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Editorial

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Digitising of past issues of North West Geologist is under way. They will be downloadable as PDF files from the three contributing societies' websites.

The Lancashire Group has changed its name to GeoLancashire and has a new website at www.geolancashire.org.uk *Jennifer Rhodes*

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The emplacement of dykes in North Wales and Shropshire during the Palaeogene

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(based on an MSc dissertation completed at Lancaster University in 2014)

Abstract

The flow processes and emplacement timing of NW-SE trending dykes in North Wales and Shropshire were investigated using anisotropy of magnetic susceptibility (AMS) measurements, geochemical analysis and field observations. Three sets of NW-SE trending dykes were identified for this analysis, two located on the island of Anglesey and one in Shropshire.

AMS measurements and field work observations revealed a range of emplacement processes and some complex flow patterns in the dykes investigated. Magma flow seems to have been predominantly oblique or sub vertical, and little evidence was found for lateral flow from a distant source, such as the Carlingford complex in Northern Ireland. Fieldwork and geochemistry results support the idea that these dykes were fed by multiple injections of magma more or less directly from the mantle, as in the case of the Holy Island Dyke, or via a period of temporary storage within the crust.

Keywords: *Anisotropy of magnetic susceptibility (AMS), British Palaeogene Igneous Province (BPIP), Dyke emplacement processes, Magnetic fabric.*

Introduction

The core aim of this study was to investigate emplacement processes in NW-SE trending dykes located in North Wales and Shropshire which are generally believed to have an origin during the early Cenozoic period. A secondary aim was to determine if these dykes shared any commonalities with Palaeogene dyke swarms in Northern Ireland in terms of emplacement timing and magma source.

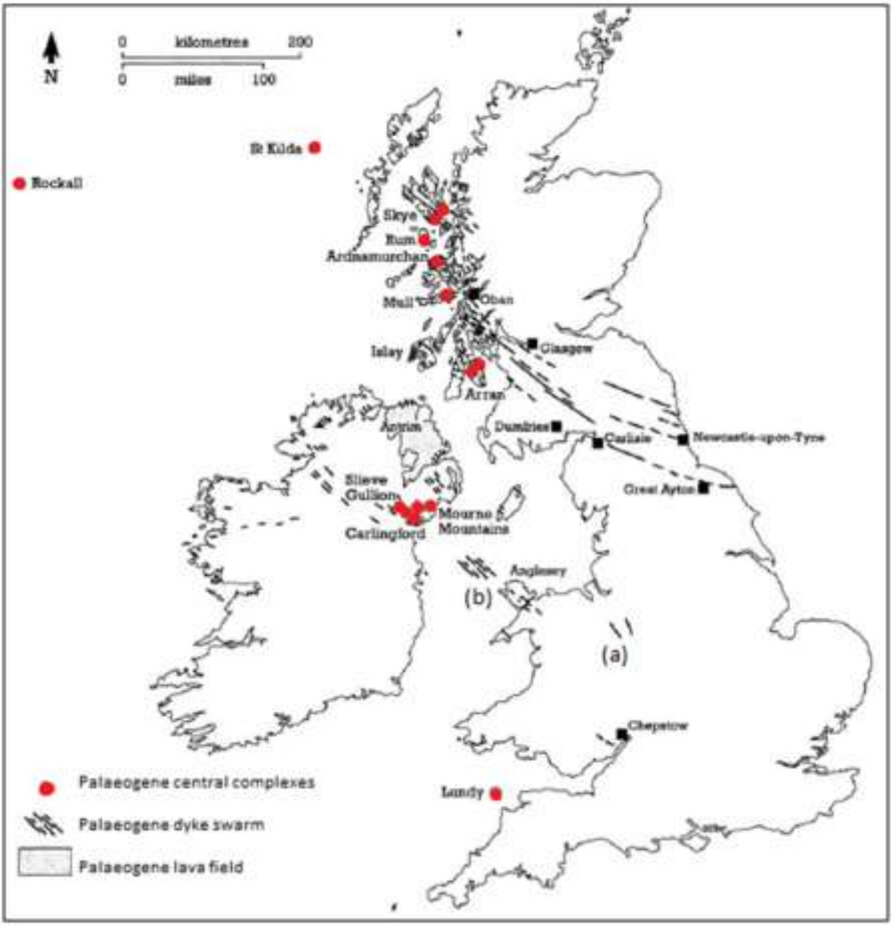

Figure 1: British Palaeogene Igneous Province (modified from Emeleus *et al*., 1992)
(a) Palaeogene dyke swarm in Shropshire (Thompson & Winchester, 1995)
(b) Palaeogene dyke swarm off the NW coast of the island of Anglesey and mainland North Wales (Kirton & Donato, 1984; Beamish & White, 2011)

Geological setting

The Palaeogene igneous rocks of the British Isles, referred to collectively as the British Palaeogene Igneous Province (BPIP), form part of a Large Igneous Province (LIP), emplaced along the continental margins of Greenland and NW Europe in the early Cenozoic, Figure 1. The bulk of basic volcanism occurred between 61 million years (Ma) and 59Ma ago (Chambers & Fitton, 2000).

The significant magmatism observed in this LIP [volume (6-10) × 10^6 km^3] is generally attributed to the arrival of the ancestral Iceland plume beneath Greenland (White and McKenzie, 1989). Mantle plumes are believed to be blobs of hot, thermally buoyant material which rise vertically from a source at the core/mantle boundary. Their relatively rapid rise towards the lithosphere invariably leads to adiabatic decompression, partial melting and the production of huge quantities of basaltic magma. Mantle plumes are commonly associated with very large topographic swells and the significant tensional stresses, resulting from domal uplift above the rising plume, can lead to rifting and large scale surface volcanism, a feature that is often the precursor to seafloor spreading.

Domal uplift of approximately 500m and rifting associated with the arrival of a mantle plume during the early Cenozoic led to the creation of a topographic high across northern Britain, evidence of which is preserved in North Sea sedimentary records (Lovell, 2010). Corresponding evidence of volcanism is preserved in the form of flood basalts (Antrim, Mull, Skye), intrusive igneous complexes (Arran, Ardnamurchan, Skye, Mull, Northern Ireland, Lundy) and basic dyke swarms which extend away from these complexes for several tens to hundreds of kilometres.

Palaeogene dyke swarms

Four distinct NW-SE trending Palaeogene dyke swarms have been identified in Northern Ireland, emplaced in the period 64Ma to 56Ma. The identification of these chronologically distinct dyke swarms points to multiple periods of magmatism during the Palaeogene linked to separate episodes of extension, melt production and intrusion (Cooper & Johnston, 2004; Cooper, 2012). Many of these dykes show evidence of being created via composite events, indicating multiple injections of magma through time.

Aeromagnetic surveys have uncovered a NW–SE trending Palaeogene dyke swarm beneath the Irish Sea off the NW coast of the island of Anglesey (Kirton and Donato, 1984), Figure 1, which appears to be centred on the Carlingford Volcanic Complex in Northern Ireland.

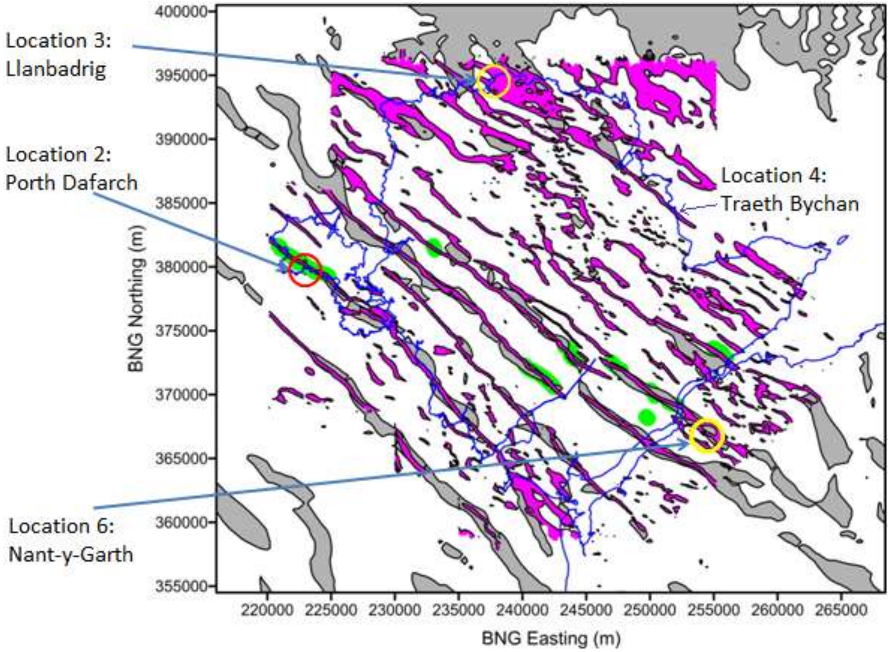

Figure 2: High resolution airborne geophysical survey (HiRES) of the island of Anglesey and the NW Wales mainland revealing the largely concealed NW-SE trending Palaeogene dyke swarm. Tilt derivative response (TDR) HiRES data with the interval from 45° to 90° is shown in purple (Beamish & White, 2011)

The presence of near-surface magnetic features equating to the presence of a NW-SE trending Palaeogene dyke swarm has also been identified on the island of Anglesey and the North Wales mainland (Beamish and White, 2011), Figure 2. The discovery of sinistral offsets in the alignment of these dykes has provided conclusive evidence of strike-slip fault movement in North Wales during the Cenozoic, by 1.5km in the case of the Berw Fault (Bevins *et al*., 1996). The average depth to the upper surfaces of concealed Palaeogene dykes is 44m.

NW–SE trending Palaeogene dykes also outcrop in England, for example at Grinshill in Shropshire (Thompson and Winchester, 1995). The Shropshire dykes have been dated at 62.85 ± 2.87Ma

(Lewis *et al*., 1992) and the Holy Island Dyke at 63.5Ma - 58.7Ma (Evans *et al*., 1973), making them broadly contemporaneous with dykes in Northern Ireland. A date of 68.57 ± 3.64Ma has also been obtained for dykes in Shropshire (Lewis *et al*., 1992), suggesting that there were also pulses of tholeiitic magma in the late Cretaceous.

The ages of dykes in the Cemaes Bay area are currently marked as unknown on British Geological Survey maps. The observed NW-SE trend of dykes near Llanbadrig church hints at a Palaeogene origin, although other unpublished work proposes that dykes in the area also have a Caledonian origin.

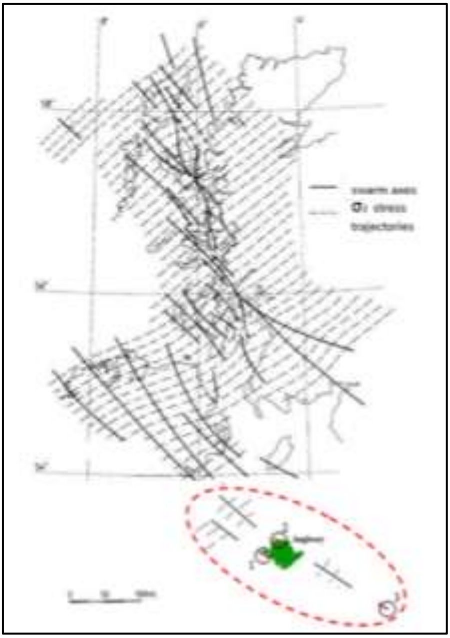

Figure 3: Map showing the spatial orientation of the minimum principal stress trajectories σ across the BPIP as derived from local extension directions indicated by the alignment of dykes (modified from Speight *et al*., 1982). In the area circled in red, these orientations of σ have been extrapolated based on the alignment of known Palaeogene dykes in North Wales and Shropshire. Approximate locations of the Holy Island, Llanbadrig and Grinshill dykes are circles 1, 2 & 3 respectively.

A dyke is a sub-vertical tabular or sheet intrusion of magma which has cut a pathway through the surrounding rock. The opening up of dykes creates a plumbing system for the transport of magma into shallow crustal levels, and where they reach the surface they will feed an eruption. Dykes are intruded perpendicular to the plane of minimum principal stress (σ_3) existing in the rock strata during emplacement.

As noted above, Palaeogene dykes in the British Isles have a very distinctive NW-SE trend. England (1988), utilised dyke trajectories to map out the palaeostresses that must have existed at the time and concluded that NE-SW extension was the overriding control on dyke emplacement during the early Cenozoic, Figure 3. The arrival of the ancestral Iceland plume and the resulting domal uplift, NE-SW extension, rifting and volcanism eventually led to the commencement of sea-floor spreading and the formation of the North Atlantic Ocean.

Rock magmatism and inferring magma flow in dykes using AMS
Anisotropy of magnetic susceptibility (AMS) is a physical property of rocks arising from the preferred orientation of anisotropic magnetic minerals such as magnetite. AMS can be described as a second-order tensor, visualised as an ellipsoid (similar in shape to a rugby ball) with three principal axes (K_1, K_2 and K_3) where ($K_1 \geq K_2 \geq K_3$).

The fabric of magmatic rocks can be characterised by the way in which anisotropic phenocrysts/mineral grains are arranged within the groundmass. Foliation in a rock can be observed when mineral grains form into sheet-like layers where K_1 and K_2 axes (the foliation plane) is defined by the average planar orientation of tabular phenocrysts. Lineation in a rock is defined by the average alignment of phenocryst long axes (K_1 axis). Magnetite grains are late crystallising and it is believed that they acquire their orientation by mimicking the pre-existing silicate structure acquired as a result of magma flow (Hargraves *et al*., 1991).

AMS principal axes are plotted on a lower hemisphere stereographic projection diagram in order to aid the interpretation of magnetic lineation and foliation, using the convention of K_1 axes as squares, K_2 axes as triangles, and K_3 axes as circles, Figure 4. A dyke with a "normal magnetic fabric" will reveal a magnetic foliation plane (K_1

and K_2 axes) roughly parallel to the dyke margin and K_3 axes perpendicular to the dyke margin. However, simple shear induced by the flow of magma at dyke margins leads to the principal axes of anisotropic grains becoming tilted in the form of a flow imbrication. The angle of this flow imbrication (α) dips toward the source of the flow and can therefore be used to identify the source of the magma (Knight and Walker, 1988). The direction and plunge of magma flow can be inferred from the magnetic lineation.

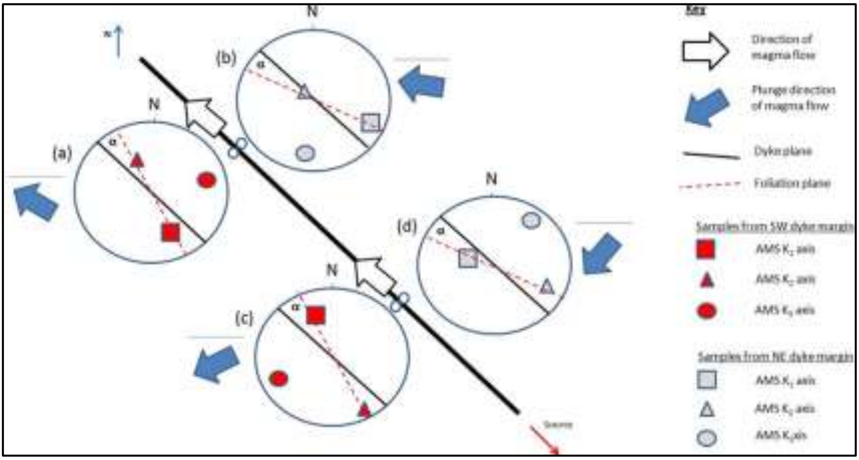

Figure 4: A conceptual model of mirror imbrication of magnetic lineation fabric in a NW-SE trending vertical dyke plotted on lower hemisphere projection diagrams. (a) Sample from SW margin. K_1 axes plot on western side of dyke trend on lower hemisphere projection so flow was upwards. (c) Sample from SW margin. K_1 axes plot on eastern side of dyke trend on lower hemisphere projection so flow was downwards. The angle of imbrication α indicates magma flow was from a source located to the SE.

