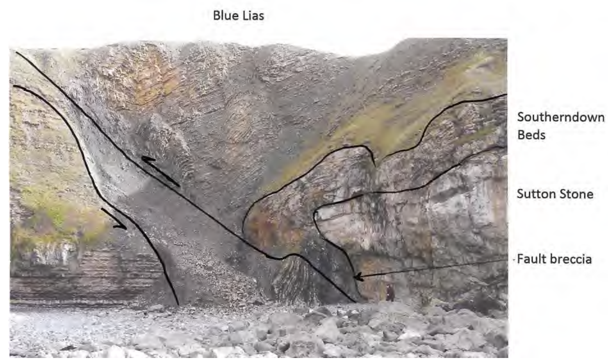

Image 13: Dunraven bay fault zone

Image 14: Fault breccia in Blue Lias (left) and Sutton Stone (right)

On the beach extensive ledges of the Blue Lias limestone beds were well exposed and cleaned by the sea, displaying abundant Liassic fossils. The large convex valves of the bivalve *Plagiostoma giganteum,* clusters of *Gryphaea arcuata* (the Devil's Toenail) and the diamond shaped shell of the Fan Mussel *Pinna* (image 15) were particularly common. This species of bivalve lived vertically in the substrate with just the top third in the water. After death the top would break off to fall horizontally in the sediment, leaving the diamond shaped base to become fossilised in situ. Also found were *Liostrea* species and a few pieces of fossil wood on which oysters were attached. While looking at the cliff and the faults, it was noticed that two Ravens were rolling and tumbling in flight at the top, to be followed by a Peregrine Falcon which dived steeply towards the beach, no doubt hoping for a raven for afternoon tea. Without success, however!

Image 15: Bivalve 'Pinna' in cross section

We returned to the causeway and then walked to the west over the ledges of Southerndown Beds in which were large numbers of small chert pebbles derived from the Carboniferous Limestone as it was eroded away. Above the chert beds are the ledges of Blue Lias limestones and shales in which fossil oysters and ammonites (*Arietites* species?) up to 30 cm in diameter are visible.

We had started off in very unpromising conditions but intrepidly stuck to the itinerary, to be rewarded by sunny weather, excellent exposures and plenty of interesting features, all very clearly pointed out and described by Dr Geriant Owen. Our Chairman at the time, Maurice Tucker passed a vote of thanks to Dr Owen, expressing the gratitude of the members for giving up his time to lead us on a rewarding trip.

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BOOK REVIEW by Isabel Buckingham
The Story of the Earth in 25 Rocks
by Donald R. Prothero
Pub Columbia university Press 2018 as hard back or e book

Donald Prothero taught palaeontology and geology at various institutions in California and has previously written about fossils.

By choosing 25 different rocks he tells the stories associated with their place in the development and understanding of geological ideas theories and understanding. Some names are familiar such as James Hutton and William Smith, others less so such as James Croll who's C19th work on the earth's elliptical orbit, wobble and albedo was almost forgotten then developed by Milankovitch who survived two World Wars. This is well written and researched although I could quibble about details.

New ideas are not often welcomed and their acceptance can be a long uphill struggle. The problem of how to date meteorites led Patterson to work on lead products and find a very recent increase. The wrath of companies who added lead tetraethyl to car fuel to try and discredit him and it is to the credit of Caltech that he was allowed to continue when his integrity was questioned.

This is a good read if you accept the USA bias. Stories of the individuals and interwoven with the clear explanations of the development of the understanding.

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Lulworth Cove Field Trip – April 2017
Graham Hickman

The party gathered in the Lulworth Cove car park, excited by the day ahead and the glorious spring weather. Professor Maurice Tucker, from the University of Bristol and Bath Geological Society, addressed the attendees and described the programme for the day.

Figure 1 – Lulworth Cove Overlook. Maurice described the geological history of the area.

The plan was to spend the morning on the West side of Lulworth Cove and work our way around the bay in the afternoon to Mupe Bay.

Figure 2- Lulworth Cove is a classic geological section of the Jurassic Coast World Heritage Site.

During Carboniferous to Devonian times there was an ocean to the south, with limestones being deposited on southern flank of an ancient landmass. This ocean closed during what is described as the "Variscan orogeny" as the Gondwana and Laurasia tectonic plates collided to form the supercontinent Pangea. The Permian period was tectonically quiet, then during Triassic times Pangea being splitting. Old faults were reactivated to form the Wessex basin. East- west faults allowed subsidence and the deposition of several kilometres of Jurassic and Triassic sediment. During the Early Cretaceous period further tectonic movements resulted in uplift, erosion and tilting. During the Late Cretaceous global sea level rise returned the area to fully marine conditions with the widespread deposition of Chalk. Finally as the Alps formed in Europe the area experience compressive forces again with thrust faults and folds being reactivated.

Figure 3 - Stair Hole. The Lulworth crumple zone

The group next visited Stair Hole (Figure 3). Here the rocks are steeply inclined and small tight folds are easily seen. This is known as the 'Lulworth Crumple' these high frequency faults and folds have developed on the northern limb of a major monocline, reactivation of deep normal faults has led to local compressional features. The Portland Beds form a strong barrier to erosion from the sea, while the Purbeck beds are softer and more easily eroded. It has been suggested that some of the features we see may have been karst caves; when sea level rose 15,000 year ago the sea has eroded them to become arches.

Figure 4 - Maurice standing on the Cinder Beds.