Fieldwork

Table 1 includes a list of locations where dykes are observable in the field. Three sites were identified for analysis based on ease of access, the quality of the exposures, and the ability to sample from one or opposing dyke margins.

Field location 1: Grinshill Stone Quarry, Shropshire

Previous surveys have identified dykes extending for 4.2km in a belt up to 160m wide around Clive, Grinshill and Acton Reynald in Shropshire (Thompson and Winchester, 1995). A 0.3m wide

Palaeogene dyke is currently exposed in Grinshill Stone Quarry, Table 1. Three samples were extracted for analysis. The dyke rock is composed of highly porphyritic basalt with plagioclase crystals, up to 5mm long, set in a medium-grey fine-grained matrix.

Field location 2: Holy Island Dyke

There are excellent exposures of the mostly subsurface Palaeogene dyke swarm along the west coast of Holy Island in the vicinity of Trearddur Bay and Porth Dafarch, Figure 5. The dyke cuts through rocks of the South Stack Group (Cambrian). These exposures are relatively wide (24m) and sub-vertical (observed dip ranging between approximately 5^{o} to NE and 25^{o} to SW). The dyke is segmented into approximately 1km long sections offset between 50m and 200m. These displacements may be the result of subsequent sinistral strike slip faulting or they may indicate that the dyke was emplaced in the form of a series of en-echelon segments.

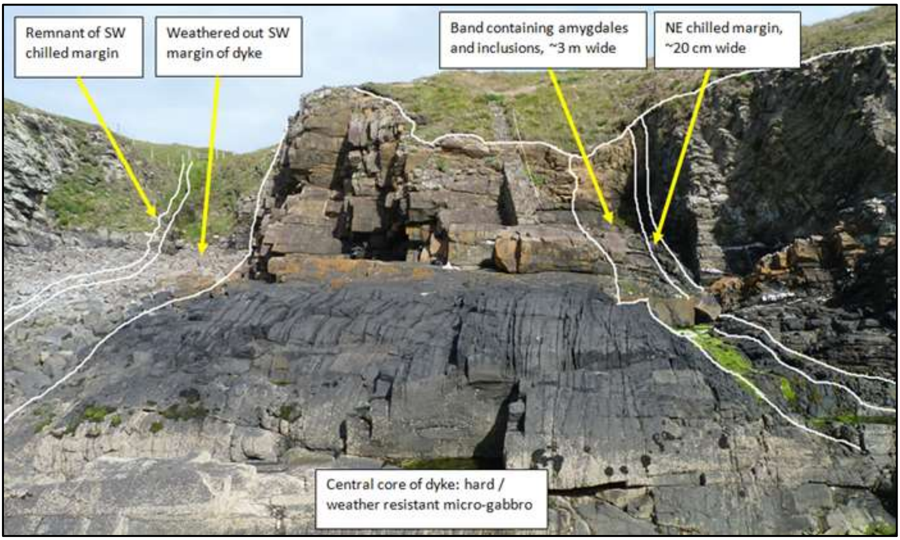

Figure 5: Holy Island Dyke exposure at Porth-y-Corwgl (~24m wide) Field observations highlighted.

The broad main body of the Holy Island Dyke is approximately 20m wide and has a medium-grained micro-gabbro texture, which appears to be devoid of vesicles. The formation as a whole is massively jointed, Figure 5. On the NE dyke margin, sitting parallel to the chilled margin and the main body of the dyke, is an approximately 3m wide band, containing abundant slightly stretched amygdales (up to 1.5cm long) and inclusions (up to 15cm long). The chilled margins of the dyke are composed of dark grey-coloured fine-grained basalt containing spots and small amygdales, up to 1mm wide. The contact surface between the dyke and the country rock is bumpy and irregular on both margins. Only one intact exposure on the SW dyke margin was identified in the field, a section approximately 10m long and 1.5m wide, composed of narrow bands of solid basalt separated by bands of lineated material with a sheared appearance.

Field location 3: Llanbadrig Dyke

Figure 6: Llanbadrig dyke field observations. The dyke meanders along a mean trend of 300°, dips ~15° towards the NE and has a fractured interior varying in thickness from <1 to >50cm

A series of dykes is exposed close to Llanbadrig Church, near Cemaes Bay. One of these dykes (approximately 50m long, 2m wide and dipping 15° towards the NE) cuts through rocks of the Gwna Melange sequence (Cambrian) and appears to follow a sinuous track through the landscape, Figure 6. The chilled margins of the dyke have been mostly weathered out, leaving a large gully between the country rock and the dyke on both margins. The dyke rock is grey to light blue in colour and has a fine-grained micro-porphyritic texture with small rounded amygdales (<1mm). The interior of the dyke has a fractured appearance, Figure 6. At two locations the dyke can be seen to bifurcate into two separate units.

Sample collection and preparation

The rock sampling process involved identifying rocks in situ which had not been significantly weathered and had a flattish surface for orientation purposes. Samples were oriented in the field using a compass inclinometer to measure the strike and dip of the rock surface. Back in the lab, each rock sample was prepared for drilling by setting it in dental plaster with the orientated rock surface horizontal and face upwards. 25mm diameter cores were drilled out of each rock sample and cut into 22mm cylinders for AMS measurement using a magnetometer. These AMS measurements were undertaken at the University of Liverpool Geomagnetism Laboratory with an AGICO MFK1-FA multi-function Kappabridge instrument.

AMS Results

Grinshill

AMS measurements, samples 40-43, Table 2, reveal a complex rock fabric. The random orientations of AMS susceptibility axes (and plagioclase phenocrysts) in the dyke would suggest that magma flow was turbulent during emplacement.

Holy Island Dyke

AMS measurements, samples 2–25, Table 2, reveal good clustering of AMS principal susceptibility axes, indicative of a normal magnetic fabric. AMS results indicate that magma flowed up as well as down in what appear to be large circular motions during emplacement, Figure 7. The amygdale band close to the NE margin of the dyke supports the idea that, prior to any degassing, the magma flowing through the dyke was highly vesicular and therefore strongly buoyant.

Assuming magma flow is laminar, the velocity gradient at the margin of dykes will decrease over inward irregularities and increase across protrusions (Pollard, 1987). The irregular dyke walls observed in the field seem to be mirrored in the imbrication of magnetic lineation results where α ranges between <5^{o} and 40^{o}, Figure 7, and may support the idea that these lumps and bumps had an important influence on magma emplacement processes.

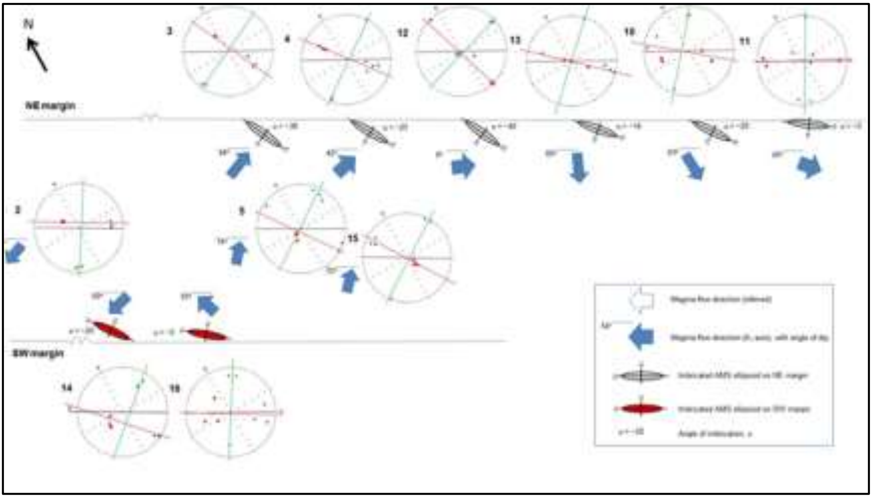

Figure 7: Magma flow determination diagram: Holy Island Dyke at Porth-y-Corwgl. AMS principal axes for each sample are plotted on a lower hemisphere projection diagram and positioned in their relative *in situ* position. Magma flow (blue arrow) is interpreted from the imbrication of magnetic lineations. AMS ellipsoids have been drawn in their imbrication position to illustrate flow determination. *(Despite weak resolution in the figure, which we were unable to rectify, magma flow direction can be discerned – ed.)*

Llanbadrig Dyke

A dyke approaching the surface will experience a decrease in pressure leading to the exsolution of gas. This gas will accumulate in the dyke tip and act as a driving force for upwards propagation (Pinkerton *et al*., 2002). In these conditions shear stresses in the magma flow are likely to be high.

AMS measurements, samples 30-32, Table 2, reveal good clustering of AMS principal susceptibility axes, indicative of a normal magnetic fabric, Figure 8. Magnetic lineation results indicate that magma flow was close to vertical (K_1 axes close to the centre of the plot).

In each sampling location, the magnetic foliation plane is twisted by around 45° and this could be interpreted as high shear stresses being resolved on the dyke wall during emplacement. Observed dyke bifurcation, the fractured band in the centre of dyke and the sinuous dyke morphology also point to high shear stresses in the magma flow and turbulence in the propagating dyke tip, during dyke emplacement.

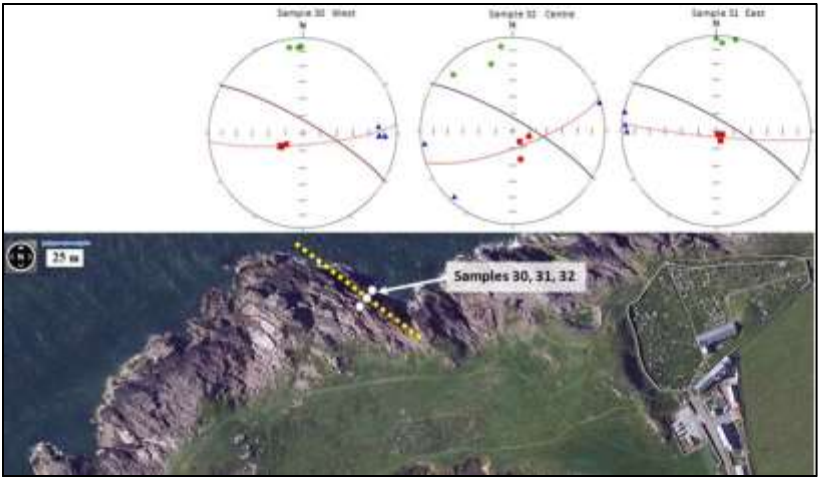

Figure 8: AMS results for Llanbadrig dyke. Llanbadrig church and graveyard is on the right. The line of the exposed NW-SE trending dyke is represented by a yellow dotted line. Lower hemisphere stereographic projection diagrams are presented for samples 30, 31 and 32; black solid lines represent the dyke plane, red dashed lines are foliation planes. Satellite image modified from Bing Maps © Microsoft

Geochemistry Results

All geochemistry tests were performed at Hafren Scientific Ltd, using inductively coupled plasma optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS), Tables 3, 4 and 5. A Total Alkali Silica (TAS) Diagram summarises the results, Figure 9.

Rare Earth Element (REE) concentrations in all the dykes studied are very similar, hinting at a common magma source, most likely normal mid-ocean ridge basalt (N-MORB), generated within the mantle (Pearce, 1983). According to Kent & Fitton (2000), the presence of N-MORB would indicate that the melting regime beneath the British Isles in the Palaeogene was similar to that observed beneath present day Hawaii; a vigorous plume, an intact lithosphere, polybaric melting and average melt fractions of >7%.

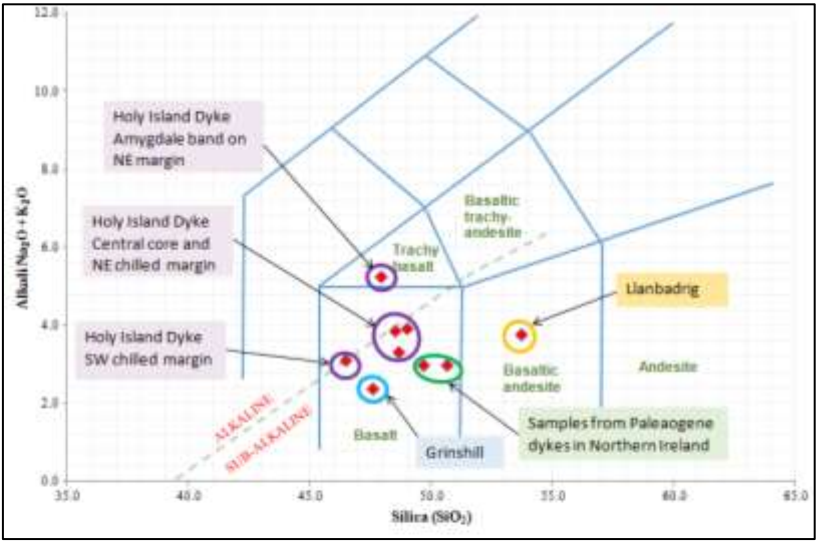

Figure 9: Total Alkali Silica (TAS) Diagram

The main body of the Grinshill dyke is composed of tholeiitic basalt. Marked enhancement in Al_2O_3, K_2O, alongside depletion in MgO and CaO, has been attributed to chemical alteration (Thompson and Winchester, 1995). Relative Rb Th enrichment and Ni Cr depletion may be evidence of crustal contamination, indicating that these dykes may have been fed from a proximal source where magma resided for a period of time before intrusion.

The chilled margins and the main body of the Holy Island Dyke are composed of tholeiitic basalt. The banded rock on the SW margin of the Holy Island Dyke is composed of tholeiitic basalt with a relatively low silica content. The 3m wide amygdaloidal zone on the NE margin is composed of trachybasalt. These variations in geochemistry suggest that intrusions on the outer margins of the dyke were generated at a different time from that of the main body.

The Llanbadrig Dyke is composed of basaltic-andesite. Assuming the parental magma was basalt, this would indicate that the magma was subject to a period of temporary storage within the crust prior to dyke injection.

Discussion

Grinshill Dyke

AMS and geochemistry results suggest that basalt magma flowed turbulently into this narrow dyke from a temporary crustal source. The dyke rock is highly porphyritic so the basalt magma would have had a relatively high viscosity, a factor that would have contributed to the turbulence observed.

Holy Island Dyke

AMS and geochemistry results suggest that basalt magma was injected into this dyke sub-vertically from a deep source and subsequently flowed in large circular motions along the dyke plane. Magma failed to reach the surface and exposures have been revealed as a result of the erosion of the overlying rock.

Field work observations and geochemistry indicate that there were at least three distinct phases of magma injection, mirroring the composite dyke injection events observed in Northern Ireland. An interpretation of this multi-phase intrusion is shown in Figure 10.

Llanbadrig Dyke

AMS and geochemistry results suggest that magma flowed into this dyke vertically from a temporary crustal source, e.g. a sill or shallow magma chamber.

Evidence of turbulent flow in the centre of the dyke may be the result of magma accelerating in upper crustal levels, possibly reaching the surface to form a fissure eruption. A simplified model for the emplacement of the Llanbadrig Dyke based on AMS results is presented in Figure 11.

Summary

Several authors have proposed that the arrival of a mantle plume beneath Greenland in the early Cenozoic led to uplift in Northern

Britain, the generation of regional NE-SW stresses and the emplacement of NW-SE trending dyke swarms.

Speight *et al.*, (1982) proposed that Palaeogene dyke swarms were the surface expression of deep-seated linear ridges of magma rising from the base of the crust, fed by partial melting of the mantle. Field observations, AMS results and geochemistry presented in this paper support these broad ideas. There was little or no evidence for lateral flow of magma into these dykes from a distal source such as the Carlingford volcanic complex in Northern Ireland.