The Purbeck formation records a transition from shallow marine conditions to muddy alluvial rivers in the Wealden, this is the transition from the Jurassic to Cretaceous Periods. One bed of note is the Cinder Beds (Figure 4), so called for their slightly blue

Figure 5 - West Cliff Lulworth Cove – examination of the Unio Member.

appearance. However, it has nothing to do with volcanic ash or cinder. The beds have their colour from an abundance of oysters Praeexogyra *distorta.*

The group made their way back from Stair hole into Lulworth Cove and started walking along the beach to the west cliff. Here a close up view could be had of the uppermost beds on the Purbeck formation. The glauconitic sandstone Unio Member (Figure 5) named for the presence of the bivalve Unio valdensis. Normally glauconite is indicative of sub-oxic marine conditions, however the presence of freshwater bivalves, crocodile and turtle bones suggests an origin as a lake or lagoon deposit.

Figure 6 – intra clast conglomerate with lime clasts

Figure 7 –West Cliff Lulworth Cove – the Broken Beds.

Further along the west cliff, near the base of the Purbeck, is an interesting conglomerate with lime clasts incorporated into the rock and interpreted to have been derived from a period of desiccation. Conditions where the lagoon dried, lime mud became exposed, flacked, cracked and then redeposited. (Figure 6).

Further along the west cliff, a complex set of strata were observed called the Broken Beds (Figure 7). These are 4 -5m in thickness and consist of folded, floating and brecciated beds. These beds occur in the monocline crumple zone but their origin is not simply from later fracturing. Further East the Purbeck section can be shown to have evaporates, such as anhydrite and halite, in the subsurface (Figure 8). At this location the dissolution of the anhydrite is believed to have resulted in a collapse breccia.

Figure 8 –West Cliff Lulworth Cove – Maurice explains the Broken Beds. Pink shading are evaporites in the subsurface.

After lunch the group made their way across the back of Lulwoth Cove noting the presence of Greensand and the Lower Chalk and the absence of Gault Clay. The Greensand being rich in bivalve fossils and serpulids worm tubes. The Chalk contained pale brown nodules and shell fragments of the bivalve inoceramus.

After climbing the cliff on the East side of Lulworth bay, the group was pleased to see the MOD gate open allowing access to the Lulworth Range. From the cliff top path the fossil forest could be observed. Unfortunately following a cliff fall in 2015 the stairs down to the ledge were still closed. Although some wood however has been silicified, the majority of what is preserved of the fossil forest is the stumps, mostly empty moulds, preserved by 'stromatolitic' microbial mounds (Figure 9).

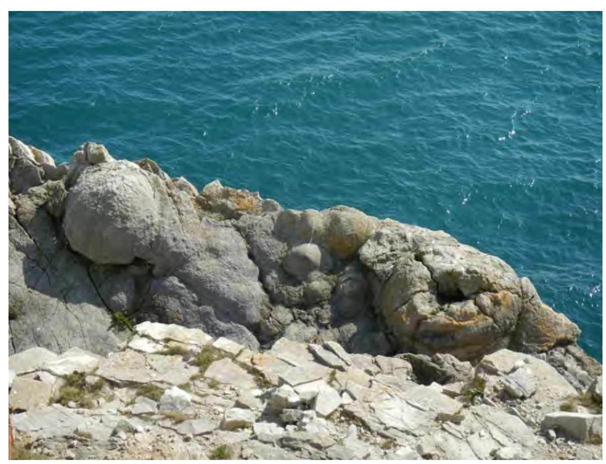

Figure 9 – Fossil Forest

The group walked on until we reach the overlook to Mupe Rock (Figure 10), where we observed the scenic but inaccessible stacks. The stack in the foreground having a Purbeck cap overlying the Portland Broken Beds and Portland Freestone.

Figure 10 – Mupe Rock

As the trip drew to a close the group thanked Maurice for a very informative and enjoyable field trip.

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"Directional Drilling – From Geometry to Geology"
By Phil Burge

Introduction

Within the upstream oil and gas industry there has been, and to some extent remains a tension between the drillers and the geologists. The former are driven by a "can do" attitude where the aim is to drill and complete the well as quickly as possible (within the necessary bounds of safety and well integrity), while the geologists would like to extract as much information as possible about the formations being drilled, which requires time and adds to costs. Horizontal drilling and geosteering has brought the two disciplines together such that drilling performance and well productivity are increased by geological interpretation in real time.

Old time drillers attempted to keep the wells vertical. This is not easy, creating problems as wells tended to intercept or end up draining a neighbouring property, intentionally or otherwise! Directional drilling, pioneered by John Eastman began in the 1930's. Enabled by simple surveying tools providing inclination and azimuth data and using mechanical properties of the drillstring, drillers could drill away from the rig location in a preferred direction. These methods were used until the 1970's and early 1980's when bent sub motors and then steerable downhole motors provided greater control of the well path.

Steerable motors in conjunction with Measurement While Drilling tools (MWD) allowed more complex directional wells to be drilled leading to horizontal drilling and multilateral drilling. In the mid 1990's Rotary Steering Tools (RST) were developed. These tools greatly increase the efficiency of directional and horizontal drilling in particular, allowing geologists to target more complex reservoirs and drillers to plan more complex well paths.

Introduced in 1939, mud logging was the main information gathering method. Samples of drilled cuttings were examined at surface, indications of hydrocarbons noted and a log of the formations drilled compiled. The mud loggers worked closely with the wellsite geologist. Geological and formation fluid data lagged drilling by some time as mud loggers and geologists had to wait for samples to appear at surface.