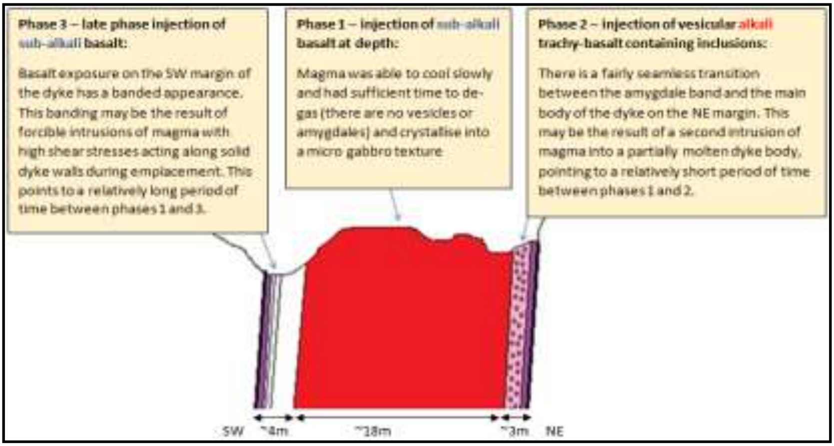

Figure 10: Holy Island Dyke; evidence for multiple phases of emplacement

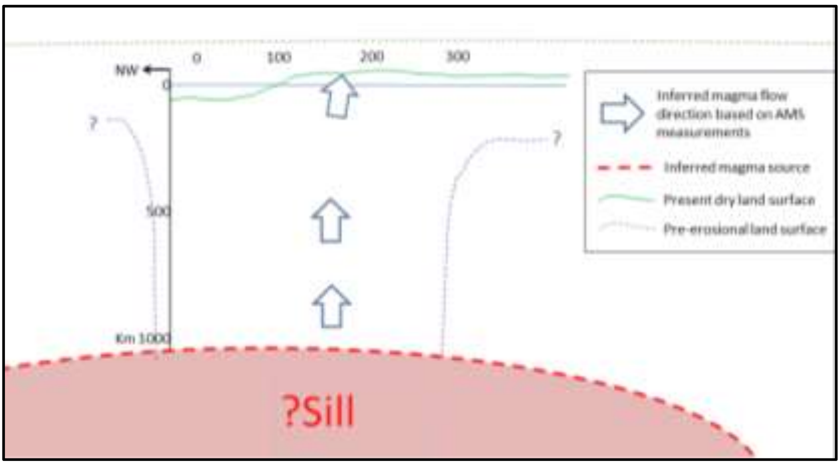

Figure 11: A simplified model for the emplacement of the Llanbadrig Dyke based on AMS results. The cross-section lies along the NW-SE trend of the dyke.

Table 1: Palaeogene dykes in North Wales and Shropshire. Field location notes.

Field	OS Grid reference	Location	Width	Notes
1	SJ 52561 23825	Grinshill stone quarries, Shropshire, SY4 3LF	Approx. 0.3m	Palaeogene dyke cuts through Sherwood Sandstone Group, and terminates upwards in the Tarporley Siltstone, at the base of the Mercia Mudstone Group.
2a	SH 23279 79977	Porth Dafarch	Approx. 23m	Exposure in cliff on north side of the bay. Good quality exposures in the centre and on NE dyke margin only.
2b	SH 23410 79924	Porth Dafarch	Approx. 23m	Dyke exposure on the beach on the south side of the bay. Poor quality exposures in the centre. Highly weathered exposure on NE dyke margin.
2c	SH 23807 79616	Porth-y-Corwgl	Approx. 23m	Dyke exposed at base of cliff. Good quality exposures in the centre and on opposing dyke margins.
2d	SH 21648 80935	Porth-y-Gwyddel	Approx. 25m	Palaeogene dyke exposure below cliff, approximately 500 m long. Unfortunately, site only accessible via abseil or boat.
3a	SH 37412 94678	Llanbadrig	Approx. 2m	Palaeogene dyke exposure intruding into Gwna Formation. Not indicated on BGS map.
3b	SH 35788 94494	Wylfa Head	Approx. 1 - 2m	Dyke exposures indicated on BGS map.
4	SH 51416 84937	Traeth Bychan	0.5m	Traeth Bychan dyke viewable on wave cut platform, north side of the bay. Ray Humphreys, North Wales Geological Association (NWGA).
5	SH 521 692	Plas Newydd, Menai Straits	Approx. 25m	Palaeogene dyke exposure documented in various sources, confirmed by Jan Heiland, NWGA. Highly weathered exposure.
6	SH 54611 67903	Nant-y-Garth dykes, with exposures 7km to	Approx. 25m	Two Palaeogene dyke exposures. Not easy to access, highly weathered. Jan Heiland, NWGA.
7	SH 56002 72936	Plas Cadnant, Menai Bridge, Anglesey	Approx. 25m	BGS map indicates dyke exposure on side of Afon Cadnant valley. Not confirmed.
8	SH 6431 6053 SH 6419 6069	Ogwen Cottage	Unknown	Weathered, poorly exposed Palaeogene dyke, confirmed by Jan Heiland, NWGA.

Table 2: AMS measurements for dyke samples collected from the Holy Island (samples 2-25), Llanbadrig (samples 30-32) and Grinshill (samples 40-43) dykes.

Spec	K (µSI)	L	F	P	P'	T	U	H%	E	k1-Dec	k1-Inc	k2-Dec	k2-Inc	k3-Dec	k3-Inc
2.1	31430	1.008	1.012	1.020	1.020	0.208	0.203	1.914	1.004	318	57	106	29	204	15
2.2	31470	1.007	1.013	1.020	1.020	0.337	0.333	1.952	1.007	323	58	118	29	214	11
2.3	32540	1.007	1.013	1.020	1.020	0.287	0.282	1.942	1.006	323	60	114	27	210	13
3.1	50410	1.004	1.022	1.026	1.028	0.683	0.680	2.546	1.018	351	54	146	33	244	12
3.2	49190	1.005	1.021	1.027	1.028	0.587	0.583	2.608	1.016	349	53	153	36	249	8
4.1	40040	1.010	1.017	1.027	1.027	0.244	0.238	2.603	1.006	328	34	126	54	231	10
4.2	43750	1.004	1.022	1.026	1.028	0.688	0.685	2.539	1.018	328	49	134	40	230	7
4.3	41930	1.013	1.007	1.020	1.021	-0.322	-0.327	1.984	0.994	326	44	150	46	58	2
5.1	36060	1.005	1.012	1.017	1.017	0.403	0.400	1.635	1.007	228	67	334	7	67	22
5.2	37990	1.003	1.016	1.019	1.020	0.659	0.657	1.843	1.012	251	75	150	3	59	14
5.3	35700	1.004	1.015	1.018	1.020	0.608	0.605	1.807	1.011	254	79	139	4	48	10
7.1	44210	1.003	1.029	1.032	1.035	0.816	0.813	3.067	1.026	43	43	302	11	201	45
7.2	42250	1.005	1.030	1.035	1.038	0.718	0.714	3.358	1.025	78	29	329	31	201	46
7.3	42290	1.010	1.021	1.031	1.032	0.375	0.368	3.037	1.012	54	33	312	18	199	51
7.4	43760	1.003	1.033	1.036	1.040	0.835	0.832	3.484	1.030	53	46	308	14	206	41
10.1	45160	1.009	1.010	1.019	1.019	0.082	0.077	1.909	1.002	279	38	143	43	29	24
10.2	46055	1.012	1.015	1.027	1.027	0.096	0.090	2.573	1.003	119	66	326	22	232	10
10.3	44470	1.009	1.012	1.021	1.021	0.119	0.114	2.064	1.002	286	37	145	46	32	20
11.1	40720	1.008	1.018	1.026	1.027	0.4	0.394	2.522	1.010	293	21	91	68	200	8
11.2	33210	1.002	1.026	1.027	1.031	0.874	0.872	2.656	1.024	122	18	341	67	217	13
11.3	37080	1.002	1.030	1.032	1.036	0.856	0.854	3.117	1.027	305	15	136	75	36	3
12.1	50450	1.009	1.017	1.025	1.026	0.323	0.317	2.473	1.008	168	1	272	85	78	5
12.2	53380	1.008	1.023	1.032	1.033	0.468	0.462	3.080	1.015	166	3	276	80	75	9
12.3	54905	1.008	1.024	1.031	1.032	0.523	0.517	2.991	1.016	346	2	245	81	76	9
13.1	36030	1.004	1.023	1.027	1.029	0.704	0.700	2.626	1.019	141	58	316	32	47	2
13.2	39280	1.002	1.030	1.033	1.037	0.855	0.853	3.185	1.028	318	87	136	3	226	0
13.3	38250	1.010	1.032	1.042	1.044	0.501	0.493	4.062	1.021	312	76	133	14	43	0
14.1	45960	1.005	1.015	1.020	1.021	0.493	0.490	1.978	1.010	281	66	156	14	62	19
14.2	53570	1.014	1.015	1.029	1.029	0.005	-0.003	2.805	1.000	245	55	152	2	61	35
14.3	54485	1.012	1.017	1.029	1.029	0.201	0.194	2.806	1.006	254	57	153	7	59	33
15.1	36010	1.010	1.007	1.017	1.017	-0.174	-0.178	1.709	0.997	162	72	332	17	62	3
15.2	35970	1.008	1.009	1.017	1.017	0.036	0.031	1.713	1.001	153	67	322	23	54	4
15.3	37170	1.011	1.010	1.021	1.021	-0.042	-0.047	2.060	0.999	134	77	321	13	230	2
16.1	41590	1.007	1.016	1.023	1.024	0.371	0.366	2.280	1.009	342	50	107	25	212	28
16.2	42680	1.008	1.013	1.021	1.021	0.234	0.229	2.064	1.005	266	62	136	18	39	20
16.3	46730	1.001	1.020	1.021	1.023	0.906	0.905	2.016	1.019	281	39	137	45	27	19
23.1	39060	1.010	1.039	1.049	1.052	0.605	0.597	4.690	1.029	100	30	290	60	192	4
23.2	37080	1.005	1.042	1.047	1.052	0.796	0.792	4.513	1.037	147	14	265	62	51	24
23.3	35390	1.005	1.032	1.037	1.040	0.708	0.703	3.571	1.026	151	15	265	57	52	29
24.2	45080	1.011	1.027	1.038	1.039	0.425	0.417	3.617	1.016	193	57	82	13	345	29
24.3	45550	1.013	1.033	1.047	1.049	0.418	0.408	4.500	1.019	188	55	82	10	346	33
24.4	43390	1.011	1.027	1.038	1.039	0.435	0.428	3.663	1.016	196	63	90	8	356	25
25.1	31660	1.006	1.011	1.017	1.017	0.254	0.250	1.690	1.004	333	55	111	27	212	20
25.2	34440	1.007	1.011	1.019	1.019	0.227	0.222	1.834	1.004	322	47	108	37	212	17
25.3	32400	1.008	1.010	1.017	1.018	0.114	0.109	1.719	1.002	317	50	109	36	210	14
30.1	649.7	1.009	1.011	1.019	1.020	0.109	0.104	1.910	1.002	235	73	92	13	359	10
30.3	672.2	1.010	1.013	1.024	1.024	0.131	0.126	2.339	1.003	241	68	92	19	358	10
30.4	631	1.010	1.011	1.021	1.021	0.055	0.050	2.048	1.001	240	67	92	20	357	11
31.1	39240	1.036	1.038	1.075	1.075	0.018	0.000	6.987	1.001	155	81	274	4	4	8
31.2	23210	1.033	1.042	1.076	1.077	0.121	0.103	7.091	1.009	160	87	282	1	12	2
31.3	34000	1.032	1.038	1.071	1.072	0.089	0.072	6.665	1.006	117	84	270	6	360	3
32.1	780.3	1.016	1.007	1.023	1.024	-0.388	-0.392	2.240	0.991	164	64	72	1	342	26
32.2	729.7	1.021	1.010	1.031	1.032	-0.357	-0.364	3.016	0.989	147	79	262	4	352	10
32.3	742.2	1.018	1.009	1.027	1.027	-0.359	-0.364	2.610	0.991	109	75	222	6	313	13
40.1	457.75	1.005	1.006	1.011	1.011	0.141	0.138	1.051	1.002	278	7	18	56	183	34
40.2	555.2	1.005	1.005	1.009	1.009	0.025	0.023	0.888	1.000	195	5	306	77	104	12
40.3	490.35	1.001	1.006	1.007	1.007	0.774	0.773	0.625	1.005	229	6	320	15	120	75
41.1	455.6	1.002	1.002	1.003	1.003	0.138	0.138	0.323	1.001	297	26	204	4	106	64
41.2	525.7	1.001	1.002	1.003	1.003	0.482	0.481	0.261	1.001	141	7	140	28	329	61
41.3	390.95	1.004	1.002	1.006	1.006	-0.178	-0.179	0.594	0.999	11	31	104	6	203	58
42.1	536.45	1.003	1.002	1.005	1.005	-0.253	-0.254	0.428	0.999	152	23	41	40	263	41
42.2	682.5	1.007	1.003	1.010	1.011	-0.391	-0.393	1.019	0.996	309	21	213	15	90	64
42.3	613.1	1.006	1.006	1.012	1.012	-0.026	-0.029	1.151	1.000	129	49	290	39	28	10
43.1	219.9	1.002	1.004	1.006	1.006	0.383	0.382	0.619	1.002	53	41	315	9	215	48
43.2	287.7	1.003	1.006	1.010	1.010	0.361	0.359	0.945	1.003	54	42	317	7	219	47
43.3	307.3	1.002	1.009	1.011	1.012	0.564	0.562	1.103	1.006	51	42	314	8	216	47

Table 3: Major element geochemistry results. Data for samples 13, 14, 21, 25, 30 and 41 was provided by Chemostrat Ltd. Data for Northern Ireland basalt samples was sourced from Barrat and Nesbitt (1996). Geochemistry data for Grinshill Dyke A was sourced from Thompson and Winchester (1995).

	Major elements (wt%)								
	Northern Ireland (ATM3-LBF)	Northern Ireland (ATM33-UBF)	Holy Island: NW margin (14)	Holy Island: Main body (25)	Holy Island: Vesicular band (13)	Holy Island: NE margin (21)	Llanbadrig (30)	Grinshill (41)	Grinshill (Dyke A)
SiO_2	46.40	46.64	46.45	48.49	47.87	48.62	53.68	48.96	47.56
TiO_2	1.99	1.56	1.72	1.84	1.89	1.78	2.88	2.16	2.69
Al_2O_3	15.50	15.93	15.51	15.88	14.34	16.00	15.26	14.23	14.32
Fe_2O_3	13.77	13.94	13.89	14.04	14.13	14.18	12.63	8.56	6.64
MnO	0.18	0.18	0.26	0.23	0.25	0.28	0.07	0.10	0.11
MgO	9.10	9.40	8.13	7.58	8.05	8.09	7.20	1.73	3.09
CaO	9.33	9.67	8.43	8.75	7.08	8.64	1.99	8.47	8.45
Na_2O	2.70	2.61	2.68	3.08	4.26	2.96	3.57	2.17	1.24
K_2O	0.47	0.31	0.43	0.80	1.03	0.40	0.22	1.79	1.15
P_2O_5	0.24	0.20	0.27	0.32	0.35	0.27	0.36	0.35	0.45
Total	99.68	100.44	97.77	100.99	99.25	101.22	97.85	88.52	85.70

Table 4: Trace element geochemistry results. Data for samples 13, 14, 21, 25, 30 & 41 was provided by Chemostrat Ltd. Data for Northern Ireland basalt samples was sourced from Barrat and Nesbitt (1996). Geochemistry data for Grinshill Dyke A was sourced from Thompson and Winchester (1995).