Beginning in the 1920's through the work of the Schlumberger brothers, and developed continuously ever since, electric logging, or wireline logging has been used to gather geophysical information providing detail on rock and fluid properties. Electric logs are deployed into the well by wireline and as such the data is collected after drilling an interval of the well.

From the early 1980's electric logging sensors were, along with existing directional sensors added to Measurement While Drilling (MWD) tools. The initial benefit of MWD was in improved directional drilling performance. As geophysical measurements became more reliable and sophisticated, FEMWD (Formation Evaluation MWD) began to add to or in some cases replace electric wireline.

A real game changer was the combination of RST (a drilling tool) and FEMWD (a geophysical measurement tool) and the development of remote real time data centres. Real time geophysical data is now interpreted away from the wellsite and decisions on steering the well and are made by collocated multi discipline teams. The history of these developments are shown in the time line in **Figure 1.**

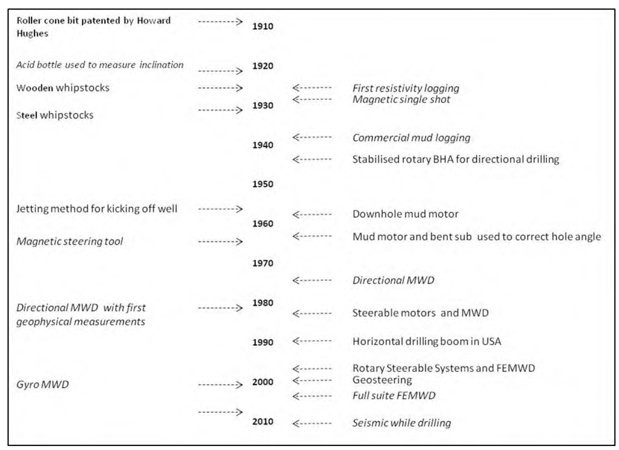

Figure 1: *Time line of major drilling and measurement technologies. Measurement technologies shown in italics*

The industry has moved from drilling based on geometry to drilling based on geology and from interpretation days or hours after drilling to seconds. The consequences in terms of performance and productivity have been game changing.

This paper will review the development of directional drilling and data collection technologies in the context of the geology.

Fundamentals of drilling

Drilling for oil and gas uses many of the same principles as drilling a hole in a wall using an electric drill. Ever tried this and placed the hole in the wrong place, drilled into the wall at the wrong angle, broken the drill bit or got it stuck in the wall, hit something you didn't mean to hit like a water pipe? If so, then you have encountered the same problems facing oilfield drillers!

What do you need to drill a well? As a minimum:

- A drill bit – These come in three types; roller cone, diamond and PDC (polycrystalline diamond compact). The selection of the drill bit is determined by the geology (hardness, abrasiveness, homogeneity and variation).
- Drill string – The drill string comprises numerous types of pipe that connect the drill bit to the surface and provides: a fluid path for the drilling fluid (mud) from the surface through the drill bit and back to the surface (hydraulic energy), weight and rotation at the drill bit (mechanical energy)) and stabilise the drill string in the well. The drill string includes drill collars, stabilisers, measuring tools as required and usually a directional control device either a steerable motor or a rotary steerable tool. All the components below the drillpipe comprise the Bottom Hole Assembly (BHA)
- Drilling fluid – The drilling fluid (mud) has numerous functions including lubrication and cooling the bit, controlling downhole pressure, providing support to the wellbore to prevent collapse, and controlling chemical reactions between the mud and the rock and transport drill cuttings to the surface for examination.

To drill a well path along a prescribed trajectory to a specific target requires a means of initiating the well in the correct direction and adjusting the well direction and inclination as required to avoid intersecting other wells and to reach and remain within the geological target. We shall now look at how these technologies have evolved.

How geology determines drilling performance
Drilling Hazards

Rock types present a range of potential drilling hazards, some of which are summarised below:

- Mud rocks from claystone to shale are the most common rocks drilled in a sedimentary basin. Major basins outside of the Middle East include the Gulf of Mexico, the North Sea and the Niger basin in West Africa. In many parts of the North Sea a well would need to be drilled 3,000 meters through Quaternary and Tertiary clay and shale before reaching potential reservoirs in the Cretaceous and Jurassic. Shale causes problems due to swelling of hydrophilic clay minerals (smectite) and collapse (sloughing) due to insufficient pressure exerted by the drilling fluid.
- Salt can cause problems either by plastic deformation into the wellbore which causes the drillstring to become stuck or by dissolving into water based drilling fluid. An enlarged borehole can lead to problems running and cementing casing. Salt can be drilled easily with the correct drilling fluid density and chemistry, commonly a salt saturated fluid.
- Chert and anhydrite can be difficult to drill given their hardness. Problems arising include damage to the drillbit and shock and vibration leading to damaged drillstring components and even to failure (snapping) of the drillpipe.
- Conglomerates, due to their heterogeneity present similar problems to those of chert.

Stresses within the formations due to local or regional tectonics, from small scale faults to Andean tectonic stresses can lead to wellbore failure characterised by collapse and in the latter case severe wellbore enlargement[1]. This problem is more apparent in high angle and horizontal wells.

Then there is geological uncertainty particularly in exploration drilling. Included in this category are uncertainties in pore pressure regime (higher than anticipated) and uncertainties in geological prognosis (subsalt plays for instance).

Crooked hole country

Figure 2 shows an oilfield from the early days of the industry; fields were developed by drilling hundreds of densely packed wells. Not only is this inefficient but the drillers had no way of knowing where the well was actually being drilled. It might well be drilling into a neighbour's well and it was might well be drilled into a neighbours part of the field. It is in fact very difficult to drill a vertical well. This is in large part due to geology. Drillers used the expression "crooked hole country"[2] to describe areas where the well deviates from vertical and back again as each successive formation is drilled. Imagine a sequence of rock formations each of different hardness and dipping at some angle. The drill bit will get deviated towards the harder formation as the drillbit starts to drill the up dip hard formation and vice versa as the drillbit starts to drill the down dip soft formation. This is analogous to the refraction of light.

Figure 2*: Drilling at Signal Hill, Long Beach California in 1920's. The large number of rigs (and hence wells) shows that this field was drilled before the advent of directional drilling and before much of an appreciation of reservoir engineering.*

Similarly, drilling across a fault can cause the drill bit to be deviated. In the early days drillers fought the geology to keep a wellbore close to vertical. Local knowledge on the part of the driller was essential.

The development of directional drilling

Directional drilling as a discipline started once drillers appreciated that wells were not vertical! Thus a key aspect of directional drilling is measurement of inclination (angle of the well from vertical) and azimuth (compass direction from north).

The first magnetic single-shot and multi-shot instruments using magnetic compass and plumb bob were developed in 1929 by John Eastman to measure inclination and azimuth. These sensors were dropped down the drillstring to land on a muleshoe. After a set time, a photo was taken to record the compass direction and angle of the plumb bob. It was soon realised that wells which were thought to be vertical could have inclinations up to 50 degrees! [3]

Once the inclination and azimuth at a particular point in the well is known, the well path between two survey points can be calculated using trigonometry. The mathematics of survey calculations became more complex and accurate as the mathematics moved from simple tangential methods to more advanced radius of curvature methods first used in the 1970's. Even with advanced mathematics various errors, such as sensor calibration, distance between surveys and magnetic interference cumulate to provide an overall "ellipse of uncertainty", that is a range of possible actual wellbore position characterised by an ellipse around the wellbore as shown in **Figure 3**. We shall return to this problem later in the story.

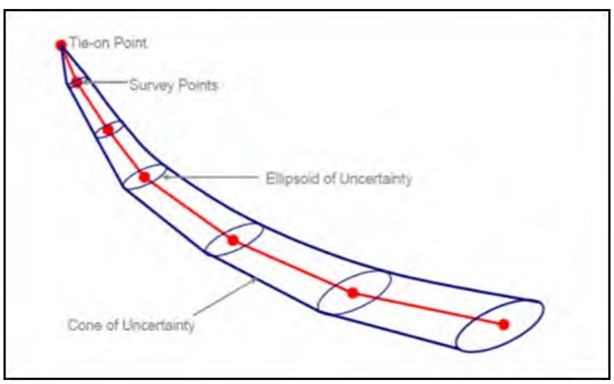

Figure 3: *The "ellipse of uncertainty" – how far off you can be if you rely on geometric placement of the wellbore.*

Although directional drilling started as a means of keeping a well near vertical, intentional directional drilling has many applications, not least of which must be the capability of drilling 10 – 30 wells from an offshore platform. Without directional drilling offshore fields would not have been developed.

An initial direction for the well was achieved either through use of a whipstock or by jetting. A whipstock is a metal wedge placed in the hole with the hypotenuse of the wedge oriented in the preferred azimuth. Jetting, first used in the 1950's is where the drill bit is held at a particular depth and, without rotating the drillstring high pressure drilling fluid washes out the side of the wellbore. (**Figure 4**). This creates a ledge that is used to nudge the well in the desired direction. A reasonably useful method in soft formations.

Figure 4: *Use of drill bit nozzle in jetting and whipstock. Both used to initiate a directional well*

From the early 1940's, controlling direction and azimuth while drilling was achieved by adjusting the location of stabilisers along the BHA as shown in **Figure 5**. Three different assemblies were used[4]:

- To build angle (inclination) a fulcrum assembly is used. In this assembly a stabiliser is placed directly above the drillbit and a second stabiliser placed 20 – 30 metres above the first. If the well has any inclination then this BHA will bend creating a side force at the drill bit and bit tilt.
- To drop angle a pendulum assembly is used. Here the near bit stabiliser is removed and gravity acts on the bit and lower drill collars causing a downward tilt of the bit.
- To hold angle a packed hole assembly is used. This assembly has up to five stabilisers located at around 10 metre intervals in the BHA. The packed hole assembly limits bit side force and bit tilt to nearly zero.

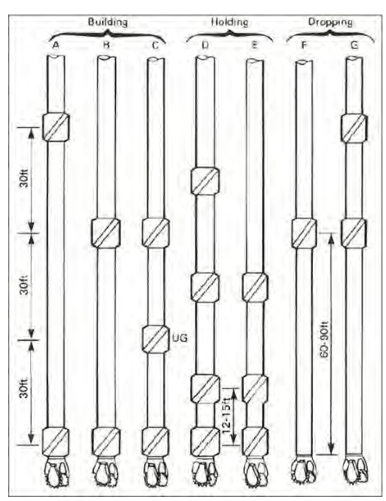

Figure 5*: Bottom Hole Assembly design for build, hold and drop. Used from 1940's to 1980's. Placement of the stabilisers creates either a build, hold or drop tendency.*

In the early 1960's downhole mud motors were used for the first time in conjunction with a bent sub. The downhole motor is an inverted Moineau pump. Pumping mud through the motor causes the drill bit to rotate which means the drill bit will rotate when the drillstring is not rotating. The motor is around 12 metres long and on top is placed a bent sub (a short length of drill collar) . This sub has an offset connection which gives a tilt to the motor of a few degrees. This creates a bend between the drillbit and the top of the bent sub, which if the drillstring is held in the same orientation, will drill a known curve (radius of curvature), either up or down or left or right.