	Trace elements (ppm)								
	Northern Ireland (ATM3-LBF)	Northern Ireland (ATM33-UBF)	Holy Island: NW margin (14)	Holy Island: Main body (25)	Holy Island: Amygdale band (13)	Holy Island: NE margin (21)	Llanbadrig (30)	Grinshill (41)	Grinshill (Dyke A)
Ba	-	64	259.46	429.22	721.96	229.56	232	8057	-
Cr	241	229	241.83	207.29	180.55	233.34	69	13	21
Ga	20	15	18.27	19.05	16.46	18.12	20	24	29
Nb	3	7	9.82	13.48	12.21	10.80	20	15	18
Ni	179	166	132.13	127.05	93.88	130.17	27	29	27
Pb	1	<1	6.98	5.04	7.39	5.72	7	543	162
Rb	4	3	10.50	18.56	24.45	10.30	8	23	16
Sr	439	212	241.91	284.66	248.20	277.44	115	246	77
Th	-	0.4	2.06	2.65	2.89	2.17	4.08	4.28	-
V	268	174	331.20	335.17	334.12	341.36	378	228	215
Y	26	30	34.65	37.81	44.10	34.98	50	71	93
Zn	84	68	95.29	92.06	104.85	88.99	84	12609	6230
Zr	147	106	113.45	131.81	156.43	122.51	278	257	313

Table 5: Rare earth elements (REE) geochemistry results, reported as parts per million by weight. Data for samples 13, 14, 21, 25, 30 & 41 was provided by Chemostrat Ltd. Data for Northern Ireland basalt samples was sourced from Barrat and Nesbitt (1996). Geochemistry data for Grinshill Dyke A was sourced from Thompson and Winchester (1995).

	Rare earth elements (REE) geochemistry results, reported as parts per million by weight.								
	Northern Ireland (ATM3-LBF)	Northern Ireland (ATM33-UBF)	Holy Island: SW margin (14)	Holy Island: Main body (25)	Holy Island: Amygdale band (13)	Holy Island: NE margin (21)	Llanbadrig (30)	Grinshill (41)	Grinshill (Dyke A)
La		3.92	13.84	16.12	18.01	14.02	24.00	20.00	21
Ce		10.84	30.19	34.65	39.05	30.70	53.78	43.41	63
Pr		1.95	4.03	4.60	5.22	4.09	7.15	6.15	
Nd		10.03	17.56	20.16	22.49	18.28	30.32	28.48	44
Sm		3.34	4.55	4.96	5.78	4.74	7.39	7.84	
Eu		1.23	1.75	1.90	1.97	1.59	2.08	2.98	
Gd		3.95	5.07	5.57	6.31	5.01	7.44	9.10	
Tb			0.88	0.94	1.05	0.86	1.29	1.57	
Dy		4.22	5.59	5.94	6.77	5.57	8.04	10.65	
Ho			1.23	1.30	1.53	1.25	1.82	2.45	
Er		2.5	3.13	3.33	3.87	3.29	4.67	6.39	
Tm			0.47	0.52	0.60	0.48	0.70	0.96	
Yb		2.24	2.97	3.28	3.82	3.12	4.58	6.28	
Lu			0.45	0.50	0.57	0.45	0.68	0.94	

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Palaeoecological lessons from a plate of oysters

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Introduction

When I eat oysters with my son, Pelham, aged 16, there is always friendly competition to see who has the most interesting shell. To what substrate did the oyster attach? Was the oyster valve bored? What encrusted the oyster? All good fun and, in part, it is a way to encourage Pelham to think more about the natural environment. Indeed, he once had a shell that was so unusual – the oyster had attached inside the aperture of a dead gastropod and grown out of this confined space – that I wrote a brief account for publication (Donovan 2013).

My partner, Karen, who lives in Worsley, also enjoys a good restaurant, particularly an Italian, although she does not share my taste for oysters. On a recent visit (Easter Monday 2015) we found ourselves in the Piccolino Restaurant in Clarence Street, Manchester. I ordered my favourite starter, six oysters, but only received four as they were the only ones that my waiter considered fit for consumption. While four is not six, I did appreciate my (sometimes delicate) tum receiving such kind consideration.

The oysters were good and, of course, I turned them over to inspect the external surface of the shells. What a treasure trove! I had a joke with the waiter when he came to clear the plates and was astonished that I also appeared to have eaten the shells. They had, of course, already disappeared into my bag, but re-emerged so that I could explain my interest to the waiter and the manager.

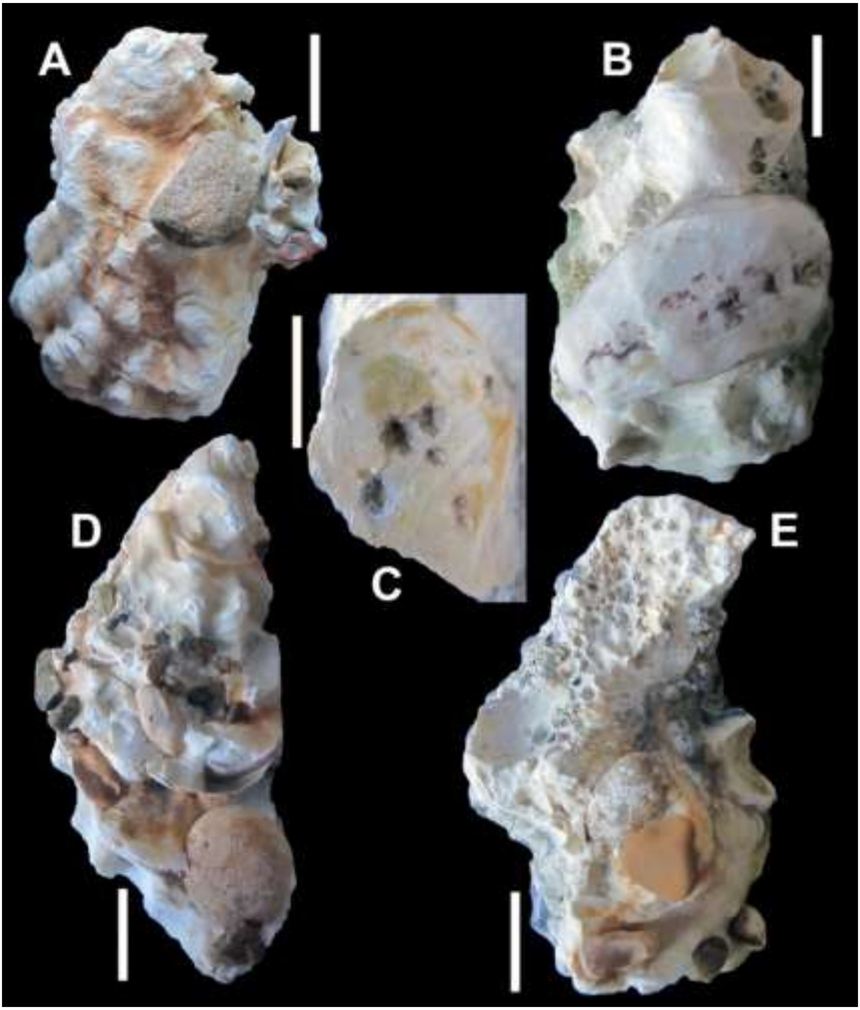

Figure 1: *Crassostrea gigas* (Thunberg) from the Piccolino Restaurant, Manchester. All images illustrate the external surfaces of attached (left) valves.

(See facing page for details – ed.)

Figure 1: *Crassostrea gigas* (Thunberg)
(A) RMNH.5003963, showing attachment to polymict pebbles.
(B, C) RMNH.5003966.
(B) Juvenile valve attached diagonally across valve.
(C) Attachment scar at umbo, preserving balanid barnacles which were originally attached to the pebble substrate (rotated through 180º from (B)). Scale bar represents 10 mm.
(D) RMNH.5003964, dense attachment to pebbles and, just below mid length and to the right, a section through the curved shell of the gastropod *Crepidula* sp.
(E) RMNH.5003965, originally attached to a cobble, trending top to left mid-length, encrusted by balanid barnacles which are now embedded in the oyster valve.
Scale bars in A,B,D &E represent 20mm

Materials and methods

The Piccolino menu describes this starter as Mersea Island rock oysters. Mersea Island is in Essex and oyster culture is an important local industry (http://www.visitessex.com/discover/maritime/Mersea_Island.aspx).

My initial identification of these oysters as *Ostrea edulis* Linné, the common European oyster, was based mainly on the character that the "Adductor muscle scar [is] white or only slightly discoloured" (Tebble 1976, p. 52; see also Beedham 1972; Campbell 1976). In two specimens it is white and it is only weakly discoloured in the other two, as it is in the juvenile attached to RMNH.5003966, but none appeared to be as dark as *Crassostrea* spp. (Tebble 1976, pl. 4a, c). However, the elongate shells are more like *Crassostrea* than *Ostrea* and Mr Jeroen Goud (Naturalis, Leiden) kindly corrected my error; these shells represent *Crassostrea gigas* (Thunberg), the Japanese oyster, which was only introduced to European waters about 1980 (Moerdijk *et al*. 2010), thus post-dating all the guides that I had used in my initial determination.

The four attached (= left) valves were cleaned in household bleach diluted with tap water and subsequently rinsed. The remains of adductor muscles were removed mechanically and the muscle scars scrubbed clean with a soft brush to remove any last tissues that were adhering. They were then rinsed again and left to dry in a gentle natural heat on tissue paper. After about 12 days, the free valve of the juvenile attached to RMNH.5003966 (Figure 1B) had opened, the soft tissues were putrefying and the shell needed further cleaning in bleach.

Photography was under natural light using a Canon G11 digital camera. Specimens are deposited in the Recent molluscs collections of the Naturalis Biodiversity Center, Leiden, the Netherlands (prefix RMNH).

Description

All left valves show evidence of attachment to a pebble-rich substrate (fixed-sessile *sensu* Schäfer 1972, p. 154) with an associated shelly biota incorporating elements that were both live and dead at the time of harvesting of the oysters. RMNH.5003963 (about 92mm in maximum dimension = height) grew on and around a group of lithic pebbles and shell fragments (Figure 1A). Pebbles are siliceous, including quartzite, chert, jasper and, the largest, a well-cemented, medium-grained sandstone. Identifiable shell fragments that were similarly cemented to and overgrown by the oyster are a balanid barnacle and a bivalve, possibly a cockle.

RMNH.5003964 (about 117mm in height) is similar although more pebbles are spread over a wider area; recognisable lithologies include cherts and sandstones (Figure 1D). A dead shell of the gastropod *Crepidula* sp. has been overgrown by the oyster (compare with Donovan 2013). Around the raised margins of the left valve, the oyster itself has been encrusted by balanid barnacles, early juvenile oysters and calcareous algae. The balanids and juveniles were alive when the oyster was harvested as neither is disarticulated. The white calcareous algae are most obvious on pebbles, but in at least one area the algae have grown onto the adjacent oyster. Fragments of bryozoan colonies are small and very incomplete.

The remaining pair of oysters is yet more exotic. RMNH.5003965 (about 94mm in height) again preserves abundant pebbles from the substrate; one just below the centre of the figure is encrusted by calcareous algae that have not overgrown the oyster, but, rather, are overgrown by the valve. The initial attachment was to a small, rounded and elongate cobble, now lost, but over 62mm long and which was partly encrusted in balanids (Fig. 1E, top and sloping to mid-height on the left). These were alive when encrusted as individuals preserve the opercular valves *in situ*, sealing the apertures; these plates are commonly lost soon after death (for an explanation of the descriptive terminology of the balanid shell and their ecology, see Schäfer 1972, pp. 112-120; Southward 2008; Collins *et al*., 2014). Thus, much of this attachment scar is lined with balanids seen in basal view. At some time the cobble was lost, most probably because the weight of the oyster was too great for the attached, cemented, but dead balanids. Subsequently, the now-exposed bases of the barnacles were encrusted by bryozoans. As in RMNH.5003964, areas of the valve that were raised above the substrate are encrusted by balanids preserving opercular valves in the apertures (that is, they were alive when harvested).

RMNH.5003966 (about 97mm in height) had a similar attachment to RMNH.5003965, that is, attached to a pebble (now lost) encrusted by living balanid barnacles (Figure 1B, C). The shell then seems to have rolled over on the seafloor, as the attached valve is encrusted by the most diverse biota of these specimens, including green algae (apparent after the first bleach bath, but now lost), branching, twig-like calcareous algae, balanid barnacles, bryozoans and, most spectacularly, an articulated juvenile oyster (now disarticulated following a second bleaching). The juvenile oyster was still sealed when photographed, but subsequently opened and needed a second bleach bath to remove organic tissues. Note that the free valve of the juvenile itself preserves partial attached valves of two even younger oysters (Figure 1B, in shadow to the right).

Discussion

A description of a group of oysters from a restaurant may appear whimsical, but there is a serious purpose in examining them in detail. Once eaten and cleaned, these shells are in a state of preservation analogous to that of fossil oysters from any Cenozoic or older deposit, without the disadvantage of adhering rock matrix obscuring details. It is good practice for the palaeoecologist to flex their powers of observation on such specimens in the knowledge that fossil oysters will seldom be quite so well preserved.

The principal interest of these oyster valves to the palaeoecologist is in the evidence of substrates and organism-organism interactions. These oysters are not locally grown – Mersea Island is over 200km from Manchester as the crow flies – and in geological vernacular are allochthonous. Yet, taken together, these four valves provide a small snapshot of the seafloor at distant Mersea Island. There is ample evidence that the substrate is comprised of siliceous pebbles, varying from well-rounded to sub-angular (Figure. 1); the largest (now lost) was a cobble over 62mm long (Figure 1E). Shell fragments were a minor part of the substrate (dead balanids, *Crepidula*, cockle) and oysters also attached to them. That the oysters were growing in the photic zone is determined by the presence of green plants, that is, calcareous algae. The oysters acted as hard substrates themselves, most notably for balanid barnacles, but also algae, bryozoans and juvenile oysters.

Encrusting by juvenile oysters is hardly unexpected and is well known in the fossil record (see, for example, the spectacular examples illustrated by Littlewood and Donovan 1988, pl. 91, Figures 4 & 10), but is presumably less likely on attached rather than free (right) valves. This is a good indication that, despite initially cementing to pebbles, the oyster eventually reached a size that could be turned over by a storm event. This left the attached valve uppermost and available for infestation by various organisms, including other oysters.

Acknowledgement
I thank the Naturalis Biodiversity Center, Leiden, for supporting my fieldwork in the UK (although I paid for lunch). Special thanks to Jeroen Goud (Naturalis, Leiden) for correcting my original misidentifications of the oysters – oops!

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Liverpool Geological Society field visit to Almeria 3-10 January 2016

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Five members of Liverpool Geological Society departed a wet and windy Liverpool and flew to a much sunnier Malaga where we met our field leader, Graham Sherwood. After picking up hire cars we drove 220km east to the Almeria region of S.E. Spain and our base in the small town of Gádor, some 15km north of Almeria, Figure 1.