Measurement of inclination and azimuth was initially by single shot sensors and then by steering tools. Steering tools use magnetometers and inclinometers to provide continuous data along an electric wireline running inside the drillstring and through a side entry sub at the surface. With this method the drillstring cannot be rotated and once the change in hole inclination and or azimuth has been effected the entire drillstring is removed from the well and replaced by a packed hole assembly as described above.

A major breakthrough in both measurement and directional drilling control came in the late 1970's and early 1980's with the introduction of Measurement While Drilling (MWD) tools and steerable motors. The first MWD tools consisted of the same sensors as used in the steering tool with the addition of a means to transmit data via pressure pulses through the drilling fluid. This is done by partially restricting the flow of drilling fluid to create a positive pressure pulse and opening the valve to return the pressure to normal, thus a simple binary code can be transmitted to surface.

The steerable motor is a downhole motor but the bent sub has been moved from above the motor to above the bit. Doing this means that a much smaller angle of tilt creates the same radius of curvature as the larger angled top bent sub. With a smaller tilt angle the steerable motor can be rotated from surface once the required change in hole inclination and or azimuth has been achieved. This means that the motor does not have to be removed from the well and replaced by a packed hole assembly but can, by a sequence of non-rotating and rotating drill along a prescribed well path. **Figure 6** demonstrates the way in which three points of contact along the length of the steerable motor define the arc creating the change in wellbore inclination or direction.

Perhaps the most significant advancement in directional drilling was horizontal drilling using steerable motor/ MWD combinations, which rejuvenated the Austin Chalk play in 1989. The Austin Chalk, a late Cretaceous formation in West Texas had been producing since the 1920's from vertical fracture porosity. Production had been maintained and even increased by the use of acidisation and hydraulic fracturing, Even so, drilling was a bit hit and miss. However, with horizontal drilling a well could be drilled that intersected numerous fractures and increased production rates.

Horizontal drilling and hydraulic fracturing is now being used to develop the underlying Eagle Ford shale.
At the end of the 1980's the prevailing wisdom was "why drill horizontal wells", after the success of the Austin Chalk and similar field redevelopment in the USA, this switched to "why not drill a horizontal well?". As the statistics show in **Figure 7** almost 90% of wells drilled in the USA are horizontal. The same is rue for many other areas of the world.

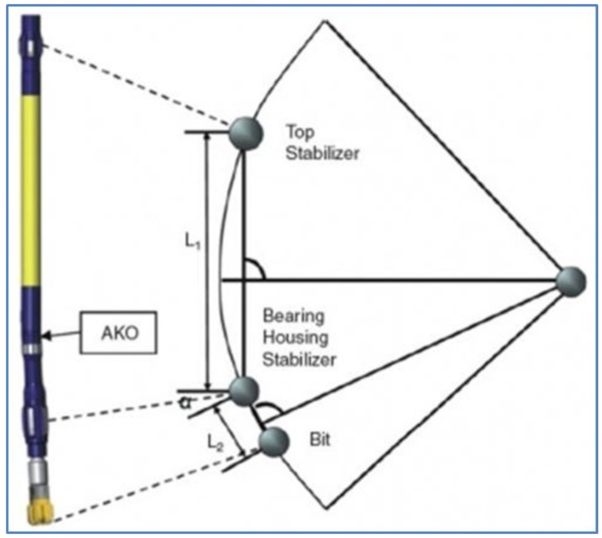

Figure 6: *Principle of steerable motor using 3 point geometry to create an arc. From Baker Hughes.*

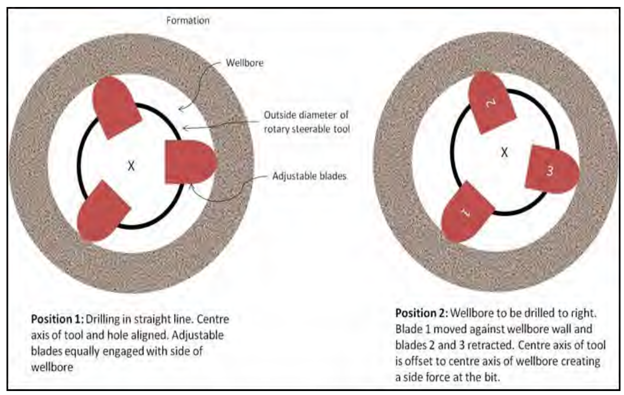

Figure 7: *Representation of operation of rotary steerable tool.*

While we have focussed on the directional sensors in MWD tools, geophysical measurements were also being developed, initially simple Gamma Ray sensors measuring natural radiation and used to identify shale, and basic resistivity measurements used to identify formation fluids. In the late 1990's developments took off! Logging While Drilling (LWD) tools incorporate the necessary directional sensors and a full range of geophysical sensors from Gamma Ray to NMR (nuclear magnetic resonance) to provide a complete interpretation of the geology and fluid properties.