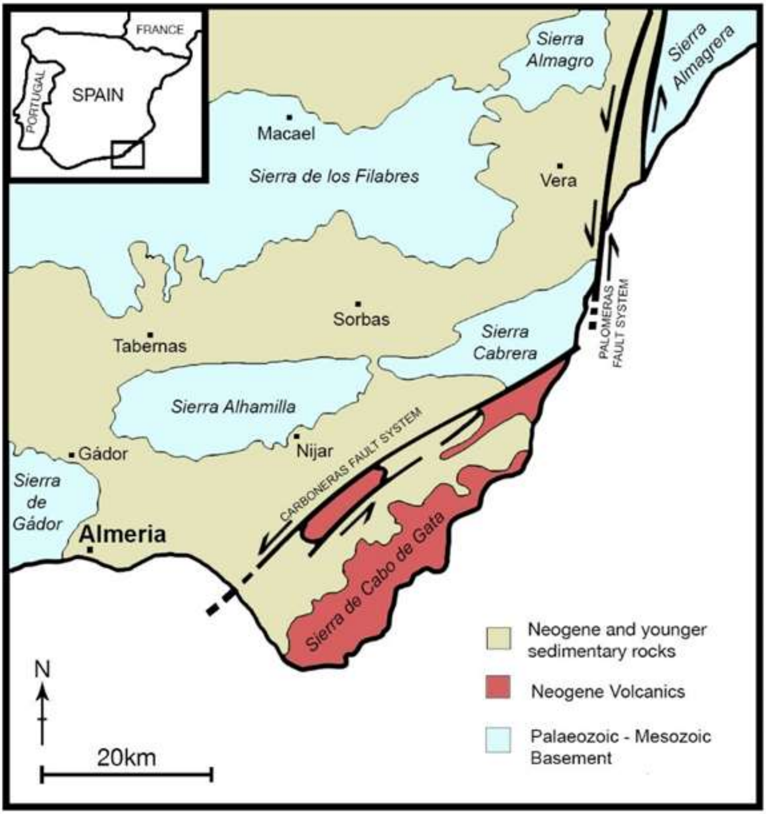

Figure 1: General geology and location map

In general, Spanish roads are a pleasure to drive. Once off main highways, however, we tackled some exciting roads, not for the faint-hearted. Gravel surfaces, hairpin bends, mega-potholes and precipitous drops were made even more challenging by low-angled sun early and late in the day. Another major challenge was eating a four course ‘menu of the day’ for lunch and then staying awake in the afternoon.

The geology is complex, mainly due to phased and continuing uplift in different sedimentary basins in the area, creating different levels, which have then been deeply incised and dissected. Table 1 is an attempt to summarize what was seen on the field visit.

The oldest rocks form the metamorphic basement, Figure 2. It is thought that they were formed between the Carboniferous and Jurassic with the metamorphism occurring in the Lower Miocene some 25Ma ago, associated with the compressional uplift of the Betic mountain chain as the African Plate interacts with the European Plate. The area around Macael is the main marble producing area in Spain and the rock has been exploited to such an extent that whole mountain tops have been removed, Figure 3.

Figure 2: (a) Augen gneiss and (b) tourmaline gneiss. Metamorphic basement in Sierra de los Filabres. Photos: W.J.Iley

Table 1: Summary of the geology seen in the Almeria region.

Period	Member	Event	Rock	Interpretation	Features	Location
Holocene					Hot Springs	Los Baños de la Sierra Alhamilla
Holocene					Coastal lagoons and salt pans	Las Salinas
Holocene					Modern alluvial fans and sheet	Tabernas Basin
Holocene					Caliche	Everywhere
Holocene					Travertine curtains	Tabernas Basin (Bar Alfaro)
Holocene					Gypsum karst	Sorbas Basin
Quaternary			Conglomerates and sandstones	Alluvial fans and river terraces		Everywhere
Quaternary		Carboneras strike slip fault displaces rocks <12Ma and possibly still active			Associated hydrothermal alteration in fault zone	Rambla de la Granatilla near Solpalmo
Pliocene	Gochar (or equivalent)		Alluvial fans			Sorbas and Tabernas Basins
U. Miocene		Mineralisation associated with the fault zone and the volcanics	Gold, iron, lead and arsenic			Rodalquilar gold mine Lucianena de las Torres iron mines
U. Miocene (Messinian)	Sorbas		Symmetrical rippled sandstone above algal stromatolites. Herringbone cross stratification Bioturbation	Shallow marine/beach barrier		Various locations around Sorbas
U. Miocene (Messinian)	Yesares		Gypsum	Messinian salinity crisis	Massive beds of gypsum. Some exhibit Christmas tree formations	Sorbas basin. Los Yesares Quarry, Rio de Aguas
U. Miocene (Messinian)			Limestone with trace and body fossils. Cross bedding	Shallow marine		La Molata. El Palayazo
U. Miocene (Messinian)			Unusual volcanics (containing garnets) and ultra potassic volcanics (containing phlogopite mica)			El Hoyazo Nijar. Vera
U. Miocene (Tortonian)	Cabo de Gata Volcanics		Andesitic volcanics, pyroclastics, agglomerates and lavas	Submarine or emergent volcanoes		Cabo de Gata
U. Miocene (Tortonian)			Marls and turbidites. Includes the Gordo Megabed (slumps)	Deep water marine with earthquake activated large scale slumps. Distal turbidites – seismites		Tabernas Basin (Rambla de Tabernas at Llanos de Rueda)
M. Miocene (Serravallian)			Conglomerates/breccias /mega breccias/sands.	Transition from continental to deep water marine conditions		Tabernas Basin (Rambla de la Sierra)
M. Miocene (Serravallian)		Trans Alboran Shear Zone		Lateral shear created basin and range terrain		
L. Miocene		Metamorphism of the basement rocks	Schists, gneisses and weathered amphibolites. Marbles			Sierra de Alhamilla, Sierra de los Filabres. Macael marble quarries
Carboniferous to Jurassic		Deposition of basement rocks				

Figure 3: Macael marble quarries. Photos: H.E.Clark & W.J.Iley

Figure 4: View towards Cerro El Barronal over the landscape developed on the volcanic rocks of the Cabo de Gata range. Photo: W.J.Iley


Figure 5: Andesitic agglomerate, Cabo de Gata volcanics, Upper Miocene, Monsul beach. Photos: H.E.Clark

The Middle Miocene was a period of andesitic volcanics associated with the interaction of the African and European plates, Figures 4, 5. These rocks can be seen at various locations within the Cabo de Gata-Nijar National Park. There are also some “unusual” volcanic rocks. At El Hoyazo the calc-alkaline dacites contain cordierite and euhedral almandine garnets derived from the underlying schists. The garnets are washed out and carried downstream to form placer deposits, Figure 6, which were exploited for abrasives. At Vera the ultrapotassic rocks (verities) contain phlogopite micas.

Contemporaneously, the Middle Miocene conglomerates, breccias, mega breccias and sands, Figure 7, in the Tabernas basin indicate a transition from continental to deep water marine conditions. The convolute bedding of the Gordo Megabeds, Figure 8, has been interpreted as a seismite - a slump on the continental shelf triggered by an earthquake. This bed can be traced for many kilometres.

Figure 6: Garnet sands placer deposit derived from 'unusual' volcanic rocks at El Hoyazo, Nijar. Photo: W.J.Iley

Figure 7: Middle Miocene conglomerate. Rambla del la Sierra, Tabernas Basin. Photo: H.E.Clark

The Upper Miocene can be seen in the Tabernas and Sorbas Basins and represents a shallowing upwards sequence from deep marine turbidites and marls to shallow marine and beach barrier conditions. The Yesares Formation, comprising in excess of 100m of gypsum, denotes the Messinian salinity crisis when the Mediterranean almost dried out. Cone-like, inverted "Christmas tree" formations are interpreted as resulting from the competition between the growth of gypsum and the deposition of contemporaneous muddy sediments, Figure 9. The gypsum is soluble and karst features such as caves and sink holes develop. Unique to the area are gypsum tumuli which are formed as the gypsum dehydrates and then reabsorbs water, Figures 10, 11. The Sorbas Formation exhibits features associated with shallow water/beach environments such as herringbone and trough cross stratification in clean, washed calcareous sandstones, Figure 12, symmetrical ripples and stromatolites, Figure 13.

Figure 8: Large scale slump features of the Gordo mega beds (Upper Miocene) in Rambla de Tabernas at Llanos de Rueda. Photo: E.Thompson

Figure 9: Inverted 'Christmas tree'-like cones in the massive beds of gypsum of the Yesares Member, Upper Miocene. Rio de Aguas, Sorbas Basin. Photo: W.J.Iley

Figure 10: Examining gypsum karst features, Sorbas Basin. Insert: twinned gypsum crystals in the Yesares Member, Upper Miocene, Sorbas Basin. Photos: H.E.Clark, W.J.Iley

Figure 11: Large 'tumulus' developed in gypsum as the crystals absorb water. These features are exclusive to the Sorbas area. Yesares Member, U. Miocene, Sorbas Basin. Photo: W.J.Iley

Figure 12: Possible herringbone cross-stratification and bioturbated units in the Sorbas Member, Upper Miocene. Ramblas de los Chopos, Sorbas, Sorbas Basin. Photos: H.E.Clark & W.J.Iley

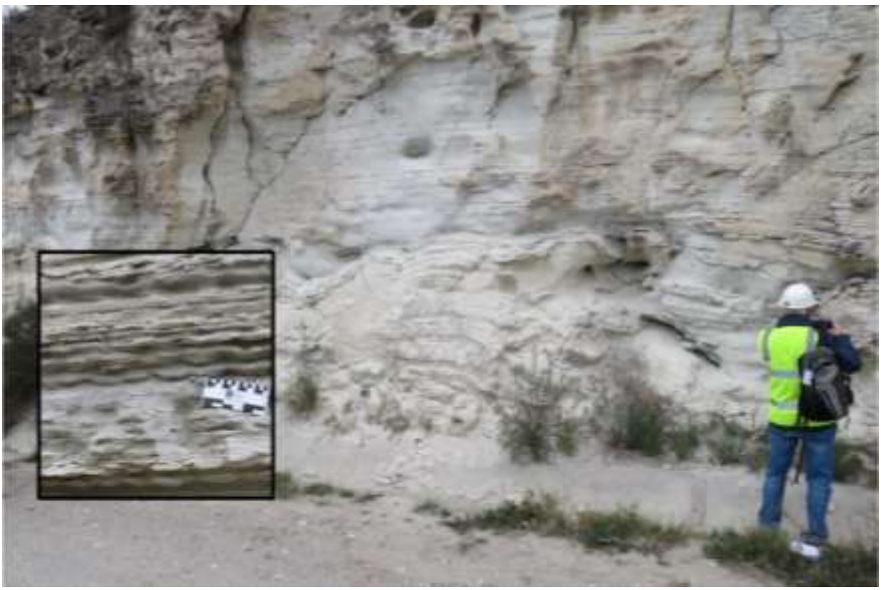

Figure 13: Stromatolite dome at the base of the section overlain by symmetrically rippled fine sands (inset). Note the effect of weathering on soft sediment once the surface crust has been breached. Sorbas Member, Upper Miocene. Sorbas road cutting, Sorbas basin. Photos: H.E.Clark

Figure 14: Quaternary alluvial fan deposits, Rambla de la Sierra, Tabernas Basin. Photo: H.E.Clark

Figure 15: The Badlands landscape developed in Miocene sediments around Bar Alfaro, Tabernas basin, has been used extensively as film sets. Photos: H.E.Clark & W.J.Iley

Figure 16: Carboneras strike-slip fault provides a pathway for mineralisation of the Triassic marls. 'The Painted Badlands', Rambla de la Granatilla near Solpalmo. Photo: W.J. Iley

Figure 17: Holocene travertine curtain at Bar Alfaro, Tabernas Basin.
Photos: H.E.Clark & W.J.Iley

Figure 18: Copper Age archaeological site at Los Millares.
Photos: H.E.Clark & E.Thompson

Figure 19: Part of the 4.5km network of tunnels of the Spanish Civil War air-raid shelters which run 9m below the length of the main street in Almeria. They protected about 37,000 people from German and Italian bombing raids. Photo: H.E.Clark

The Pliocene, Quaternary and Holocene rocks were not studied in detail but were evident as we drove and viewed the landscape of fans and terraces, Figure 14. The landscape is entirely dependent on rock type and structure. The relatively resistant metamorphic and igneous rocks form most of the high ground with sudden changes in elevation created by the effect of major strike slip faults e.g. the Carboneras Fault system. The relatively soft Miocene sedimentary rocks have been eroded into "badlands" topography, Figure 15, much in demand for film sets from the spaghetti westerns of Sergio Leone to El Cid and Indiana Jones.

Other features of interest are the painted badlands created by mineralisation along the Carboneras Fault, Figure 16, and the travertine curtains produced where mineral rich ground water seeps along a fault plane, Figure 17.

The final day was devoted to archaeological and historical sites, starting with the Copper Age site at Los Millares, a fortified hill site with extensive walls, buildings and tombs, Figure 18. We then went to the reconstruction of how the site would have looked during occupation.

After a walk through the old quarter of Almeria via an unexpected statue of John Lennon (who wrote *Strawberry Fields Forever* here) we visited the Alcazaba – a Moorish fort dominating the high ground near the harbour. Then a visit to the Spanish Civil War air raid shelters, Figure 19, which run at a depth of 9m under the length of the main street, Paseo de Almeria, and provide a poignant reminder of the horrors of war. The tunnel depth was determined by a band of resistant rock, making excavation below 9m difficult.

An excellent time was had by all. Our thanks to Graham for his knowledge of the area, linguisitic skills, organisational and hospitality finesse. There were definite advantages to booking the hire cars and insurance in advance while paying for everything from a periodically topped up communal kitty prevented any stress over payments on a day to day basis.

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The Clitheroe pinnacle

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Figure 1: The pinnacle in the grounds of Clitheroe Castle

Introduction

In the gardens of Clitheroe Castle is a pinnacle, Figure 1, which is something of a surprise as it doesn't seem to belong. It has nothing to do with the castle and is constructed from magnesian limestone rather than the local crinoidal Carboniferous limestone. The plaque tells the story. The pinnacle was one of many which adorned the roof of the Houses of Parliament, formally known as the Palace of Westminster, Figure 2.

In 1834 a great fire destroyed the Palace of Westminster buildings and a competition to design a replacement was won by Charles Barry, who was later assisted with the detailed design by Augustus Welby Pugin.

The first stone of his perpendicular gothic building was laid by Barry's wife on 27 August 1840. Barry estimated a construction time of six years at a cost of £724,986, but the project took more than 26 years and cost over £2 million. In 1852 Barry received a knighthood from Queen Victoria, marking the completion of the main interiors.

By the 1920s some of the original 1840s pinnacles had become so weakened by weathering that they had to be removed for safety reasons. One cause was a hundred years of sulphurous pollution from coal burning, which also gave rise to the famous “pea-souper” smogs. Another was that quality control both in the quarry and on site was not as good as it should have been, owing to the enormous pressure that all were under to build one of the largest single masonry construction projects Britain had ever seen.

Figure 2: Pinnacles today on the Houses of Parliament

The hazardous pinnacles were removed and sold. Clitheroe's MP, Captain Sir William Brass, purchased one and presented it to the town to commemorate the coronation of King George VI in 1937.

In recent years, the pinnacle was showing increasing signs of distress and if left unattended it would probably have collapsed.

A group from Clitheroe Civic Trust Society (CCS) decided that as part of Clitheroe's heritage it should be conserved for posterity. An initial application for £60,000 to cover the cost of repairs, conservation and interpretation, was prepared and submitted to the Heritage Lottery Fund (HLF) by CCS's Vice Chairman. On the success of this preliminary application, in March 2015, a Pinnacle Project Committee was formed, which put together a bid for the cost of repairing the pinnacle with minimal replacement of damaged stonework. They drew up a detailed programme for the whole project, including appointment of local conservation architects, IWA Associates, and other key consultants. Project Partnerships were also established with numerous local and regional community organisations, and educational establishments. The project was supported by the Heritage Lottery Fund, the Duchy of Lancaster's Benevolent Fund, Clitheroe Town Council, Lancashire County Council, the Rotary Club of Clitheroe and individual sponsors. CCS also undertook fund raising events and initiatives to make up the funding shortfall.