The modern era
From vertical drilling to rotary steerables

Before we get too deep into the modern era we need to revisit the fact that drilling a vertical well is difficult. In the mid 1980's the German government sponsored a project, the Kontinentales Tiefbohringprojekt (KTP) which ran between 1986 and 1995[5] . The aim of this project was to drill to the *Erbendorfkörper* – a deep-lying mass that is believed to be on the boundary of a former continental plate and is identified by its characteristic reflection of seismic waves. The target depth was between 10 and 14 Km at a location in northern Bavaria. Previous deep hole drilling on the Kola project in Russia had shown that deviations in wellbore inclination led to excessive friction between the rotating drillstring and the wellbore. To avoid this, a "vertical drilling machine" was designed and developed by Eastman Christensen (taken over by Baker Hughes in 1989). This drilling tool used the same principles of side force at the bit and measurement using on board inclinometers, with the side force achieved by the use of a near bit adjustable stabiliser. When the inclinometers measured a deviation from vertical in a certain direction, the stabiliser blade in that direction was extended creating a side force in the opposite direction. By using three stabiliser blades 360 degrees of freedom can be realised. The basic principle of is shown in **Figure 8** . This well was drilled to 9,101 metres with inclination deviations less than 2degrees. **Figure 9** shows the complexity of the geology and highlights the hazards to vertical drilling of dipping beds and faults.

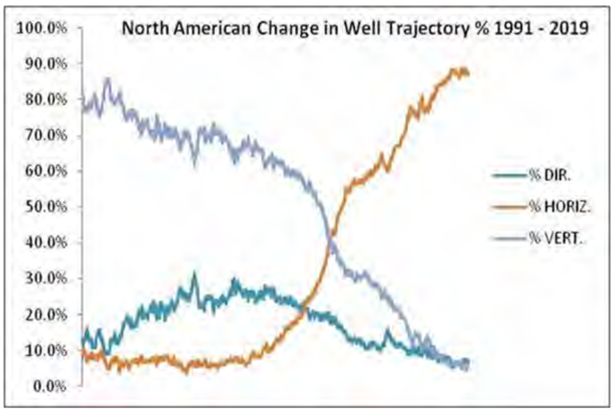

Figure 8: *US Well Trajectory Changes 1991 – 2019. Clearly shown is the change in percentage of wells drilled horizontally versus vertical and directional wells. This is largely driven by the oil shale drilling boom. Data from Baker Hughes Rig Count.*

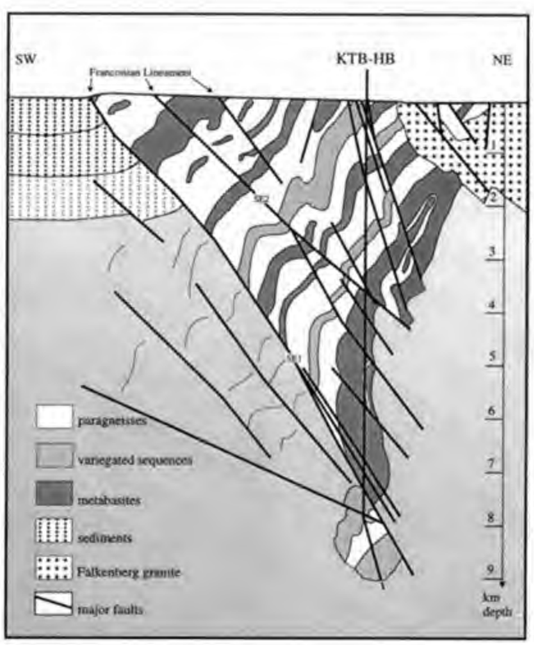

Figure 9: *Cross section of KTP borehole showing dipping beds and faults. Impossible to drill a vertical well in this geological and structural environment.*

Having established the principle of closed loop control of inclination of the wellbore it is a logical step to employ the same principles to control both inclination and azimuth. Thus was born the rotary steerable tool (RST). This technology allows the wellbore to be steered in a continuous smooth path making the drilling process more efficient and providing a high quality wellbore.

Geosteering

So far in the story, directional drilling regardless of technology has been concerned with the geometric placement of the wellbore in 3D space.

As reservoirs become thinner and more complex, geometric placement becomes more problematic due to calibration errors, sensor resolution, and magnetic interference amongst others. Significant errors in wellbore position particularly at higher angles of inclination are the result. Suppose the cumulative error of azimuthal measurements is +/- 1 degree. By geometry this will lead to a positional error of +/- 5.25 after 300 metres of well drilled.

When drilling long horizontal wells, even holding the well inclination at 90 degrees and maintaining a constant azimuth means that the actual well lies within a range of uncertainty that could be quite substantial. From the example above, a 3,000 metre horizontal would have a positional error of +/- 52.5 metres.

Until the advent of geosteering, geologists had to rely on data that arrived long after the formation was drilled. Drill cuttings could take 2 – 3 hours to return to surface for examination and FEMWD data lagged actual drilled depth as the sensors are located 15 – 30 meters behind the drill bit.

To drill into a small target and remain within the target means that you have to overcome the positional uncertainty and the time lag in data.

Even if we hit the top of the target zone there is still geological uncertainty for instance a channel sand or lagoonal environment, and structural complexity (dipping formations, faults). What is needed is a means of controlling the direction of the wellbore so as to keep the well within the "sweet spot" to optimise production. The "sweet spot" might be defined as a vertical distance below the top of the formation or a vertical distance above the oil-water contact. Every metre of horizontal drilled outside the "sweet spot" means reduced production.

Resistivity and gamma ray FEMWD sensors allow the drilling team to recognise changes in geology before the drill bit has entered the target formation and while drilling the target formation. We have now moved away from geometry as our means of determining where the well is and where it is to go, to the use of geological parameters. This is called geosteering.

Resistivity logs measure the ability of rocks to conduct electrical current and are scaled in units of ohm-meters. The resistivity measurement is a function of the formation fluids, water having low resistivity and oil higher. Resistivity tools are designed with a range of depths of investigation with modern FEMWD resistivity sensors having a depth of investigation of over 60 meters and provide measurements in multiple (32) discrete directions. This is called azimuthal measurement, where azimuth refers to high side of the hole. Using the combination of deep and shallow measurements oncoming bed boundaries or faults or proximity to the oil – water contact can be predicted and the well steered in the appropriate direction.

Nowadays many geosteered wells are coordinated from a Real Time Operations Centre. Data from the rig is sent to an office facility manned by geologists, geophysicists, directional drillers and FEMWD analysts. All the expertise necessary to drill a complex well are collocated and can collaborate to achieve the objectives of the well. A spin off of this technology is that a group of experts can collaborate on a number of wells simultaneously reducing the demand for expertise at the rig site.

Summary

The combination of directional drilling and downhole sensor technology has been a game changer in terms of the types of well that can be drilled, the size of targets, the redevelopment of older fields, the capability of horizontal drilling and the development of shale plays. The latter has been instrumental in driving the development of many technologies in addition to directional drilling.

The industry has moved from individual disciplines, and tension between these disciplines, to a much more of a collaboration brought about by the move away from geometry and towards geology as the deciding factor in placing a wellbore.

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Tintern Geology Field Trip – Led by Dave Green
By Bob Mustow.

The discussion over the first sample Dave showed us, a stone off the path he had just broken open, went like this:
Dave: “You can see what this is…”
Me: “Limestone”
Dave: “…Sandstone”
So don’t expect anything too technical in the following article!

The Wye Valley at Tintern is 217m at a trig. point near the car park north of Tidenham Chase, and 10m at the river, so about 207m or 680ft deep and covers a period from the end of the Devonian, (about 340mya), to the beginning of the Carboniferous, (about 360 mya).

Two theories of the way the Wye meanders ignoring any geological or geographical features. The generally accepted one is that the curves of a mature river formed in some higher material subsequently eroded way and, helped by uplift, caused the path to be eroded into the underlying strata. Or, secondly, the route may have been carved by huge volumes of glacial melt water loaded with debris perhaps flowing from a collapsed lake dam. Whatever the cause, it has given us easy access to the geological sequence here.

Fig 1: Heathland

We started by walking from the free car park just north of Tidenham Chase, through the wood and, crossing Miss Grace’s Lane, (which leads to the second longest cave system in the Forest of Dean area), out onto the plateau grassland towards Offa’s Dyke and the Devil’s Pulpit [Fig 1]. This area is Dybrook Sandstone; a free-draining, porous, non-cemented material, grey in colour as it is free of iron which would colour it red. Soluble bases leach down to lower strata leaving the quartz rock free of basic minerals, so the soil is acidic giving rise to areas of heathland here which are the subject of a project to restore these to their natural state [Fig 2].

As we approached the trees above Offa’s Dyke we crossed thin bands of Whitehead Limestone and then Crease Limestone. The Whitehead Limestone formed in quiet lagoons over the Crease Limestone around 340 mya. It is fine grained and was known as ‘Chinastone’ by quarrymen because of this and the white colour.

The Crease Limestone is more dolomitised than the Whitehead: some of the Calcium has been replace by Magnesium giving rise to $MgCO_3$ rather than $CaCo_3$. It does not fizz so much with hydrochloric acid. It is quite a dark grey here, massive with vertical joints, and glints in the light.

Fig 2: Grassland

Dropping down a little the next rock layer is the Lower Dolomite and the obvious features here are the Devil's Pulpit, Offa's Dyke and a fine view of Tintern Abbey way below across the river Wye through a gap in the trees thoughtfully provided by the Forestry Commission [Figs 3 and 4]. In years past there were few trees here, giving a wide panoramic view. In a small, old quarry on the other side of the Dyke to the Devil's Pulpit is an ancient yew tree, with its roots grown into and around a pile of limestone rocks. Presumably the quarrymen decided to leave this tree in place [Fig 5].

Fig 3: Devil's Pulpit

Fig 4: Tintern Abbey

Fig 5: Quarry Yew

We now walked steeply down the valley side through a thicker band (about 50m) of the Lower Dolomite. As limestone is generally less easily eroded than sandstone, the slopes are steeper here than over the sandstone. Here the limestone is dark grey and an exposure can be found where the path drops down after crossing a forest track at about the 120m contour. [Fig 6]. It is known as 'Stinkstone' because it smells strongly if broken, reminiscent to me of stagnant ponds or a damp room or maybe a gasworks, all things that are rarely experienced these days. It is presumably from decayed organic matter trapped in the formation 350 million years ago.

Fig 6: Interbedded Lower Sandstone Shales

We were told that dolomitised rock is harder than a copper coin and calcite is softer. Also, if you hit sandstone it gives a dull thud whereas limestone rings. Dave Green feds us a continuous flow of useful information!

We then came to a second rough flight of steps, each step created from a level in the strata. I believe this is the top of the Tintern Sandstone formation [Fig 7].

Fig 7: Steps

At the bottom of these steps, at about the 80m contour, we are back on the less-steep sandstone, the Tintern Sandstone, which is light grey here although the soil gives it a red appearance. The dismantled Wye Valley Railway, opened in 1876 and later run and owned by the Great Western Railway, runs in a tunnel under here, through the Sandstone, on its way from Chepstow to Monmouth.