Introduction to building stones

This article is about building stones, their geology, and the selection of a suitable stone to use in the repair of the Clitheroe pinnacle.

The search for papers on building stone durability for the preparation of this article, revealed a large volume of detailed research. The importance of biological processes in stone weathering also became apparent.

This informal paper deals with four different limestones and a sandstone.

To select stone for use on the outside of a building it is necessary to consider attributes such as colour, appearance, texture, strength, ease of carving, durability and cost. Stone may change colour with weathering so that would also have to be considered.

Limestone, calcium carbonate, consists of the hard parts of once living organisms cemented together. The cement which binds the hard parts together is normally also calcium carbonate, dissolved and re-precipitated from solution.

If you visit an area where carbonate sediments are being formed today you will see a wide variety of depositional environments. In high energy areas, such as those regularly swept by tides, shoals of ooids may form. Oolitic limestone is a favoured building stone, an example of which is illustrated in the notes about Ketton freestone below. Today's coral reefs are biological build-ups, perhaps best described as 'framework' reefs. While coral provides the framework, up to fifty percent of the build-up may be of algal origin.

In low energy areas, such as in lagoons behind reefs, carbonate mud accumulates. This may be so fine grained that as a rock it is homogeneous, with bioclasts too small to distinguish with the naked eye.

A wide variety of depositional environments and a propensity for diagenesis results in the formation of many types of limestone, from the hard Carboniferous limestone of Derbyshire to the soft Cretaceous chalk. Limestone from different parts of a single quarry may not have the same building stone attributes.

In the short term, durability is difficult to assess, but some building stones have been used for centuries and their performance, good or bad, is known. It isn't a simple story, as a brief inspection of St. Ann's Church in central Manchester will reveal. The Permian 'Binney' sandstone from quarries in Collyhurst, used in its construction, must have been of particularly variable quality. Some stone blocks contained lenses of mud, causing premature failure. The walls are a patchwork of replaced stonework, Figure 3. The latest phase of stone replacement is currently in progress.

Figure 3: St. Ann's Church, Manchester

Jurassic limestone from Ketton Quarry (Rutland) and nearby quarries, such as Clipsham.

The pale brown Jurassic limestone found at Ketton and nearby quarries was formed about 170Ma ago when England was located about half way between the equator and its present position. The Gulf coast of Florida and the Florida Keys would be a reasonable modern analogue for the depositional environment of the Jurassic at Ketton. Ketton freestone, which is an oolitic limestone, has been widely used for building stone for hundreds of years. Many buildings in the centre of Stamford and several Cambridge colleges are built from it. A close-up picture of this freestone, Figure 4, reveals that it consists of ooids with very little cement. If you look carefully you can see small scars on the surface of each ooid marking the fracture surface. In thin section, Figure 5, the lack of interstitial cement is clear. The scars are located at the point contacts between ooids. It is mainly pressure dissolution and local re-precipitation of calcite which binds the ooids together. Despite the sparse cement the stone is strong enough for most building applications. Ketton's limestone, and other similar oolitic limestone, is called freestone because it has no preferred planes of weakness along which to fracture. This makes it easy to carve, as can be seen in the carved faces in Figure 6, probably based on real people. In stark contrast roofing slate, which preferentially splits into parallel sheets, would be almost impossible to carve with hammer and chisel.

Figure 4: Fracture surface of oolitic limestone from the Lincolnshire Limestone at Ketton. Diameter of ooids ~0.5mm

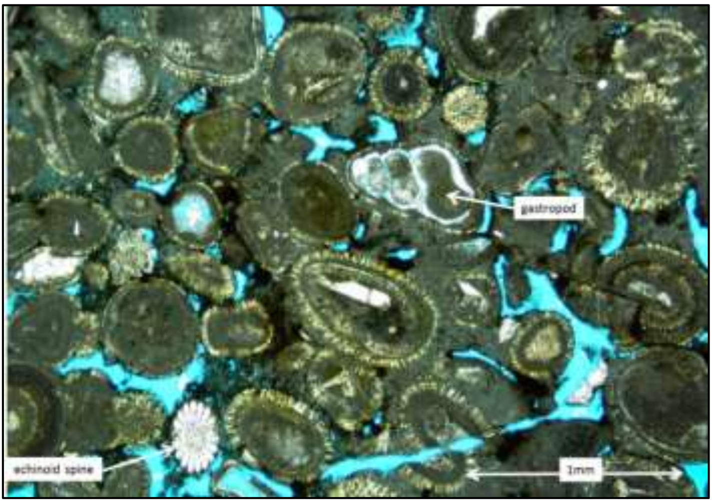

Figure 5: Photomicrograph in plane-polarised light (ppl) of oolitic Lincolnshire Limestone from Ketton. The blue colouration is adhesive used in making the slide, now filling the pore spaces between the ooids.

Figure 6: Decorative faces carved from oolitic Lincolnshire Limestone.

Figure 7: Quarry face in Lincolnshire Limestone at Ketton. The oolitic freestone is found in the 'high energy' beds with cross sets.

In Ketton quarry the limestone is 20m thick, Figure 7, barely two metres of which is freestone. Freestone was mined in the past, Figure 8, but the quantity available was probably too restricted for use in the Houses of Parliament.

Clipsham stone is oolitic and very similar to Ketton stone. Both have such high porosity that water entering the pore space can readily drain out, which improves frost resistance. Clipsham stone has been used as a replacement in parts of the Houses of Parliament, York Minster and a number of college buildings in Oxford. Both Clipsham and Ketton stone are suitable for copings, cornices and for monumental work.

Figure 8: Freestone mine at Ketton, age uncertain, now populated by bats.

Oolitic and other porous limestones have 'self-healing' properties. When they become wet a tiny fraction of limestone dissolves. The solution is brought to the surface by capillary action as the rock dries out, leaving a skin of limestone behind as the water evaporates. The process of stalactite and flowstone formation is similar. It is possible to see the results of self-healing on the Clitheroe magnesian limestone pinnacle. The skin largely hides the true texture of the limestone, which is not oolitic. A diligent search is required to locate an example of the original texture and a hand lens is needed to see shell fragments.

Salthill and Chatburn limestones, Clitheroe

The Carboniferous limestone at Salthill is about 350Ma old. It was formed when England was located just south of the equator. One must be wary about modern analogues of the Carboniferous because many genera living at that time, including all Carboniferous corals, did not survive past the end Permian mass extinction, 250Ma ago, which was much more severe than the end Cretaceous event, 65Ma ago, which saw the demise of the dinosaurs.

Despite these reservations, the Trucial coast of the Arabian Gulf is considered to have a similar depositional environment to the limestone of the Chatburn quarries. Limestone found at Salthill is of two principal types, one a uniform grey in colour and devoid of macrofossils, the other replete with fossil crinoids. The thin section, Figure 9, is from the Chatburn Limestone, less pure and somewhat older than the limestone found at Salthill.

The uniform grey limestone might be carved with difficulty but the crinoidal variety would be unsuitable because crinoids fracture along cleavage planes and therefore unevenly. The crinoidal limestone is attractive when used in blocks because the crinoids stand proud on a weathered surface, Figure 10. The calcite in crinoids has a well-ordered molecular structure, making it more resistant to dissolution by rainwater than the limestone matrix.

The front of Clitheroe's United Reformed Church, located near the top of Moor Lane, has been built with limestone from Salthill. There are spectacular examples of crinoid stems in the limestone blocks of the façade, Figure 10.

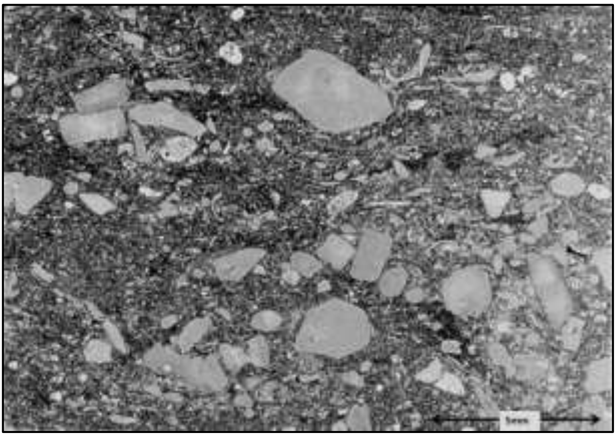

Figure 9: Photomicrograph (ppl) of Chatburn Limestone, showing (relatively large) crinoid fragments in a matrix of finely comminuted bioclasts

Colour doesn't immediately come to mind when you look at fossil crinoids, but modern crinoids are very colourful, Figure 11. Some modern crinoids 'walk'. The animal in the top left image is clinging to seaweed. Crinoids feed by catching small organisms floating past their ‘arms’ on the current.

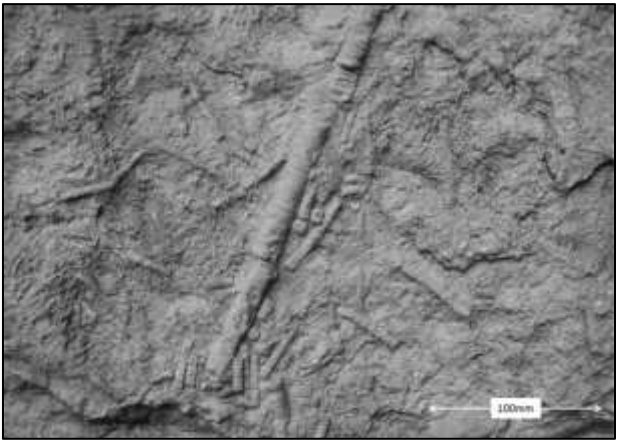

Figure 10: Crinoid stems on the UR church, Clitheroe.

Figure 11: Living crinoids from the Red Sea (Prof. Charles Messing & National Oceanography Centre, Southampton).

Portland Stone

The 145Ma old Jurassic limestone from Portland in Dorset was deposited in an environment similar to that of Florida. Portland Stone weathers almost white and has been used throughout the country in a huge number of high status monuments and buildings. The cenotaphs in London and Manchester are made from it, Figure 12. The Central Library (St Peter's Square), Ship Canal House (98 King Street) and several other central Manchester buildings are either built or faced with it. Most Portland Stone is oolitic and like Ketton freestone is readily carved, Figure 13.

Figure 12: Portland Stone on the walls of the Cenotaph in St, Peter's Square, Manchester.

Figure 13: Carving in Portland Stone, Manchester City Centre

In Portland stone fossils tend to weather out, so what starts as rather a dull texture becomes more attractive with age. The fossil illustrated in Figure 12 is a bivalve. Close examination of the pillars at the entrance to the Library reveals abundant ooids. A thin section of a specimen of Portland Stone, Figure 14, shows a thin layer of isopachous (equal thickness) calcite cement. In this example, the calcite cement is the main binding agent. When the interstitial space between the ooids is fully filled with cement the limestone is no longer a freestone.

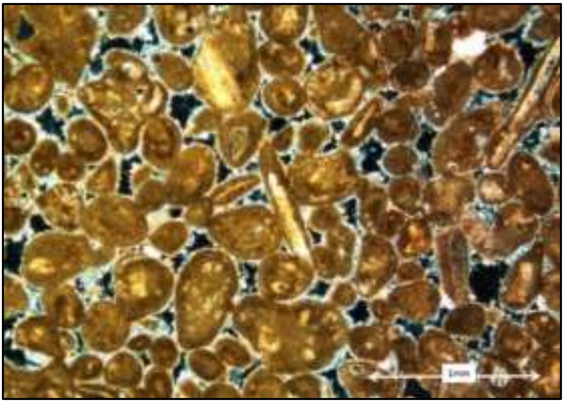

Figure 14: Photomicrograph in crossed polars (xpl) of Portland Stone showing ooids with an isopachous (equal thickness) calcite cement around each ooid. Dark areas are pore spaces.

Magnesian limestone

The pale coloured, late Permian Magnesian Limestone, about 255Ma old, was deposited on the margins of what is known as the Zechstein Sea, Figure 15. Magnesian limestone formed in reefs and in large shallow lagoons behind the reefs of the Zechstein Sea shore. At that time, Britain was located within the supercontinent of Pangaea in an environment similar to that of the Sahara Desert.

The Zechstein Sea, isolated from the ocean on at least five occasions, was repeatedly evaporated, perhaps even to dryness. Salt and gypsum/anhydrite accumulated in beds up to 100m thick. Such evaporative events are not unique in earth history. About 6 million years ago the Mediterranean Sea was cut off from the ocean on several occasions. As a result of evaporation, more than a million cubic kilometres of salt, 600-1000m thick, accumulated (Ryan, 2009), much of it remaining under the present day Mediterranean sea floor.

Map of the end Permian Zechstein Sea, 260-248 million years ago.
Map reproduced from Lott G.K. & Cooper A.H., Field guide to the building limestones of the Upper Permian Cadeby Formation (magnesian limestone) of Yorkshire. Published by the English Stone Forum on the web.
http://www.englishstone.org.uk/York/ESF%20-%20Lott%20&%20Cooper-1.pdf

Figure 15: Palaeogeographic map of the Zechstein basin.

'Normal' limestone is composed of calcium carbonate. If half the atoms of calcium are replaced by magnesium atoms the rock is known as dolomite, named after the mountains in northern Italy close to the Austrian and Swiss borders. In magnesian limestone rather less than half the calcium atoms have been replaced by magnesium. The chemical reactions which convert limestone to dolomite are not fully understood. Geologists refer to this as the 'dolomite problem'.

Much of the calcium carbonate in the Magnesian Limestone was originally aragonite, a form which is less stable than calcite, and tends to dissolve, Figure 16, and re-precipitates as calcite. Some calcium carbonate has been dolomitised. Some dolomite has then been de-dolomitised. The story of magnesian limestone is a complicated one and the processes of diagenesis tend to destroy evidence of the original depositional environment. Diagenesis also changes the physical properties of the rock, especially its permeability. The thin section in Figure 17 shows an altered oolitic limestone. The (aragonite) ooids have dissolved and left voids. This would make it a potential reservoir for oil or gas.

Figure 16: Hand specimen (50mm) of Magnesian Limestone from Sunderland. The ooids have dissolved leaving a high degree of porosity.

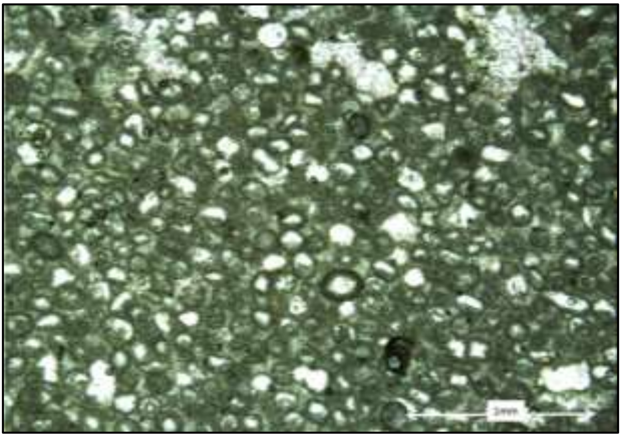

Figure 17: Photomicrograph (ppl) of Magnesian Limestone showing considerable alteration of ooids compared with Ketton and Portland stones.

York Minster was built from magnesian limestone, probably from Jackdaw Crag Quarry, near Tadcaster. At the time of its construction, stone transport would have been by horse and cart, so local stone would certainly have been preferred.

Sandstone

Quartz grains are both physically robust and resistant to chemical attack, but sandstone rarely consists of silica-cemented quartz alone. Arkoses are immature sandstones with a substantial proportion of feldspar, which is less chemically resistant.

Sandstones may also contain micaceous fine partings which lead to lamination and spalling. It is the dominant persistent partings which make rock useful as a building stone, whether tens of centimetres apart for blocks or two or three centimetres for flagstones.

Figure 18: Weathered sandstone setts in Lancaster city centre, showing splitting along micaceous partings.

Figure 19: Sandstone in Manchester city centre. Spalling probably caused by salt damage.

Salts damage sandstone through differential thermal expansion, osmotic swelling of clays, hydration pressure and enhanced wet/dry cycling caused by deliquescent salts, (Doehne 2000). The setts in Figure 18 and column base in Figure 19 were almost certainly exposed to road salt and to wet/dry cycles. Salts arising from Portland cement mortar are an important source of decay to historic building materials, (Moropoulou, 2002).

Figure 20: Photomicrograph (ppl) of a Westphalian sandstone showing mica flakes (dark brown/black). 2mm field of view.

In Figure 20 the mica flakes provide planes of weakness which increase the propensity for the type of weathering seen in Figure 18. In Figure 21 the absence of mica flakes and grains of feldspar makes this sandstone much more durable.

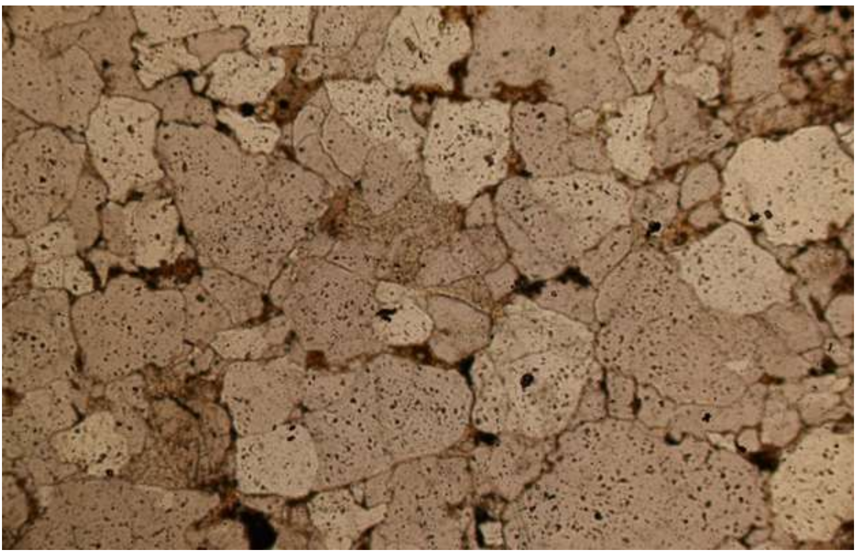

Figure 21: Photomicrograph (ppl) of a Namurian sandstone. 4mm field of view.

The matrix, the cement and the proportion of feldspars have the greatest influence on a sandstone's durability. Calcite cemented sandstones are especially vulnerable. Some clay minerals are expansive, i.e. expand and contract through wet and dry cycles. The forces generated may exceed the strength of the intergranular cement. Thermal expansion and contraction was thought to be a contributor to weathering in desert environments, but that is no longer considered a viable process. The impact of wet/dry processes arising from dew is a more certain factor.

Limestone weathering

The impact of air pollution has changed over time, (Grossi & Brimblecombe, 2007). In the 19th Century the dramatic increase in burning of coal in urban areas and consequent liberation of sulphur dioxide (SO_2) made a significant impact on calcareous building stones. Monitoring of atmospheric quality was very limited, so it is not possible to relate concentrations to modern values. However it is clear that SO_2 concentrations have been falling for many decades. More recently the deposition of soot, from diesel engine exhausts, has increased markedly. Soot is responsible for most stone blackening.

SO_2 oxidises to sulphuric acid. The reaction with calcite is then:

$CaCO_3$	+ H_2SO_4	+ H_2O	>	$CaSO_4.2H_2O$	+ CO_2
calcite	+ sulphuric acid	+ water	>	gypsum	+ carbon dioxide

A molecule of gypsum occupies more volume than a molecule of calcite so when this reaction takes place in pores the expansion pressure can physically break apart the surrounding carbonate rock. When not heavily rain-washed, a hard gypsum skin forms, often blackened by soot particles. In areas where stone is frequently washed by rainwater the gypsum dissolves and there may be direct dissolution of carbonate.

The reaction of sulphuric acid with dolomite (and magnesian limestone) leads to the formation of magnesium sulphate ($MgSO_4$) as well as gypsum. $MgSO_4$ is more soluble than gypsum and finds its way deeper into the rock, where damage can take place due to recrystallisation, (Grossi and Brimblecombe, 2007). Sandstones with calcite cement weather severely by the above mechanisms.

Bio-weathering

Bio-weathering can seriously damage building stones (Siegesmund 2002). Colonisation of carbonate rocks by endolithic microorganisms such as cyanobacteria, chlorophycaceae, fungi and lichens is ubiquitous. Siegesmund found that in carbonate rocks, under a residual protective layer on the surface, photobiontic microorganisms occupied more than 60% of the dissolved rock volume. Bio-activity is more likely to be significant in areas of 'permanent' wetness, on the lee side of buildings in the north west of England for instance. The presence of soot increases the potential for bio-activity. Silicate minerals provide nutrients for living organisms, Figure 22. Lichens are not growing on the quartz laminae.

Figure 22: Bio-activity on a schist erratic, highlighting the less siliceous laminae.

Building stones used in the Houses of Parliament

In 1839, a Royal Commission was set up to oversee the construction of the 'new' Houses of Parliament and a public competition held to invite designs, though it was stipulated that the new Houses of Parliament should be in Gothic or Elizabethan style, those being considered the only ones appropriate. Its report begins:

The result of an inquiry, undertaken under the Authority of the Lords Commissioners of Her Majesty's Treasury, by **Charles Barry**, Esquire, **H.T. De la Beche**, Esquire, FRS &FGS, **William Smith**, Esquire, DCL & FGS, and Mr **Charles H. Smith**, with reference to the selection of stone for building the new Houses of Parliament.

London, 16th March 1839
My Lords and Gentlemen
In conformity with your instructions, we have the honour to report that, in the months of August, September and October last, we have made a tour of inspection to various stone quarries in the kingdom, and visited numerous public buildings, with a view to the selection of a proper stone to be employed in the erection of the new Houses of Parliament.

William Smith, considered to be the father of modern geology, was the man who created the first geological map, 'The map that changed the world' (Simon Winchester, 2001). Its 200th anniversary was celebrated in 2015. In 1808, seven years before the publication of his map, Smith invited a small delegation from the Geological Society of London to see his fossil collection and a preliminary edition of his map. The delegation was less than friendly. Smith was not of the right social class. That he was a working geologist and dependent for his living on the practical application of geology was not gentlemanly and he was clearly not fit to be part of the social and dining club which characterised the Geological Society at that time. Worse for Smith, Sir James Hall and George Bellas Greenhough embarked on a plan to produce their own version of the map, heavily plagiarised from Smith's. The first edition of Smith's map was published in 1815 and Greenhough's map came out in 1819. At that time, Smith was close to bankruptcy and spent time in a debtor's prison. By 1831, though, the Geological Society had changed. Smith, then aged 62, was showered with honours including the first award of the Wollaston Medal, presented to him by the new president Sir Roderick Impey Murchison. In 1865, long after Smith's death, the Society went some way further to restoring Smith's precedence. All further editions of the map were to appear with the words, 'A Geological Map of England and Wales, by G.B. Greenhough Esq., FRS (on the basis of the original map by Wm. Smith, 1815).'

The report of the Royal Commission was comprehensive and included physical testing of cubes of rock. Granite and similar rocks were ruled out because of the enormous expense of working them. It was also recognised that suitable sedimentary stone found in a quarry might be covered by a large amount of lower quality rock which would have to be removed, providing a temptation to use poorer quality stone.

The report's authors found that the durability of sandstone used in historic buildings was variable, even in a single building. The sandstone used in Haddon Hall was in particularly good condition while that used in Durham Cathedral was poor. Magnesian limestone was found in perfect condition, with carvings still crisp in the Norman portions of Southwell Church. However, that used in York Minster was so decomposed that the carvings were effaced. Buildings constructed of oolitic limestone, both Ancaster and Portland, fared well.

The report concluded:

> If, however, we were called upon to select a class of stone for the more immediate object of our inquiry, we should give the preference to limestones, on account of their more general uniformity of tint, their comparatively homogeneous structure, and the facility and economy of their conversion to building purposes; and of this class we prefer those which are most crystalline.
> In conclusion, having weighed to the best of our judgement the evidence in favour of the various building stones which have been brought under our consideration, and freely admitting that many sandstones as well as limestones possess very great advantages as building materials, we feel bound to state that for durability, as instanced in Southwell Church, etc., and the results of experiments, as detailed in the accompanying Tables; for crystalline character, combined with a close approach to the equivalent proportions of carbonate of lime and carbonate of magnesia; for uniformity in structure; facility and economy in conversion; and for advantage of colour; the magnesian limestone or dolomite, of Bolsover Moor and its neighbourhood is in our opinion the most fit and proper material to be employed in the proposed new Houses of Parliament.
> We have the honour to be,
> My Lords and Gentlemen
> Your very humble and obedient servants

> (signed)
> **Charles Barry**
> **H.T. De la Beche**
> **William Smith**
> **Charles H. Smith**
>
> [Houses of Parliament Papers Online, 2006]

Crystalline magnesian limestone was favoured because of its resistance to chemical attack. As a result, the 1830s pinnacles were constructed using magnesian limestone from Anston in the West Riding of Yorkshire.

In the 1920s it was evident that some pinnacles were in such a poor state of repair that they would need to be replaced. In 1928, the Department of Scientific and Industrial Research produced a comprehensive report, marked 'Strictly Confidential'.

> The Selection of Building Stone in relation to its Weathering Qualities, with Particular Reference to the Proposed Repairs to the Houses of Parliament by R.J. Schaffer, BA, BSc, (Oxon)

The report detailed the results of extensive work on weathering, both chemical and physical, and other factors influencing the choice of replacement stone. Some of the results were based on laboratory testing. It concluded that use of sandstone to patch the damaged parts of the pinnacles would be disastrous as the universal experience was that contiguous limestone had a very negative impact on sandstone durability. It identified that the major problem at the Houses of Parliament had been the impact of sulphur dioxide gas from coal burning, the principal cause of the London smogs. The report also identified the negative impact on durability of rusting iron dowels.

The report considered use of Ketton and Clipsham stone:

> The suggested use of Ketton Stone and Clipsham Stone.
>
> Both Ketton Stone and Clipsham Stone, which are now under consideration, have been observed to exhibit good weathering qualities and there is much to be said in favour of the recommendation to use either or both these materials.

Cement mortar was considered to present a risk of efflorescence, so it seems very likely that lime mortar was used.

> Although Portland Cement mortars appear to differ considerably in their tendency to form efflorescences, and, indeed, certain brands have been successfully used for jointing Clipsham Stone in Oxford, the danger exists and it is suggested that the use of Portland Cement mortar should be more fully investigated.

In the 1930s, following the recommendations of this report, some pinnacles were replaced using Clipsham stone from Rutland. Clipsham was chosen because its weathered colour was more similar to Anston than Ketton freestone.

The Clitheroe Pinnacle

Considerable time was spent researching the best stone to use for the recent repair of the 'Clitheroe' Pinnacle. The Parliamentary Estates Department advised that the most recent repairs to the masonry of the Houses of Parliament had been undertaken using Clipsham stone and this was the stone which was referred to in the tender documentation. However, conservation contractor and consultant Len Middleton, drew the team's attention to a letter in the Natural Stone Specialist by Dr David Jefferson of Jefferson Consulting, suggesting that Clipsham stone could have a detrimental effect if laid adjacent to the Anston magnesian limestone. Subsequently Dr Jefferson persuaded the team and their professional advisors that the better stone to use would be that sourced from the Jackdaw Crag Quarry, near Tadcaster in North Yorkshire.

Though the replacement stone is strikingly different in appearance from the weathered stone, the project team, architects and the conservation contractors, Heritage Conservation Restoration Ltd., are all confident that, with time, the new stone will weather to match. This belief is reinforced by the similarity of the new stone to unweathered cross-sections of the original which were exposed during the dismantling of the pinnacle.

From historic reports, site surveys, historic practice and visual evidence it was expected that the masonry blocks would have been secured using metal dowels and cramps. Some ferrous dowels were visible where sections of the often very slender and delicate stones were missing. Cracks evident in the structure were also consistent with corroding and expanding ferrous dowels. Although some damage was caused by the corrosion of ferrous dowels it was not as extensive as had been expected, because in 1937 the mason had elected, for the most part, to use slate 'pegs' as dowels. Carbon-fibre dowels were used in the repair to avoid any future adverse effects on the structure.

The latest refurbishment of the Houses of Parliament
Some idea of the challenge facing the latest refurbishment is indicated in Figure 23. It is estimated that 4000 windows will have to be refurbished.

The website, see references, contains much of interest.

Figure 23: Window surround (left) and cast iron tower (reproduced with permission)

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Stone Selection report for the new Houses of Parliament building, 1839.

Stone Selection report for repairs to the Houses of Parliament building, 1928.

A field guide to aspects of the geology of Worsley Woods Nature Reserve, west of Manchester

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Field guides are an important part of the 'landscape' of geological publishing. It is surely a rare geologist who has never been guided to an important exposure by a field guide or report of a field meeting. They are published either separately or as papers within research journals. One of the largest of the UK's geological societies, the Geologists' Association, regularly publishes reports of field meetings in their *Proceedings* (e.g. Robinson, 1996) and has a long-running series of informative pocket field guides (e.g. Broadhurst *et al*., 1970; Clements, 2010). The Geological Society of America produced an impressive series of six field guides to mark its centenary and regularly publishes guides linked to conference field trips (e.g. Hunt and Catlos, 2013).

I could add many more examples to this list, but I am sure that you understand my opinion. Field guides enrich the most basic part of the science of geology, that in the field. A further point is that almost any geological phenomena can be approached using an appropriate field guide, such as building stones (e.g., Simpson and Broadhurst, 2014). The keen observer will know of local sites of geological interest which can be linked together to make an interesting geological ramble. By the keen observer, I mean you. The literature of our science would be enriched by more field guides to local geological phenomena. It is always educational to make a trip to some 'foreign field', whether it be only an hour away by public transport or in another country, but often geologists are guilty of failing to report on the geology on their own doorstep. For example, the town in the Netherlands where I live, Hoofddorp, is geologically unspectacular, yet there are still rare examples of geological objects that I see as worthy of comment (Donovan, 2014a, b).

To illustrate this opinion, I present a short field guide to part of the Worsley Woods Nature Reserve in Roe Green, Worsley, which is managed by Salford City Council (www.salford.gov.uk/worsleywoods.htm).

I do not live there, but my partner does, and I have explored various parts of the woods over a number of years when visiting. This guide was written in draft over the Christmas period of 2014, partly for my own entertainment, but mainly to demonstrate that, even in an essentially urban area, there are geological phenomena worth recording. To slightly change the words of Eric Sykes (2005), if you don't write it, nobody else will.

How to get there

Motorists need to drive to Greenleach Lane, adjacent to the motorway bridge, SD 753 014, Figure 1. There is room to park one or two cars off the road at this entrance to the woods. Sadly, the Bolton to Manchester railway was closed in 1969 (Suggitt, 2004, p.71), so it is no longer possible to take a train to Worsley from Manchester Victoria via Eccles, but the track bed is now a cycle path (N55) with a good surface. Access by bus is more difficult, the only direct service being the number 68 (Farnworth via Little Hulton, Walkden and Eccles to the Trafford Centre); book to Greenleach Lane Post Office, Figure 1, less than five minutes from the start. Other services, including Vantage V1, V2, V3 link Manchester to the A580 Wardley Park and Ride, from where a footpath (SD 758 017) leads through Wardley Woods to Greenleach Lane, where the field guide walk begins.