At the bottom of the final flight of rocky steps is the track bed of the branch line that ran over the Wye into Tintern. There, on the other side of the A466 and up the Angidy Valley, had been extensive wireworks for 300 years. The branch was ready a year or two before the main line but, in that time, the works ceased trading! Another company did briefly run a tinplate and wire works some years later but no passenger station was opened so a hoped-for tourism traffic did not materialise. The line closed in 1935.

Anyway, returning to these lower sandstone steps, there are at least two bands of a whiter rock which is calcrete [Fig 8]. It was formed from water percolating through the porous sandstone depositing calcite, clay and silt forming a nodular form like dolomite.

Fig 8: Steps, calcrete

In the afternoon we climbed steeply up the north side of the Angidy Valley, up Barbadoes Hill. There, in the woods, we found a quarry of Tintern Sandstone which is thought to be where the rock used to build Tintern Abbey came from. It would have been relatively easy to lower the rock down the hillside to the road [Fig 9]. Other quarries in the area are unlikely to be the source as the rock is simply not the same type.

Fig 9: Tintern Sandstone potential Abbey Quarry

So ended another excellent day with Dave Green, it is a pity so few attended.

Thanks to Mike Parr and Sue Price for some of the photos.

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Port Askaig tillite
By Isabel Buckingham

I have seen this deposit in the Garvellach Islands when I'd walked much of the length of Grabh Eileach, been taken round the islands by boat and seen the justifiably famous drop stone.

Image 1: The scale object is a 2p piece. I chose this location as the clasts were well rounded and of various sizes. As the rock face was wet the fine laminations show up. I thought "down" was in the 8 o'clock position.

Image 2: This was just to the right of the first image and with the scale object. The pink coarse grained granite clast is very different; larger and angular with the corners not smoothed at all.

Having been on Islay for almost a week, I'd seen a variety of recent fluvo-glacial deposits including what is generally accepted to be a diamictite formed under a floating ice shelf.

Simply, as the continent of Rodinia broke up, (approximately 750 ma ago), and the Iapetus Ocean started to form, initial spreading was followed by the formation of a series of rifted basins. At the base sits the Argyll group (670-600 Ma) which contains the Port Askaig tillites indicating glaciation. This is followed in the sequence by warm water carbonates.

There is not much parking space in Port Askaig. The superb section illustrated in the guide* is now 7/8ths bolted and netted to prevent rock fall onto the traffic. Only the most easterly part can be approached and seen clearly as trapped debris obscures much of the remainder. It is nothing like what I saw on the Garvellachs. The dark grey matrix is very fine grained and has just perceptible laminations and tiny ripples. The rocks was of very varied sizes, some smooth and rounded and others very angular as shown with 2p as scale object. I could accept this as formed under floating ice.

*A guide to the Geology of Islay by
David Webster, roger Anderton & Alasdair Skelton.

This guide includes 12 geological walks with a whisky recommendation for each. Carol Isla distillery is built on this deposit.

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Sarsens on Fyfield Down. Bath Geological Field trip led by Isobel Geddes, June 2018

Geological Word Search

D E W Q T I V J Y Y A C P H X T R T L Z V Y C D S I U H P K

Y W A G P P M Z R B B A E M E C L S J H U N S D K T T A Y T

C S R M F S L O F N Y I M Y C U E N W Y H P Q T S S E I Q C

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Y S A T S O S I N T I J E V D T V A W F N B O S U D S R X E

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VARISCAN
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CALCIFICATION
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LIAS
SEISMIC
DIP

POLYMORPH
BASALT
PLIOSAUR
PALEOGENE
FACIES

SOCIETY ACTIVITIES 2019

LECTURE MEETINGS

February 7th
AGM and Limestone, Microbes & Viruses
Professor Maurice Tucker, School of Earth Sciences, University of Bristol

March 7th
Oil and Gas Fields for the 22nd Century
Dr Tiago Alves, Cardiff University

April 4th
The shale gas boom: A history of "fracking" from the 19th to the 21st centuries
Dr James Verdon, University of Bristol

May 2nd
Luminescence dating, Climate Change and Hominins
Professor Phillip Toms, University of Gloucestershire

June 6th
Granite Petrogenesis – where on Earth did that come from?
Dr Mike Fowler, School of Earth and Environmental Sciences, University of Portsmouth

July 4th
Climate, chronology and conundrums in the North Atlantic region
Dr Alison Mcleod, University of Reading

September 5th
The Dinosaurs Rediscovered: How a Scientific Revolution is Rewriting History
Professor Michael J. Benton, University of Bristol

3rd October
William Smith - Geological Investigations in Somerset And the Reconstruction of His Country Map
Dr Peter Wigley

7th November
Jurassic calamari: life, death and preservation of fossil squid in the Jurassic rocks of the Wessex Basin
Professor Malcolm Hart, School of Geography, Earth & Environmental Sciences, University of Plymouth,

5th December
Geology in Paradise
Graham P Hickman

FIELD MEETINGS

Saturday, 2nd March
Brown's Folly Nature Reserve
Leader: Professor Maurice Tucker, University of Bristol

Saturday, 4th May
The Etches Collection & Kimmeridge Bay
Leader: Graham Hickman, Bath Geological Society

Saturday, 6th July
Lower Wye Valley AONB – Tintern and Barbadoes Hill areas
Leader - Dave Green

Friday, 20th September
Guided Geology Trail Around Bath
Leader: Professor Maurice Tucker, University of Bristol

Friday, 1st November
Moon's Hill Quarry, Tedbury Camp & De la Beche Unconformity
Leader: Somerset Earth Science Centre

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