Enter Worsley Woods at the Greenleach Lane entrance, adjacent to the M60 motorway bridge, Figure 1, and walk uphill, with the stream in the V-shaped valley, on the right. Locality 1 is the bridge over the closed railway, Figure 2, now the N55 cycle path, built from what I presume to be local Upper Carboniferous (Pennsylvanian = Coal Measures) sandstone and probably quarried from the cutting below. Contrast this with the adjacent motorway bridge of reinforced concrete and thus derived from a limestone area further afield (Nield, 2014). Thus, the 19th Century bridge is made from local stone whereas the 20th Century bridge is composed of more exotic material, although both may be Carboniferous in origin.

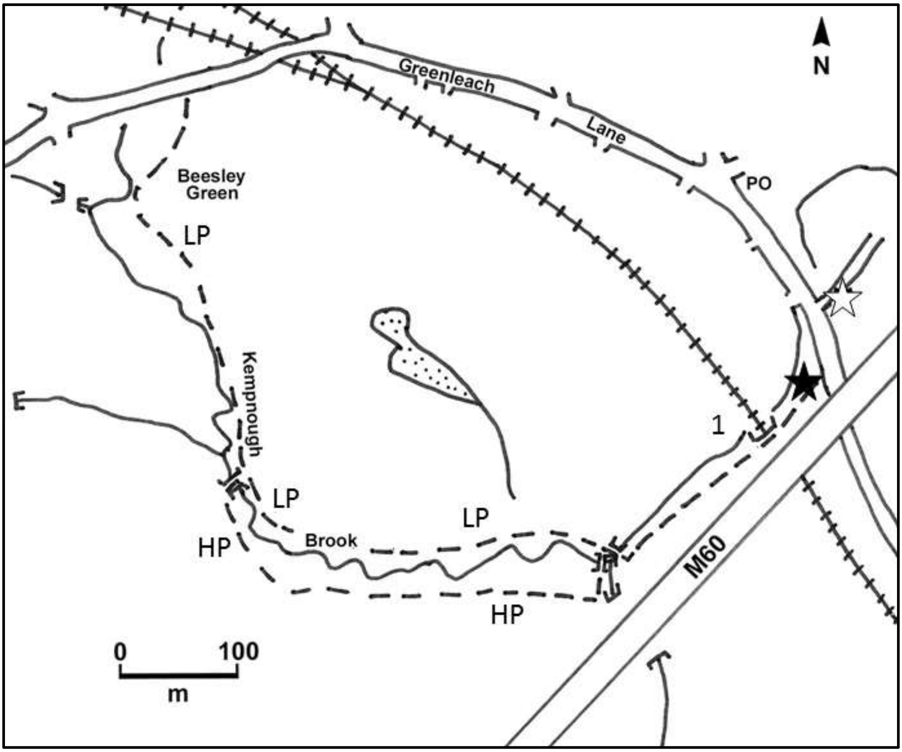

Figure 1: Locality map of the geological excursion guide to the Worsley Woods Nature Reserve, west of Manchester, based on various sources. The excursion starts at the entrance in Greenleach Lane adjacent to the M60 motorway overbridge (black star) and follows the dashed line to Beesley Green. **Key:** 1 = Locality 1; LP = low path; HP = high path; PO = Greenleach Lane Post Office; white star = position of lamp post in Manthorpe Avenue shown in Figure 6B; solid lines = streams; trellised lines = N55 cycle path (on closed railway).

Do not drop down to the N55 via the steps at the right on the far side of the bridge. Rather, continue straight on the path down the slope, between the M60 and the stream, to a junction of paths by a second motorway overbridge. The stream is still to the right; note that for much of this section it is artificially straightened by stone walls and, at the far end, a concrete trough.

Figure 2: Locality 1, two bridges. (A) The view walking up from Greenleach Lane to the bridge over the closed railway; the motorway and motorway bridge are on the left. (B) The view of the 19th Century stone (in front) and 20th Century concrete (behind) bridges from the closed Bolton-Manchester railway, now the cycle path N55, looking south-east towards Eccles.

Before the M60 overbridge, take the right turn towards Beesley Green over a footbridge. On the other side of this bridge there is a choice of routes, either straight ahead along the valley bottom with the stream on the left, low path, or take the footbridge on the left, up the steps to the level of the M60 and turn right along the top of the valley side with the stream down below on the right, high path. The high and low paths reunite near Beesley Green, Figure 1. My own preference is to walk the low path one way and return on the high path, thus getting two contrasting views of the same landscape. (*Note that this guide is based on what was obvious in December; some features may be more cryptic when the trees are in leaf.*)

Because this small valley contains an active stream, the Kempnough Brook, Figure 1, geometry may change with the next major flood, so, rather than describe it as a series of numbered localities, I am going to discuss geological and geomorphological features under broad headings, supported by photographs with descriptive captions, Figures 3-6. This will, I trust, explain what is to be seen while encouraging anyone who uses this guide to make their own observations. Note the asymmetry of the valley, the result of the stream cutting through an original topography.

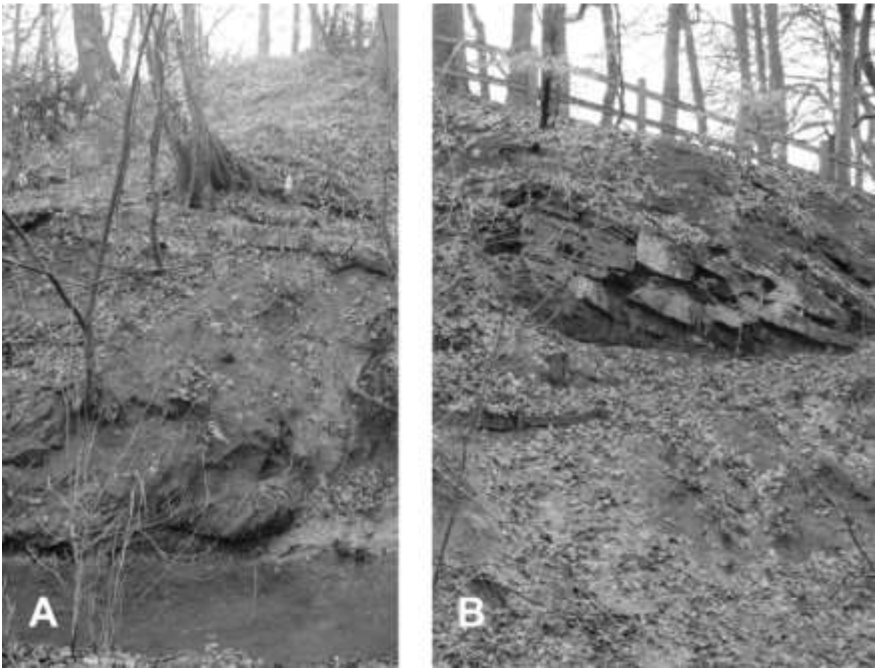

Figure 3: Upper Carboniferous (Pennsylvanian = Coal Measures) geology; both views taken from about the same position, looking in slightly different directions at the valley side below the high path.

(A) Exposure of sandstone (lower centre, just above river meander) steeply dipping to the left. The dip of this exposure bears no relationship to other sandstones and is presumed to represent a loose block, largely concealed by slipped soil.

(B) In situ sandstone beds with shallow dip in a different direction to (A); this dip is consistent with the other, rare exposures of sandstone in this valley.

Carboniferous geology

Exposures of blocky – that is, well-jointed – Upper Carboniferous (Coal Measures) sandstones (Edwards *et al*., 1954, Figure 20) are few, mainly of one or a few beds with a shallow, near-horizontal dip exposed in the slope beneath the high path, Figure 3B. The maximum thickness of an *in situ* bed is about 20cm. One sandstone exposure in a stream meander has a steep dip in an obviously different direction to other exposures and is presumed to be a fallen block partly concealed by slipped material, Figure 3A, in the absence of any evidence for folding or faulting.

Shallow-rooted trees are perhaps an indication, at least in part, that hard sandstones are close to the surface beneath a thin veneer of soil, Figure 5A. Where roots are exposed by fallen trees, the soil is a brown colour similar to that of the sandstones, blocks of which may be tangled in the roots, Figure 5C.

Stream morphology

The valley bottom here is flatter and broader than for the stream mentioned at the beginning of the guide. It is in part in a man-made channel close to the footbridges after Locality 1, Figure 4A, but is essentially meandering (Harvey, 2012, pp. 69-74). Meanders show typical features such as steep sided banks on the outer curve, where current flow is fastest and at its most erosive, and shallower on the inner sides where sediment has been deposited under slower current flow, Figures 4B & 4C. In an attempt to control erosion, at least one meander has been artificially protected, Figure 4D.

Slope dynamics

Tree roots are commonly exposed, particularly on the valley side below the high path, suggesting either active soil erosion (Harvey, 2012, pp. 56-64), the roots are unable to penetrate deeply (see above) or both. From the high path, a common form of tree growth is with a J-shaped curvature just above the soil surface, indicative of soil creep, Figure 5B.

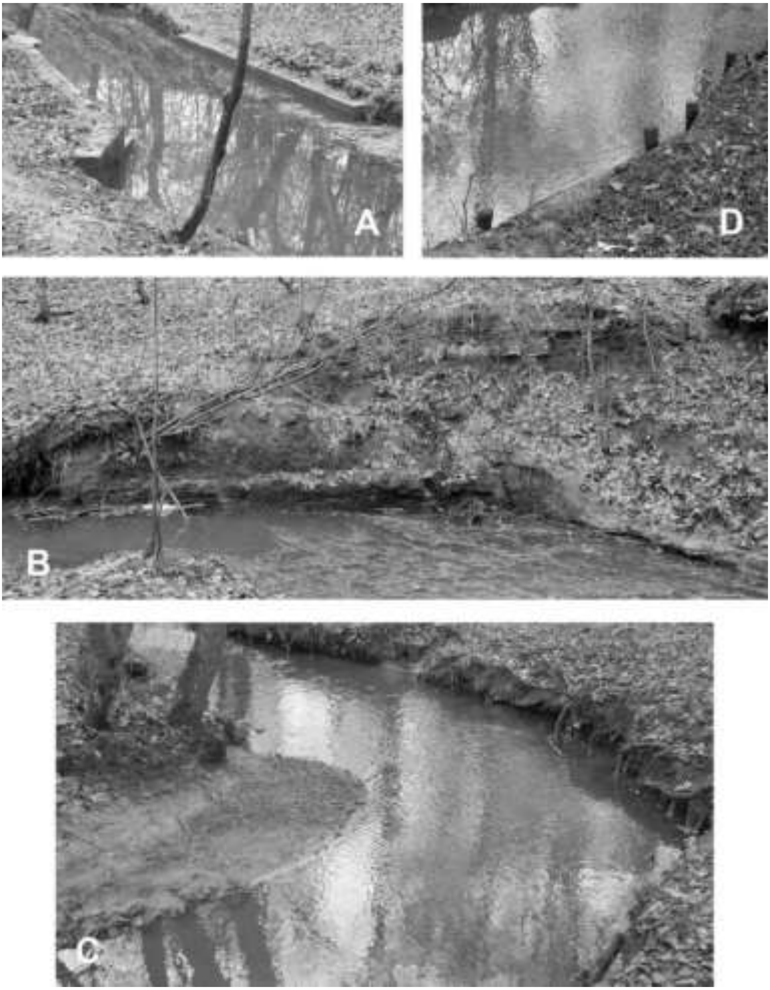

Figure 4: Stream morphology of Kempnough Brook. (A) Man-made channel near the dividing of the low and high paths. (B) River meander cutting into the valley side below the high path. (C) Meander erosion exposing roots of trees on the right near the low path and depositing sediment on the lower energy inner side (left). (D) Wooden posts supporting boards at a meander, attempting to slow erosion.

Neoichnology

Most of the recent traces seen in Worsley Woods are footprints of humans and their dogs. But where smooth tree bark is covered by algae, it is likely that meandering land snail grazing traces may be common; they were also seen on a lamp post in Manthorpe Avenue, near the Greenleach Lane entrance, Figures 1 & 6. Carefully examination shows that the latter traces have serrated edges produced by the radulae of grazing land snails. No shells or snails were seen and the sandy soil would not be conducive to shelled gastropods, so these recent traces are probably the spoor of slugs. That the traces on the lamp post show the better detail is most probably due to their being made on a particularly smooth surface; that is, differences between Figures 6A and B are likely to be taphonomic (=preservational) rather than systematic (=produced by different snail species).

Figure 5: Slope dynamics as demonstrated by trees; photographs taken from high path unless stated otherwise. (A) These roots have presumably been exposed by the loss of soil, seen from the low path, but may also have had difficulty in penetrating sandstone beds close to the surface. (B) J-shaped curvature of tree roots on the right indicates down-slope movement by soil creep. (C) A fallen tree spanning the Kempnough Brook. The roots provide a section through the soil including angular blocks of sandstone.

Figure 6: Neoichnology; differing morphology of land snail grazing traces determined by substrate. (Scales in cm.) (A) A tree trunk near Beesley Green with trails clearly visible where snails have been grazing the algae growing on the bark. (B) Similar trails on a steel lamp post in Manthorpe Avenue, off Greenleach Lane. The detail of the pattern of grazing is better preserved on this smoother surface.

Acknowledgements

I thank my partner, Karen, for her gracious hospitality, and for understanding that sometimes a geologist needs to go and just look.

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GeoLancashire

A Local Group of the Geologists' Association
Established 1922
Charity number XT17278

http://www,geolancashire.org.uk

GeoLancashire began as the Lancashire Local Group of the Geologists' Association in 1922. The Lancashire RIGS Group was established in 1991 to identify, record and monitor sites of geological and geomorphological interest in the administrative county of Lancashire. In 2015, these two groups merged to become GeoLancashire.

A programme of illustrated talks and workshops is held during the winter months with field excursions, mainly in the summer months, to locations both within Lancashire and further afield.

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Publications

Ribble Valley/Catchment Geotrail Guides

Preston	Brockholes	Ribchester	Dinckley Gorge
Clitheroe	Long Preston	Shedden	

Other geological Guides

White Coppice (near Chorley), 2003
Clougha, Crook o'Lune and the Conder Valley
Beacon Fell Country Park (nearest station, Preston), 2008
Geology and Landscapes of Lancashire, 2008
Jumbles Country Park (near Bolton), 2009
The Hodder Valley, 2009
Lancaster Town Geotrail Guide (*in press*)

Contact: Jennifer Rhodes secretary@geolancashire.org.uk

Manchester Geological Association

Founded 1925

http://www.mangeolassoc.org.uk

MGA was formed in 1925 to bring together professional and amateur geologists in and around Manchester.

It is actively concerned in the conservation of key geological sites in the area and supports the work of Greater Manchester RIGS.

During the summer, field excursions are organised to places such as the Lake District, Scotland, Peak District and North Wales. In the winter, monthly lectures by expert speakers are held at the School of Earth, Atmospheric and Environmental Sciences at the University of Manchester.

Quarterly newsletters giving full details of trips and other news are mailed to members.

Full Membership (with correspondence by email) costs £16. If correspondence by post is requested, the cost is £18 per year. Associate members residing at the same address costs an additional £2 per adult per year.

Publications

A Lateral Key for the Identification of Commoner Lower Carboniferous Coral Genera (£2.25)
Contact: Niall Clarke, niallclarke01@gmail.com

Geology of Knutsford's Buildings and Cobbles (£1.50)
Contact Fred Owen, fredjowen@btinternet.com

A Building Stones Guide to Central Manchester (£6.00)
Contact Jennifer Rhodes, secretary@geolancashire.org.uk